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TONGA WATER SUPPLY MASTER PLAN PROJECT

Water Resources Report

by

A. Falkland

for

PPK Consultants Pty Ltd

and

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List of Abbreviations and Units

CL	chloride ion concentration
EC	electrical conductivity (or specific conductance)
ENSO	El Nino Southern Oscillation
ha	hectare (equivalent to ten thousand square metres)
kL	kilolitre (one thousand litres, equivalent to a cubic metre (m^3) of water
kL/day	kilolitres per day (same as cubic metres per day, m^3/day)
km	kilometre
km^2	square kilometres
L	litre
L/min	litres per minute
L/p/d	litres per person per day
L/s	litres per second
m	metre
m^3	cubic metre (equivalent to a kilolitre)
mm	millimetre
ML	megalitre (one million litres, equivalent to 1,000 m^3)
ML/day	megalitre per day
msl	mean sea level
RL	reduced level
SOI	Southern Oscillation Index
µS/cm	microsiemens per centimetre (unit of electrical conductivity).

Executive summary

Introduction

This report, one of a series of reports from the Tonga Water Supply Master Plan Study, presents the findings of a recent water resources study of the islands in the Kingdom of Tonga. It summarises previous work, documents recent and current investigations and recommends further investigations to gain a better understanding of the water resources. It also outlines details of a proposed national monitoring and protection programme and makes recommendations about legislation for water resource management and protection. It provides guidelines for the future development of water resources on each of the island groups.

Conclusions

The water resources of Tonga are primarily in the form of groundwater. Surface water resources are not present on most islands; exceptions are 'Eua and a number of the volcanic islands including Niuafo'ou and Niuatoputapu. Groundwater is mainly found as freshwater lenses which form beneath the surface of the limestone islands and above seawater due to the density difference between freshwater and seawater. There is not a sharp interface between the freshwater and underlying seawater but rather a transition from one to the other. The transition zone is often much wider than the freshwater zone. Freshwater lenses can only occur where there is sufficient recharge from rainfall and where the permeability of the island's geological formation is not too high as to cause rapid mixing of the recharge to the freshwater and underlying seawater.

As reported in previous reports on the water resources of the islands of Tonga, the available data on which to base a water resource assessment is sparse. Hence, a major conclusion is that the results of this study in terms of water resource assessment should be considered as preliminary only. The current initiatives of the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources to obtain basic and much needed water resource assessment data are a positive step to overcome this problem. It will be several years, however, before the preliminary estimates of yield of the water resources made in this report can be confirmed.

The Hydrogeology Unit has set up a well census database and salinity, temperature, pH and water level data are regularly obtained from a number of these wells and entered into the database. This information is a good start to an ongoing water resources monitoring programme in the Kingdom of Tonga.

The rainfall and climatic data collected in a number of islands of Tonga, particularly that data collected since 1947 by the New Zealand Meteorological Service, and more recently by the Tonga Meteorological Service, has enabled recharge estimates to be made from each of the main island. The recharge estimates are based on a water balance study using rainfall measurements, potential evaporation estimates and knowledge of soils and vegetation derived from a number of sources. Monthly recharge estimates have been made for the 44 year period from January 1947 until December 1990 for Tongatapu, Lifuka in the Ha'apai group and Vava'u island in the Vava'u group. Estimates of recharge on 'Eua have been made using assumed rainfall patterns based on a correlation of available data between 'Eua and Tongatapu.

Using the water balance approach, the following average recharge estimates as a proportion of rainfall and as an annual total were made:

- Tongatapu: 30% 528 mm
- Lifuka, Ha'apai group: 28% 478 mm
- Vava'u island, Vava'u group: 41% 917 mm.

Recharge on a monthly and annual basis can vary considerably. In drought periods recharge is often zero and, on islands where the roots of trees such as the coconut tree can reach the water table, the recharge can be negative. Negative recharge denotes a net loss of water due to the ongoing transpiration of the trees.

Recharge in the past decade has been below the long term average due to a lower average rainfall during this period. For instance, the rainfall on Tongatapu for the years 1981-1990 is only 80% of the 44 year average from 1947-1991.

Despite the shortage, and in some cases absence, of basic groundwater data, preliminary estimates have been made of the sustainable yields of freshwater lenses on the islands of Tonga. These estimates are based on the estimated recharge and a preliminary knowledge of the island's ability to retain fresh groundwater. The latter knowledge has been gained primarily from measurements of the thickness of freshwater using geophysical techniques supplemented by measurements of water table elevation and limited vertical salinity profiles. The sustainable yield estimates will be refined from groundwater monitoring information.

Current water use is estimated to be 38% of the sustainable yield in the western portion of Tongatapu and 9% for the remainder of the island. The proposed water development strategy in the Master Plan will increase the demand by the year 2011 to 90% of the sustainable yield in the western portion of the island and to 18% in the remainder of Tongatapu.

Daily rainfall data was used to analyse rainwater catchments estimate the optimum combination of roof area and storage volume. From the analyses of 20 years of daily rainfall data for Tongatapu, rainwater catchments cannot be viewed as a viable option as a sole source of water supply for average households on Tongatapu. The use of rainwater as a supplementary source of water is a viable option for domestic potable water. Some of the islands of the Kingdom of Tonga are too small to sustain a permanent freshwater lens and rainwater is therefore the only practical alternative.

In general, there are adequate but not plentiful water resources for basic needs on most islands, particularly in the most populated islands. As has been the general practice, groundwater should be utilised as a first priority. The supplementary use of rainwater for potable purposes should be encouraged. Where surface water exists (for example, 'Eua and Niuafo'ou), it can be used to supplement groundwater supplies.

On islands with the largest populations the stress on the groundwater resources is the highest. Tongatapu has the greatest population and the greatest development of groundwater. In general the available information including salinity data from 1965 to 1991 has shown that groundwater pumping from the lens is not leading to a destruction of the freshwater lens. Localised problems are evident in the narrow western end of the island, near the coastline particularly in the south and northeast, and in the narrow part of the island between the Mu'a villages and Haveluliku. In all but the last case, the slight increase in salinity could be as a result of natural causes. There has generally been a slight increase in salinity of groundwater at the water table during the past decade but this is believed to be caused by the lower than average recharge.

Significantly, the pumping from the Mataki'eua/Tongamai wellfield which supplies Nuku'alofa with water does not indicate any long-term deleterious effect on the freshwater lens in that location. This observation must be regarded as preliminary as it is based on limited salinity information and only information at the surface of the lens. Unfortunately and despite the excellent recommendations of some previous authors on the subject of water resources, a proper monitoring programme was not established until recently. In particular the recommendation of Lao (1985) concerning the need for monitoring boreholes which can provide vertical salinity profile information through the lens have gone unheeded. Now there is the opportunity to install such monitoring systems at selected locations.

The main islands in the Ha'apai group, particularly Lifuka show the effects of inappropriate pumping. The pumping at the Tonga Water Board wells is at too high a rate for the very thin freshwater zone and at those locations which has resulted in saltwater upconing at the wells. The lens can recover as has been shown when the pumps at wells are not used for some months, particularly if high recharge is experienced. For these islands which are much smaller than Tongatapu, it is considered that pump rates per well should not exceed 0.5 litres per second (L/s). On Lifuka, any further pumping wells should be sited closer to the western side of the island than the sites of the two Tonga Water Board wells.

In general the existing groundwater development on Vava'u has not caused any significant problems. However, the pump rates at the Neiafu wellfield on Vava'u island should be closely monitored as recent salinity readings indicate that the sustainable yield at this location may have been exceeded. Further water supply demands should be met by a new wellfield towards the centre of the island, about 2 km north of the existing wellfield.

It is essential that an ongoing monitoring programme be established throughout the Kingdom of Tonga, particularly in those areas where the greatest demands are made on the available water resources. Salinity measurements of the groundwater taken at the water table and very limited vertical salinity profiles taken at a number of sites on Tongatapu and on Lifuka in the Ha'apai group have shown their usefulness as a primary means of ongoing monitoring of the groundwater resources. Simple electrical conductivity meters have provided the salinity data for the monitoring programme established by the Hydrogeology Unit and will form an integral component of ongoing data collection.

It is essential that legislation be enacted to enable the freshwater resources of Tonga, particularly groundwater resources, to be properly managed including adequate planning, assessment, development, control, monitoring and protection. A Water Resources Act based on the draft prepared by Wilkinson (1985) should be prepared.

While electricity and diesel provide the main sources of power for water pumping, other alternatives (wind and solar) have also been tried. Wind powered pumping has not been generally successful due to damage to the towers in cyclones and severe weather. The towers are also susceptible to corrosion in the exposed marine environment. Extensive clearing of trees in some areas would be required to make wind pumping viable. For these reasons, the future of wind pumping in Tonga is doubtful.

Solar pumping has been tried with mixed success for a number of reasons, including poor initial selection of panel and pump combinations. Solar power does however provide a potential alternative to conventional power sources, particularly for relatively small pump rates. One of its potential disadvantages is that pumping can only occur for about one third of the 24 hour day which means that instantaneous pump rates must be about 3 times that of a continuously operating pump. In many circumstances, this mode of pumping will not adversely affect the quality of the groundwater. Solar pumping should be further evaluated particularly for the smaller water supply schemes.

Recommendations

It is recommended that:

1. Further groundwater and surface water investigations to obtain baseline water resources assessment data should be carried out in each of the island groups (refer to sections 5.1.9, 5.2.8, 5.3.9, 5.4.9 and 5.5.9).
2. Comprehensive water resources legislation in the form of a Water Resources Act should be drafted and introduced for the proper planning, assessment, development, control, monitoring and protection of water resources throughout the Kingdom of Tonga. The new legislation should use as a basis the draft legislation prepared by Wilkinson (1985) (refer to section 7).
3. The Water Resources Act should concentrate on issues related to water resources management and not be concerned with the details of water supply (such as metering, charging policy, etc.). It is recommended that water supply matters should be included into a revised Tonga Water Board Act or a new Water Supply Act.
4. The agency responsible for administering the Act should be the Ministry of Lands, Survey and Natural Resources. This Ministry is the agency with the necessary skills to monitor and protect the water resources of Tonga and accordingly it is appropriate that it should administer the provisions of the Act. A number of other agencies should be involved in supporting roles (refer to section 6.3).
5. The water resources monitoring programme started by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources be encouraged and strengthened to

become a national monitoring programme. The monitoring programme should primarily be undertaken by the Hydrogeology Unit with supplementary information provided by the Tonga Water Board, Ministry of Health and Village Water Committees (refer to section 6).

6. Salinity measurements of the groundwater should be used as the primary means of groundwater monitoring and resource evaluation with other methods including measurements of water table movement as useful secondary approaches.
7. Monitoring systems to obtain vertical salinity profiles in the freshwater lenses on Tongatapu, Lifuka in the Ha'apai group and Vava'u island should be installed and/or monitored at regular intervals. Installation costs, primarily associated with drilling, should be funded, if necessary, by an aid donor (refer to sections 5.1.9, 5.3.9, 5.4.9 and 6.10.5).
8. The ground water resources database maintained by the Hydrogeology Unit should be expanded to include other water resources information including surface water flows, rainfall and climatic data. This will enable all water resources data to be stored centrally and allow data analysis to be undertaken in a more effective way. A major data input to the expanded database is the rainfall and climatic data collected by the Tonga Meteorological Service.
9. Comprehensive water resource databases used in Australia and elsewhere should be evaluated for use in Tonga for the collection, processing, archiving, analysing and reporting of water resources and related information (refer to section 6.10.2).
10. An additional staff member should be allocated to the Hydrogeology Unit to assist with the processing, archiving and analysis of hydrological and hydrogeological data (refer to section 6.10.1).
11. Additional computing resources including a personal computer, printer and ancillary equipment should be procured (refer to section 6.10.3).
12. Training of staff in the Hydrogeology Unit in hydrology and hydrogeology should be part of an ongoing programme of staff development and training. As there are no suitable courses in Tonga, overseas training will be required. In addition, training in the use of computers including standard software packages is required. Computer training should be provided locally (refer to section 6.10.4).
13. Future upgrading of groundwater wellfields should include monitoring systems to obtain vertical salinity profiles. As a guide one monitoring system should be installed for every 10 production wells (refer to section 5.1.9).
14. Water resources development should follow the principles outlined in section 8. Use should be made of groundwater as a primary source of water wherever possible.
15. Drilled wells should be used as the primary means of groundwater development. In general these should not be sited closer to the coast than 500 m.
16. Pumping from wells should be continuous, where possible, rather than intermittent to minimise the effects of pumping from the freshwater lenses.
17. The supplementary use of rainwater should also be encouraged. Future rainwater catchment analyses for Tonga should make use of simulation methods using the long daily rainfall records which are available from a number of stations throughout the Kingdom.
18. Conventional desalination plants are not considered to be an appropriate technology at present for general use in Tonga due mainly to their high operation and maintenance requirements. The operation of the desalination plants on Nomuka should be monitored by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources to determine if this type of technology is an appropriate long-term strategy for that island.
19. Solar pumping should be properly evaluated from a technical and economic viewpoint for water pumping particularly in the many water supply systems on the remote smaller islands of the Kingdom of Tonga.
20. After approximately two more years of data collection, the available data should be reviewed and analysed in order to refine the estimates of sustainable yield provided in this report. Subsequent reviews should be undertaken at intervals not exceeding five years.

1. Introduction

This report presents the findings of a recent water resources study of the islands in the Kingdom of Tonga. It summarises previous work, documents recent and current investigations and recommends further investigations to gain a better understanding of the water resources. It also outlines details of a proposed national monitoring and protection programme and makes recommendations about legislation for water resource management and protection. It provides guidelines for the future development of water resources on each of the island groups.

This report is one of a series of reports from the Tonga Water Supply Master Plan Study. It was prepared, however, in such a way to be an independent report on water resources matters.

2. Organisations involved in Water Resources

The following organisations are involved in water resources assessment, development and management:

- The Ministry of Lands, Survey and Natural Resources is the agency responsible for assessment and monitoring (quantity and physical and chemical quality) of water resources throughout Tonga and for advice on future development and management of water resources. In particular, the recently established Hydrogeology Unit of this Ministry undertakes all the detailed technical assessment of water resources, establishes and maintains relevant databases concerning water resources development and monitoring and advises the Ministry on development proposals which impinge on the water resources.
- The Tonga Meteorological Service of the Ministry of Civil Aviation is responsible for operation and maintenance of key climatic stations throughout the Kingdom of Tonga, collection of records from other stations and forwarding of information to the New Zealand Meteorological Service for processing and archiving of data.
- The Ministry of Health is the agency responsible for implementing and maintaining village water supply schemes and for monitoring and surveillance of the biological quality of public water supply schemes.
- The Tonga Water Board is responsible for the planning, installation, operation and maintenance of public water supply systems in selected urban areas of Tongatapu, 'Eua, Ha'apai and Vava'u.
- The Village Water Committees are responsible for operating and maintaining the physical components of village water supply systems.
- The Central Planning Department is responsible for overall co-ordination and monitoring of aid projects, and for co-ordination of development plans including those affecting the water sector. They also provide the secretariat to the Water Resources Committee.
- The Water Resources Committee, a sub-committee of the Development Co-ordination Committee, is responsible for initiating and reviewing development and other proposals related to water resources, and making recommendations to the Development Co-ordination Committee for forwarding to Cabinet. The Water Resources Committee comprises representatives from government organisations with interests and responsibilities in water. It is chaired by the Director of Planning (Central Planning Department) and currently includes the following members:
    - Director of Health
    - Director of Works
    - Director of Agriculture
    - Manager Tonga Water Board
    - Secretary for Finance
    - Secretary for Lands, Survey and Natural Resources
    - Secretary for Labour, Commerce and Industries
    - Solicitor General.

- The Ministry of Works owns the only drilling rig used for production and monitoring boreholes in the Kingdom of Tonga.
- The Ministry of Agriculture is responsible for promoting agricultural production and the possible use of irrigation for sustaining growth of vegetables during prolonged dry periods. This Ministry is also responsible for the Vaini Experimental Farm where a well equipped climate station is operated and maintained.
- The Ministry of Finance is responsible for the national budget and thus has an impact on capital and recurrent funding of water resources and water supply projects.
- Private consumers in the domestic, industrial and agricultural sectors. Some of these consumers pump significant quantities of groundwater from the freshwater lens (for example, the Church of the Latter Day saints at Liahona on Tongatapu) or use significant quantities of water from the reticulated water supply (for example, the Royal Beer factory in Nuku'alofa).

It is apparent that there are a large number of organisations with interests in water. Further details of institutional arrangements as they affect the water sector are contained in the accompanying Institutional Strengthening and Community Master Plan.

3. Physical description

3.1 Physiography

The Kingdom of Tonga consists of over 175 named islands spread between latitudes 15°S and 23°30"S and longitudes 173°W and 177°W in the South Pacific Ocean (Figure 4.1). The total land area is 747 km^2 while the sea area extends over about 397,000 km^2 (ESCAP, 1990). The population lives on 43 of the islands with a total land area of 649 km^2 (87% of the total land area).

The Kingdom of Tonga (Figure 4.2) consists of three main island groups: the Tongatapu group in the south, the Ha'apai group in the centre and the Vava'u group in the north. Further to the north of the Vava'u group are the Niuas consisting of three inhabited islands, namely, Niuafo'ou, Niuatoputapu and Tafahi. To the south of the Tongatapu group lies the uninhabited island of 'Ata.

The islands can be separated into a western line of islands of volcanic origin, steep topography and generally high elevations and an eastern line of generally low-lying limestone and mixed geology islands. Amongst the western group are Tofua (507 m), Kao (1030 m), Late (519 m), Niuafo'ou (260 m), Niuatoputapu (106 m) and Tafahi (548 m). The eastern group where the majority of the population lives consists of Tongatapu (65 m), 'Eua (312 m) and most of the islands of the Ha'apai and Vava'u groups.

3.2 Climate and hydrology

3.2.1 General

The climate of Tonga has been well described by Thompson (1986) and it is not intended to reiterate the descriptions and detailed data presented therein except to provide a summary of these elements which affect water resources.

In summary, the Kingdom of Tonga has a semi-tropical climate with moderate rainfall and high relative humidity. A seasonal trend is noticed with a relatively wet season extending from November to April and a relatively dry season from May to October. On average, approximately two thirds of the annual rainfall falls during the wet season.

Mean temperatures vary in Tongatapu between 21.4°C in July to 26.3°C in February. In Niuatoputapu, mean temperatures vary between 25.5°C in August to 27.4°C in February. In addition throughout the islands of Tonga:

- Mean vapour pressures (and relative humidities) are highest in February and lowest in July
- Sunshine hours, an indicator of solar radiation, are highest in the months of November to January and lowest in July

- Average wind run is variable between months and islands. Most winds are from the east and south-east.

Cyclones periodically affect the islands of Tonga, the last major one being Cyclone Isaac in March 1982. Considerable damage to property and crops was sustained during the passage of Isaac, particularly on Tongatapu and in the Ha'apai group of islands.

The El Nino Southern Oscillation (ENSO) phenomenon, a feature of the climate of the Pacific Ocean, has a marked effect on the climate of Tonga. Its effect is particularly noticeable on the rainfall patterns. The major ENSO event in 1982/83 caused an extensive drought throughout the islands of Tonga as in many other parts of the western Pacific (van der Brug, 1983; Falkland, 1989).

3.2.2 Availability of records

Climatic information (including rainfall, temperature, vapour pressure, wind speed and direction, sunshine hours and cloud cover) is available from the following stations:

- Nuku'alofa, Tongatapu (1947-1990)
- Fua'amotu, Tongatapu (1983-1990)
- Lifuka, Ha'apai (1947-1990)
- Neiafu, Vava'u (1947-1990)
- Niuatoputapu (Keppel) (1947-1990)
- Niuafo'ou (1971-1990).

Similar climatic information is also available from the Vaini Experimental Farm on Tongatapu since 1981. Intermittent climatic information is available from 'Eua. Additional rainfall information has been collected at the following locations on Tongatapu: Fua'amotu, Mu'a, Vaini, Mataki'eua (formerly Fuala), Liahona (now closed) and Fo'ui (formerly Kolovai).

The data is assembled by the Tonga Meteorological Service and forwarded to the New Zealand Meteorological Service for processing and archiving.

In addition to the above official records, rainfall records have been collected discontinuously since 1881 on Tongatapu (Thompson, 1986) but records are not readily available for this period. Intermittent monthly rainfall data from 1927 is tabulated in Taylor (1973). Hasan (1989) refers to a study by Spennemann which reviewed rainfall data from 1888 to 1987. The study by Spennemann (1989) refers to intermittent records from 1988 as follows: monthly mean data from 1888 to 1891, monthly and annual data for the years 1913-1914 1923-1924, 1926-1941 and 1945-1987, and annual data for the period 1917-1921. One significant aspect of the Spennemann study is that the drought in 1982 was the longest from the available record.

The period of record from 1947-1990 was used for most of the water resources studies used in this report. Reference to the available earlier records is made for comparison purposes.

3.2.3 Rainfall

The islands of Tonga are influenced by rainfall of both convectional and cyclonic origin. Orographic influences can affect rainfall distribution on high islands but not on the low lying islands.

Using the rainfall record from 1947 to 1990, the annual rainfall statistics as shown in Table 4.1 were derived.

Full listings and selected statistics (mean, standard deviation, coefficient of variation, maximum and minimum) of monthly and annual rainfall from 1947 to the present for the first four stations in Table 4.1 are shown in Appendix A. Appendix B contains a listing of annual rainfall for the same four stations from 1927 to the present.

The annual rainfall patterns on Tongatapu, Ha'apai, Vava'u and Niuatoputapu for the period 1947 to 1990 are plotted in Figure 4.3 for comparison purposes. The higher rainfall in Vava'u and Niuatoputapu than in Tongatapu and Vava'u are evident from these figures.

A measure of the variability of rainfall is the coefficient of variation (Cv). Cv values for annual rainfall are listed for the main climate stations in Table 4.1. The Cv for Niuafo'ou rainfall is the highest but this is due mainly to the shorter period of record. For the stations with the longer records, Ha'apai shows the highest annual Cv followed by Tongatapu. Vava'u and Niuatoputapu show the lowest annual Cv values. Thus, the northern islands in Tonga have higher and less variable annual rainfall than those in the centre (Ha'apai) and south (Tongatapu).

Table 4.1 Annual rainfall statistics for period 1947-1990

Location	Records	Mean	Std Dev	Cv	Max	Min
Nuku'alofa, Tongatapu	1947-90	1,770	425	.24	2,655	838
Lifuka, Ha'apai	1947-90[a]	1,716	450	.26	2,664	826
Neiafu, Vava'u	1947-90	2,231	436	.20	3,020	1,281
Niuatoputapu (Keppel)	1947-90[b]	2,301	461	.20	3,119	1,435
Niuafo'ou	1971-90[c]	2,343	635	.27	3,573	878

Notes:

a: 6 years with missing data : 1959,1960,1969,1972,1976,1982

b: 6 years with missing data : 1955,1966,1977-80

c: 3 years with missing data : 1972,1976,1980 (8 years of data had one month missing which was estimated using the mean monthly value. These were 1971,1973,1975,1977,1979,1987,1988 and 1990)

Std Dev: standard deviation

Cv: coefficient of variation

Mean monthly rainfalls for the period 1947 to 1990 for the same four stations are plotted in Figure 4.4. The trend of highest rainfall from November to April can be seen, although Tongatapu indicates a lower mean monthly rainfall in November than in the preceding two months. The highest monthly rainfalls are recorded in March at all stations except Vava'u with it showing the highest in February. In the dry season, the differences between the monthly rainfalls at each of the four stations is small yet in the wet season the higher rainfalls on Niuatoputapu and in the Vava'u group than on Tongatapu and in the Ha'apai group are evident.

The Cv of monthly rainfalls are plotted in Figure 4.3 which shows that in general the least variability occurs on all islands in the month of March and the highest in November. In general, Niuatoputapu shows lower values of monthly Cv than the other islands.

Further comments on rainfall according to islands or island groups are provided in sections 5.1 to 5.5. An analysis of the spatial variation of rainfall on Tongatapu was undertaken using the available records from the rainfall stations on the island. The results are summarised in section 5.1.1.

3.2.4 Evaporation

For water resource assessment studies, evaporation is a key component. The actual evaporation from an island such as those in the Kingdom of Tonga is controlled by many factors including the amount of solar radiation, the temperature, the vapour pressure (or relative humidity), the wind speed, the soils and the vegetation.

Mean monthly potential evaporation estimates are provided by Thompson (1986) for a number of the islands in Tonga using climatic data. These were derived from climatic data using the Penman equation (Penman 1948, 1956). The potential evaporation estimates and climatic data are reproduced in tabular form in Appendix C for Tongatapu, Ha'apai, Vava'u and Niuatoputapu and in graphical form in Figure 4.6. As can be easily seen from Figure 4.6, the highest potential evaporation occurs in the wet season from November to April and the lowest occurs in the dry season from May to October.

On Tongatapu, daily pan evaporation records were available from the Vaini Research Farm from 1982 until 1989. These were processed into monthly pan evaporation figures and are shown in Appendix D. There are some anomalies in the data which may need further investigation but in general the data appears to give reasonable estimates of pan evaporation. To convert the mean annual pan evaporation to mean annual potential evaporation (from Thompson, 1986), a pan factor of 0.82 is required which is a typical value for the factor. For individual months the pan factor varies from 0.72 to 0.99. This data was used as a check on the water balance results using the potential evaporation estimates (refer section 5.1.6).

3.3 Geology

The islands of Tonga are situated on the Tonga-Kermadec Ridge to the east of the Lau Basin and to the west of the Tonga Trench, a deep sea trench (10,000 m below sea level) which separates two tectonic plates, the Indo-Australian Plate from the Pacific Plate. The ridge is formed by the subduction of the western edge of the Pacific Plate under the eastern edge of the Indo-Australian Plate. Located within the island group and approximately parallel with the Tonga trench is a smaller scale depression (1,800 m below sea level) called the Tofua Trough.

The islands to the west of the trough are of volcanic origin and some are still active with more than 35 recorded eruptions in the last 200 years. The western islands include 'Ata, Hunga Ha'apai, Hunga Tonga, Tofua, Late, Niuafo'ou, Niuatoputapu and Tafahi (refer Figure 4.2).

The islands to the east of the trough are generally low-lying coral limestone islands built from reef deposits deposited at times when sea level was higher. The eastern islands, which are older than the western islands, are built on Tertiary to recent volcanic sediments. These islands include Tongatapu and the Ha'apai and Vava'u groups of islands. A number of small sand cays are also evident in the eastern islands, most notably in the Ha'apai group.

Islands of mixed geology also occur, the most notable being 'Eua which is comprised of reef limestones over a volcanic basement which is exposed on the eastern side of the island. This island is unique in the eastern group in that its elevation reaches over 300 m compared to the relative flat topography of most of the other eastern islands. The island of Mango in the Ha'apai group is another example of a mixed geology island with coral limestone capping two volcanic hills at each end of the island (Wilson and Beecroft, 1983).

3.4 Outline of water resources

3.4.1 Groundwater

The freshwater resources of the Kingdom of Tonga consist mainly of groundwater in the form of freshwater lenses. Freshwater lenses form on top of seawater in many of the islands due to the difference in density of the two fluids. The interface, or boundary, between the two fluids is not sharp but rather is in the form of a transition zone. Within the transition zone the water salinity increases from that of freshwater to that of seawater over a number of meters.

The upper surface of a freshwater lens is the water table. The salinity of the upper surface can be obtained by measurements at exposed water surfaces such as existing wells and pumping galleries or additional dug or drilled holes.

The lower surface of the freshwater zone can only be determined by establishing a recognisable salinity limit for freshwater and drilling through the lens to find where the limit occurs.

The salinity limit adopted for freshwater (suitable for drinking water) is taken as 2,500 µS/cm (also referred to as µS/cm) at 25ºC as measured by an electrical conductivity (specific conductance) meter. This is approximately equivalent in small limestone islands to a chloride ion concentration of 600 mg/l which is the 'maximum permissible' limit shown in the former World Health Organisation guidelines for drinking water quality (WHO, 1971). The more recent WHO guidelines (WHO, 1984) give a more stringent guideline value of 250 mg/l. WHO recognise that this limit for chloride is not based on health considerations but rather on taste considerations. The higher limit of 600 mg/l is considered appropriate given the setting of these islands. Other small islands and nations (for example, Kiribati) have also adopted the higher limit. In most cases, the salinity of groundwater supplies used for potable purposes will be less than this upper limit.

A cross section through a typical small island showing the main features of a freshwater lens is presented in Figure 4.7. It must be noted that there is considerable vertical exaggeration in the diagram. Also, the transition zone tends to be thicker in comparison with the freshwater zone on many small atolls and there is often an asymmetric shape to the lens with the deepest portion displaced towards one side of the island.

The thickness of freshwater and transition zones are dependent on many factors but the most important are:

- Rainfall amount and distribution
- Amount and nature of surface vegetation and the nature and distribution of soils (these factors influence the evapotranspiration)
- Size of the island, particularly the width from sea to lagoon
- Permeability and porosity of the geological formation, and the presence of cave systems and solution cavities
- Tidal range
- Methods of extraction and quantity of water extracted by pumping.

According to classical 'Ghyben-Herzberg' theory (Badon Ghyben, 1889; Herzberg, 1901), for every unit height of fresh water occurring above mean sea level (msl) there will be about 40 equal units of underlying fresh water below msl. This theory assumes that the two fluids, freshwater and seawater, are immiscible (i.e. that they do not mix). In practice, the two fluids do mix due to mechanical and molecular diffusion and a transition zone forms with salinity gradually increasing from that of freshwater to that of seawater. In practical situations, the 1:40 ratio can be used as a guide to determine the mid-point of the transition zone from the water table elevation above msl. It does not provide a means of determining the base of the freshwater zone. Other methods particularly vertical salinity profiles obtained from properly installed observation boreholes are required to determine the salinity gradient from the freshwater to the mid-point of the transition zone.

For small coral sand islands, a relationship has been derived (Oberdorfer and Buddemeier, 1988) between freshwater lens thickness, annual rainfall and island width as follows:

$$H/P = 6.94 \log a - 14.38$$

where

H = lens thickness (depth (m) from water table to sharp interface or mid-point of transition zone)

P = annual rainfall (m)

a = island width (m).

This equation indicates that no permanent freshwater lens can occur regardless of rainfall where the island width is less than about 120 m. Using an annual rainfall of 1,700 mm (likely minimum in Tonga), the minimum island width for a small freshwater lens (say 5 m thick) to occur is 300 m. However, most of the islands within Tonga are made of limestone and have much higher aquifer permeabilities (typically 1000 m/day or more) than coral sand islands (typically 10 to 100 m/day in the freshwater zone). This means that freshwater and seawater can more easily mix in the limestone islands and that a wider island than 300 m would be required to support a freshwater lens. As freshwater lens thickness is inversely proportional to the square root of the aquifer permeability (refer section 5.4.6), the minimum width for a permanent freshwater lens to occur on a limestone island in Tonga is between about 900 m and 3 km. Not all islands are comprised entirely of high permeability limestone, so that smaller widths of say 500 m to 900 m may well support freshwater lenses where sand deposits are present within the limestone.

Groundwater may also be available from fractured rock aquifers on the volcanic islands. There do not appear to have been any investigations into this type of groundwater on the volcanic islands of Tonga. Based on tests on other volcanic islands in the region (for example, Waterhouse and

Petty, 1986), yields of freshwater from fractured rock aquifers on small volcanic islands are low (typically about 1 L/s).

3.4.2 Surface water

Surface water resources are only evident on some of the high volcanic and mixed geology islands in the form of springs and lakes. Crater lakes exist, for instance, on the islands of Niuafo'ou and Tofua. It is reported that the former lake has been used in dry periods as a source of potable water. Surface water is collected from cave systems on the island of 'Eua and used for potable water supply.

3.4.3 Rainwater

Rainwater systems are another freshwater resource for the islands and they represent an important source of potable water on many of the islands. On some of the smaller islands in the Ha'apai and Vava'u groups they are the only source of freshwater.

3.4.4 Desalination

Desalination systems represent a possible further means of freshwater production. It is reported (Pacific Islands Monthly, 1991) that two small desalination plants were installed for public water supply on the island of Nomuka in the Ha'apai group in early 1991. The combined capacity of these reverse osmosis plants is 25 kL/day. These plants were supplied under a United States aid project (US Army Pacific's Expanded Relations Project) and was reported to have cost US$80,000. Operation of the plants is left to the residents of Nomuka.

The operation of the desalination plants on Nomuka should be monitored by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources to determine if this type of technology is an appropriate long-term strategy for that island.

3.5 Soils

Most of the islands of Tonga have a soil layer overlying coral limestone. The soils are mainly derived from andesitic tephra (volcanic ash). Other soils including coral sands and lagoonal sands and mud are also found.

It is believed that the tephra was deposited by a series of volcanic eruptions from emergent volcanoes such as Tofua and Kao and from submarine volcanoes to the west. Two types of tephra are found, corresponding to two main phases of ash accumulation, one occurring earlier than 20,000 years ago and the other occurring between 5,000 and 10,000 years ago. Generally, soils on the west side of the islands are thicker and have larger particle sizes while those on the east side are thinner and are made of finer ashes.

Detailed soil studies on many of the islands of Tonga have been undertaken. These include:

- Tongatapu: Gibbs (1976) and Cowie (unpublished)
- 'Eua: Wilde and Hewitt (1983)
- Ha'apai group: Wilson and Beecroft (1983
- Vava'u group: Orbell et al (1985).

It is not intended to give a detailed description of the soil types in this report as these are peripheral to the topic of water resources. Only those factors which impinge on water resources are considered.

From a groundwater resources viewpoint, the factors which are important with soils are the rate of infiltration, the thickness and the moisture contents at both field capacity and wilting point.

The soils over most of the island are highly permeable and allow rainfall to readily infiltrate. Lao (1978) reports an infiltration test at Mataki'eua on Tongatapu which showed that about 300 mm could infiltrate in one hour followed by 75 mm in a second hour. These infiltration rates are very high and are the reason that surface runoff does not occur except in local areas of compacted soils.

In some areas of the islands of Tonga, for instance along the northern coast and around the lagoon of Tongatapu, the soils are far less permeable and ponded water is often found after rainfall. These less permeable soils cover a small proportion only of the islands and it can reasonably be assumed from a water resources viewpoint that surface runoff into the sea or lagoon is nil. This assumption was used in the water balance studies. The one exception is 'Eua where surface runoff occurs due to springs emanating at cave entrances in elevated terrain. Further discussion of the surface runoff component in the water balance of 'Eua is given in section 5.2.6.

The thickness of the soil for the purposes of the water balance studies (refer sections 5.1.6, 5.3.6 and 5.4.6) was selected as 1 m (1,000 mm). While thicker soil zones are present on some islands and parts of other islands, the root zone of most crops except the tall trees is within the top metre of soil.

Field capacity (the maximum moisture content that soil can retain) and wilting point (the minimum soil moisture content to sustain plant growth) have been measured for a number of soils in different parts of Tonga. No data could be found for Tongatapu soils (not reported in either Gibbs, 1976 or Cowie, unpublished) yet reports on the soils of 'Eua (Wilde and Hewitt, 1983), the Ha'apai group (Wilson and Beecroft, 1983) and the Vava'u group (Orbell et al, 1985) have considerable data. This data was derived from laboratory tests by applying certain suctions to soils (normally 15 bar for field capacity and 0.3 bar for wilting point) and measuring the water content. Results are summarised in Table 4.2.

Table 4.2 Soil moisture properties

Island	Field capacity (FC)	Wilting point (WP)	Available water (FC - WP)
'Eua	0.43-0.65	0.30-0.53	0.08-0.29
Ha'apai	0.49-0.64	0.27-0.50	0.14-0.23
Vava'u	0.37-0.60	0.30-0.53	0.07-0.15

The differences for each island are due to both soil type and depth of sample.

Values of 55% and 40% were selected as reasonable estimates for field capacity and wilting point giving the available water within the soil zone as 15%. These values were used in the water balance analyses, as described in sections 5.1.6, 5.3.6 and 5.4.6. A sensitivity analysis was conducted in the case of the Tongatapu water balance to determine the effects of varying these parameters (refer section 5.1.6).

As the soils on Tongatapu have physical properties similar to many of those found on other islands throughout Tonga, it is a reasonable approach to use average values derived from soils on other islands.

3.6 Vegetation

There is a wide diversity of vegetation types throughout the islands of Kingdom of Tonga. A description of the various types are given in ESCAP (1990).

From a water balance viewpoint, the vegetation can be classified as either shallow rooted or deep rooted. The shallow rooted vegetation which includes grasses, crops and shrubs obtain their moisture requirements from the soil moisture zone. The deep rooted vegetation consists of those trees whose roots can, where conditions are favourable, penetrate below the soil moisture zone and through the unsaturated zone to the water table. Coconut trees are a typical example of deep rooted vegetation on the islands of Tonga. In relatively shallow areas, coconut trees typically have some roots within the soil moisture zone and some which penetrate to the water table.

The significance of roots which can reach the water table is that transpiration can occur directly from the freshwater lens, even during drought periods. Vegetation of this type is referred to as a phreatophyte and is common on coral atolls where the depth to the water table is typically 2 to 3 m. Coconut trees have been reported (Ohler, 1984) to extend their roots to a depth of at least 5.5 m.

There is no direct evidence to substantiate the rooting depth of coconut trees in Tonga but it could reasonably be assumed that a proportion of the roots of coconut trees growing on areas of the islands where the depth to water table is 5 m or less can reach the water table.

On most parts of the main islands of the Ha'apai group the depth from the surface to water table is higher being in the order of 5 to 8 m in many places and up to 15 and more metres in elevated parts of the islands. On Tongatapu the depth to water table in the area close to the lagoon is less than about 5 m. However, in these low lying areas there are not many deep rooted trees present in comparison to shallow rooted vegetation. On 'Eua and in the Vava'u the depths to water table are generally too high for roots to penetrate through to the water table.

Further discussion of the influence of vegetation on the water balance in each of the islands or island groups are contained in sections 5.1.6 (Tongatapu), 5.3.6 (Ha'apai) and 5.4.6 (Vava'u).

4. Water Resources Assessment

4.1 Tongatapu

4.1.1 Physical outline

Physiography and demography

The island of Tongatapu is the largest in the Kingdom of Tonga with a surface area of approximately 257 km^2. It is centred about latitude 21°10' S and longitude 174°10' W. The surface of the island is roughly triangular in shape with a 'hook' in the northwest (Figure 5.1).

An enclosed lagoon has an entrance along the northern coastline and has the effect of separating the island into three geographical regions: western, southeastern and eastern. These arbitrary regions have been used by other authors (for example, Lao, 1978 and Kafri, 1989) and will also be used in this report to describe the island.

The island's topography is subdued with the island rising slowly from the north to elevated terrain and cliffs along much of the southern and eastern shorelines. The maximum elevation on the island is 65 m above msl which occurs approximately 500 m in from the coastline in the southeastern part of the island.

The population of the island is 63,794 (1986 census). Most of the population is located in the capital, Nuku'alofa.

Geology

Tongatapu is a raised coral atoll and is located on the crest of a large submarine fold. It is located west of the Tonga Trench and east of the Tofua Trough. Like other low lying islands in the eastern side of Tonga, Tongatapu is being subducted into the Trench.

The surface geology consists of coral limestone overlain in most parts of the island by a layer of soil derived from volcanic ash. The thickness of the limestone varies from about 170 m near Nuku'alofa to about 230 m on the east coast.

Test drilling for oil on the island to a depth of about 2,600 m indicated that a complex sequence of marine sediments and volcanic strata exists below the limestone.

Further details of the geology of the island are presented in Pfeiffer and Stach (1972) and Lao (1978).

Hydrogeology

The coral limestone layer is the important feature from a hydrogeologic viewpoint as it is within this zone that fresh groundwater is found in the form of a freshwater lens floating on denser seawater. A transition zone exists between freshwater and seawater. Freshwater from the lens discharges to seawater at the edge of the island as either diffuse or concentrated outflow. Water may be seen in some places around the edge of the island discharging as springs and diffuse flow during low tide. Freshwater can also be lost from the lens by mixing with underlying seawater due to diffusion, largely induced by tidal fluctuations, variations in recharge and pumping.

The limestone is karstic in nature with many large openings including caves at sea level. From drilling information, solution cavities are known to exist at different levels above sea level. Discharge from the freshwater lens is increased by the presence of solution cavities and caves.

At a regional scale, the limestone on Tongatapu has a high permeability within the freshwater and transition zones. Based on pump test data from a borehole at Mataki'eua, a permeability estimate of approximately 1,300 m/day was derived by Hunt (1978). Recent modelling of the freshwater lens in the western portion of the island using a sharp interface model (MODFLOW) by the Hydrogeology Unit showed that a permeability of about 1,500 – 2,000 m/day was required to calibrate the model against observed water table elevations.

There are no permanent drainage paths on Tongatapu owing to the highly permeable soils and surface geology. Temporary runoff occurs on a local scale in areas where the soils are compacted or paved. Most of the runoff ponds in depressions where it either evaporates or infiltrates the soil. A very small proportion of this runoff may discharge to the sea or the lagoon.

<u>Soils</u>

The soils of Tongatapu which overlie coral limestone are mainly derived from andesitic tephra (volcanic ash). Other soils which cover relatively small portions of the island are coral sands and lagoonal sands and mud.

The older tephra layer (refer section 4.5) varies from about 1 m to 2.5 m in thickness and is strongly weathered. The older tephra is overlaid in all but the extreme east of the island by a younger tephra. The thickness of the younger tephra varies from about 3.5 m on the western coast to less than 0.4 m on the eastern coast.

Coral sands occur mainly along the north coast of the island. In some places such as the north west of the island the sands contain significant quantities of pumiceous lapilli and tephra. Lagoonal sands and muds border the lagoon and are also found along parts of the northern coast.

A discussion of soils as it affects the water balance of the island is provided in section 5.1.6.

<u>Vegetation</u>

The island is planted with a variety of vegetation including coconut trees and many crops including tapioca, yams and other root crops. In recent years crops such as squash pumpkin have been more popular as cash crops owing to high demand from overseas. Details of crops are given in ESCAP (1990).

The impact of vegetation on the water balance of the island is discussed in section 5.1.6.

4.1.2 Present water resources development

Water resources development on the island consists of groundwater extraction from public and private wells, both dug and drilled, and collection of rainwater from roofs.

Most villages on the island have a dug or drilled well which is pumped for a number of hours each day to a head tank. Water is reticulated to houses in most cases. Records are not kept of pumping hours, except on some newly installed pumps which are equipped with hour meters, so it is difficult to assess the amount of water pumped from each well. Kafri (1989) estimated that the combined village or 'rural' pumping on Tongatapu in 1989 was between 3.3 and 4.1 megalitres per day (ML/day). The instantaneous pump rates at each well vary according to the type and age of motor and pump, and the length of suction and delivery pipes. Most estimates of pump rate are about 3 to 5 L/s).

The largest groundwater development is at Mataki'eua/Tongamai located about 5 km southwest of the centre of Nuku'alofa. At present (March 1991) there are 31 dug and drilled wells at the Mataki'eua/Tongamai wellfield (24 at Mataki'eua and 7 at Tongamai). Of the 31 wells, 24 are equipped with either electric or diesel pumps (22 at Mataki'eua and 2 at Tongamai) and 22 of these were operating in March 1991. The remaining wells are not equipped with pumps or have been abandoned. The location of the wells and the corresponding well numbers (from the recent well census by the Ministry of Lands, Survey and Natural Resources) are shown in Figure 5.1. The total pump rate of the 22 operating pumps is approximately 5.3 ML/day (or 61 L/s). The average pump rate of each operating well is, therefore, about 2.8 L/s.

4.1.3 Previous water resources investigations

A number of groundwater investigations and studies were conducted prior to those recently undertaken by the Hydrogeology Unit within the Ministry of Lands, Survey and Natural Resources.

The most relevant of the previous studies are:

- Pfeiffer and Stach (1971, 1972)
- Waterhouse (1976)
- Hunt (1978)
- Lao (1978)
- Kafri (1989)
- Hasan (1989).

Before the recent investigations by the Hydrogeology Unit, knowledge of the groundwater resources was largely based on observations of water table elevations and surface salinity readings in wells. Observations were not made on a regular basis until recently when a systematic monitoring programme was implemented by the Hydrogeology Unit.

Three deep boreholes which penetrated through to seawater were drilled in 1974 to enable vertical salinity profiles through the freshwater and transition zones to be obtained. Initial sampling was considered too crude to provide useful results (Lao, 1978). During Lao's visit to the island in late 1978, in situ electrical conductivity readings were obtained from the three deep holes (Figure 5.2). From Figure 5.2, it can be seen that the thickness of the freshwater zone (defined by an upper limit of electrical conductivity of 2,500 µS/cm) varied from 11 to 13 m at the three locations. The thickness of the lens to the mid-point of the transition zone is approximately 17 m in all three cases. It could reasonably be assumed that the maximum thickness of the freshwater lens on Tongatapu, as measured to the mid-point of the transition zone, is about 20 m. Unfortunately all three boreholes cannot presently be sampled: two are now production boreholes while the third, at Kolonga, has an obstruction in it. The boreholes are open so that any monitoring results would need to be treated with caution as mixing in the water column can lead to salinity profiles being unrepresentative of the surrounding aquifer.

In addition to the collection of basic data, studies of recharge and sustainable yield have been undertaken by a number of authors. Details are presented in section 5.1.6.

Salinity and water table level data from some wells on the island have been obtained at irregular intervals since 1965 (and in one case since 1959). Years when such data was obtained from wells include 1971, 1979, 1980, 1981, 1983 and 1987. Salinity data takes the form of chloride ion concentrations on some occasions and electrical conductivity readings on other occasions. Most of this data is available from a summary sheet on a Tonga Water Board file with additional data listed in Kafri (1989). The type and accuracy of the instruments used to obtain the data and the accuracy of the transcriptions to summary sheets and other reports is not known. Discussions with the Manager of the Tonga water Board (Mr. Filipe Koloi) revealed that most of the early measurements were done with a portable meter which eventually became unusable. He suggested that some of the readings should be treated with caution.

Water samples from different areas of Tongatapu were tested in 1989 for residues of two types of pesticides, carbofuran and oxamyl. Nine samples were tested for carbofuran and three samples were tested for oxamyl. All samples were found to be free of residue. The samples were tested for levels of 0.1 parts per billion Tongatapu for carbofuran and 20 parts per billion for oxamyl.

4.1.4 Recent groundwater resources investigations

The investigations outlined in this section are primarily those which have been undertaken by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources.

The investigations by the Hydrogeology Unit were commenced in early 1990 with the appointment of a hydrogeologist under the Australian Staffing Assistance Scheme on a two year contract to assist them with the investigations, assessment, planning for development and management of the water resources of the Kingdom of Tonga.

The recent investigations by the Hydrogeology Unit, many of which are ongoing, are summarised as:

- A census of all public and many of the private wells (dug wells and drilled wells) on the island including collection of data about the location, co-ordinates, reduced level (where possible) of a surface benchmark, and type of pump if fitted. Approximately 220 wells are included in the well census,
- Depth to water table and water quality measurements (electrical conductivity, temperature and pH) at selected wells),
- Tide recording to determine magnitude of sea level fluctuations,
- Electromagnetic and electrical resistivity surveys adjacent to the Mataki'eua/Tongamai wellfield,
- Level surveys of benchmarks at wells in the western end of the island,
- Establishment of an automatic recording station for water table elevation, rainfall and barometric pressure at Liahona,
- Calibration of a computerised groundwater model (United States Geological Survey 'MODFLOW' program) for the western part of the island using recently surveyed water table elevation data with the objective of using the model to better understand the freshwater lens dynamics, including the effects of groundwater extraction from present and proposed wellfields,
- Siting and drilling of production wells for a number of villages on the island. Water quality tests obtained at these new holes has assisted the knowledge of salinity variations at the water table over Tongatapu, and
- Siting and drilling of four wells for monitoring vertical salinity profiles (refer Figure 5.1). Three salinity monitoring boreholes are located between the Mataki'eua wellfield and Fanga'uta lagoon. These have openings at various depths below the water table to measure the variation of salinity with depth. A similar hole was drilled at Fuala quarry between Mataki'eua and Liahona. The results of this recent investigation of vertical salinity profiles were not available in time to incorporate them into the main body of the report; they are summarised, however, in section 5.1.7 with further details provided in Appendix E.

Recent investigations also include water quality sampling of wells by the Tonga Water Supply Master Plan project team in conjunction with staff from the Hydrogeology Unit in February/March 1990. This work involved the inspection and collection of salinity (electrical conductivity) data at selected wells and other sites on Tongatapu. Similar tests were made on 'Eua and the main islands of the Ha'apai and Vava'u groups.

The results of water quality and water level tests were entered into a database called 'MONITOR' (using the dBaseIII+ computer software package) which is shown in Appendix F for each well included in the recent census. Where zero values are shown in the results, no reading was obtained. Figure 5.1 shows the location of the wells and Appendix G provides selected details of each well from the well census database (called 'WELLS'). Some data is missing and other data requires further checking to ensure its accuracy. Thus, the data as shown should be regarded as indicative only at this stage.

Early salinity data was recorded as chloride ion concentration while later data, including that obtained recently (1990/1991), is recorded in electrical conductivity units. The early data (1965 to 1971) was converted from chloride ion concentration to electrical conductivity to allow comparisons between the two sets of data to be made. The conversion was done using a relationship (refer Figure 5.3) derived from water samples obtained from wells on Lifuka in the Ha'apai group in August 1985 (as listed in Stoll, 1986). No comparative data for water with salinities in the range suitable for drinking water was found from samples of water on Tongatapu. The data from Lifuka is considered to be reasonably representative of all limestone islands within Tonga since the dominant ion in all cases is chloride, and there is a strong correlation between chloride ion concentration and electrical conductivity. The correspondence between a chloride ion concentration of 600 mg/l (the limit of freshwater as described in section 4.4.1) and an electrical conductivity reading of 2,500 µS/cm is similar to results from other small coral limestone islands.

Analyses and interpretation of results of recent and past groundwater investigations together with the results of the recharge analysis (refer section 5.1.6) are given in section 5.1.7.

Testing for five persistent pesticides (Lindane, Heptachlor, endosulfan, DDT and Aldrin) in 24 wells on Tongatapu showed that serious contamination has not occurred. Four wells showed trace amounts of pesticides but the levels were 10 to 100 times below WHO guidelines. Analysis of nitrate and phosphate levels indicated that heavy use of fertilizers had not affected the groundwater. The maximum nitrate concentration was 3.8 mg/l compared with the WHO guideline of 10 mg/l (WHO, 1984). Assessment of a spillage at Tokomololo of a wood preserving compound containing copper, chromium and arsenic showed no contamination of surrounding groundwater wells. While it is noted that there are no significant adverse effects from agrochemicals showing in the groundwater at present, there is no room for complacency in this matter. In some cases, the long travel times of the groundwater from pollution source to monitoring location may be one reason for the relatively low present levels of agrochemical residue in sampled water. Further study of this matter is warranted and it is encouraging that a full review is scheduled for late 1991 (refer section 5.1.9).

In summary, much recent work has been undertaken to better understand the nature of the fresh groundwater resources of Tongatapu. Much of the required work is still to be undertaken (refer section 5.1.9) and eventually parts of it will become regular activities as part of an ongoing monitoring programme (refer section 6).

4.1.5 Rainfall analyses

The mean annual rainfall on the island based on records collected at Nuku'alofa for the period 1947-1990 is 1,770 mm (refer Table 4.1). Mean annual rainfall statistics show generally higher values: for example, Thompson (1986) states the mean annual rainfall as being 1,888 mm for the period 1951-1980. The lower value for the longer period is due to lower annual rainfalls in the last decade. For the period 1981 to 1990, the mean annual rainfall is only 1,406 mm or about 80% of the mean annual rainfall for the 44 years since the start of 1947. The ENSO events of 1982/83 and 1986/87 had a major influence on the lower rainfall pattern in the last decade. A similar effect is found on other islands in the Kingdom of Tonga.

Figure 5.4 shows the annual rainfall pattern for the period 1947 to 1990. Additional rainfall records between 1927 and 1940 (from Taylor, 1973) are shown with the later record in Figure 5.5.

A comparison of annual rainfall records between Tongatapu and representative islands in other parts of the Kingdom of Tonga (Lifuka in the Ha'apai group, Vava'u and Niuatoputapu) is shown in Figure 4.3.

The mean monthly rainfall pattern at Nuku'alofa is shown in Figure 5.6 for two periods of record: 1947 to 1990 and 1981 to 1990. Figure 5.6 shows that the mean monthly rainfall is lower during the period 1981 to 1990 than during the period 1947 to 1990 for all months except for May and December. There is a trend during the last decade of lower rainfall during the wet season: mean rainfall in the months of November, January and March and April are much lower during the last decade than during the full 44 year period.

Comparison of the mean monthly rainfall pattern on Tongatapu with other island groups of the Kingdom of Tonga is shown in Figure 4.4. The mean monthly rainfall in Tongatapu is generally higher than in the Ha'apai group but is generally less than in Vava'u and Niuatoputapu.

Maximum, mean and minimum monthly rainfall statistics are shown in Appendix A and are plotted in Figure 5.7. The wet season months have the highest maximum monthly rainfall. The highest monthly rainfall was 783 mm which fell in December 1971. The lowest monthly rainfall (3 mm) has occurred in the months of November and December.

The temporal variability of rainfall in Tongatapu is discussed in section 4.2.3.

Relatively short rainfall records on a monthly basis are also available from other locations on Tongatapu (refer Figure 5.8) as follows:

- Fua'amotu
- Mu'a
- Vaini
- Mataki'eua (moved from Fuala in 1989)
- Liahona (now closed)
- Fo'ui (moved from Kolovai in February 1983).

Thompson (1986) indicates that many of these stations started in either 1980 or 1981. However, records from 1982 only were available from the Tonga Meteorological Service. Some stations had more complete records than others. A listing of the available monthly records is shown in Appendix H.

The rainfall records from the other locations on the island show some across-island variability. For example, the mean annual rainfall at Fua'amotu is 1,599 mm for the 11 year period from 1980-1990 compared with 1,472 mm at Nuku'alofa (refer Table 5.1).

Table 5.1 Comparison of annual rainfall at Nuku'alofa and Fua'amotu, Tongatapu

Year	Nuku'alofa rainfall (mm)	Fua'amotu rainfall (mm)
1980	2,126	2,378
1981	874	1,146
1982	1,733	2,220
1983	838	929
1984	1,311	1,647
1985	1,363	1,160
1986	1,269	1,285
1987	901	1,137
1988	1,761	1,633
1989	2,163	2,014
1990	1,849	2,039

On average, therefore, about 9% more rainfall occurs in the southeastern portion of the island than at Nuku'alofa. Records indicate that annual rainfall at Fua'amotu was higher for every year during the 11 year period than at Nuku'alofa except for 1985 and 1989.

As would be expected from the proximity of the two sites to each other, the correlation between annual and monthly rainfall is high. Using the 11 years of annual rainfall data, a regression analysis between the two station records indicated a correlation coefficient (r) of 0.90 and a regression equation as follows:

$$\mathbf{P_{Fua'amotu\text{-}A} = 0.93\ P_{Nuku'alofa\text{-}A} + 231}$$

where $\mathbf{P_{Fua'amotu\text{-}A}}$ = annual rainfall (mm) at Fua'amotu

$\mathbf{P_{Nuku'alofa\text{-}A}}$ = annual rainfall (mm) at Nuku'alofa.

A regression analysis for the 132 months of rainfall data indicated that the correlation coefficient (r) was 0.93 and that the regression equation was:

$$\mathbf{P_{Fua'amotu\text{-}M} = 0.973\ P_{Nuku'alofa\text{-}M} + 11}$$

where $\mathbf{P_{Fua'amotu\text{-}M}}$ = monthly rainfall (mm) at Fua'amotu

$\mathbf{P_{Nuku'alofa\text{-}M}}$ = monthly rainfall (mm) at Nuku'alofa.

The above equations can be used as reasonable approximations for annual and monthly rainfall at Fua'amotu based on observed records at Nuku'alofa.

Rainfall at the other stations on Tongatapu was also compared with that at Nuku'alofa. Figure 5.9 is a graphical comparison of annual rainfall at Nuku'alofa, Mu'a, Fua'amotu, Vaini and Mataki'eua for the period 1983 to 1990 and Figure 5.10 compares annual rainfall at the first four of these stations and at Liahona and Fo'ui for the period 1982 to 1986. In order to produce these graphs six months of missing rainfall at three stations were estimated to be the same as for Nuku'alofa. These estimates were for the following months and stations: Mu'a: December 1986, January 1987 and January 1989; Vaini: May 1990; and Liahona: May and June 1985. The same overall rainfall trend from year to year can be seen for each station.

In order to compare the relative depths of rainfall at each station, the cumulative annual rainfalls shown in Figures 5.11 and 5.12 are more useful. These figures show that rainfalls at Mu'a and Fua'amotu are approximately the same or slightly higher than at Nuku'alofa. It is also apparent that the rainfall at Vaini is slightly higher than elsewhere on the island during the period of record. During the period 1983 to 1990, Vaini had 12,134 mm (1 month estimated) which was 6% more than at Nuku'alofa (11,455 mm). Rainfall at the western end of the island, as shown by the records from Liahona and Fo'ui, is approximately the same as at Nuku'alofa. During the period 1982 to 1986, the rainfall recorded at Liahona (6,405 mm) and at Fo'ui (6,613 mm) were 2% less and 2% more, respectively, than at Nuku'alofa.

The rainfall at Mataki'eua (and at nearby Fuala) is also approximately the same as at Nuku'alofa, as can be seen from Figures 5.9 and 5.11.

From the available records, it is apparent that the rainfall in the southern and southeastern part of the island is slightly higher than elsewhere on the island, particularly at Nuku'alofa in the north and at in the eastern part of the island.

Regression analyses using available monthly records (refer Appendix H) were carried out between Nuku'alofa and the other rainfall stations on Tongatapu. These are summarised in Table 5.2 including the results for Fua'amotu. The regression equation parameters 'a' and 'b' refer to the following general equation:

$$\mathbf{P_{Station\text{-}M} = a\, P_{Nuku'alofa\text{-}M} + b}$$

where $\mathbf{P_{Station\text{-}M}}$ = monthly rainfall (mm) at the selected station,

$\mathbf{P_{Nuku'alofa\text{-}M}}$ = monthly rainfall (mm) at Nuku'alofa.

Table 5.2 Monthly rainfall correlations on Tongatapu

Station	Regression equation parameters		Correlation Coefficient	Number of months
	(a)	(b)	(r)	(n)
Fua'amotu	0.973	11	0.93	108
Mu'a	0.907	15	0.89	105
Vaini	1.003	12	0.93	107
Mataki'eua	1.001	2	0.94	102
Liahona	1.026	-5	0.88	58
Fo'ui	1.039	-2	0.89	71

The correlation coefficients in Table 5.2 indicate good to very good correlations between the various rainfall stations and that at Nuku'alofa. This result is not surprising given the size and relatively flat topography of the island. Correlations between each station and the other stations on the island showed similar results to those above. The regression equations summarised in Table 5.2 can be used as reasonable approximations for monthly rainfall at the various rainfall stations based on observed records at Nuku'alofa. It must be noted that rainfall in individual months can vary considerably from the estimates derived from such equations.

4.1.6 Recharge analysis

Recharge is necessary to prevent freshwater lenses from disappearing due to the natural processes of freshwater outflow at the edges of an island and mixing with underlying saline water. It is essential that accurate estimates of recharge be obtained to derive estimates of sustainable yield.

This section contains a summary of previous recharge estimates, an outline of other simple approaches for recharge estimation and a description of a more detailed and accurate water balance approach.

Previous recharge estimates

Recharge estimates have been provided in a number of previous studies.

Pfeiffer and Strach (1972) assumed recharge to be between 5 and 15% of rainfall based on 'previous experience' and some knowledge of the island's physical and climatic features. They adopted a figure of 10% of mean annual rainfall (taken as 1,750 mm) and estimated the mean annual recharge to be 175 mm. Using the island's total area of 257 km^2, they calculated the annual recharge in volumetric terms to be 45 million m^3/year or about 125 ML/day.

Lao (1978) described a number of approaches to estimating recharge. He used a water balance approach and assumed runoff to be 5% of rainfall and evaporation losses to be 70% of rainfall. He derived an estimate of average annual recharge of about 450 mm (25% of the then average annual rainfall of 1,823 mm). This is equivalent to about 115 million m^3/year or about 320 ML/day. Lao's estimate is thus about 2.5 times greater than that of Pfeiffer and Strach (1972).

Using a sharp interface mathematical model of the freshwater lens and calibrating it against water table elevations at wells, Hunt (1978, 1979) estimated recharge to be between 25 and 30% of rainfall.

Kafri (1989), using the ratio of chloride ion concentration in rainwater to shallow groundwater as an indicator of recharge, estimated the recharge to be 35% of rainfall. The chloride ion method has been used for preliminary recharge estimates elsewhere, for example on the island of Guam (Ayers, 1981). By comparison, the chloride ion method gave a recharge estimate for Guam of 38% of the mean annual rainfall of 2,180 mm. Kafri (1989), however, assumed a more conservative value of 25% based on the previous studies of Tongatapu recharge. Using an estimated mean annual rainfall of 1,800 mm, he estimated the recharge to be the same as that of Lao (1978).

Hasan (1989) estimated that mean annual recharge to be approximately 355 mm or 20% of mean annual rainfall (taken to be 1,775 mm). His approach was a monthly water balance using mean monthly rainfall and monthly crop water requirements based on a study of crop types and areal distributions.

In summary, the previous estimates of recharge vary between 10% and 35% of rainfall depending on the method used. None of the methods have used a time series analysis of rainfall and evaporation records to estimate the recharge pattern over the period of rainfall records. Where the water balance approach has been used, mean values of each of the parameters have been used which has the effect of underestimating recharge.

Other simple recharge estimates

A curvilinear relationship has been developed between mean annual recharge and mean annual rainfall for a number of small islands. This relationship was first developed by Chapman (1985) and further developed by the author based on additional island studies.

Figure 5.13 shows the relationship and data points for a number of small low-lying islands (from Falkland, 1990). A number of methods have been used to derive the data points but mainly a water balance approach has been used. The data point for Tonga is based on the work of Hunt (1978, 1979) where recharge was estimated as 30% of rainfall. It can be seen from Figure 5.13 that the 30% estimate is a reasonable first approximation based on the position of the curve, which was fitted by eye to the data. Using the long term mean annual rainfall of 1,770 mm, the mean annual recharge is approximately 530 mm. The location of Tongatapu within the figure is intermediate between a group of low rainfall and a group of high rainfall islands.

Recharge based on water balance analysis

Recharge is the water remaining from rainfall after all evaporative losses have been deducted and soil moisture requirements have been met. It can be described in terms of a water balance equation for the zone extending from above the surface of the island to the water table. In this zone the flow of water is essentially vertical. By contrast, the flow in the groundwater system or the zone below the water table is essentially horizontal.

The water balance equation for the upper zone on a coral limestone island or coral atoll can be described as:

$$\mathbf{R = P - E + dV}$$

where R = recharge

P = rainfall

E = evaporation from all surfaces

dV = change in storage within the soil moisture zone (positive or negative change).

In the above water balance equation, there is no term for surface runoff as it is essentially nil because of the very high infiltration capacity of the coral soils. Runoff occurs from paved surfaces such as roads and airstrips but this is normally directed onto adjacent ground and not to the sea. Lao (1978) assumed 5% runoff from the island but even this low estimate is considered to be too high. From a practical viewpoint the runoff from Tongatapu and other limestone islands within the Kingdom of Tonga can be assumed as zero except for large paved areas. One exception on Tongatapu is the town of Nuku'alofa which has large paved or compacted areas and where a rudimentary stormwater drainage system is provided. However, as seen later in this section the area of the island where Nuku'alofa is located is not included in the effective recharge area of the island,

The evaporation term (E) in the water balance equation includes the evaporation from interception stores (leaves of trees, bushes and grass) and from the transpiration of vegetation. Most of the water for transpiration comes from the soil moisture zone but some may come from the freshwater lens if the roots of trees penetrate to the water table.

A computer model (called WATBAL) was used to simulate the water balance of the zone above the water table, as described in the equation above and as summarised in Figure 5.14. The following description outlines the major features of the WATBAL model.

Daily or monthly rainfall can be used in the model. Daily data is preferable, as described by Chapman (1985). Computations with a monthly time step should only be used if daily data is not available or if checks on the difference between daily and monthly results are made.

Monthly rainfall data for Nuku'alofa was used in the water balance study of Tongatapu, and also for Ha'apai and Vava'u as described later in this section. Daily rainfall data was not available from the Tonga Meteorological Service except for recent years and although it was later obtained from the New Zealand Meteorological Service, it was not available within the time frame for the recharge analyses.

The use of monthly rather than daily rainfall data tends to underestimate recharge and thus introduces an element of conservatism in the result. While the magnitude of the difference was not checked for Tongatapu, it is likely to result in an underestimation of recharge by about 5% based on comparative studies of monthly and daily rainfall records on other small islands (Hunt and Peterson, 1980; Falkland, 1988; Falkland, 1990).

The use of data from Nuku'alofa as representative of the whole of Tongatapu introduces a further element of conservatism in the estimation of recharge since rainfall in the southern and southeastern parts of the island are slightly greater than at Nuku'alofa (refer section 5.1.5).

Daily or monthly potential evaporation estimates can be used in the model. In this case, mean monthly data was used. Estimates of mean monthly potential evaporation were available from Thompson (1986). Pan data from the Vaini experimental farm for the period 1982-1990 was also used with an appropriate pan factor as a check on the other results. The use of the two types of potential evaporation data led to almost identical estimates of recharge on a long-term basis. It was decided to use the Penman estimates from Thompson (1986) as these are more readily available and they were in fact used to estimate an appropriate pan factor for the pan evaporation records. Thus, the pan records were converted to potential evaporation records using the mean annual potential evaporation records derived by Thompson (1986). The use of mean monthly rather than daily or even a sequence of historical monthly evaporation records has very little effect on the outcome of water balance analyses especially in tropical and sub-tropical regions. This is due to the constant nature of climatic conditions within a month and between the same months in consecutive years. Thus, mean monthly evaporation records were considered suitable for use in the water balance study.

The model allows for interception storage. A maximum value for the interception storage (ISMAX) is defined and it is assumed that this store must be filled before water is made available to the soil moisture storage. Typical values of ISMAX are 1 mm for predominantly grassed catchments and 3 mm for catchments consisting predominantly of trees. Where grasses and crops are thick and tall as often occurs on Tongatapu, a larger ISMAX than 1 mm would apply. It was assumed that the value of ISMAX on Tongatapu is 3 mm which is considered to be a conservative approach. Evaporation is assumed to occur from this zone at the potential rate.

The model assumes a soil moisture zone from which the roots of shallow rooted vegetation (grasses, bushes) and the shallow roots of trees can obtain water. Water requirements of plants tapping water from this zone are assumed to be met before water drains to the water table. Maximum (field capacity) and minimum (wilting point) limits are set for the soil moisture in this zone. Above the field capacity, water is assumed to drain to the water table. Below the wilting point, no further evaporation is assumed to occur.

The thickness of the soil moisture zone (SMZ) was estimated to be 1,000 mm and values of field capacity and wilting point were assumed to be 0.55 and 0.4, respectively, as explained in section 4.5.

Water losses from the soil moisture zone are dependent on the available soil moisture content. As stated earlier, zero losses due to evaporation are assumed to occur from this zone at wilting point. Maximum or potential evaporation is assumed to occur when the soil moisture zone is at field capacity. A linear evaporative loss relationship is assumed to apply between the two soil moisture limits. Thus, at a soil moisture content midway between FC and WP, for instance, the evaporation rate is half that of the potential rate.

Water entering the water table is considered to be 'gross recharge' to the freshwater lens. A further loss, however, can be experienced due to transpiration of trees whose roots penetrate to the water table. 'Net recharge' is the effective recharge after this additional loss is subtracted from 'gross recharge'. Because the movement of the water table is relatively small, even during drought periods, roots which reach the water table are capable of allowing transpiration to occur even when the soil moisture store has been depleted. This is the reason that trees, particularly coconut trees, are able to survive prolonged drought periods on coral islands when other shallow rooted vegetation has reached wilting point and possibly died.

On Tongatapu the depth from surface to water table is generally too great for the roots of coconut trees to penetrate through to the water table. It was assumed for the purposes of the water balance analysis that no roots reached the water table.

Vegetation is assigned a 'crop factor' according to type. The concept of crop factors has been used by Doorenbos and Pruitt (1977) in a major study of evaporative losses and crop water requirements. This approach was used by Hasan (1989) in his study of crop water requirements on Tongatapu. Using this approach, each type of plant (or crop) has its evaporative potential compared with that of a 'reference crop'. The 'reference crop' evaporation (or evapotranspiration) is defined as the 'rate of evapotranspiration from 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'.

The reference crop evaporation is equal to the potential evaporation as derived from a recognised approach such as the Penman equation (Penman, 1948, 1956). The 'crop factor' is a coefficient which is used to derive an adjusted potential evaporation for other crops from the potential evaporation (or the 'reference crop' evaporation).

It is generally assumed that the 'crop factor' for most grasses and other shallow rooted vegetation is equal to 1.0 as they assumed to evaporate at the same rate as the reference crop. Hasan (1989) provides estimates of crop factors for many types of crop. These are often less than 1.0 for each crop. However, because of the mixed cropping system whereby more than one crop is planted in the same area the 'combined' crop factor reaches and may exceed 1.0. Hasan (1989) implies that the average 'combined' crop factor for Tongatapu is approximately 1.1 based on the ratio of his total crop water requirements and the reference crop evaporation (assumed equal to potential evaporation) in Table 6 of his report. His results are based on an assumed 105 km^2 of the island (approximately 40% of the surface area) under crops. Since the other area includes some cleared land including areas devoid of vegetation (for example, roads, housing, airport), an overall crop factor of 1.0 was assumed for non-treed areas.

The crop factor for coconut trees was assumed to be 0.8 based on values for similar types of trees listed in Doorenbos and Pruitt (1977). Thus, the potential evaporation rate for coconut trees is taken as 80% of that for grasses or other shallow rooted vegetation. It was assumed that other deep rooted vegetation also had crop factors of 0.8.

The proportions of surface areas covered by deep rooted vegetation to total lens areas were estimated from aerial photographs. For Tongatapu in the location of the freshwater lens, this ratio was estimated to be 0.3.

The initial interception storage and soil moisture contents are were assumed to be 50 mm per month and 500 mm, respectively. The chosen values are average values.

<u>Water balance study results</u>

Results of the water balance study using the data and parameter values as described above are shown on a month by month basis in Appendix I for Tongatapu for the 44 years of analysis corresponding to the 44 year rainfall record from 1947 to 1990.

The mean annual recharge from this analysis was calculated as 528 mm or 30% of mean annual rainfall. This result is similar to that estimated by Hunt (1978, 1979) and slightly higher than most of the other estimates.

A sensitivity analysis was conducted to determine the effects of changing some of the parameter values. Changing ISMAX from 90 mm (average of 3 mm per day) to 60 mm (average of 2 mm/day) increased the recharge to 32% of rainfall. Changing the value of field capacity from 0.55 to 0.60, decreased the recharge to 28% of rainfall. If 10% of the roots of coconut trees were assumed to reach the water table rather than zero as assumed above, the reduction in recharge was less than 1% of rainfall. Increasing the soil moisture zone thickness available to plant roots from 1,000 mm to 1,500 mm reduced the recharge to 28% of rainfall. Thus, changes to parameter values within reasonable limits had only minor effects on the mean annual recharge and it can be concluded that the estimate of mean annual recharge being 30% of mean annual rainfall is reasonable.

A summary sheet showing the values of monthly and annual recharge is included at the end of Appendix I. Figure 5.15 shows the annual recharge pattern from 1947 to 1990 based on the results of the water balance simulation. It is noteworthy that the recharge in the 1980's is less than the average with the years 1981 and 1983 receiving no recharge.

The relationship between annual rainfall and annual recharge is shown in Appendix I but can be seen more clearly in Figure 5.16. It can be seen that the relationship between the two parameters is not constant as it is dependent not only on the magnitude of the rainfall but also the distribution of rainfall throughout the year.

Turnover time

Turnover time is an index of the average residence time for water in a lens (Chapman, 1985) and is calculated by dividing the average lens volume by the average flow through the lens. The average flow through a lens can be estimated from either long-term average recharge (total lens inflow) or from total lens outflow. Since it is not possible to measure total outflow, turnover time is normally estimated from recharge.

An alternative approach using recharge to estimate turnover time is to use the average depth of recharge and divide it into the average freshwater thickness within the lens. This approach was used in this study. The thickness of freshwater in the lens was based on the best available information.

Based on data from salinity profiles through the lens, it is assumed that the average thickness of the freshwater zone within the lens on Tongatapu is about 10 m (refer section 5.1.7). Not all of this is freshwater as the lens is an aquifer consisting of a rock/water matrix. For this type of aquifer it is assumed that the specific yield, or the amount of water that can be extracted from a given volume of saturated rock, is 0.3. Thus, the actual thickness of freshwater within the lens is about 3.3 m. The turnover time of freshwater in the lens is then about 6 years (3.3 m divided by 0.528 m = 6.3 years).

Under present extraction conditions, the freshwater lens should be able to withstand years when much less than normal and even zero recharge occurs, such as occurred in some of the years in the decade of the 1980's. This observation is at least partly confirmed by the increases in well salinity in that decade, which were slight rather than extreme except in marginal freshwater areas of the island.

What is not known at this stage is the movement of salts vertically below the freshwater area which may have the effect of diminishing the thickness of the lens during extended periods without recharge. This latter factor can only be assessed after monitoring salinity profiles in freshwater lenses under stress from nil or negative recharge. This highlights the need for long-term monitoring of the groundwater resources in this and other islands of the Kingdom of Tonga.

4.1.7 Analysis and interpretation of results

General

Unfortunately, despite the recommendations of many previous studies some of which are nearly 20 years old, there is only a very small amount of data with which to compare the results of recent groundwater investigations, particularly salinity taken at the water table in selected wells. Some of the early data is of doubtful quality which adds to the problem of interpretation. Thus, the determination of long term trends in salinity as a result of natural influences such as tides and variations in recharge and pumping from the lens.

The limited amount of the most useful information for the study of freshwater lenses, namely vertical salinity profiles at a number of locations, has also impeded a thorough analysis. Despite strong recommendations from Lao (1978) and other authors, there has been no progress until very recently on the installation of additional salinity monitoring boreholes (refer section 5.1.4) or collection of salinity data from the three boreholes drilled in 1978.

It is stressed, therefore, that the interpretations of available data given in this section must be regarded as preliminary only. This fact is ample demonstration of the need for further investigation and an ongoing monitoring programme. With the establishment of the Hydrogeology Unit within the Ministry of Lands, Survey and Natural Resources and a greater awareness of the need to for a comprehensive water resource assessment on Tongatapu and other islands of the Kingdom of Tonga, future analyses of data should be able to provide more informed interpretations.

In summary, the available groundwater data to enable an interpretation of the status of the freshwater lens on Tongatapu consist of:

- Intermittent salinity data measured at the water table from selected wells since 1965.
- Three vertical salinity profiles taken in November 1978.

- Intermittent water table elevation data, in some cases related to survey data with dubious accuracy, at selected wells since 1965.
- Data from four salinity monitoring boreholes drilled in 1991, as outlined in section 5.1.4 and Appendix E.

In addition, electromagnetic surveys and electrical resistivity surveys were carried out during 1991 at the Mataki'eua and Tongamai wellfields to estimate the thickness of freshwater and to calibrate the results against the vertical salinity profiles from monitoring boreholes. This information, details of which are not presented in this report but which are held by the Hydrogeology Unit, will be useful in assessing freshwater zones and saltwater intrusion on other parts of Tongatapu.

Other recently collected water quality data (pH and temperature), while useful to establish baseline values, are not directly relevant to the study of the freshwater lens. It is noted that the pH values are generally within the limits for potable water and any outlier values are suspected to be due to incorrect calibration setting at the time of obtaining the readings.

<u>Salinity data</u>

The salinity of the freshwater lens measured at the water table can provide an approximate guide to the nature of the freshwater lens. Where the salinity is low it can be expected that the freshwater lens is of reasonable thickness and where the salinity is reaching the upper limit for drinking water (2,500 µS/cm), the freshwater lens is generally thin.

The Hydrogeology Unit has prepared a coloured map of Tongatapu showing areas of low to high salinity from the salinity readings for May 1990. Most areas of Tongatapu are underlain by freshwater but some areas indicate seawater intrusion as a result of natural and possible man induced (pumping) conditions. Figure 5.17 is a summary of the May 1990 results showing areas where the water quality is above and below the freshwater limit. High salinities are most probably caused by natural influences due to proximity to the coast and, in some cases, cave systems under the island (for example, at Haveluliku). In the area near the Mu'a villages, seawater intrusion may be exacerbated by pumping from 4 bores to the southeast of Tatakamatonga (wells 18, 19, 20 and 21). The relative effects of natural and pumping influences cannot be determined from the sparse data available.

The trends in salinity at selected wells were analysed by plotting available salinity data against the year of observation for selected wells where records extended back to 1965. The amount of data between 1965 and 1991 varied between wells (refer Appendix F for details). In most cases, it was possible to obtain data for the following years: 1965, 1971, 1980, 1981, 1983, 1987 and 1990. In a limited number of cases, one year of data was interpolated to allow a full record to be plotted. Salinity trends for the selected wells are shown in Figures 5.18 to 5.25, as listed below. The wells in each figure were selected as representative of particular areas of the island as listed below. The locations of the wells are shown in Figure 5.1.

- Figure 5.18: far west (wells 155, 153, 68, 65, 157)
- Figure 5.19: central west (wells 144, 133, 166, 168, 89)
- Figure 5.20: inner west (wells 89, 109, 103, 88, 161)
- Figure 5.21: central (wells 79, 27, 201)
- Figure 5.22: northeast (wells 52, 61, 48, 45 and 35)
- Figure 5.23: southeast (wells 19, 71, 180, 42 and 14)
- Figure 5.24: Mataki'eua/Tongamai wellfield, 1st graph (wells 101, 102, 109, 111)
- Figure 5.25: Mataki'eua/Tongamai wellfield, 2nd graph (wells 102, 106, 107, 109).

Two scales were used in the figures for electrical conductivity. Where the water was within (or just beyond) the freshwater limit an upper limit of 2,500 µS/cm was used, otherwise an upper limit of 10,000 µS/cm was used. Only Figures 5.18 and 5.22 required the latter scale and in both cases only one well exceeded the freshwater limit by a large margin.

From Figures 5.18 to 5.25, a general but slight increase in salinity can be detected in most wells from 1965 to 1990 with a drop in salinity in 1991. When interpreting the results, it must be remembered that they were obtained using different instruments over the period and the results from 1965 to 1971 required conversion from chloride ion concentration to electrical conductivity units to have a basis for comparison (refer to section 5.1.4). The accuracy of the earlier readings cannot be guaranteed. Possible inaccuracies or lack of calibration in meters may, therefore, account for some of the variation in salinity readings over the years. As there are large gaps between readings, shorter term variations obviously are not detected by this analysis. In particular there are large gaps in data from 1965 to 1971 and from 1971 to 1980 which prevent likely variations within these periods from being determined.

The results for selected wells are discussed in detail below.

Well 155 (Figure 5.18) at Ha'avakatolo has higher salinities than the other selected wells in the far west of the island. This is to be expected given the location of the well on the relatively narrow western 'hook' of the island. This well provides a better opportunity to analyse salinity variations over time than some other wells since greater salinity variations are likely with recharge in areas which are on the edge of the freshwater lens as in the case of this well. Well 155 shows a salinity trend as follows: increasing from 1965 to 1971, decreasing from 1971 to 1980, generally increasing from 1980 to 1990 and then decreasing to 1991. This trend is most probably caused by variations in recharge with an increase in salinity caused by a reduction in recharge and vice versa. Inspection of Figure 5.15 and Appendix I shows generally low recharge from 1965 to 1971, then higher than normal recharge in the 1970's followed by low recharge in the 1980's. The relatively high recharge in late 1990 and early 1991 has undoubtedly caused the reduction in salinity from 1990 to early 1991, as elsewhere on the island.

Well 79 (Figure 5.21) at Folaha shows a similar pattern to that for well 155 except that there are some differences in the 1980's. Overall there is a reduction in salinity in the 1970's, an increase in the 1980's and a decrease in the 1990's. This well is also located in an area at the edge of the freshwater lens.

Well 52 (Figure 5.22) at Navutoka shows a very high salinity in 1987. As this result is not reflected elsewhere on the island and there is no reason to suspect a major increase in pumping at this well at the time, it is suspected that the reading is erroneous.

Well 19 (Figure 5.23) at the small wellfield east of Tatakamatonga shows a large increase in salinity during the 1980's and then a slight reduction to 1991. As mentioned previously, the increase in salinity at this location is probably partially due to the effects of pumping. The close proximity of Well 19 to other pumping wells in a relatively narrow section of the island and where there are known karstic features on both ocean and lagoon sides is an indication that this is a less than ideal site for large extraction of groundwater.

Wells in the centre of the island or near the edge where the island is widest generally show lowest salinities. Examples are wells 166, 168 and 89 (Figure 5.19), 88 (Figure 5.20), 201 (Figure 5.21), 48 (Figure 5.22), 71, 180 and 42 (Figure 5.23) which have rarely exceeded 1,000 µS/cm in the available record. Some wells in the Mataki'eua/Tongamai wellfield fall into the same category (wells 101 and 111: Figure 5.24, and wells 102 and 109: Figure 5.25).

<u>Vertical salinity profiles</u>

In addition to the above analysis of available salinity data obtained from the water table in a number of bores, the vertical salinity profile information from the four recently installed monitoring bores (refer section 5.1.4 and Appendix E) provides some additional insight. The salinity data obtained from the Fuala quarry monitoring borehole (number 222 in Figure 5.1) on 6th May and 17th July 1991 indicated that the freshwater zone is about 9 to 9.5 m thick. Similarly the salinity data obtained from monitoring boreholes (numbers 223 and 225) between Mataki'eua and Fanga'Uta lagoon on the same days indicated a freshwater zone thickness of about 8 to 10 m. These freshwater zone thicknesses compare with 11 m obtained at the Liahona salinity monitoring borehole in November 1978 (refer Figure 5.2). As the Liahona site is further inland than the sites mentioned above, it could be expected that the freshwater zone would be slightly thicker than those closer to the sea or lagoon. This is demonstrated by the above results, within the accuracy of the available data and given that the monitoring boreholes were constructed differently and that antecedent recharge conditions were not the same. The conclusion from the recent salinity profile investigations is that the freshwater zone of the lens in the general area of Liahona and Mataki'eua has not altered significantly between 1978 and the present time.

As there is no general trend of a major increase in salinity over the island, it appears that the prevailing natural and man-induced (pumping) conditions are not leading to a destruction of the freshwater lens. Areas for concern are in the far west of Tongatapu where it appears that a permanent freshwater lens is unlikely to exist and near Tatakamatonga where a combination of natural conditions and pumping are probably combining to induce salinity beyond the freshwater limit.

Because of its importance to the water supply for the largest town and centre of population on the island, Nuku'alofa, the salinity trends at the Mataki'eua/Tongamai wellfield were analysed in more detail. All the available data for 7 of the wells at the wellfield is shown in Figures 5.24 and 5.25. The results in these figures do not show any major differences in trends from other wells on the island. Figure 5.20 shows a comparison between two of the wells at the Mataki'eua/Tongamai wellfield (103 and 109) with other wells in the inner western part of the island. While the salinities at wells 103 and 109 are slightly higher in recent years than the others, there is no evidence that the pumping at the Mataki'eua/Tongamai wellfield is causing a long term rise in salinity.

Most wells at the Mataki'eua/Tongamai wellfield show a decrease in salinity from 1990 to 1991 as shown from the results of four recent tests (Table 5.3).

Table 5.3 Electrical conductivity (µS/cm) at Mataki'eua/Tongamai wells

Well No	Date				Change in EC (%)	
	29/2/90	6/8/90	1/11/90	1/3/91		
	(A)	(B)	(C)	(D)	(from B to C)	(from B to D)
101		1,069	930	880	-13	-18
102		727	793	930	- 9	**+28**
103		1,278	1,140	1,073	-11	-16
104		1,363	1,242	1,220	- 9	-10
105		1,580	1,453	1,321	- 8	-16
106		681	639	935	- 6	**+37**
107		1,417	1,156	970	-18	-32
108		1,492	1,383	1,347	- 7	-10
109		1,305	1,159	973	-11	-26
110		1,280	1,183	-	- 8	-
111	1,000	1,020	942	899	- 8	-12
112		1,128	1,028	746	- 9	-34
113		1,195	994	969	-17	-19
114		1,182	1,035	997	-12	-16
115		1,056	974	931	- 8	-12
116		1,217	971	929	-20	-24
117		927	850	832	- 8	-10
118	850	835	780	730	- 7	-13
119		,1051	-	930	-	-12
120		980	827	740	-16	-16
121		-	-	879	-	-
122		-	841	832	-	-
124		349	242	450	-31	-29
129		-	-	988	-	-
131	3,500	-	-	109*	-	-
211		613	544	935	-11	**+52**
212		457	358	1,060	-22	**+132**
Main tank at Mataki'eua	1500	-	-	850	-	-

Note: * sample obtained on 23/1/91: suspected rainwater in bore

The salinity decrease shown in Table 5.3 was due to recent high recharge experienced on the island. Some wells (102, 106, 211 and 212) show an increase in salinity during this period. It was noted that wells 102, 211 and 212 all had wind pumps replaced by diesel pumps which may have caused the increase in salinity. The dates of changeover from wind to diesel power were not determined during this study but could be obtained from the Tonga Water Board. It is believed that the reading in March 1991 from well 212 is erroneous. The increase in salinity at well 106 in March 1991 is unexplained. Salinities at the wells showing an increase (102, 106, 211 and 212) should be checked again in the near future to see if the trends shown below are confirmed.

Water table elevation data

Water table elevations have been recorded on an intermittent basis at selected wells on Tongatapu sine 1965. Available data is shown in Appendix F. The usefulness of much of the data is questionable owing to doubts about the accuracy of previous survey work. Also the datums used for measuring from the top of the well to the water surface are not necessarily consistent between the earlier readings and the recent readings (1990/1991).

The Hydrogeology Unit is, however, pursuing an ongoing programme of resurveying benchmarks and datum points at the top of selected wells. Levels will be related to msl once sufficient records have been obtained from the automatic tide recorder on Vuna wharf in Nuku'alofa.

For this study it was not considered a worthwhile exercise to examine water table elevations in detail during this study. However, recent data obtained from the Mataki'eua/Tongamai wellfield (refer Table 5.4) was viewed to detect trends. This data is referenced to the current msl estimate which will be reviewed in light of recent tide records.

Table 5.4 Water table elevations (m) at Mataki'eua/Tongamai wellfield

Well Number	RL (m)	Date			Change in elevation (%)	
		6/8/90 (A)	1/11/90 (B)	1/3/91 (C)	(from B to C)	(from B to D)
101	12.50	.32	.40	-	+0.08	-
102	20.32	1.41 ?	1.47 ?	1.58 ?	Suspected survey error	
103	12.89	.41	.45	-	+0.04	-
105	15.02	.29	-	.35	-	+0.06?
106	21.87	.36	.40	.17 ?	+0.04	Error?
107	13.59	.25	.29	4.92 ?	+0.04	Error?
109	11.44	.25	.34	.49	+0.07	+0.24
110	18.12	.36	.40	.53	+0.04	+0.17
111	10.06	.34	.40	.54	+0.06	+0.20
113	16.92	.23	.28	.42	+0.05	+0.19
115	12.29	.37	.41	.56	+0.04	+0.19
117	12.74	.37	.45	.51	+0.08	+0.14
118	13.49	.41	.44	.59	+0.03	+0.18
119	12.54	-.10 ?	-	.04 ?	Suspected survey error	
124	0.92	-22.19 ?	-22.16 ?	-22.03 ?	Suspected survey error	

Table 5.4 lists only those wells where the reduced level (RL) on the top of the well was available and where readings were available on at least two of the three days when recent readings were obtained.

The RL data was obtained from one of the databases used for the well census information. From the results in Table 5.4 it is suspected that there is a survey error or a transcription error in the case of wells 102, 119 and 124. The survey data for these wells should be checked and adjusted as necessary. Readings at wells 106 and 107 on 1 March 1991 are also in error, most probably due to a measurement error, and those should be re-measured.

Despite the obvious problems above, the data in Table 5.4 shows an increase in water table elevation from 6 August to 11 November 1990 of between 30 mm and 80 mm. Over the period 6 August 1990 to 1 March 1991, the increase was between 170 mm and 240 mm (one odd result was obtained for well 105 which needs to be checked).

These increases in water table elevation are to be expected with the recharge over these periods. From 6 August to 11 November 1990, the recharge to groundwater was approximately 160 mm (refer Appendix I) which is equal to about 30% of mean annual recharge occurring in about 25% of the year. From 6 August 1990 to 1 March 1991, the recharge was about 529 mm which is equal to the mean annual recharge (in a period of only 7 months).

The increases in water table elevation are accompanied by expected decreases in salinity of the water at the water table, as seen from Table 5.3.

Levels at the surface of the lens provide useful supplementary information to the salinity information and assist with providing a better understanding of lens dynamics. Used in isolation, water levels can provide misleading information about the state of the lens and caution, therefore, must be exercised in the use of such data. Some of the problems with, and requirements for, obtaining and using water table elevation data are:

- Errors in manual measurement with measuring tapes can easily be +/- 10 mm even with good quality tapes. Readings should, therefore, be made with extreme care.
- Reference points (datums) at the top of wells and boreholes must be accurately surveyed to enable accurate water level information to be obtained. Preferably datums should be surveyed to an accuracy of +/- 10 mm or better.
- Datums at the top of wells should be well marked and recorded so that measurements are made from the same point at each inspection. Sometimes the edges of wells are ill-defined which can lead to different personnel undertaking measurements from different levels leading to systematic errors in information obtained over multiple visits. Errors of this type can easily be 20 mm or more. Hence, datums should be well marked at well defined concrete edges and, preferably, recovery survey marks such as bolts set in concrete should be located nearby to each well to enable easy resurvey in case of damage or loss of datums at well edges. The tops of boreholes do not generally cause a problem of this nature as the edge of the casing or concrete surround is generally well defined.
- A further error can occur in the case of some wells where there is not a clearly defined route for the tape measure to be lowered to the water level. This can occur in dug wells equipped with ladders. Different measurements can be obtained depending on the method of lowering the tape around the ladder. Errors of at least 10 mm could be introduced due to this factor.
- Water table elevations are generally measured at random time intervals and, hence, not at the same time with respect to the tidal signal within the lens. A time series of water level observations at a particular borehole may therefore show differences caused by tidal fluctuations in addition to variations in recharge. Tidal fluctuations at individual sites will vary according to the degree of hydraulic connection with the sea. There is often not a linear relation between distance to the sea and the strength of the tidal signal since the tidal signal can be propagated both vertically as well as horizontally. Tidal fluctuations at wells on Tongatapu have not been measured on a systematic basis and this should be done using automatic recorders. As it would be very expensive to install them at all sites, selected sites should be equipped with automatic recorders. Additional sites can be manually observed at regular intervals and these can be related to the continuous records from the automatic recorders. Many sites can be periodically instrumented by 'roving' recorders in order to establish tidal lags (time lag between tidal signal in sea and at groundwater observation point) and tidal efficiencies (ratio of the range between high and low water level at the groundwater observation point to that in the sea). It is therefore essential that an automatic tide recorder be in operation. At present there is only one such recorder located at Vuna wharf in Nuku'alofa but it is planned to establish temporary tide recorders in Ha'apai and Vava'u.

- Water levels in closely spaced and otherwise similar holes can be different at a particular time due to differences in drilled or dug depth. Holes which are drilled or dug deeper will tend to have higher tidal efficiencies and lower tidal lags than shallower holes.
- Short term rises in the water table can be introduced after major recharge events. The response of the water surface can be a hydrograph with a relatively rapid rise (a few hours to a few days) and a slower recession to a more average level. Water levels obtained after major recharge events may give artificially high levels and lead to erroneous conclusions about the freshwater head and its implications for thickness of the freshwater lens.

On islands where water table elevations have been measured for many years it is recognised that their usefulness is limited. Visher and Mink (1964) state that water level elevation data is of little practical value in determining the magnitude of changes in the thickness of the freshwater lens. This is supported by Rowe (1984) in discussing the use of water table elevation data on Bermuda. Rowe reports that even on a yearly basis the water table elevation is not a good guide to the interface (mid-point of transition zone). In dry years the Ghyben Herzberg ratio (water table elevation above msl divided by depth of mid-point of transition zone below msl) is low while in wet years it is high. At one location the ratio has varied from 25 to 58, where theory would have it at approximately 40. The differences must be due to a lag between water table variations and corresponding movements at the mid-point of the transition zone.

The problems of using water table elevations as a means of assessing the freshwater zone thickness are also demonstrated by observations from Christmas Island (Kiritimati), a large coral atoll in the Republic of Kiribati. Experiences there indicated that large errors could result if water table elevations were used to estimate freshwater zone thickness. For instance, the elevations of the water table at two sites were found to be almost identical (about 0.45 m above msl) yet the thickness of freshwater, as determined from vertical salinity profiles in adjacent monitoring boreholes, were, respectively, 1 m and 8 m despite the fact that the depths to the mid-point of the transition zone were approximately equal. This large difference in the freshwater zones is another indication of the caution that must be taken when attempting to use water table elevations for quantitative assessment of freshwater lenses.

It is because of the problems outlined above that water table elevations should not be used as a primary technique for assessing the freshwater lens thickness and dynamics. They should only be used as a supplementary source of data with major reliance being placed on salinity data obtained from surface measurements (at water table), vertical salinity profiles and possibly indirect methods (geophysical techniques).

With due care given to survey and measurement techniques, and sufficient automatic recorders to at least separate some of the time dependent perturbations (tidal signals, major recharge), water level measurements do enable useful information to be derived. Once time dependent influences are allowed for, water level information obtained from a number of boreholes can enable regional maps of water table elevation to be derived. These will give an indication on a general basis as to the preferred locations for locating extraction systems. On a local scale, continuous records from automatic recorders enable the influence of pumps on the water table to be determined. Studies elsewhere (e.g. Cocos Islands: Falkland, 1988) have used continuous records to determine the relative effects of pumping and tidal signals which has aided the selection of appropriate pump rates.

Further comments on future water level measurements are provided in section 6.7.2.

4.1.8 Sustainable yield estimate

<u>General</u>

The sustainable (or safe) yield of an aquifer is the rate at which water can be extracted without causing adverse effects. For non-coastal mainland aquifers, the sustainable yield can be approximately equated to the long-term recharge. For small island and many coastal mainland aquifers, such an approximation is not valid, as only a small portion of the recharge is available as sustainable yield: most is required for 'maintenance' of the lens by literally flushing away salt at the top of the transition zone.

To avoid adverse effects from extraction (i.e. to avoid an increase in the salinity of extracted water), the overall pump rate from the lens should be less than the sustainable yield. This will ensure that after pumping commences, the lens will reduce to a new equilibrium volume but will not be in danger of total depletion.

An additional requirement for avoiding adverse effects is that pumping must be distributed over the surface of the lens to avoid local upconing of saline water.

In this section, estimation methods are reviewed, previous estimates of sustainable yield of the fresh groundwater on Tongatapu are reviewed, and a revised estimate is given on the basis of the recharge analysis results.

Estimation methods

There are a number of approaches to the estimation of sustainable yield. Two of the most common are:

- Detailed numerical modelling
- Judgement and empirical formulae based on experience.

The selection of the appropriate approach is based on available time, money and data.

Detailed numerical modelling has been used for the analysis of a number of freshwater lenses on islands and, in particular, for the estimation of sustainable yields. The various models can be categorised as either sharp interface or dispersion models. The former type of model is based on the Ghyben-Herzberg theory of a sharp interface between two immiscible fluids, namely, freshwater and seawater. The latter type of model allows for a transition zone between freshwater and seawater by solving additional equations concerned with salt transport. Numerical methods for the solution of the necessary equations are generally based on either finite differences or finite elements.

In theory, the sharp interface type model should only be used where the transition zone is extremely thin, a situation which is almost impossible to find on a small island. In practice, however, this type of model can be applied with reasonable confidence to lenses where the transition zone thickness does not exceed about 30% of the freshwater zone thickness. The advantage of this type of model is that it is relatively easy and cheap to run once data has been collected. Sharp interface models have been used to analyse freshwater lenses, amongst others, on Grand Cayman Island in the Caribbean Sea (Chidley and Lloyd, 1977), Tarawa (Department of Housing and Construction, 1982), Christmas Island (Falkland, 1983) and Northern Guam in the Pacific (Contractor, 1983; Contractor and Srivastava, 1990), Bribie Island off the coast of Queensland (Isaacs and Walker, 1984) and Bermuda in the Atlantic Ocean (Ayers and Vacher, 1983; Thomson, 1985, 1989). The model used by Hunt (1978, 1979) for the study of Tongatapu was a sharp interface model. A sharp interface type model using the U.S. Geological Survey computer program MODFLOW is currently being calibrated by the Hydrogeology Unit for the western part of Tongatapu. A sharp interface type model was also used by Warbrick (1989) to model the groundwater of 'Eua.

The dispersion type of model can better describe the actual situation as it accounts for a transition zone. Disadvantages are its greater complexity, greater data requirements and greater time and expense to run than the former type. For these reasons, there has been only limited application of this type of model to small island situations. One such dispersion model is SUTRA which was developed by the United States Geological Survey and has been used to simulate freshwater lens dynamics on a number of small and large islands (for example, Oahu in the Hawaiian Islands: Voss and Souza, 1987; Enewetak Atoll, Marshall Islands: Oberdorfer and Buddemeier, 1988; and, Nauru: Ghassemi et al, 1990). While this type of model is theoretically superior to the sharp interface approach, it cannot be recommended as a practical solution for Tonga at this stage because of the very large computer requirements. The only computing resources on the island are personal computers which are not large or fast enough for a dispersion type model. Consideration could be given to the use of a research student undertaking a groundwater project and attempting a dispersion model. Even if this could be arranged, further data would need to be collected. In particular salinity profile data would be required from a network of observation boreholes before such an exercise could be justified.

For Tongatapu, there is not sufficient data available to indicate even which model should be used. However, the salinity profiles obtained in the three boreholes which were drilled through to seawater indicate that the transition zone may not be too thick to preclude a sharp interface model, if only as a first approximation to the actual conditions.

In summary, it was not considered warranted to undertake detailed numerical modelling (using either a sharp interface or dispersion type model) to assist in estimating sustainable yield. Rather, sustainable yield was estimated using experiences from other small islands with thin freshwater lenses and applying a conservative empirical approach to the problem.

Mink (1976), in a study of a freshwater lens on Guam, suggested an extraction equal to 25% of 'flux' (flow through the lens) was a good first approximation to the sustainable yield. This approach was used as a guide in determining sustainable yields on the atolls of Kwajalein, Marshall Islands (Hunt and Peterson, 1980); Christmas Island, Kiribati (Falkland, 1983); Majuro, Marshall Islands (Hamlin and Anthony, 1987) and South Keeling in the Cocos (Keeling) Islands (Falkland, 1988).

The water balance equation within the lens is as follows:

Net Recharge = Flux + Extraction + Change in Storage

where

> Net Recharge is the recharge into the lens after all evapotranspiration losses have been taken into account, including transpiration directly from the lens by deep-rooted vegetation,
>
> Flux is the flow through the lens which either flows out at the edge of the lens or mixes with the transition zone at the base of the lens,
>
> Extraction is the total amount of water pumped from the lens, and
>
> Change in Storage is the change to the freshwater volume.

In the long term, changes in storage tend to be negligible and the last term can be removed from the equation. Hence, the equation can be rewritten as:

Recharge = Flux + Extraction

This equation indicates that extraction should be less than 20% of the recharge based on the condition that extraction should be less than 25% of flux.

In relatively stable lenses, a proportion greater than 20% of the available recharge could be extracted without adverse effects on the lens. In a recent study of the Central Lens on Bermuda, for instance, it has been suggested that about 75% of recharge could be extracted (Rowe, 1984). This is not considered appropriate for the freshwater lenses on Tongatapu or other islands in the Kingdom of Tonga at least until further monitoring results provide a more accurate insight into lens dynamics.

<u>Previous estimates for Tongatapu</u>

Pfeiffer and Stach (1972) assumed that 20% of recharge could be safely extracted from the Tongatapu freshwater lens. This amount is equivalent to 25 ML/day.

Lao (1978) also assumed 20% was an appropriate safety factor for deriving a sustainable yield estimate from recharge. Using his estimate of recharge, he derived a sustainable yield estimate of 61.8 ML/day. He also estimated sustainable yield on a 'regional' basis for the 3 arbitrary regions as follows:

- Liahona (west region) : 25.4 ML/day
- Fua'amotu (southeast region): 23.2 ML/day
- Kolonga (east region) : 13.2 ML/day

Other authors such as Kafri (1989) and Hasan (1989) provided summaries of the above estimates and derived others of their own. No new information was provided.

<u>Present estimate</u>

Based on the above discussion, and in the interests of retaining a conservative approach until further data (particularly vertical salinity profiles through the freshwater lens) are obtained, it is recommended that 20% of recharge be adopted as an estimate of sustainable yield. In depth terms, this is equivalent to 106 mm/year (0.2 x 528 mm/year).

Past studies have converted the depth to a volume by multiplying by the island's total area (normally taken to be 257 to 260 km^2). However, some areas of the island are not effective recharge zones. From observations of salinities in wells, it is apparent that the freshwater lens does not extend within about 500 m of the coastline on the outer edge of the island. This area is one where freshwater is quickly dispersed with seawater due to tidal and other effects to produce a brackish water well beyond freshwater limits. Around parts of the lagoon where finer sediments tend to decrease the aquifer permeability, freshwater can be found within 100 m of open saline water (for example, the salinity is very low in well 82 which is near 'Atele and about 100 m from the shore of Fanga'uta lagoon). For this study, it was decided to only include the 'effective recharge zone' or that area of the island underlain by a known freshwater lens. All area within 500 m of the coastline and within 100 m of the lagoon in its south-western part were deleted from consideration. The resulting 'effective recharge zone' of the island is approximately 180 km^2 or 70% of the total area.

Sustainable yield is therefore estimated as 19.1 million m^3/year or 52 ML/day for the whole of Tongatapu. On a per unit area basis in areas where the freshwater lens occurs, the sustainable yield is approximately 0.3 ML/day/km^2.

Some areas of the island may have slightly higher sustainable yield potential than others but there is insufficient data to substantiate this at present.

For Tongatapu, the estimate of sustainable yield is equivalent to 6% of mean annual rainfall.

<u>Comparisons with other small islands</u>

Comparisons with other small islands show that the sustainable yield estimate for Tongatapu is not unreasonable. On the semi-karstic limestone island of New Providence in the Bahamas, where the land area is 208 km^2, the maximum width is about 1 km and the mean annual rainfall is 1,352 mm, the safe limit of extraction has been estimated as between 0.45 and 1.56 ML/day/km^2 by various authors (Peach and Swann, 1989). Where extraction has exceeded the lower bound estimate in some parts of the island, there is evidence of increasing salinity. In other parts of the island, the lower bound estimate is considered to be an underestimate. Where extraction rates remain low and steady (less than about 0.65 ML/day/km^2), salinities have remained low (Hadwen and Cant, 1980). If 0.65 ML/day/km^2 is taken to be a reasonable estimate of sustainable yield for the island, then it is equivalent to 18% of mean annual rainfall.

On the coral atoll of Tarawa in the Republic of Kiribati, where the maximum width of the islands is about 1 km and the mean annual rainfall is 1,980 mm, a total of about 1 ML/day is extracted from coral sands using infiltration galleries. This extraction is based on an assessment of the sustainable yield of freshwater lenses designated for extraction (Department of Housing and Construction, 1982). In the main aquifer on the island of Bonriki, about 0.8 ML/day is extracted from an area of about 0.8 km^2. This is equivalent to about 1 ML/ day/km^2. Monitoring of the lens by vertical salinity profiling in observation boreholes over several years of pumping has not detected any significant reductions in freshwater storage. At present, therefore, it would appear that the estimate of sustainable yield for the island is reasonable if not conservative. This estimate and the current extraction represent about 18% of mean annual rainfall.

On Bermuda, a limestone island in the Atlantic Ocean, where the mean annual rainfall is 1,470 mm. The main freshwater lens, the 'Central lens', with an area of about 6 km^2 (Thomson, 1989) is estimated to have a sustainable yield of approximately 6.8 ML/day (Thomas, 1989). Present extraction from this lens is about 5.5 ML/day (Rowe, 1991). The sustainable yield is equivalent to about 1.1 ML/day/km^2. The sustainable yield estimate is based on the assumption of a maximum permissible thinning of the lens by 50 to 60% of the natural lens thickness which is equivalent to about 75% of recharge.

The estimate of sustainable yield for Bermuda is equivalent to 27% of mean annual rainfall which is 50% higher than on New Providence in the Bahamas and on Tarawa. It is noted that these percentages are given as an approximate means of comparison between islands and other factors such as island width, permeability, variability of recharge, tidal influences, extraction patterns will also influence an island's sustainable yield.

Bermuda has adopted a much less conservative approach to the development of their groundwater resources than on some other small islands. However, this has only been done after a substantial data collection programme including monitoring of the effects of groundwater extraction over a number of years.

The same approach as on Bermuda is not recommended for Tongatapu until basic data is collected about lens dynamics in response to natural influences (such as variations in recharge and tidal effects) and man-induced influences (pumping). At present, the estimate of sustainable yield for Tongatapu of 6% of mean annual rainfall is considered conservative yet appropriate. After a period of monitoring and data analysis it may well be possible to revise the sustainable yield estimate and it is believed that this estimate will increase.

<u>Comparison with present groundwater extraction</u>

Present extraction from the Mataki'eua/Tongamai wellfield (refer section 5.1.2) is approximately 5.3 ML/day which represents about 10% of Tongatapu's estimated sustainable yield of 52 ML/day.

The 'rural extraction' or the additional extraction from public and private village wells is estimated in 1989 to be between 3.3 and 4.1 ML/day (Kafri, 1989). Furness (1990c) estimates that village wells produce between about 10 and 100 kL/day. Given that there are about 50 villages on the island of varying sizes, the estimates from the two sources would be approximately the same. Assuming that the upper estimate given by Kafri (1989) has increased by about 10%, the maximum rural extraction would now be about 4.5 ML/day. The present total extraction on the island is estimated to be a maximum of 9.8 ML/day or about 19% of the sustainable yield.

Most of the present extraction takes place in the western region of the island. For present purposes the western region is defined as that area within the bounds of the 'effective recharge zone' defined earlier and an imaginary line running south from Pea at the western end of Fanga'uta lagoon to the southern coastline. This is slightly smaller than the western region defined by Lao (1978). The area of the currently defined western region is about 60 km^2 and its sustainable yield is one third of the total sustainable yield or about 18 ML/day. The total extraction in this area includes the Mataki'eua/Tongamai wellfield and an estimated one third of the island's rural extraction or about 1.5 ML/day. Thus, the total extraction in the western region as defined above is about 6.8 ML/day or 38% of the sustainable yield for this region. A further 11.2 ML/day is available for future water resource development from this region.

For the areas of Tongatapu other than the western region, total current extraction is approximately 3 ML/day (two thirds of 4.5 ML/day). This is about 9% of the sustainable yield for this area (34 ML/day).

<u>Comparison with future groundwater extraction</u>

The estimated water requirement for Nuku'alofa by the year 2011 is 13.3 ML/day. This represents an increase of 250% on present requirements. It is assumed in the Master Plan for Nuku'alofa that the additional requirement will be met by groundwater pumped from the freshwater lens in the western region.

It can reasonably be assumed that the 'rural' demand in the western region will double to about 3 ML/day by the year 2011.

The estimated total water demand from the western region by the year 2011 is thus about 16.3 ML/day or just over 90% of the estimated sustainable yield. Hence, there will not be much more available freshwater in the western region unless the sustainable yield estimates are revised upwards in the light of further information about the freshwater lens dynamics.

If it is similarly assumed that the total water demand in the area of the island other than the western region doubles by the year 2011, then 6 ML/day will need to be developed, which represents about 18% of the estimated sustainable yield for this area. There would be some scope, therefore, for further development of the water resources in the southern and eastern parts of the island.

4.1.9 Proposed investigations

One of the most important and useful groundwater assessment techniques for the study of freshwater lenses on small islands is a series of monitoring boreholes for obtaining salinity profiles, as discussed previously. These can be used to obtain at regular intervals the thickness of the freshwater zone and transition zone at selected locations.

A number of methods can be used to install such monitoring boreholes. Open holes drilled through to seawater are not appropriate because mixing can occur in the borehole leading to an incorrect assessment being made about the salinity profile in the surrounding formation. Where the depth from ground surface to the water table is less than about 4 m, single boreholes fitted with thin tubes (typically 6 mm nylon) to different depths each hydraulically isolated from each other by bentonite layers and backfilled between the bentonite layers with a granular material can be used in some formations. They are ideal for coral atolls and low lying limestone islands where depths to water table are typically about 2 to 3 metres. A small pump can be used to lift water samples from each depth for salinity measurement with a portable meter.

Where the depth to water table is greater than about 4 m, as on Tongatapu, single holes can be fitted with a number of PVC conduits terminated at different depths and large enough to allow a salinity probe to be lowered to the bottom of the hole. The water at the base of each conduit will be representative of the salinity in the freshwater lens at that depth and in the vicinity of the conduit. Alternatively, several closely spaced drilled holes terminating at different depths can provide the same result. Selection of method is largely dictated by the relative cost with the former option being generally cheaper than the latter option since only one hole needs to be drilled. Low lying locations should be selected, where possible, to lower the overall cost of drilling. The base of quarries offer ideal locations for such drilling.

As mentioned in section 5.1.4, a number of salinity monitoring boreholes have been installed. It is recommended that additional salinity monitoring boreholes be installed with a minimum of four holes in each cluster (or four conduits within each hole). The terminating depths of the four holes or conduits should be set to coincide approximately with the following four features:

- The mid point of the freshwater zone
- The base of the freshwater zone (where the electrical conductivity is 2,500 µS/cm)
- The midpoint of the transition zone (where the electrical conductivity is 25,000 µS/cm)
- The base of the transition zone (where the electrical conductivity is 50,000 µS/cm).

It is recommended that a minimum of four additional monitoring systems be installed at the following locations:

- One in the western region away from the influence of pumping. One of the quarries to the east and west of Liahona may be suitable.
- One in the middle of the Mataki'eua/Tongamai wellfield. A suitable location would be near well 119.
- One in the southeast of the island. This could be sited near the village of Pelehake where the depth to water table is about 17 m based on depths at nearby wells 71 and 72.
- One in the north east of the island. The original salinity monitoring hole (well 77) could possibly be cleaned out and fitted with conduits. Otherwise another monitoring system should be installed nearby to allow comparison of salinity profiles with that originally obtained.

Preferably, additional monitoring systems should be installed if funding can be made available. Additional monitoring holes would be useful in other parts of the island including:

- To the south of the village of Veitongo near well 201.
- Between the village of Vaini and Vaini Experimental Farm (between well 1 and well 25).

- To the southeast of the pumping wells used for the Mu'a villages (about 500 m south of wells 18, 19, 20 and 21).

Similar monitoring systems should accompany any expansion of the wellfield in the vicinity of the Mataki'eua/Tongamai wellfield. With the proposed expansion, it is recommended that as a guide one monitoring hole should be drilled and equipped for every 10 production holes.

It is recommended that the proposed monitoring systems be installed during 1991 or in early 1992. It is further recommended that funding be made available as part of a special aid project for the installation of monitoring systems if recurrent funds are insufficient to cover them.

Following recent tests for pesticide contamination in the groundwater (refer sections 5.1.3 and 5.1.4), a full review of the use of pesticides and fertilizers is scheduled to be conducted by a WHO consultant in November 1991.

Other proposed work includes ongoing monitoring according to the list of activities outlined in section 6.

4.2 'Eua

4.2.1 Physical outline

Physiography and demography

'Eua is an elevated island situated 20 km southeast of Tongatapu at latitude 21°20' S and longitude 174°55' W. It has a surface area of approximately 87 km^2 and is the second largest island in the Kingdom of Tonga. The distance from north to south is approximately 19 km while its maximum width from east to west is approximately 7 km (refer Figure 5.26).

The shape of the island is roughly triangular. A ridge extends along the eastern side of the island with often a steep gradient towards vertical cliffs on the eastern coast. The maximum elevation is about 310 m. The island slopes towards the west with a series of three terraces evident at different levels. The tilting of the island towards the west indicates greater uplift on the eastern side.

The population of the island is 4,393 (1986 census).

Geology

There have been many geological studies on 'Eua and these are summarised in Warbrick (1989). It is not intended to give a detailed description in this report but rather a summary of the main features as they influence water resources.

The geology of 'Eua is more complex than that of many of the other islands in Tonga and is comprised mainly of karstified limestone with interlayerings of volcanic rock. The island is formed on volcanic rock of Eocene age which is essentially impermeable (Warbrick, 1989). A thick layer of limestone also of Eocene age overlies the volcanic basement with its highest point at approximately 310 m above msl. It is reported to be over 90 m thick and dips to the west. Overlying this layer in the elevated central part of the island is a thinner volcanic ash layer of Miocene age. This layer also dips to the west. Two limestone layers overtop the volcanic ash layer, the lower one being of Pliocene age and the upper one, which is exposed over most of the western side of the island, is of Quaternary age. The Eocene limestone and Miocene volcanic ash layers have low permeabilities while the overlying limestone layers have higher permeabilities as determined from rock samples (Warbrick, 1989). A recent hole drilled to water table at 69 m below surface level to the east of 'Ohonua was entirely within limestone. Permeability of the limestone was confirmed as very high as evidenced by large losses of drilling fluid (Furness, 1990b).

Hydrogeology and surface water

Freshwater is known to exist in the form of a fresh groundwater lens at sea level on the western side of the island, from the existence of a well at Tufuvai on the western coast, approximately 3 km south of 'Ohonua and from recent drilling which confirmed the presence of fresh groundwater to the east of 'Ohonua (Furness, 1990b). The thickness and lateral extent of the freshwater lens are unknown but it is likely to extend throughout the western portion of the island within the highly permeable limestone. The thickness may well be thicker than would be the case in a fully limestone island above msl because it is apparent that water from the eastern side of the island is being directed to the west on top of the relatively impermeable volcanic ash layer.

A second aquifer is likely to be the Eocene limestone which outcrops on the eastern side of the island. Practical difficulties in developing this potential aquifer owing to its distance from existing settlement and the much greater drilling depth required than on the west, preclude this aquifer from further consideration at present.

'Eua is one of the few islands within the Kingdom of Tonga with surface water flow occurring from perched groundwater and direct runoff from elevated areas. The springs (or outflows from caves) are at an elevation of approximately 120 m and are caused by the relatively impermeable Miocene volcanic ash layer (or layers) underlying limestone on the eastern side of the island. The spring flows, unless collected by a number of spring collection systems, travel westwards over the surface and discharge either back into the ground in more permeable areas to the west or into a network of intermittent streams which discharge into Nafanua harbour.

There are also some streams which flow intermittently into Nafanua harbour near 'Ohonua and on the eastern side of the island. These are fed from the surface water flows in the central area of the island.

Soils

Wilde and Hewitt (1983) describe in detail the soils of 'Eua. As with other islands in Tonga, a volcanic ash soil overlies most of the island. Exceptions occur on the steep slopes (no soil), near the beaches (coral sands), in the central valley (volcanic alluvium) and in some of the elevated terrain (volcanic collovium).

Measurements of physical properties which are important to the water balance of the island indicate that similar values of soil moisture zone thickness, field capacity and wilting point to other islands in the Kingdom of Tonga can be used (refer section 4.6).

Vegetation

The vegetation on the island is a mixture of low shrubs, grasses and trees, predominantly coconut trees. Agricultural activities are mainly centred in the middle of the island and are similar to those used in other parts of Tonga.

From a water resources viewpoint the types of vegetation are similar to those on Tongatapu. The percentage of total area covered by potentially deep rooted vegetation such as coconut trees is considered to be 50% which is higher than the assumed 30% for Tongatapu.

4.2.2 Present water resources development

Water resources development consists of spring collection systems, rainwater catchments and the dug well at Tufuvai previously mentioned.

There are three developed springs or groups of springs on the island, all in elevated terrain. The term 'spring' is used here although in most cases the discharges are more akin to streams emanating from the mouth of cave systems rather than conventional springs emanating from a rock face. The water supply systems including the spring source developments on the island are operated and maintained by the Tonga Water Board.

Kahana Spring is located inside a cave in the north of the island, approximately 2 km northeast of Houma. Until about two years ago water from this spring was piped to a concrete tank near the mouth of the cave and then pumped to another concrete tank above the village of Houma for its water supply. At present Houma is reliant on rain water catchments for water supply.

Another spring (Veimumuni spring) is located in the south of the island and supplies water to the prison.

Three springs located in the central part of the island ('Ana Peka Beka, Matavai and Saoa) are the main source of water for the island. These central springs emanate from the 'Ana Peka Beka Cave system, the Fish Cave (Matavai) system and the Shower Cave/Collapse Cave (Saoa) system.

Details of these cave systems are given in the report of a caving expedition to the island (Lowe and Gunn, 1986) and a descriptive summary is given in the 'Eua Water Supply Master Plan report. A weir is constructed in each system to direct the flow into collector pipes. Flows in the collector pipes join into a common pipeline to supply water to the villages in the central part of 'Eua.

Waterhouse (1984) reports that two other springs (Hafu and Heke) to the north of these three were abandoned. Warbrick (1989) states that their closure was due to silt contamination during heavy rainfall. The silt derives from eroding surfaces which have apparently been exacerbated due to increased felling of trees.

The Hango Agricultural college obtains water from a Hango spring which is located approximately 3 km east of the college (Warbrick, 1989). It is reported that this source has a continuous flow of 1.7 L/sec or about 100 L/min (Belz, 1988)

4.2.3 Previous water resources investigations

Previous water resources investigations on the island are limited. Studies have been made by:

- Muller (1978)
- Lao (1986: Appendix 12)
- Waterhouse (1984)
- Warbrick (1989)
- Hasan (1989).

Muller's report is concerned mainly with water supply problems on 'Eua. He described problems encountered at the spring intake structures and in the reticulation pipelines and recommended that groundwater would be a more reliable water source than surface water. He suggested a possible borehole for groundwater near the centre of the island.

Based on a two day site visit, Lao (1986) described the surface water and groundwater flow pattern on the island and how these were controlled by ash beds dipping to the west. He suggested that tunnelling into the ash bed(s) could provide an adequate water supply for the island. He also recommended the need for an in-depth investigation including baseline data on elevations of surface springs, metered flow records from springs, rainfall data from the higher elevations and drilling to establish whether the ash beds exposed at high elevation continue towards the western side.

Waterhouse (1984) gave an outline of the springs and their problems, particularly their unreliable yields and their susceptibility to pollution from eroded soils, animals and pesticides. He recommended that the springs should not be further developed or modified and reiterated Muller's recommendation about the need to develop the groundwater resource.

Hasan (1989) briefly summarised some of the features of 'Eua. He estimated the flow from 'two perennial streams [which] flow across the island in a westerly direction' to be 250-300 L/s on the date of his visit to the island (24 November 1989).

Warbrick (1989) provides the most comprehensive report of the water resources of 'Eua. This report details the findings of a geophysical (electrical resistivity) programme which was rather inconclusive in determining freshwater lens thickness. This is largely caused by the difficult site conditions for the electrical resistivity technique to work successfully. The thick unsaturated limestone layer with a high resistivity prevented successful interpretations being made. Also the use of a layer model which excluded a very low resistivity layer corresponding to seawater under the island would also have meant that the thickness of freshwater could not be obtained if the other problem had not existed.

Warbrick used a finite element type of sharp interface model to analyse the behaviour of an assumed freshwater lens under the western side of the island. Results are outlined in section 5.2.8. His analysis showed that a pump rate of 4.5 ML/day from a well location sited about 2 km northwest from the island's centroid would not reduce the thickness of the lens, assumed to be initially between about 13 m and 17 m thick, by more than 50%. This degree of thinning he assumed to be an upper limit for sustainability of the lens. He then applied a factor of safety and concluded that the sustainable yield was approximately 1 ML/day.

Warbrick also made recommendations about the optimal location for production boreholes. He suggested they should be drilled in an area between 2 and 3 km from the west coat of the island where the deepest part of the freshwater lens was presumed to be. He also recommended that the holes be drilled just below sea level, that the pump intake be set at a level no lower than sea level and that conductivity probes be installed in all wells to measure salinity.

4.2.4 Recent water resources investigations

Surface water

Unfortunately, no systematic flow records from the springs 'Eua have been collected, despite recommendations in previous reports. This means that there is very little quantitative data on springflows available. It is known, however, that the springflows vary considerably in quantity and quality. After periods of heavy rainfall, the central springs are known to discharge relatively large and highly turbid flows. The high turbidity makes this source of water unfit for human consumption without treatment.

Flow records obtained on 1 March 1990 during a visit to the island by a team including personnel from the Hydrogeology Unit and the Tonga Water Supply Master Plan Project are summarised in Table 5.5.

Table 5.5 Springflows on 'Eua island on 1 March 1990

Spring location	Flow (L/min)	Method of measurement	Electrical conductivity @ 25ºC (µS/cm)
Kahana Spring (NE of Houma)	2	Graduated jug	520
Central springs (combined)	400	Pipe meter	300
Veimumuni (SE part of 'Eua)	5	Estimated	450

It was reported that the water meter on the pipeline from the central springs was broken in early 1991 so that flow estimates are not easily obtainable at present. However, recent flow estimates for the central springs were reported by the Tonga Water Board for 30 July 1991 as follows; 'Ana Peka Beka : 115 L/min, Matavai : 2,400 L/min, Saoa : 120 L/min. The combined flow of these three springs on 30th July is therefore slightly greater than 2,600 L/min. By early October 1991 the flow at Matavai had reduced to a trickle showing the high variability of the springflows.

Other flow estimates have been obtained and these are summarised below:

- Kahana spring (Waterhouse, 1984):
  - 1977 (no day or month given): 18 L/min
  - 1978 (between 18 Feb & 3 Mar): 4.5 L/min
  - 1984 (30 September): 'trickle'.
- Kahana spring (Warbrick, 1989):
  - 1987 (December, no date): <0.17 L/min.
- Central springs (2 of them: Hasan, 1989):
  - 1989 (24 November): 15,000-18,000 L/min.
- Hango spring (Belz, 1988): 100 L/min.

In addition, verbal comments by various people indicate that flows in dry periods become very low.

The low flows above correspond to extensive prior periods of nil or low recharge, as determined from the recharge analysis for Tongatapu (refer Appendix I for details). The very high flow figures shown by Hasan (1989) must have occurred after an intense downpour or possibly there is an error in the units he used (he quotes 250-300 L/sec which may have been 250-300 L/min). Unfortunately, daily rainfall records for November 1989 on 'Eua were not available so a check could not be made. On the 24th of November, no rainfall was recorded on Tongatapu yet on the 23rd, 21 mm and 24 mm were recorded at Fua'amotu and Nuku'alofa, respectively. No conclusion can be reached at this stage until a correlation between daily and possibly hourly rainfall and springflows is made. It is not possible given the available data to support one suggestion that the springflows on the island reduced over time. Rather, it is much more likely that the variation in flows at springs is controlled by natural variations in rainfall and recharge on the island.

Groundwater

Two investigated boreholes were drilled on 'Eua by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources in November 1990 (Furness, 1990b).

The first hole was drilled at Kolomaile to 33 metres through limestone and two small volcanic ash layers. The limestone was found to be highly permeable with rapid and complete loss of drilling fluid at two of three caves or fissures intersected during drilling. No water was found even on the thin volcanic ash layers, as had been surmised in some earlier reports. which may have occurred on a thin volcanic ash layer.

The second hole was drilled to a depth of 69 m entirely in limestone on the eastern side of 'Ohonua. Static water level after drilling was at a depth of 65 m which is less than 1 m above msl. As with the first hole the limestone was highly permeable as indicated by large losses of drilling fluid. A water sample bailed from the bottom of the hole had an electrical conductivity reading of 830 µS/cm, indicating its chemical quality was suitable for potable purposes.

The 1990 Hydrogeology Unit report concluded that drilling along the western side of the island (to the water table of the freshwater lens) can be expected to yield similar results. It also recommended that further investigatory drilling should not be carried out in the centre of the island near Kolomaile, despite the likely presence of perched water in the area, due to the cavernous limestone causing problems and subsequent high costs with the drilling. This author concurs with these conclusions and recommendations.

4.2.5 Rainfall analysis

The raingauge at 'Eua is presently located at 'Ohonua although previously it was located at the Government sawmill at Vaitaki (Thompson, 1986). The date of the move from one site to the other is presumed to be in early 1989. Thompson states that rainfall records have been collected since 1983. Warbrick (1989) refers to a complete rainfall record since September 1986. However, only limited monthly rainfall records were available for 'Eua from the Tonga Meteorological Service since there were many missing days and hence months of data.

Appendix H lists the 40 available months of records. These were obtained from various sources within the Tonga Meteorological service including hand written sheets since 1989 and New Zealand Meteorological service summaries prior to this. The available record was as follows:

- 1984: March, April, July-December (8 months)
- 1985: January, March-October (9 months)
- 1986: January, February (2 months)
- 1989: full record (12 months)
- 1990: all months except June, Aug & Sept (9 months).

For the full 40 months of record, 'Eua recorded a total of 4,968 mm compared with 5,171 mm at Nuku'alofa and 5,117 mm at Fua'amotu for the same period. Thus the cumulative rainfall at 'Eua over this non-continuous period was 4% less than at Nuku'alofa and 3% less than at Fua'amotu.

For the 21 months of record since January 1989, 'Eua (3,811 mm) recorded 8% higher rainfall than at Nuku'alofa (3,541 mm) and 7% higher rainfall than at Fua'amotu (3,567 mm). Figure 5.27 shows the monthly rainfalls for the three stations during this period.

Thus, it could be concluded from the available record that the rainfall on the western side of 'Eua is approximately the same as on the eastern side of Tongatapu. This is contrary to the results of a preliminary analysis by Thompson (1985) in which he suggested that the Vaitaki site on 'Eua received about 25% more rainfall than at Fua'amotu. It also highlights the ongoing need for regular daily rainfall readings on 'Eua so that long-term rainfall trends can be more adequately established.

There is a possibility of a rain shadow effect on 'Eua caused by the elevated terrain in the east. This would cause the mean rainfall for the whole island to be greater than on the western side as a higher rainfall is likely to fall on the eastern side due to orographic effects. Confirmation of this possibility is required by recording rainfall on the eastern side before any conclusions can be made.

A regression analysis between monthly rainfall at 'Eua and at Nuku'alofa for the 40 months of data indicated that the correlation coefficient (r) was 0.87 and that the regression equation was:

$$\mathbf{P_{'Eua\text{-}M} = 0.996\ P_{Nuku'alofa\text{-}M} - 2}$$

where

$\mathbf{P_{'Eua\text{-}M}}$ = monthly rainfall (mm) at ‘Eua

$\mathbf{P_{Nuku'alofa\text{-}M}}$ = monthly rainfall (mm) at Nuku'alofa.

Similarly, a regression analysis between monthly rainfall at 'Eua and at Fua'amotu for the 40 months of data indicated that the correlation coefficient (r) was 0.90 and that the regression equation was:

$$\mathbf{P_{'Eua\text{-}M} = 1.05\ P_{Fua'motu\text{-}M} - 9}$$

where $\mathbf{P_{'Eua\text{-}M}}$ = monthly rainfall (mm) at ‘Eua

$\mathbf{P_{Fua'motu\text{-}M}}$ = monthly rainfall (mm) at Fua'amotu.

The above equations can be used as reasonable approximations for monthly rainfall at 'Eua based on observed records at Nuku'alofa and Fua'amotu with the latter equation preferred due to the slightly higher correlation between rainfall at 'Eua and Fua'amotu.

4.2.6 Recharge analysis

Detailed recharge analyses were not undertaken for 'Eua because of the paucity of meteorological data. However, as the rainfall and evaporation are similar to Tongatapu and as the vegetation and soils are similar from a hydrological perspective to Tongatapu, the recharge pattern as determined for Tongatapu is a reasonable estimate for 'Eua.

It is noted that 'Eua has some surface runoff but this is mainly within the island and does not represent a major net loss from the island. One stream does discharge intermittently into Nafanua harbour but its relative significance is considered to be low. As a first approximation, therefore, the water balance equation for the whole island can reasonably delete the surface runoff component, as for Tongatapu. It would be a worthwhile exercise as part of a long-term water resource assessment of the island to install a small stream gauging station near the outlet of the stream at Nafanua harbour. When dealing with a water balance of parts of the island surface runoff may however need to be considered.

The soil and vegetation of 'Eua is considered to be similar to that of Tongatapu from a water resources viewpoint except that the proportion of trees is higher (50% compared with 30%: refer section 5.2.1). As none of the roots of the trees are assumed to penetrate to the water table on 'Eua due to the high surface elevation, the difference in mean annual recharge between the two islands due to this factor would be small.

The mean annual recharge for 'Eua is estimated as 528 mm assuming it to be the same as for Tongatapu. Warbrick (1989) assumed the mean annual recharge to be 450 mm (25% of 1,800 mm) in his analysis of the groundwater resource. These two estimates are within 15% of each other.

4.2.7 Sustainable yield estimates

Surface water

The sustainable yield of the surface water component is unknown at present as there are very few flow readings of any of the springs on the island. Hence, no reasonable estimate can be given until after a period of flow measurements.

Groundwater

Warbrick (1989) used a finite element type of sharp interface model to analyse the behaviour of the freshwater lens under the western side of the island. He assumed that the freshwater lens extended from the west coast to approximately the middle of the island. The surface area of this assumed lens was 46.6 km^2. He also assumed aquifer permeability decreased from west to east with values in the range from 3,000 to 500 m/day. He used three different permeability patterns to test his model (3,000 to 1,500 m/day, 2,500 to 1,000 m/day and 2,000 to 500 m/day) specific yield of 20% was assumed. His analysis showed that a pump rate of 4.5 ML/day from a well location sited about 2 km northwest from the island's centroid would not reduce the thickness of the lens, assumed to be initially between about 13 and 17 m thick, by more than 50%. This degree of thinning he assumed to be an upper limit for sustainability of the lens. Warbrick applied a factor of safety to the pump rate above and concluded that the sustainable yield was approximately 1 ML/day.

As part of this study, the sustainable yield from the freshwater lens on 'Eua was estimated using the same approach as for Tongatapu. The effective area of the lens island was measured as 60 km^2 or about 70% of the island's total area of 87 km^2 using the assumption that the freshwater lens does not extend closer than 500 m to the coastline around the island. This is considered to be an upper limit to the area of the freshwater lens. Given the geological structure of the island, it is possible that the freshwater lens does not extend into the eastern side of the island. If this is the case then the area assumed by Warbrick (1989) of 46.6 km^2 could be taken as a lower limit to the areal extent of the freshwater lens.

The surface area of the island contributing to the recharge of the lens is likely to be larger than the area of the lens itself. This is due to the westerly dipping volcanic ash layer which is known to direct at least some of the rainfall falling on the eastern side of the island across to the west. Without further knowledge at this stage, it is assumed that 75% of the island's surface area or about 65 km^2 recharges the freshwater lens on the western side. This area is slightly larger than the upper estimate for the area of the freshwater lens. It is this area that is used for computing sustainable yield.

Assuming that the surface water component of the water balance is negligible and that the same proportion of recharge can be safely extracted as assumed for Tongatapu (i.e. 20%), then the sustainable yield of the freshwater lens on 'Eua is estimated to be 6.7 million m^3/year or about 1.8 ML/day. This estimate is equivalent to about 200 L/s and is 80% greater than that of Warbrick (1989) partly because of a higher assumed depth of mean annual recharge and partly because of a higher assumed recharge area.

The sustainable yield of the groundwater would need to be reduced by the amount of any extracted surface water multiplied by a factor of 5. The factor of 5 is required as surface water extraction removes a proportion of potential groundwater recharge which then needs to be divided by 5 in order to obtain the groundwater sustainable yield. Thus from a water quantity viewpoint, it is desirable to maximise the amount of surface runoff extracted. Other factors such as water quality and the relative economics of collection, treatment and distribution of surface and groundwater need also to be taken into consideration.

The present estimate of sustainable yield (1.8 ML/day) compares with the present water demand of 0.83 ML/day and an estimated water demand in the year 2011 of very close to 1 ML/day ('Eua Master Plan study). Thus, the water requirements for the next 20 years should be capable of being satisfied from groundwater alone. If surface water is also used as part of a conjunctive surface and ground water scheme, then the picture is even more favourable.

Comments on proposed locations and capacities of individual production wells are given in section 8.7.

4.2.8 Proposed investigations

Surface water

Flow at the major springs on the islands should be gauged. To undertake this exercise, it is recommended that all springs be fitted with simple V-notch weirs and staff gauges for manual readings. Manual readings should be obtained on at least a daily basis for a period of at least six months. The date, time and gauge height should be recorded in a book at each visit. During and following periods of heavy rain additional; readings would be very helpful.

One of the spring weirs should be equipped with an automatic recorder to enable continuous stage (height) measurements. It is recommended that the largest of the central located springs on the island be gauged automatically.

For this purpose one of the electronic data loggers and pressure probes (0-1 m range) owned by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources could possibly be used. Alternatively, equipment could be independently procured and handed over to the Hydrogeology Unit after the period of data collection is concluded. A tipping bucket raingauge should be attached to the same data logger to record rainfall if a suitable location can be found within the close vicinity of the gauging station. If not, another data logger would be required to enable independent logging of rainfall at a nearby site suitable for rainfall measurement. Note that a suitable site is one where there is protection from winds but no obstructions which might cause less rainfall to be caught.

Ideally a site where the distance to nearby objects is twice the height of those objects is required for a raingauge. The rainfall measuring site should be within the catchment of the spring flow being continuously measured. On 'Eua such a site may possibly be found in a cleared area to the east of the springs. Inspection of aerial photographs should provide some indication of whether such a site is available. It two data loggers are required they must be synchronised in time to enable meaningful results to be obtained.

The continuous flow record at one of the springs and the manual records at that and other springs will enable some correlation to be made between the flows at the different springs. Also, by analysing the continuously recorded flow and rainfall records, a simple rainfall-runoff relationship could be derived. These correlations should enable flows at each of the springs to be estimated from rainfall records. It will also enable a correlation between the rainfall station at 'Ohonua and the raingauge in the centre of the island. This will assist in determining if there is any significant spatial rainfall variation on the island. However, to properly analyse cross-island variations, a third raingauge on the eastern side of the island should be installed. This would enable any rain shadow effect as a result of the central ridge to be determined.

It would be a worthwhile exercise as part of a long-term water resource assessment of the island to install a small stream gauging station near the outlet of the stream at Nafanua harbour. A V-notch weir and automatic level recorder at this site would suffice as a stream gauging station. Flow records at this site would enable the component of surface water outflow to be quantified and for a more exact estimate of groundwater recharge made. Some estimation of outflow from the island from other intermittent streams would also be useful.

Groundwater

Because of the elevated terrain on the island and the relatively high cost of drilling on the island, it is not recommended that further detailed investigations be conducted at this stage. Geophysical techniques for identifying freshwater zones and their thickness have very limited application on the island owing to the large depths to water table. Drilling is relatively expensive for the same reason and it is therefore suggested that further investigations be restricted to the drilling of one monitoring hole for vertical salinity profiling (similar in design to those recommended for Tongatapu). This should be done at the time when production boreholes are drilled.

4.3 Ha'apai

4.3.1 Physical outline

Physiography and demography

The Ha'apai group consists of 51 islands of which 16 are inhabited. The islands are located between latitudes 19°30' and 20°35' S and longitude 174°15' and 175°0' W (refer Figure 5.28).

Three main island types are evident in the Ha'apai group as follows:

- Low-lying limestone islands with gently undulating topography. These islands are raised coral atolls.
- High and steeply rising volcanic islands.
- Sand cays (for example, Uoleva).

The group has been subdivided into three sub-regions (Ha'apai 1988/95 Regional Plan, 1988). These are the Hahake sub-region which consists of the northeastern islands and where most of the population lives, the Lulunga sub-region consisting of the central and western islands and the Mu'omu'a sub-region consisting of the southern islands.

This report is concerned mainly with the islands in the Hahake sub-region but some of the general observations can be applied to other similar islands in the Ha'apai group. In the Hahake sub-region the largest and most populated islands are (from north to south): Ha'ano (area: 6.6 km^2, population 728), Foa (area: 13.4 km^2, population: 1,409, Lifuka (area: 11.4 km^2, population 2,840) and 'Uiha (area 5.4 km^2, population 913). All population figures are from the 1986 census).

The population is settled in a number of villages in the populated islands. The villages of Pangai and Hihifo on the island of Lifuka are often considered as a joint township owing to their proximity to each other.

Geology

The islands of the Ha'apai group are predominantly low-lying, limestone islands but there are some volcanic islands. As mentioned in section 4.3, the islands to the west of the Tofua Trough (for example, Tofua and Kao) are volcanic while those to the east are limestone islands or have mixed limestone and volcanic sequences above sea level (e.g. Mango).

The islands of Ha'apai which are of most concern to this study are all low-lying limestone islands. These islands are slightly tilted with the eastern side being higher than the west. In this respect they are similar to 'Eua but with much lower elevations, the maximum elevation being about 15 m (compared with about 310 m on 'Eua). The exposed cliffs on the eastern side of the islands show karstic features. On the island of Lifuka, small outcrops of volcanic rock are evident on the eastern beach (Furness, 1991).

Hydrogeology and surface water resources

Freshwater is known to exist in the form of fresh groundwater lenses at sea level on the larger limestone islands. The general comments made about water resources on small islands in section 4.2 apply to many islands in the Ha'apai group. Also, many of the comments made for Tongatapu in section 5.1.1 but at a smaller scale apply also to the larger islands of the Ha'apai group. Some of the smaller limestone islands in the Ha'apai group are reported as having no freshwater lens.

There is no fresh surface water on the limestone islands. Brackish water swamps and lakes or lagoons are known to exist on Foa and Nomuka, respectively.

A freshwater crater lake with a top water level of about 20 m above msl is present in the volcanic island of Tofua. Although there is very little known about the hydrogeology of Tofua, some insight to it is given by a brief unnamed report on a file at Vaini Experimental Farm. The report states that "Although the rainfall is high, drainage is almost entirely underground, the water seeping readily through the interbedded lavas and pyroclast deposits, and especially through the overlying ash which almost everywhere occurs as a surface deposit 10-20 feet (approx. 3-6 m) thick. Presumably this water emerges below sea-level as no springs were observed above high water mark. Even after 3 to 4 inches (75 to 10 mm) of torrential rain, there was no sign of surface runoff in gullies or stream beds. On the paths where the ash was compacted, surface runoff and severe scouring had occurred, and in very few gullies excavated in lava on the higher slopes of the mountain, there were pools of water, and signs of flow. However, these streams had not reached the sea. On the lower outer slopes of the caldera only one stream, that draining the north-western slopes, had a bed of fresh water-deposited sediments indicating frequent flow. elsewhere the floors, even of deep gullies with considerable catchment areas, were completely covered with stable vegetation and soil, often cultivated, indicating no flow at all for decades, and perhaps centuries. How deep gullies, in some cases preserving traces of substantial falls over lava flows, could have been excavated, and then all surface flow and erosion cease, is uncertain. A sufficient climatic change is unlikely. More possibly, after ash eruptions and in the absence of a vegetative cover, the ash surface becomes self-cemented and form a weak crust. This is sufficiently impermeable to permit surface runoff and erosion. With the re-establishment of vegetation, the ash surface becomes loose and friable, and drainage becomes entirely underground. It is significant that in the very young ash deposits within the caldera, where there is no vegetation, the surface has a thin weak crust which is sufficiently impermeable for surface runoff. These ash deposits are undergoing scouring and gullying. However, where there is vegetation the ash is no longer encrusted and signs of surface drainage disappear". This extract indicates that there may well be a freshwater aquifer within the volcanic rock of which the island is entirely composed. No conclusions are possible, however, without a thorough hydrogeological investigation. Owing to the remoteness of the island and the limited and intermittent population which lives there, such an investigation would be of low priority.

The description of the nature of surface runoff over the volcanics may have some bearing on investigations in the Niuas (refer section 5.5).

Soils

Wilson and Beecroft (1983) provide a detailed description of the soils on the islands of the Ha'apai group. As with other islands in Tonga, a volcanic ash soil overlies most of the islands.

Measurements of physical properties which are important to the water balance of the island indicate that similar values of soil moisture zone thickness, field capacity and wilting point to other islands in the Kingdom of Tonga can be used (refer section 4.6).

Vegetation

The vegetation on the main islands of the Ha'apai group is a mixture of low shrubs, grasses and trees, predominantly coconut trees. Agricultural activities are similar to those used in other parts of Tonga.

From a water resources viewpoint the types of vegetation are similar to those on Tongatapu and 'Eua. The percentage of total area covered by potentially deep rooted vegetation such as coconut trees is considered to be 50% which is higher than the assumed 30% for Tongatapu and the same as for 'Eua.

4.3.2 Present water resources development

Present water resources development consists of groundwater pumped from wells and rainwater catchments. There is no surface water development. Two desalination plants have recently been installed on the island of Nomuka (refer section 4.4.4).

Public water supply systems using groundwater are operated and maintained by the Tonga Water Board for most villages on the islands of Lifuka, Foa and 'Uiha. These islands also have a number of private wells in the village areas. All wells listed in a recent census including all public and many of the private wells are shown in Figure 5.29.

Rainwater catchments are also utilised by some houses on all of the islands.

On Foa, four separate wells dug along the centre of the island provide water to the villages of:

- Faleloa and Ha'afakehanga
- Lotofoa

- Fotua
- Fangala'ounga.

On Lifuka, two wells were dug in 1971 approximately 200 m apart in the middle of the widest part of the island. Water is currently pumped from the western of these two wells to Pangai and Hihifo.

On 'Uiha separate water supply systems consisting of well, pump, headtank and reticulation pipes operate in the villages of 'Uiha and Felemea.

Many houses on the main islands of the Ha'apai group have rainwater tanks. Some are in good condition but many are in varying states of disrepair.

4.3.3 Previous water resources investigations

A number of studies of water resources have been undertaken in the Ha'apai group, primarily on the larger islands in the Hahake sub-region. These most notable studies have been:

- Waterhouse (1984): Foa and Lifuka
- Lao (1986): Foa and Lifuka
- Stoll (1987): Foa and Lifuka
- Enersol (1987): Lifuka
- Dale et al (1988): Uoleva.

Other reports have been written about water supply systems on the islands including:

- Belz (1984)
- Stoll (1986)
- Sharp (1989).

The main findings in relation to water resources of the above studies are that:

- The two Tonga Water Board wells located to the east of Hihifo on Lifuka, which were dug in 1970-71 (Waterhouse, 1984), are overpumped and yield highly brackish water to consumers in Pangai/Hihifo. Within the pumped wells, salinity increases with depth, even though the depth of water is only about 0.4 m (Lao, 1986). Salinity of the well water increases rapidly when pumps are switched on (Waterhouse, 1984; Lao, 1986),
- The public wells on Foa are not so overpumped and yield lower salinity water than those near Hihifo on Lifuka but are still beyond the salinity limit for drinking water,
- The high salinities in pumped wells are at least partially attributed to the high pump rates,
- Pump tests (Waterhouse, 1984) have indicated that the transmissivity (or the ability to allow water flow) of the aquifers are very high, a result which is of no surprise given that the formation is porous and cavernous limestone,
- Hydrogeological investigations leading to estimation of the sustainable yield from the freshwater lens are required before further development is contemplated from the groundwater resources (Waterhouse, 1984; Lao, 1986). Details of well design and spacing, extraction rates and monitoring systems and programmes are also required (Waterhouse, 1984),
- Several deep monitor wells penetrating though to seawater are necessary to determine the vertical salinity profile though the lens and the effects of pumping (Lao, 1986). Lao also provided details of a proposed monitoring programme,
- The close proximity of sanitation facilities to private wells is cause for concern. Waterhouse (1984) recommended that the use of water from private wells be discouraged for this reason,
- The use of rainwater catchments should continue to be encouraged at least as a supplementary supply of freshwater (Waterhouse, 1984),
- Water samples from a 27 wells on Lifuka were tested in 1985 (Lao, 1986) for salinity and all were within recognised limits for freshwater except for the pumped well used for public water supply,

- Lao (1986) proposed a two aquifer model to explain the lower tidal response of wells located on the western side of the islands than in the centre of the island. He proposed that the main aquifer is the basal freshwater lens and that a shallower aquifer is formed on the western side of the island by the presence of a compacted clay layer found in excavations.
- To decrease the salinity of the pumping wells on Lifuka, Lao (1986) proposed two solutions: pump at half the rate for twice the time and extend the influence of the wells by excavating infiltration tunnels at the base of the wells
- After his investigations of water quality in drilled test wells, Stoll (1987) concluded that there is no well defined freshwater lens and little or no possibility of developing groundwater of potable quality on Foa. On Lifuka, however, he concluded that a freshwater lens does exist to the north of the pumped wells. The salinity profile in one test well showed a freshwater zone of 8 m thickness (refer Figure 5.30). At this test well, organic gases of apparently unknown origin were released. The pH of the water was 5.2 indicating that it was quite acidic.
- A small freshwater lens exists on Uoleva based on salinity tests at wells and limited electrical resistivity by Dale (1988). He recommended that the resource was not sufficient for it to be considered for possible piping to Lifuka.

4.3.4 Recent groundwater resources investigations

Recent groundwater resources investigations have been undertaken mainly by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources.

<u>Pumping facilities</u>

In March 1990 members of both the Hydrogeology Unit and the Tonga Water Supply Master Plan project team visited the island, inspected water supply facilities and carried out some salinity tests at selected wells.

No recent flow records are available as meters are either not fitted or not operational. On Lifuka the pump rate from the western well near Hihifo (Well 46 in Figure 5.29) of the two Tonga Water Board wells was estimated at approximately 5 L/s when the pumps are running, which is estimated at about 3-4 hours per day. The second or eastern well near Hihifo was not being pumped. If these estimates are correct, the total volume of water being pumped is approximately between 54 kL/day and 72 kL/day.

<u>Salinity readings at wells</u>

In March 1990, salinity (electrical conductivity) readings at selected wells, both public and private, were obtained on the islands of Foa, Lifuka and 'Uiha. Results are listed in Appendix J for the selected wells. Where zero values are shown in the results, no reading was obtained. The listing of wells is shown in Appendix G while Figure 5.29 shows the locations of these wells. The March 1990 results tend to confirm the results from earlier investigations, namely, that:

- The pumped well near Hihifo on Lifuka used for the public water supply system was very brackish (12,500 µS/cm). The second well which had not been pumped for several months was much less brackish (3,120 µS/cm).
- The public wells on Foa were less salty but nevertheless beyond the salinity limit for drinking water.
- The private wells, particularly those in Pangai/Hihifo, had salinities which were acceptable for potable purposes.

Well census and monitoring work was carried out by the Hydrogeology Unit in September 1990. The well census established the numbering system shown in Appendix G for most of the wells on Foa, Lifuka and 'Uiha. A total of 63 wells have been registered, including all wells used for public water supply and most of the private wells. Not all private wells were included for a number of reasons, the main one being proximity to another already registered. Monitoring was conducted at each well, where possible, of water level relative to a fixed surface mark, electrical conductivity, temperature and pH. Results for the September monitoring work and subsequent monitoring at selected wells in late January and early February 1991 are listed in Appendix F. A description and interpretation of the results obtained in September 1990 are provided in Furness (1990a). A summary of these and further comments based on recharge analyses are presented in section 5.3.7.

Also in Appendix F are the results from five pumped wells taken from Lao (1986). Unfortunately, the private wells on Lifuka listed by name and sector in Lao (1986) do not correspond in many cases to those in the present census despite the fact that many of them must be in both lists. This prevents trends in salinity from being determined. A closer study of names and/or sectors may lead to cross matching but this was not possible within the time frame of this study.

Geophysical programme

An electrical resistivity programme was undertaken in late January/early February 1991 which included a series of soundings on Ha'ano, Foa, Lifuka and 'Uiha. Soundings were done using the recently procured ABEM SAS 300 Terrameter. The field data was interpreted in March 1991 using an ABEM (VES) software package. A four layer model was generally used to describe the hydrogeological conditions. The upper layer corresponded to the soil layer with a moderate resistivity, the second layer corresponded to the unsaturated limestone layer with a high resistivity and a typical thickness of 3 to 8 metres, the third layer describes the freshwater layer where it exists or alternatively a brackish water layer. The resistivity of the third layer is low for freshwater and lower for brackish water. The fourth layer corresponds to very brackish to seawater with a very low resistivity. Four layer models have been used on other similar islands to describe the hydrogeological conditions.

In conjunction with the electrical resistivity survey, an electromagnetic (EM) survey was conducted on the four islands mentioned above using a Geonics EM34 instrument.

Results from the resistivity survey on Lifuka are summarised in section 5.3.7. Locations of the soundings are shown in Figure 5.31. The field results for Ha'ano, Foa and 'Uiha were still under analysis at the end of the author's site visit in February/March 1991.

Drilling programme

Ten sets of salinity monitoring boreholes were drilled in August 1991 on Lifuka (refer Figure 5.31) to further investigate the freshwater lens configuration on the island and to check the estimates of freshwater lens thickness provided by the geophysical programme. Six of the monitoring boreholes consisted of a series of PVC pipes terminating at different depths, similar to the design used at Fuala and Mataki'eua on Tongatapu (refer section 5.1.4 and Appendix E). The locations of the six monitoring borehole systems around the villages of Pangai and Hihifo were chosen as three pairs on each side of the freshwater lens area identified by the geophysical programme (refer Figure 5.31).

The results of this recent investigation of vertical salinity profiles were not available in time to incorporate them into the main body of the report; they are summarised, however, in section 5.3.7 with further details provided in Appendix E.

4.3.5 Rainfall analyses

There is only one official raingauge in the Ha'apai group of islands, situated at the meteorological station at Pangai, Lifuka. It is assumed, for the purposes of this report, that the rainfall at Pangai on Lifuka island is indicative of rainfall on the other islands in the Ha'apai group except the high islands such as Tofua and Kao where the orographic influences of the elevated terrain will most probably change the rainfall regime to some extent.

Monthly rainfall records (refer Appendix A) are available continuously from January 1947 to the present except for 14 months as follows:

- May to December 1959 (8 months)
- December 1960 (1 month)
- August 1969 (1 month)
- May 1971 (1 month)
- December 1976 (1 month)

- February to March 1982 (2 months).

Reasons for the loss of record in all months is not known. It is known that Cyclone Isaac caused the loss of February 1982 and part of March 1982 records from the meteorological station.

Figure 5.32 shows the annual rainfall pattern for the period 1947 to 1990. Additional rainfall records between 1932 and 1940 (from Taylor, 1973) are shown with the later record in Figure 5.33.

The mean annual rainfall derived from the available record for the period 1947 to 1990 is 1,716 mm which is 3% lower than at Nuku'alofa on Tongatapu. By comparison the mean annual rainfall in the Ha'apai group during the last decade (1981 to 1990) is only 1,435 mm or 84% of the long term mean annual rainfall. This indicates that the Ha'apai group, assuming Lifuka is indicative of the other Ha'apai islands, has experienced drier conditions in the last decade than the average conditions over the last 44 years. The ENSO events of 1982/83 and 1986/87 had a major influence on the lower rainfall pattern in the last decade. A similar effect is found on other islands in the Kingdom of Tonga.

A graphical comparison of annual rainfall patterns on Ha'apai with other islands in the Kingdom of Tonga (Tongatapu, Vava'u and Niuatoputapu) is shown in Figure 4.3.

The mean monthly rainfall pattern at Lifuka is shown in Figure 5.34 for two periods of record: 1947 to 1990 and 1981 to 1990. The latter period shows the mean rainfall to be lower in all months except for May and June. The major trend of the last decade appears to be lower wet season rainfall than normal. Mean rainfall in the months of November, January and March can be seen to be much lower in the last decade than in the past 44 years.

Comparison of the mean monthly rainfall pattern in the Ha'apai group with other island groups of the Kingdom of Tonga can be seen in Figure 4.4. It can be seen from Figure 4.4 that the mean monthly rainfall in the Ha'apai group is generally less than in the other parts of Tonga. Ha'apai's mean monthly rainfall is less than that in Vava'u for all months, less than that in Niuatoputapu for all months except August and less than that in Tongatapu except for March, April, May and December.

Maximum, mean and minimum monthly rainfall statistics are shown in Appendix A and plotted in Figure 5.35. The wet season months tend to have the highest maximum monthly rainfall. The highest monthly rainfall was 649 mm which fell in January 1957. Generally, the dry season months have the lowest minimum monthly rainfall with May and October both having recorded zero rainfall.

The variability of rainfall in the Ha'apai group is discussed in section 4.2.3. A slightly higher annual variability of rainfall is evident in the Ha'apai group (refer Table 4.1) than in other parts of the Kingdom of Tonga.

4.3.6 Recharge analyses

A recharge analysis based on a water balance simulation using monthly rainfall records and potential evaporation estimates for the Ha'apai group was undertaken. Details of the approach are given in section 5.1.6.

The recharge analysis for Ha'apai, like that for Tongatapu and Vava'u, involved an appreciation of the thickness and moisture properties of the soils (refer section 4.5) and the type and density of vegetation (refer section 4.6).

For the purpose of the water balance study in the Ha'apai islands, particularly Lifuka, it was assumed that:

- Interception losses are a maximum of 3 mm per day (or 90 mm per month) as for Tongatapu
- Thickness of the soil moisture zone where roots of vegetation obtained water is 1,000 mm
- Field capacity and wilting points of the soil are, respectively, 0.55 and 0.40
- Initial interception storage and soil moisture contents are average values (50 mm per month and 500 mm, respectively)

- Ratio of deep rooted to shallow rooted vegetation is 50% based on areal coverage (estimated from aerial photographs)
- Ratio of the roots of the deep rooted vegetation reaching the water table was 10% with the other 90% being located within or just below the soil moisture zone
- Crop factors are 0.8 for deep rooted vegetation and 1.0 for shallow rooted vegetation.

Using the values of the parameters above and the water balance model as described in section 5.1.6 and Figure 5.14, a water balance simulation was run using monthly rainfall data (from Tonga Meteorological Service: refer Appendix A) and potential evaporation estimates (from Thompson, 1986: refer Appendix C) for the period 1947 to 1990.

Results of the simulation showing values of relevant parameters at the end of each monthly time step are shown in Appendix K. A summary sheet showing the values of monthly and annual recharge is included at the end of Appendix K. Figure 5.36 shows the annual recharge pattern from 1947 to 1990 based on the results of the water balance simulation.

The mean annual recharge on Lifuka as determined from this water balance simulation is 478 mm or 28% of the mean annual rainfall of 1,725 mm. The mean annual recharge on Lifuka is thus about 90% of the mean annual recharge of 528 mm computed for Tongatapu (refer section 5.1.6).

The relationship between the two time series of annual rainfall and annual recharge is shown in Appendix K but can be seen more clearly in Figure 5.37. It can be seen that the relationship between the two parameters is not constant as it is dependent not only on the magnitude of the rainfall but also the distribution of rainfall throughout the year.

From the data in Appendix K and Figure 5.36 it can be seen that recharge fluctuates widely on a monthly and annual basis. It can also be seen that in some years (1952 and 1983), negative recharge is experienced. Negative recharge implies a net loss of freshwater from a freshwater lens and is caused when evapotranspiration losses exceed recharge from rainfall. The factor which allows this to occur is the transpiration directly from the freshwater lens by deep roots from coconut trees. If it is assumed that none of the coconut roots reach the water table, as was assumed for Tongatapu and Vava'u, then negative recharge cannot occur.

The longest period (refer Appendix K) without any recharge occurred from June 1982 to December 1983, a period of 19 months. Another long dry period occurred from October 1951 to January 1953 (16 months).

The recharge pattern over more than one year can be seen clearly in Figure 5.36. This shows that long periods of low recharge years can occur, for example, the 11 year period from 1958 to 1969 (mean annual recharge of 334 mm which is 70% of the long term mean annual recharge) and the 10 year period from 1979 to 1988 (mean annual recharge of 212 mm or only 44% of the long term mean annual recharge). Long periods of higher than average recharge have also occurred, the most notable period being the 7 year period from 1970 to 1977 (mean annual recharge of 794 mm which is 66% higher than the long term mean annual recharge). The lowest recharge occurred in 1983 (-35 mm) while the highest occurred in 1957 (1,297 mm).

A graphical comparison of the annual recharge patterns from 1947 to 1990 in Tongatapu, Ha'apai and Vava'u is shown in Figure 5.38. A clearer picture for the period 1965 to 1990 is shown in Figure 5.39. These figures show that Ha'apai has a much lower recharge in most years than Vava'u and normally a lower recharge than Tongatapu.

<u>Turnover time</u>

If it is assumed that the mean thickness of a typical freshwater lens on the larger islands of the Ha'apai group is approximately 5 m, then the turnover time of freshwater in the lens is about 3 years (0.3 x 5 m divided by 0.478 m). This compares with about 6 years for Tongatapu.

While this is only a preliminary estimate at this stage, it does show that the freshwater lens under natural conditions can withstand drought periods of considerable length. A freshwater lens of 5 m thickness should be able to withstand the worst historical drought in the last 44 years (1982/83 drought) if dispersion of salts from underlying seawater is not a major factor in diminishing the thickness volume of the lens during extended periods without recharge. This latter factor is unknown and can only be assessed after monitoring salinity profiles in freshwater lenses under stress from nil or negative recharge. This highlights the need for long-term monitoring of the groundwater resources in the Ha'apai group as elsewhere in the Kingdom of Tonga.

4.3.7 Analysis and interpretation of results

General

As with Tongatapu there is only a limited amount of data available at present to make an assessment of the areal extent, thickness, variability and sustainable yield of the freshwater lens on the main islands of the Ha'apai group. It is again stressed, therefore, that the interpretations of available data given in this section must be regarded as preliminary only. It is obvious that further investigations and long-term monitoring are essential to gain a reasonable assessment of the nature of the freshwater lenses in the Ha'apai group.

In summary, the available groundwater data to enable an interpretation of the status of the freshwater lens on the main islands of the Ha'apai group consist of:

- Limited salinity data at wells as presented in Appendix J
- Vertical salinity profiles from test holes drilled on Foa and Lifuka in August 1985 and from recently installed monitoring boreholes on Lifuka (refer Figure 5.30 and Appendix E)
- Limited depth measurements to water table which are not yet related to msl (also in Appendix J)
- Electrical resistivity soundings on Lifuka in January 1991.

Salinity data at the water table

As mentioned in section 5.1.7, the salinity of a freshwater lens measured at the water table can provide an approximate guide to the nature of the freshwater lens. Where the salinity is low it can be expected that the freshwater lens is of reasonable thickness and where the salinity is reaching the upper limit for drinking water (2,500 µS/cm), the freshwater lens is generally thin.

In general, the pumped wells on the main Ha'apai islands (Foa, Lifuka and 'Uiha) show high salinities which reflect the degree of pumping. The private wells which are bailed or pumped by hand generally show salinities within the limit for drinking water provided that they are not too close to the coastline where tidal effects can induce seawater intrusion. In one case a bailed well on the west side of Hihifo (well 5) has freshwater even though it is sited within 20 m of the beach.

The Hydrogeology Unit has prepared a coloured map of Foa and Lifuka showing areas of low to high salinity from the salinity readings for September 1990. A simplified map is presented in Furness (1990c). These maps indicate areas of high and low salinity but there are many parts of both islands where there is insufficient data to determine the salinity of the groundwater. Areas in the vicinity of the pumping wells near Hihifo on Lifuka are obviously saline as are low lying parts of Foa where saline lakes occur. Because of the limited data available, these maps must be regarded as preliminary at this stage and are not reproduced in this report. When the results of further geophysical work and test drilling are available then a clearer areal salinity map of each of the main islands can be prepared.

One aspect of chemical quality not yet commented about is the pH of the water (refer Appendix J). All wells that were tested for pH had values varying between 7.1 and 8.4 with one exception (well 49 had a pH of 9.85 on 31 January 1991). The results are typical of groundwater from small limestone island environments, except for the outlier which is unexplained at present.

Effects of pumping on salinity

As mentioned in section 5.3.4, five pumped wells on the islands of Foa, Lifuka and 'Uiha have limited salinity records spanning the period from 1985 to 1991. The results of salinity tests at these five wells and one additional well at 'Uiha village on 'Uiha are shown in Table 5.6.

Table 5.6 Comparison of salinities at selected Ha'apai wells

Location	Well number (present census)	Electrical conductivity (µS/cm)			
		2/8/85 - 3/8/85	3/3/90 - 4/3/90	21/9/90 - 22/9/90	31/1/90 - 7/2/91
Lotofoa well, Foa	34	5,600	5,100	3,490	6,000
Fangale'ounga well, Foa	38	3,400	6,880	5,130	-
Hihifo well 1, Lifuka	45	12,800	3,120	2,940	2,190
Hihifo well 2, Lifuka	46	9,200	12,500	10,000	8,730
'Uiha well, 'Uiha	23	-	1,700	880	2,830
Felemea well, 'Uiha	24	1,930	4,000	1,470	2,190

The salinities in Table 5.6 show variations most of which are induced by pumping. The two wells on Foa show some variation over time from 1985 to 1991 but there is no definite trend. The reduction in salinity at well 45 on Lifuka from 1985 to 1990/1991 is undoubtedly caused by the fact that the well was being pumped in 1985 and it had not been pumped for some months before the tests in 1990/1991. The salinity at well 46 on Lifuka shows a rise from 1985 to 1990 and then a reduction to 1991. These variations are most probably due to variations in recharge as the pump was operating on the day of each test. The wells on 'Uiha show a decrease in salinity from March to September 1990 which was caused by the cessation of pumping at both wells (Furness, 1990a). This decrease in salinity occurred despite the fact that the water balance analysis showed that there was no recharge to groundwater during this period (refer section 5.3.6 and Appendix K). The increase in salinity from September 1990 to late January 1991 is due to a resumption of pumping.

The effects of pumping on the salinity at the wells on both Lifuka and 'Uiha are obvious: the instantaneous pump rates are too high for these thin freshwater lenses. Underlying saline water is being upconed due to the excessive pump rates. The recovery in salinity at these wells when pumping is ceased is evidence of the fact that freshwater lens do recover after being overpumped provided that sufficient time is given. Any pumping strategy on these islands in future must decrease the groundwater extraction at individual extraction points to a level where freshwater is being 'skimmed' off the surface of the lens. Further comments on the design of groundwater extraction facilities for the islands are provided in section 8.

Water levels

At this stage the limited water level data that has been collected since September 1990 has not been related to msl since msl is yet to be determined in the Ha'apai group. Thus, the water level data can offer no absolute values of water table elevation above msl.

An inspection of the data in Appendix J reveals nothing conclusive from the limited relative levels that can be obtained for wells with more than one depth reading. Only seven wells have 2 water level readings at this stage, the first taken in September 1990 and the second in late January 1991.

Two of the three wells on Lifuka showed a rise in water table: 30 mm at Hihifo well 1 (well 45) and 150 mm at Hihifo well 2 (well 46) while the third (well 49) showed a decrease of 50 mm. Some of these variations are due to tidal fluctuations since it has been established that the tidal response at well 45 (Lao, 1986) is in the order of 30 mm. The larger difference at well 46 could be due to the effects of pumping as well as tidal influences.

The results for wells on 'Uiha showed greater variations. The 'Uiha village well (well 23) showed an increase in water table elevation of 580 mm between the two test dates. An error in measurement is suspected in this case although some of this difference could be due to readings being done at different parts of the tidal cycle. However, the fact that the well was not being pumped in September 1990 and may well have been pumped in late January 1991 conflicts with a rise in elevation. The opposite was found at the Felemea well (well 24) where a decrease of 290 mm was detected. Tidal effects could have caused part of this difference as could have different pump status on the two dates. However, a further error may be suspected here. In light of these large differences, it is recommended that automatic water level recordings be made at both wells as part of the ongoing hydrogeological investigations on 'Uiha.

Two wells on Foa were tested and showed quite plausible results. Well 28 (Faleloa) and well 34 (Lotofoa) had variations of +20 mm and +100 mm between the two test dates. These variations can easily be explained by a combination of factors including tidal cycle, pumping and recharge variations.

Lao (1986) makes the observation that the tidal response in wells on the western side of Lifuka is much less than in the centre of towards the eastern side as manifested in the Tonga Water Board wells to the east of Hihifo. Water level recordings by Lao indicated that the tidal response in well 42 (Selutute guest house on the western side of Lifuka) was only 10 mm while the tidal response at Hihifo well 1 (well 45) was 200 mm. This difference is most probably caused by an across the island permeability in the aquifer material, probably caused by infilling of the limestone matrix on the eastern side by sand and clay material. Variations of permeability across islands are not unusual and have been observed by similar water level measurements on other limestone islands (for example, Bermuda: Vacher, 1978) and on coral atolls (for example, Christmas Island, Kiribati: Falkland, 1983, and Deke island on Pingelap atoll: Ayers et al, 1984). This is likely to occur on islands where one side is more exposed to wind and wave action than the other. For example, the ocean side of an atoll has typically course sediments deposited by wind and wave action compared with finer sediments on the lagoon side where these have been laid down in more tranquil conditions. On the islands of Ha'ano, Foa, Lifuka and 'Uiha, the eastern side has been more exposed to the prevailing weather than the western side and the suspected differences in permeability could be due to this factor. There is evidence of the build up of sand deposits on the western side of the island which have a lower permeability and are more favourable for the formation of a freshwater lens than the limestone to the east. This across-island difference led to a 'two island' theory by Lao (1986). Further comments on the across-island variation and their effects on freshwater lens occurrence are given at the end of this section.

<u>Vertical salinity profiles</u>

Salinity profiles obtained in two test holes drilled by Stoll (1987) are shown in Figure 5.30. The locations of these holes are shown in Figure 5.31. Although five holes were drilled only two showed freshwater zones (holes 5 and 6 as shown in Figures 5.30 and 5.31).

Salinity profile information from six of the ten recently drilled monitoring boreholes (refer section 5.3.4) is summarised in tabular form in Appendix E.

<u>Electrical resistivity soundings</u>

Interpretations of the 13 electrical resistivity soundings conducted in January 1991 (refer Figure 5.31) for Lifuka are summarised in Table 5.7.

From the results in Table 5.7, it can be seen that there is considerable uncertainity in the results of some of the electrical resistivity soundings.

<u>Summary of interpretations</u>

From the electrical resistivity data, the well census and the vertical salinity profile information, the freshwater lens area appears to be limited mainly to the western part of Lifuka where it varies in thickness from about one to six metres. The main area of the freshwater lens only area is shown in Figure 5.31. This is the area where a significant and contiguous freshwater lens has formed.

It would appear that the freshwater lens thickness of 8 m as found in the well drilled by Stoll in 1987 at the location of electrical resistivity sounding number 5 (refer Figure 5.31) is an anomalous result and does not reflect the nature of the freshwater lens to the east of the Pangai/Hihifo area. It is noted that the electrical resistivity sounding number 5 (refer Table 5.7) did not confirm the presence of an 8 m thickness of freshwater at this location. This could have resulted, however, from limitations of the electrical resistivity method.

Table 5.7 Resistivity sounding results for Lifuka

Resistivity sounding number	Estimated thickness (m) [and resistivity (ohm-m)] of fresh or brackish water layer	Comments
1	6 [15]	Brackish water to water table
2	7 [12]	Brackish water to water table
3	13 [38]	Freshwater, but the thickness is high & needs confirmation
4	?	Uncertain result: repeat
5	3 [25]	Large errors in model fit:
		may need repeating
6	0	Saline water to water table
7	7 [20]	Freshwater or brackish water?
8	?	Uncertain result: repeat
9	?	Uncertain result: repeat
10	8 [33]	Freshwater
11	6 [40]	Freshwater
12	3 [24]	Freshwater or brackish water?
13	?	Uncertain result: need to repeat

Note: Estimated thickness are to nearest metre

In summary, while parts of the area to the east of the villages of Pangai and Hihifo indicated a presence of a thin freshwater layer, it is evident from the data available that its extent and thickness is not significant. This area to the east of the villages is underlain by highly permeable limestone with a thin layer of compacted clay (Lao, 1986; Furness, 1991) near the surface. The limestone enables easy mixing of fresh and saline water while the clay layer may have the effect of diverting some of the recharge to the west of the island. The western part of the island is underlain by sand deposits below which the limestone extends. The sand is less permeable thus being more amenable to the formation of a freshwater lens. Additional recharge may be diverted from the eastern part into this freshwater lens. The exact extent of the additional area contributing to the area underlain by a freshwater lens is unknown. The sand deposits along the western side of the island represent more recent deposition against an older limestone shoreline corresponding approximately to the eastern limit of the freshwater lens shaded area in Figure 5.31. The thickness of the freshwater zone as obtained from recent salinity profiling (refer Appendix E) varies from about 1 to 6 metres.

Unfortunately, a large part of the known freshwater lens is located directly under the villages and is thus subject to contamination human and animal wastes. In particular, pit latrines used for sewage disposal represent a major source of contamination.

The location and the pumping rates of production wells will need to be carefully chosen to minimise the risk of saline intrusion and contamination.

The investigations to date in the area of Holopeka and Koulo indicate that there is no significant freshwater lens in the northern part of Lifuka, although some dug wells in the area do have freshwater.

4.3.8 Preliminary sustainable yield estimate

A preliminary estimate of sustainable yield was made for Lifuka from the available data. It is stressed, however, that any future data collected by the Hydrogeology Unit concerning the areal extent and thickness of fresh groundwater on the island should be used to update this estimate before proposed groundwater development schemes are designed.

Using the data collected to date, the area of the island underlain by a freshwater lens would be about 1.5 km^2. As mentioned in section 5.3.7 an additional recharge area may contribute to this freshwater lens. It is considered that a reasonable estimate of the total area contributing to the freshwater lens is about 2 km^2.

Using the same approach as adopted for Tongatapu, namely that 20% of the recharge can be safely extracted, a preliminary estimate of the sustainable yield in depth units for the island of Lifuka is 96 mm/year. Using the estimated contributing area to the freshwater lens of 2 km^2, this sustainable yield estimate is equivalent to 0.5 ML/day or about 6 L/s.

By comparison, the present groundwater extraction from the one pumping well which is currently operated on Lifuka is about 0.1 ML/day based on an estimated pumping at 5 L/s for 6 hours each day. This represents about 20% of the maximum sustainable yield from the freshwater lens.

It is not considered useful to make estimates of sustainable yield for the other main populated islands ('Uiha, Foa and Ha'ano) until further investigations are completed.

4.3.9 Proposed investigations

Groundwater

There is a need for further investigation and monitoring to confirm areas of fresh groundwater on the islands of Ha'ano, Foa, Lifuka and 'Uiha. This should include geophysical (electrical resistivity and electromagnetic mapping) and drilling of additional test bores to calibrate the geophysical survey information. The exact extent of further investigations should be determined by the Hydrogeology Unit.

Existing monitoring boreholes should be sampled regularly to detect fluctuations in salinities with depth. Additional monitoring boreholes should be installed near the location of future production wells on Lifuka for investigation purposes on Ha'ano Foa and 'Uiha. The number of holes for the latter purpose should be decided by the Hydrogeology Unit but is estimated to be a minimum of 3 and a maximum of 6.

To assist with estimation of the freshwater lens thickness, accurate survey levels at present and future wells are required and these must be related to msl. There is a need, therefore, for accurate levels at each of the monitored wells to be obtained. This could be done either by standard terrestrial survey techniques or by satellite observations.

msl should be established for the Ha'apai group by simultaneous measurements of tidal fluctuations at a suitable location on Lifuka and at Tongatapu for a reasonable period of time. A period of at least a month is essential and preferably a period of three or more months should be used for this project. The records can then be used to compute the relative average levels at both Neiafu and Tongatapu and knowing the value of msl at Tongatapu, a value of msl at Lifuka can be established. Automatic recorders should be used for this purpose. The Hydrogeology Unit has recently procured suitable electronic data loggers and electric pressure transducers to enable this work to be undertaken. The establishment of msl at Lifuka in the Ha'apai group will have benefits other than for the hydrogeological investigations.

All survey levels used in subsequent hydrogeological investigations throughout the Ha'apai group should be referred to the msl datum.

When additional investigation and monitoring data is available for Lifuka, the preliminary estimate of sustainable yield should be reassessed.

The other populated and possibly some of the unpopulated islands should be given at least a cursory groundwater resource assessment using EM and electrical resistivity equipment. Samples of water from wells should be tested for conductivity, temperature and pH to assist with mapping freshwater areas. One island which would benefit from a groundwater resource assessment is Nomuka where there are known saline lakes but where there may be areas of freshwater. Depending on the salinity of the groundwater it could possibly be used instead of or as a supplement to the desalination plants installed there (refer section 4.4.4).

Surface water

Most islands in the Ha'apai group have no surface water resources. Exceptions are saline lakes and swamps in low lying areas on some islands (for example, Foa and Nomuka) and a crater lake on the volcanic island of Tofua. The water quality of the low-lying lakes and swamps is generally too saline for potable purposes. The quality of the water on Tofua is not known and although it is not a high priority at this stage, it should be tested to determine its suitability for potable and possible agricultural purposes.

4.4 Vava'u

4.4.1 Physical outline

Physiography and demography

The Vava'u group of islands consists of Vava'u island and a number of smaller islands to the north, south and west of it (refer Figure 4.2). The islands are located between latitudes 18° and 19°30' S and longitude 173°50' and 174°40' W. Vava'u island is the largest island of the group and is where the town of Neiafu and many of the villages are located. Four of the islands around Vava'u island are connected to it by causeways. Thirteen of the islands are populated. Figure 5.40 shows the location of most of the islands within the Vava'u group excluding the volcanic islands to the north and west of Vava'u island.

The terrain in the Vava'u group is generally more elevated than on Tongatapu and in the Ha'apai group. The maximum elevation on Vava'u island is 213 m in the southwest corner. The volcanic island of Late has a maximum elevation of 519 m.

The population in the Vava'u group of islands using 1986 census figures is 15,175.

Geology

The islands of the Vava'u group are predominantly limestone islands but there are some volcanic islands, most notably Late and Fonualei.

Hydrogeology and surface water resources

Freshwater is known to exist in the form of fresh groundwater lenses at sea level on the larger limestone islands. The general comments made about water resources on small islands in section 4.2 apply to many islands in the Vava'u group. Many of the comments made for Tongatapu in section 5.1.1 apply also to the larger islands of the Vava'u group.

There is no fresh surface water on the limestone islands. Brackish water is found in Lake Ano in the southwestern part of Vava'u island. A water sample from the lake tested in March 1990 had an electrical conductivity reading of 15,000 µS/cm.

Soils

Orbell et al (1985) provide a detailed description of the soils on the islands of the Vava'u group. A volcanic ash soil overlies most of the islands, as with other islands in Tonga. The thickness ranges from a few centimetres on steep slopes to 10 m or more in depressions and flat areas. The western areas have generally thicker soils than the eastern areas within the Vava'u group.

Measurements of physical properties which are important to the water balance of the island indicate that similar values of soil moisture zone thickness, field capacity and wilting point to other islands in the Kingdom of Tonga can be used (refer section 4.6).

Vegetation

The vegetation on the main islands of the Vava'u group is a mixture of low shrubs, grasses and trees, predominantly coconut trees. Agricultural activities are generally similar to those used in other parts of Tonga. Vanilla is the most valuable crop in the Vava'u group.

From a water resources viewpoint the types of vegetation are similar to those on Tongatapu.. The percentage of total area covered by potentially deep rooted vegetation such as coconut trees is considered to be 50% which is higher than the assumed 30% for Tongatapu and the same as for 'Eua and the Ha'apai group.

4.4.2 Present water resources development

The town of Neiafu with a population of 3879 (1986 census) obtains groundwater from a wellfield to the north of the town. Many other villages throughout Vava'u also obtain groundwater from dug and drilled wells. The higher terrain on much of the island means that drilled or dug wells are on average deeper than in the other islands. The deepest measured well is near Feletoa on Vava'u island where the depth to water table is over 60 m.

Many villages rely on rainwater catchments as a supplementary source of freshwater. In some villages, rainwater is at present the only source of freshwater. Some villages, for example Hunga on Hunga island, supplement rainwater with water transported by boat in small containers from nearby islands.

4.4.3 Previous water resources investigations

While there have been many water resources investigations for Tongatapu and the Ha'apai group, there has been very little reported about the water resources of the Vava'u group. There have been no investigations of the freshwater lenses (ESCAP, 1990).

Waterhouse (1984) provides a summary of well details, pump tests and village water supplies. At the time of his study there were 18 wells (dug and drilled) supplying the villages on Vava'u. Waterhouse refers to a report by Claridge (1981) which provides details of 7 of the drilled wells; this report was not located during the course of this study.

Important points raised in the Waterhouse (1984) report are:

- The levels of wells (top and base) are not accurately known and the effects of pumping on the water table, particularly at the wellfield for Neiafu, are unknown. This shows the necessity for accurate survey of wells and for these to be related to msl datum.
- There is no on-going monitoring of:
    - salinity in the wells or the reticulated water
    - water level in the wells
    - flows from pumps
    - leaks in pipelines
    - potential for pollution of the groundwater and water supplies is high given the highly permeable soils and limestone and the proximity of animals and housing to the Neiafu water supply pumps.

Waterhouse recommended that no further development or pumping from the Neiafu water supply reserve should be occur until adequate monitoring procedures were established and the results analysed. He also recommended the desirability of searching for alternative sites for future groundwater extraction to supply Neiafu.

Other water related reports for Vava'u are concerned with water quality and rainwater catchment systems.

Fuavao and Tiueti (1988) analysed trace metal concentrations in water samples obtained from a number of wells and other sites on Vava'u island. They concluded that the concentrations are generally within the limits advised in WHO guidelines.

Wolff (1988a, 1988b) describes details of a rainwater catchment project undertaken by the Foundation for the Peoples of the South Pacific in villages on the outer islands of the Vava'u group. Further discussion of rainwater catchments is in section 5.6.

4.4.4 Recent water resources investigations

The Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources conducted a well census and sampling programme in September 1990 (Furness, 1990a). A list of wells is shown in

Appendix G for the 26 wells on Vava'u island located during the census and a further 5 wells in villages on 3 other islands (Ovaka, Nuapupu and Kapa). The latter 5 wells were previously tested for electrical conductivity in March 1990 along with some of the wells on Vava'u island. Results of the sampling programme including depths to water table, electrical conductivity and temperature are shown in Appendix L. Where zero values are shown in the results, no reading was obtained. Figure 5.40 shows the location of the wells and Appendix G provides selected details of each well from the well census database (called 'WELLS').

4.4.5 Rainfall analysis

Monthly rainfall records (refer Appendix A) are available continuously from January 1947 to the present for the rainfall station at Neiafu. For the purposes of this report, the rainfall record for Neiafu is assumed to be indicative of the whole Vava'u island group. This is a reasonable assumption given that the distances between the islands of the Vava'u group are not large. Minor local differences are likely, however, given that orographic effects from elevated terrain may influence rainfall across some of the islands.

The annual rainfall pattern for the period 1947 to 1990 is shown in Figure 5.41. Additional rainfall records between 1934 and 1940 (from Taylor, 1973) are shown with the later record in Figure 5.42.

A graphical comparison of annual rainfall patterns between the Vava'u group and other islands in the Kingdom of Tonga is shown in Figure 4.3 in section 4.

The mean annual rainfall derived from the 44 year record (1947 to 1990) is 2,231 mm. This is 26% higher than at Nuku'alofa on Tongatapu.

The mean annual rainfall in the last decade (1981 to 1990) is 2,051 mm or 92% of the long term average. Compared with both Tongatapu and the Ha'apai group, the rainfall reduction in the Vava'u group in the last decade was not as severe. In particular, the reduction in rainfall due to the ENSO events of 1982/83 and 1986/87 was not as severe as in the other two locations.

The mean monthly rainfall pattern at Neiafu is shown in Figure 5.43 for two periods of record: 1947 to 1990 and 1981 to 1990. The latter period shows the mean rainfall to be lower in 6 months, higher in 5 months and equal in one month. No major seasonal rainfall trends between the two periods of record are detectable as they were in Ha'apai (refer section 5.3.5).

Maximum, mean and minimum monthly rainfall statistics are shown in Appendix A and plotted in Figure 5.44. The wet season months tend to have the highest maximum monthly rainfalls. The highest monthly rainfall was 1009 mm which fell in January 1967. The lowest monthly rainfall occurred in January 1987 when only 5 mm was registered. This low rainfall was most probably caused by the ENSO event of 1986/1987. The low rainfall appears to be a special case as the next lowest rainfall for the month of January was 50 mm. Apart from this special case, the dry season months have the lowest minimum monthly rainfall.

The variability of rainfall in the Vava'u group is shown in section 4.2.3 (refer to Table 4.1 and Figure 4.5). In general, the rainfall in the Vava'u group on an annual and monthly basis is lower than at the rainfall stations to the south of it (Ha'apai and Tongatapu).

4.4.6 Recharge analysis

A recharge analysis based on a water balance simulation using monthly rainfall records and potential evaporation estimates for the Vava'u group was undertaken. Details of the approach are given in section 5.1.6.

For the Vava'u group of islands, it was assumed that:

- Interception losses are a maximum of 3 mm per day (or 90 mm per month) as for Tongatapu and Ha'apai
- Thickness of the soil moisture zone where roots of vegetation obtained water is 1,000 mm
- Field capacity and wilting points of the soil are, respectively, 0.55 and 0.40
- Initial interception storage and soil moisture contents are average values (50 mm per month and 500 mm, respectively)

- Ratio of deep rooted to shallow rooted vegetation is 50% based on areal coverage (estimated from aerial photographs)
- None of the roots of the deep rooted vegetation reach to the water table
- Crop factors are 0.8 for deep rooted vegetation and 1.0 for shallow rooted vegetation.

Using the values of the parameters above and the water balance model as described in section 5.1.6 and Figure 5.14, a water balance simulation was run using monthly rainfall data (from Tonga Meteorological Service: refer Appendix A) and potential evaporation estimates (from Thompson, 1986: refer Appendix C) for the period 1947 to 1990.

Results of the simulation showing values of relevant parameters at the end of each monthly time step are shown in Appendix M. A summary sheet showing the values of monthly and annual recharge is included at the end of Appendix M. Figure 5.45 shows the annual recharge pattern from 1947 to 1990 based on the results of the water balance simulation.

The mean annual recharge on Vava'u island as determined from this water balance simulation is 917 mm or 41% of the mean annual rainfall of 2,232 mm. The mean annual recharge for Vava'u is nearly 75% higher than that for Tongatapu (528 mm). It is interesting to note that the annual recharge using the relationship in Figure 5.13 is about 1,000 mm, indicating that this simplified approach gives a reasonable approximation of the estimated recharge using the water balance method.

The relationship between the two time series of annual rainfall and annual recharge is shown in Appendix M but can be seen more clearly in Figure 5.47. It can be seen that the relationship between the two parameters is not constant as it is dependent not only on the magnitude of the rainfall but also the distribution of rainfall throughout the year.

From the data in Appendix M and Figure 5.46 it can be seen that recharge fluctuates widely on a monthly and annual basis. The longest period without any recharge occurred from April 1952 to February 1953, a period of 11 months. Another relatively long dry period occurred from April to November 1983 (8 months). By comparison with Ha'apai, the length of the dry periods in Vava'u is only moderate.

The recharge pattern over more than one year can be seen clearly in Figure 5.46. Periods of lower than average recharge occurred in the 6 year period from 1983 to 1988 (mean annual recharge of 626 mm which is 68% of the long term mean annual recharge) and the 4 year period from 1963 to 1967 (mean annual recharge of 628 mm, also 68% of the long term mean annual recharge). The longest period of higher than average recharge occurred in the nine year period from 1954 to 1962 (mean annual recharge of 1,181 mm which is 29% higher than the long term mean annual recharge). The lowest recharge occurred in 1952 (82 mm) while the highest occurred in 1967 (1,714 mm). The latter total was largely caused by very high recharge in January 1952 (864 mm from 1,009 mm of rainfall) and emphasises the nature of recharge in these islands, namely, that recharge is mainly affected by the occurrence of short duration, high intensity storms. As mentioned earlier, a more accurate description of recharge can be obtained from daily rather than monthly rainfall data as the daily rainfall records do not smooth out the rainfall patterns which tend to fluctuate widely from day to day.

A graphical comparison of the annual recharge patterns from 1947 to 1990 in Tongatapu, Ha'apai and Vava'u is shown in Figure 5.38. A clearer picture for the period 1965 to 1990 is shown in Figure 5.39. These figures show that Vava'u normally has a much higher annual recharge than Tongatapu and Ha'apai.

<u>Turnover time</u>

No data is available on the thickness of the freshwater lens on Vava'u island, but an indirect approach can be used to estimate its thickness.

Based on present knowledge of the lens on Tongatapu, where the estimated maximum freshwater lens thickness as measured to the mid-point of the transition zone is about 20 m (refer section 5.1.6), and the relative widths and recharge rates of Vava'u and Tongatapu, and assuming the permeabilities of the aquifers to be similar, it can reasonably be estimated that the freshwater lens on Vava'u reaches a similar maximum thickness of about 20 m. This is based on the fact that freshwater lens thickness is directly proportional to an island's dimensions and to the square root of recharge, and inversely proportional to the square root of the aquifer permeability. For a circular island, the maximum thickness of a freshwater lens, H, can be expressed as:

$$\mathbf{H \approx R\ (W\alpha/2k)^{0.5}}$$

where

R = radius of island (m)

W = recharge rate per unit area ($m/d/m^2$)

α = Ghyben-Herzberg ratio (ratio of the specific weight of freshwater to the difference between the specific weights of seawater and freshwater

k = aquifer permeability (m/d).

In this comparison, as α is the same for both islands and k is assumed to be the same for both islands, these two parameters can be removed from the equation.

It was assumed that the western zone of Tongatapu near Liahona of the southeastern portion near Fua'amotu could be approximated by circular island's with a radius of 4 km. By comparison, the northern part of Vava'u island could be approximated by a circular island with a radius of 3 km. Substituting these values and the recharge values into the above equation, the values of H for Tongatapu and for Vava'u are approximately equal. In other words the smaller dimension of Vava'u is compensated for by its higher recharge in comparison to Tongatapu.

Using the estimate of 20 m for the maximum thickness and assuming that the mean thickness of the freshwater zone of the lens in the northern part of Vava'u is about 10 m (same as for Tongatapu), then the turnover time of freshwater in the lens is about 3.5 years (0.3 x 10 m divided by 0.917 m). The turnover time in other parts of Vava'u island where the width of the island is less would be less than this and may be as low as 1 to 2 years.

4.4.7 Analysis and interpretation of results

The results in Appendix L show that the water quality in most wells is less than the recommended limit for potable water (EC = 2,500 µS/cm). However, some areas show problems. The salinity of the water at Tu'anekivale (well no. 8) is considerably above the recommended limit for potable water. This is presumably due to the well's location in a narrow part of the island where seawater intrusion is greater than elsewhere. The results from this well are indicative of the need for adequate investigations prior to the siting of wells.

The salinity of the wells at the Neiafu wellfield (nos. 23, 24, 25, 26, 27 and 28) are within the recommended limit for potable water. However, the increase in salinity at two of the three wells at the Neiafu which had data from both March and September 1990 was significant. One of these wells (no. 25) showed an increase of EC from 760 to over 1,900 µS/cm. This is a clear indication that pumping may be approaching or may have exceeded the sustainable yield of the lens in that location. As stated in Furness (1990a), a suitable location for additional pumping requirements can be found to the north of the existing wellfield.

4.4.8 Preliminary sustainable yield estimate

A preliminary estimate of sustainable yield was made for Vava'u island from the available data. As for Lifuka in the Ha'apai group (refer section 5.3.8) it is stressed, however, that further data concerning the areal extent and thickness of fresh groundwater on the island is required before a reliable estimate of sustainable yield can be made.

For present purposes it is assumed that a freshwater lens extends over the whole island except within 500 m of the sea or saline lake/inlet. Using this assumption, the area underlain by a freshwater lens on Vava'u island is approximately 55 km^2.

Adopting the same proportion of recharge, namely 20%, that can be safely extracted, the sustainable yield in depth units is equivalent to 183 mm/year. Using the estimated freshwater lens area of 55 km^2, this sustainable yield estimate is equivalent to 27 ML/day or about 310 L/s. This estimate could well be lower once the results of more detailed groundwater investigations are available.

4.4.9 Proposed investigations

Groundwater

At present the extent of knowledge of the groundwater resources on the island is very limited. There is some good baseline data on salinity levels at the water table in a number of wells on the island but there is no data which can provide an estimate of the vertical salinity profile through the freshwater lens and hence enable the freshwater thickness to be obtained.

Due to the thick unsaturated zones in the largely elevated terrain of Vava'u island and many of the others in the Vava'u group, the use of geophysical methods (electrical resistivity and electromagnetics) is very limited. These methods do not work well or at all where thick, high resistivity layers overlie thinner, lower resistivity layers (the principle of suppression: Mooney, 1980). An example of an area where geophysical techniques could be used is on Nuapapu island near the village of Matamaka where the land is relatively low-lying.

Two methods are available to estimate freshwater lens thickness at different parts of the islands of Vava'u. Firstly, water table elevations relative to msl can be used to estimate the freshwater zone as previously discussed. These should not be used in isolation without confirmation of the nature of the vertical salinity variations through and below freshwater areas and a second method should be used for this, namely, drilling of salinity monitoring boreholes.

To enable an estimate of the freshwater lens thickness to be obtained, accurate survey levels at the wells are required and these must be related to msl. There is a need, therefore, for accurate levels at each of the monitored wells to be obtained. This could be done either by standard terrestrial survey techniques or by satellite observations.

msl should be established for the Vava'u group by simultaneous measurements of tidal fluctuations at Neiafu and at Tongatapu for a reasonable period of time. A period of at least a month is essential and preferably a period of three or more months should be used for this project. The records can then be used to compute the relative average levels at both Neiafu and Tongatapu and knowing the value of msl at Tongatapu, a value of msl at Neiafu can be established. Automatic recorders should be used for this purpose. The Hydrogeology Unit has recently procured suitable electronic data loggers and electric pressure transducers to enable this work to be undertaken. The establishment of msl at Neiafu in the Vava'u group will have benefits other than for the hydrogeological investigations.

All survey levels used in subsequent hydrogeological investigations throughout the Vava'u group should be referred to the msl datum.

It is considered that a number of permanent monitoring boreholes should be drilled to enable vertical salinity profiles to be obtained in the future as these provide the most direct means of observing natural and man-induced (pumping) influences on freshwater lens behaviour. Owing to the large depths to water table, the number of monitoring holes should be minimised. It is considered that two clusters of holes, drilled in the same fashion as those recommended for Tongatapu (refer section 5.1.9), should be provided. One of these should be in an area where there are minimal effects from pumping so as to establish the variations in salinity profiles due to natural fluctuations in recharge and tidal effects. The other should be located in an area where pumping is being carried out. This could either be at the present Neiafu wellfield or in the area of the proposed additional wellfield to the north of the present one. The exact locations are not specified as they should be left to the discretion of the Ministry of Lands, Survey and Natural Resources' hydrogeologist.

4.5 Niuas

4.5.1 Physical outline

Physiography and demography

There are three populated islands in the Niuas group, namely, Niuafo'ou, Niuatoputapu and Tafahi (refer Figure s 4.2 and 5.47) and several other unpopulated islands. Niuafo'ou is the most northerly island in the Kingdom of Tonga, located at latitude 15°35' S and longitude 175°40' W. It has an area of approximately 35 km^2 and a maximum elevation of 260 m. Niuatoputapu is located at latitude 15°55' S and longitude 173°45' W and has an area of about 15 km^2 and a maximum elevation of 110 m. Tafahi with an area of 3.5 km^2 and a maximum elevation of 650 m is located about 10 km north of Niuatoputapu.

The population in the Niuas group of islands using the 1986 census is 2,368.

Geology

The islands are volcanic. Niuafo'ou is a basalt shield volcano surmounted by an andesitic cone which has collapsed to form a large water filled caldera about 4 km across (Vai Lahi). Other smaller lakes have also formed (Vai Si'i, Vai Fo, Vai Mo'unga, Vai Molemole, Vai Kona, Vai Inu and Vai Sulifia). Niuafo'ou is still geologically active with the last major eruption in 1946.

Niuatoputapu is a lower relief volcanic island characterised by a central ridge varying in height between 60 m and 110 m. The island is not volcanically active. It consists of a wide range of andesitic tephra and flow material. The ground slopes from the ridge to an abrupt cliff which drops between 3 m and 10 m to a lower terrace. The lower terrace slopes gently towards a fringing coral reef. Coral sands and limestone are evident in the lower parts of the island.

Tafahi is a conical andesitic volcano with no record of activity.

Hydrogeology and surface water

The hydrogeology of these volcanic islands is largely unknown.

Surface water resources on Niuafo'ou exist in the form of brackish water in crater lakes. Further details are provided in section 5.5.3.

4.5.2 Present water resources development

Rainwater is used as the primary source of water for both potable and non-potable purposes. The lake water is used as a supplementary source of non-potable water in dry periods. Rarely is the lake water used for potable purposes.

On Niuatoputapu, four wells have been used for village water supplies for several years. There are two wells at Hihifo and one at each of Falehau and Vaipoa.

4.5.3 Knowledge of water resources

The water resources of the islands have not been investigated in any systematic manner to the author's knowledge. The comments below are largely based on a short trip to the Niuas in mid 1991 by a joint Tonga Water Supply Master Plan/Hydrogeology Unit team and on reconnaissance soil survey notes on a file from the Vaini Research Farm. A summary of the main features are provided in this report. Some further details are provided in the Niuas Master Plan Report.

Niuafo'ou

All lakes have relatively steep catchments. Vai Lahi is the largest lake with an approximate catchment area of 1250 ha and a water surface area of 860 ha. The second largest is Lake Si'i with an approximate catchment area of 108 ha and a water surface area of 28 ha. Vai Fo is the third largest lake with an approximate catchment area of 10 ha and a water surface of 2.2 ha.

Smaller lakes include Vai Inu, a relatively shallow lake with an approximate catchment area of 5.8 ha and a water surface of 0.6 ha and Vai Molemole, located on Motu Molemole within Vai Lahi, which has an approximate catchment area of 1.6 ha and a water surface of 0.2 ha. Both lakes are considered to be of inadequate capacity to be considered for water supply for Niuafo'ou consumers. Also, Vai Inu had a dark red-brown colour presumably caused by clay deposits being washed into the lake at eroded hill cuttings to the south east of the lake. Vai Molemole also suffers from access problems being located on an island about 300 m from the edge of Vai Lahi.

The water level of Vai Lahi, Vai Si'i and Vai Fo appear to remain reasonably constant. The water level of Vai Inu varies significantly.

Reference is made in the file report ('Reconnaissance soil survey of Niuafo'ou island, Preliminary report and map' based on fieldwork undertaken between 24th August and 7th September 1970) to tests in 1966 by the World Health Organisation of the potability of the water in the lakes on Niuafo'ou. These tests were not sighted during the course of this study but may be available on a Tonga water board file (No. N9/23/19A). Apparently a salinity test of the water from the main lake (Vai Lahi) was not available from the WHO tests.

The file report offers the other relevant information about Vai Lahi. It is approximately 270 feet (about 80 m) deep and its surface is about 7.5 feet (about 2.5 m) above sea level. Apparently, the lake level has dropped about 5 feet (about 1.5 m) since 1930. The water is 'slightly alkaline tasting but potable being used by cows and horses though not be people'. Water temperature at a depth of 0.3 m is the same as air temperature. The lake is yellow-green in colour with a secchi transparency of less than one metre.

The same file report gives some information about the other smaller lakes on Niuafo'ou. Vai Si'i is similar to Vai Lahi while Vai Mo'unga is 'less turbid'. Vai Fo and Vai Molemole are 'clear and fresh'. Vai Kona bubbles a foul smelling clear gas. Vai Sulifia is mentioned but not described.

A water sample was obtained from the surface of Vai Lahi in March 1991 by visitors to the island. On return to Tongatapu, the sample was tested for electrical conductivity and a high value of 7,160 µS/cm was obtained. The sample was subsequently laboratory tested in Sydney and the results are shown in Table 5.8.

Table 5.8 Water quality of sample from Vai Lahi, Niuafo'ou

Parameter	Unit	Value
Electrical conductivity (@ 25°C)	µS/cm	6380
pH	pH units	8.6
Total dissolved solids	mg/l	3,749
Chloride (CL)	mg/l	1,710
Sulphate (SO_4)	mg/l	142
Carbonate (CO_3)	mg/l	243
Bicarbonate (HCO_3)	mg/l	366
Potassium (K)	mg/l	1.2
Magnesium (Mg)	mg/l	173
Sodium (Na)	mg/l	989
Calcium (Ca)	mg/l	10.7
Magnesium (Mg)	mg/l	173
Iron (Fe)	mg/l	<0.1
Manganese (Mn)	mg/l	<0.1
Total hardness as Ca CO_3	mg/l	994

The main conclusion from the recent tests is that the water in Vai Lahi has been confirmed as brackish and well above the limit for potable water (approx. 2,500 µS/cm) and for irrigation of crops. The water could, however, be used for some non-potable applications.

Other water quality tests were conducted during the field visit in August 1991. The electrical conductivity of the water in Vai Si'i was field tested as 3,850 µS/cm (from two samples). This is also above the limit of freshwater. The electrical conductivity of the water in Vai Fo was field tested as 470 µS/cm indicating that it had a relatively low salinity.

Niuatoputapu

A file report ('Reconnaissance soil survey of Niuatoputapu island, Interim report' based on fieldwork undertaken between 13 March and 3 April 1972) refers to a perennial freshwater stream 3 feet (1 m) deep which 'issues from coral limestone in Hihifo'. The report also states that the water table on the lower terrace is high and 'all fresh water wells are 6-12 feet deep (approx. 2 m to 3.5 m deep). Apparently much of the terrace is flooded during the wet season and it is stated that 'excess ground water drains north and eastward around the uplands until it enters the sea north of Falehau.'

The streamflow at Hihifo mentioned above was observed as flowing at 90 L/s during the field visit in August 1991. The electrical conductivity of this water was field tested at 860 µS/cm and a sample collected for subsequent laboratory analysis. Similarly the wells at Vaipoa and Felehau were field tested for electrical conductivity. The results were, respectively, 1,120 and 1,030 µS/cm. All three sites had values less than that considered as an upper limit for potable purposes (i.e. 2,500 µS/cm).

4.5.4 Rainfall analysis

For Niuatoputapu, monthly rainfall records (refer Appendix A) are available continuously from January 1947 to the present except for 14 months as follows:

- March to May, August to December 1951 (8 months)
- April 1966 (1 month)
- May 1977 (1 month)
- April 1978 (1 month)
- April 1979 (1 month)
- March and April 1980 (2 months).

The annual rainfall pattern for the period 1947 to 1990 is shown in Figure 5.48. Some years have missing data and consequently show nil annual rainfall in Figure 5.48. Additional annual rainfall data between 1933 and 1940 (from Taylor, 1973) is shown with the later record in Figure 5.49.

Figure 4.3 in section 4 shows the comparison of annual rainfall records between Niuatoputapu and other island groups in the Kingdom of Tonga.

The mean annual rainfall derived from the available record for the period 1947 to 1990 is 2,301 mm which is 30% higher than at Nuku'alofa on Tongatapu and 3% higher than at Neiafu in Vava'u.

For the decade from 1981 to 1990 the mean annual rainfall on Niuatoputapu was 2,078 mm or 90% of the long term average. The rainfall reduction in the last decade on Niuatoputapu is thus similar to that experienced in the Vava'u group and not as severe as experienced on Tongatapu and in the Ha'apai group. In particular, the reduction in rainfall due to the ENSO events of 1982/83 and 1986/87 was not as severe as in the other two locations.

The mean monthly rainfall pattern at Falehau, Niuatoputapu is shown in Figure 5.50 for two periods of record: 1947 to 1990 and 1981 to 1990. The latter period shows the mean rainfall to be lower in 9 months of the year with 3 of the wet season months (January, February and April) showing a slight increase. Like Vava'u, no major seasonal rainfall trends between the two periods of record are detectable as they were in Ha'apai (refer section 5.3.5).

Maximum, mean and minimum monthly rainfall statistics are shown in Appendix A and plotted in Figure 5.51. The wet season months tend to have the highest maximum monthly rainfalls except that July also shows a high maximum. The highest monthly rainfall was 648 mm which fell in December 1970. The lowest monthly rainfall occurred in September 1987 when only 2 mm was registered. This low rainfall was most probably caused by the ENSO event of 1986/1987. Generally the dry season months have the lowest minimum monthly rainfall.

The variability of rainfall on Niuatoputapu is discussed in section 4.2.3 (refer to Table 4.1 and Figure 4.5).

For Niuafo'ou, rainfall records were available from the Tonga Meteorological service from 1971 to the present except for 22 months as follows: December 1971, February and November 1972, January 1973, June 1975, March, May and June 1976, April 1977, January 1979, April to December 1980, January 1987, July 1988 and November 1990.

Because of missing records, only 9 of the 20 years can produce an annual rainfall total. From these 9 years (1974, 1978, 1981-1986, 1989), the mean annual rainfall is 2,007 mm. For the 8 year period in which complete and simultaneous records (deleting 1978 from the above list) are available on both islands, the mean annual rainfall on Niuafo'ou is 2,005 mm compared with 2,043 mm on Niuatoputapu. Hence, the mean annual rainfall on the two main Niua islands is similar over this relatively short period. However, a regression analysis between annual rainfall at Niuafo'ou and Niuatoputapu for the same 8 years showed a poor correlation. This indicates that the rainfall patterns on both islands are not similar. Time did not permit a more detailed assessments (including monthly correlations and a double mass curve analysis of monthly rainfall) to be conducted for this study.

4.5.5 Proposed investigations

Surface water

To better understand the salinity of Vai Lahi, variations of salinity with depth should be measured using the 100 m salinity probe belonging to the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources. It is suggested that two or three salinity-depth profiles be obtained in different parts of the lake. It is expected that salinity will increase with depth in the lake but this should be confirmed. If this is the case it will provide evidence of connections between the sea and the lake through fractures and/or fissures in the volcanic rock. The brackish water on the surface of the lake would be a result of the mixing between rainfall and underlying seawater. Depending on the nature and surface salinity of the smaller lakes it may be useful to obtain similar salinity-depth profiles at these sites as well.

Groundwater

Any wells should be mapped and field tests made of electrical conductivity, temperature and pH. If practical, the tidal response over several tidal highs and lows should be measured. These latter measurements will enable an assessment of the degree of hydraulic connection between the well sites and the ocean to be made.

Once the basic on-site hydrological and hydrogeological conditions have been assessed/confirmed, it may be appropriate to undertake an analysis of the water balance to assess groundwater recharge. For this purpose, some basic data about soils and vegetation are required. Areal coverage of vegetation should be assessed, especially the coverage of deep rooted vegetation such as coconut trees. The presence of deep rooted vegetation on the lower terrace of Niuatoputapu may be particularly important to the water balance on that island if the ground surface is less than 5 m above the water table.

4.6 Rainwater catchment analyses

4.6.1 Purpose

The simulation of rainwater catchment systems using actual rainfall data over long periods of time can provide useful design information. Roof catchment areas and storage volumes can be optimised for different areas.

This section does not attempt to justify the use of rainwater catchment systems in preference to other sources, particularly groundwater. Decisions about the preferred source of water are dependent on many factors including availability of water from different sources, water quality considerations and the relative economics of development, operation and maintenance. The aim of this section is to provide useful design information if rainwater catchments are used.

4.6.2 Procedure

The analysis of rainwater catchments involves the calculation of the size of roof area and the volume of storage required to satisfy a specified water usage or demand with a specified probability of failure (inability of the stored water to meet the specified demand).

A computer programme described in Chapman (1986), based on an analysis method proposed by Perrens (1982a and 1982b), was used. Using daily rainfall data, the method develops a relationship between two derived parameters, namely, the number of days of storage required and an area factor. This approach means that specific roof areas, storage volumes and demands need not be input to each analysis. The number of days of storage can be converted to storage volume once the demand is specified. The area factor relates actual roof area to a theoretical minimum roof area (obtained from the daily demand divided by the average daily rainfall).

A number of assumptions were made for the computer simulations as follows:

- Roofs were assumed not to leak and gutters were assumed to be adequately designed to collect all runoff from roofs and divert to storage tanks.
- The runoff coefficient (C) of roofs was assumed to be 0.8. This coefficient allows for evaporative losses caused when some of the rainfall is retained on roofs and in gutters by surface tension. Initial loss (I) was assumed to be zero. There is some debate over the most appropriate values of C and I for roof catchments, as outlined in Chapman (1985). The debate is not helped by the limited experimental data available. However, a study of non-absorbent roof catchments in the Adelaide area found that C = 0.8 and I = 0 gave the best fit for a set of 11 storm events. These same values were adopted for a study of rainwater catchments on Christmas Island, Republic of Kiribati (Falkland, 1983) and for the Cocos (Keeling) Islands in the Indian Ocean (Falkland, 1988).
- The tanks were assumed to be half full at the start of the daily rainfall record.
- No rationing schemes were considered.

A sensitivity analysis of changes to the parameters was not undertaken due to time constraints.

4.6.3 Analyses and results

<u>Tongatapu</u>

Simulations were conducted using daily rainfall record from the Nuku'alofa meteorological station. The longest data sequence available from a computer file obtained from the New Zealand Meteorological Service was 20 years covering the period 1 January 1971 to 31 December 1990. While it would have been better to use the full record of 44 years from 1947 to 1990, the available daily data does cover one of the worst droughts experienced in Tonga (1982/1983).

Analyses were conducted for three conditions. The first condition was the 'no failure' condition in which tanks were assumed to always supply the required daily demand. The second and third conditions allowed 'failures' to occur, respectively, once in 10 years and once in 2 years. No exact probability of failure can be assigned to the first condition.

Figure 5.52 shows the relationship between the required days of storage and the area factor for the three conditions mentioned above. A trade-off is evident between storage volume, expressed as days of storage, and catchment area, expressed as area factor, to provide for a given demand with a given level of reliability. Each of the curves is approximately asymptotic to limiting values of storage volume and catchment area. As stated by Perrens (1982a), these represent the two basic limitations of any water supply system, namely, sufficient area to generate the required runoff and sufficient storage to ensure supply in periods of low or zero runoff.

Based on the curve for the 'no failure' condition in Figure 5.52, actual or potential roof catchments and storages on Tongatapu were assessed on the basis of using rainwater catchments for either sole and supplementary sources of freshwater.

Rainwater as sole water supply source

The 'no failure' curve indicates that a reasonable combination of storage and roof area occurs where the number of days of storage is between about 150 and 200, and the area factor is between about 2.4 and 2. If storage is reduced below 150 days, the required roof area starts to rapidly increase. Alternatively, if the area factor is reduced below 2, the required storage starts to rapidly increase. The true optimum point on the curve can only be decided after a detailed economic analysis of roofing and storage costs is undertaken.

In order to use rainwater as a sole water supply source in a typical house on Tongatapu there would need to be sufficient water collected and stored for a daily demand of about 1,000 L/day (10 people using 100 litres per person per day, L/p/d). Examples of required combinations of roof area and storage volume are listed in Table 5.9.

Table 5.9 Rainwater as sole water source, Tongatapu

Option	Days of Storage	Area Factor	Storage Volume (kL or m^3)	Roof Area (m^2)
1	200	2.0	200	410
2	150	2.4	150	490

Note: Roof areas are shown to the nearest 10 m^2

The values in Table 5.9 show the trade-off between storage volume and roof area. It is evident that large storages and areas are required. For instance, if option 2 is considered, the required storage volume is 200 kL (200 m^3) which would require a tank with a height 2 m and diameter of greater than 11 m. Such a tank would be expensive to construct and take up a large area. The roof area required is beyond the size of domestic houses in Tongatapu.

Even if a lower level of water supply security was adopted, large areas and volumes are required. For instance, if a failure of once in two years was acceptable, the storage volume for a roof area of 410 m^2 would be about 160 kL or 80% of the 'no failure' requirement.

The analyses did not take account of any rationing schemes during drought periods which would reduce storage and catchment area requirements. This option was not investigated but is not considered to significantly alter the above results.

Rainwater as a supplementary water supply source

A number of analyses were conducted for different combinations of daily water demand and roof area to determine the required storage volumes for different failure conditions. The daily water demands are based on 10 L/p/d which is considered to be a basic requirement for drinking and cooking. Assuming the average number of house residents to be 10, a typical minimum daily demand per household of 100 litres is derived where the rainwater is used for potable purposes and where other sources such as well water are used for non-potable uses such as washing.

The results in Table 5.10 indicate that the range of roof areas and storage volumes are not unreasonable. The optimum combination of area and volume are not computed here but would generally prefer smaller storage volumes and larger roof areas, as in many cases the required roof area is already available as part of the house. The results also show (as does Figure 5.52) that there is not a large difference between the requirements of area and volume for the different probabilities of failure.

A probability of failure of once every 2 years seems to be a practical compromise given that the groundwater can also be used for potable purposes. It should be noted that the duration of the 'failure' (i.e. dry tank condition) is not shown and may in many cases be only a few days.

The analyses did not consider any rationing schemes. If rationing was applied during periods when the tank was approaching an empty condition then smaller areas and volumes than those shown in Table 5.10 could be used.

Table 5.10 Rainwater as supplementary water source, Tongatapu

Failure Probability	Days of Storage	Area Factor	Storage Volume (kL or m^3)	Roof Area (m^2)
Nil in 20 yrs	200	2.0	20	40
"	150	2.4	15	50
"	100	3.4	10	70
1 in 10 yrs	200	1.9	20	40
"	150	2.3	15	50
"	100	3.4	10	70
1 in 2 yrs	200	1.8	20	40
"	150	2.1	15	45
"	100	2.6	10	55
"	50	4.2	5	90

Note: Roof areas are shown to the nearest 5 m^2

<u>Ha'apai, Vava'u and the Niuas</u>

Rainwater catchment analyses using daily rainfall data were conducted by PPK Tonga for Lifuka in the Ha'apai group, Vava'u island (Neiafu) in the Vava'u group and for both Niuatoputapu and Niuafo'ou in the Niuas.

These results are shown in Appendix O as there was insufficient time to incorporate them into the main body of the report.

It is noted that the daily rainfall sets supplied by the New Zealand Meteorological Service and used in the analyses were shorter than the full period available. This explains the fact that the mean annual rainfalls listed on each of the diagrams in Appendix O are different from those listed elsewhere in this report (for example, Table 4.1).

4.6.4 Comparisons with previous methods

No previous studies of rainfall harvesting using roof catchments in Tonga appear to have applied the simulation method. In most cases it is not clear what method has been used to size storage volumes as there is very little information on this aspect of rainwater systems in available reports. Most reports are concerned with materials and methods of construction and the financial and management aspects of projects to implement rainwater catchment improvements in Ha'apai and Vava'u.

The only design information that could be found in available reports, which included Lindborg (1986), Jayaprakesh (1987), Wolff (1988a), Wolff (1988b) and ESCAP (1990), was a brief mention in Wolff (1988a) of minimum acceptable roof areas for rainwater harvesting in Vava'u. These minimum areas were 325 ft^2 (about 30 m^2) for a 10 kL tank and 270 ft^2 (about 25 m^2) for an 8.3 kL tank. No mention of the probability of 'failure' or estimates of loss from roofs and gutters was provided so it is not possible to make direct comparisons. Given that the rainfall in Vava'u is greater than in Tongatapu, the first combination of roof area and storage volume appears reasonable when compared with the results in Table 5.10. A simulation using daily rainfall for Vava'u would allow confirmation of this. The second combination which shows a decrease in <u>both</u> roof area and storage volume requirements is not very plausible given that there is an inverse relationship (refer Figure 5.52) between these two parameters.

4.6.5 Conclusions

From the analyses of 20 years of daily rainfall data for Tongatapu, rainwater catchments cannot be viewed as a viable option as a sole source of water supply for average households on Tongatapu. The use of rainwater as a supplementary source of water is a viable option for domestic potable water.

It is suggested that any future rainwater catchment analyses for Tonga make use of simulation methods using the long daily rainfall records which area available from a number of stations throughout the Kingdom. This is particularly important for those islands where rainwater is the only viable option for potable water.

For the other island groups in the Kingdom of Tonga, no detailed assessment of the results (refer Appendix O) was made owing to shortage of time. This should be done as part of future assessments for these island groups.

4.7 Implications for water use

The results of the water resources assessment in section 5 indicate that there are adequate but not plentiful water resources for basic needs on most islands. The most critical location in terms of limited groundwater resources is the Ha'apai group particularly on Lifuka where the largest centre of population in the group is located. As has been the general practice, groundwater should be utilised wherever possible and supplemented with rainwater and, if available, surface water (for example, 'Eua).

The limited water resources within the Kingdom of Tonga, even on the main island of Tongatapu, means that uses other than water supply for domestic, commercial and small industrial uses will be necessarily limited. For this reason it is not possible to consider any large scale irrigation. Small scale irrigation combined with the necessary monitoring and control of extraction is possible after a thorough assessment of the impacts on the freshwater lens and other water uses has been undertaken. As stated in Furness (1990c), approval for irrigation should only be allowed after essential steps have been taken as follows: monitoring, modelling, legislation enactment and a trial irrigation scheme.

5. National Groundwater Monitoring and Protection

5.1 Objectives

The objectives of the national groundwater monitoring and protection programme are to:

- Enable the water resources of the Kingdom of Tonga to be properly assessed using long term records of indicative parameters (rainfall, evaporation, surface water flows, groundwater thickness as determined by salinities and water table elevations),
- To provide estimates of groundwater sustainable yields based on a knowledge of recharge, extraction rates and their effects on groundwater volumes,
- To enable water resources to be protected from over-extraction and pollution by informed selection of pump locations and pump rates, and proper land use planning including effective separation of water supply extraction locations from potential pollution sources (especially sanitation facilities and agricultural chemicals).

5.2 Outline of recommended programme

The monitoring programme should consist of routine data collection, checking, archiving and analysis of relevant meteorological, hydrological and other parameters. Details are given in section 6.4.

The monitoring programme should include the collection of key parameters as follows:

- Rainfall
- Evaporation
- Recharge
- Groundwater parameters:
    - quantity (thickness and volume, based on salinity and other measurements).
    - water quality (physical, chemical and bacteriological.
    - extraction rates (for water supply and other uses).

- Tidal variations
- Surface water parameters:
    - flows
    - water quality (physical, chemical and bacteriological)
    - diversions (for water supply and other uses).

These parameters should be collected on a regular basis from selected sites as outlined later in this section.

Controls on the extraction from the groundwater should only be as firm as is necessary. One option is to implement strict licensing arrangements whereby potential users of water must apply for a licence to extract a fixed quantity of water over a defined time period. Licensing of water extraction is common in many countries particularly where multiple users wish to develop scarce water resources. Another option is to have a less stringent system whereby potential well developers submit an application to the regulating agency, pump rates are set by the regulating agency and are then periodically monitored to ensure that over-extraction is not occurring.

A number of factors should be considered in deciding on the preferred option. Most of the water resources of the island are in the form of groundwater requiring wells in order to develop it. Although wells can be developed by either digging vertical shafts or drilling holes to slightly below the water table, the latter method is now preferred and used almost exclusively. There is only one drilling rig in the whole of the Kingdom of Tonga capable of drilling water wells. This drilling rig is owned by the Ministry of Works and operated by its trained drilling staff. The drilling rig is only used for water well drilling under the supervision of personnel from the Ministry of Lands, Survey and Natural Resources who select well sites, advise on target depths for drilling, specify the well construction details and the allowable pump rates. These details are set only after an assessment of the sustainable yield of the freshwater lens. Thus, the level of control over the development of groundwater resources is already high owing to the limited opportunity to develop them.

Given this limited opportunity for developing groundwater in Tonga, it is considered preferable to adopt the option which does not require formal licencing procedures so as to avoid unnecessary administrative procedures. This procedure is favoured by the Hydrogeologist in the Hydrogeology Unit.

While this option does not require formal licencing procedures, a set of protocols should be specified as follows:

- No wells should be developed without the permission of the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources. Potential well developers should be required to submit an application for well development to the Hydrogeology Unit where it should be reviewed,
- Pump rates should only be set after proper consultation between the applicant and the Hydrogeology Unit. Pump rates should take account of all factors influencing the freshwater lens at the proposed extraction site,
- Well construction details should be prepared by the Hydrogeology Unit, and
- Well drilling should be supervised and logged by the Hydrogeology Unit,
- Pump rates should be monitored by the Hydrogeology Unit at regular monitoring inspections. Pump rates at the Tonga Water Board wells should also be monitored by the Board.

The groundwater monitoring, protection and control mechanisms should be included in Regulations under the proposed Water Resources Act (refer section 7). Exact details should be determined by the Hydrogeology Unit and ratified by the Water Resources Committee.

5.3 Outline of responsibilities

5.3.1 Regulating agencies

Ministry of Lands, Survey and Natural Resources

The primary regulating agency should be the Ministry of Lands, Survey and Natural Resources. One of its primary responsibilities relates to 'natural resources' of which water resources is an important component. There is general agreement that this Ministry is the most appropriate to take charge of monitoring, protection and control activities. This is reflected in the recent establishment of the Hydrogeology Unit within the Ministry to assess, monitor and advise on the development of water resources. The Hydrogeology Unit has the technical and professional expertise to undertake the necessary assessment and monitoring of the water resources and to advise on water resources development issues in the Kingdom of Tonga.

Ministry of Health

Another regulating agency in the water sector is the Ministry of Health. It is responsible for monitoring and surveillance of the water quality of potable water supplies to ensure they meet public health standards. It is primarily concerned with the water as supplied to consumers and not directly with the water resources. Water samples are collected by Ministry of Health inspectors from designated sites on a regular basis and forwarded for testing at the Ministry's laboratory located at the Vaiola Hospital on Tongatapu. The surveillance programme is primarily concerned with the bacteriological quality of water supplies and, consequently, the tests carried out at the laboratory are primarily bacteriological in nature. Little or no chemical testing of water is done in the laboratory.

It is appropriate that the Ministry of Health continues to undertake the monitoring and surveillance of the public health aspects of water supplies. The type and frequency and testing should be in accordance with World Health Organisation guidelines (WHO, 1984).

5.3.2 User agencies

Tonga Water Board

The main water using agency in the Kingdom of Tonga is the Tonga Water Board which operates water supply schemes on Tongatapu and 'Eua, on Foa, Lifuka and 'Uiha in the Ha'apai group, and for Neiafu in the Vava'u group.

The Tonga Water Board should be responsible for the installation, calibration, maintenance, repair and reading of flow meters at groundwater pumping stations operated by the Board throughout the Kingdom of Tonga. Readings should be obtained from each meter on a weekly basis and these should be recorded on data sheets. A data base should be established on the Tonga Water Board's computer to enable the meter data to be archived and later analysed.

The Tonga Water Board should also obtain regular salinity (electrical conductivity) readings on the water supply systems that they operate (refer section 6.7.2 for details).

Village Water Committees

The Village Water Committees who operate the village water supplies throughout Kingdom of Tonga should be responsible for the installation, calibration and reading of flow meters on pump(s) at their well(s). The data should be recorded at weekly intervals and recorded onto similar booking sheets to those used by the Tonga Water Board. This data should be forwarded to the Hydrogeology Unit for entry into the database.

Salinity tests at village water supplies should be undertaken by the Hydrogeology Unit as part of their regular monitoring programme.

Some use is made of water from freshwater lenses by individuals for domestic and in some cases agricultural use. This use represents a very small proportion of the current extraction of groundwater. Monitoring of salinity at these locations should be undertaken as part of the Hydrogeology Unit regular monitoring programme.

5.3.3 Co-ordinating agency

The Water Resources Committee, a sub-committee of the Development Co-ordination Committee, is responsible for initiating and reviewing development and other proposals related to water resources, and making recommendations to the Development Co-ordination Committee for forwarding to Cabinet. The Water Resources Committee comprises representatives from government organisations with interests and responsibilities in water (refer section 3 for membership).

The Water Resources Committee should monitor progress on all aspects of water resources assessment, development and management and should take an active role in the review of the draft water resources legislation to ensure that all affected parties are properly informed and their interests safeguarded.

5.3.4 Other agencies

Ministry of Works

The Ministry of Works owns and operates the only drilling rig on the island. It charges for the use of the rig. There is no reason to change the existing arrangements which appear to work smoothly.

Tonga Meteorological Service

The Tonga Meteorological Service of the Ministry of Civil Aviation is responsible for operation and maintenance of key climatic stations throughout the Kingdom of Tonga, collection of records from other stations and forwarding of information to the New Zealand Meteorological Service for processing and archiving of data. It is appropriate that this agency continues to be the primary data collection agency for climatic data.

5.4 Rainfall data

Rainfall data is extremely important for the national monitoring system. There is a reasonably good network of rainfall stations within the island and data has been collected for a number of key stations at least since 1947 on a continuous (daily read) basis.

There are some serious problems in data availability at present. This data is only available from the New Zealand Meteorological Service in Wellington, New Zealand. Historically the stations were run by the New Zealand Meteorological Service but they were handed over to the Tonga Meteorological Service in the late 1980's. Data is submitted on hand written sheets on a monthly basis to New Zealand for computer entry, processing and archiving. The New Zealand Meteorological Service continues to provide annual inspections to ensure that standards are maintained.

It is recommended that formal arrangements be made between the Government of Tonga and the New Zealand Meteorological Service to enable processed daily rainfall data in computer compatible format to be forwarded to an appropriate Ministry in Tonga for archiving and analysis. The current arrangements where data must be obtained on an ad hoc basis from New Zealand is cumbersome and wasteful of resources.

A suitable database for the storage and analysis of rainfall needs to be obtained as dBaseIII+ is not suitable for large amounts of time series data. Options for this type of database are discussed in section 6.10.2.

5.5 Evaporation data

The existing climate stations in the Kingdom of Tonga should be continued. The current list of climatic variables being measured is suitable from a water resource viewpoint as they allow determination of potential evaporation using a well recognised empirical formula such as the Penman equation (Penman (1956, 1948).

A range of stations are in operation which enable evaporation estimates to be derived. These are operated by the Tonga Meteorological Service and the Vaini Research Farm. All climatic data and pan evaporation data should be stored on a similar computerised database as for rainfall. Typical parameters are temperature, vapour pressure, sunshine hours, wind speed, pan evaporation and solar radiation.

The data which is forwarded to New Zealand (most of the data) should be obtained as outlined in section 6.5 and stored on computer. Other data which is collected and stored in the country (such as that from the Vaini Research Farm) should be manually entered into an appropriate time series database.

5.6 Recharge estimation

A water balance approach such as used in this study is the most suitable method for estimating recharge in both the short term (over periods of months) and long term (over periods of years).

Future water balance studies should incorporate daily rainfall rather than monthly rainfall data. Further refinement of some of the parameter values used in the water balance may be necessary in the light of further research. It is not considered necessary to undertake further work on recharge estimation in the near future. After about five years, however, it would be appropriate to review the methodology and assumptions adopted for the recharge estimation in study and any additional relevant data which becomes available either within Tonga or in other similar islands.

5.7 Groundwater data

5.7.1 Well census database

Databases containing relevant information about wells used for the extraction of water should be maintained and updated as necessary. Databases have been established on a personal computer in the office of the Hydrogeology Unit using the software package dBaseIII+.

Well census data stored is stored on a database titled 'WELLS' which includes information about the following attributes:

- Island descriptor
- Well number
- Well location (descriptive)
- Well co-ordinates (easting and northing)
- Reduced level at top of well
- Depth of well
- Type of well (drilled or dug)
- Details of pump, motor and tank(s) as applicable.

Most wells on each of the islands are included in the 'WELLS' database. Locations of these wells are stored by geographical co-ordinates and are also shown on maps. Figures 5.1, 5.29 and 5.40 show the location of most of the wells on Tongatapu, in the Ha'apai group and in the Vava'u group, respectively.

Selected census data for each of the wells in the 'WELLS' database is shown in Appendix G (data current to March 1991).

A second database 'MONITOR' stores the data obtained from monitoring of selected parameters at wells. The information in this database is as follows:

- Island descriptor
- Well number
- Date (of monitoring)
- Depth to water table
- Electrical conductivity, temperature and pH of well water
- Pump status (operating or not operating).

The contents of this database (to March 1991) grouped according to island groups are listed in Appendices F (Tongatapu), J (Ha'apai group) and L (Vava'u group).

5.7.2 Groundwater quantity

For freshwater lenses the most important information for assessing and monitoring freshwater lens thickness (and hence volumes) is salinity. Water level measurements at the water table can provide useful supplementary information.

Thus, the groundwater monitoring programme, as outlined below is based primarily on salinity measurements with additional water table elevation measurements.

<u>Salinity measurements</u>

Salinity measurements should be obtained at defined locations and should include a network of monitoring points both on the surface of the lens (i.e. water table), where samples are relatively easy to obtain and measure, and vertically through the lens at selected monitoring boreholes. This enables a three-dimensional view of the lenses to be obtained.

Most of the salinity monitoring should be performed by the Ministry of Lands, Survey and Natural Resources with supplementary monitoring by the Tonga Water Board.

Measurements of electrical conductivity (EC) should be the primary means of detecting salinity changes in the groundwater. The Ministry of Lands, Survey and Natural Resources has four portable, digital read-out EC meters which are suitable for a range of applications including shallow and deep wells. The staff of the Hydrogeology Unit are trained in the use of the equipment.

For samples obtained from the surface of the lens, it is recommended that a system of primary and secondary sampling points be adopted. The primary sampling points should be monitored once every three months while the secondary points should be sampled on a rotating basis such that each one is sampled at least once every twelve months. This enables a compromise to be reached between an excessive amount of data and time taken to collect and process it and the need to ensure that sufficient baseline data is collected to enable trends to be determined. The need to reduce the data collection and processing to a manageable level is most pronounced on Tongatapu where there are approximately 220 wells and boreholes registered in the Hydrogeology Unit's database (refer Appendix G).

The primary sampling points should include:

- Approximately one-third of the boreholes and wells on Tongatapu
- All registered wells on Ha'apai
- All registered boreholes and wells on Vava'u.

The need for monitoring boreholes to obtain vertical salinity profiles has been discussed in sections 5.1.7 to 5.1.9. Proposed locations for these monitoring boreholes are listed in sections 5.1.9 (Tongatapu), 5.3.9 (Ha'apai group) and 5.4.9 (Vava'u group). It is not suggested that monitoring boreholes be drilled on 'Eua due to the large depths to water table; on this island water samples from production boreholes should be regularly sampled.

The above mentioned monitoring should be done by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources.

The Tonga Water Board should obtain regular salinity (electrical conductivity) readings from each pumped well and at a suitable point on the bulk water supply system (for example, central storages or a test point on the main supply pipeline from all pumps) for each water supply scheme operated by the Board. The main water storages are or will be:

- Mataki'eua on Tongatapu
- New storage to be constructed on 'Eua
- Pangai on Lifuka
- Neiafu on Vava'u
- Others as they are built.

The reason for the sampling at the main water storages is to determine the changes in salinity of the mixed water obtained in each case from multiple sources.

The frequency of salinity testing should be monthly which is considered to be a reasonable compromise between the need for regular data and the desirability of reducing the workload to a minimum. To obtain the salinity data, the Tonga Water Board should purchase its own portable electrical conductivity meters or negotiate with the Hydrogeology Unit for use of their equipment. The former option is considered preferable as the Hydrogeology Unit may not be able to ensure availability of their equipment at particular locations and times. For logistic reasons, three meters are required with one being used for Tongatapu and 'Eua, one for the Ha'apai group and one for the Vava'u group of islands.

All monitoring data collected by the Tonga Water Board should be forwarded to the Hydrogeology Unit for archiving on the Unit's database. The salinity data should be recorded by the Tonga Water Board onto standard sheets provided by the Hydrogeology Unit, and forwarded on a monthly basis to the Hydrogeology Unit. The water meter records in computer database format should be forwarded to the Hydrogeology Unit on an as-required basis but at least once every year.

Water table elevation measurements

Levels at the surface of the lens provide some useful information which can be used in conjunction with the salinity information to build up a better picture of lens dynamics.

By themselves, water levels can, however, provide misleading information about the state of the lens so caution must be exercised in the use of the data.

The comments made in section 5.1.7 caution the use of water level data from being used as a primary tool for determining thickness and dynamics of the lens.

It is recommended that the programme of manual water level observations during regular monitoring runs be obtained with due regard been given to the problems listed in section 5.1.7. The objective should be to obtain and confirm regional water table information but not to use it for conclusions in relation to particular wells. The manual water level measurements should be entered into the database

Automatic recorders should be used at selected boreholes and wells in conjunction with a tide recorder to establish tidal lags and efficiencies (refer section 6.8), short term influences from recharge events and the effects of pumping. The continuous record from automatic recorders can allow a number of influences to be analysed. The use of automatic recorders rather than manual measurements also removes the random measurement errors which are potentially made at each manual observation.

By using multiple automatic recorders at pumped and non-pumped wells in the same general location, the effects of pumping can be seen. Also, it is useful to switch selected pumps on and off for periods of a few hours and possibly days to analyse the effects of pumping at production wells and boreholes.

The Hydrogeology Unit now has a number of electronic data loggers and electric pressure sensors suitable for measuring water level variations in wells. It is intended that these will be deployed to selected well sites.

Geophysical data

The collection and processing of geophysical data (electrical resistivity and electromagnetic data) is done by either manual means or using proprietary software and hardware. It is not intended that this data be entered into the database of other information but rather the data files should be stored in relevant directories on the Hydrogeology Unit's personal computer and backed up on diskettes.

Groundwater modelling

A sharp interface model (MODFLOW developed by the United States Geological Survey) has been used to analyse the freshwater lens dynamics on Tongatapu. To date the model has been developed for the western portion of the island where accurate survey levels of boreholes has been completed. The basis for calibration of the model is observed water table elevations.

Using measured water table elevations and a steady state recharge of 580 mm (one third of the then assumed average annual rainfall), a specific yield of the freshwater aquifer of 0.3, the permeability required to calibrate the model to known water table elevations varied between 1,500 and 2,000 m/day. These values are similar to the value of 1,800 m/day derived by Hunt (1978) in his modelling of the freshwater lens. These values are typical of raised atolls with karstic limestone aquifers (for example, Guam: Contractor and Srivastava, 1990; and Nauru: Ghassemi et al, 1990).

It is intended to run MODFLOW with a transient recharge rather than steady state recharge. This will give a more realistic assessment of how the lens responds to natural variations in recharge. The monthly recharge data computed using the water balance model (refer to section 5.1.6 and Appendix I) can be used for this purpose.

The use of water table elevations for calibration, while being the only option currently available, is potentially not as accurate as known freshwater depths or depths to the transition zone mid-point. Also, the use of a sharp interface model, while giving an idea of the position of the mid-point of the transition zone using a time series of recharge and pumping, does not provide information about salinity variations in the transition zone. These salinity variations are most important as the width of the freshwater component of the lens can be markedly diminished if there are abrupt changes in salinity.

Consequently, a sharp interface model will be of only limited value for long term management of the lens at least until correlations between estimates from the model and vertical salinity profiles at selected locations. The calibration of the model would probably be more successful using salinity profiles from deep boreholes rather than relying on observed water table observations. In the absence of salinity profiles, there is no other choice but to use water table information at present.

In addition to sharp interface models, dispersion models (also called variable density models or solute transport models) which simulate the salinity variations in the transition zone are available. Details of this type of model and some of its applications to islands are described in section 5.1.8.

While the latter type of model is theoretically more applicable to small islands, it has some disadvantages. The level of complexity, data requirements and computing resource requirements are much higher than for sharp interface models. It would not be possible given the computing resources available on the island to contemplate using such a model. It may be feasible for such a model to be developed from a research viewpoint and not as a management tool at an overseas academic institution by an interested postgraduate student.

<u>Future water resources assessment work</u>

For the majority of islands within the Kingdom of Tonga the methods of assessment should be as described in previous sections of this report. Primary emphasis should be placed, where possible, on salinity profiles in boreholes drilled to below the mid point of the transition zone. Extensive use should be made of geophysical (electrical resistivity and electromagnetic) methods to provide additional and relatively easily obtainable information. Additional salinity measurements at the water table wherever it is exposed also provide useful supplementary information.

It is recommended that the traditional pump test be avoided as these tests inevitably prove the obvious conclusion that the hydraulic conductivity of the aquifer is high. Such tests are not necessary and may in fact be detrimental to the freshwater lens in the short term by inducing upconing of underlying saline water.

5.7.3 Groundwater quality

The groundwater monitoring programme should include regular water quality monitoring of selected physical and chemical parameters as follows:

- Salinity (electrical conductivity), as detailed in section 6.7.2
- Temperature
- pH.

This data should be collected at the frequencies specified in section 6.7.2. After two years of data collection, the temperature and pH data collection programme should be reviewed to determine whether it should be continued in its present form or scaled down. The collection of salinity data should is an ongoing programme and major modifications are not envisaged. However, minor modifications to suit future requirements are possible and a review of the programme after two years is recommended.

Regular bacteriological sampling at sources is not considered necessary unless the monitoring of drinking water quality at the user end indicates a need for this. The routine sampling programme of the bacteriological quality of drinking water by the Ministry of Health should ensure that sources are tested if higher than recommended levels of bacterial are detected.

Monitoring of pesticides in the groundwater should be carried out on an annual basis, coinciding with the squash pumpkin season from July to December. The WHO consultant (due to visit in late 1991) should make recommendations about the frequency and method of testing for pesticides and nutrients.

5.7.4 Groundwater extraction

All new wells should be equipped with water meters and hours run meters on the motor/pump to determine the total flow volumes and flow rates during pumping hours. Data should be recorded by the user (e.g. Tonga Water Board, Village Water Committees) on a daily basis on standard forms and submitted to the Hydrogeology Unit on a monthly basis. This procedure would be similar to that used in many parts of the world for the daily recording of raingauges whereby a reader measures the rainfall on a daily basis and submits monthly returns to a central agency for storage and analysis.

The data should be included in a computerised database (dBaseIII+) for storage and analysis.

5.8 Tidal movement data

An automatic recorder (Ott paper chart type) is located on Vuna wharf, Nuku'alofa. This recorder provides a continuous trace showing the fluctuations of the sea level due to tidal, barometric and other influences. The ongoing operation of the recorder is very useful to the groundwater monitoring programme (as well as for other purposes). The tidal and barometric variations can be used to determine the tidal lags and efficiencies at different locations within the groundwater body (refer section 5.1.7)

As mentioned in sections 5.3.9 and 5.4.9, it is essential that tide recorders be established, at least temporarily, in the Ha'apai and Vava'u groups. This will enable msl to be established at these two locations as a basis for determining a common datum for survey work throughout Tonga. Concurrent measurement of the variations of selected well water levels and sea levels at these locations will assist in the understanding of the freshwater lens dynamics.

5.9 Surface water data

Although surface water resources are limited within the islands of the Kingdom of Tonga, they should nevertheless be properly monitored to determine their quantity and quality. This is particularly important in the case of 'Eua where surface water flows from the cave systems in the central part of the island represent an important water resource.

Details of the monitoring programme should be determined after the recommended basic data collection exercise recommended in section 5.2.8 and mentioned in section 6.2.3. The comments below give some idea of the type of monitoring programme that should be adopted.

5.9.1 Flows

Calibrated weir structures should be maintained at the source of surface water flows from the cave systems on 'Eua to measure discharge. Initially, it is advisable to install water level sensors connected to electronic data loggers to obtain continuous records of water level. Using this record and the known rating curve (height versus discharge) for the weir, continuous discharge records can be obtained.

Manual readings of the water level at the weirs should be obtained on a daily basis by the staff of the Tonga Water Board at least for the first twelve months. These readings should be taken in the pool formed by the weir and away from the drawdown zone of the weir outlet. The manual readings should be compared with the automatically recorded data to provide a means of cross-checking.

All data should be forwarded to the Hydrogeology Unit where it should be processed, archived and analysed.

After the initial period of data collection, the surface water flows on 'Eua should be monitored on an ongoing basis in the future. The exact nature of the monitoring programme should be detailed after the proposed investigations (refer section 5.2.8) are substantially completed, the results analysed and any recommendations made regarding the type of ongoing monitoring.

Continuous rainfall measurements should simultaneously be obtained by deploying a tipping bucket raingauge connected to a data logger in the central elevated terrain. The simultaneous rainfall and discharge records should then be analysed to determine if there is a relationship between the two parameters. Simple linear correlations could be tried but it is most likely that a recognised non-linear rainfall-runoff model may be required to adequately relate the two parameters. This analysis may need the assistance of a hydrologist.

The aim of the rainfall-runoff model is to see if rainfall records can be used as a means of accurately determining flows from the cave systems. Exact details of sites, equipment requirements, length of records to be collected and selection of analysis procedures are need to be resolved in conjunction with the hydrogeologist attached to the Hydrogeology Unit.

The rainfall and discharge records need to be collected over a period of at least a year and the results analysed.

5.9.2 Water quality data

It is not considered necessary to test the physical and chemical water quality of the surface water on 'Eua on a regular basis. The main problem with the surface water is that it becomes turbid after significant rainfall. Turbidity can be measured by in-situ sensors but these are expensive to purchase (approx. A$2,000 each) and require regular calibration to obtain good quality data. It is not considered appropriate to purchase and install such sensors as there are very limited support facilities to enable such a programme to be effectively conducted.

Water quality treatment should include settlement tanks to remove suspended solids. Inflows to the treatment and storage facilities should be designed to prevent inflows of water after heavy rain to prevent highly turbid water from entering the water supply system. This could be achieved by diverting flows away from intakes after water flows reach a threshold.

5.10 Resource requirements

To set up the proposed national monitoring and protection programme, there are some essential resources required many of which are already in place.

5.10.1 Personnel

The Hydrogeology Unit with a staff of four provides the professional and technical input to the programme. This Unit consists of

- An expatriate hydrogeologist to implement, supervise and train local staff in the use of equipment and associated procedures
- Two trainee technical staff on a part time basis (studying in Suva for part of the year)
- One labourer.

Additional assistance is available from the Geology Unit which has two permanent staff, the survey section and other parts of the Ministry of Lands, Survey and Natural Resources.

It is considered necessary that the staff of the Hydrogeology Unit be expanded by one additional trained staff member to process the data collected, to archive and maintain the data, to analyse the data and to produce reports as required on the results of the data collection programme. The data processing officer should be rotated through the field duties and vice versa to provide broad training of all concerned.

5.10.2 Databases

There is a need for a suitable database system to enable processing, editing, archiving, analysing and reporting of water resources data on a personal computer. Much of the data will be instantaneous records, for example water depth and quality information from selected observation points. There will also be data of a continuous type, for example, continuous tide and groundwater levels obtained from electronic data loggers and/or chart recorders. In addition, daily rainfall records and possibly some pluviograph (continuous rainfall) records are available.

It is considered appropriate that a comprehensive national database of water resources information be established. Presently, groundwater monitoring information is being stored into a database program (dBase111+) in the Ministry of Lands, Survey and Natural Resources. While this is sufficient for current entering and retrieving discrete data such as regular salinity readings, it is not an efficient means of processing and analysing related time series data such as continuous water level records or daily rainfall, evaporation and recharge data.

A more comprehensive computer package such as HYDSYS from Australia or Micro-TIDEDA from New Zealand would allow more efficient entry, archiving, analysis and reporting. Both packages are capable of handling discrete and time series data and both can run on personal computers. These should be evaluated with a view to purchasing the required hardware and software to meet the growing needs of water resources information on Tonga.

Both the above mentioned software packages are available at commercial rates. It may be possible to obtain a less comprehensive version of HYDSYS in the near future which would be suitable for use with the data for the national archive.

5.10.3 Equipment

A considerable amount of hydrogeological equipment has been purchased as part of the Master Plan Study. This equipment, listed in Appendix N, is stored at and used by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources. The equipment needs of the Hydrogeology Unit have now largely been satisfied.

To effectively undertake the ongoing monitoring work, it is considered necessary to procure an additional personal computer with enhanced facilities to those already available. It is considered that a desk top 386SX personal computer is the most suitable computer for this purpose. It should be equipped with a 60 Mb hard disk drive and at least one floppy disk drive, preferably a 3 ½ inch 1.4 Mb type. It should also have a maths co-processor, mouse and modem. A laser printer should also be purchased to enable printed output to be made. The Hydrogeology Unit already has a plotter for its use. Adequate backup facilities should also be provided. The 'Bernoulli' type of external disk drive offers a number of advantages being both a backup unit and a means of updating programs from elsewhere such as HYDSYS.

5.10.4 Training

Training in the use of word processing and database systems is considered essential for the staff of the Hydrogeology Unit. Where possible use should be made of locally available training facilities. On-site training in the use of word processing software and dbaseIII+ may be available from the Tonga Defence Service.

Training in the use of specialised software packages such as HYDSYS or Micro-TIDEDA would need to be arranged through consultants from Australia or New Zealand, respectively. In the case of HYDSYS, some on-site training is included in the purchase and installation costs.

To maximise the benefits from training in the use of databases, it would seem appropriate to invite personnel from the Tonga Meteorological Service to training sessions.

Training in hydrology, hydrogeology and water resources is considered necessary for the staff of the Hydrogeology Unit. At present, junior staff receive some training in geology but very little in the other areas. There are a number of overseas courses at which should be of benefit to personnel from the Hydrogeology Unit. There are no known courses which are specifically devoted to island hydrology but many courses cover a range of subjects which can be broadly applied to many environments including islands.

The known courses include a 3 month course in surface and groundwater hydrology at the University of New South Wales in Sydney and a 12 month course in hydrology and water sciences at Monash University in Melbourne. These are both Unesco sponsored postgraduate courses and would therefore only be applicable to graduates within the Hydrogeology Unit. Training for non-graduates is available at a number of institutions in Australia.

5.10.5 Costs and funding

The following costs are identified for the items raised in the preceding sub-sections.

- Cost of an additional staff member in the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources. Funding would be required from the Government's recurrent budget. Initial 12 months funding could be considered from an aid donor.
- Cost of computer hardware and software as follows:

  Hardware:
  - 386SX personal computer with VGA monitor, 60 Mb hard disk drive, 3 ½ inch, 1.4 Mb floppy disk drive, 2 Mb memory and maths coprocessor, mouse and modem: $5,000
  - Laser printer: $3,000
  - Bernoulli backup drive and 3 disk pack: $3,000
  - Miscellaneous cables, wiring, diskettes, etc: $,1000
  - Sub-total for computer hardware: $12,000.

  Software
  - HYDSYS or similar data processing and archiving package including 1 week on-site training: allow $15,000.

Funding for the computer hardware and software ($27,000) should be sought from an aid donor.

Installation of salinity monitoring systems by the Ministry of Works (and supervised by the Hydrogeology Unit) as follows:

- 4 to 7 monitoring systems on Tongatapu (refer section 5.1.9)
- 3 to 6 monitoring systems in the Ha'apai group (refer section 5.3.9
- 2 monitoring systems on Vava'u island (refer section 5.4.9).

The total cost of this work is estimated to be about $20,000.

Funding for the monitoring systems should be sought from a suitable aid donor.

6. Water Resources Legislation

6.1 Background

The need for comprehensive water resources legislation has been recognised for a number of years.

The existing legislation related to water consists of the Tonga Water Board Act and associated Water Supply Regulations, and parts of the Public Health Act. The existing legislation is primarily concerned with water supply with very little coverage of water resources management issues.

During the 1983 drought, an inter-departmental committee called the Irrigation Committee was established to investigate ways of overcoming that drought and future droughts. The formation of the committee was also prompted by difficulties being experienced in obtaining external funding for irrigation projects owing to the lack of water resources data and monitoring systems. The Food and Agriculture Organisation (FAO) were approached for advice in 1983 and one of their recommendations was the need for water resources legislation. This led to the production of draft water resources legislation by an FAO legal officer (Wilkinson, 1985). Since 1985, the legislation has been widely discussed and the need for further modifications is apparent.

The necessity for introducing proper legislation to regulate the overall management and utilisation of water resources is well recognised by the Government. Such legislation is one of the primary water resources objectives in the Fifth Five Year Development Plan (CPD, 1987) and is one of the Terms of Reference of the Tonga Water Supply Master Plan Study.

6.2 Draft legislation for Tonga

6.2.1 Outline

The draft water resources legislation (Wilkinson, 1985) was prepared in response to the following terms of reference:

- Review any existing legislation bearing on regulation of use of ground water in the Kingdom of Tonga
- Recognising the diversity of conditions obtaining within and between the different islands of the Kingdom, draft appropriate national legislation providing for regulation of the use of groundwater so as to safeguard the health and well being of the people and the condition of the fresh water lens
- Offer suggestions on the design of a system to monitor salinity levels in groundwater and identify the circumstances in which, under the draft legislation, domestic and agricultural ground water use should be regulated
- After consultation, recommend the most appropriate body to enforce the proposed legislation, the procedures to be utilised for enforcement, and the penalties for infringement of the directives of that legislation
- Draft the terms of reference for a separate mission, if necessary, to draft legislation for the regulation of surface water use on 'Eua Island.

In summary, Wilkinson's findings were:

- The existing water legislation of Tonga needs updating and re-drafting,
- There is an almost complete lack of data concerning water availability of data concerning water availability and consumption within the Kingdom of Tonga,
- No factual basis exists for any meaningful planning of water resources development,
- There is an anomalous division of responsibility for water supply between the Tonga Water Board and the Ministry of Health,
- Water pricing policy should be more clearly set forth,
- The Tonga Water Board appears to be understaffed,
- The composition of the Tonga Water Board is unclear, and
- Existing law lacks adequate provisions concerning the monitoring and control of water pollution.

Wilkinson recommended that:

- The existing Water Board Act should be repealed and replaced by a comprehensive National Water Resources Act,
- New water resources legislation should address the lack of technical water data,
- A conservation oriented water pricing policy should be established,
- The staff of the Tonga Water Board should be restructured to more efficiently deal with the Board's increased water management responsibility,
- The membership of the Tonga Water Board should be clearly delineated and should promote an inter-disciplinary approach to water resources management,

- The divided responsibility for water supply which now exists in the Kingdom should be ended as rapidly as possible, and
- Approved water pollution monitoring and control should be an objective of the new water legislation.

Using his findings and recommendations, Wilkinson prepared a draft Water Resources Act to replace and expand on the existing legislation. The intentions of the draft legislation were to:

- Provide a coherent legislative scheme for water resources management and close the numerous gaps in the existing legislation,
- Provide for the establishment of a technical data base necessary to support intelligent water resources development planning,
- Provide for more intelligent water pricing and more efficient water charge collection,
- Establish the Tonga Water Board as a water planning body and provide for gradual elimination of the division of water supply responsibility between the Board, the Ministry of Health and various village committees,
- Restructure the staff of the Tonga Water Board to provide for more efficient water management,
- Provide for a diverse Water Board membership that would promote inter-disciplinary water resources management, and
- Establish the legal requirements for the monitoring of water extraction and use and the monitoring and control of pollution.

The draft Water Resources Act is very detailed and is divided into the following sub sections:

- Preliminary clauses
- The Tonga Water Board
- The national water resources development plan
- Public water supply plan
- Water metering and monitoring
- Water charges
- Alteration, suspension or termination of water use
- Water pollution control
- Water source protection
- Appeals
- Repeals and savings.

Based on additional advice, Wilkinson considered that separate water resources legislation for 'Eua was not necessary because the draft national legislation was broad enough to cover both surface water and groundwater and that it was most likely that in future the groundwater resources of 'Eua would need to be developed.

6.2.2 Shortcomings

The main shortcoming of the draft Water Resources Act, based on more recent written (for example, Hadwen, 1988) and verbal comments, is that all aspects of water resources management are seen as being the responsibility of the Tonga Water Board. This has the potential for creating a conflict of interest since the Tonga Water Board would be both the responsible authority for water resources management and one of the major user's of the water resources. This could result in the one agency favouring its own needs at the expense of other user's needs.

It is now considered by most that the appropriate agency for administering the water resources legislation is the Ministry of Lands, Survey and Natural Resources.

Another problem with the draft legislation is that it may be too comprehensive and detailed (Gatliff, 1989). It is considered that some of the detail such as penalty provisions including monetary values for fines would be better placed in a set of Regulations under the Act.

It is also suggested that the water resource management issues only be covered in the Water Resources Act with the water supply issues being covered in a revised Tonga Water Board Act (or 'Water Supply Act'). This would have the advantage of separating out those issues which should be administered by a water resources policy and management agency from those which are the responsibility of agencies to supply water. The proposed Water Supply Act needs to identify the areas of responsibility of the agencies currently involved (Tonga Water Board, Ministry of Health and Village Water Committees). This latter aspect is dealt with in more detail in the accompanying Institutional Strengthening and Community Master Plan Report.

6.3 Legislation from other islands

This section is intended to bring to the attention of personnel involved in the drafting of final water resources legislation in Tonga, some additional reference material which may be of assistance.

A review article on the topic of water resources legislation and administration, based on experiences with these matters on islands in the Caribbean Sea, is presented by Davis (1980). This author makes some worthwhile suggestions about the scope of water resources legislation. He suggests that although legislation should be comprehensive it also should be framed in the simplest way possible. A good approach is for the main body of legislation not to be too detailed but to provide a general framework of powers and responsibilities and restraints. Within this framework, the detailed and exhaustive rules and regulations can be drafted as subsidiary legislation. This approach enables modifications, repeal and amendments to be made without tedious and time-consuming parliamentary processes as responsibility for the subsidiary legislation can be delegated to a Minister or Cabinet of Ministers.

Other general guidelines for water resources legislation are covered in ESCAP (1983). Case studies for some small islands in the Caribbean Sea are provided in United Nations (1986). Drafting of water resources legislation for a number of island countries in the Pacific Ocean has been sponsored by the United Nations Water Resources Assessment and Planning in Pacific Islands Project (RAS/87/009). This Project is based in Suva, Fiji.

6.4 Recommendations for final legislation

It is essential that legislation be enacted to enable the freshwater resources of Tonga, particularly groundwater resources, to be properly managed including adequate planning, assessment, development, monitoring, protection and control. A Water Resources Act based on the draft prepared by Wilkinson (1985) should be prepared.

Specific recommendations are:

- The Act should be simplified as far as possible with most of the detailed provisions to be included in supporting legislation (Regulations under the Act).
- The Water Resources Act should concentrate on issues related to water resources management and not be concerned with the details of water supply (such as metering, charging policy, etc.). It is suggested that water supply matters should be included into a revised Tonga Water Board Act or a new Water Supply Act. The Water Resources Act should, however, stress that the primary use of the water resources is an adequate, safe and equitable water supply to the people of Tonga.
- The agency responsible for administering the Act should be the Ministry of Lands, Survey and Natural Resources. This Ministry is the agency with the necessary skills to monitor and protect the water resources of Tonga and accordingly it is appropriate that it should administer the provisions of the Act. Other agencies should be involved in supporting roles as described in section 6.3.
- The legislation must stress the importance of a national water resources monitoring and protection programme. The draft legislation needs to be modified in line with the recommendations in this report concerning monitoring and protection of water resources. It is noted that the draft legislation (Sections 19(l) and 40) emphasises the need for water level recording to monitor available freshwater lens quantity. There is no mention of the

more important measurements of salinity both at the surface and in vertical profiles through the lens.

- Under the legislation, water resources development and extraction should be adequately controlled. It is important that there be a balance made between the need for control over water extraction and a system which is overly bureaucratic. This can best be obtained by requiring potential well sites to be reviewed, and for pump rates to be set, by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources (refer section 6.2 for details). This agency is the one which will keep all records of well construction, pump type and rate and data pertaining to water quantity and water quality. The exact details of the protection and control mechanisms should be determined by the Hydrogeology Unit, ratified by the Water Resources Committee and set into Regulations under the Act.
- The legislation must include provision for the prevention of pollution to water resources. This must cover both point source pollution (e.g. sewage discharge) and non-point source pollution (e.g. agricultural chemicals). Sections 8 and 9 of the draft Wilkinson legislation recognise the problems of pollution and provide a good basis for final legislation. While the draft legislation has provision for controlling land use activities as a basis for preventing non-point source pollution, consideration should be given to an explicit mention of the need to control the future use of quarries on Tongatapu. These quarries which are excavated to the water table offer no means of preventing pollutants entering the freshwater lens. They pose a severe threat to the quality of the freshwater lens if inappropriate uses such as waste disposal are considered for these sites.

There are many aspects of the draft Wilkinson legislation which require some 'fine tuning'. Some of these are covered in this section while others will need to be the subject of further discussion between legal personnel and technical personnel with knowledge of the groundwater dynamics of the islands of Tonga.

It is essential that the proposed water resources legislation be reviewed and cleared by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources before it is submitted to the Water Resources Committee for discussion.

7. Water Resources Development and Management

7.1 Options

There are a number of options for the development of water resources development. As the water resources are primarily groundwater, concentration is placed on development options for this resource.

Both dug wells and drilled wells (boreholes) are the only methods used to date. In recent years drilled wells have replaced dug wells as the preferred option due to the relative ease of drilling with the one available Walkerwell drilling rig. The cost of drilling a production bore complete with casing is approximately A$60/m.

Other possible options for groundwater development are horizontal conduits within the freshwater zone. On islands where the depth to water table is reasonably shallow (typically 2 to 3 metres) trenches can be dug by mechanical excavators (normally backhoes on tractors) and/or manual labour. In the trenches and just below water table, slotted PVC pipe can be laid and then backfilled. One or more pipes laid in this way can then be directed to a sump from where water can be pumped. The system of infiltration pipes is often referred to as an infiltration gallery and this method of groundwater extraction is often used on coral atolls. This approach has the effect of skimming water off the surface of the lens in the region of the pipes. Shallow water table conditions are not normally found, however, on the islands of Tonga as most tend to be raised atolls with larger depths to water table. In these conditions, therefore, the excavation of trenches except in low lying areas is impractical. The method of construction, however, should not be ruled out entirely as there are some areas which could benefit from this approach. Details of gallery design and construction methods are not presented here but can be obtained from other references (for example, Falkland, 1988; 1989).

Another form of horizontal conduit which utilises the same skimming principle is a tunnel. These could be constructed by mining an inclined access tunnel to the water table and then horizontally tunnelling in one or more directions. This concept was raised in Lao (1978). A less expensive option that could be considered for tunnelling is from the bottom of quarries which have been excavated to or close to the water table. A number of such quarries exist on Tongatapu and some are located in areas of known fresh groundwater resources (for example, the quarries near Liahona). The invert of the tunnel should be above water table for ease of access with an adjacent central or side 'drain' dug below water table to allow water to drain to a central sump which could be located at the entrance to the tunnel from the quarry. Tunnelling at water table on limestone islands has been carried out in the past for groundwater development. In some instances, tunnels have been driven from the base of vertical dug shafts. Examples of islands where tunnels have been used to develop groundwater are:

- Malta: Camilleri (1978); Spiteri Staines (1989)
- Guam: Washbourne and Moore (1945); Fil (1950)
- Bermuda: Rowe (1991)
- Barbados: Goodwin (1980, 1984).

Tunnels for groundwater development could be developed over long distances if required. Some advantages of this approach over drilled wells are the need for a lower land-take for pumping installations, a centralised pumping installation requiring less maintenance of individual pumps. The major disadvantages are that it is unknown technology on the island and would require specialised excavation equipment and trained operators. This would inevitably lead to higher construction costs at this stage than for an equivalent pumping capacity based on individual drilled wells.

On the volcanic islands and mixed geology islands such as 'Eua, potential options are surface water collection from spring discharges or collection of water stored as crater lakes (for example, Tofua and Niuafo'ou). Groundwater development on the volcanic islands is also possible but as yet no hydrogeological investigations have been undertaken to determine their suitability in terms of both water quantity and quality. On the elevated limestone island of 'Eua where spring flows occur, the springs can be used to supply a supplementary supply to groundwater.

Other options for water resources development are rainwater catchments, desalination and importation.

Rainwater catchment systems are a well developed technology in the Kingdom of Tonga and should be encouraged on those islands with limited or no surface and groundwater resources. The cost of supplying water from rainwater catchments is high compared with other methods if used as a sole source of supply. However, it is a very useful and generally affordable if it is used as a supplementary source of water and restricted to potable purposes only.

While desalination has been used in other parts of the world, primarily in the oil rich Middle Eastern countries, it has many disadvantages in an island country such as the Kingdom of Tonga. Capital costs are moderate to high, operating costs are high and the resource requirements in terms of skilled operators are also high.

Importation of bulk water requires a suitable and reliable source, such as a river discharging to the sea or a large groundwater development. There are no such sources in the Kingdom of Tonga and they would therefore need to be sought in another country. Nearby island groups such as Western Samoa and Fiji could be approached but there is no guarantee that a reliable source could be made available on a permanent basis. This raises the political problem of obtaining water from another country. The cost of infrastructure to enable water to be discharged from ships or from sea-towed containers would be expensive as would the cost of transport.

A detailed study of the comparative costs of the various options has not been undertaken but information derived from such studies on other small low-lying islands (Christmas Island, Kiribati: Falkland, 1983; Cocos (Keeling) Islands, Australia: Falkland, 1988) show that the cheapest option is groundwater development.

7.2 Preferred options

As stated above the preferred option is to develop groundwater resources as the primary source of water.

A choice between the various methods for groundwater development is dictated by economic considerations. At present, the drilling of wells provides a cost effective method of groundwater development on the raised coral atolls and the technology is well known on the islands of Tonga. It is, therefore, the most sensible approach at present to groundwater development on most of the islands of Kingdom of Tonga. The other options identified above (galleries, tunnels) should not be entirely dismissed as the situation may arise when either or both may be technically and/or economically more viable or groundwater development at sustainable pumping rates.

Where both surface and groundwater are available such as on 'Eua, the groundwater resource is preferable as it is more sustainable during drought periods and has a relatively constant water quality. By comparison the water quality of spring low on 'Eua is affected by high turbidity levels following heavy rainfall.

On those small islands where neither surface nor groundwater is available, the use of rainwater catchment systems is seen as the only viable alternative.

7.3 Well design criteria

The design of individual groundwater extraction points is most important on small islands in order to minimise the upconing of saline water under the influence of the pump. It must be remembered that any disturbance to the natural flow in the lens will induce some salinity variation. The objective must therefore be to extract freshwater in such a way so as not to induce salinity changes which will exceed the freshwater limit at the pump inlet.

To achieve this objective, two criteria must be met. Firstly the average rate of extraction from a freshwater lens should not exceed the assessed sustainable yield for the freshwater lens. Secondly, the design and spacing of extraction facilities and extraction rates of individual pumps should be carefully selected to minimise the local upconing.

Factors which are important in the design of wells are:

- Optimising the spacing of wells and the pumping rates at each well within the constraints of available land area and the sustainable yield of the lens within that land area. On Tongatapu, individual well yields should be restricted to 2 L/s for village and private wells and to 3 L/s at Mataki'eua. On the smaller islands such as in the Ha'apai group, individual well yield should not exceed 0.5 L/s,
- Minimising the depth of each borehole or well. It is recommended that each well should not be drilled more than 2 m below water table (which in many cases will be about 1.5 m msl,
- Setting the pump inlet within the borehole or well to be at or just below msl (maximum of 1 m below water table),
- Pumping at a constant rate rather than intermittently to minimise the instantaneous pumping rate.
- Drilled wells should be cased using PVC pipes,
- Bore casings should be extended above ground level to prevent surface water which may be contaminated with oil, grease and other pollutants from entering the borehole. For the same reason, hand dug wells should have a raised concrete surround,
- Storage of oils and fuels in leakproof areas. A concrete apron with a raised edge should be built around the motor and pump to contain any spillages of oil of fuel during filling or as a result of mechanical problems.
- Concrete plug at base if salinity problems occur.

Figure 5.53 shows a standard drilled well design for application in Tonga. This figure shows dimensions to be used for borehole diameter, casing and depth of hole relative to msl.

It is expected that most new wells in the Kingdom of Tonga will be drilled rather than dug owing to the availability of a drilling rig. On some of the more remote outer islands to which it is difficult to transport the rig (e.g. Hunga in the Vava'u group). It is likely that dug wells may be installed to develop groundwater resources. It this done then the standard design used at the dug wells at Mataki'eua would be suitable. This design incorporates a concrete base with raised edges at the base of the well which is excavated to about 0.5 m below water table. The suction pipe of the pump is set at a level below the raised edge of the concrete base.

7.4 Location of new wells and selection of pump rates

The selection of a pump rate on islands with freshwater lenses is as yet not an exact science. A number of mathematical approaches have been adopted but these are only approximations to the true situation, owing mainly to the heterogeneity of the aquifers and the difficulty of accurately modelling the salinity gradients close to the pumping locations. Empirical formulae, sharp interface models and dispersion models have all been used to select pump rates for individual extraction points on small islands. Another approach is to select a reasonably conservative rate of pumping and to monitor the effects of pumping on the freshwater lens particularly with regard to fluctuations in the freshwater and transition zones. A combination of both approaches has also been adopted for some islands.

The data available from some of the pumping sites on the islands of Tonga enable the current pumping rates to be evaluated. At Mataki'eua on Tongatapu the available data indicates that the pumping rates at most sites within the wellfield are not adversely affecting the freshwater lens at that location. On the other hand, the pump rates at the wells on Lifuka are considered to be too high as indicated by the high salinities of the pumped water and the lowering of salinity in the wells following periods of no pumping. The same observation also applies to some of the wells on Foa and 'Uiha in the Ha'apai group. The total groundwater extraction from the wellfield for Neiafu on Vava'u island may have reached or exceeded the sustainable yield of the freshwater lens at that location.

7.4.1 Tongatapu

<u>Additional wellfield development for Nuku'alofa</u>

To expand the wellfield for supplying additional water to Nuku'alofa and surrounding areas, it is considered that the same spacing of wells and the same pump rates as at the Mataki'eua/Tongamai wellfield are suitable. Thus a pump rate of approximately 3 L/s from wells located no closer together than 150 m (and preferably further apart) is considered reasonable for a future wellfield within Tongatapu for water supply to Nuku'alofa. The overall extraction from a given area of the island should not exceed the sustainable yield as given in section 5.1.8.

Based on the water requirement for Nuku'alofa in the year 2011 of 12.3 ML/day (approx. 142 L/s) a total of 48 pumps will be required.

New pumps should be designed to run continuously rather than intermittently. For this reason, extra wells and pumps will be required as stand-by capacity.

The wells within a new wellfield should be located in a linear pattern parallel with the coastline similar to those at Tongamai rather than clustered as at Mataki'eua. A new wellfield should be sited at least 1 km from the existing wellfield at Mataki'eua /Tongamai. It should also not be within 500 m of the cluster of wells near Liahona. The wells should not be closer than 500 m to either the sea or low lying land which is affected by periodic sea inundation. A suitable location will need to be decided after considering these principles and land ownership matters. The final decision should be made by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources. One option is to site the linear pattern of wells to the north and west of the Mataki'eua/Tongamai wellfield such that the line of wells is approximately parallel with the coastline.

Given the present Mataki'eua/Tongamai wellfield pump rate of 5.3 ML/day (refer section 5.1.2), a further amount of 7 ML/day (approx. 80 L/s) will be required by the year 2011. The minimum number of additional wells and pumps required is, therefore, 27 based on an average of 3 L/s from each pump. To allow for some pumps being out of service at any time, the actual number of installations required is about 32 allowing for 15% spare capacity. If these wells are located at 200 m spacing then they would form a line 5.4 km long. If the spacing was 150 m the total lineal requirement would be reduced to 4 km. Allowing for a number of spare pumps/wells, it can be assumed that a line of pumps over a distance of between 4.5 and 6 km will be required by the year 2011.

Groundwater development for other parts of Tongatapu

As a general rule, wells for villages should be located no closer than 500 m from the coastline. Adjacent to the lagoon, however, wells could be located slightly closer to open saline water because of the lower permeability of the sediments in that area. Exact locations should be determined only after consultation with the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources.

For the villages selected as part of the Master Plan Study, the groundwater sources have been selected already except in one case. Listed below are details for each of the villages from the west to the east of Tongatapu. The well numbers are shown in Figure 5.1.

- Houma currently has a number of wells from which it can obtain its water supply and it is seen that one or more of these can continue to supply the village,
- Te'ekiu has recently had a new well (well 73) drilled to supply it with water now and in the future,
- Pea currently derives its water supply from well 88. The Master plan Study proposes that Pea should obtain its future water requirements from the wellfields which supply Nuku'alofa,
- Vaini currently derived its water from wells 27 and 28 and it is intended that these will continue to supply the village. If more water is required then a well to the south of Vaini would seem to be the most appropriate,
- The Mu'a villages, Lapaha and Tatakamatonga, currently obtain their water from a wellfield (wells 18 to 21) to the southeast of the villages. Owing to relatively high salinities in these wells (refer section 5.1.7 and Figure 5.17) and the narrowness of the island at this location, it is recommended that any further expansion of the wellfield be made to the south where the island widens. As a guide, any future wells should be at least 1 km southwest of the road between the Mu'a villages and Haveluliku and approximately midway across the island. Preferably the wells should be even further south, and
- Haveluliku has recently had a new well (well 50) drilled to supply it with water now and in the future.

7.4.2 'Eua

To develop the groundwater on 'Eua a series of wells should be drilled on the western side of the island to the south of 'Ohonua and at least 500 m from the ocean. Exact locations should be determined by the Hydrogeology Unit.

Yields of surface water resources are not adequately known at this stage to recommend development and require further investigation of their potential, primarily by installation of gauging weirs and regular measurement of flows.

7.4.3 Ha'apai

Lifuka

Investigations of the water resources have found a limited freshwater lens on the western side of Lifuka largely underlying the villages of Pangai and Hihifo. The sustainable yield is estimated at 0.5 ML/day or about 6 L/s (refer section 5.3.8). The most practical development option would be a row of 12 pumps each with a capacity of 0.5 L/s spaced about 200 m apart along the eastern side of the villages of Pangai and Hihifo and within the boundaries of the freshwater lens shown in Figure 5.31. Exact locations should be specified by the Hydrogeology Unit. Additional installations should be provided to allow for breakdowns but the total pumping should not exceed 6 L/s (unless the sustainable yield estimate is increased in the light of further knowledge of the lens). This flow rate is approximately equal to a supply rate of 0.5 ML/day.

'Uiha

The villages of 'Uiha and Felemea on the island of 'Uiha are included as village water supplies to be studied as part of the Master Plan Study. In both cases water is currently pumped from the island's freshwater lens. In both cases, also, the wells are located in the middle of the island and to the east of the village (well 24 for 'Uiha and well 23 for Felemea as shown in Figure 5.29). At present the pump rates from these wells appear to be excessive (refer section 5.3.7) as on Lifuka, and it is recommended that pump capacities be no greater than 0.5 L/s. If multiple wells are required these should be separated by 200 m and arranged in a linear pattern in the middle of the island and along the main axis (northeast to southwest) of the island. These locations have been based on geophysical work which has identified an area of freshwater in the middle of the island.

Other islands

Groundwater extraction systems with small pump rates (no greater than 0.5 L/s) are likely to become the model for any future water resources development on the small islands of the Ha'apai group and possible the Vava'u group. On very small islands, where fresh groundwater is unavailable on a permanent basis, rainwater catchments are the most viable option (refer section 8.1 and 8.2).

7.4.4 Vava'u

Neiafu

Although, the salinity of the wells at the Neiafu wellfield are within the recommended limit for potable water, there was a significant increase in salinity in one of the wells between March and September 1990 (refer section 5.4.7). This is a clear indication that pumping may be approaching or may have exceeded the sustainable yield of the lens in that location.

Future expansion of groundwater extraction facilities should be away from the present wellfield and nearer the centre of the island where the available information indicates the lowest salinity groundwater occurs. A suitable location for additional pumping requirements can be found about 2 km to the north of the existing wellfield. Exact locations for additional drilled wells should be determined by the Hydrogeology Unit.

The drilling depths to water table on Vava'u island are equal to or greater than for most other locations being studied as part of the Master Plan Study.

Groundwater development for other parts of Vava'u

The villages of Tu'anuku and Longomapu on Vava'u island are included as village water supplies to be studied as part of the Master Plan Study.

At Tu'anuku, the water from the well (well 17: refer Figure 5.40) is close to or above the limit for potable water based on two monitoring visits (refer Appendix L). It is believed that the pump rate on the pump is excessive and that a smaller pump running continuously at between 0.3 and 0.5 L/s should overcome the problem. A second well may be required to meet the projected demand to the year 2011. The siting of a new well should be determined by the Hydrogeology Unit.

There is a drilled well at Longomapu which has not been utilised owing either to the well being dry (not drilled deep enough) or to an obstruction at the bottom. A diesel pump was on site in early 1990 during a site visit but had not been installed owing to this problem. The village currently relies on rainwater catchments for its water supply. The pump at the site is much too large for the job and would undoubtedly cause saltwater intrusion if it had been used. The pump rate at this site per well should not be greater than 0.5 L/s. The number of wells will need to be decided based on demand estimates for Longomapu and consideration of the need for standby pumping capacity. The siting of new wells should be determined by the Hydrogeology Unit. As Longomapu is located in a narrow part of the island between the sea and Lake Ano it may be advisable to site any new wells to the north of the village where the island width is greater. The land area between Longomapu and Tu'anuku may also be a suitable site for both villages as the island also widens there and would therefore have the potential for a thicker and more dependable freshwater lens. Further investigations by the Hydrogeology Unit would need to confirm this assumption.

As mentioned here and previously, groundwater extraction systems with small pump rates (no greater than 0.5 L/s) are likely to become the model for any future water resources development. On very small islands, where fresh groundwater is unavailable on a permanent basis, rainwater catchments are the most viable option (refer section 8.1 and 8.2).

7.4.5 Niuas

The main water resources of Niuatoputapu are in the form of freshwater lenses within limestone and are comparable with islands such as Tongatapu and Vava'u. The wells on Niuatoputapu are reported to be in limestone and produce yields in the range from 2 to 4 L/s. Yields in the volcanic rock are expected to be less than 1 L/s.

Niuafo'ou is entirely volcanic and its water resources are limited by the low fracture porosity of the rocks. At present, the drilling rig owned by the Ministry of Works is not capable of drilling in this type of rock. Hence, it is not possible to undertake any detailed investigations of hydrogeological conditions at present. Should the drilling capability be upgraded then it is possible that testing of the water resources on the island could take place.

Tafahi is similar to Niuafo'ou in that it is composed entirely of volcanic rocks with low porosity. It is unlikely to have significant groundwater resources.

7.5 Energy sources

As most of the water supplies in the Kingdom of Tonga are based on groundwater, pumps are required. The energy for pumping of water can come from a variety of sources. Hand pumps are not generally suitable owing to the large depths from ground surface to water table. Where the depths are small (less than about 4 m), hand pumps have been used, for instance in some of the villages in the Ha'apai group. Where the depths exceed about 4 m, other energy options must be explored. Those which are commonly used for pumping include the following:

- Fossil fuels (mainly diesel)
- Electricity
- Solar radiation
- Wind.

At present only the first two options are used in Tonga. Both electric and diesel powered pumps are used at the Mataki'eua/Tongamai wellfield. Of the 22 pumps operating at the wellfield in March 1991, 7 had electric motors and 15 had diesel motors. In the villages, diesel driven pumps are most common since diesel motors are easier to install and do not suffer from the power fluctuations common in the present electricity supply. In remote areas where electricity is not reticulated, diesel pumps are the only pumps found.

Wind pumping has also been tried at the Mataki'eua wellfield where three Southern Cross windpumps are installed but are presently unused. Windmills have been installed in the past in some of the villages. However, they have not had a good record mainly due to the effects of high winds and cyclones. It is reported that all those except the ones at Mataki'eua/Tongamai were destroyed in Cyclone Isaac in 1982 (Jayaprakesh, 1987).

Wind energy in the islands of Tonga is only moderate. Average wind speeds in Ha'apai for instance are 4.1 m/s (Enersol, 1987). From available data, Thompson (1986) shows that the wind power potential is greatest on Tongatapu near Fua'amotu. The next highest wind power potential is found in the Ha'apai group followed by the Vava'u group and lastly the Niuas. In the evenings wind speeds drop considerably. In order to take advantage of the available wind, wind mill towers would need to be high, often more than 30 m to be higher than surrounding coconut trees, or situated on elevated terrain. It is not considered desirable to carry out large scale clearing of coconut trees to provide suitable locations for windmills. Also, the occasional cyclones which hit the islands can cause destruction of windmills as has happened in the past. High steel towers need to be heavily galvanised to prevent corrosion from the highly corrosive marine environment. The cost of wind pumps delivered to the island is approximately equal to equivalent capacity solar powered pumps. Based on these problems, it is concluded that wind energy for pumping is not a preferred option for water pumping.

Solar pumps have been trialled in a number of villages. The only successful one is reported at Ha'alalo on Tongatapu while one at Fatai was a failure due to a mismatch in power between the power developed by the solar panels and that required for the pump (Jayaprakesh, 1987).

One of the potential disadvantages of solar pumping is that it can only occur for about one third of the 24 hour day. This means that instantaneous pump rates must be about 3 times that of a continuously operating pump unless batteries are used to store the electrical energy. Large battery banks would be required and these are not considered appropriate in the humid tropical atmosphere. Thus, the direct solar pumping option is the only feasible alternative. In many circumstances, pumping at 3 times the average rate for one third of the time will not adversely affect the quality of the groundwater. Solar pumping also has the disadvantage of low efficiency during long cloudy periods which do occur in Tonga. This means that water storage requirements are high to provide adequate reserves of water in periods of non-pumping. It is considered necessary to provide diesel backup systems if solar pumping is adopted.

Despite these problems, it is considered that solar pumping should be further evaluated particularly for the smaller water supply schemes. The errors of previous systems should be thoroughly evaluated to ensure that the same problems are not repeated.

7.6 Treatment

Generally, all public surface and groundwater supplies used for potable purposes should be disinfected owing to the proximity of many water supply and sanitation facilities and the highly permeable nature of the soils and subsurface geology. In the case of groundwater, exceptions may apply where it can be demonstrated that water extraction facilities are not located down gradient of actual or potential sources of pollution. Minimum safe distances between sanitation and water supply are difficult to estimate given the highly permeable geological conditions. These should be assessed by an experienced hydrogeologist taking account of locations of water supply and sanitation facilities with respect to each other and the coast, the drawdown induced by water pumping and the nature and quantity of pollutants. It is certainly not acceptable to apply minimum safe distances (commonly 30 to 50 m) derived from continental situations where often totally different conditions apply. If there is any uncertainty, especially in the case of public water supplies, disinfection should be included as an essential element of the water supply system. Disinfection is normally carried out by either chlorination or boiling.

Surface water supplies may also require treatment for removal of suspended matter and turbidity. Groundwater supplies are not generally affected in the same way and no treatment of this nature is required.

It is not considered necessary, despite some obvious difficulties with the hardness of the groundwater, to remove hardness. This form of treatment is rarely practiced on small islands owing to the additional operational and maintenance requirements including costs.

8. Conclusions and Recommendations

8.1 Conclusions

The water resources of Tonga are primarily in the form of groundwater. Surface water resources are not present on most islands; exceptions are 'Eua and a number of the volcanic islands including Niuafo'ou and Niuatoputapu. Groundwater is mainly found as freshwater lenses which form beneath the surface of the limestone islands and above seawater due to the density difference between freshwater and seawater. There is not a sharp interface between the freshwater and underlying seawater but rather a transition from one to the other. The transition zone is often much wider than the freshwater zone. Freshwater lenses can only occur where there is sufficient recharge from rainfall and where the permeability of the island's geological formation is not too high as to cause rapid mixing of the recharge to the freshwater and underlying seawater.

As reported in previous reports on the water resources of the islands of Tonga, the available data on which to base a water resource assessment is sparse. Hence, a major conclusion is that the results of this study in terms of water resource assessment should be considered as preliminary only. The current initiatives of the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources to obtain basic and much needed water resource assessment data are a positive step to overcome this problem. It will be several years, however, before the preliminary estimates of yield of the water resources made in this report can be confirmed.

The Hydrogeology Unit has set up a well census database and salinity, temperature, pH and water level data are regularly obtained from a number of these wells and entered into the database. This information is a good start to an ongoing water resources monitoring programme in the Kingdom of Tonga.

The rainfall and climatic data collected in a number of islands of Tonga, particularly that data collected since 1947 by the New Zealand Meteorological Service, and more recently by the Tonga Meteorological Service, has enabled recharge estimates to be made from each of the main island. The recharge estimates are based on a water balance study using rainfall measurements, potential evaporation estimates and knowledge of soils and vegetation derived from a number of sources. Monthly recharge estimates have been made for the 44 year period from January 1947 until December 1990 for Tongatapu, Lifuka in the Ha'apai group and Vava'u island in the Vava'u group. Estimates of recharge on 'Eua have been made using assumed rainfall patterns based on a correlation of available data between 'Eua and Tongatapu.

Using the water balance approach, the following average recharge estimates as a proportion of rainfall and as an annual total were made:

- Tongatapu: 30% 528 mm
- Lifuka, Ha'apai group: 28% 478 mm
- Vava'u island, Vava'u group: 41% 917 mm.

Recharge on a monthly and annual basis can vary considerably. In drought periods recharge is often zero and, on islands where the roots of trees such as the coconut tree can reach the water table, the recharge can be negative. Negative recharge denotes a net loss of water due to the ongoing transpiration of the trees.

Recharge in the past decade has been below the long term average due to a lower average rainfall during this period. For instance, the rainfall on Tongatapu for the years 1981-1990 is only 80% of the 44 year average from 1947-1991.

Despite the shortage, and in some cases absence, of basic groundwater data, preliminary estimates have been made of the sustainable yields of freshwater lenses on the islands of Tonga. These estimates are based on the estimated recharge and a preliminary knowledge of the island's ability to retain fresh groundwater. The latter knowledge has been gained primarily from measurements of the thickness of freshwater using geophysical techniques supplemented by measurements of water table elevation and limited vertical salinity profiles. The sustainable yield estimates will be refined from groundwater monitoring information.

Current water use is estimated to be 38% of the sustainable yield in the western portion of Tongatapu and 9% for the remainder of the island. The proposed water development strategy in the Master Plan will increase the demand by the year 2011 to 90% of the sustainable yield in the western portion of the island and to 18% in the remainder of Tongatapu.

Daily rainfall data was used to analyse rainwater catchments estimate the optimum combination of roof area and storage volume. From the analyses of 20 years of daily rainfall data for Tongatapu, rainwater catchments cannot be viewed as a viable option as a sole source of water supply for average households on Tongatapu. The use of rainwater as a supplementary source of water is a viable option for domestic potable water. Some of the islands of the Kingdom of Tonga are too small to sustain a permanent freshwater lens and rainwater is therefore the only practical alternative.

In general, there are adequate but not plentiful water resources for basic needs on most islands, particularly in the most populated islands. As has been the general practice, groundwater should be utilised as a first priority. The supplementary use of rainwater for potable purposes should be encouraged. Where surface water exists (for example, 'Eua and Niuafo'ou), it can be used to supplement groundwater supplies.

On islands with the largest populations the stress on the groundwater resources is the highest. Tongatapu has the greatest population and the greatest development of groundwater. In general the available information including salinity data from 1965 to 1991 has shown that groundwater pumping from the lens is not leading to a destruction of the freshwater lens. Localised problems are evident in the narrow western end of the island, near the coastline particularly in the south and northeast, and in the narrow part of the island between the Mu'a villages and Haveluliku. In all but the last case, the slight increase in salinity could be as a result of natural causes. There has generally been a slight increase in salinity of groundwater at the water table during the past decade but this is believed to be caused by the lower than average recharge.

Significantly, the pumping from the Mataki'eua/Tongamai wellfield which supplies Nuku'alofa with water does not indicate any long-term deleterious effect on the freshwater lens in that location. This observation must be regarded as preliminary as it is based on limited salinity information and only information at the surface of the lens. Unfortunately and despite the excellent recommendations of some previous authors on the subject of water resources, a proper monitoring programme was not established until recently. In particular the recommendation of Lao (1985) concerning the need for monitoring boreholes which can provide vertical salinity profile information through the lens have gone unheeded. Now there is the opportunity to install such monitoring systems at selected locations.

The main islands in the Ha'apai group, particularly Lifuka show the effects of inappropriate pumping. The pumping at the Tonga Water Board wells is at too high a rate for the very thin freshwater zone and at those locations which has resulted in saltwater upconing at the wells. The lens can recover as has been shown when the pumps at wells are not used for some months, particularly if high recharge is experienced. For these islands which are much smaller than Tongatapu, it is considered that pump rates per well should not exceed 0.5 litres per second (L/s). On Lifuka, any further pumping wells should be sited closer to the western side of the island than the sites of the two Tonga Water Board wells.

In general the existing groundwater development on Vava'u has not caused any significant problems. However, the pump rates at the Neiafu wellfield on Vava'u island should be closely monitored as recent salinity readings indicate that the sustainable yield at this location may have been exceeded. Further water supply demands should be met by a new wellfield towards the centre of the island, about 2 km north of the existing wellfield.

It is essential that an ongoing monitoring programme be established throughout the Kingdom of Tonga, particularly in those areas where the greatest demands are made on the available water resources. Salinity measurements of the groundwater taken at the water table and very limited vertical salinity profiles taken at a number of sites on Tongatapu and on Lifuka in the Ha'apai group have shown their usefulness as a primary means of ongoing monitoring of the groundwater resources. Simple electrical conductivity meters have provided the salinity data for the monitoring programme established by the Hydrogeology Unit and will form an integral component of ongoing data collection.

It is essential that legislation be enacted to enable the freshwater resources of Tonga, particularly groundwater resources, to be properly managed including adequate planning, assessment, development, control, monitoring and protection. A Water Resources Act based on the draft prepared by Wilkinson (1985) should be prepared.

While electricity and diesel provide the main sources of power for water pumping, other alternatives (wind and solar) have also been tried. Wind powered pumping has not been generally successful due to damage to the towers in cyclones and severe weather. The towers are also susceptible to corrosion in the exposed marine environment. Extensive clearing of trees in some areas would be required to make wind pumping viable. For these reasons, the future of wind pumping in Tonga is doubtful.

Solar pumping has been tried with mixed success for a number of reasons, including poor initial selection of panel and pump combinations. Solar power does however provide a potential alternative to conventional power sources, particularly for relatively small pump rates. One of its potential disadvantages is that pumping can only occur for about one third of the 24 hour day which means that instantaneous pump rates must be about 3 times that of a continuously operating pump. In many circumstances, this mode of pumping will not adversely affect the quality of the groundwater. Solar pumping should be further evaluated particularly for the smaller water supply schemes.

8.2 Recommendations

It is recommended that:

1. Further groundwater and surface water investigations to obtain baseline water resources assessment data should be carried out in each of the island groups (refer to sections 5.1.9, 5.2.8, 5.3.9, 5.4.9 and 5.5.9).
2. Comprehensive water resources legislation in the form of a Water Resources Act should be drafted and introduced for the proper planning, assessment, development, control, monitoring and protection of water resources throughout the Kingdom of Tonga. The new legislation should use as a basis the draft legislation prepared by Wilkinson (1985) (refer to section 7).
3. The Water Resources Act should concentrate on issues related to water resources management and not be concerned with the details of water supply (such as metering, charging policy, etc.). It is recommended that water supply matters should be included into a revised Tonga Water Board Act or a new Water Supply Act.
4. The agency responsible for administering the Act should be the Ministry of Lands, Survey and Natural Resources. This Ministry is the agency with the necessary skills to monitor and protect the water resources of Tonga and accordingly it is appropriate that it should administer the provisions of the Act. A number of other agencies should be involved in supporting roles (refer to section 6.3).
5. The water resources monitoring programme started by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources be encouraged and strengthened to become a national monitoring programme. The monitoring programme should primarily be undertaken by the Hydrogeology Unit with supplementary information provided by the Tonga Water Board, Ministry of Health and Village Water Committees (refer to section 6).
6. Salinity measurements of the groundwater should be used as the primary means of groundwater monitoring and resource evaluation with other methods including measurements of water table movement as useful secondary approaches.
7. Monitoring systems to obtain vertical salinity profiles in the freshwater lenses on Tongatapu, Lifuka in the Ha'apai group and Vava'u island should be installed and/or monitored at regular intervals. Installation costs, primarily associated with drilling, should be funded, if necessary, by an aid donor (refer to sections 5.1.9, 5.3.9, 5.4.9 and 6.10.5).
8. The ground water resources database maintained by the Hydrogeology Unit should be expanded to include other water resources information including surface water flows, rainfall and climatic data. This will enable all water resources data to be stored centrally and allow data analysis to be undertaken in a more effective way. A major data input to the expanded database is the rainfall and climatic data collected by the Tonga Meteorological Service.
9. Comprehensive water resource databases used in Australia and elsewhere should be evaluated for use in Tonga for the collection, processing, archiving, analysing and reporting of water resources and related information (refer to section 6.10.2).
10. An additional staff member should be allocated to the Hydrogeology Unit to assist with the processing, archiving and analysis of hydrological and hydrogeological data (refer to section 6.10.1).
11. Additional computing resources including a personal computer, printer and ancillary equipment should be procured (refer to section 6.10.3).

12. Training of staff in the Hydrogeology Unit in hydrology and hydrogeology should be part of an ongoing programme of staff development and training. As there are no suitable courses in Tonga, overseas training will be required. In addition, training in the use of computers including standard software packages is required. Computer training should be provided locally (refer to section 6.10.4).
13. Future upgrading of groundwater wellfields should include monitoring systems to obtain vertical salinity profiles. As a guide one monitoring system should be installed for every 10 production wells (refer to section 5.1.9).
14. Water resources development should follow the principles outlined in section 8. Use should be made of groundwater as a primary source of water wherever possible.
15. Drilled wells should be used as the primary means of groundwater development. In general these should not be sited closer to the coast than 500 m.
16. Pumping from wells should be continuous, where possible, rather than intermittent to minimise the effects of pumping from the freshwater lenses.
17. The supplementary use of rainwater should also be encouraged. Future rainwater catchment analyses for Tonga should make use of simulation methods using the long daily rainfall records which are available from a number of stations throughout the Kingdom.
18. Conventional desalination plants are not considered to be an appropriate technology at present for general use in Tonga due mainly to their high operation and maintenance requirements. The operation of the desalination plants on Nomuka should be monitored by the Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources to determine if this type of technology is an appropriate long-term strategy for that island.
19. Solar pumping should be properly evaluated from a technical and economic viewpoint for water pumping particularly in the many water supply systems on the remote smaller islands of the Kingdom of Tonga.
20. After approximately two more years of data collection, the available data should be reviewed and analysed in order to refine the estimates of sustainable yield provided in this report. Subsequent reviews should be undertaken at intervals not exceeding five years.

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Appendix A

Monthly and annual rainfall, 1947-1991

(i) Nuku'alofa, Tongatapu

(ii) Pangai, Lifuka island, Ha'apai group

(iii) Neiafu, Vava'u island, Vava'u group

(iv) Niuatoputapu (Keppel)

(i) Monthly and annual rainfall (mm) at Nuku'alofa, Tongatapu, Jan 1947 - Feb 1991

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1947	118	248	94	73	84	74	142	69	287	115	32	272	1,608
1948	230	212	112	225	49	226	28	23	120	22	351	168	1,766
1949	243	217	201	210	24	26	103	203	66	83	7	251	1,634
1950	249	249	334	210	17	67	259	148	155	131	146	132	2,097
1951	202	564	304	104	127	72	104	26	187	42	21	3	1,756
1952	582	443	289	126	25	153	164	130	100	21	119	154	2,306
1953	128	198	193	288	69	116	49	36	23	39	72	115	1,326
1954	110	218	114	450	65	242	38	133	302	133	49	581	2,435
1955	197	83	388	78	61	64	122	122	38	103	289	220	1,765
1956	259	342	340	334	153	27	190	86	133	274	150	6	2,294
1957	401	447	131	48	74	242	69	147	94	47	62	70	1,832
1958	31	306	269	138	38	7	118	116	56	337	138	77	1,631
1959	203	61	366	118	114	84	56	273	184	192	41	106	1,798
1960	70	323	469	194	101	163	102	34	54	133	207	231	2,081
1961	372	228	242	112	47	58	83	152	89	65	202	66	1,716
1962	382	188	263	111	139	75	85	53	41	70	116	242	1,765
1963	145	147	227	69	203	102	60	150	107	135	11	24	1,380
1964	99	288	280	141	117	8	256	102	191	105	255	215	2,057
1965	397	289	211	40	210	31	67	131	76	129	178	17	1,776
1966	85	95	84	458	63	45	52	46	181	180	29	159	1,477
1967	189	105	243	203	55	25	63	32	152	147	25	15	1,254
1968	527	244	296	96	59	85	27	204	92	93	26	51	1,800
1969	177	296	348	85	22	43	136	17	132	50	52	5	1,363
1970	179	373	137	110	96	83	63	57	41	373	106	352	1,970
1971	187	210	248	176	188	36	18	112	198	131	368	783	2,655
1972	197	162	326	124	166	151	160	209	341	340	33	167	2,376
1973	35	256	205	303	37	103	108	25	207	112	343	294	2,028
1974	243	462	279	346	78	115	67	90	196	452	151	74	2,553
1975	203	83	174	163	140	135	95	160	84	133	322	54	1,746
1976	252	371	231	365	94	50	61	59	212	129	246	46	2,116
1977	377	284	266	43	46	17	73	130	56	17	6	48	1,363
1978	40	151	214	248	204	46	82	250	102	272	229	92	1,930
1979	115	77	261	183	208	243	75	237	271	60	133	159	2,022
1980	139	123	291	267	45	111	144	161	189	399	114	143	2,126
1981	60	98	118	72	102	94	23	56	66	54	90	41	874
1982	386	238	253	136	241	58	87	149	75	34	19	57	1,733

1983	37	102	73	9	26	69	118	66	41	108	24	165	838
1984	222	217	71	126	26	75	70	41	142	64	80	177	1,311
1985	97	162	212	54	102	140	56	27	28	53	3	429	1,363
1986	12	69	113	285	118	215	62	98	16	57	25	199	1,269
1987	57	204	169	17	85	35	54	17	25	40	41	157	901
1988	280	242	114	215	69	32	101	46	313	114	26	209	1,761
1989	143	726	168	153	221	47	131	55	95	140	173	111	2,163
1990	220	58	116	122	191	104	194	192	175	25	223	229	1,849
1991	325	251											

Summary of rainfall data, Nuku'alofa, Tongatapu, 1947 - 1990

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean (a)	204	238	224	169	100	91	96	106	130	131	121	163	1,770
Mean (b)	151	212	141	119	118	87	90	75	98	69	70	177	1,406
Maximum	582	726	469	458	241	243	259	273	341	452	368	783	2,655
Minimum	12	58	71	9	17	7	18	17	16	17	3	3	838
SD (c)	132	138	93	110	64	65	55	69	85	108	106	152	426
CV (d)	0.65	0.58	0.42	0.65	0.64	0.72	0.58	0.65	0.65	0.83	0.88	0.93	0.24

Notes:
(a) 44 year period 1947-1990
(b) 10 year period 1981-1990
(c) SD: Standard Deviation
(d) Cv: Coefficient of Variation (= SD/Mean): calculated using Mean (a)

(ii) Monthly and annual rainfall (mm) at Pangai, Lifuka, Ha'apai group, Jan 1947 - Feb 1991

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1947	201	189	313	109	177	105	115	99	201	88	16	254	1,867
1948	432	147	202	251	52	108	45	17	51	139	245	294	1,983
1949	259	270	212	171	16	38	238	114	203	255	20	285	2,081
1950	237	118	470	334	101	42	156	33	156	128	247	353	2,375
1951	233	336	330	165	74	12	57	11	308	50	26	14	1,616
1952	159	105	199	31	36	110	43	145	19	110	70	66	1,093
1953	125	238	350	330	100	173	65	32	12	27	25	76	1,553
1954	37	96	321	288	43	135	48	122	38	112	18	530	1,788
1955	147	182	428	234	233	87	71	178	86	69	98	373	2,186
1956	223	222	348	339	32	60	152	78	109	163	169	38	1,933
1957	649	300	508	88	161	187	217	202	31	41	101	156	2,641
1958	49	230	119	303	55	5	99	40	47	134	225	28	1,334
1959	512	35	313	177									
1960	125	130	234	155	21	73	94	111	34	42	70		
1961	290	262	432	69	185	39	193	118	34	98	201	102	2,023
1962	394	119	53	126	64	128	44	22	84	61	131	286	1,512
1963	182	218	550	99	110	27	26	214	34	69	40	49	1,618
1964	50	212	593	96	30	10	208	96	294	123	188	105	2,005
1965	213	360	217	137	104	22	35	122	208	120	134	52	1,724
1966	106	137	112	279	88	46	83	62	42	167	95	144	1,361
1967	123	168	329	190	146	18	52	12	49	294	26	66	1,473

1968	337	90	233	77	68	52	21	116	61	145	82	143	1,425
1969	274	134	496	111	14	18	148		7	89	199	56	
1970	183	302	214	326	224	106	20	13	91	21	351	252	2,103
1971	287	96	244	203	155	69	69	218	103	95	512	613	2,664
1972	170	141	476	332		110	102	226	283	316	33	44	
1973	88	310	230	332	29	116	178	63	227	114	226	101	2,014
1974	152	403	111	254	167	122	138	73	163	199	120	153	2,055
1975	281	265	207	74	161	75	191	144	85	135	380	313	2,311
1976	245	299	354	254	68	26	55	96	144	6	36		
1977	271	339	168	158	70	42	57	76	46	39	11	46	1,323
1978	123	145	308	170	161	15	2	245	137	41	73	33	1,453
1979	104	50	223	40	70	146	48	126	199	47	111	115	1,279
1980	61	61	402	204	0	91	92	174	75	79	92	154	1,485
1981	88	356	180	54	94	30	11	32	71	41	70	128	1,155
1982	261			436	217	54	59	74	156	14	24	80	
1983	15	68	177	21	48	8	59	21	95	157	61	96	826
1984	230	238	52	217	34	92	94	95	216	44	5	60	1,377
1985	35	236	238	130	35	116	231	66	38	13	4	172	1,314
1986	88	77	154	307	98	231	163	75	50	63	11	12	1,329
1987	21	110	352	2	47	41	64	103	6	0	3	385	1,134
1988	236	108	145	113	210	35	84	20	237	114	27	209	1,538
1989	131	486	348	437	430	74	38	41	97	96	134	221	2,533
1990	270	88	264	157	263	163	77	104	108	129	29	57	1,709
1991	442												

Summary of rainfall data, Pangai, Lifuka, Ha'apai group, 1947 - 1990													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Mean (a)	198	197	284	190	107	76	94	96	110	100	110	164	1,716
Mean (b)	138	196	212	187	148	84	88	63	107	67	37	142	1,435
Maximum	649	486	593	437	430	231	238	245	308	316	512	613	2,664
Minimum	15	35	52	2	0	5	2	11	6	0	3	12	826
SD (c)	131	107	132	111	86	54	64	64	83	72	112	141	450
CV (d)	0.66	0.54	0.47	0.59	0.80	0.72	0.68	0.67	0.76	0.72	1.02	0.86	0.26

Notes:

(a) 44 year period 1947-1990

(b) 10 year period 1981-1990

(c) SD: Standard Deviation

(d) Cv: Coefficient of Variation (= SD/Mean): calculated using Mean (a)

(e) Blank spaces indicate missing data

(iii) Monthly and annual rainfall (mm) at Neiafu, Vava'u island, Vava'u group, Jan 1947 - Dec 1990

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1947	316	103	657	55	161	287	134	73	90	172	65	312	2,425
1948	463	360	329	183	61	115	51	17	65	113	503	490	2,750
1949	199	98	364	133	47	14	103	148	192	148	39	363	1,848
1950	313	238	466	366	68	65	252	112	177	258	312	393	3,020
1951	255	277	457	129	116	114	42	28	330	59	29	58	1,894
1952	239	117	222	62	66	103	66	81	139	165	84	96	1,440
1953	126	134	252	300	53	92	111	14	12	54	75	58	1,281
1954	256	222	495	275	83	167	22	162	79	177	102	604	2,644
1955	109	193	384	91	139	393	322	236	188	247	244	182	2,728
1956	258	168	617	235	98	139	110	80	47	105	581	90	2,528
1957	759	491	126	259	65	173	157	99	44	11	108	346	2,638
1958	60	408	358	243	158	9	70	146	66	217	283	14	2,032
1959	191	128	610	231	129	101	66	68	456	251	60	50	2,341
1960	239	211	711	296	70	48	208	273	94	34	56	211	2,451
1961	470	127	799	144	176	67	102	138	119	118	218	415	2,893
1962	324	320	237	509	131	196	78	27	150	84	473	231	2,760
1963	105	438	359	200	202	20	118	177	78	112	75	186	2,070
1964	50	224	680	117	91	44	266	50	187	100	258	81	2,148
1965	362	261	327	204	206	56	42	60	109	247	80	29	1,983
1966	244	15	176	155	33	57	153	78	178	281	134	165	1,669
1967	1,009	311	213	438	240	97	61	44	81	314	81	65	2,954
1968	546	74	175	104	150	102	34	114	107	109	152	122	1,789
1969	132	248	284	267	7	16	78	12	158	192	38	178	1,610
1970	122	210	200	266	122	199	54	62	51	53	329	468	2,136
1971	173	415	189	251	370	49	80	125	174	206	169	456	2,657
1972	293	172	257	136	104	38	159	156	167	163	44	44	1,733
1973	159	443	393	304	31	57	467	109	197	115	333	310	2,918
1974	178	642	229	363	425	163	71	108	80	83	313	164	2,819
1975	495	344	303	120	91	158	300	228	105	66	483	269	2,962
1976	357	334	207	208	91	16	47	87	75	62	255	133	1,872
1977	239	297	493	71	134	36	218	127	39	35	12	65	1,766
1978	472	204	418	178	224	77	11	267	173	215	112	217	2,568
1979	135	215	395	270	209	288	51	133	70	359	149	154	2,428
1980	162	161	343	368	69	84	84	202	197	76	91	104	1,941
1981	138	461	312	210	314	83	61	75	91	120	117	146	2,128
1982	611	420	368	473	177	56	73	199	151	17	115	213	2,873
1983	173	218	480	42	78	20	34	21	51	42	86	520	1,765
1984	172	276	126	410	56	34	71	77	199	28	42	308	1,799
1985	143	340	408	206	124	81	160	30	36	38	16	147	1,729
1986	92	80	186	277	80	451	99	66	189	159	18	60	1,757
1987	5	224	152	27	298	135	49	127	25	26	72	586	1,726
1988	292	99	142	187	191	115	58	25	332	145	319	230	2,135
1989	367	630	283	127	213	28	28	9	81	166	188	658	2,778
1990	255	159	82	192	210	262	160	18	167	84	29	202	1,820

Summary of rainfall data, Neiafu, Vava'u island, Vava'u group, 1947-1990													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean (a)	274	264	353	221	138	108	112	104	131	134	170	232	2,242
Mean (b)	216	291	280	233	160	109	72	83	135	82	106	297	2,063
Maximum	1,009	642	799	509	425	451	467	273	456	359	581	658	3,020
Minimum	5	15	126	27	7	9	11	9	12	11	12	14	1,281
SD (c)	196	144	169	117	91	97	94	70	88	87	146	173	487
CV (d)	0.71	0.55	0.48	0.53	0.66	0.90	0.83	0.67	0.68	0.65	0.86	0.74	0.22

Notes:
(a) 44 year period 1947-1990
(b) 10 year period 1981-1990
(c) SD: Standard Deviation
(d) Cv: Coefficient of Variation (= SD/Mean): calculated using Mean (a)

(iv) Monthly and annual rainfall (mm) at Niuatoputapu (Keppel), Jan 1947 - Dec 1990

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1947	295	320	237	133	347	191	215	55	113	99	299	444	2,748
1948	375	636	157	416	109	127	75	37	30	122	176	338	2,598
1949	155	197	433	235	281	48	151	204	142	449	23	226	2,544
1950	215	223	312	80	275	70	178	49	87	135	288	323	2,235
1951	312	92	170	195	113	135	74	6	159	61	324	156	1,797
1952	269	89	227	161	217	63	108	60	167	346	148	258	2,113
1953	521	187	267	302	139	94	69	6	60	212	81	125	2,063
1954	183	266	253	271	275	231	37	293	137	164	204	272	2,586
1955	194	160				98	131						
1956	471	571	396	109	21	265	138	33	44	62	507	86	2,703
1957	537	379	398	315	195	33	65	42	35	26	87	266	2,378
1958	177	241	252	223	168	53	172	166	79	286	261	72	2,150
1959	229	389	438	52	138	40	145	96	200	292	511	163	2,693
1960	441	216	509	159	152	56	147	51	39	111	178	584	2,643
1961	108	165	419	71	46	75	46	78	101	90	291	353	1,843
1962	399	351	227	209	177	219	102	173	193	202	165	243	2,660
1963	232	223	394	104	91	169	134	78	13	156	137	111	1,842
1964	121	64	179	200	114	50	169	24	350	101	248	148	1,768
1965	105	236	157	330	173	73	43	7	55	131	62	63	1,435
1966	297	20	68		129	105	149	156	44	245	499	107	
1967	324	266	226	564	216	139	186	138	202	414	122	240	3,037
1968	448	477	113	220	140	77	34	144	118	258	59	45	2,133
1969	205	205	188	577	13	26	79	83	150	67	182	140	1,915
1970	72	156	417	372	107	113	137	81	45	133	211	648	2,492
1971	197	312	151	311	325	221	93	55	507	348	99	500	3,119
1972	299	204	444	192	162	186	59	44	346	412	264	368	2,980
1973	152	278	193	411	280	37	542	139	180	295	436	166	3,109
1974	290	431	288	85	189	114	27	54	125	199	323	225	2,350
1975	332	192	224	588	116	51	99	162	117	105	156	239	2,381
1976	218	190	173	174	158	355	130	22	31	9	309	217	1,986
1977	270	206	503	232		88	88	27	147	125	81	41	

1978	236	72	580		266	54	4	148	134	196	306	226	
1979	285	260	443		112	259	233	95	341	266	183	346	
1980	225	84			53	205	71	157	173	141	152	220	
1981	134	277	144	264	133	168	18	83	19	221	183	160	1,804
1982	518	224	71	125	120	24	166	66	165	39	294	24	1,836
1983	162	221	436	57	102	51	45	20	37	129	228	186	1,674
1984	308	290	398	289	126	204	69	67	53	71	55	250	2,180
1985	501	304	215	248	131	34	53	125	17	67	37	69	1,801
1986	252	92	122	631	153	78	173	68	153	77	87	287	2,173
1987	61	267	245	148	117	91	40	35	2	37	37	462	1,542
1988	257	226	184	469	325	154	147	77	307	249	290	278	2,963
1989	296	462	258	304	66	51	18	44	35	343	348	254	2,479
1990	243	236	362	116	136	43	194	62	97	154	218	416	2,277

Summary of rainfall data, Niuatoputapu (Keppel), 1947-1990													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Mean (a)	271	249	283	255	160	114	115	84	129	178	213	241	2,290
Mean (b)	273	260	244	265	141	90	92	65	89	139	178	239	2,073
Maximum	537	636	580	631	347	355	542	293	507	449	511	648	3,119
Minimum	61	20	68	52	13	24	4	6	2	9	23	24	1,435
SD (c)	123	129	131	154	81	78	88	61	108	114	128	144	455
CV (d)	0.45	0.52	0.46	0.60	0.51	0.69	0.77	0.73	0.84	0.64	0.60	0.60	0.20

Notes:

(a) 44 year period 1947-1990

(b) 10 year period 1981-1990

(c) SD: Standard Deviation

(d) Cv: Coefficient of Variation (= SD/Mean): calculated using Mean (a)

(e) Blank spaces indicate missing data

Appendix B

Annual rainfall, 1927-1990

Year	Nuku'alofa	Ha'apai	Vava'u	Niuatoputapu
1927	1,890			
1928	1,489			
1929	1,801			
1930	1,033			
1931	1,765			
1932	1,832	1,338		
1933	1,434			2,756
1934	1,445	1,619	1,898	2,758
1935	1,681	1,618	2,182	3,104
1936	1,969	1,749	1,935	2,155
1937				
1938	1,532	1,549	1,976	2,734
1939	1,650	1,788	2,079	3,086
1940	1,221	1,291	1,222	1,824
1941				
1942				
1943				
1944				
1945	1,282			
1946	1,516			
1947	1,608	1,867	2,425	2,748
1948	1,766	1,983	2,750	2,798
1949	1,634	2,081	1,848	2,544
1950	2,097	2,375	3,020	2,235
1951	1,756	1,616	1,894	1,797
1952	2,246	1,093	1,440	2,113
1953	1,316	1,553	1,281	2,062
1954	2,435	1,788	2,644	2,606
1955	1,765	2,186	2,708	
1956	2,294	1,933	2,528	2,703
1957	1,832	2,641	2,638	2,378
1958	1,631	1,334	2,032	2,090
1959	898	1,852	2,341	2,693
1960	2,081	1,260	2,451	2,643
1961	1,716	2,023	2,893	1,843
1962	1,765	1,512	2,760	2,660
1963	1,380	1,618	2,070	1,842
1964	2,057	2,005	2,148	1,768
1965	1,776	1,724	1,983	1,435
1966	1,477	1,361	1,669	
1967	1,254	1,473	2,954	3,037
1968	1,800	1,425	1,789	2,133
1969	1,363	1,658	1,610	1,915
1970	1,970	2,103	2,136	2,492
1971	2,655	2,664	2,657	3,119
1972	2,376	2,328	1,733	2,980

1973	2,028	2,014	2,918	3,109
1974	2,553	2,055	2,819	2,350
1975	1,746	2,311	2,962	2,581
1976	2,116	1,754	1,872	1,986
1977	1,363	1,323	1,766	
1978	1,930	1,453	2,568	
1979	2,022	1,279	2,428	
1980	2,126	1,485	1,941	
1981	874	1,155	2,128	1,804
1982	1,733	1,827	2,873	1,836
1983	838	826	1,765	1,684
1984	1,311	1,377	1,799	2,180
1985	1,363	1,314	1,729	1,837
1986	1,269	1,329	1,757	2,173
1987	901	1,134	1,726	1,542
1988	1,761	1,538	2,135	2,963
1989	2,163	2,533	2,778	2,479
1990	1,849	1,709	1,820	2,277

Notes

1. data prior to 1947 is from Taylor (1963), An atlas of Pacific islands rainfall
2. data from 1947 to 1990 is from New Zealand and Tonga Meteorological Service records

Appendix C

Mean monthly potential evaporation estimates and summary of climatic data

(i) Nuku'alofa, Tongatapu

(ii) Pangai, Lifuka island, Ha'apai group

(iii) Neiafu, Vava'u island, Vava'u group

(iv) Niuatoputapu (Keppel)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tongatapu	164	137	139	108	89	77	85	96	116	144	152	154	1,461
Ha'apai	161	144	145	113	103	89	101	109	121	145	156	161	1,548
Vava'u	151	134	135	112	103	90	99	108	117	142	151	159	1,501
Niuatoputapu	149	130	138	112	108	99	106	116	129	143	148	152	1,530

Note: data from Table 25 of Thompson (1986), The climate and weather of Tonga.

Summary of Climatic Data

Nuku'alofa			**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Air Temp	Mean	ºC	25.9	26.3	26.1	25.0	23.3	22.5	21.4	21.3	21.8	22.6	23.7	25.0	23.7
	Max	ºC	28.9	29.3	29.0	28.2	26.6	25.7	24.6	24.6	25.0	25.8	27.0	28.2	26.9
	Min	ºC	22.8	23.2	23.1	21.8	20.0	19.3	17.9	18.0	18.6	19.4	20.6	21.8	20.5
Vapour Pressure		hPa	27.8	29.3	28.5	26.2	23.7	22.7	19.8	20.1	20.8	21.2	23.0	26.2	24.1
Sunshine		hrs	201	179	178	170	165	156	156	169	162	176	200	200	2,112
Wind Run		km/day	445	401	401	312	356	356	356	356	401	401	445	401	386
Penman ET		mm	164	137	139	108	89	77	85	96	116	144	152	154	1,461

Ha'apai			**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Air Temp	Mean	ºC	26.4	26.9	26.6	25.9	24.5	24.0	23.0	22.6	23.2	23.9	24.8	25.6	24.8
	Max	ºC	29.3	29.8	29.4	28.8	27.2	26.7	25.7	25.5	26.0	26.6	27.6	28.5	27.6
	Min	ºC	23.6	23.9	23.8	22.8	21.7	21.3	20.1	19.7	20.3	21.1	22.0	22.8	21.9
Vapour Pressure		hPa	27.7	28.3	27.6	26.5	24.2	23.2	20.5	20.7	21.5	22.8	24.4	26.1	24.5
Sunshine		hrs	197	178	192	170	175	163	160	170	172	183	196	195	2,151
Wind Run		km/day	356	356	356	267	401	356	401	401	356	401	445	401	375
Penman ET		mm	161	144	145	113	103	89	101	109	121	145	156	161	1,548

Vava'u			**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Air Temp	Mean	ºC	26.7	26.9	26.6	26.1	25.1	24.4	23.4	23.3	23.9	24.6	25.4	26.1	25.2
	Max	ºC	29.8	30.2	29.9	29.3	28.0	27.4	26.5	26.6	27.1	27.6	28.5	29.2	28.3
	Min	ºC	23.4	23.5	23.2	22.9	21.8	21.3	20.3	20.0	20.8	21.5	22.3	22.9	22.0
Vapour Pressure		hPa	27.9	28.8	27.9	26.9	24.4	23.5	21.7	22.0	23.7	23.6	25.4	26.8	25.2
Sunshine		hrs	196	178	192	171	176	164	161	171	172	182	194	193	2,150
Wind Run		km/day	223	223	223	223	312	312	356	356	312	312	356	267	289
Penman ET		mm	151	134	135	112	103	90	99	108	117	142	151	159	1,501

Niuatoputapu (Keppel)			**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Air Temp	Mean	ºC	27.3	27.4	27.2	27.0	26.5	26.1	25.6	25.5	25.8	26.1	26.4	26.9	26.5
	Max	ºC	30.3	30.4	30.6	30.2	29.5	29.0	28.4	28.4	28.8	29.0	29.4	29.9	29.5
	Min	ºC	25.1	25.2	25.1	25.1	24.4	24.1	23.5	23.2	23.7	23.9	23.3	24.8	24.3
Vapour Pressure		hPa	29.7	31.2	29.8	29.8	28.5	26.9	24.8	25.0	25.6	26.9	27.8	28.6	27.9
Sunshine		hrs	190	173	203	172	182	184	177	186	186	189	196	191	2,229
Wind Run		km/day	223	223	223	178	312	312	312	312	312	312	312	276	275
Penman ET		mm	149	130	138	112	108	99	106	116	129	143	148	152	1,530

Note: data taken from Hasan (1989); originally from Thompson (1986)

Appendix D

Monthly and annual pan evaporation data from Vaini Research Farm, Tongatapu, 1982 - 1989

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1982	95	252	145	126	128	88	107	119	155	182	266	243	1,906
1983	238	171		151	148	99	162	134	160	220	201	157	
1984	168	83	126	109	110	94	102	116	139	177	170	156	1,550
1985	182	147	119	132	100	92	82	141	148	166			
1986	190	174	142	113	100	79	103	123	128	165	182	206	1,705
1987	196	158	165	170	131	97	125	141	138	205	172	186	1,884
1988	181	190	155	131	101	101	148	114	285	183	197	164	1,950
1989	178	123	129	156	105	93	107	125	135	150	185	198	1,684
Mean	**179**	**162**	**140**	**136**	**115**	**93**	**117**	**127**	**161**	**181**	**196**	**187**	**1,780**

Appendix E

Data from recently installed salinity monitoring boreholes on Tongatapu and Lifuka (Ha'apai group)

(a) Tongatapu

As mentioned in section 5.1.4 and 5.1.7, four specially constructed salinity monitoring boreholes were drilled: three between Mataki'eua and Fanga'Uta lagoon (well numbers 223, 224 and 225) and one (well number 222) in Fualu quarry (refer Figure 5.1 for locations).

These wells were constructed by installing open ended 20 mm PVC conduits to different depths inside a standard drilled hole (190 mm hole) and then backfilling the hole with sand. The last 300 mm of each PVC conduit was slotted. This method of well construction enables the water occurring at the bottom of each of the PVC conduits to be tested for salinity by lowering an electrical conductivity probe. Salinity readings at the base of each conduit can be plotted to obtain a salinity profile showing depth below surface against electrical conductivity.

Tabulated below are the results of salinity tests at each of the four salinity monitoring boreholes.

Depth (m) / electrical conductivity (μS/cm) in salinity monitoring boreholes on Tongatapu

Date	Well number			
	222	223	224	225
6th April 1991				
WL(m):	0.40	5.81	5.86	9.36
	1 / 460	7 / blocked	7 / 1,060	11 / 1,940
	5 / 720	11 / 910	9 / blocked	17 / 2,210
	10 / 3,550	12 / 2,290		22 / 12,030
	14 / 5,000	21 / 27,510		
	17 / 9,700			
17th July 1991				
WL(m):	0.50	9.29	6.49	9.89
	1 / 582	7 / blocked	7 / 836	11 / lost
	7 / 503	11 / 623	9 / blocked	17 / 1,004
	10 / 2,560	16 / 712		22 / 13,300
	14 / 3,730	21 / 24,700		
	17 / 12,140			
26th September 1991				
	all destroyed	7 / 830	7 / 830	11 / lost
		11 / 910	9 / blocked	17 / 1,148
		16 / 1,595		22 / destroyed
		21 / 23,400		

Note: WL(m) refers to the depth to water table below ground level

In addition to the four salinity monitoring boreholes mentioned above, other similar wells have either recently been drilled or are proposed to be drilled on Tongatapu.

(b) Lifuka

As mentioned in sections 5.3.4 and 5.3.7, six specially constructed salinity monitoring boreholes were drilled. These were similar in construction to those on Tongatapu except for monitoring borehole number 5 which consisted of one fully slotted PVC pipe.

Results of salinity tests at each of the six salinity monitoring boreholes are tabulated below.

Depth (m) / electrical conductivity (µS/cm)
in Lifuka salinity monitoring boreholes, 2nd September 1991

	Salinity monitoring borehole number					
	1	**2**	**3**	**4**	**5**	**6**
WL(m):	4.08	3.88	3.75	5.02	13.25	3.90
	4/dry	4.45/dry	4/dry	4/dry	13.75/13360	4/790
	6/2180	6/3620	6/2980?	6/1506	14.25/18190	6/13730?
	9/3870	9/5660	9/1238	9/1938	14.75/19130	9/5400
	12/10410	11.2/11870	12/2360	12/3780	15.25/19330	12/15430

Note: WL(m) refers to the depth to water table below ground level

Appendix F

Water quality and level monitoring information, Tongatapu

(from dbase file TBUWELLS.DBF)

Well No	Date	Depth to water (m)	Electrical Conductivity (µS/cm)	Temperature (ºC)	pH	Pump status (TRUE = ON, FALSE = OFF)
2	26/07/1990	0.00	1,184	22.6	7.97	FALSE
4	12/04/1990	0.00	760	0.0	0.00	FALSE
4	2/11/1990	24.32	693	25.0	7.31	FALSE
5	1/01/1987	0.00	1,040	0.0	0.00	FALSE
5	23/05/1990	0.00	1,235	26.8	0.00	FALSE
5	7/08/1990	13.98	1,365	25.1	7.73	FALSE
7	31/10/1990	12.81	0	0.0	0.00	FALSE
8	1/01/1987	0.00	350	0.0	0.00	FALSE
8	23/05/1990	0.00	670	28.7	0.00	TRUE
8	24/07/1990	32.14	650	24.6	7.53	FALSE
8	2/11/1990	0.00	619	25.9	7.90	TRUE
10	1/01/1987	0.00	350	0.0	0.00	FALSE
10	2/03/1990	0.00	670	0.0	0.00	TRUE
10	24/07/1990	44.30	570	23.2	8.08	FALSE
10	2/11/1990	44.29	556	24.7	7.50	FALSE
10	22/01/1991	44.26	594	23.2	7.10	FALSE
12	6/06/1990	0.00	570	26.9	0.00	TRUE
13	1/07/1979	35.95	880	24.0	0.00	FALSE
13	1/01/1987	0.00	670	0.0	0.00	FALSE
13	12/04/1990	0.00	980	0.0	0.00	FALSE
13	24/07/1990	35.89	969	24.6	7.47	FALSE
13	2/11/1990	35.96	595	31.1	7.27	TRUE
13	21/01/1991	35.95	880	27.6	7.14	FALSE
14	3/02/1965	0.00	800	0.0	0.00	FALSE
14	1/02/1971	29.60	880	0.0	0.00	FALSE
14	1/07/1979	29.32	1,000	25.0	0.00	FALSE
14	1/03/1980	29.25	1,000	25.0	0.00	FALSE
14	1/05/1981	29.20	1,000	24.5	0.00	FALSE
14	1/04/1983	29.55	1,200	24.0	0.00	FALSE
14	1/01/1987	0.00	900	0.0	0.00	FALSE
14	1/06/1990	0.00	1,070	27.6	0.00	TRUE
15	2/03/1990	0.00	1,300	0.0	0.00	TRUE
15	24/07/1990	31.07	0	0.0	0.00	FALSE
15	21/01/1991	0.00	1,187	26.1	7.50	TRUE
17	1/05/1978	28.20	1,950	25.0	0.00	FALSE
17	1/07/1979	28.20	2,150	25.0	0.00	FALSE
17	1/03/1980	28.00	2,100	24.0	0.00	FALSE
17	1/05/1981	28.15	2,350	24.5	0.00	FALSE
17	1/04/1983	28.10	2,300	24.0	0.00	FALSE
17	1/01/1987	0.00	2,860	0.0	0.00	FALSE
17	1/06/1990	0.00	2,510	27.3	0.00	TRUE
17	24/07/1990	27.88	3,010	25.0	7.48	TRUE
18	1/02/1971	10.78	1,580	0.0	0.00	FALSE
18	2/03/1990	0.00	2,050	0.0	0.00	TRUE
18	24/07/1990	10.73	1,520	24.9	7.80	FALSE
18	31/10/1990	10.80	1,300	26.0	7.29	FALSE
19	4/02/1965	0.00	1,100	0.0	0.00	FALSE

19	1/07/1979	9.20	0	0.0	0.00	FALSE
19	1/03/1980	9.20	1,050	24.5	0.00	FALSE
19	1/05/1981	9.35	1,990	24.0	0.00	FALSE
19	1/04/1983	9.38	1,800	24.0	0.00	FALSE
19	1/01/1987	0.00	1,870	0.0	0.00	FALSE
19	1/05/1987	0.00	5,400	0.0	0.00	FALSE
19	24/07/1990	9.12	2,580	24.9	7.80	TRUE
19	31/10/1990	9.20	1,968	25.7	7.40	TRUE
19	21/01/1991	9.15	1,921	25.7	7.27	TRUE
21	1/06/1990	0.00	2,450	28.5	0.00	TRUE
21	24/07/1990	9.82	291	24.8	8.25	FALSE
22	26/07/1990	0.00	1,383	24.7	7.83	FALSE
22	7/11/1990	8.67	1,233	25.7	7.29	FALSE
23	8/03/1965	24.57	550	0.0	0.00	FALSE
23	1/02/1971	24.57	600	0.0	0.00	FALSE
23	1/06/1990	0.00	1,736	25.5	0.00	TRUE
23	26/07/1990	24.42	1,802	24.7	7.90	FALSE
23	6/11/1990	24.42	1,260	36.1	7.48	FALSE
23	22/01/1991	0.00	1,150	26.9	7.23	FALSE
26	1/06/1990	0.00	1,820	26.0	0.00	TRUE
26	6/11/1990	27.15	1,490	25.6	7.43	FALSE
27	31/08/1965	0.00	670	0.0	0.00	FALSE
27	1/02/1971	4.55	690	0.0	0.00	FALSE
27	1/07/1979	4.10	900	24.5	0.00	FALSE
27	1/03/1980	4.45	500	24.0	0.00	FALSE
27	1/05/1981	4.60	600	24.0	0.00	FALSE
27	1/04/1983	4.52	700	24.0	0.00	FALSE
27	1/01/1987	0.00	940	0.0	0.00	FALSE
27	1/06/1990	0.00	1,260	27.1	0.00	TRUE
27	26/07/1990	4.43	1,266	25.0	7.65	TRUE
27	2/11/1990	4.51	1,143	25.3	7.30	TRUE
27	22/01/1991	4.48	1,123	28.3	6.64	FALSE
28	1/06/1990	0.00	1,346	26.9	0.00	TRUE
28	26/07/1990	4.08	1,341	24.5	7.67	FALSE
28	2/11/1990	4.16	1,255	27.1	6.76	TRUE
29	1/06/1990	0.00	952	26.4	0.00	TRUE
29	26/07/1990	4.32	1,002	24.5	7.51	FALSE
29	2/11/1990	4.41	993	25.0	7.16	FALSE
30	1/03/1980	15.10	1,100	24.5	0.00	FALSE
30	1/05/1981	15.10	1,100	24.0	0.00	FALSE
30	1/04/1983	15.15	1,000	24.5	0.00	FALSE
30	1/06/1990	0.00	1,035	26.8	0.00	TRUE
32	1/01/1987	0.00	400	0.0	0.00	FALSE
32	1/06/1990	0.00	779	26.3	0.00	TRUE
33	1/06/1990	0.00	664	25.5	0.00	TRUE
33	2/11/1990	21.38	580	25.6	7.44	TRUE
34	24/07/1990	21.35	0	0.0	0.00	FALSE
35	15/06/1965	0.00	620	0.0	0.00	FALSE
35	1/02/1971	0.00	900	0.0	0.00	FALSE
35	1/03/1980	5.80	850	24.4	0.00	FALSE
35	1/05/1981	5.81	850	24.0	0.00	FALSE
35	1/04/1983	5.83	900	24.0	0.00	FALSE
35	1/01/1987	0.00	1,850	0.0	0.00	FALSE
35	1/06/1990	0.00	2,340	27.9	0.00	TRUE
35	31/10/1990	0.00	2,110	28.4	7.57	TRUE
36	1/06/1990	0.00	2,490	33.2	0.00	TRUE

37	1/06/1990	0.00	2,320	34.0	0.00	TRUE
38	1/06/1990	0.00	430	0.0	0.00	TRUE
38	31/10/1990	0.00	3,350	26.1	7.84	FALSE
39	1/01/1987	0.00	600	0.0	0.00	FALSE
39	23/05/1990	0.00	770	28.0	0.00	TRUE
39	24/07/1990	0.00	776	23.1	7.83	FALSE
41	1/01/1987	0.00	550	0.0	0.00	FALSE
42	3/02/1965	0.00	620	0.0	0.00	FALSE
42	1/02/1971	42.77	620	0.0	0.00	FALSE
42	1/07/1979	42.45	800	25.0	0.00	FALSE
42	1/03/1980	0.00	850	24.0	0.00	FALSE
42	1/05/1981	42.75	850	24.0	0.00	FALSE
42	1/04/1983	42.70	950	24.0	0.00	FALSE
42	1/01/1987	0.00	600	0.0	0.00	FALSE
42	23/05/1990	0.00	875	28.9	0.00	TRUE
42	24/07/1990	42.45	838	24.9	7.49	FALSE
42	2/11/1990	42.50	760	25.4	7.40	FALSE
43	23/05/1990	0.00	790	30.7	0.00	TRUE
43	2/11/1990	0.00	560	24.9	7.63	FALSE
44	7/08/1990	25.18	691	34.8	7.83	FALSE
44	2/11/1990	25.14	660	38.3	7.57	FALSE
45	5/07/1963	0.00	960	0.0	0.00	FALSE
45	1/02/1971	19.76	1,080	0.0	0.00	FALSE
45	1/05/1978	19.46	0	0.0	0.00	FALSE
45	1/03/1980	19.80	1,300	24.0	0.00	FALSE
45	1/05/1981	20.01	1,300	24.0	0.00	FALSE
45	1/04/1983	20.01	1,300	24.5	0.00	FALSE
45	1/10/1986	0.00	620	0.0	0.00	FALSE
45	1/01/1987	0.00	660	0.0	0.00	FALSE
45	23/05/1990	0.00	1,800	0.0	0.00	TRUE
45	20/07/1990	19.45	1,247	0.0	0.00	FALSE
45	23/07/1990	19.47	1,780	24.5	7.42	TRUE
45	31/10/1990	19.46	1,516	26.8	7.49	TRUE
45	21/01/1991	19.52	1,205	26.0	6.94	FALSE
46	11/02/1970	0.00	1,820	0.0	0.00	FALSE
46	1/02/1971	7.52	1,970	0.0	0.00	FALSE
46	1/03/1980	7.48	1,850	25.0	0.00	FALSE
46	1/05/1981	7.48	1,500	24.5	0.00	FALSE
46	1/04/1983	7.50	1,555	24.0	0.00	FALSE
46	1/05/1987	0.00	1,100	0.0	0.00	FALSE
46	27/05/1990	0.00	3,280	0.0	0.00	TRUE
46	23/07/1990	7.57	3,340	24.6	7.64	FALSE
46	21/01/1991	7.54	1,979	24.6	7.00	FALSE
47	1/07/1979	7.68	1,550	24.0	0.00	FALSE
47	1/03/1980	7.65	1,500	24.0	0.00	FALSE
47	1/05/1981	7.65	1,500	24.5	0.00	FALSE
47	1/04/1983	7.68	1,450	24.0	0.00	FALSE
47	1/01/1987	0.00	1,390	0.0	0.00	FALSE
47	1/05/1987	0.00	3,020	0.0	0.00	FALSE
47	27/05/1990	0.00	1,733	27.7	0.00	TRUE
47	24/07/1990	7.67	1,800	24.9	7.59	FALSE
47	31/10/1990	7.78	1,577	26.3	7.21	TRUE
47	21/01/1991	7.71	1,381	25.3	6.90	FALSE
48	2/09/1965	0.00	620	0.0	0.00	FALSE
48	1/02/1971	3.78	720	0.0	0.00	FALSE
48	1/07/1979	3.57	0	0.0	0.00	FALSE

48	1/03/1980	0.00	950	23.0	0.00	FALSE
48	1/05/1981	3.56	1,100	24.5	0.00	FALSE
48	1/04/1983	3.55	1,000	24.0	0.00	FALSE
48	1/01/1987	0.00	970	0.0	0.00	FALSE
48	1/05/1987	0.00	980	0.0	0.00	FALSE
48	27/05/1990	0.00	1,080	28.2	0.00	TRUE
48	31/10/1990	3.64	1,162	25.1	7.26	FALSE
48	21/01/1991	3.64	1,080	26.5	6.95	FALSE
49	27/05/1990	0.00	1,080	36.0	0.00	TRUE
49	31/10/1990	4.60	767	25.5	7.30	FALSE
50	20/07/1990	22.56	802	25.3	0.00	FALSE
50	21/01/1991	0.00	1,426	29.1	7.46	FALSE
51	31/10/1990	0.00	1,580	26.1	7.26	FALSE
52	4/02/1965	0.00	1,730	0.0	0.00	FALSE
52	1/02/1971	0.00	2,190	0.0	0.00	FALSE
52	1/03/1980	6.50	1,600	23.5	0.00	FALSE
52	1/05/1981	6.63	1,600	24.5	0.00	FALSE
52	1/04/1983	6.60	1,600	24.0	0.00	FALSE
52	1/05/1987	0.00	4,800	0.0	0.00	FALSE
52	1/05/1987	0.00	7,600	0.0	0.00	FALSE
52	27/05/1990	0.00	3,300	27.7	0.00	TRUE
52	23/07/1990	6.75	3,360	24.7	7.46	FALSE
52	31/10/1990	6.75	0	0.0	0.00	FALSE
52	21/01/1991	6.63	2,760	25.4	6.81	TRUE
53	27/05/1990	0.00	1,378	28.9	0.00	TRUE
54	10/02/1970	0.00	620	0.0	0.00	FALSE
54	1/02/1971	12.52	830	0.0	0.00	FALSE
54	1/03/1980	12.36	1,000	24.5	0.00	FALSE
54	1/05/1981	12.60	1,100	24.0	0.00	FALSE
54	1/04/1983	12.62	1,100	24.5	0.00	FALSE
54	1/01/1987	0.00	1,260	0.0	0.00	FALSE
54	27/05/1990	0.00	1,645	28.8	0.00	TRUE
54	24/07/1990	12.42	1,580	24.9	7.49	FALSE
54	31/10/1990	12.51	1,163	25.3	7.33	FALSE
54	22/01/1991	12.47	1,357	26.2	6.62	FALSE
55	1/03/1980	12.40	950	24.5	0.00	FALSE
55	1/05/1981	12.40	1,000	24.0	0.00	FALSE
55	1/04/1983	12.40	1,000	24.5	0.00	FALSE
55	1/01/1987	0.00	810	0.0	0.00	FALSE
55	27/05/1990	0.00	1,100	29.4	0.00	TRUE
55	24/07/1990	12.20	1,095	24.5	7.04	FALSE
55	21/01/1991	12.22	975	25.9	7.11	FALSE
56	20/07/1990	14.22	1,321	0.0	0.00	FALSE
57	20/07/1990	7.67	1,209	24.6	0.00	FALSE
57	31/10/1990	0.00	1,502	32.9	6.99	TRUE
58	1/01/1987	0.00	990	0.0	0.00	FALSE
58	27/05/1990	0.00	1,090	41.5	0.00	TRUE
59	1/01/1987	0.00	1,070	0.0	0.00	FALSE
59	1/05/1987	0.00	2,580	0.0	0.00	FALSE
59	27/05/1990	0.00	1,310	36.1	0.00	TRUE
59	31/10/1990	0.00	1,251	25.8	7.58	FALSE
60	27/05/1990	0.00	1,300	37.1	0.00	TRUE
60	31/10/1990	0.00	1,244	32.0	7.34	TRUE
61	2/09/1965	0.00	700	0.0	0.00	FALSE
61	1/02/1971	0.00	1,150	0.0	0.00	FALSE
61	1/03/1980	17.58	1,000	24.0	0.00	FALSE

61	1/05/1981	17.70	1,000	24.5	0.00	FALSE
61	1/04/1983	17.70	1,000	24.0	0.00	FALSE
61	1/01/1987	0.00	1,090	0.0	0.00	FALSE
61	1/05/1987	0.00	2,500	0.0	0.00	FALSE
61	23/07/1990	17.76	1,290	25.0	7.44	FALSE
61	31/10/1990	17.79	0	0.0	0.00	FALSE
61	21/01/1991	17.76	1,157	25.6	6.91	FALSE
62	1/01/1987	0.00	3,600	0.0	0.00	FALSE
62	1/05/1987	0.00	3,800	0.0	0.00	FALSE
62	27/05/1990	0.00	2,250	32.9	0.00	TRUE
62	23/07/1990	2.12	1,900	27.8	7.52	FALSE
62	31/10/1990	2.15	2,060	25.3	7.34	TRUE
62	21/01/1991	2.07	1,710	29.6	7.15	FALSE
64	27/05/1990	0.00	2,250	29.2	0.00	TRUE
64	31/10/1990	5.42	2,080	32.2	7.58	TRUE
65	8/01/1965	0.00	820	0.0	0.00	FALSE
65	1/02/1971	5.87	890	0.0	0.00	FALSE
65	1/05/1978	5.35	1,000	0.0	0.00	FALSE
65	1/07/1979	5.37	1,030	24.0	0.00	FALSE
65	1/03/1980	5.25	1,000	25.0	0.00	FALSE
65	1/05/1981	5.30	600	24.0	0.00	FALSE
65	1/04/1983	5.32	750	24.5	0.00	FALSE
65	1/10/1986	0.00	1,130	0.0	0.00	FALSE
65	1/01/1987	0.00	1,040	0.0	0.00	FALSE
65	27/05/1990	0.00	1,840	26.7	0.00	TRUE
65	31/07/1990	5.48	1,737	25.2	7.28	FALSE
65	7/11/1990	5.47	1,478	35.6	7.09	FALSE
65	22/01/1991	5.44	1,440	25.5	6.96	FALSE
65	27/02/1991	5.38	1,395	25.6	6.66	FALSE
66	1/03/1980	8.36	1,000	23.0	0.00	FALSE
66	1/05/1981	8.38	1,000	24.0	0.00	FALSE
66	1/04/1983	8.40	1,100	24.0	0.00	FALSE
66	1/01/1987	0.00	980	0.0	0.00	FALSE
66	27/05/1990	0.00	1,200	26.8	0.00	TRUE
66	1/08/1990	8.46	1,097	25.1	7.46	TRUE
66	23/01/1991	8.42	990	25.7	6.99	FALSE
67	27/05/1990	0.00	830	0.0	0.00	TRUE
67	31/10/1990	13.58	0	0.0	0.00	FALSE
68	10/09/1965	0.00	880	0.0	0.00	FALSE
68	1/02/1971	4.65	1,100	0.0	0.00	FALSE
68	1/07/1979	4.68	1,350	24.0	0.00	FALSE
68	1/03/1980	4.65	1,000	24.0	0.00	FALSE
68	1/05/1981	4.78	1,500	24.0	0.00	FALSE
68	1/04/1983	4.75	1,200	24.0	0.00	FALSE
68	1/10/1986	0.00	1,490	0.0	0.00	FALSE
68	1/01/1987	0.00	1,480	0.0	0.00	FALSE
68	27/05/1990	0.00	1,930	26.0	0.00	TRUE
68	31/07/1990	4.80	1,522	24.8	7.39	FALSE
68	7/11/1990	4.78	1,489	25.7	7.17	FALSE
68	22/01/1991	4.35	1,462	31.6	7.03	TRUE
68	27/02/1991	4.71	1,374	28.8	6.95	FALSE
69	27/05/1990	0.00	1,270	0.0	0.00	TRUE
71	3/02/1965	0.00	450	0.0	0.00	FALSE
71	1/02/1971	0.00	550	0.0	0.00	FALSE
71	1/07/1979	16.70	800	24.5	0.00	FALSE
71	1/03/1980	16.67	780	24.0	0.00	FALSE

71	1/05/1981	16.65	850	24.0	0.00	FALSE
71	1/04/1983	16.62	1,000	24.5	0.00	FALSE
71	1/01/1987	0.00	400	0.0	0.00	FALSE
71	27/05/1990	0.00	770	27.5	0.00	TRUE
71	24/07/1990	16.70	820	24.6	7.43	FALSE
71	2/11/1990	16.71	759	25.8	7.27	TRUE
72	22/01/1991	16.69	779	25.4	6.87	TRUE
73	7/11/1990	0.00	1,530	32.3	7.43	TRUE
74	23/05/1990	0.00	996	26.7	0.00	TRUE
76	16/04/1970	0.00	820	0.0	0.00	FALSE
76	1/02/1971	7.25	1,150	0.0	0.00	FALSE
76	1/07/1979	7.12	1,000	25.0	0.00	FALSE
76	1/03/1980	7.20	650	24.0	0.00	FALSE
76	1/05/1981	7.23	700	24.5	0.00	FALSE
76	1/04/1983	7.30	800	24.0	0.00	FALSE
76	1/01/1987	0.00	1,080	0.0	0.00	FALSE
76	23/05/1990	0.00	1,910	27.2	0.00	TRUE
76	2/11/1990	0.00	1,610	25.2	7.64	FALSE
76	22/01/1991	0.00	1,475	26.4	6.73	FALSE
77	23/05/1990	0.00	942	26.0	0.00	TRUE
78	24/05/1990	0.00	2,370	27.9	0.00	TRUE
79	20/04/1967	0.00	960	0.0	0.00	FALSE
79	1/02/1971	8.51	1,040	0.0	0.00	FALSE
79	1/07/1979	8.40	1,100	23.5	0.00	FALSE
79	1/03/1980	8.35	550	24.0	0.00	FALSE
79	1/05/1981	8.60	1,770	24.0	0.00	FALSE
79	1/04/1983	8.58	1,200	24.5	0.00	FALSE
79	1/01/1987	0.00	2,120	0.0	0.00	FALSE
79	2/11/1990	8.36	1,433	25.4	7.32	FALSE
79	22/01/1991	8.31	1,440	25.8	6.70	FALSE
80	26/07/1990	0.00	2,300	22.9	8.37	FALSE
80	2/11/1990	8.29	0	0.0	0.00	FALSE
81	1/01/1987	0.00	1,040	0.0	0.00	FALSE
81	24/05/1990	0.00	1,479	27.4	0.00	TRUE
81	26/07/1990	6.14	1,108	25.8	7.08	FALSE
81	2/11/1990	6.27	952	25.3	7.17	FALSE
81	22/01/1991	6.25	1,130	26.0	6.49	FALSE
82	24/05/1990	0.00	786	26.9	0.00	TRUE
82	7/11/1990	8.05	675	25.8	7.99	FALSE
83	26/07/1990	0.00	1,107	24.3	8.03	FALSE
83	7/11/1990	8.25	1,072	25.0	7.51	FALSE
84	7/11/1990	5.64	952	26.0	7.42	FALSE
85	27/07/1990	5.31	820	24.4	7.40	FALSE
85	7/11/1990	5.36	799	25.5	7.11	TRUE
86	24/05/1990	0.00	885	0.0	0.00	TRUE
86	27/07/1990	4.16	952	22.7	7.55	FALSE
86	22/01/1991	4.17	854	26.3	7.04	FALSE
87	27/07/1990	5.42	1,015	22.1	7.63	FALSE
87	7/11/1990	5.45	940	29.0	7.32	FALSE
88	5/02/1966	0.00	450	0.0	0.00	FALSE
88	1/02/1971	0.00	530	0.0	0.00	FALSE
88	1/05/1978	7.05	0	0.0	0.00	FALSE
88	1/07/1979	6.90	700	24.0	0.00	FALSE
88	1/03/1980	7.00	800	24.0	0.00	FALSE
88	1/05/1981	7.02	900	24.5	0.00	FALSE
88	1/04/1983	7.01	900	24.0	0.00	FALSE

88	1/01/1987	0.00	630	0.0	0.00	FALSE
88	24/05/1990	0.00	867	27.2	0.00	TRUE
88	27/07/1990	7.04	868	24.9	7.56	TRUE
88	7/11/1990	7.10	808	25.4	7.41	TRUE
89	3/09/1965	0.00	720	0.0	0.00	FALSE
89	1/02/1971	8.64	820	0.0	0.00	FALSE
89	1/07/1979	8.40	860	24.5	0.00	FALSE
89	1/03/1980	8.42	900	25.5	0.00	FALSE
89	1/05/1981	8.60	900	24.5	0.00	FALSE
89	1/04/1983	8.50	850	24.0	0.00	FALSE
89	1/10/1986	0.00	870	0.0	0.00	FALSE
89	1/01/1987	0.00	870	0.0	0.00	FALSE
89	24/05/1990	0.00	1,160	26.7	0.00	TRUE
89	31/07/1990	8.48	1,108	24.2	7.46	FALSE
89	7/11/1990	8.44	939	26.6	7.27	FALSE
89	22/01/1991	8.43	914	26.0	7.21	FALSE
89	27/02/1991	8.37	809	26.0	6.83	FALSE
90	1/03/1980	3.33	800	23.5	0.00	FALSE
90	1/05/1981	3.13	950	23.5	0.00	FALSE
90	1/04/1983	3.33	1,000	24.0	0.00	FALSE
90	1/01/1987	0.00	2,450	0.0	0.00	FALSE
90	9/03/1990	0.00	1,500	0.0	0.00	FALSE
90	24/05/1990	0.00	2,270	26.9	0.00	TRUE
90	31/07/1990	3.10	1,515	24.2	7.57	FALSE
90	7/11/1990	3.03	1,467	25.7	7.26	FALSE
90	22/01/1991	2.99	787	26.0	7.12	FALSE
90	27/02/1991	3.00	1,305	26.3	6.85	FALSE
91	24/05/1990	0.00	1,010	27.3	0.00	TRUE
91	31/07/1990	3.65	950	24.6	7.43	FALSE
91	7/11/1990	3.70	1,025	25.5	7.22	FALSE
92	24/05/1990	0.00	410	23.6	0.00	TRUE
93	24/05/1990	0.00	1,230	26.7	0.00	TRUE
93	31/07/1990	4.24	1,219	24.6	7.28	FALSE
93	7/11/1990	4.19	1,133	34.0	7.52	FALSE
93	22/01/1991	4.15	1,078	26.8	7.36	FALSE
93	27/02/1991	4.15	1,069	27.9	7.39	FALSE
95	24/05/1990	0.00	832	26.4	0.00	TRUE
96	24/05/1990	0.00	843	26.2	0.00	TRUE
97	24/05/1990	0.00	780	25.9	0.00	TRUE
98	24/05/1990	0.00	672	26.1	0.00	TRUE
99	24/05/1990	0.00	835	25.8	0.00	TRUE
100	24/05/1990	0.00	834	25.3	0.00	TRUE
101	23/11/1966	0.00	550	0.0	0.00	FALSE
101	1/02/1971	12.31	660	0.0	0.00	FALSE
101	6/08/1990	12.18	1,069	25.6	7.39	FALSE
101	1/11/1990	12.10	930	26.5	7.22	TRUE
101	1/03/1991	0.00	880	27.0	7.36	TRUE
102	15/03/1971	18.75	500	0.0	0.00	FALSE
102	1/07/1979	18.75	590	24.0	0.00	FALSE
102	1/03/1980	18.70	680	24.0	0.00	FALSE
102	1/05/1981	18.71	800	24.0	0.00	FALSE
102	1/04/1983	18.71	800	24.0	0.00	FALSE
102	6/08/1990	18.91	727	25.3	7.41	FALSE
102	1/11/1990	18.85	793	24.5	7.13	FALSE
102	1/03/1991	18.73	930	26.0	5.16	TRUE
103	23/11/1966	0.00	400	0.0	0.00	FALSE

103	1/02/1971	13.02	820	0.0	0.00	FALSE
103	1/07/1979	12.70	910	24.0	0.00	FALSE
103	1/03/1980	12.80	1,050	24.0	0.00	FALSE
103	1/05/1981	12.25	1,100	24.0	0.00	FALSE
103	1/04/1983	12.30	1,200	24.0	0.00	FALSE
103	6/08/1990	12.58	1,278	25.5	7.42	FALSE
103	1/11/1990	12.54	1,140	25.5	7.30	TRUE
103	1/03/1991	0.00	1,073	28.3	7.33	FALSE
104	6/08/1990	0.00	1,363	24.6	7.48	FALSE
104	1/11/1990	0.00	1,242	24.6	7.29	FALSE
104	1/03/1991	0.00	1,220	26.0	5.13	TRUE
105	1/07/1979	14.78	870	23.5	0.00	FALSE
105	1/03/1980	14.80	900	24.0	0.00	FALSE
105	1/05/1981	14.78	1,050	24.0	0.00	FALSE
105	1/04/1983	14.80	1,000	24.0	0.00	FALSE
105	6/08/1990	14.73	1,580	24.5	7.44	FALSE
105	1/11/1990	0.00	1,453	25.8	7.12	TRUE
105	1/03/1991	14.67	1,321	26.0	5.22	TRUE
106	15/03/1971	21.37	500	0.0	0.00	FALSE
106	1/07/1979	21.20	700	23.5	0.00	FALSE
106	1/03/1980	21.10	900	24.0	0.00	FALSE
106	1/05/1981	21.10	950	25.0	0.00	FALSE
106	1/04/1983	21.20	900	24.0	0.00	FALSE
106	6/08/1990	21.51	681	24.6	7.44	FALSE
106	1/11/1990	21.47	639	24.8	7.22	FALSE
106	1/03/1991	21.70	935	25.9	8.19	TRUE
107	9/05/1968	0.00	500	0.0	0.00	FALSE
107	1/02/1971	13.28	720	0.0	0.00	FALSE
107	1/07/1979	13.35	750	23.5	0.00	FALSE
107	1/03/1980	0.00	970	24.0	0.00	FALSE
107	1/05/1981	13.32	1,100	24.0	0.00	FALSE
107	1/04/1983	13.32	1,100	24.0	0.00	FALSE
107	6/08/1990	13.34	1,417	25.0	7.40	FALSE
107	1/11/1990	13.30	1,156	25.5	7.14	TRUE
107	1/03/1991	0.00	970	25.9	7.24	TRUE
108	6/08/1990	0.00	1,492	24.7	7.37	FALSE
108	1/11/1990	0.00	1,383	25.1	7.27	TRUE
108	1/03/1991	0.00	1,347	25.8	9.48	TRUE
109	23/11/1966	0.00	500	0.0	0.00	FALSE
109	1/02/1971	11.16	680	0.0	0.00	FALSE
109	1/07/1979	11.28	850	24.0	0.00	FALSE
109	1/03/1980	11.30	1,000	24.0	0.00	FALSE
109	1/05/1981	11.30	950	24.0	0.00	FALSE
109	1/04/1983	11.28	1,100	24.0	0.00	FALSE
109	6/08/1990	11.19	1,305	25.2	7.45	FALSE
109	1/11/1990	11.10	1,159	25.5	7.22	TRUE
109	1/03/1991	10.95	973	26.0	7.27	TRUE
110	15/03/1971	17.67	450	0.0	0.00	FALSE
110	1/07/1979	17.58	650	23.5	0.00	FALSE
110	1/03/1980	17.60	700	24.0	0.00	FALSE
110	1/05/1981	17.60	750	24.0	0.00	FALSE
110	1/04/1983	17.58	1,700	24.0	0.00	FALSE
110	6/08/1990	17.76	1,280	24.4	7.74	FALSE
110	1/11/1990	17.72	1,183	25.6	7.35	TRUE
110	1/03/1991	17.59	0	0.0	0.00	FALSE
111	23/11/1966	0.00	450	0.0	0.00	FALSE

111	1/02/1971	9.40	600	0.0	0.00	FALSE
111	28/02/1990	0.00	1,000	0.0	0.00	TRUE
111	6/08/1990	9.72	1,020	25.5	7.44	FALSE
111	1/11/1990	9.66	942	26.1	7.14	TRUE
111	1/03/1991	9.52	899	26.4	7.30	TRUE
112	6/08/1990	0.00	1,182	24.4	7.46	FALSE
112	1/11/1990	0.00	1,028	24.9	7.47	TRUE
112	1/03/1991	0.00	746	25.3	7.60	TRUE
113	6/08/1990	16.69	1,195	24.5	7.58	FALSE
113	1/11/1990	16.64	994	25.0	7.25	TRUE
113	1/03/1991	16.50	969	25.7	7.66	TRUE
114	6/08/1990	0.00	1,182	24.9	7.53	FALSE
114	1/11/1990	0.00	1,035	25.2	7.18	TRUE
114	1/03/1991	0.00	997	25.7	7.34	TRUE
115	6/08/1990	11.92	1,056	25.3	7.45	FALSE
115	1/11/1990	11.88	974	25.5	7.26	TRUE
115	1/03/1991	11.73	931	26.1	7.39	TRUE
116	6/08/1990	0.00	1,217	24.5	7.73	FALSE
116	1/11/1990	0.00	971	25.2	7.17	TRUE
116	1/03/1991	0.00	929	27.0	7.39	TRUE
117	6/08/1990	12.37	927	25.0	7.42	FALSE
117	1/11/1990	12.29	850	25.5	7.30	TRUE
117	1/03/1991	12.23	832	26.0	7.46	TRUE
118	28/02/1990	0.00	850	0.0	0.00	TRUE
118	6/08/1990	13.08	835	25.0	7.48	FALSE
118	1/11/1990	13.05	780	25.2	7.23	TRUE
118	1/03/1991	12.90	730	26.7	7.43	TRUE
119	6/08/1990	12.64	1,051	23.3	7.42	FALSE
119	1/03/1991	12.50	930	28.7	7.70	TRUE
120	6/08/1990	0.00	980	24.7	7.63	FALSE
120	1/11/1990	0.00	827	26.4	7.35	FALSE
120	1/03/1991	0.00	740	25.8	7.47	TRUE
121	1/03/1991	0.00	879	26.2	5.20	TRUE
122	1/11/1990	0.00	841	25.4	7.32	TRUE
122	1/03/1991	0.00	832	26.3	7.98	TRUE
123	1/03/1991	11.46	0	0.0	0.00	FALSE
124	6/08/1990	23.11	349	24.5	7.42	FALSE
124	1/11/1990	23.08	242	22.2	7.52	FALSE
124	1/03/1991	22.95	450	25.6	5.05	FALSE
126	1/03/1991	8.80	0	0.0	0.00	FALSE
129	1/03/1991	8.11	988	26.6	5.09	TRUE
131	28/02/1990	0.00	3,500	0.0	0.00	TRUE
131	23/01/1991	7.54	109	25.1	7.62	FALSE
131	27/02/1991	7.47	940	25.3	6.63	FALSE
132	1/07/1979	3.03	800	24.5	0.00	FALSE
132	1/03/1980	3.40	900	23.5	0.00	FALSE
132	1/05/1981	3.19	750	24.0	0.00	FALSE
132	1/04/1983	3.20	750	24.5	0.00	FALSE
132	1/10/1986	0.00	990	0.0	0.00	FALSE
132	24/05/1990	0.00	739	26.9	0.00	TRUE
133	8/09/1965	0.00	600	24.5	0.00	FALSE
133	1/02/1971	4.32	670	0.0	0.00	FALSE
133	1/07/1979	4.10	1,000	25.0	0.00	FALSE
133	1/03/1980	4.12	850	0.0	0.00	FALSE
133	1/05/1981	4.19	750	0.0	0.00	FALSE
133	1/04/1983	4.10	800	0.0	0.00	FALSE

133	1/10/1986	0.00	670	0.0	0.00	FALSE
133	1/01/1987	0.00	1,040	0.0	0.00	FALSE
133	24/05/1990	0.00	1,438	26.8	0.00	TRUE
133	31/07/1990	4.22	1,229	24.4	7.37	FALSE
133	7/11/1990	4.18	1,298	25.7	7.24	TRUE
133	22/01/1991	4.16	1,223	26.2	7.61	FALSE
133	27/02/1991	4.11	1,118	25.7	7.23	TRUE
134	10/07/1970	0.00	400	0.0	0.00	FALSE
134	1/02/1971	5.52	500	0.0	0.00	FALSE
134	1/07/1979	0.00	850	24.0	0.00	FALSE
134	1/03/1980	5.38	850	25.0	0.00	FALSE
134	1/05/1981	5.60	900	24.0	0.00	FALSE
134	1/04/1983	5.50	900	24.0	0.00	FALSE
134	28/05/1990	0.00	960	26.7	0.00	TRUE
134	7/08/1990	5.55	1,044	24.7	7.35	FALSE
134	23/01/1991	5.46	854	25.9	7.02	FALSE
134	27/02/1991	5.39	841	25.8	7.12	FALSE
135	7/08/1990	0.00	1,034	21.5	7.82	FALSE
136	7/08/1990	6.39	807	23.0	7.51	FALSE
137	28/05/1990	0.00	856	26.8	0.00	TRUE
138	28/05/1990	0.00	850	25.6	0.00	TRUE
138	7/08/1990	4.99	850	24.5	7.29	FALSE
142	29/05/1990	0.00	958	24.4	0.00	TRUE
143	29/05/1990	0.00	653	24.5	0.00	TRUE
144	16/07/1965	0.00	550	0.0	0.00	FALSE
144	1/02/1971	4.34	560	0.0	0.00	FALSE
144	1/07/1979	4.20	800	24.0	0.00	FALSE
144	1/03/1980	0.00	900	25.0	0.00	FALSE
144	1/05/1981	4.74	500	24.0	0.00	FALSE
144	1/04/1983	4.30	800	24.5	0.00	FALSE
144	29/05/1990	0.00	940	26.3	0.00	TRUE
144	31/07/1990	4.30	923	25.4	7.36	FALSE
144	7/11/1990	4.29	888	25.5	7.20	TRUE
144	22/01/1991	4.25	893	25.6	6.98	FALSE
144	27/02/1991	4.19	865	25.8	7.08	TRUE
145	29/05/1990	0.00	947	0.0	0.00	TRUE
147	9/09/1965	0.00	600	0.0	0.00	FALSE
147	1/02/1971	7.29	710	0.0	0.00	FALSE
147	1/07/1979	7.53	920	24.5	0.00	FALSE
147	1/03/1980	7.40	950	24.5	0.00	FALSE
147	1/05/1981	7.50	1,200	24.0	0.00	FALSE
147	1/04/1983	7.48	1,000	24.5	0.00	FALSE
147	29/05/1990	0.00	1,274	25.7	0.00	TRUE
147	31/07/1990	7.56	1,147	24.4	7.52	FALSE
147	23/01/1991	7.54	854	25.4	7.00	TRUE
147	27/02/1991	7.46	955	25.3	7.05	TRUE
149	7/11/1990	3.45	0	0.0	0.00	FALSE
151	29/05/1990	0.00	2,340	26.7	0.00	TRUE
151	31/07/1990	7.10	1,995	24.8	7.35	TRUE
151	7/11/1990	7.09	1,795	25.7	7.13	TRUE
151	23/01/1991	7.09	1,904	25.1	7.07	TRUE
151	27/02/1991	7.03	1,830	25.7	6.89	TRUE
152	29/05/1990	0.00	2,900	26.0	0.00	TRUE
152	31/07/1990	5.76	0	0.0	0.00	FALSE
152	7/11/1990	5.77	0	0.0	0.00	TRUE
153	20/07/1965	0.00	1,150	0.0	0.00	FALSE

153	1/02/1971	7.39	1,730	0.0	0.00	FALSE
153	1/05/1978	0.00	2,050	25.0	0.00	FALSE
153	1/07/1979	7.45	1,930	25.0	0.00	FALSE
153	1/05/1981	7.65	1,900	24.0	0.00	FALSE
153	1/04/1983	7.60	2,000	24.0	0.00	FALSE
153	1/10/1986	0.00	2,470	0.0	0.00	FALSE
153	1/01/1987	0.00	2,560	0.0	0.00	FALSE
153	31/07/1990	7.46	1,748	24.6	7.39	FALSE
154	29/05/1990	0.00	2,900	28.0	0.00	TRUE
154	31/07/1990	0.00	2,180	24.1	7.49	FALSE
155	1/02/1965	0.00	2,640	0.0	0.00	FALSE
155	1/02/1971	7.91	3,690	0.0	0.00	FALSE
155	1/05/1978	7.71	1,690	24.5	0.00	FALSE
155	1/07/1979	7.70	1,880	25.0	0.00	FALSE
155	1/03/1980	7.79	850	24.0	0.00	FALSE
155	1/05/1981	7.71	1,400	24.5	0.00	FALSE
155	1/04/1983	7.75	1,200	24.0	0.00	FALSE
155	1/10/1986	0.00	4,050	0.0	0.00	FALSE
155	1/01/1987	0.00	4,800	0.0	0.00	FALSE
155	9/03/1990	0.00	4,400	0.0	0.00	FALSE
155	29/05/1990	0.00	4,800	26.1	0.00	TRUE
155	31/07/1990	0.00	4,750	24.0	7.56	FALSE
155	7/11/1990	7.69	2,950	25.7	7.32	FALSE
155	23/01/1991	7.69	3,430	25.6	7.05	FALSE
155	27/02/1991	7.62	2,320	26.0	7.08	FALSE
156	1/07/1979	15.35	0	0.0	0.00	FALSE
156	1/03/1980	15.40	1,100	24.5	0.00	FALSE
156	1/05/1981	15.52	1,200	24.0	0.00	FALSE
156	1/04/1983	15.50	1,100	24.0	0.00	FALSE
156	29/05/1990	0.00	1,534	26.0	0.00	TRUE
156	1/08/1990	15.55	1,343	25.3	7.37	FALSE
156	23/01/1991	15.49	1,235	24.9	7.07	FALSE
157	2/02/1965	0.00	700	0.0	0.00	FALSE
157	1/02/1971	14.19	870	0.0	0.00	FALSE
157	1/07/1979	14.00	0	0.0	0.00	FALSE
157	1/03/1980	14.02	1,150	24.5	0.00	FALSE
157	1/05/1981	14.16	1,100	24.0	0.00	FALSE
157	1/04/1983	0.00	1,050	24.5	0.00	FALSE
157	1/01/1987	0.00	1,080	0.0	0.00	FALSE
157	29/05/1990	0.00	1,460	25.6	0.00	TRUE
157	1/08/1990	14.08	1,228	25.2	7.65	TRUE
157	23/01/1991	14.07	1,248	25.5	7.04	FALSE
159	1/07/1979	12.03	0	0.0	0.00	FALSE
159	1/03/1980	12.28	600	24.0	0.00	FALSE
159	1/05/1981	12.60	800	24.5	0.00	FALSE
159	1/04/1983	12.40	900	24.0	0.00	FALSE
159	29/05/1990	0.00	744	35.3	0.00	TRUE
159	27/07/1990	12.34	818	24.7	0.00	FALSE
159	23/01/1991	12.35	781	25.6	7.14	TRUE
159	27/02/1991	12.22	765	25.8	7.23	FALSE
160	1/08/1990	15.94	870	25.0	7.38	FALSE
160	7/08/1990	0.00	927	22.0	8.33	FALSE
161	7/01/1965	0.00	620	0.0	0.00	FALSE
161	1/02/1971	26.01	670	0.0	0.00	FALSE
161	1/07/1979	25.80	0	0.0	0.00	FALSE
161	1/03/1980	25.38	900	23.0	0.00	FALSE

161	1/05/1981	25.30	900	23.0	0.00	FALSE
161	1/05/1981	26.00	900	24.0	0.00	FALSE
161	1/04/1983	26.10	1,000	24.5	0.00	FALSE
161	1/01/1987	0.00	630	0.0	0.00	FALSE
161	1/01/1987	0.00	720	0.0	0.00	FALSE
161	29/05/1990	0.00	893	26.6	0.00	TRUE
161	1/08/1990	25.84	961	25.3	7.88	TRUE
161	23/01/1991	25.75	947	24.7	7.64	TRUE
162	29/05/1990	0.00	833	25.0	0.00	TRUE
162	7/08/1990	21.93	921	21.9	7.76	FALSE
163	1/01/1987	0.00	720	0.0	0.00	FALSE
163	29/05/1990	0.00	955	26.1	0.00	TRUE
166	3/09/1965	0.00	560	0.0	0.00	FALSE
166	1/02/1971	16.13	700	0.0	0.00	FALSE
166	1/05/1978	15.75	790	24.5	0.00	FALSE
166	1/07/1979	15.94	0	0.0	0.00	FALSE
166	1/03/1980	15.90	1,000	23.0	0.00	FALSE
166	1/05/1981	0.00	1,000	24.0	0.00	FALSE
166	1/04/1983	15.90	900	24.5	0.00	FALSE
166	1/01/1987	0.00	780	0.0	0.00	FALSE
166	29/05/1990	0.00	1,048	26.1	0.00	TRUE
166	23/01/1991	15.89	790	25.6	7.04	FALSE
167	9/03/1990	0.00	1,160	0.0	0.00	FALSE
168	23/10/1959	0.00	500	0.0	0.00	FALSE
168	1/02/1971	9.91	600	0.0	0.00	FALSE
168	1/05/1978	10.06	870	24.5	0.00	FALSE
168	1/07/1979	10.10	800	24.0	0.00	FALSE
168	1/03/1980	10.20	800	24.5	0.00	FALSE
168	1/05/1981	10.20	1,000	24.0	0.00	FALSE
168	1/04/1983	10.25	1,100	24.0	0.00	FALSE
168	29/05/1990	0.00	978	26.1	0.00	TRUE
169	29/05/1990	0.00	941	26.2	0.00	TRUE
170	30/07/1990	9.64	710	24.9	7.67	FALSE
171	29/05/1990	0.00	900	26.6	0.00	TRUE
171	6/08/1990	7.76	1,008	24.5	7.52	FALSE
172	29/05/1990	0.00	803	33.4	0.00	TRUE
173	29/05/1990	0.00	5,100	26.9	0.00	TRUE
173	6/11/1990	13.83	5,260	25.9	7.63	FALSE
174	29/05/1990	0.00	6,000	28.0	0.00	TRUE
174	6/11/1990	22.11	6,100	27.1	7.59	FALSE
175	22/04/1966	0.00	650	0.0	0.00	FALSE
175	1/02/1971	0.00	720	0.0	0.00	FALSE
175	1/07/1979	0.00	1,000	24.0	0.00	FALSE
175	1/03/1980	4.70	800	24.3	0.00	FALSE
175	1/05/1981	4.60	1,000	24.3	0.00	FALSE
175	1/04/1983	4.62	1,150	24.0	0.00	FALSE
176	26/07/1990	0.00	987	0.0	0.00	FALSE
177	31/10/1990	6.30	718	25.4	7.83	FALSE
178	26/07/1990	28.77	4,490	24.6	8.00	FALSE
178	6/11/1990	29.07	3,640	24.9	7.97	FALSE
179	30/07/1990	32.10	0	0.0	0.00	FALSE
179	2/11/1990	30.10	0	0.0	0.00	FALSE
180	3/02/1965	0.00	350	0.0	0.00	FALSE
180	1/02/1971	44.55	450	0.0	0.00	FALSE
180	1/07/1979	44.20	650	25.0	0.00	FALSE
180	1/03/1980	44.26	700	24.0	0.00	FALSE

180	1/05/1981	44.18	700	24.0	0.00	FALSE
180	1/04/1983	44.20	700	24.5	0.00	FALSE
180	29/05/1990	0.00	650	0.0	0.00	TRUE
181	7/08/1990	10.67	716	24.9	7.36	FALSE
183	2/11/1990	25.04	557	25.1	7.64	FALSE
185	2/11/1990	25.44	0	0.0	0.00	FALSE
188	7/11/1990	9.27	1,141	25.5	7.72	FALSE
188	22/01/1991	7.08	811	25.5	0.71	TRUE
192	1/07/1979	14.50	650	25.0	0.00	FALSE
192	1/03/1980	14.50	500	23.5	0.00	FALSE
192	1/05/1981	14.50	600	24.0	0.00	FALSE
192	1/04/1983	14.50	600	24.0	0.00	FALSE
192	27/07/1990	14.00	822	24.8	7.40	FALSE
192	23/01/1991	14.00	800	25.7	7.11	FALSE
193	17/07/1990	28.71	449	0.0	0.00	TRUE
195	6/08/1990	7.70	0	0.0	0.00	FALSE
198	6/08/1990	9.33	0	0.0	0.00	FALSE
199	6/08/1990	9.41	0	0.0	0.00	FALSE
200	1/01/1987	0.00	860	0.0	0.00	FALSE
200	7/08/1990	7.64	1,214	22.3	7.46	FALSE
200	7/11/1990	0.00	999	25.3	8.21	TRUE
201	3/09/1965	0.00	620	0.0	0.00	FALSE
201	1/02/1971	0.00	650	0.0	0.00	FALSE
201	1/07/1979	10.50	900	24.0	0.00	FALSE
201	1/03/1980	10.50	800	25.0	0.00	FALSE
201	1/04/1983	10.52	780	24.0	0.00	FALSE
201	1/01/1987	0.00	730	0.0	0.00	FALSE
201	7/08/1990	10.68	980	25.1	7.48	FALSE
201	7/11/1990	10.60	889	25.7	7.24	TRUE
201	22/01/1991	10.60	866	25.4	7.09	TRUE
203	2/11/1990	21.98	0	0.0	0.00	TRUE
205	7/08/1990	31.46	6,990	25.0	8.05	FALSE
205	6/11/1990	31.28	6,100	24.9	7.97	FALSE
206	22/01/1991	0.00	1,088	0.0	7.77	TRUE
207	7/08/1990	0.00	891	23.8	7.79	FALSE
211	6/08/1990	19.95	613	24.8	7.65	FALSE
211	1/11/1990	19.91	544	24.9	7.67	FALSE
211	1/03/1991	0.00	935	26.1	8.18	TRUE
212	6/08/1990	17.58	457	24.4	7.58	FALSE
212	1/11/1990	17.53	358	25.0	7.64	FALSE
212	1/03/1991	0.00	1,060	26.0	8.26	TRUE
213	10/08/1990	13.24	1,014	24.7	7.57	FALSE
213	6/11/1990	13.15	953	25.4	7.29	FALSE
214	10/08/1990	1.78	879	23.5	7.27	FALSE
215	10/08/1990	10.60	790	24.5	7.44	FALSE
215	7/11/1990	10.52	791	25.6	7.37	FALSE
216	10/08/1990	5.99	1,072	25.0	7.44	FALSE

Appendix G

Well census information for Tongatapu, Ha'apai and Vava'u

(from WELLS.DBF)

Island	Well No	Location	Reduced Level (m)	Depth (m)	Type
TBU	2	LDS Vaini		10.00	drilled
TBU	3	Kelepi Hala (Vaini)			dug
TBU	4	Hon. Ma'afu Tukuilahi			dug
TBU	5	Beulah college No.1			dug
TBU	6	Beulah college No.2			drilled
TBU	7	LDS Malapo		10.00	drilled
TBU	8	Taliai camp No.1			
TBU	9	Taliai camp No.2		24.38	dug
TBU	10	Fua'amotu Primary Sch			dug
TBU	11	Fua'amotu Primary Sch			drilled
TBU	12	Fua'amotu primary Sch			drilled
TBU	13	Lavengatonga village		33.53	dug
TBU	14	Fatumu village No.1		30.48	dug
TBU	15	Fatumu village No.2			drilled
TBU	16	Titali private well			drilled
TBU	17	Haveluliku village		24.38	dug
TBU	18	Tatakamotonga village		10.97	dug
TBU	19	Tatakamotonga village		10.97	drilled
TBU	20	Tatakamotonga village		10.97	dug
TBU	21	Tatakamotonga village		16.20	drilled
TBU	22	Veitongo village			drilled
TBU	23	Vaini Farm			
TBU	24	Vaini farm			
TBU	25	Vaini Farm			drilled
TBU	26	Mahinae'a College			dug
TBU	27	Vaini well No.1		4.88	dug
TBU	28	Vaini well No.2		4.88	drilled
TBU	29	Vaini well No.3		4.88	dug
TBU	30	Hu'atolitoli well		10.97	dug
TBU	31	Hu'atolitoli well			
TBU	32	Tupou College No.1		18.29	drilled
TBU	33	Tupou College No.2		18.29	dug
TBU	34	Tupou College No.3			dug
TBU	35	Lapaha village No.1		10.97	drilled
TBU	36	Lapaha village No.2		10.97	dug
TBU	37	Lapaha Primary Sch		10.97	dug
TBU	38	Mu'a LDS			
TBU	39	Nakolo village No.1			
TBU	40	Nakolo village No.2		42.67	drilled
TBU	41	Ha'asini/Hamula No.1		36.58	drilled
TBU	42	Ha'asini/Hamula No.2		36.58	drilled
TBU	43	Fua'amotu airport		38.10	drilled
TBU	44	End of runway			
TBU	45	Niutoua village		12.80	dug
TBU	46	Afa village		8.23	dug
TBU	47	Hoi village		6.71	dug
TBU	48	Kolonga village No.1		3.66	dug

TBU	49	Kolonga village No.2		3.66	
TBU	50	Haveluliku vil. new		24.38	
TBU	51	Niutoua vil. new			
TBU	52	Navutoka old well		6.10	dug
TBU	53	Alakifonua well		13.72	drilled
TBU	54	Holonga village		12.19	dug
TBU	55	Malapo village		12.19	dug
TBU	56	Navutoka vil. new			
TBU	57	Afa vil. new			
TBU	58	Nukuleka village		7.92	dug
TBU	59	Makaunga village		6.71	drilled
TBU	60	Talafo'ou vil. new		12.19	drilled
TBU	61	Talafo'ou vil. old		12.19	dug
TBU	62	Manuka well		3.05	dug
TBU	63	Alakifonua pri. well		13.72	
TBU	64	Alakifonua pri. well			dug
TBU	65	Te'ekiu vil.	5.92	4.88	dug
TBU	66	Vaotu'u vil.	8.95	21.34	dug
TBU	67	Lapaha vil. new			drilled
TBU	68	Masilamea village	5.09	4.88	dug
TBU	69	Vaotu'u vil. new			
TBU	70	LDS Vaotu'u	8.89		
TBU	71	Pelehake vil. new		14.33	drilled
TBU	72	Pelehake vil. old		14.33	dug
TBU	73	Te'ekiu vil. new			drilled
TBU	74	Veitongo vil.		11.58	dug
TBU	75	Veitongo pri.		11.58	dug
TBU	76	Longoteme vil.		6.10	
TBU	77	Folaha pri.		7.92	dug
TBU	78	Folaha vil. No.1		7.92	dug
TBU	79	Folaha vil. No.2		7.92	dug
TBU	80	Folaha LDS		7.92	
TBU	81	Nukuhetulu vil.		7.92	
TBU	82	Golf club 'Atele		6.10	dug
TBU	83	Ha'ateiho LDS		6.10	drilled
TBU	84	Tokomololo LDS	6.03	6.10	drilled
TBU	85	Tokomololo Agr.	5.75	6.10	
TBU	86	Tokomololo vil.	7.11	6.10	dug
TBU	87	Tokomololo pri.	5.82	6.10	
TBU	88	Pea vil.	7.55	6.10	dug
TBU	89	Hofoa vil.	8.92	8.41	dug
TBU	90	Puke vil.	3.53	4.57	dug
TBU	91	Sia'atoutai vil.	4.14	4.57	dug
TBU	92	Sia'atoutai pri.		4.57	dug
TBU	93	Sia'atoutai col.	4.75	4.57	drilled
TBU	94	Sia'atoutai col.		4.57	drilled
TBU	95	Sia'atoutai col.		4.57	dug
TBU	96	Sia'atoutai col.		4.57	dug
TBU	97	Sia'atoutai col.		4.57	dug
TBU	98	Sia'atoutai col.		4.57	dug
TBU	99	Sia'atoutai col.		4.57	dug
TBU	100	Sia'atoutai col.		4.57	dug
TBU	101	Mataki'Eua	12.5		
TBU	102	Mataki'Eua	20.3		
TBU	103	Mataki'Eua	12.8		

TBU	104	Mataki'Eua	16.5		
TBU	105	Mataki'Eua	15.0		
TBU	106	Mataki'Eua	21.8		
TBU	107	Mataki'Eua	13.5		
TBU	108	Mataki'Eua	21.5		
TBU	109	Mataki'Eua	11.4		
TBU	110	Mataki'Eua	18.1		
TBU	111	Mataki'Eua	10.0		
TBU	112	Mataki'eua	16.5		
TBU	113	Mataki'eua	16.9		
TBU	114	Mataki'eua	11.9		
TBU	115	Mataki'eua	12.2		
TBU	116	Mataki'eua	13.1		
TBU	117	Mataki'eua	12.7		
TBU	118	Mataki'eua	13.4		
TBU	119	Mataki'eua	12.5		
TBU	120	Mataki'eua	13.8		
TBU	121	Tongamai	12.5		
TBU	122	Mataki'eua	17.8		
TBU	123	Tongamai	12.0		
TBU	124	Mataki'eua	0.92		
TBU	125	Tongamai	9.87		
TBU	126		9.32		
TBU	127	Tongamai	9.21		
TBU	128		8.37		
TBU	129	Tongamai	8.59		
TBU	130		8.03		
TBU	131	Tongamai	8.11		
TBU	132	Sia'atoutai college		4.57	dug
TBU	133	Fatai village	4.74	5.49	dug
TBU	134	Lakepa village	6.04		dug
TBU	135	Lakepa lds church	6.18		
TBU	136	Lakepa private well	6.78		
TBU	137	Private well dairy			
TBU	138	Private well dairy	5.34		
TBU	139	Liahona lds church	8.49		
TBU	140	Liahona			dug
TBU	141	Fatai lds church	3.42		
TBU	142	Fatai private well		5.49	
TBU	143	Fatai private well		5.49	
TBU	144	Nukunuku village no 1	4.80	5.49	dug
TBU	145	Nukunuku village no 2		5.49	dug
TBU	146	Nukunuku village no 3		5.49	drilled
TBU	147	Matahau village	7.69	7.92	dug
TBU	148	Matahau lds church	8.02	7.92	
TBU	149	Nukunuku lds church	4.00	5.49	
TBU	150	Te'ekiu lds church	4.62		
TBU	151	Fo'ui village	7.46		dug
TBU	152	Fo'ui village	6.14		drilled
TBU	153	Fo'ui village	7.81		dug
TBU	154	Fo'ui lds church	5.79		
TBU	155	Ha'avakatolo village	7.98	6.10	dug
TBU	156	Kala'au village	15.8	15.24	dug
TBU	157	Fahefa village		18.29	dug
TBU	158	Fahefa lds church	16.5	0.00	

TBU	159	Kahoua village next t	12.8	7.32	dug
TBU	160	Utulau lds church	23.4	18.29	
TBU	161	Utulau village	26.1	18.29	dug
TBU	162	Ha'alalo village	22.3	20.73	dug
TBU	163	Ha'akame village		21.34	drilled
TBU	164	Ha'akame lds church	22.4	21.34	
TBU	165	Houma lds church	22.1	23.16	
TBU	166	Houma village	16.4	23.16	dug
TBU	167	Houma village		23.16	drilled
TBU	168	Liahona high school			drilled
TBU	169	Liahona high school w			drilled
TBU	170	Liahona high school e	10.1		dug
TBU	171	Liahona piggery	8.22		dug
TBU	172	S.Mafi private well a		6.10	
TBU	173	Keleti beach resort a			
TBU	174	Private well piggery			drilled
TBU	175	Ha'ateiho village		6.10	dug
TBU	176	Ha'ateiho village		6.10	drilled
TBU	177	Kolonga investigation			
TBU	178	Makeke lds church			
TBU	179	Tevita Liti at vaini			
TBU	180	Fua'amotou lds church			
TBU	181	Private well liahona	11.1		
TBU	182	Fu'amotu primary scho		44.50	drilled
TBU	183	Tuipelehake [lafalafa		18.20	
TBU	184	Semisi matakaiongo			drilled
TBU	185	Tailoa			drilled
TBU	186	Malapo village			drilled
TBU	187	Bahai temple Nualei			drilled
TBU	188	U.S.P campus			
TBU	189	Liahona village			drilled
TBU	190	Holonga village no. 2			
TBU	191	Private well at Pea			
TBU	192	Halaloto village well	14.4		
TBU	193	Airport extension wel			
TBU	194	Private well opposite	6.84	6.10	dug
TBU	195	Liahona High School			dug
TBU	196	Liahona High School			dug
TBU	197	Liahona High School			dug
TBU	198	Liahona High School			dug
TBU	199	Liahona High School			dug
TBU	200	Tonga College at ha'a		6.10	
TBU	201	Veitongo village		11.58	
TBU	202	Hon Ma'afu near priso		4.88	
TBU	203	Saimone Taumoepeau ne			
TBU	204	Maka Taumoepeau at va			
TBU	205	Sione Tualau at Makek			
TBU	206	Ha'ateiho new well			
TBU	207	Gibson			
TBU	208	Masao Soakai			
TBU	209	Masao Soakai			
TBU	210	Vili Pele privat wel		4.88	drilled
TBU	211	Mataki'eua windmill n			
TBU	212	Mataki'eua windmill n			
TBU	213	Metui panuve at nuale			dug

TBU	214	Panase mamahi at nual			dug
TBU	215	Pasi Vulangi at Nuale			dug
TBU	216	Private well at Havel			dug
TBU	217	Puke private well			
TBU	218	Puke village no. 2		5.80	
TBU	219	Ha'ateiho		9.60	
TBU	220	Nukunuku		5.80	
TBU	221	Hoi		12.00	
TBU	222	Fualu quarry investig		21.00	
TBU	223	Matatoa middle invest		21.00	inves
TBU	224	Matatoa/ tauafa'ahau		10.00	inves
TBU	225	Matatoa west investig		23.00	inves
TBU	226	S.Tupouniua(Havelu)	5.4	8.00	
TBU	227	Palace (Fua'amotu)			
TBU	228	Baron Tuita (Houma)			
TBU	229	Veitongo			
TBU	230	HRH Mataki'Eua Palace			
TBU	231	Beulah College Tsutom			
TBU	232	Beulah College Tsutom			
TBU	233	Vaini Tsutom Nakao			
TBU	234	Vaini Tsutom Nakao			
TBU	234	Fie'eiki (Kanokupolu)			
TBU	235	Baron Tuita Well			
TBU	235	Matatoa (King's Well)			
TBU	236	Ha'avakatolo Sione Ma			
TBU	236	Lavengatonga (Village			
TBU	237	Liahona Private well			
TBU	237	Data Logger(airpt)			
TBU	238	Vaini private well			
TBU	238	Lafalafa (University)	28.5	30.20	drilled
TBU	239	Fo'ui private well			
TBU	239	Hihifo (New Vil. wel)			
TBU	240	Fahefa old vil. well			
TBU	241	Dr. Moi (Fua'amotu)			
TBU	242	Private wel. Ngele'ia			
TBU	243	P.'Otukolo (Fu'amotu)		40.37	
TBU	244	Dr. Wong's Hotel			
TBU	245	Hihifo new well 1994	6.73	7.73	drilled
TBU	246	Fahefa new well 1994	14.5	15.50	drilled
TBU	247	Nukunuku new well 94	3.67	5.82	drilled
TBU	248	Pea new village well	7.1	8.42	drilled
TBU	249	'Uluvalu	30.1	34.00	drilled
TBU	250	'Utulau	25.5	27.50	drilled
TBU	251	Saia Ma'afu (Vaini)	11.5	13.50	drilled
TBU	252	'Alani Ramsey (Vaini)	11.9	14.40	drilled
TBU	253	'Olioni Kupu (Toloa)	30.1	32.10	drilled
TBU	254	Nukuleka Vil. Well	10.4	23.40	drilled
TBU	255	Siaosi Blake Ha'akame			
TBU	256	Hamula vil. well	53	54.80	drilled
TBU	257	Veitongo Bird Park	26.4	27.30	drilled
TBU	258	Tevita Fatafehi Minoi	11.4	12.60	drilled
TBU	259	Tupou College		22.17	drilled
TBU	260	Lloyd Belz (Tofoa)		8.36	drilled
TBU	261	Sione Katoa(Tatakamo)		17.27	drilled
HAP	1	Lolohea		4.35	

HAP	2	Talanoa		5.29	
HAP	3	Taniela		2.30	
HAP	4	Hingano		1.49	
HAP	5	Afepua		2.11	
HAP	6	Viliami Fisilau		2.30	
HAP	7	Masi Tu'ifua		3.04	
HAP	8	Isieta Tu'i		1.33	
HAP	9	Isileli 'Otunuku		2.71	
HAP	10	Kite Saafi		2.19	
HAP	11			2.13	
HAP	12	Epeli Musie		2.69	
HAP	13	Maukie Hafoka		1.96	
HAP	14	Fakakai hospital		1.97	
HAP	15	Vai ko Kanakana at Pu		1.66	
HAP	16	Peni Nau		2.57	
HAP	17	Viliami Tausinga		3.44	
HAP	18	Moala Feleti		3.13	
HAP	19	Samiu Vaitohi		2.69	
HAP	20	Sesimani 'Ufi		1.89	
HAP	21	Ha'ahao		2.13	
HAP	22	Kilikiti Fakatou		2.47	
HAP	23	Felemea well		4.01	
HAP	24	'Uiha well		3.66	
HAP	25	Henele Saafi		3.42	
HAP	26	Fepale Tafuna		3.29	
HAP	27	Sa'ili		2.65	
HAP	28	Faleloa tap water		11.40	
HAP	29	Inoke Hafoka		9.70	
HAP	30	Fakafanua resort			
HAP	31	Sinamoni		2.70	
HAP	32				
HAP	33	Tanumafili			
HAP	34	Lotofoa		5.14	
HAP	35	NGata Hoeft			
HAP	36	Fotua well No.1			
HAP	37	Fotua well No.2		6.92	
HAP	38	Fangale'ounga		4.25	
HAP	39	Airport at Koulo		4.05	
HAP	40	Holopeka			
HAP	41	Vaifono at Holopeka		2.94	
HAP	42	Niuakalo motel		2.64	
HAP	43			2.63	
HAP	44	Sefili Finau		2.65	
HAP	45	Hihifo well No.1		7.23	
HAP	46	Hihifo well No2		7.18	
HAP	47	Peni Lalahi		4.00	
HAP	48	Pilolevu College		4.15	
HAP	49	WHO No.5			
HAP	50	Sione Tu'ineau		2.65	
HAP	51	Kuongakovi		2.30	
HAP	52	Sione 'Utumoengalu		2.22	
HAP	53			1.89	
HAP	54	Pule Mataka		2.43	
HAP	55			2.17	
HAP	56	Police site		1.46	

HAP	57	Tufau Siaki		2.80	
HAP	58	Police station		1.46	
HAP	59	Pepa Latu Kakau		2.82	
HAP	60	Vili and Fifita Le'ot		2.34	
HAP	61	Fale'one Prison		6.55	
HAP	62	Samisoni Kaifoto		3.16	
HAP	63	Fa'atoto well at west		2.23	
HAP	64	Forestry Ha'apai	10.5	11.50	drilled
VAV	1	Makave			
VAV	2	Fatai			
VAV	3	Loto'uiha for Mangia			
VAV	4	Ha'akio			
VAV	5	Houma			
VAV	6	Ta'anea village			
VAV	7	Ta'anea			
VAV	8	Tu'anekivale			

Appendix H

Monthly rainfall for all stations on Tongatapu and ‘Eua, 1982-1990

Year	Month	Nuku’alofa	Mua	Fua'amotu	Vaini	Mataki'eua	Liahona	Fo'ui	'Eua
1982	1	386	424	473	585		447	457	
1982	2	238	302	370	311		377	378	
1982	3	253	313	287	363		283	365	
1982	4	136	131	200	226		101	84	
1982	5	241	331	317	298		288	282	
1982	6	58	70	79	86		87	94	
1982	7	87	89	91	85	148	186	130	
1982	8	149	194	169	178	178	122	51	
1982	9	75	105	102	92	91	64	65	
1982	10	34	46	27	41	70	60	56	
1982	11	19	40	33	25	42	28	21	
1982	12	57	77	72	59	41	36	46	
1983	1	37	22	47	20	29	17	19	
1983	2	102	176	102	122	127	19	119	
1983	3	73	76	92	78	73	146	84	
1983	4	9	15	18	14	7	30	6	
1983	5	26	32	25	31	25	34	12	
1983	6	69	84	53	61	63	60	21	
1983	7	118	123	121	130	146	126	104	
1983	8	66	34	50	40	40	8	19	
1983	9	41	56	59	56	141	35	47	
1983	10	108	134	122	122	152	111	147	
1983	11	24	24	43	29	40	40	30	
1983	12	165	172	197	211	185	93	157	
1984	1	222	236	273	212	155	197	124	
1984	2	217	254	339	358	190	183	201	
1984	3	71	54	64	75	100	109	74	55
1984	4	126	147	191	162	131	94	65	346
1984	5	26	54	32	57	43	79	74	
1984	6	75	93	117	122	102	113	67	
1984	7	70	104	44	87	100	100	42	17
1984	8	41	44	60	44	48	31	32	109
1984	9	142	139	158	151	77	53	129	58
1984	10	64	81	62	85	71	30	59	7
1984	11	80	72	80	82	78	73	68	97
1984	12	177	288	227	237	181	119	99	166
1985	1	97	108	85	94	3	0	74	233
1985	2	162	106	108	120	96	101	205	
1985	3	212	220	253	260	241	329	273	104
1985	4	54	53	40	61	72	50	70	5
1985	5	102	83	88	110	99	102	108	26

1985	6	140	97	113	121	84	140	273	28
1985	7	56	52	49	49	49	44	59	3
1985	8	27	26	39	35	29	23	27	19
1985	9	28	18	21	20	22	17	26	14
1985	10	53	45	29	36	54	33	29	41
1985	11	3	56	22	8	69	21	4	
1985	12	429	347	313	359	499	416	393	
1986	1	12	5	4	18	10	0	21	15
1986	2	69	74	51	150	58	50	170	41
1986	3	113	131	156	161	72	194	191	
1986	4	285	252	290	292	178	289	275	
1986	5	118	133	122	120	80	71	54	
1986	6	215	198	239	277	262	243	211	
1986	7	62	57	84	72	70	68	68	
1986	8	98	101	113	116	87	102	110	
1986	9	16	25	28	21	19	17	12	
1986	10	57	43	74	57	54	29	47	
1986	11	25	25	23	22	13	35	18	
1986	12	199	85	101	110	124	52	122	
1987	1	57	57	100	97	71			
1987	2	204	189	225	222	240			
1987	3	169	293	259	247	251			
1987	4	17	22	21	13	38			
1987	5	85	83	86	97	80			
1987	6	35	32	42	54	31			
1987	7	54	45	83	81	60			
1987	8	17	15	16	15	13			
1987	9	25	65	66	61	43			
1987	10	40	64	58	53	79			
1987	11	41	38	31	37	35			
1987	12	157	70	150	148	144			
1988	1	280	190	172	237	258			
1988	2	242	162	215	194	319			
1988	3	114	118	107	121	130			
1988	4	215	206	189	187	189			
1988	5	69	353	49	56	59			
1988	6	32	45	19	18	23			
1988	7	101	112	105	100	97			
1988	8	46	58	67	83	50			
1988	9	313	246	371	326	380			
1988	10	114	112	105	128	106			
1988	11	26	5	28	15	36			
1988	12	209	13	206	244	253			
1989	1	143	143	132	117	172		216	131
1989	2	726	714	662	660	767			737
1989	3	168	126	165	160	158			110
1989	4	153	176	172	186	172			225

1989	5	221	190	200	172	162		210	235
1989	6	47	68	50	62	41		34	50
1989	7	131	141	137	124	124			137
1989	8	55	58	79	69	65		49	63
1989	9	95	92	82	87	93		84	104
1989	10	140	116	111	121	133			153
1989	11	173	126	124	119	136			173
1989	12	111	111	100	98	104			92
1990	1	220	228	192	185	203			205
1990	2	58	76	49	84	49		52	53
1990	3	116	130	162	207	128		130	184
1990	4	122	110	113	131	120		130	132
1990	5	191	229	305	191	213			313
1990	6	104	134	108	109	98			
1990	7	194	188	179	162	159		145	172
1990	8	192	196	229	253	220		206	
1990	9	175	164	257	206	178		148	
1990	10	25	26	24	27	25			34
1990	11	223	247	263	271	249			235
1990	12	229	183	158	224	165			118

Appendix I

Water balance results for Tongatapu, 1947-1990

The results of water balance calculations using 44 years of monthly rainfall and evaporation data are shown on the attached sheets.

Explanations for the column headings are listed below:

RAIN	:	rainfall
ET	:	potential evaporation
EI	:	interception loss
SMC1	:	soil moisture content at start of month
ES	:	evaporation from soil moisture store
XCESS	:	rainfall minus evaporation losses above (EI + ES)
AVSMDEF	:	average daily soil moisture deficit for the month
SMC2	:	soil moisture content at end of month
GWR	:	recharge to freshwater lens
TL	:	transpiration due to deep rooted vegetation
EA	:	sum of all evaporation losses (EI + ES + TL)
NETR	:	net recharge to freshwater lens (GWR - TL)
RECHARGE RATIO	:	ratio of net recharge (NETR) to rainfall (RAIN)

PROGRAM WATBAL.6

Water Balance Program to compute Recharge to Groundwater using MONTHLY RAINFALL and AVERAGE MONTHLY EVAPORATION data

- allows for interception losses
- assumes linear relation between evapotranspiration
- ratio (EA/ET) and soil moisture content

RAINFALL & EVAPORATION DATA USED IN WATER BALANCE

Name of Daily Rainfall File : NUKUALOF.RAI
Title of Rainfall Data : Monthly rain data: Nuku'alofa: Tongatapu: 1947-90

Name of Monthly Evap File : TONGTAP1.EVA
Title of Evaporation : Monthly evap (Penman):Tongatapu: (from Thompson, 1986)

No.of Years of Rain Record : 44
First Year of Rain Record : 1947
Last Year of Rain Record : 1990

INPUT SOIL AND VEGETATION PARAMETERS

Interception Store Capacity (ISMAX) in mm = 90
Initial Interception Store (IIS) in mm = 50
Soil Moisture Zone Thickness(SMZ) in mm = 1000
Field Capacity(FC)= .55
Wilting Point(WP)= .4
Max. Soil Moisture Content(SMCMAX=SMZ*FC) is: 550
Min. Soil Moisture Content(SMCMIN=SMZ*WP) is: 400
Initial Soil Moisture Content(ISMC) in mm = 500
Deep Rooted Vegetation(eg Coconut Trees) Ratio(DRVR)= .3
Ratio of these roots reaching water table(DRWT)= 0
Crop Factor for Deep Rooted Vegetation(CROPFD)= .8
Crop Factor for Shallow Rooted Vegetation(CROPFS)= 1
Linear Relation of Ea/Et(actual/potential evap) ratio to SMC

YEAR 1947

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
118	164	90	500	46	32	50	532	0	0	136	0	+0.00
248	137	90	532	39	119	18	550	101	0	129	101	+0.41
94	139	90	550	46	-42	0	508	0	0	136	0	+0.00
73	108	73	508	24	-24	42	484	0	0	97	0	+0.00
84	89	84	484	3	-3	66	482	0	0	87	0	+0.00
74	77	74	482	2	-2	68	480	0	0	76	0	+0.00
142	85	85	480	0	52	70	532	0	0	85	0	+0.00
69	96	74	532	18	-18	18	514	0	0	92	0	+0.00
287	116	90	514	19	178	36	550	142	0	109	142	+0.50
115	144	90	550	51	-26	0	524	0	0	141	0	+0.00
32	152	32	524	93	-93	26	431	0	0	125	0	+0.00
272	154	90	431	12	170	119	550	50	0	102	50	+0.19
1608	1461	962		352				294	0	1314	294	+0.18

YEAR 1948

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
230	164	90	550	70	70	0	550	70	0	160	70	+0.31
212	137	90	550	44	78	0	550	78	0	134	78	+0.37
112	139	90	550	46	-24	0	526	0	0	136	0	+0.00
225	108	90	526	14	121	24	550	97	0	104	97	+0.43
49	89	49	550	38	-38	0	512	0	0	87	0	+0.00
226	77	77	512	0	136	38	550	98	0	77	98	+0.44
28	85	41	550	41	-41	0	509	0	0	82	0	+0.00
23	96	23	509	50	-50	41	459	0	0	73	0	+0.00
120	116	90	459	10	20	91	479	0	0	100	0	+0.00
22	144	22	479	61	-61	71	419	0	0	83	0	+0.00
351	152	90	419	7	254	131	550	122	0	97	122	+0.35
168	154	90	550	60	18	0	550	18	0	150	18	+0.11
1766	1461	842		440				484	0	1282	484	+0.27

YEAR 1949

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
243	164	90	550	70	83	0	550	83	0	160	83	+0.34
217	137	90	550	44	83	0	550	83	0	134	83	+0.38
201	139	90	550	46	65	0	550	65	0	136	65	+0.32
210	108	90	550	17	103	0	550	103	0	107	103	+0.49
24	89	24	550	61	-61	0	489	0	0	85	0	+0.00
26	77	26	489	28	-28	61	460	0	0	54	0	+0.00
103	85	85	460	0	13	90	473	0	0	85	0	+0.00
203	96	90	473	3	115	77	550	39	0	93	39	+0.19
66	116	66	550	47	-47	0	503	0	0	113	0	+0.00
83	144	83	503	39	-39	47	464	0	0	122	0	+0.00
7	152	7	464	58	-58	86	406	0	0	65	0	+0.00
251	154	90	406	2	159	144	550	14	0	92	14	+0.06
1634	1461	831		416				387	0	1247	387	+0.24

YEAR 1950

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
249	164	90	550	70	89	0	550	89	0	160	89	+0.36
249	137	90	550	44	115	0	550	115	0	134	115	+0.46
334	139	90	550	46	198	0	550	198	0	136	198	+0.59
210	108	90	550	17	103	0	550	103	0	107	103	+0.49
17	89	17	550	68	-68	0	482	0	0	85	0	+0.00
67	77	67	482	5	-5	68	477	0	0	72	0	+0.00
259	85	85	477	0	169	73	550	96	0	85	96	+0.37
148	96	90	550	6	57	0	550	57	0	96	57	+0.39
155	116	90	550	24	41	0	550	41	0	114	41	+0.26

131	144	90	550	51	-10	0	540	0	0	141	0	+0.00
146	152	90	540	54	2	10	542	0	0	144	0	+0.00
132	154	90	542	57	-15	8	527	0	0	147	0	+0.00
2097	1461	979		442				699	0	1421	699	+0.33

YEAR 1951

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
202	164	90	527	59	53	23	550	30	0	149	30	+0.15
564	137	90	550	44	430	0	550	430	0	134	430	+0.76
304	139	90	550	46	168	0	550	168	0	136	168	+0.55
104	108	90	550	17	-3	0	547	0	0	107	0	+0.00
127	89	89	547	0	37	3	550	34	0	89	34	+0.27
72	77	73	550	4	-4	0	546	0	0	77	0	+0.00
104	85	85	546	0	14	4	550	10	0	85	10	+0.10
26	96	31	550	61	-61	0	489	0	0	92	0	+0.00
187	116	90	489	14	83	61	550	21	0	104	21	+0.11
42	144	42	550	96	-96	0	454	0	0	138	0	+0.00
21	152	21	454	44	-44	96	410	0	0	65	0	+0.00
3	154	3	410	9	-9	140	401	0	0	12	0	+0.00
1756	1461	794		395				694	0	1189	694	+0.39

YEAR 1952

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
582	164	90	401	0	492	149	550	342	0	90	342	+0.59
443	137	90	550	44	309	0	550	309	0	134	309	+0.70
289	139	90	550	46	153	0	550	153	0	136	153	+0.53
126	108	90	550	17	19	0	550	19	0	107	19	+0.15
25	89	25	550	60	-60	0	490	0	0	85	0	+0.00
153	77	77	490	0	63	60	550	3	0	77	3	+0.02
164	85	85	550	0	87	0	550	87	0	85	87	+0.53
130	96	90	550	6	39	0	550	39	0	96	39	+0.30
100	116	90	550	24	-14	0	536	0	0	114	0	+0.00
21	144	21	536	104	-104	14	431	0	0	125	0	+0.00
119	152	90	431	12	17	119	448	0	0	102	0	+0.00
154	154	90	448	19	45	102	493	0	0	109	0	+0.00
2306	1461	928		333				952	0	1261	952	+0.41

YEAR 1953

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
128	164	90	493	43	-5	57	488	0	0	133	0	+0.00
198	137	90	488	26	82	62	550	20	0	116	20	+0.10
193	139	90	550	46	57	0	550	57	0	136	57	+0.30
288	108	90	550	17	181	0	550	181	0	107	181	+0.63

69	89	69	550	19	-19	0	531	0	0	88	0	+0.00
116	77	77	531	0	26	19	550	7	0	77	7	+0.06
49	85	62	550	22	-22	0	528	0	0	84	0	+0.00
36	96	36	528	48	-48	22	480	0	0	84	0	+0.00
23	116	23	480	47	-47	70	433	0	0	70	0	+0.00
39	144	39	433	22	-22	117	411	0	0	61	0	+0.00
72	152	72	411	6	-6	139	406	0	0	78	0	+0.00
115	154	90	406	2	23	144	428	0	0	92	0	+0.00
1326	1461	828		297				265	0	1125	265	+0.20

YEAR 1954

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
110	164	90	428	13	7	122	435	0	0	103	0	+0.00
218	137	90	435	10	118	115	550	3	0	100	3	+0.01
114	139	90	550	46	-22	0	528	0	0	136	0	+0.00
450	108	90	528	14	346	22	550	324	0	104	324	+0.72
65	89	65	550	23	-23	0	527	0	0	88	0	+0.00
242	77	77	527	0	152	23	550	129	0	77	129	+0.53
38	85	51	550	32	-32	0	518	0	0	83	0	+0.00
133	96	90	518	4	39	32	550	7	0	94	7	+0.05
302	116	90	550	24	188	0	550	188	0	114	188	+0.62
133	144	90	550	51	-8	0	542	0	0	141	0	+0.00
49	152	49	542	92	-92	8	450	0	0	141	0	+0.00
581	154	90	450	20	471	100	550	371	0	110	371	+0.64
2435	1461	962		330				1021	0	1292	1021	+0.42

YEAR 1955

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
197	164	90	550	70	37	0	550	37	0	160	37	+0.19
83	137	83	550	51	-51	0	499	0	0	134	0	+0.00
388	139	90	499	30	268	51	550	217	0	120	217	+0.56
78	108	78	550	28	-28	0	522	0	0	106	0	+0.00
61	89	61	522	21	-21	28	500	0	0	82	0	+0.00
64	77	64	500	8	-8	50	492	0	0	72	0	+0.00
122	85	85	492	0	32	58	524	0	0	85	0	+0.00
122	96	90	524	5	32	26	550	7	0	95	7	+0.05
38	116	38	550	73	-73	0	477	0	0	111	0	+0.00
103	144	90	477	26	-13	73	464	0	0	116	0	+0.00
289	152	90	464	25	174	86	550	88	0	115	88	+0.30
220	154	90	550	60	70	0	550	70	0	150	70	+0.32
1765	1461	949		397				419	0	1346	419	+0.24

YEAR 1956

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO

259	164	90	550	70	99	0	550	99	0	160	99	+0.38
342	137	90	550	44	208	0	550	208	0	134	208	+0.61
340	139	90	550	46	204	0	550	204	0	136	204	+0.60
334	108	90	550	17	227	0	550	227	0	107	227	+0.68
153	89	89	550	0	63	0	550	63	0	89	63	+0.41
27	77	28	550	46	-46	0	504	0	0	74	0	+0.00
190	85	85	504	0	100	46	550	54	0	85	54	+0.28
86	96	90	550	6	-5	0	545	0	0	96	0	+0.00
133	116	90	545	24	19	5	550	15	0	114	15	+0.11
274	144	90	550	51	133	0	550	133	0	141	133	+0.49
150	152	90	550	58	2	0	550	2	0	148	2	+0.01
6	154	6	550	139	-139	0	411	0	0	145	0	+0.00
2294	1461	928		500				1005	0	1428	1005	+0.44

YEAR 1957

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
401	164	90	411	5	306	139	550	167	0	95	167	+0.42
447	137	90	550	44	313	0	550	313	0	134	313	+0.70
131	139	90	550	46	-5	0	545	0	0	136	0	+0.00
48	108	48	545	54	-54	5	490	0	0	102	0	+0.00
74	89	74	490	9	-9	60	482	0	0	83	0	+0.00
242	77	77	482	0	152	68	550	84	0	77	84	+0.35
69	85	82	550	3	-3	0	547	0	0	85	0	+0.00
147	96	90	547	6	51	3	550	49	0	96	49	+0.33
94	116	90	550	24	-20	0	530	0	0	114	0	+0.00
47	144	47	530	79	-79	20	451	0	0	126	0	+0.00
62	152	62	451	29	-29	99	422	0	0	91	0	+0.00
70	154	70	422	12	-12	128	410	0	0	82	0	+0.00
1832	1461	910		310				612	0	1220	612	+0.33

YEAR 1958

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
31	164	31	410	9	-9	140	402	0	0	40	0	+0.00
306	137	90	402	1	215	148	550	67	0	91	67	+0.22
269	139	90	550	46	133	0	550	133	0	136	133	+0.49
138	108	90	550	17	31	0	550	31	0	107	31	+0.23
38	89	38	550	48	-48	0	502	0	0	86	0	+0.00
7	77	7	502	45	-45	48	457	0	0	52	0	+0.00
118	85	85	457	0	28	93	485	0	0	85	0	+0.00
116	96	90	485	3	28	65	513	0	0	93	0	+0.00
56	116	56	513	43	-43	37	471	0	0	99	0	+0.00
337	144	90	471	24	223	79	550	144	0	114	144	+0.43
138	152	90	550	58	-10	0	540	0	0	148	0	+0.00
77	154	77	540	67	-67	10	472	0	0	144	0	+0.00
1631	1461	834		360				375	0	1194	375	+0.23

YEAR 1959

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
203	164	90	472	34	79	78	550	2	0	124	2	+0.01
61	137	61	550	71	-71	0	479	0	0	132	0	+0.00
366	139	90	479	24	252	71	550	180	0	114	180	+0.49
118	108	90	550	17	11	0	550	11	0	107	11	+0.09
114	89	89	550	0	24	0	550	24	0	89	24	+0.21
84	77	77	550	0	0	0	550	0	0	77	0	+0.00
56	85	64	550	20	-20	0	530	0	0	84	0	+0.00
273	96	90	530	5	178	20	550	158	0	95	158	+0.58
184	116	90	550	24	70	0	550	70	0	114	70	+0.38
192	144	90	550	51	51	0	550	51	0	141	51	+0.27
41	152	41	550	104	-104	0	446	0	0	145	0	+0.00
106	154	90	446	18	-2	104	443	0	0	108	0	+0.00
1798	1461	962		369				496	0	1331	496	+0.28

YEAR 1960

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
70	164	70	443	26	-26	107	418	0	0	96	0	+0.00
323	137	90	418	5	228	132	550	96	0	95	96	+0.30
469	139	90	550	46	333	0	550	333	0	136	333	+0.71
194	108	90	550	17	87	0	550	87	0	107	87	+0.45
101	89	89	550	0	11	0	550	11	0	89	11	+0.11
163	77	77	550	0	74	0	550	74	0	77	74	+0.45
102	85	85	550	0	25	0	550	25	0	85	25	+0.25
34	96	39	550	54	-54	0	496	0	0	93	0	+0.00
54	116	54	496	37	-37	54	459	0	0	91	0	+0.00
133	144	90	459	20	23	91	482	0	0	110	0	+0.00
207	152	90	482	32	85	68	550	17	0	122	17	+0.08
231	154	90	550	60	81	0	550	81	0	150	81	+0.35
2081	1461	954		297				724	0	1251	724	+0.35

YEAR 1961

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
372	164	90	550	70	212	0	550	212	0	160	212	+0.57
228	137	90	550	44	94	0	550	94	0	134	94	+0.41
242	139	90	550	46	106	0	550	106	0	136	106	+0.44
112	108	90	550	17	5	0	550	5	0	107	5	+0.05
47	89	47	550	39	-39	0	511	0	0	86	0	+0.00
58	77	58	511	13	-13	39	497	0	0	71	0	+0.00
83	85	83	497	1	-1	53	496	0	0	84	0	+0.00
152	96	90	496	4	58	54	550	5	0	94	5	+0.03
89	116	89	550	25	-25	0	525	0	0	114	0	+0.00
65	144	65	525	62	-62	25	463	0	0	127	0	+0.00
202	152	90	463	24	88	87	550	0	0	114	0	+0.00
66	154	66	550	83	-83	0	467	0	0	149	0	+0.00

1716	1461	948		428				422	0	1376	422	+0.25

YEAR 1962

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
382	164	90	467	31	261	83	550	178	0	121	178	+0.47
188	137	90	550	44	54	0	550	54	0	134	54	+0.29
263	139	90	550	46	127	0	550	127	0	136	127	+0.48
111	108	90	550	17	4	0	550	4	0	107	4	+0.04
139	89	89	550	0	49	0	550	49	0	89	49	+0.35
75	77	76	550	1	-1	0	549	0	0	77	0	+0.00
85	85	85	549	0	0	1	549	0	0	85	0	+0.00
53	96	53	549	40	-40	1	509	0	0	93	0	+0.00
41	116	41	509	51	-51	41	458	0	0	92	0	+0.00
70	144	70	458	27	-27	92	431	0	0	97	0	+0.00
116	152	90	431	12	14	119	445	0	0	102	0	+0.00
242	154	90	445	18	134	105	550	29	0	108	29	+0.12
1765	1461	954		287				441	0	1241	441	+0.25

YEAR 1963

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
145	164	90	550	70	-15	0	535	0	0	160	0	+0.00
147	137	90	535	40	17	15	550	3	0	130	3	+0.02
227	139	90	550	46	91	0	550	91	0	136	91	+0.40
69	108	69	550	37	-37	0	513	0	0	106	0	+0.00
203	89	89	513	0	113	37	550	76	0	89	76	+0.38
102	77	77	550	0	13	0	550	13	0	77	13	+0.13
60	85	73	550	11	-11	0	539	0	0	84	0	+0.00
150	96	90	539	5	55	11	550	44	0	95	44	+0.29
107	116	90	550	24	-7	0	543	0	0	114	0	+0.00
135	144	90	543	48	-3	7	539	0	0	138	0	+0.00
11	152	11	539	123	-123	11	416	0	0	134	0	+0.00
24	154	24	416	13	-13	134	403	0	0	37	0	+0.00
1380	1461	883		418				226	0	1301	226	+0.16

YEAR 1964

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
99	164	90	403	1	8	147	411	0	0	91	0	+0.00
288	137	90	411	3	195	139	550	55	0	93	55	+0.19
280	139	90	550	46	144	0	550	144	0	136	144	+0.51
141	108	90	550	17	34	0	550	34	0	107	34	+0.24
117	89	89	550	0	27	0	550	27	0	89	27	+0.23
8	77	9	550	64	-64	0	486	0	0	73	0	+0.00
256	85	85	486	0	166	64	550	102	0	85	102	+0.40

102	96	90	550	6	11	0	550	11	0	96	11	+0.11
191	116	90	550	24	77	0	550	77	0	114	77	+0.40
105	144	90	550	51	-36	0	514	0	0	141	0	+0.00
255	152	90	514	44	121	36	550	85	0	134	85	+0.33
215	154	90	550	60	65	0	550	65	0	150	65	+0.30
2057	1461	993		317				600	0	1310	600	+0.29

YEAR 1965

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
397	164	90	550	70	237	0	550	237	0	160	237	+0.60
289	137	90	550	44	155	0	550	155	0	134	155	+0.54
211	139	90	550	46	75	0	550	75	0	136	75	+0.36
40	108	40	550	64	-64	0	486	0	0	104	0	+0.00
210	89	89	486	0	120	64	550	56	0	89	56	+0.27
31	77	32	550	42	-42	0	508	0	0	74	0	+0.00
67	85	67	508	12	-12	42	496	0	0	79	0	+0.00
131	96	90	496	4	37	54	533	0	0	94	0	+0.00
76	116	76	533	33	-33	17	500	0	0	109	0	+0.00
129	144	90	500	34	5	50	505	0	0	124	0	+0.00
178	152	90	505	41	47	45	550	2	0	131	2	+0.01
17	154	17	550	129	-129	0	421	0	0	146	0	+0.00
1776	1461	861		518				525	0	1379	525	+0.30

YEAR 1966

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
85	164	85	421	11	-11	129	411	0	0	96	0	+0.00
95	137	90	411	3	2	139	413	0	0	93	0	+0.00
84	139	84	413	4	-4	137	408	0	0	88	0	+0.00
458	108	90	408	1	367	142	550	225	0	91	225	+0.49
63	89	63	550	24	-24	0	526	0	0	87	0	+0.00
45	77	45	526	25	-25	24	500	0	0	70	0	+0.00
52	85	52	500	21	-21	50	480	0	0	73	0	+0.00
46	96	46	480	25	-25	70	455	0	0	71	0	+0.00
181	116	90	455	9	82	95	537	0	0	99	0	+0.00
180	144	90	537	46	44	13	550	30	0	136	30	+0.17
29	152	29	550	116	-116	0	434	0	0	145	0	+0.00
159	154	90	434	14	55	116	490	0	0	104	0	+0.00
1477	1461	854		299				256	0	1153	256	+0.17

YEAR 1967

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
189	164	90	490	42	57	60	547	0	0	132	0	+0.00
105	137	90	547	43	-28	3	519	0	0	133	0	+0.00

243	139	90	519	36	117	31	550	85	0	126	85	+0.35
203	108	90	550	17	96	0	550	96	0	107	96	+0.47
55	89	55	550	32	-32	0	518	0	0	87	0	+0.00
25	77	25	518	38	-38	32	480	0	0	63	0	+0.00
63	85	63	480	11	-11	70	469	0	0	74	0	+0.00
32	96	32	469	28	-28	81	441	0	0	60	0	+0.00
152	116	90	441	7	55	109	496	0	0	97	0	+0.00
147	144	90	496	33	24	54	521	0	0	123	0	+0.00
25	152	25	521	96	-96	29	425	0	0	121	0	+0.00
15	154	15	425	21	-21	125	403	0	0	36	0	+0.00
1254	1461	755		404				181	0	1159	181	+0.14

YEAR 1968

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
527	164	90	403	1	436	147	550	289	0	91	289	+0.55
244	137	90	550	44	110	0	550	110	0	134	110	+0.45
296	139	90	550	46	160	0	550	160	0	136	160	+0.54
96	108	90	550	17	-11	0	539	0	0	107	0	+0.00
59	89	59	539	26	-26	11	513	0	0	85	0	+0.00
85	77	77	513	0	0	37	513	0	0	77	0	+0.00
27	85	35	513	35	-35	37	478	0	0	70	0	+0.00
204	96	90	478	3	111	72	550	39	0	93	39	+0.19
92	116	90	550	24	-22	0	528	0	0	114	0	+0.00
93	144	90	528	43	-40	22	487	0	0	133	0	+0.00
26	152	26	487	69	-69	63	418	0	0	95	0	+0.00
51	154	51	418	12	-12	132	407	0	0	63	0	+0.00
1800	1461	878		322				597	0	1200	597	+0.33

YEAR 1969

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
177	164	90	407	3	84	143	490	0	0	93	0	+0.00
296	137	90	490	27	179	60	550	120	0	117	120	+0.40
348	139	90	550	46	212	0	550	212	0	136	212	+0.61
85	108	85	550	22	-22	0	528	0	0	107	0	+0.00
22	89	22	528	54	-54	22	474	0	0	76	0	+0.00
43	77	43	474	16	-16	76	459	0	0	59	0	+0.00
136	85	85	459	0	46	91	505	0	0	85	0	+0.00
17	96	22	505	49	-49	45	456	0	0	71	0	+0.00
132	116	90	456	9	33	94	489	0	0	99	0	+0.00
50	144	50	489	52	-52	61	437	0	0	102	0	+0.00
52	152	52	437	23	-23	113	414	0	0	75	0	+0.00
5	154	5	414	13	-13	136	401	0	0	18	0	+0.00
1363	1461	724		313				332	0	1037	332	+0.24

YEAR 1970

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
179	164	90	401	0	89	149	489	0	0	90	0	+0.00
373	137	90	489	26	257	61	550	196	0	116	196	+0.53
137	139	90	550	46	1	0	550	1	0	136	1	+0.01
110	108	90	550	17	3	0	550	3	0	107	3	+0.03
96	89	89	550	0	6	0	550	6	0	89	6	+0.06
83	77	77	550	0	0	0	550	0	0	77	0	+0.00
63	85	70	550	14	-14	0	536	0	0	84	0	+0.00
57	96	57	536	33	-33	14	503	0	0	90	0	+0.00
41	116	41	503	48	-48	47	454	0	0	89	0	+0.00
373	144	90	454	18	265	96	550	169	0	108	169	+0.45
106	152	90	550	58	-42	0	508	0	0	148	0	+0.00
352	154	90	508	43	219	42	550	177	0	133	177	+0.50
1970	1461	964		305				552	0	1269	552	+0.28

YEAR 1971

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
187	164	90	550	70	27	0	550	27	0	160	27	+0.15
210	137	90	550	44	76	0	550	76	0	134	76	+0.36
248	139	90	550	46	112	0	550	112	0	136	112	+0.45
176	108	90	550	17	69	0	550	69	0	107	69	+0.39
188	89	89	550	0	98	0	550	98	0	89	98	+0.52
36	77	37	550	38	-38	0	512	0	0	75	0	+0.00
18	85	18	512	47	-47	38	465	0	0	65	0	+0.00
112	96	90	465	2	20	85	485	0	0	92	0	+0.00
198	116	90	485	14	94	65	550	29	0	104	29	+0.15
131	144	90	550	51	-10	0	540	0	0	141	0	+0.00
368	152	90	540	54	224	10	550	214	0	144	214	+0.58
783	154	90	550	60	633	0	550	633	0	150	633	+0.81
2655	1461	954		443				1258	0	1397	1258	+0.47

YEAR 1972

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
197	164	90	550	70	37	0	550	37	0	160	37	+0.19
162	137	90	550	44	28	0	550	28	0	134	28	+0.17
326	139	90	550	46	190	0	550	190	0	136	190	+0.58
124	108	90	550	17	17	0	550	17	0	107	17	+0.14
166	89	89	550	0	76	0	550	76	0	89	76	+0.46
151	77	77	550	0	62	0	550	62	0	77	62	+0.41
160	85	85	550	0	83	0	550	83	0	85	83	+0.52
209	96	90	550	6	118	0	550	118	0	96	118	+0.57
341	116	90	550	24	227	0	550	227	0	114	227	+0.66
340	144	90	550	51	199	0	550	199	0	141	199	+0.59
33	152	33	550	112	-112	0	438	0	0	145	0	+0.00
167	154	90	438	15	62	112	500	0	0	105	0	+0.00
2376	1461	%1004		385				1037	0	1389	1037	+0.44

YEAR 1973

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
35	164	35	500	81	-81	50	419	0	0	116	0	+0.00
256	137	90	419	6	160	131	550	29	0	96	29	+0.12
205	139	90	550	46	69	0	550	69	0	136	69	+0.34
303	108	90	550	17	196	0	550	196	0	107	196	+0.65
37	89	37	550	49	-49	0	501	0	0	86	0	+0.00
103	77	77	501	0	13	49	514	0	0	77	0	+0.00
108	85	85	514	0	31	36	545	0	0	85	0	+0.00
25	96	30	545	60	-60	5	485	0	0	90	0	+0.00
207	116	90	485	14	103	65	550	38	0	104	38	+0.18
112	144	90	550	51	-29	0	521	0	0	141	0	+0.00
343	152	90	521	47	206	29	550	177	0	137	177	+0.52
294	154	90	550	60	144	0	550	144	0	150	144	+0.49
2028	1461	894		430				654	0	1324	654	+0.32

YEAR 1974

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
243	164	90	550	70	83	0	550	83	0	160	83	+0.34
462	137	90	550	44	328	0	550	328	0	134	328	+0.71
279	139	90	550	46	143	0	550	143	0	136	143	+0.51
346	108	90	550	17	239	0	550	239	0	107	239	+0.69
78	89	78	550	10	-10	0	540	0	0	88	0	+0.00
115	77	77	540	0	25	10	550	15	0	77	15	+0.13
67	85	80	550	5	-5	0	545	0	0	85	0	+0.00
90	96	90	545	5	-5	5	540	0	0	95	0	+0.00
196	116	90	540	23	83	10	550	73	0	113	73	+0.37
452	144	90	550	51	311	0	550	311	0	141	311	+0.69
151	152	90	550	58	3	0	550	3	0	148	3	+0.02
74	154	74	550	75	-75	0	475	0	0	149	0	+0.00
2553	1461	%1029		404				1195	0	1433	1195	+0.47

YEAR 1975

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
203	164	90	475	35	78	75	550	3	0	125	3	+0.02
83	137	83	550	51	-51	0	499	0	0	134	0	+0.00
174	139	90	499	30	54	51	550	3	0	120	3	+0.02
163	108	90	550	17	56	0	550	56	0	107	56	+0.34
140	89	89	550	0	50	0	550	50	0	89	50	+0.36
135	77	77	550	0	46	0	550	46	0	77	46	+0.34
95	85	85	550	0	18	0	550	18	0	85	18	+0.19
160	96	90	550	6	69	0	550	69	0	96	69	+0.43
84	116	84	550	30	-30	0	520	0	0	114	0	+0.00
133	144	90	520	41	2	30	522	0	0	131	0	+0.00

322	152	90	522	48	184	28	550	157	0	138	157	+0.49
54	154	54	550	94	-94	0	456	0	0	148	0	+0.00
1746	1461	%1012		351				402	0	1363	402	+0.23

YEAR 1976

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
252	164	90	456	26	136	94	550	42	0	116	42	+0.17
371	137	90	550	44	237	0	550	237	0	134	237	+0.64
231	139	90	550	46	95	0	550	95	0	136	95	+0.41
365	108	90	550	17	258	0	550	258	0	107	258	+0.71
94	89	89	550	0	4	0	550	4	0	89	4	+0.04
50	77	51	550	24	-24	0	526	0	0	75	0	+0.00
61	85	61	526	19	-19	24	507	0	0	80	0	+0.00
59	96	59	507	25	-25	43	482	0	0	84	0	+0.00
212	116	90	482	13	109	68	550	41	0	103	41	+0.19
129	144	90	550	51	-12	0	538	0	0	141	0	+0.00
246	152	90	538	54	102	12	550	91	0	144	91	+0.37
46	154	46	550	102	-102	0	448	0	0	148	0	+0.00
2116	1461	936		421				767	0	1357	767	+0.36

YEAR 1977

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
377	164	90	448	22	265	102	550	163	0	112	163	+0.43
284	137	90	550	44	150	0	550	150	0	134	150	+0.53
266	139	90	550	46	130	0	550	130	0	136	130	+0.49
43	108	43	550	61	-61	0	489	0	0	104	0	+0.00
46	89	46	489	24	-24	61	465	0	0	70	0	+0.00
17	77	17	465	24	-24	85	441	0	0	41	0	+0.00
73	85	73	441	3	-3	109	437	0	0	76	0	+0.00
130	96	90	437	1	39	113	476	0	0	91	0	+0.00
56	116	56	476	29	-29	74	447	0	0	85	0	+0.00
17	144	17	447	38	-38	103	410	0	0	55	0	+0.00
6	152	6	410	9	-9	140	401	0	0	15	0	+0.00
48	154	48	401	1	-1	149	400	0	0	49	0	+0.00
1363	1461	666		302				443	0	968	443	+0.32

YEAR 1978

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
40	164	40	400	0	-0	150	400	0	0	40	0	+0.00
151	137	90	400	0	61	150	461	0	0	90	0	+0.00
214	139	90	461	19	105	89	550	16	0	109	16	+0.08
248	108	90	550	17	141	0	550	141	0	107	141	+0.57
204	89	89	550	0	114	0	550	114	0	89	114	+0.56

46	77	47	550	28	-28	0	522	0	0	75	0	+0.00
82	85	82	522	2	-2	28	520	0	0	84	0	+0.00
250	96	90	520	4	156	30	550	125	0	94	125	+0.50
102	116	90	550	24	-12	0	538	0	0	114	0	+0.00
272	144	90	538	47	135	12	550	123	0	137	123	+0.45
229	152	90	550	58	81	0	550	81	0	148	81	+0.35
92	154	90	550	60	-58	0	492	0	0	150	0	+0.00
1930	1461	978		260				600	0	1238	600	+0.31

YEAR 1979

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
115	164	90	492	43	-18	58	474	0	0	133	0	+0.00
77	137	77	474	28	-28	76	446	0	0	105	0	+0.00
261	139	90	446	14	157	104	550	53	0	104	53	+0.20
183	108	90	550	17	76	0	550	76	0	107	76	+0.42
208	89	89	550	0	118	0	550	118	0	89	118	+0.57
243	77	77	550	0	154	0	550	154	0	77	154	+0.63
75	85	85	550	0	0	0	550	0	0	85	0	+0.00
237	96	90	550	6	144	0	550	144	0	96	144	+0.61
271	116	90	550	24	157	0	550	157	0	114	157	+0.58
60	144	60	550	79	-79	0	471	0	0	139	0	+0.00
133	152	90	471	28	15	79	486	0	0	118	0	+0.00
159	154	90	486	35	34	64	521	0	0	125	0	+0.00
2022	1461	%1018		273				702	0	1291	702	+0.35

YEAR 1980

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
139	164	90	521	56	-7	29	514	0	0	146	0	+0.00
123	137	90	514	34	-1	36	513	0	0	124	0	+0.00
291	139	90	513	35	166	37	550	129	0	125	129	+0.44
267	108	90	550	17	160	0	550	160	0	107	160	+0.60
45	89	45	550	41	-41	0	509	0	0	86	0	+0.00
111	77	77	509	0	21	41	530	0	0	77	0	+0.00
144	85	85	530	0	67	20	550	47	0	85	47	+0.32
161	96	90	550	6	70	0	550	70	0	96	70	+0.44
189	116	90	550	24	75	0	550	75	0	114	75	+0.39
399	144	90	550	51	258	0	550	258	0	141	258	+0.65
114	152	90	550	58	-34	0	516	0	0	148	0	+0.00
143	154	90	516	46	7	34	522	0	0	136	0	+0.00
2126	1461	%1017		368				739	0	1385	739	+0.35

YEAR 1981

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO

60	164	60	522	80	-80	28	443	0	0	140	0	+0.00
98	137	90	443	13	-5	107	438	0	0	103	0	+0.00
118	139	90	438	12	16	112	454	0	0	102	0	+0.00
72	108	72	454	12	-12	96	442	0	0	84	0	+0.00
102	89	89	442	0	12	108	454	0	0	89	0	+0.00
94	77	77	454	0	5	96	459	0	0	77	0	+0.00
23	85	36	459	18	-18	91	441	0	0	54	0	+0.00
56	96	56	441	10	-10	109	431	0	0	66	0	+0.00
66	116	66	431	10	-10	119	421	0	0	76	0	+0.00
54	144	54	421	12	-12	129	409	0	0	66	0	+0.00
90	152	90	409	4	-4	141	406	0	0	94	0	+0.00
41	154	41	406	4	-4	144	402	0	0	45	0	+0.00
874	1461	821		174				0	0	995	0	+0.00

YEAR 1982

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
386	164	90	402	1	295	148	550	147	0	91	147	+0.38
238	137	90	550	44	104	0	550	104	0	134	104	+0.44
253	139	90	550	46	117	0	550	117	0	136	117	+0.46
136	108	90	550	17	29	0	550	29	0	107	29	+0.21
241	89	89	550	0	151	0	550	151	0	89	151	+0.63
58	77	59	550	17	-17	0	533	0	0	76	0	+0.00
87	85	85	533	0	0	17	533	0	0	85	0	+0.00
149	96	90	533	5	56	17	550	39	0	95	39	+0.26
75	116	75	550	39	-39	0	511	0	0	114	0	+0.00
34	144	34	511	77	-77	39	435	0	0	111	0	+0.00
19	152	19	435	29	-29	115	406	0	0	48	0	+0.00
57	154	57	406	4	-4	144	402	0	0	61	0	+0.00
1733	1461	868		278				587	0	1146	587	+0.34

YEAR 1983

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
37	164	37	402	2	-2	148	400	0	0	39	0	+0.00
102	137	90	400	0	12	150	412	0	0	90	0	+0.00
73	139	73	412	5	-5	138	407	0	0	78	0	+0.00
9	108	9	407	4	-4	143	403	0	0	13	0	+0.00
26	89	26	403	1	-1	147	402	0	0	27	0	+0.00
69	77	69	402	0	-0	148	402	0	0	69	0	+0.00
118	85	85	402	0	28	148	430	0	0	85	0	+0.00
66	96	71	430	5	-5	120	425	0	0	76	0	+0.00
41	116	41	425	12	-12	125	413	0	0	53	0	+0.00
108	144	90	413	4	14	137	427	0	0	94	0	+0.00
24	152	24	427	21	-21	123	405	0	0	45	0	+0.00
165	154	90	405	2	73	145	478	0	0	92	0	+0.00
838	1461	705		57				0	0	762	0	+0.00

YEAR 1984

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
222	164	90	478	36	96	72	550	24	0	126	24	+0.11
217	137	90	550	44	83	0	550	83	0	134	83	+0.38
71	139	71	550	64	-64	0	486	0	0	135	0	+0.00
126	108	90	486	10	26	64	512	0	0	100	0	+0.00
26	89	26	512	44	-44	38	468	0	0	70	0	+0.00
75	77	75	468	1	-1	82	467	0	0	76	0	+0.00
70	85	70	467	6	-6	83	461	0	0	76	0	+0.00
41	96	41	461	21	-21	89	440	0	0	62	0	+0.00
142	116	90	440	6	46	110	485	0	0	96	0	+0.00
64	144	64	485	43	-43	65	443	0	0	107	0	+0.00
80	152	80	443	19	-19	107	423	0	0	99	0	+0.00
177	154	90	423	9	78	127	501	0	0	99	0	+0.00
1311	1461	877		304				107	0	1181	107	+0.08

YEAR 1985

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
97	164	90	501	47	-40	49	461	0	0	137	0	+0.00
162	137	90	461	18	54	89	515	0	0	108	0	+0.00
212	139	90	515	35	87	35	550	52	0	125	52	+0.24
54	108	54	550	51	-51	0	499	0	0	105	0	+0.00
102	89	89	499	0	12	51	511	0	0	89	0	+0.00
140	77	77	511	0	51	39	550	12	0	77	12	+0.09
56	85	69	550	15	-15	0	535	0	0	84	0	+0.00
27	96	27	535	58	-58	15	477	0	0	85	0	+0.00
28	116	28	477	42	-42	73	434	0	0	70	0	+0.00
53	144	53	434	20	-20	116	415	0	0	73	0	+0.00
3	152	3	415	14	-14	135	401	0	0	17	0	+0.00
429	154	90	401	0	339	149	550	190	0	90	190	+0.44
1363	1461	760		300				254	0	1060	254	+0.19

YEAR 1986

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
12	164	12	550	143	-143	0	407	0	0	155	0	+0.00
69	137	69	407	3	-3	143	404	0	0	72	0	+0.00
113	139	90	404	1	22	146	426	0	0	91	0	+0.00
285	108	90	426	3	192	124	550	68	0	93	68	+0.24
118	89	89	550	0	28	0	550	28	0	89	28	+0.24
215	77	77	550	0	126	0	550	126	0	77	126	+0.59
62	85	75	550	9	-9	0	541	0	0	84	0	+0.00
98	96	90	541	5	3	9	543	0	0	95	0	+0.00
16	116	16	543	90	-90	7	454	0	0	106	0	+0.00
57	144	57	454	29	-29	96	424	0	0	86	0	+0.00
25	152	25	424	19	-19	126	405	0	0	44	0	+0.00
199	154	90	405	2	107	145	512	0	0	92	0	+0.00

1269	1461	780		305				222	0	1085	222	+0.17

YEAR 1987

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
57	164	57	512	75	-75	38	437	0	0	132	0	+0.00
204	137	90	437	11	103	113	540	0	0	101	0	+0.00
169	139	90	540	43	36	10	550	26	0	133	26	+0.15
17	108	17	550	86	-86	0	464	0	0	103	0	+0.00
85	89	85	464	2	-2	86	463	0	0	87	0	+0.00
35	77	35	463	17	-17	87	446	0	0	52	0	+0.00
54	85	54	446	9	-9	104	437	0	0	63	0	+0.00
17	96	17	437	18	-18	113	419	0	0	35	0	+0.00
25	116	25	419	11	-11	131	408	0	0	36	0	+0.00
40	144	40	408	5	-5	142	403	0	0	45	0	+0.00
41	152	41	403	2	-2	147	401	0	0	43	0	+0.00
157	154	90	401	0	67	149	468	0	0	90	0	+0.00
901	1461	641		278				26	0	919	26	+0.03

YEAR 1988

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
280	164	90	468	31	159	82	550	76	0	121	76	+0.27
242	137	90	550	44	108	0	550	108	0	134	108	+0.45
114	139	90	550	46	-22	0	528	0	0	136	0	+0.00
215	108	90	528	14	111	22	550	89	0	104	89	+0.41
69	89	69	550	19	-19	0	531	0	0	88	0	+0.00
32	77	32	531	37	-37	19	494	0	0	69	0	+0.00
101	85	85	494	0	11	56	505	0	0	85	0	+0.00
46	96	51	505	30	-30	45	476	0	0	81	0	+0.00
313	116	90	476	12	211	74	550	136	0	102	136	+0.44
114	144	90	550	51	-27	0	523	0	0	141	0	+0.00
26	152	26	523	97	-97	27	426	0	0	123	0	+0.00
209	154	90	426	10	109	124	535	0	0	100	0	+0.00
1761	1461	893		392				409	0	1285	409	+0.23

YEAR 1989

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
143	164	90	535	62	-9	15	525	0	0	152	0	+0.00
726	137	90	525	37	599	25	550	574	0	127	574	+0.79
168	139	90	550	46	32	0	550	32	0	136	32	+0.19
153	108	90	550	17	46	0	550	46	0	107	46	+0.30
221	89	89	550	0	131	0	550	131	0	89	131	+0.59
47	77	48	550	27	-27	0	523	0	0	75	0	+0.00
131	85	85	523	0	41	27	550	14	0	85	14	+0.10
55	96	60	550	34	-34	0	516	0	0	94	0	+0.00

95	116	90	516	19	-14	34	502	0	0	109	0	+0.00
140	144	90	502	35	15	48	518	0	0	125	0	+0.00
173	152	90	518	46	37	32	550	5	0	136	5	+0.03
111	154	90	550	60	-39	0	511	0	0	150	0	+0.00
2163	1461	%1002		383				802	0	1385	802	+0.37

YEAR 1990

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
220	164	90	511	51	79	39	550	39	0	141	39	+0.18
58	137	58	550	74	-74	0	476	0	0	132	0	+0.00
116	139	90	476	23	3	74	478	0	0	113	0	+0.00
122	108	90	478	9	23	72	502	0	0	99	0	+0.00
191	89	89	502	0	101	48	550	53	0	89	53	+0.28
104	77	77	550	0	15	0	550	15	0	77	15	+0.14
194	85	85	550	0	117	0	550	117	0	85	117	+0.60
192	96	90	550	6	101	0	550	101	0	96	101	+0.53
175	116	90	550	24	61	0	550	61	0	114	61	+0.35
25	144	25	550	112	-112	0	438	0	0	137	0	+0.00
223	152	90	438	15	118	112	550	6	0	105	6	+0.03
229	154	90	550	60	79	0	550	79	0	150	79	+0.34
1849	1461	964		375				471	0	1339	471	+0.25

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1770	1461	893		348				528	0	1242	528	+0.30

Summary of Monthly Recharge (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Recharge	Annual Rainfall
1947	0	101	0	0	0	0	0	0	142	0	0	50	294	1,608
1948	70	78	0	97	0	98	0	0	0	0	122	18	484	1,766
1949	83	83	65	103	0	0	0	39	0	0	0	14	387	1,634
1950	89	115	198	103	0	0	96	57	41	0	0	0	699	2,097
1951	30	430	168	0	34	0	10	0	21	0	0	0	694	1,756
1952	342	309	153	19	0	3	87	39	0	0	0	0	952	2,246
1953	0	20	57	181	0	7	0	0	0	0	0	0	265	1,316
1954	0	3	0	324	0	129	0	7	188	0	0	371	1,021	2,435
1955	37	0	217	0	0	0	0	7	0	0	88	70	419	1,765
1956	99	208	204	227	63	0	54	0	15	133	2	0	1,005	2,294
1957	167	313	0	0	0	84	0	49	0	0	0	0	612	1,832
1958	0	67	133	31	0	0	0	0	0	144	0	0	375	1,631
1959	2	0	180	11	24	0	0	158	70	51	0	0	496	898
1960	0	96	333	87	11	74	25	0	0	0	17	81	724	2,081
1961	212	94	106	5	0	0	0	5	0	0	0	0	422	1,716
1962	178	54	127	4	49	0	0	0	0	0	0	29	441	1,765
1963	0	3	91	0	76	13	0	44	0	0	0	0	226	1,380
1964	0	55	144	34	27	0	102	11	77	0	85	65	600	2,057
1965	237	155	75	0	56	0	0	0	0	0	2	0	525	1,776
1966	0	0	0	225	0	0	0	0	0	30	0	0	256	1,477
1967	0	0	85	96	0	0	0	0	0	0	0	0	181	1,254
1968	289	110	160	0	0	0	0	39	0	0	0	0	597	1,800
1969	0	120	212	0	0	0	0	0	0	0	0	0	332	1,363
1970	0	196	1	3	6	0	0	0	0	169	0	177	552	1,970
1971	27	76	112	69	98	0	0	0	29	0	214	633	1,258	2,655
1972	37	28	190	17	76	62	83	118	227	199	0	0	1,037	2,376
1973	0	29	69	196	0	0	0	0	38	0	177	144	654	2,028
1974	83	328	143	239	0	15	0	0	73	311	3	0	1,195	2,553
1975	3	0	3	56	50	46	18	69	0	0	157	0	402	1,746
1976	42	237	95	258	4	0	0	0	41	0	91	0	767	2,116
1977	163	150	130	0	0	0	0	0	0	0	0	0	443	1,363
1978	0	0	16	141	114	0	0	125	0	123	81	0	600	1,930
1979	0	0	53	76	118	154	0	144	157	0	0	0	702	2,022
1980	0	0	129	160	0	0	47	70	75	258	0	0	739	2,126
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	874
1982	147	104	117	29	151	0	0	39	0	0	0	0	587	1,733
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	838
1984	24	83	0	0	0	0	0	0	0	0	0	0	107	1,311
1985	0	0	52	0	0	12	0	0	0	0	0	190	254	1,363
1986	0	0	0	68	28	126	0	0	0	0	0	0	222	1,269
1987	0	0	26	0	0	0	0	0	0	0	0	0	26	901
1988	76	108	0	89	0	0	0	0	136	0	0	0	409	1,761
1989	0	574	32	46	131	0	14	0	0	0	5	0	802	2,163
1990	39	0	0	0	53	15	117	101	61	0	6	79	471	1,849

Appendix J

Water quality and level monitoring information, Ha'apai

(from dbase file HAPWELLS.DBF)

Well No	Date	Depth to water (m)	Electrical Conductivity (µS/cm)	Temperature (ºC)	pH	Pump status (TRUE = ON, FALSE = OFF)
1	3/03/1990	0.00	2,450	0.0	0.00	FALSE
1	19/09/1990	4.35	1,878	23.9	8.14	FALSE
2	19/09/1990	5.29	1,925	25.3	7.95	FALSE
3	19/09/1990	2.30	1,096	25.2	7.59	FALSE
4	19/09/1990	1.49	1,245	24.9	7.85	FALSE
5	3/03/1990	0.00	840	0.0	0.00	FALSE
5	19/09/1990	2.11	837	25.2	7.77	FALSE
6	20/09/1990	2.30	1,218	24.6	7.82	FALSE
7	20/09/1990	3.04	2,610	25.0	7.83	FALSE
8	20/09/1990	1.33	433	22.9	8.39	FALSE
9	20/09/1990	2.71	641	23.6	8.16	FALSE
10	20/09/1990	2.19	861	24.2	0.00	FALSE
11	20/09/1990	2.13	523	23.0	0.00	FALSE
12	20/09/1990	2.69	356	23.0	8.08	FALSE
13	20/09/1990	1.96	543	23.8	7.96	FALSE
14	20/09/1990	1.97	1,038	23.7	0.00	FALSE
15	20/09/1990	1.66	674	24.8	7.84	FALSE
16	20/09/1990	2.57	342	24.2	7.96	FALSE
17	20/09/1990	3.44	1,560	24.6	7.90	FALSE
18	20/09/1990	3.13	795	25.2	8.04	FALSE
19	20/09/1990	2.69	1,035	23.8	7.98	FALSE
20	4/03/1990	0.00	2,800	0.0	0.00	FALSE
20	21/09/1990	1.89	1,475	24.6	7.74	FALSE
21	21/09/1990	2.13	684	23.5	8.25	FALSE
22	21/09/1990	2.47	782	23.8	7.99	FALSE
23	4/03/1990	0.00	1,700	0.0	0.00	TRUE
23	21/09/1990	4.01	881	23.8	7.93	FALSE
23	7/02/1991	3.43	2,830	26.1	0.00	FALSE
24	3/08/1985	0.00	1,930	24.0	0.00	TRUE
24	4/03/1990	0.00	4,000	0.0	0.00	TRUE
24	21/09/1990	3.66	1,466	24.8	7.95	FALSE
24	7/02/1991	3.95	2,190	26.0	0.00	FALSE
25	4/03/1990	0.00	1,100	0.0	0.00	FALSE
25	21/09/1990	3.42	646	23.6	8.21	FALSE
26	21/09/1990	3.29	990	23.6	8.26	FALSE
27	21/09/1990	2.65	858	24.4	7.94	FALSE
28	3/03/1990	0.00	2,730	0.0	0.00	FALSE
28	22/09/1990	11.40	2,230	25.1	7.50	FALSE
28	31/01/1991	11.42	0	0.0	0.00	FALSE
29	22/09/1990	9.70	0	0.0	0.00	FALSE
30	22/09/1990	0.00	6,230	0.0	0.00	FALSE
31	3/03/1990	0.00	990	0.0	0.00	FALSE
31	22/09/1990	2.70	926	24.1	8.33	FALSE
32	3/03/1990	0.00	810	0.0	0.00	FALSE
32	22/09/1990	0.00	753	25.0	8.07	FALSE
33	3/03/1990	0.00	830	0.0	0.00	FALSE
33	22/09/1990	0.00	659	25.4	7.82	FALSE

34	3/08/1985	0.00	5,600	24.8	0.00	TRUE
34	3/03/1990	0.00	5,100	0.0	0.00	FALSE
34	22/09/1990	5.14	3,490	25.7	7.10	FALSE
34	31/01/1991	5.24	6,000	26.4	0.00	FALSE
35	22/09/1990	0.00	1,811	25.3	7.85	FALSE
36	22/09/1990	0.00	353	25.0	7.97	FALSE
37	3/03/1990	0.00	8,700	0.0	0.00	FALSE
37	22/09/1990	6.92	5,980	24.9	7.20	FALSE
38	3/08/1985	0.00	3,400	25.4	0.00	TRUE
38	3/03/1990	0.00	6,880	0.0	0.00	FALSE
38	22/09/1990	4.25	5,130	27.2	7.37	FALSE
39	5/03/1990	0.00	1,200	0.0	0.00	FALSE
39	22/09/1990	4.05	1,539	23.9	8.06	FALSE
40	22/09/1990	0.00	1,449	26.0	8.01	FALSE
41	22/09/1990	2.94	5,290	23.8	7.80	FALSE
42	4/03/1990	0.00	12,300	0.0	0.00	TRUE
42	22/09/1990	2.64	6,520	24.5	7.92	FALSE
43	22/09/1990	2.63	3,470	23.6	8.28	FALSE
44	3/03/1990	0.00	520	0.0	0.00	FALSE
44	22/09/1990	2.65	542	23.2	8.21	FALSE
45	1/08/1985	0.00	11,900	25.0	0.00	TRUE
45	2/08/1985	0.00	12,800	25.0	0.00	TRUE
45	3/03/1990	0.00	3,120	0.0	0.00	FALSE
45	22/09/1990	7.23	2,940	24.2	7.44	FALSE
45	31/01/1991	7.20	2,190	27.8	7.24	FALSE
46	2/08/1985	0.00	9,200	25.0	0.00	TRUE
46	3/03/1990	0.00	12,500	0.0	0.00	TRUE
46	22/09/1990	7.18	10,030	26.1	7.30	FALSE
46	31/01/1991	7.05	8,730	26.7	7.22	TRUE
47	22/09/1990	4.00	853	23.6	7.80	FALSE
48	22/09/1990	4.15	4,150	26.2	0.00	FALSE
49	22/09/1990	8.80	883	0.0	0.00	FALSE
49	31/01/1991	8.85	1,000	27.1	9.85	FALSE
50	22/09/1990	2.65	869	24.8	8.10	FALSE
51	22/09/1990	2.30	839	24.7	8.13	FALSE
52	22/09/1990	2.22	771	24.7	7.78	FALSE
53	22/09/1990	1.89	826	25.3	8.28	FALSE
54	22/09/1990	2.43	2,390	24.2	0.00	FALSE
55	22/09/1990	2.17	2,620	24.5	7.84	FALSE
56	22/09/1990	3.82	1,410	24.5	8.14	FALSE
57	22/09/1990	2.80	1,436	23.1	0.00	FALSE
58	22/09/1990	1.46	866	24.8	7.97	FALSE
59	22/09/1990	2.82	886	23.7	0.00	FALSE
60	22/09/1990	2.34	1,038	23.8	8.11	FALSE
61	22/09/1990	6.55	2,030	25.5	7.44	FALSE
62	22/09/1990	3.16	1,137	24.0	0.00	FALSE
63	5/03/1990	0.00	3,400	0.0	0.00	FALSE
63	22/09/1990	2.23	550	23.2	8.31	FALSE

Appendix K

Water balance results for Ha'apai, 1947-1990

The results of water balance calculations using 44 years of monthly rainfall and evaporation data are shown on the attached sheets.

Explanations for the column headings are listed below:

RAIN	:	rainfall
ET	:	potential evaporation
EI	:	interception loss
SMC1	:	soil moisture content at start of month
ES	:	evaporation from soil moisture store
XCESS	:	rainfall minus evaporation losses above (EI + ES)
AVSMDEF	:	average daily soil moisture deficit for the month
SMC2	:	soil moisture content at end of month
GWR	:	recharge to freshwater lens
TL	:	transpiration due to deep rooted vegetation
EA	:	sum of all evaporation losses (EI + ES + TL)
NETR	:	net recharge to freshwater lens (GWR - TL)
RECHARGE RATIO	:	ratio of net recharge (NETR) to rainfall (RAIN)

PROGRAM WATBAL.6

Water Balance Program to compute Recharge to Groundwater using MONTHLY RAINFALL and AVERAGE MONTHLY EVAPORATION data

- allows for interception losses

- assumes linear relation between evapotranspiration

- ratio (EA/ET) and soil moisture content

RAINFALL & EVAPORATION DATA USED IN WATER BALANCE

Name of Daily Rainfall File : HAAPAI.RAI
Title of Rainfall Data : Monthly rainfall data: Ha'apai: Tonga: 1947-90

Name of Monthly Evap File : HAAPAI.EVA
Title of Evaporation : Monthly evap (Penman): Ha'apai : (from Thompson, 1986)

No.of Years of Rain Record : 44
First Year of Rain Record : 1947
Last Year of Rain Record : 1990

INPUT SOIL AND VEGETATION PARAMETERS

Interception Store Capacity (ISMAX) in mm = 90
Initial Interception Store (IIS) in mm = 50
Soil Moisture Zone Thickness(SMZ) in mm = 1000
Field Capacity(FC)= .55
Wilting Point(WP)= .4
Max. Soil Moisture Content(SMCMAX=SMZ*FC) is: 550
Min. Soil Moisture Content(SMCMIN=SMZ*WP) is: 400
Initial Soil Moisture Content(ISMC) in mm = 500
Deep Rooted Vegetation(eg Coconut Trees) Ratio(DRVR)= .5
Ratio of these roots reaching water table(DRWT)= .1
Crop Factor for Deep Rooted Vegetation(CROPFD)= .8
Crop Factor for Shallow Rooted Vegetation(CROPFS)= 1
Linear Relation of Ea/Et(actual/potential evap) ratio to SMC

YEAR 1947

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
201	161	90	500	41	120	50	550	70	3	134	67	+0.34
189	144	90	550	46	53	0	550	53	2	139	50	+0.27
313	145	90	550	47	176	0	550	176	2	140	174	+0.55
109	113	90	550	20	-1	0	549	0	1	111	-1	-0.01
177	103	90	549	11	76	1	550	75	1	102	75	+0.42
105	89	89	550	0	15	0	550	15	0	89	15	+0.14
115	101	90	550	9	17	0	550	17	0	100	16	+0.14
99	109	90	550	16	-7	0	543	0	1	107	-1	-0.01
201	121	90	543	25	86	7	550	78	1	117	77	+0.38
88	145	88	550	49	-49	0	501	0	2	139	-2	-0.03
16	156	16	501	81	-81	49	420	0	6	103	-6	-0.35
254	161	90	420	8	156	130	550	26	3	101	23	+0.09
1867	1548	%1003		355				509	22	1379	488	+0.26

YEAR 1948

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
432	161	90	550	61	281	0	550	281	3	154	278	+0.64
147	144	90	550	46	11	0	550	11	2	139	8	+0.06
202	145	90	550	47	65	0	550	65	2	140	62	+0.31
251	113	90	550	20	141	0	550	141	1	111	140	+0.56
52	103	52	550	44	-44	0	506	0	2	98	-2	-0.04
108	89	89	506	0	18	44	524	0	0	89	0	+0.00
45	101	46	524	39	-39	26	485	0	2	87	-2	-0.05
17	109	17	485	45	-45	65	440	0	4	66	-4	-0.22
51	121	51	440	16	-16	110	424	0	3	70	-3	-0.05
139	145	90	424	8	41	126	465	0	2	100	-2	-0.02
245	156	90	465	25	130	85	550	46	3	117	43	+0.18
294	161	90	550	61	143	0	550	143	3	154	140	+0.48
1983	1548	885		412				686	27	1323	660	+0.33

YEAR 1949

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
259	161	90	550	61	108	0	550	108	3	154	105	+0.41
270	144	90	550	46	134	0	550	134	2	139	131	+0.49
212	145	90	550	47	75	0	550	75	2	140	73	+0.34
171	113	90	550	20	61	0	550	61	1	111	60	+0.35
16	103	16	550	75	-75	0	475	0	3	94	-3	-0.22
38	89	38	475	22	-22	75	453	0	2	62	-2	-0.05
238	101	90	453	3	145	97	550	48	0	94	47	+0.20
114	109	90	550	16	8	0	550	8	1	107	7	+0.06
203	121	90	550	27	86	0	550	86	1	118	85	+0.42
255	145	90	550	47	118	0	550	118	2	140	116	+0.45
20	156	20	550	117	-117	0	433	0	5	142	-5	-0.27
285	161	90	433	13	182	117	550	65	3	106	62	+0.22
2081	1548	884		495				702	27	1406	675	+0.32

YEAR 1950

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
237	161	90	550	61	86	0	550	86	3	154	83	+0.35
118	144	90	550	46	-18	0	532	0	2	139	-2	-0.02
470	145	90	532	41	339	18	550	320	2	134	318	+0.68
334	113	90	550	20	224	0	550	224	1	111	223	+0.67
101	103	90	550	11	-0	0	550	0	1	102	-1	-0.01
42	89	42	550	40	-40	0	509	0	2	84	-2	-0.04
156	101	90	509	7	59	41	550	19	0	97	18	+0.12
33	109	33	550	65	-65	0	485	0	3	101	-3	-0.09
156	121	90	485	15	51	65	536	0	1	106	-1	-0.01
128	145	90	536	43	-5	14	531	0	2	135	-2	-0.02

247	156	90	531	50	107	19	550	88	3	142	86	+0.35
353	161	90	550	61	202	0	550	202	3	154	199	+0.56
2375	1548	975		461				939	23	1459	916	+0.39

YEAR 1951

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
233	161	90	550	61	82	0	550	82	3	154	79	+0.34
336	144	90	550	46	200	0	550	200	2	139	197	+0.59
330	145	90	550	47	193	0	550	193	2	140	191	+0.58
165	113	90	550	20	55	0	550	55	1	111	54	+0.33
74	103	74	550	25	-25	0	525	0	1	100	-1	-0.02
12	89	12	525	55	-55	25	470	0	3	70	-3	-0.26
57	101	57	470	18	-18	80	452	0	2	76	-2	-0.03
11	109	11	452	29	-29	98	423	0	4	44	-4	-0.36
308	121	90	423	4	214	127	550	87	1	95	86	+0.28
50	145	50	550	82	-82	0	468	0	4	136	-4	-0.08
26	156	26	468	51	-51	82	417	0	5	82	-5	-0.20
14	161	14	417	15	-15	133	403	0	6	35	-6	-0.42
1616	1548	694		453				616	34	1181	582	+0.36

YEAR 1952

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
159	161	90	403	1	68	147	471	0	3	94	-3	-0.02
105	144	90	471	22	-7	79	464	0	2	114	-2	-0.02
199	145	90	464	20	89	86	550	3	2	112	0	+0.00
31	113	31	550	71	-71	0	479	0	3	105	-3	-0.11
36	103	36	479	31	-31	71	449	0	3	69	-3	-0.07
110	89	89	449	0	20	101	469	0	0	89	0	+0.00
43	101	44	469	23	-23	81	446	0	2	69	-2	-0.05
145	109	90	446	5	50	104	496	0	1	96	-1	-0.01
19	121	19	496	56	-56	54	440	0	4	79	-4	-0.21
110	145	90	440	13	7	110	447	0	2	105	-2	-0.02
70	156	70	447	23	-23	103	424	0	3	97	-3	-0.05
66	161	66	424	13	-13	126	411	0	4	83	-4	-0.06
1093	1548	805		277				3	30	1112	-27	-0.02

YEAR 1953

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
125	161	90	411	4	31	139	441	0	3	97	-3	-0.02
238	144	90	441	13	135	109	550	27	2	105	24	+0.10
350	145	90	550	47	213	0	550	213	2	140	211	+0.60
330	113	90	550	20	220	0	550	220	1	111	219	+0.66
100	103	90	550	11	-1	0	549	0	1	102	-1	-0.01

173	89	89	549	0	83	1	550	82	0	89	82	+0.47
65	101	66	550	30	-30	0	520	0	1	98	-1	-0.02
32	109	32	520	53	-53	30	467	0	3	88	-3	-0.10
12	121	12	467	42	-42	83	425	0	4	58	-4	-0.36
27	145	27	425	17	-17	125	408	0	5	49	-5	-0.17
25	156	25	408	6	-6	142	402	0	5	36	-5	-0.21
76	161	76	402	1	-1	148	401	0	3	80	-3	-0.04
1553	1548	777		245				541	31	1052	511	+0.33

YEAR 1954

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
37	161	37	401	1	-1	149	400	0	5	43	-5	-0.13
96	144	90	400	0	6	150	406	0	2	92	-2	-0.02
321	145	90	406	2	229	144	550	85	2	94	83	+0.26
288	113	90	550	20	178	0	550	178	1	111	177	+0.62
43	103	43	550	52	-52	0	498	0	2	97	-2	-0.06
135	89	89	498	0	45	52	543	0	0	89	0	+0.00
48	101	49	543	43	-43	7	501	0	2	94	-2	-0.04
122	109	90	501	11	21	49	522	0	1	102	-1	-0.01
38	121	38	522	58	-58	28	464	0	3	99	-3	-0.09
112	145	90	464	20	2	86	466	0	2	112	-2	-0.02
18	156	18	466	52	-52	84	414	0	6	75	-6	-0.31
530	161	90	414	6	434	136	550	298	3	98	295	+0.56
1788	1548	814		263				562	29	1107	532	+0.30

YEAR 1955

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
147	161	90	550	61	-4	0	546	0	3	154	-3	-0.02
182	144	90	546	45	47	4	550	43	2	137	41	+0.22
428	145	90	550	47	291	0	550	291	2	140	289	+0.67
234	113	90	550	20	124	0	550	124	1	111	123	+0.53
233	103	90	550	11	132	0	550	132	1	102	131	+0.56
87	89	87	550	2	-2	0	548	0	0	89	-0	-0.00
71	101	71	548	26	-26	2	523	0	1	98	-1	-0.02
178	109	90	523	13	75	27	550	47	1	104	47	+0.26
86	121	86	550	30	-30	0	520	0	1	118	-1	-0.02
69	145	69	520	52	-52	30	468	0	3	124	-3	-0.04
98	156	90	468	26	-18	82	450	0	3	118	-3	-0.03
373	161	90	450	20	263	100	550	163	3	113	160	+0.43
2186	1548	%1033		353				800	21	1407	779	+0.36

YEAR 1956

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO

223	161	90	550	61	72	0	550	72	3	154	69	+0.31
222	144	90	550	46	86	0	550	86	2	139	83	+0.38
348	145	90	550	47	211	0	550	211	2	140	209	+0.60
339	113	90	550	20	229	0	550	229	1	111	228	+0.67
32	103	32	550	61	-61	0	489	0	3	96	-3	-0.09
60	89	60	489	15	-15	61	474	0	1	76	-1	-0.02
152	101	90	474	5	57	76	531	0	0	95	-0	-0.00
78	109	78	531	23	-23	19	508	0	1	103	-1	-0.02
109	121	90	508	19	-0	42	508	0	1	110	-1	-0.01
163	145	90	508	34	39	42	547	0	2	126	-2	-0.01
169	156	90	547	56	23	3	550	20	3	148	18	+0.10
38	161	38	550	106	-106	0	444	0	5	149	-5	-0.13
1933	1548	928		493				618	25	1446	593	+0.31

YEAR 1957

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
649	161	90	444	18	541	106	550	435	3	111	432	+0.67
300	144	90	550	46	164	0	550	164	2	139	161	+0.54
508	145	90	550	47	371	0	550	371	2	140	369	+0.73
88	113	88	550	22	-22	0	529	0	1	111	-1	-0.01
161	103	90	529	10	61	22	550	40	1	100	39	+0.24
187	89	89	550	0	97	0	550	97	0	89	97	+0.52
217	101	90	550	9	119	0	550	119	0	100	118	+0.54
202	109	90	550	16	96	0	550	96	1	107	95	+0.47
31	121	31	550	77	-77	0	473	0	4	112	-4	-0.12
41	145	41	473	43	-43	77	429	0	4	88	-4	-0.10
101	156	90	429	11	-0	121	429	0	3	104	-3	-0.03
156	161	90	429	12	54	121	483	0	3	105	-3	-0.02
2641	1548	969		312				1321	23	1304	1297	+0.49

YEAR 1958

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
49	161	49	483	54	-54	67	430	0	4	107	-4	-0.09
230	144	90	430	9	131	120	550	11	2	101	8	+0.04
119	145	90	550	47	-18	0	532	0	2	140	-2	-0.02
303	113	90	532	17	196	18	550	177	1	108	176	+0.58
55	103	55	550	41	-41	0	509	0	2	98	-2	-0.03
5	89	5	509	52	-52	41	456	0	3	61	-3	-0.67
99	101	90	456	4	5	94	462	0	0	94	-0	-0.00
40	109	40	462	24	-24	88	437	0	3	67	-3	-0.07
47	121	47	437	16	-16	113	422	0	3	66	-3	-0.06
134	145	90	422	7	37	128	459	0	2	99	-2	-0.02
225	156	90	459	22	113	91	550	22	3	115	19	+0.08
28	161	28	550	114	-114	0	436	0	5	148	-5	-0.19
1334	1548	764		408				209	31	1204	178	+0.13

YEAR 1959

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
512	161	90	436	14	408	114	550	293	3	107	290	+0.57
35	144	35	550	94	-94	0	456	0	4	133	-4	-0.12
313	145	90	456	18	205	94	550	112	2	110	109	+0.35
177	113	90	550	20	67	0	550	67	1	111	66	+0.37
90	103	90	550	11	-11	0	539	0	1	102	-1	-0.01
70	89	70	539	15	-15	11	524	0	1	86	-1	-0.01
85	101	85	524	11	-11	26	512	0	1	97	-1	-0.01
106	109	90	512	12	4	38	516	0	1	103	-1	-0.01
99	121	90	516	21	-12	34	504	0	1	112	-1	-0.01
98	145	90	504	33	-25	46	480	0	2	125	-2	-0.02
125	156	90	480	30	5	70	484	0	3	123	-3	-0.02
142	161	90	484	34	18	66	502	0	3	127	-3	-0.02
1852	1548	%1000		314				472	22	1336	450	+0.24

YEAR 1960

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
125	161	90	502	42	-7	48	496	0	3	134	-3	-0.02
130	144	90	496	30	10	54	506	0	2	122	-2	-0.02
234	145	90	506	33	111	44	550	67	2	126	64	+0.27
155	113	90	550	20	45	0	550	45	1	111	44	+0.29
21	103	21	550	71	-71	0	479	0	3	95	-3	-0.16
73	89	73	479	7	-7	71	472	0	1	81	-1	-0.01
94	101	90	472	5	-1	78	472	0	0	95	-0	-0.00
111	109	90	472	8	13	78	485	0	1	99	-1	-0.01
34	121	34	485	42	-42	65	443	0	3	80	-3	-0.10
42	145	42	443	25	-25	107	417	0	4	71	-4	-0.10
70	156	70	417	9	-9	133	409	0	3	82	-3	-0.05
171	161	90	409	4	77	141	486	0	3	96	-3	-0.02
1260	1548	870		294				112	27	1191	85	+0.07

YEAR 1961

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
290	161	90	486	35	165	64	550	101	3	128	98	+0.34
262	144	90	550	46	126	0	550	126	2	139	123	+0.47
432	145	90	550	47	295	0	550	295	2	140	293	+0.68
69	113	69	550	38	-38	0	512	0	2	109	-2	-0.03
185	103	90	512	8	87	38	550	49	1	99	48	+0.26
39	89	39	550	43	-43	0	507	0	2	84	-2	-0.05
193	101	90	507	7	96	43	550	53	0	97	53	+0.27
118	109	90	550	16	12	0	550	12	1	107	11	+0.09
34	121	34	550	75	-75	0	475	0	3	112	-3	-0.10
98	145	90	475	24	-16	75	459	0	2	116	-2	-0.02
201	156	90	459	23	88	91	548	0	3	115	-3	-0.01
102	161	90	548	60	-48	2	500	0	3	153	-3	-0.03

2023	1548	952		422				635	24	1398	611	+0.30

YEAR 1962

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
394	161	90	500	41	263	50	550	213	3	133	210	+0.53
119	144	90	550	46	-17	0	533	0	2	139	-2	-0.02
53	145	53	533	70	-70	17	463	0	4	127	-4	-0.07
126	113	90	463	8	28	87	490	0	1	99	-1	-0.01
64	103	64	490	20	-20	60	470	0	2	86	-2	-0.02
128	89	89	470	0	38	80	508	0	0	89	0	+0.00
44	101	45	508	35	-35	42	473	0	2	82	-2	-0.05
22	109	22	473	37	-37	77	437	0	3	62	-3	-0.16
84	121	84	437	8	-8	113	429	0	1	93	-1	-0.02
61	145	61	429	14	-14	121	415	0	3	78	-3	-0.06
131	156	90	415	6	35	135	450	0	3	98	-3	-0.02
286	161	90	450	20	176	100	550	76	3	113	73	+0.26
1512	1548	868		305				289	27	1200	262	+0.17

YEAR 1963

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
182	161	90	550	61	31	0	550	31	3	154	28	+0.15
218	144	90	550	46	82	0	550	82	2	139	79	+0.36
550	145	90	550	47	413	0	550	413	2	140	411	+0.75
99	113	90	550	20	-11	0	539	0	1	111	-1	-0.01
110	103	90	539	10	10	11	549	0	1	101	-1	-0.00
27	89	27	549	53	-53	1	496	0	2	82	-2	-0.09
26	101	26	496	41	-41	54	455	0	3	70	-3	-0.12
214	109	90	455	6	118	95	550	23	1	97	22	+0.10
34	121	34	550	75	-75	0	475	0	3	112	-3	-0.10
69	145	69	475	33	-33	75	442	0	3	105	-3	-0.04
40	156	40	442	28	-28	108	414	0	5	73	-5	-0.12
49	161	49	414	9	-9	136	405	0	4	63	-4	-0.09
1618	1548	785		430				548	31	1246	517	+0.32

YEAR 1964

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
50	161	50	405	3	-3	145	402	0	4	58	-4	-0.09
212	144	90	402	1	121	148	523	0	2	93	-2	-0.01
593	145	90	523	39	464	27	550	437	2	131	435	+0.73
96	113	90	550	20	-14	0	536	0	1	111	-1	-0.01
30	103	30	536	57	-57	14	479	0	3	90	-3	-0.10
10	89	10	479	36	-36	71	443	0	3	49	-3	-0.32
208	101	90	443	3	115	107	550	9	0	93	8	+0.04
96	109	90	550	16	-10	0	540	0	1	107	-1	-0.01

294	121	90	540	25	179	10	550	169	1	116	168	+0.57
123	145	90	550	47	-14	0	536	0	2	140	-2	-0.02
188	156	90	536	51	47	14	550	32	3	144	30	+0.16
105	161	90	550	61	-46	0	504	0	3	154	-3	-0.03
2005	1548	900		359				647	26	1285	621	+0.31

YEAR 1965

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
213	161	90	504	42	81	46	550	35	3	135	32	+0.15
360	144	90	550	46	224	0	550	224	2	139	221	+0.62
217	145	90	550	47	80	0	550	80	2	140	78	+0.36
137	113	90	550	20	27	0	550	27	1	111	26	+0.19
104	103	90	550	11	3	0	550	3	1	102	2	+0.02
22	89	22	550	58	-58	0	492	0	3	82	-3	-0.12
35	101	35	492	35	-35	58	457	0	3	73	-3	-0.08
122	109	90	457	6	26	93	483	0	1	97	-1	-0.01
208	121	90	483	15	103	67	550	36	1	106	35	+0.17
120	145	90	550	47	-17	0	533	0	2	140	-2	-0.02
134	156	90	533	50	-6	17	526	0	3	143	-3	-0.02
52	161	52	526	79	-79	24	447	0	4	135	-4	-0.08
1724	1548	919		457				404	25	1401	379	+0.22

YEAR 1966

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
106	161	90	447	19	-3	103	444	0	3	112	-3	-0.03
137	144	90	444	14	33	106	477	0	2	106	-2	-0.02
112	145	90	477	24	-2	73	475	0	2	117	-2	-0.02
279	113	90	475	10	179	75	550	104	1	101	103	+0.37
88	103	88	550	13	-13	0	537	0	1	102	-1	-0.01
46	89	46	537	34	-34	13	503	0	2	82	-2	-0.04
83	101	83	503	11	-11	47	493	0	1	94	-1	-0.01
62	109	62	493	25	-25	57	468	0	2	89	-2	-0.03
42	121	42	468	31	-31	82	437	0	3	76	-3	-0.08
167	145	90	437	12	65	113	502	0	2	104	-2	-0.01
95	156	90	502	39	-34	48	469	0	3	131	-3	-0.03
144	161	90	469	28	26	81	495	0	3	121	-3	-0.02
1361	1548	951		259				104	24	1233	80	+0.06

YEAR 1967

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
123	161	90	495	39	-6	55	489	0	3	131	-3	-0.02
168	144	90	489	28	50	61	540	0	2	120	-2	-0.01
329	145	90	540	44	195	10	550	185	2	136	182	+0.55

190	113	90	550	20	80	0	550	80	1	111	79	+0.42
146	103	90	550	11	45	0	550	45	1	102	44	+0.30
18	89	18	550	61	-61	0	489	0	3	82	-3	-0.16
52	101	52	489	25	-25	61	464	0	2	79	-2	-0.04
12	109	12	464	36	-36	86	428	0	4	51	-4	-0.32
49	121	49	428	12	-12	122	417	0	3	64	-3	-0.06
294	145	90	417	5	199	133	550	65	2	97	63	+0.22
26	156	26	550	112	-112	0	438	0	5	143	-5	-0.20
66	161	66	438	21	-21	112	417	0	4	91	-4	-0.06
1473	1548	763		412				375	31	1207	344	+0.23

YEAR 1968

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
337	161	90	417	7	240	133	550	107	3	100	104	+0.31
90	144	90	550	46	-46	0	504	0	2	139	-2	-0.02
233	145	90	504	33	110	46	550	64	2	125	62	+0.26
77	113	77	550	31	-31	0	519	0	1	109	-1	-0.02
68	103	68	519	24	-24	31	495	0	1	93	-1	-0.02
52	89	52	495	20	-20	55	475	0	1	74	-1	-0.03
21	101	21	475	34	-34	75	441	0	3	59	-3	-0.15
116	109	90	441	4	22	109	462	0	1	95	-1	-0.01
61	121	61	462	21	-21	88	441	0	2	85	-2	-0.04
145	145	90	441	13	42	109	483	0	2	105	-2	-0.02
82	156	82	483	35	-35	67	448	0	3	120	-3	-0.04
143	161	90	448	19	34	102	481	0	3	112	-3	-0.02
1425	1548	901		289				171	26	1216	145	+0.10

YEAR 1969

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
274	161	90	481	33	151	69	550	82	3	126	79	+0.29
134	144	90	550	46	-2	0	548	0	2	139	-2	-0.02
496	145	90	548	47	359	2	550	357	2	139	355	+0.72
111	113	90	550	20	1	0	550	1	1	111	0	+0.00
14	103	14	550	77	-77	0	473	0	4	94	-4	-0.25
18	89	18	473	30	-30	77	444	0	3	51	-3	-0.16
148	101	90	444	3	55	106	499	0	0	93	-0	-0.00
112	109	90	499	11	11	51	510	0	1	102	-1	-0.01
7	121	7	510	72	-72	40	438	0	5	83	-5	-0.65
89	145	89	438	12	-12	112	426	0	2	103	-2	-0.03
199	156	90	426	10	99	124	525	0	3	102	-3	-0.01
56	161	56	525	75	-75	25	450	0	4	136	-4	-0.08
1658	1548	814		435				440	29	1278	411	+0.25

YEAR 1970

RAIN ET EI SMC1 ES XCESS SMDEF SMC2 GWR TL EA NETR RECHARGE

(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	RATIO
183	161	90	450	20	73	100	523	0	3	113	-3	-0.02
302	144	90	523	38	174	27	550	147	2	130	144	+0.48
214	145	90	550	47	77	0	550	77	2	140	75	+0.35
326	113	90	550	20	216	0	550	216	1	111	215	+0.66
224	103	90	550	11	123	0	550	123	1	102	122	+0.55
106	89	89	550	0	16	0	550	16	0	89	16	+0.15
20	101	21	550	69	-69	0	481	0	3	93	-3	-0.16
13	109	13	481	45	-45	69	437	0	4	62	-4	-0.30
91	121	90	437	6	-5	113	431	0	1	98	-1	-0.01
21	145	21	431	22	-22	119	409	0	5	48	-5	-0.24
351	156	90	409	3	258	141	550	117	3	96	114	+0.32
252	161	90	550	61	101	0	550	101	3	154	98	+0.39
2103	1548	864		343				796	27	1234	768	+0.37

YEAR 1971

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
287	161	90	550	61	136	0	550	136	3	154	133	+0.46
96	144	90	550	46	-40	0	510	0	2	139	-2	-0.02
244	145	90	510	35	119	40	550	79	2	127	77	+0.31
203	113	90	550	20	93	0	550	93	1	111	92	+0.45
155	103	90	550	11	54	0	550	54	1	102	53	+0.34
69	89	69	550	17	-17	0	533	0	1	87	-1	-0.01
69	101	69	533	24	-24	17	508	0	1	95	-1	-0.02
218	109	90	508	12	116	42	550	75	1	103	74	+0.34
103	121	90	550	27	-14	0	536	0	1	118	-1	-0.01
95	145	90	536	43	-38	14	498	0	2	135	-2	-0.02
512	156	90	498	37	385	52	550	333	3	130	330	+0.65
613	161	90	550	61	462	0	550	462	3	154	459	+0.75
2664	1548	%1038		394				1232	20	1453	1211	+0.45

YEAR 1972

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
170	161	90	550	61	19	0	550	19	3	154	16	+0.09
141	144	90	550	46	5	0	550	5	2	139	2	+0.02
476	145	90	550	47	339	0	550	339	2	140	337	+0.71
332	113	90	550	20	222	0	550	222	1	111	221	+0.67
95	103	90	550	11	-6	0	544	0	1	102	-1	-0.01
110	89	89	544	0	20	6	550	14	0	89	14	+0.13
102	101	90	550	9	4	0	550	4	0	100	3	+0.03
226	109	90	550	16	120	0	550	120	1	107	119	+0.53
283	121	90	550	27	166	0	550	166	1	118	165	+0.58
316	145	90	550	47	179	0	550	179	2	140	177	+0.56
33	156	33	550	106	-106	0	444	0	5	144	-5	-0.15
44	161	44	444	30	-30	106	415	0	5	78	-5	-0.11
2328	1548	976		421				1066	23	1420	1044	+0.45

YEAR 1973

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
88	161	88	415	6	-6	135	408	0	3	97	-3	-0.03
310	144	90	408	3	217	142	550	76	2	95	74	+0.24
230	145	90	550	47	93	0	550	93	2	140	91	+0.39
332	113	90	550	20	222	0	550	222	1	111	221	+0.67
29	103	29	550	64	-64	0	486	0	3	96	-3	-0.10
116	89	89	486	0	26	64	512	0	0	89	0	+0.00
178	101	90	512	7	82	38	550	44	0	98	44	+0.25
63	109	63	550	40	-40	0	510	0	2	104	-2	-0.03
227	121	90	510	20	117	40	550	78	1	111	77	+0.34
114	145	90	550	47	-23	0	527	0	2	140	-2	-0.02
226	156	90	527	48	88	23	550	65	3	141	62	+0.27
101	161	90	550	61	-50	0	500	0	3	154	-3	-0.03
2014	1548	989		362				578	22	1373	555	+0.28

YEAR 1974

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
152	161	90	500	41	21	50	521	0	3	134	-3	-0.02
403	144	90	521	38	275	29	550	247	2	130	245	+0.61
111	145	90	550	47	-26	0	524	0	2	140	-2	-0.02
254	113	90	524	16	148	26	550	121	1	107	120	+0.47
167	103	90	550	11	66	0	550	66	1	102	65	+0.39
122	89	89	550	0	32	0	550	32	0	89	32	+0.26
138	101	90	550	9	40	0	550	40	0	100	39	+0.28
73	109	73	550	31	-31	0	519	0	1	105	-1	-0.02
163	121	90	519	21	52	31	550	21	1	112	20	+0.12
199	145	90	550	47	62	0	550	62	2	140	60	+0.30
120	156	90	550	57	-27	0	523	0	3	149	-3	-0.02
153	161	90	523	50	13	27	536	0	3	143	-3	-0.02
2055	1548	%1062		369				588	19	1450	569	+0.28

YEAR 1975

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
281	161	90	536	55	136	14	550	122	3	148	119	+0.42
265	144	90	550	46	129	0	550	129	2	139	126	+0.48
207	145	90	550	47	70	0	550	70	2	140	68	+0.33
74	113	74	550	34	-34	0	516	0	2	109	-2	-0.02
161	103	90	516	9	62	34	550	29	1	99	28	+0.18
75	89	75	550	12	-12	0	538	0	1	88	-1	-0.01
191	101	90	538	9	92	12	550	80	0	99	80	+0.42
144	109	90	550	16	38	0	550	38	1	107	37	+0.26
85	121	85	550	31	-31	0	519	0	1	117	-1	-0.02
135	145	90	519	38	7	31	527	0	2	130	-2	-0.02
380	156	90	527	48	242	23	550	219	3	141	216	+0.57

313	161	90	550	61	162	0	550	162	3	154	159	+0.51
2311	1548	%1044		406				847	20	1470	827	+0.36

YEAR 1976

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
245	161	90	550	61	94	0	550	94	3	154	91	+0.37
299	144	90	550	46	163	0	550	163	2	139	160	+0.54
354	145	90	550	47	217	0	550	217	2	140	215	+0.61
254	113	90	550	20	144	0	550	144	1	111	143	+0.56
68	103	68	550	30	-30	0	520	0	1	100	-1	-0.02
26	89	26	520	43	-43	30	477	0	3	72	-3	-0.10
55	101	55	477	20	-20	73	456	0	2	77	-2	-0.03
96	109	90	456	6	-0	94	456	0	1	97	-1	-0.01
144	121	90	456	10	44	94	500	0	1	101	-1	-0.01
6	145	6	500	80	-80	50	420	0	6	91	-6	-0.93
36	156	36	420	14	-14	130	406	0	5	55	-5	-0.13
171	161	90	406	3	78	144	485	0	3	95	-3	-0.02
1754	1548	821		381				617	29	1231	588	+0.34

YEAR 1977

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
271	161	90	485	35	146	65	550	81	3	127	78	+0.29
339	144	90	550	46	203	0	550	203	2	139	200	+0.59
168	145	90	550	47	31	0	550	31	2	140	29	+0.17
158	113	90	550	20	48	0	550	48	1	111	47	+0.30
70	103	70	550	28	-28	0	522	0	1	100	-1	-0.02
42	89	42	522	33	-33	28	489	0	2	77	-2	-0.04
57	101	57	489	22	-22	61	466	0	2	81	-2	-0.03
76	109	76	466	13	-13	84	454	0	1	90	-1	-0.02
46	121	46	454	23	-23	96	431	0	3	72	-3	-0.07
39	145	39	431	19	-19	119	412	0	4	62	-4	-0.11
11	156	11	412	10	-10	138	402	0	6	27	-6	-0.53
46	161	46	402	1	-1	148	401	0	5	52	-5	-0.10
1323	1548	747		297				363	32	1076	331	+0.25

YEAR 1978

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
123	161	90	401	0	33	149	433	0	3	93	-3	-0.02
145	144	90	433	10	45	117	478	0	2	103	-2	-0.01
308	145	90	478	25	193	72	550	121	2	117	119	+0.39
170	113	90	550	20	60	0	550	60	1	111	59	+0.35
161	103	90	550	11	60	0	550	60	1	102	59	+0.37
15	89	15	550	64	-64	0	486	0	3	82	-3	-0.20

2	101	2	486	49	-49	64	437	0	4	55	-4	-1.98
245	109	90	437	4	151	113	550	38	1	95	38	+0.15
137	121	90	550	27	20	0	550	20	1	118	19	+0.14
41	145	41	550	89	-89	0	461	0	4	135	-4	-0.10
73	156	73	461	29	-29	89	432	0	3	105	-3	-0.05
33	161	33	432	23	-23	118	408	0	5	61	-5	-0.16
1453	1548	794		351				300	30	1175	270	+0.19

YEAR 1979

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
104	161	90	408	3	11	142	419	0	3	96	-3	-0.03
50	144	50	419	10	-10	131	409	0	4	64	-4	-0.08
223	145	90	409	3	130	141	539	0	2	95	-2	-0.01
40	113	40	539	58	-58	11	481	0	3	101	-3	-0.07
70	103	70	481	15	-15	69	466	0	1	87	-1	-0.02
146	89	89	466	0	56	84	522	0	0	89	0	+0.00
48	101	49	522	36	-36	28	485	0	2	87	-2	-0.04
126	109	90	485	9	27	65	512	0	1	100	-1	-0.01
199	121	90	512	20	89	38	550	51	1	111	50	+0.25
47	145	47	550	84	-84	0	466	0	4	135	-4	-0.08
111	156	90	466	25	-4	84	462	0	3	118	-3	-0.02
115	161	90	462	25	-0	88	462	0	3	118	-3	-0.02
1279	1548	885		290				51	27	1201	25	+0.02

YEAR 1980

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
61	161	61	462	35	-35	88	426	0	4	100	-4	-0.07
61	144	61	426	13	-13	124	414	0	3	77	-3	-0.05
402	145	90	414	4	308	136	550	171	2	97	169	+0.42
204	113	90	550	20	94	0	550	94	1	111	93	+0.46
0	103	0	550	89	-89	0	461	0	4	93	-4	+0.00
91	89	89	461	0	1	89	462	0	0	89	0	+0.00
92	101	90	462	4	-1	88	461	0	0	94	-0	-0.00
174	109	90	461	7	77	89	539	0	1	97	-1	-0.00
75	121	75	539	37	-37	11	502	0	2	113	-2	-0.02
79	145	79	502	39	-39	48	464	0	3	120	-3	-0.03
92	156	90	464	24	-22	86	441	0	3	117	-3	-0.03
154	161	90	441	17	47	109	489	0	3	110	-3	-0.02
1485	1548	905		287				266	26	1218	240	+0.16

YEAR 1981

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
88	161	88	489	37	-37	61	452	0	3	128	-3	-0.03

356	144	90	452	16	250	98	550	152	2	108	149	+0.42
180	145	90	550	47	43	0	550	43	2	140	41	+0.22
54	113	54	550	51	-51	0	499	0	2	107	-2	-0.04
94	103	90	499	7	-3	51	496	0	1	98	-1	-0.01
30	89	30	496	32	-32	54	463	0	2	65	-2	-0.08
11	101	11	463	33	-33	87	431	0	4	47	-4	-0.33
52	109	52	431	10	-10	119	421	0	2	64	-2	-0.04
71	121	71	421	6	-6	129	415	0	2	79	-2	-0.03
41	145	41	415	9	-9	135	406	0	4	54	-4	-0.10
70	156	70	406	3	-3	144	403	0	3	76	-3	-0.05
128	161	90	403	1	37	147	440	0	3	94	-3	-0.02
1175	1548	777		253				194	31	1060	163	+0.14

YEAR 1982

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
261	161	90	440	16	155	110	550	45	3	109	42	+0.16
199	144	90	550	46	63	0	550	63	2	139	60	+0.30
253	145	90	550	47	116	0	550	116	2	140	114	+0.45
436	113	90	550	20	326	0	550	326	1	111	325	+0.75
217	103	90	550	11	116	0	550	116	1	102	115	+0.53
54	89	54	550	30	-30	0	520	0	1	86	-1	-0.03
59	101	59	520	29	-29	30	491	0	2	90	-2	-0.03
74	109	74	491	18	-18	59	473	0	1	94	-1	-0.02
156	121	90	473	13	53	77	526	0	1	104	-1	-0.01
14	145	14	526	95	-95	24	431	0	5	114	-5	-0.37
24	156	24	431	24	-24	119	408	0	5	53	-5	-0.22
80	161	80	408	4	-4	142	404	0	3	87	-3	-0.04
1827	1548	845		353				665	28	1226	637	+0.35

YEAR 1983

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
15	161	15	404	3	-3	146	401	0	6	24	-6	-0.39
68	144	68	401	0	-0	149	400	0	3	71	-3	-0.04
177	145	90	400	0	87	150	487	0	2	92	-2	-0.01
21	113	21	487	46	-46	63	441	0	4	71	-4	-0.18
48	103	48	441	13	-13	109	428	0	2	63	-2	-0.05
8	89	8	428	13	-13	122	415	0	3	24	-3	-0.41
59	101	59	415	4	-4	135	411	0	2	64	-2	-0.03
21	109	21	411	6	-6	139	406	0	4	30	-4	-0.17
95	121	90	406	1	4	144	410	0	1	92	-1	-0.01
157	145	90	410	3	64	140	474	0	2	95	-2	-0.01
61	156	61	474	40	-40	76	434	0	4	105	-4	-0.06
96	161	90	434	14	-8	116	426	0	3	106	-3	-0.03
826	1548	661		143				0	35	840	-35	-0.04

YEAR 1984

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
230	161	90	426	11	129	124	550	5	3	103	3	+0.01
238	144	90	550	46	102	0	550	102	2	139	99	+0.42
52	145	52	550	80	-80	0	470	0	4	136	-4	-0.07
217	113	90	470	9	118	80	550	38	1	100	37	+0.17
34	103	34	550	59	-59	0	491	0	3	96	-3	-0.08
92	89	89	491	0	2	59	493	0	0	89	0	+0.00
94	101	90	493	6	-1	57	492	0	0	96	-0	-0.00
95	109	90	492	10	-5	58	487	0	1	101	-1	-0.01
216	121	90	487	15	111	63	550	47	1	107	46	+0.21
44	145	44	550	87	-87	0	463	0	4	135	-4	-0.09
5	156	5	463	55	-55	87	408	0	6	66	-6	-1.21
60	161	60	408	5	-5	142	404	0	4	69	-4	-0.07
1377	1548	824		383				192	29	1236	163	+0.12

YEAR 1985

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
35	161	35	404	3	-3	146	401	0	5	43	-5	-0.14
236	144	90	401	0	146	149	547	0	2	92	-2	-0.01
238	145	90	547	46	102	3	550	98	2	138	96	+0.40
130	113	90	550	20	20	0	550	20	1	111	19	+0.15
35	103	35	550	58	-58	0	492	0	3	96	-3	-0.08
116	89	89	492	0	26	58	518	0	0	89	0	+0.00
231	101	90	518	7	135	32	550	102	0	98	102	+0.44
66	109	66	550	37	-37	0	513	0	2	105	-2	-0.03
38	121	38	513	54	-54	37	459	0	3	95	-3	-0.09
13	145	13	459	45	-45	91	414	0	5	63	-5	-0.41
4	156	4	414	13	-13	136	402	0	6	23	-6	-1.52
172	161	90	402	1	81	148	483	0	3	94	-3	-0.02
1314	1548	730		284				221	33	1046	188	+0.14

YEAR 1986

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
88	161	88	483	35	-35	67	448	0	3	126	-3	-0.03
77	144	77	448	19	-19	102	430	0	3	98	-3	-0.03
154	145	90	430	9	55	120	484	0	2	102	-2	-0.01
307	113	90	484	11	206	66	550	140	1	102	139	+0.45
98	103	90	550	11	-3	0	547	0	1	102	-1	-0.01
231	89	89	547	0	141	3	550	138	0	89	138	+0.60
163	101	90	550	9	65	0	550	65	0	100	64	+0.39
75	109	75	550	29	-29	0	521	0	1	106	-1	-0.02
50	121	50	521	49	-49	29	472	0	3	102	-3	-0.06
63	145	63	472	34	-34	78	438	0	3	100	-3	-0.05
11	156	11	438	32	-32	112	406	0	6	48	-6	-0.53
12	161	12	406	5	-5	144	401	0	6	23	-6	-0.50
1329	1548	825		244				343	29	1097	314	+0.24

YEAR 1987

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
21	161	21	401	1	-1	149	400	0	6	27	-6	-0.27
110	144	90	400	0	20	150	420	0	2	92	-2	-0.02
352	145	90	420	6	256	130	550	126	2	99	124	+0.35
2	113	2	550	95	-95	0	455	0	4	102	-4	-2.22
47	103	47	455	18	-18	95	437	0	2	67	-2	-0.05
41	89	41	437	10	-10	113	427	0	2	53	-2	-0.05
64	101	64	427	6	-6	123	421	0	1	71	-1	-0.02
103	109	90	421	2	11	129	432	0	1	93	-1	-0.01
6	121	6	432	21	-21	118	411	0	5	32	-5	-0.77
0	145	0	411	9	-9	139	402	0	6	15	-6	+0.00
3	156	3	402	2	-2	148	400	0	6	11	-6	-2.04
385	161	90	400	0	295	150	550	145	3	93	142	+0.37
1134	1548	544		170				271	40	754	231	+0.20

YEAR 1988

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
236	161	90	550	61	85	0	550	85	3	154	82	+0.35
108	144	90	550	46	-28	0	522	0	2	139	-2	-0.02
145	145	90	522	38	17	28	538	0	2	131	-2	-0.02
113	113	90	538	18	5	12	543	0	1	109	-1	-0.01
210	103	90	543	11	109	7	550	102	1	101	102	+0.48
35	89	35	550	46	-46	0	504	0	2	84	-2	-0.06
84	101	84	504	10	-10	46	493	0	1	95	-1	-0.01
20	109	20	493	48	-48	57	446	0	4	71	-4	-0.18
237	121	90	446	8	139	104	550	35	1	99	33	+0.14
114	145	90	550	47	-23	0	527	0	2	140	-2	-0.02
27	156	27	527	94	-94	23	433	0	5	126	-5	-0.19
209	161	90	433	13	106	117	539	0	3	106	-3	-0.01
1538	1548	886		442				222	26	1354	195	+0.13

YEAR 1989

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
131	161	90	539	56	-15	11	523	0	3	149	-3	-0.02
486	144	90	523	38	358	27	550	331	2	130	329	+0.68
348	145	90	550	47	211	0	550	211	2	140	209	+0.60
437	113	90	550	20	327	0	550	327	1	111	326	+0.75
430	103	90	550	11	329	0	550	329	1	102	328	+0.76
74	89	74	550	13	-13	0	537	0	1	88	-1	-0.01
38	101	38	537	50	-50	13	488	0	3	90	-3	-0.07
41	109	41	488	34	-34	62	453	0	3	78	-3	-0.07
97	121	90	453	9	-2	97	451	0	1	101	-1	-0.01

96	145	90	451	16	-10	99	441	0	2	108	-2	-0.02
134	156	90	441	15	29	109	469	0	3	108	-3	-0.02
221	161	90	469	28	103	81	550	22	3	121	19	+0.09
2533	1548	963		339				1220	23	1325	1197	+0.47

YEAR 1990

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
270	161	90	550	61	119	0	550	119	3	154	116	+0.43
88	144	88	550	48	-48	0	502	0	2	138	-2	-0.03
264	145	90	502	32	142	48	550	94	2	124	92	+0.35
157	113	90	550	20	47	0	550	47	1	111	46	+0.29
263	103	90	550	11	162	0	550	162	1	102	161	+0.61
163	89	89	550	0	73	0	550	73	0	89	73	+0.45
77	101	78	550	20	-20	0	530	0	1	99	-1	-0.01
104	109	90	530	14	-0	20	530	0	1	105	-1	-0.01
108	121	90	530	23	-5	20	525	0	1	114	-1	-0.01
129	145	90	525	39	-0	25	525	0	2	132	-2	-0.02
29	156	29	525	91	-91	25	434	0	5	125	-5	-0.18
57	161	57	434	20	-20	116	414	0	4	81	-4	-0.07
1709	1548	971		380				495	23	1374	472	+0.28

44 YEAR AVERAGES

1725	1548	873		350				505	27	1250	478	+0.28

Summary of Monthly Recharge (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Recharge	Annual Rainfall
1947	67	50	174	-1	75	15	16	-1	77	-2	-6	23	488	1,867
1948	278	8	62	140	-2	0	-2	-4	-3	-2	43	140	660	1,983
1949	105	131	73	60	-3	-2	47	7	85	116	-5	62	675	2,081
1950	83	-2	318	223	-1	-2	18	-3	-1	-2	86	199	916	2,375
1951	79	197	191	54	-1	-3	-2	-4	86	-4	-5	-6	582	1,616
1952	-3	-2	0	-3	-3	0	-2	-1	-4	-2	-3	-4	-27	1,093
1953	-3	24	211	219	-1	82	-1	-3	-4	-5	-5	-3	511	1,553
1954	-5	-2	83	177	-2	0	-2	-1	-3	-2	-6	295	532	1,788
1955	-3	41	289	123	131	0	-1	47	-1	-3	-3	160	779	2,186
1956	69	83	209	228	-3	-1	0	-1	-1	-2	18	-5	593	1,933
1957	432	161	369	-1	39	97	118	95	-4	-4	-3	-3	1,297	2,641
1958	-4	8	-2	176	-2	-3	0	-3	-3	-2	19	-5	178	1,334
1959	290	-4	109	66	-1	-1	-1	-1	-1	-2	-3	-3	450	1,852
1960	-3	-2	64	44	-3	-1	0	-1	-3	-4	-3	-3	85	1,260
1961	98	123	293	-2	48	-2	53	11	-3	-2	-3	-3	611	2,023
1962	210	-2	-4	-1	-2	0	-2	-3	-1	-3	-3	73	262	1,512
1963	28	79	411	-1	-1	-2	-3	22	-3	-3	-5	-4	517	1,618
1964	-4	-2	435	-1	-3	-3	8	-1	168	-2	30	-3	621	2,005
1965	32	221	78	26	2	-3	-3	-1	35	-2	-3	-4	379	1,724
1966	-3	-2	-2	103	-1	-2	-1	-2	-3	-2	-3	-3	80	1,361
1967	-3	-2	182	79	44	-3	-2	-4	-3	63	-5	-4	344	1,473
1968	104	-2	62	-1	-1	-1	-3	-1	-2	-2	-3	-3	145	1,425
1969	79	-2	355	0	-4	-3	0	-1	-5	-2	-3	-4	411	1,658
1970	-3	144	75	215	122	16	-3	-4	-1	-5	114	98	768	2,103
1971	133	-2	77	92	53	-1	-1	74	-1	-2	330	459	1,211	2,664
1972	16	2	337	221	-1	14	3	119	165	177	-5	-5	1,044	2,328
1973	-3	74	91	221	-3	0	44	-2	77	-2	62	-3	555	2,014
1974	-3	245	-2	120	65	32	39	-1	20	60	-3	-3	569	2,055
1975	119	126	68	-2	28	-1	80	37	-1	-2	216	159	827	2,311
1976	91	160	215	143	-1	-3	-2	-1	-1	-6	-5	-3	588	1,754
1977	78	200	29	47	-1	-2	-2	-1	-3	-4	-6	-5	331	1,323
1978	-3	-2	119	59	59	-3	-4	38	19	-4	-3	-5	270	1,453
1979	-3	-4	-2	-3	-1	0	-2	-1	50	-4	-3	-3	25	1,279
1980	-4	-3	169	93	-4	0	0	-1	-2	-3	-3	-3	240	1,485
1981	-3	149	41	-2	-1	-2	-4	-2	-2	-4	-3	-3	163	1,155
1982	42	60	114	325	115	-1	-2	-1	-1	-5	-5	-3	637	1,827
1983	-6	-3	-2	-4	-2	-3	-2	-4	-1	-2	-4	-3	-35	826
1984	3	99	-4	37	-3	0	0	-1	46	-4	-6	-4	163	1,377
1985	-5	-2	96	19	-3	0	102	-2	-3	-5	-6	-3	188	1,314
1986	-3	-3	-2	139	-1	138	64	-1	-3	-3	-6	-6	314	1,329
1987	-6	-2	124	-4	-2	-2	-1	-1	-5	-6	-6	142	231	1,134
1988	82	-2	-2	-1	102	-2	-1	-4	33	-2	-5	-3	195	1,538
1989	-3	329	209	326	328	-1	-3	-3	-1	-2	-3	19	1,197	2,533
1990	116	-2	92	46	161	73	-1	-1	-1	-2	-5	-4	472	1,709

Appendix L

Water quality and level monitoring information, Vava'u

(from dbase file VAVWELLS.DBF)

Well No	Date	Depth to water (m)	Electrical Conductivity (µS/cm)	Temperature (ºC)	pH	Pump status (TRUE = ON, FALSE = OFF)
1	26/09/1990	17.97	0	0.0	0.00	FALSE
2	26/09/1990	18.81	985	26.5	0.00	FALSE
3	5/03/1990	0.00	890	0.0	0.00	FALSE
3	26/09/1990	0.00	800	27.0	0.00	FALSE
4	5/03/1990	0.00	800	0.0	0.00	FALSE
4	26/09/1990	0.00	756	29.7	0.00	FALSE
5	5/03/1990	0.00	1,030	0.0	0.00	FALSE
5	26/09/1990	32.60	983	27.2	0.00	FALSE
6	26/09/1990	4.94	1,096	26.0	0.00	FALSE
7	5/03/1990	0.00	1,105	0.0	0.00	FALSE
7	26/09/1990	7.90	1,065	25.9	0.00	FALSE
8	5/03/1990	0.00	4,130	0.0	0.00	FALSE
8	26/09/1990	29.52	4,820	26.4	0.00	FALSE
9	5/03/1990	0.00	590	0.0	0.00	FALSE
9	26/09/1990	0.00	410	0.0	0.00	FALSE
10	7/03/1990	0.00	900	0.0	0.00	FALSE
10	26/09/1990	49.80	824	26.0	0.00	FALSE
11	26/09/1990	60.45	0	0.0	0.00	FALSE
12	26/09/1990	54.27	0	0.0	0.00	FALSE
13	26/09/1990	0.00	1,274	0.0	0.00	FALSE
14	5/03/1990	0.00	1,120	0.0	0.00	FALSE
14	26/09/1990	22.26	773	26.9	0.00	FALSE
15	5/03/1990	0.00	1,610	0.0	0.00	FALSE
15	26/09/1990	0.00	1,628	26.2	0.00	FALSE
16	5/03/1990	0.00	1,360	0.0	0.00	FALSE
16	26/09/1990	48.69	1,462	0.0	0.00	FALSE
17	5/03/1990	0.00	3,200	0.0	0.00	FALSE
17	26/09/1990	12.36	2,030	25.4	0.00	FALSE
19	26/09/1990	0.00	1,377	26.5	0.00	FALSE
20	26/09/1990	46.59	0	0.0	0.00	FALSE
22	26/09/1990	22.25	639	26.7	0.00	FALSE
23	5/03/1990	0.00	1,370	0.0	0.00	TRUE
23	26/09/1990	25.26	1,638	26.9	0.00	FALSE
24	5/03/1990	0.00	1,270	0.0	0.00	TRUE
24	26/09/1990	24.70	0	0.0	0.00	FALSE
25	5/03/1990	0.00	760	0.0	0.00	FALSE
25	26/09/1990	24.00	1,942	26.3	0.00	FALSE
26	26/09/1990	24.09	1,362	26.2	0.00	FALSE
27	26/09/1990	0.00	1,731	26.1	0.00	FALSE
28	5/03/1990	0.00	1,860	0.0	0.00	FALSE
28	26/09/1990	0.00	1,593	26.4	0.00	FALSE
35	6/03/1990	0.00	3,000	0.0	0.00	FALSE
36	6/03/1990	0.00	540	0.0	0.00	FALSE
37	6/03/1990	0.00	920	0.0	0.00	FALSE
38	6/03/1990	0.00	700	0.0	0.00	FALSE
39	6/03/1990	0.00	780	0.0	0.00	FALSE

Appendix M

Water balance results for Vava'u, 1947-1990

The results of water balance calculations using 44 years of monthly rainfall and evaporation data are shown on the attached sheets.

Explanations for the column headings are listed below:

RAIN	:	rainfall
ET	:	potential evaporation
EI	:	interception loss
SMC1	:	soil moisture content at start of month
ES	:	evaporation from soil moisture store
XCESS	:	rainfall minus evaporation losses above (EI + ES)
AVSMDEF	:	average daily soil moisture deficit for the month
SMC2	:	soil moisture content at end of month
GWR	:	recharge to freshwater lens
TL	:	transpiration due to deep rooted vegetation
EA	:	sum of all evaporation losses (EI + ES + TL)
NETR	:	net recharge to freshwater lens (GWR - TL)
RECHARGE RATIO	:	ratio of net recharge (NETR) to rainfall (RAIN)

PROGRAM WATBAL.6

Water Balance Program to compute Recharge to Groundwater using MONTHLY RAINFALL and AVERAGE MONTHLY EVAPORATION data

- allows for interception losses
- assumes linear relation between evapotranspiration
- ratio (EA/ET) and soil moisture content

RAINFALL & EVAPORATION DATA USED IN WATER BALANCE

Name of Daily Rainfall File : VAVAU.RAI
Title of Rainfall Data : Monthly rainfall data: Vava'u: Tonga: 1947-90

Name of Monthly Evap File : VAVAU.EVA
Title of Evaporation : Monthly evap (Penman): Vava'u: (from Thompson, 1986)

No.of Years of Rain Record : 44
First Year of Rain Record : 1947
Last Year of Rain Record : 1990

INPUT SOIL AND VEGETATION PARAMETERS

Interception Store Capacity (ISMAX) in mm = 90
Initial Interception Store (IIS) in mm = 50
Soil Moisture Zone Thickness(SMZ) in mm = 1000
Field Capacity(FC)= .55
Wilting Point(WP)= .4
Max. Soil Moisture Content(SMCMAX=SMZ*FC) is: 550
Min. Soil Moisture Content(SMCMIN=SMZ*WP) is: 400
Initial Soil Moisture Content(ISMC) in mm = 500
Deep Rooted Vegetation(eg Coconut Trees) Ratio(DRVR)= .5
Ratio of these roots reaching water table(DRWT)= 0
Crop Factor for Deep Rooted Vegetation(CROPFD)= .8
Crop Factor for Shallow Rooted Vegetation(CROPFS)= 1
Linear Relation of Ea/Et(actual/potential evap) ratio to SMC

YEAR 1947

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
316	151	90	500	37	239	50	550	189	0	127	189	+0.60
103	134	90	550	40	-27	0	523	0	0	130	0	+0.00
657	135	90	523	33	534	27	550	507	0	123	507	+0.77
55	112	55	550	51	-51	0	499	0	0	106	0	+0.00
161	103	90	499	8	63	51	550	12	0	98	12	+0.07
287	90	90	550	0	197	0	550	197	0	90	197	+0.69
134	99	90	550	8	36	0	550	36	0	98	36	+0.27
73	108	73	550	32	-32	0	519	0	0	105	0	+0.00
90	117	90	519	19	-19	32	499	0	0	109	0	+0.00
172	142	90	499	31	51	51	550	0	0	121	0	+0.00
65	151	65	550	77	-77	0	473	0	0	142	0	+0.00
312	159	90	473	30	192	77	550	115	0	120	115	+0.37
2425	1501	%1003			366			1056	0	1369	1056	+0.44

YEAR 1948

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
463	151	90	550	55	318	0	550	318	0	145	318	+0.69
360	134	90	550	40	230	0	550	230	0	130	230	+0.64
329	135	90	550	41	199	0	550	199	0	131	199	+0.60
183	112	90	550	20	73	0	550	73	0	110	73	+0.40
61	103	61	550	38	-38	0	512	0	0	99	0	+0.00
115	90	90	512	0	25	38	537	0	0	90	0	+0.00
51	99	51	537	40	-40	13	498	0	0	91	0	+0.00
17	108	17	498	53	-53	52	444	0	0	70	0	+0.00
65	117	65	444	14	-14	106	431	0	0	79	0	+0.00
113	142	90	431	10	13	119	444	0	0	100	0	+0.00
503	151	90	444	16	397	106	550	291	0	106	291	+0.58
490	159	90	550	62	338	0	550	338	0	152	338	+0.69
2750	1501	914		387				1449	0	1301	1449	+0.53

YEAR 1949

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
199	151	90	550	55	54	0	550	54	0	145	54	+0.27
98	134	90	550	40	-32	0	518	0	0	130	0	+0.00
364	135	90	518	32	242	32	550	210	0	122	210	+0.58
133	112	90	550	20	23	0	550	23	0	110	23	+0.17
47	103	47	550	50	-50	0	500	0	0	97	0	+0.00
14	90	14	500	45	-45	50	454	0	0	59	0	+0.00
103	99	90	454	3	10	96	464	0	0	93	0	+0.00
148	108	90	464	7	51	86	515	0	0	97	0	+0.00
192	117	90	515	19	83	35	550	49	0	109	49	+0.25
148	142	90	550	47	11	0	550	11	0	137	11	+0.08
39	151	39	550	101	-101	0	449	0	0	140	0	+0.00
363	159	90	449	20	253	101	550	152	0	110	152	+0.42
1848	1501	910		439				499	0	1349	499	+0.27

YEAR 1950

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
313	151	90	550	55	168	0	550	168	0	145	168	+0.54
238	134	90	550	40	108	0	550	108	0	130	108	+0.46
466	135	90	550	41	336	0	550	336	0	131	336	+0.72
366	112	90	550	20	256	0	550	256	0	110	256	+0.70
68	103	68	550	32	-32	0	519	0	0	100	0	+0.00
65	90	65	519	18	-18	32	501	0	0	83	0	+0.00
252	99	90	501	5	157	49	550	107	0	95	107	+0.43
112	108	90	550	16	6	0	550	6	0	106	6	+0.05
177	117	90	550	24	63	0	550	63	0	114	63	+0.35
258	142	90	550	47	121	0	550	121	0	137	121	+0.47

312	151	90	550	55	167	0	550	167	0	145	167	+0.54
393	159	90	550	62	241	0	550	241	0	152	241	+0.61
3020	1501	%1033		414				1573	0	1447	1573	+0.52

YEAR 1951

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
255	151	90	550	55	110	0	550	110	0	145	110	+0.43
277	134	90	550	40	147	0	550	147	0	130	147	+0.53
457	135	90	550	41	327	0	550	327	0	131	327	+0.71
129	112	90	550	20	19	0	550	19	0	110	19	+0.15
116	103	90	550	12	14	0	550	14	0	102	14	+0.12
114	90	90	550	0	24	0	550	24	0	90	24	+0.21
42	99	42	550	51	-51	0	499	0	0	93	0	+0.00
28	108	28	499	47	-47	51	451	0	0	75	0	+0.00
330	117	90	451	8	232	99	550	133	0	98	133	+0.40
59	142	59	550	75	-75	0	475	0	0	134	0	+0.00
29	151	29	475	55	-55	75	420	0	0	84	0	+0.00
58	159	58	420	12	-12	130	408	0	0	70	0	+0.00
1894	1501	846		416				775	0	1262	775	+0.41

YEAR 1952

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
239	151	90	408	3	146	142	550	4	0	93	4	+0.02
117	134	90	550	40	-13	0	537	0	0	130	0	+0.00
222	135	90	537	37	95	13	550	82	0	127	82	+0.37
62	112	62	550	45	-45	0	505	0	0	107	0	+0.00
66	103	66	505	23	-23	45	482	0	0	89	0	+0.00
103	90	90	482	0	13	68	495	0	0	90	0	+0.00
66	99	66	495	19	-19	55	476	0	0	85	0	+0.00
81	108	81	476	12	-12	74	464	0	0	93	0	+0.00
139	117	90	464	10	39	86	502	0	0	100	0	+0.00
165	142	90	502	32	43	48	545	0	0	122	0	+0.00
84	151	84	545	58	-58	5	487	0	0	142	0	+0.00
96	159	90	487	36	-30	63	457	0	0	126	0	+0.00
1440	1501	989		316				86	0	1305	86	+0.06

YEAR 1953

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
126	151	90	457	21	15	93	472	0	0	111	0	+0.00
134	134	90	472	19	25	78	497	0	0	109	0	+0.00
252	135	90	497	26	136	53	550	83	0	116	83	+0.33
300	112	90	550	20	190	0	550	190	0	110	190	+0.63
53	103	53	550	45	-45	0	505	0	0	98	0	+0.00

92	90	90	505	0	2	45	507	0	0	90	0	+0.00
111	99	90	507	6	15	43	522	0	0	96	0	+0.00
14	108	14	522	69	-69	28	453	0	0	83	0	+0.00
12	117	12	453	34	-34	97	420	0	0	46	0	+0.00
54	142	54	420	10	-10	130	409	0	0	64	0	+0.00
75	151	75	409	4	-4	141	405	0	0	79	0	+0.00
58	159	58	405	3	-3	145	402	0	0	61	0	+0.00
1281	1501	806		257				273	0	1063	273	+0.21

YEAR 1954

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
256	151	90	402	1	165	148	550	17	0	91	17	+0.07
222	134	90	550	40	92	0	550	92	0	130	92	+0.42
495	135	90	550	41	365	0	550	365	0	131	365	+0.74
275	112	90	550	20	165	0	550	165	0	110	165	+0.60
83	103	83	550	18	-18	0	532	0	0	101	0	+0.00
167	90	90	532	0	77	18	550	59	0	90	59	+0.35
22	99	22	550	69	-69	0	481	0	0	91	0	+0.00
162	108	90	481	9	63	69	544	0	0	99	0	+0.00
79	117	79	544	33	-33	6	511	0	0	112	0	+0.00
177	142	90	511	35	52	39	550	13	0	125	13	+0.08
102	151	90	550	55	-43	0	507	0	0	145	0	+0.00
604	159	90	507	44	470	43	550	427	0	134	427	+0.71
2644	1501	994		363				1139	0	1357	1139	+0.43

YEAR 1955

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
109	151	90	550	55	-36	0	514	0	0	145	0	+0.00
193	134	90	514	30	73	36	550	37	0	120	37	+0.19
384	135	90	550	41	254	0	550	254	0	131	254	+0.66
91	112	90	550	20	-19	0	531	0	0	110	0	+0.00
139	103	90	531	10	39	19	550	20	0	100	20	+0.14
393	90	90	550	0	303	0	550	303	0	90	303	+0.77
322	99	90	550	8	224	0	550	224	0	98	224	+0.70
236	108	90	550	16	130	0	550	130	0	106	130	+0.55
188	117	90	550	24	74	0	550	74	0	114	74	+0.39
247	142	90	550	47	110	0	550	110	0	137	110	+0.45
224	151	90	550	55	79	0	550	79	0	145	79	+0.35
182	159	90	550	62	30	0	550	30	0	152	30	+0.16
2708	1501	%1080		368				1260	0	1448	1260	+0.47

YEAR 1956

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO

258	151	90	550	55	113	0	550	113	0	145	113	+0.44
168	134	90	550	40	38	0	550	38	0	130	38	+0.23
617	135	90	550	41	487	0	550	487	0	131	487	+0.79
235	112	90	550	20	125	0	550	125	0	110	125	+0.53
98	103	90	550	12	-4	0	546	0	0	102	0	+0.00
139	90	90	546	0	49	4	550	45	0	90	45	+0.33
110	99	90	550	8	12	0	550	12	0	98	12	+0.11
80	108	80	550	25	-25	0	525	0	0	105	0	+0.00
47	117	47	525	52	-52	25	472	0	0	99	0	+0.00
105	142	90	472	23	-8	78	465	0	0	113	0	+0.00
581	151	90	465	24	467	85	550	382	0	114	382	+0.66
90	159	90	550	62	-62	0	488	0	0	152	0	+0.00
2528	1501	%1027		361				1202	0	1388	1202	+0.48

YEAR 1957

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
759	151	90	488	32	637	62	550	575	0	122	575	+0.76
491	134	90	550	40	361	0	550	361	0	130	361	+0.74
126	135	90	550	41	-5	0	546	0	0	131	0	+0.00
259	112	90	546	19	150	5	550	145	0	109	145	+0.56
65	103	65	550	34	-34	0	516	0	0	99	0	+0.00
173	90	90	516	0	83	34	550	49	0	90	49	+0.28
157	99	90	550	8	59	0	550	59	0	98	59	+0.38
99	108	90	550	16	-7	0	543	0	0	106	0	+0.00
44	117	44	543	63	-63	7	480	0	0	107	0	+0.00
11	142	11	480	63	-63	70	417	0	0	74	0	+0.00
108	151	90	417	6	12	133	429	0	0	96	0	+0.00
346	159	90	429	12	244	121	550	123	0	102	123	+0.36
2638	1501	930		334				1312	0	1264	1312	+0.50

YEAR 1958

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
60	151	60	550	82	-82	0	468	0	0	142	0	+0.00
408	134	90	468	18	300	82	550	218	0	108	218	+0.53
358	135	90	550	41	228	0	550	228	0	131	228	+0.64
243	112	90	550	20	133	0	550	133	0	110	133	+0.55
158	103	90	550	12	56	0	550	56	0	102	56	+0.36
9	90	9	550	73	-73	0	477	0	0	82	0	+0.00
70	99	70	477	13	-13	73	464	0	0	83	0	+0.00
146	108	90	464	7	49	86	513	0	0	97	0	+0.00
66	117	66	513	35	-35	37	478	0	0	101	0	+0.00
217	142	90	478	24	103	72	550	31	0	114	31	+0.14
283	151	90	550	55	138	0	550	138	0	145	138	+0.49
14	159	14	550	131	-131	0	420	0	0	145	0	+0.00
2032	1501	849		509				804	0	1358	804	+0.40

YEAR 1959

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
191	151	90	420	7	94	131	513	0	0	97	0	+0.00
128	134	90	513	30	8	37	521	0	0	120	0	+0.00
610	135	90	521	33	487	29	550	459	0	123	459	+0.75
231	112	90	550	20	121	0	550	121	0	110	121	+0.52
129	103	90	550	12	27	0	550	27	0	102	27	+0.21
101	90	90	550	0	11	0	550	11	0	90	11	+0.11
66	99	66	550	30	-30	0	520	0	0	96	0	+0.00
68	108	68	520	29	-29	30	491	0	0	97	0	+0.00
456	117	90	491	15	351	59	550	293	0	105	293	+0.64
251	142	90	550	47	114	0	550	114	0	137	114	+0.45
60	151	60	550	82	-82	0	468	0	0	142	0	+0.00
50	159	50	468	45	-45	82	424	0	0	95	0	+0.00
2341	1501	964		348				1025	0	1312	1025	+0.44

YEAR 1960

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
239	151	90	424	9	140	126	550	14	0	99	14	+0.06
211	134	90	550	40	81	0	550	81	0	130	81	+0.39
711	135	90	550	41	581	0	550	581	0	131	581	+0.82
296	112	90	550	20	186	0	550	186	0	110	186	+0.63
70	103	70	550	30	-30	0	520	0	0	100	0	+0.00
48	90	48	520	30	-30	30	490	0	0	78	0	+0.00
208	99	90	490	5	113	60	550	53	0	95	53	+0.26
273	108	90	550	16	167	0	550	167	0	106	167	+0.61
94	117	90	550	24	-20	0	530	0	0	114	0	+0.00
34	142	34	530	84	-84	20	446	0	0	118	0	+0.00
56	151	56	446	26	-26	104	420	0	0	82	0	+0.00
211	159	90	420	8	113	130	533	0	0	98	0	+0.00
2451	1501	928		332				1082	0	1260	1082	+0.44

YEAR 1961

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
470	151	90	533	48	332	17	550	314	0	138	314	+0.67
127	134	90	550	40	-3	0	547	0	0	130	0	+0.00
799	135	90	547	40	669	3	550	667	0	130	667	+0.83
144	112	90	550	20	34	0	550	34	0	110	34	+0.24
176	103	90	550	12	74	0	550	74	0	102	74	+0.42
67	90	67	550	21	-21	0	529	0	0	88	0	+0.00
102	99	90	529	7	5	21	534	0	0	97	0	+0.00
138	108	90	534	15	33	16	550	18	0	105	18	+0.13
119	117	90	550	24	5	0	550	5	0	114	5	+0.04
118	142	90	550	47	-19	0	531	0	0	137	0	+0.00
218	151	90	531	48	80	19	550	61	0	138	61	+0.28
415	159	90	550	62	263	0	550	263	0	152	263	+0.63

2893	1501	%1057		383				1436	0	1440	1436	+0.50

YEAR 1962

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
324	151	90	550	55	179	0	550	179	0	145	179	+0.55
320	134	90	550	40	190	0	550	190	0	130	190	+0.59
237	135	90	550	41	107	0	550	107	0	131	107	+0.45
509	112	90	550	20	399	0	550	399	0	110	399	+0.78
131	103	90	550	12	29	0	550	29	0	102	29	+0.22
196	90	90	550	0	106	0	550	106	0	90	106	+0.54
78	99	78	550	19	-19	0	531	0	0	97	0	+0.00
27	108	27	531	64	-64	19	467	0	0	91	0	+0.00
150	117	90	467	11	49	83	516	0	0	101	0	+0.00
84	142	84	516	41	-41	34	476	0	0	125	0	+0.00
473	151	90	476	28	355	74	550	281	0	118	281	+0.59
231	159	90	550	62	79	0	550	79	0	152	79	+0.34
2760	1501	999		390				1371	0	1389	1371	+0.50

YEAR 1963

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
105	151	90	550	55	-40	0	510	0	0	145	0	+0.00
438	134	90	510	29	319	40	550	279	0	119	279	+0.64
359	135	90	550	41	229	0	550	229	0	131	229	+0.64
200	112	90	550	20	90	0	550	90	0	110	90	+0.45
202	103	90	550	12	100	0	550	100	0	102	100	+0.50
20	90	20	550	63	-63	0	487	0	0	83	0	+0.00
118	99	90	487	5	23	63	510	0	0	95	0	+0.00
177	108	90	510	12	75	40	550	35	0	102	35	+0.20
78	117	78	550	35	-35	0	515	0	0	113	0	+0.00
112	142	90	515	36	-14	35	501	0	0	126	0	+0.00
75	151	75	501	46	-46	49	455	0	0	121	0	+0.00
186	159	90	455	23	73	95	528	0	0	113	0	+0.00
2070	1501	983		375				733	0	1358	733	+0.35

YEAR 1964

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
50	151	50	528	78	-78	22	451	0	0	128	0	+0.00
224	134	90	451	13	121	99	550	21	0	103	21	+0.09
680	135	90	550	41	550	0	550	550	0	131	550	+0.81
117	112	90	550	20	7	0	550	7	0	110	7	+0.06
91	103	90	550	12	-11	0	539	0	0	102	0	+0.00
44	90	44	539	38	-38	11	501	0	0	82	0	+0.00
266	99	90	501	5	171	49	550	121	0	95	121	+0.46
50	108	50	550	52	-52	0	498	0	0	102	0	+0.00

187	117	90	498	16	81	52	550	29	0	106	29	+0.15
100	142	90	550	47	-37	0	513	0	0	137	0	+0.00
258	151	90	513	41	127	37	550	90	0	131	90	+0.35
81	159	81	550	70	-70	0	480	0	0	151	0	+0.00
2148	1501	945		433				818	0	1378	818	+0.38

YEAR 1965

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
362	151	90	480	29	243	70	550	173	0	119	173	+0.48
261	134	90	550	40	131	0	550	131	0	130	131	+0.50
327	135	90	550	41	197	0	550	197	0	131	197	+0.60
204	112	90	550	20	94	0	550	94	0	110	94	+0.46
206	103	90	550	12	104	0	550	104	0	102	104	+0.51
56	90	56	550	31	-31	0	519	0	0	87	0	+0.00
42	99	42	519	41	-41	31	479	0	0	83	0	+0.00
60	108	60	479	23	-23	71	456	0	0	83	0	+0.00
109	117	90	456	9	10	94	466	0	0	99	0	+0.00
247	142	90	466	21	136	84	550	52	0	111	52	+0.21
80	151	80	550	64	-64	0	486	0	0	144	0	+0.00
29	159	29	486	67	-67	64	419	0	0	96	0	+0.00
1983	1501	897		396				751	0	1293	751	+0.38

YEAR 1966

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
244	151	90	419	7	147	131	550	16	0	97	16	+0.07
15	134	15	550	107	-107	0	443	0	0	122	0	+0.00
176	135	90	443	12	74	107	517	0	0	102	0	+0.00
155	112	90	517	15	50	33	550	17	0	105	17	+0.11
33	103	33	550	63	-63	0	487	0	0	96	0	+0.00
57	90	57	487	17	-17	63	470	0	0	74	0	+0.00
153	99	90	470	4	59	80	529	0	0	94	0	+0.00
78	108	78	529	23	-23	21	506	0	0	101	0	+0.00
178	117	90	506	17	71	44	550	27	0	107	27	+0.15
281	142	90	550	47	144	0	550	144	0	137	144	+0.51
134	151	90	550	55	-11	0	539	0	0	145	0	+0.00
165	159	90	539	58	17	11	550	7	0	148	7	+0.04
1669	1501	903		425				210	0	1328	210	+0.13

YEAR 1967

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
1009	151	90	550	55	864	0	550	864	0	145	864	+0.86
311	134	90	550	40	181	0	550	181	0	130	181	+0.58
213	135	90	550	41	83	0	550	83	0	131	83	+0.39

438	112	90	550	20	328	0	550	328	0	110	328	+0.75
240	103	90	550	12	138	0	550	138	0	102	138	+0.58
97	90	90	550	0	7	0	550	7	0	90	7	+0.07
61	99	61	550	34	-34	0	516	0	0	95	0	+0.00
44	108	44	516	44	-44	34	471	0	0	88	0	+0.00
81	117	81	471	15	-15	79	456	0	0	96	0	+0.00
314	142	90	456	17	207	94	550	112	0	107	112	+0.36
81	151	81	550	63	-63	0	487	0	0	144	0	+0.00
65	159	65	487	49	-49	63	438	0	0	114	0	+0.00
2954	1501	962		390				1714	0	1352	1714	+0.58

YEAR 1968

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
546	151	90	438	14	442	112	550	330	0	104	330	+0.60
74	134	74	550	54	-54	0	496	0	0	128	0	+0.00
175	135	90	496	26	59	54	550	5	0	116	5	+0.03
104	112	90	550	20	-6	0	544	0	0	110	0	+0.00
150	103	90	544	11	49	6	550	43	0	101	43	+0.29
102	90	90	550	0	12	0	550	12	0	90	12	+0.12
34	99	34	550	59	-59	0	492	0	0	93	0	+0.00
114	108	90	492	10	14	59	506	0	0	100	0	+0.00
107	117	90	506	17	-0	44	506	0	0	107	0	+0.00
109	142	90	506	33	-14	44	492	0	0	123	0	+0.00
152	151	90	492	34	28	58	520	0	0	124	0	+0.00
122	159	90	520	50	-18	30	502	0	0	140	0	+0.00
1789	1501	%1008		326				390	0	1334	390	+0.22

YEAR 1969

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
132	151	90	502	37	5	48	507	0	0	127	0	+0.00
248	134	90	507	28	130	43	550	87	0	118	87	+0.35
284	135	90	550	41	154	0	550	154	0	131	154	+0.54
267	112	90	550	20	157	0	550	157	0	110	157	+0.59
7	103	7	550	86	-86	0	464	0	0	93	0	+0.00
16	90	16	464	28	-28	86	435	0	0	44	0	+0.00
78	99	78	435	4	-4	115	431	0	0	82	0	+0.00
12	108	12	431	18	-18	119	413	0	0	30	0	+0.00
158	117	90	413	2	66	137	479	0	0	92	0	+0.00
192	142	90	479	25	77	71	550	6	0	115	6	+0.03
38	151	38	550	102	-102	0	448	0	0	140	0	+0.00
178	159	90	448	20	68	102	516	0	0	110	0	+0.00
1610	1501	781		411				404	0	1192	404	+0.25

YEAR 1970

RAIN ET EI SMC1 ES XCESS SMDEF SMC2 GWR TL EA NETR RECHARGE

(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	RATIO
122	151	90	516	43	-11	34	506	0	0	133	0	+0.00
210	134	90	506	28	92	44	550	48	0	118	48	+0.23
200	135	90	550	41	70	0	550	70	0	131	70	+0.35
266	112	90	550	20	156	0	550	156	0	110	156	+0.59
122	103	90	550	12	20	0	550	20	0	102	20	+0.17
199	90	90	550	0	109	0	550	109	0	90	109	+0.55
54	99	54	550	41	-41	0	510	0	0	95	0	+0.00
62	108	62	510	30	-30	41	479	0	0	92	0	+0.00
51	117	51	479	31	-31	71	448	0	0	82	0	+0.00
53	142	53	448	26	-26	102	422	0	0	79	0	+0.00
329	151	90	422	8	231	128	550	103	0	98	103	+0.31
468	159	90	550	62	316	0	550	316	0	152	316	+0.68
2136	1501	940		340				822	0	1280	822	+0.38

YEAR 1971

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
173	151	90	550	55	28	0	550	28	0	145	28	+0.16
415	134	90	550	40	285	0	550	285	0	130	285	+0.69
189	135	90	550	41	59	0	550	59	0	131	59	+0.31
251	112	90	550	20	141	0	550	141	0	110	141	+0.56
370	103	90	550	12	268	0	550	268	0	102	268	+0.73
49	90	49	550	37	-37	0	513	0	0	86	0	+0.00
80	99	80	513	13	-13	37	500	0	0	93	0	+0.00
125	108	90	500	11	24	50	524	0	0	101	0	+0.00
174	117	90	524	20	64	26	550	38	0	110	38	+0.22
206	142	90	550	47	69	0	550	69	0	137	69	+0.34
169	151	90	550	55	24	0	550	24	0	145	24	+0.14
456	159	90	550	62	304	0	550	304	0	152	304	+0.67
2657	1501	%1029		411				1217	0	1440	1217	+0.46

YEAR 1972

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
293	151	90	550	55	148	0	550	148	0	145	148	+0.51
172	134	90	550	40	42	0	550	42	0	130	42	+0.25
257	135	90	550	41	127	0	550	127	0	131	127	+0.49
136	112	90	550	20	26	0	550	26	0	110	26	+0.19
104	103	90	550	12	2	0	550	2	0	102	2	+0.02
38	90	38	550	47	-47	0	503	0	0	85	0	+0.00
159	99	90	503	6	63	47	550	17	0	96	17	+0.10
156	108	90	550	16	50	0	550	50	0	106	50	+0.32
167	117	90	550	24	53	0	550	53	0	114	53	+0.32
163	142	90	550	47	26	0	550	26	0	137	26	+0.16
44	151	44	550	96	-96	0	454	0	0	140	0	+0.00
44	159	44	454	37	-37	96	417	0	0	81	0	+0.00
1733	1501	936		440				491	0	1376	491	+0.28

YEAR 1973

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
159	151	90	417	6	63	133	480	0	0	96	0	+0.00
443	134	90	480	21	332	70	550	262	0	111	262	+0.59
393	135	90	550	41	263	0	550	263	0	131	263	+0.67
304	112	90	550	20	194	0	550	194	0	110	194	+0.64
31	103	31	550	65	-65	0	485	0	0	96	0	+0.00
57	90	57	485	17	-17	65	468	0	0	74	0	+0.00
467	99	90	468	4	373	82	550	292	0	94	292	+0.62
109	108	90	550	16	3	0	550	3	0	106	3	+0.03
197	117	90	550	24	83	0	550	83	0	114	83	+0.42
115	142	90	550	47	-22	0	528	0	0	137	0	+0.00
333	151	90	528	47	196	22	550	174	0	137	174	+0.52
310	159	90	550	62	158	0	550	158	0	152	158	+0.51
2918	1501	988		369				1428	0	1357	1428	+0.49

YEAR 1974

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
178	151	90	550	55	33	0	550	33	0	145	33	+0.19
642	134	90	550	40	512	0	550	512	0	130	512	+0.80
229	135	90	550	41	99	0	550	99	0	131	99	+0.43
363	112	90	550	20	253	0	550	253	0	110	253	+0.70
425	103	90	550	12	323	0	550	323	0	102	323	+0.76
163	90	90	550	0	73	0	550	73	0	90	73	+0.45
71	99	71	550	25	-25	0	525	0	0	96	0	+0.00
108	108	90	525	13	5	25	529	0	0	103	0	+0.00
80	117	80	529	29	-29	21	501	0	0	109	0	+0.00
83	142	83	501	36	-36	49	465	0	0	119	0	+0.00
313	151	90	465	24	199	85	550	114	0	114	114	+0.36
164	159	90	550	62	12	0	550	12	0	152	12	+0.07
2819	1501	%1044		355				1420	0	1399	1420	+0.50

YEAR 1975

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
495	151	90	550	55	350	0	550	350	0	145	350	+0.71
344	134	90	550	40	214	0	550	214	0	130	214	+0.62
303	135	90	550	41	173	0	550	173	0	131	173	+0.57
120	112	90	550	20	10	0	550	10	0	110	10	+0.09
91	103	90	550	12	-11	0	539	0	0	102	0	+0.00
158	90	90	539	0	68	11	550	57	0	90	57	+0.36
300	99	90	550	8	202	0	550	202	0	98	202	+0.67
228	108	90	550	16	122	0	550	122	0	106	122	+0.53
105	117	90	550	24	-9	0	541	0	0	114	0	+0.00
66	142	66	541	64	-64	9	477	0	0	130	0	+0.00
483	151	90	477	28	365	73	550	292	0	118	292	+0.60

269	159	90	550	62	117	0	550	117	0	152	117	+0.43
2962	1501	%1056		369				1537	0	1425	1537	+0.52

YEAR 1976

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
357	151	90	550	55	212	0	550	212	0	145	212	+0.59
334	134	90	550	40	204	0	550	204	0	130	204	+0.61
207	135	90	550	41	77	0	550	77	0	131	77	+0.37
208	112	90	550	20	98	0	550	98	0	110	98	+0.47
91	103	90	550	12	-11	0	539	0	0	102	0	+0.00
16	90	16	539	62	-62	11	477	0	0	78	0	+0.00
47	99	47	477	24	-24	73	453	0	0	71	0	+0.00
87	108	87	453	7	-7	97	447	0	0	94	0	+0.00
75	117	75	447	12	-12	103	435	0	0	87	0	+0.00
62	142	62	435	17	-17	115	418	0	0	79	0	+0.00
255	151	90	418	7	158	132	550	26	0	97	26	+0.10
133	159	90	550	62	-19	0	531	0	0	152	0	+0.00
1872	1501	917		356				618	0	1273	618	+0.33

YEAR 1977

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
239	151	90	531	48	101	19	550	82	0	138	82	+0.34
297	134	90	550	40	167	0	550	167	0	130	167	+0.56
493	135	90	550	41	363	0	550	363	0	131	363	+0.74
71	112	71	550	37	-37	0	513	0	0	108	0	+0.00
134	103	90	513	9	35	37	548	0	0	99	0	+0.00
36	90	36	548	48	-48	2	500	0	0	84	0	+0.00
218	99	90	500	5	123	50	550	73	0	95	73	+0.33
127	108	90	550	16	21	0	550	21	0	106	21	+0.16
39	117	39	550	70	-70	0	480	0	0	109	0	+0.00
35	142	35	480	51	-51	70	429	0	0	86	0	+0.00
12	151	12	429	24	-24	121	405	0	0	36	0	+0.00
65	159	65	405	3	-3	145	402	0	0	68	0	+0.00
1766	1501	798		391				706	0	1189	706	+0.40

YEAR 1978

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
472	151	90	402	1	381	148	550	233	0	91	233	+0.49
204	134	90	550	40	74	0	550	74	0	130	74	+0.36
418	135	90	550	41	288	0	550	288	0	131	288	+0.69
178	112	90	550	20	68	0	550	68	0	110	68	+0.38
224	103	90	550	12	122	0	550	122	0	102	122	+0.55
77	90	77	550	12	-12	0	538	0	0	89	0	+0.00

11	99	11	538	73	-73	12	465	0	0	84	0	+0.00
267	108	90	465	7	170	85	550	85	0	97	85	+0.32
173	117	90	550	24	59	0	550	59	0	114	59	+0.34
215	142	90	550	47	78	0	550	78	0	137	78	+0.36
112	151	90	550	55	-33	0	517	0	0	145	0	+0.00
217	159	90	517	48	79	33	550	46	0	138	46	+0.21
2568	1501	988		379				1053	0	1367	1053	+0.41

YEAR 1979

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
135	151	90	550	55	-10	0	540	0	0	145	0	+0.00
215	134	90	540	37	88	10	550	78	0	127	78	+0.36
395	135	90	550	41	265	0	550	265	0	131	265	+0.67
270	112	90	550	20	160	0	550	160	0	110	160	+0.59
209	103	90	550	12	107	0	550	107	0	102	107	+0.51
288	90	90	550	0	198	0	550	198	0	90	198	+0.69
51	99	51	550	43	-43	0	507	0	0	94	0	+0.00
133	108	90	507	12	31	43	538	0	0	102	0	+0.00
70	117	70	538	39	-39	12	499	0	0	109	0	+0.00
359	142	90	499	31	238	51	550	187	0	121	187	+0.52
149	151	90	550	55	4	0	550	4	0	145	4	+0.03
154	159	90	550	62	2	0	550	2	0	152	2	+0.01
2428	1501	%1021		406				1001	0	1427	1001	+0.41

YEAR 1980

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
162	151	90	550	55	17	0	550	17	0	145	17	+0.11
161	134	90	550	40	31	0	550	31	0	130	31	+0.20
343	135	90	550	41	213	0	550	213	0	131	213	+0.62
368	112	90	550	20	258	0	550	258	0	110	258	+0.70
69	103	69	550	31	-31	0	519	0	0	100	0	+0.00
84	90	84	519	4	-4	31	515	0	0	88	0	+0.00
84	99	84	515	10	-10	35	505	0	0	94	0	+0.00
202	108	90	505	11	101	45	550	55	0	101	55	+0.27
197	117	90	550	24	83	0	550	83	0	114	83	+0.42
76	142	76	550	59	-59	0	491	0	0	135	0	+0.00
91	151	90	491	33	-32	59	458	0	0	123	0	+0.00
104	159	90	458	24	-10	92	448	0	0	114	0	+0.00
1941	1501	%1033		352				657	0	1385	657	+0.34

YEAR 1981

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
138	151	90	448	18	30	102	479	0	0	108	0	+0.00

461	134	90	479	21	350	71	550	279	0	111	279	+0.60
312	135	90	550	41	182	0	550	182	0	131	182	+0.58
210	112	90	550	20	100	0	550	100	0	110	100	+0.48
314	103	90	550	12	212	0	550	212	0	102	212	+0.68
83	90	83	550	6	-6	0	544	0	0	89	0	+0.00
61	99	61	544	33	-33	6	511	0	0	94	0	+0.00
75	108	75	511	22	-22	39	489	0	0	97	0	+0.00
91	117	90	489	14	-13	61	476	0	0	104	0	+0.00
120	142	90	476	24	6	74	482	0	0	114	0	+0.00
117	151	90	482	30	-3	68	479	0	0	120	0	+0.00
146	159	90	479	33	23	71	502	0	0	123	0	+0.00
2128	1501	%1029		272				773	0	1301	773	+0.36

YEAR 1982

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
611	151	90	502	37	484	48	550	436	0	127	436	+0.71
420	134	90	550	40	290	0	550	290	0	130	290	+0.69
368	135	90	550	41	238	0	550	238	0	131	238	+0.65
473	112	90	550	20	363	0	550	363	0	110	363	+0.77
177	103	90	550	12	75	0	550	75	0	102	75	+0.43
56	90	56	550	31	-31	0	519	0	0	87	0	+0.00
73	99	73	519	19	-19	31	501	0	0	92	0	+0.00
199	108	90	501	11	98	49	550	49	0	101	49	+0.25
151	117	90	550	24	37	0	550	37	0	114	37	+0.24
17	142	17	550	113	-113	0	438	0	0	130	0	+0.00
115	151	90	438	14	11	113	449	0	0	104	0	+0.00
213	159	90	449	20	103	101	550	2	0	110	2	+0.01
2873	1501	956		380				1489	0	1336	1489	+0.52

YEAR 1983

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
173	151	90	550	55	28	0	550	28	0	145	28	+0.16
218	134	90	550	40	88	0	550	88	0	130	88	+0.41
480	135	90	550	41	350	0	550	350	0	131	350	+0.73
42	112	42	550	63	-63	0	487	0	0	105	0	+0.00
78	103	78	487	13	-13	63	474	0	0	91	0	+0.00
20	90	20	474	31	-31	76	443	0	0	51	0	+0.00
34	99	34	443	17	-17	107	426	0	0	51	0	+0.00
21	108	21	426	14	-14	124	413	0	0	35	0	+0.00
51	117	51	413	5	-5	137	408	0	0	56	0	+0.00
42	142	42	408	5	-5	142	403	0	0	47	0	+0.00
86	151	86	403	1	-1	147	402	0	0	87	0	+0.00
520	159	90	402	1	429	148	550	281	0	91	281	+0.54
1765	1501	734		284				747	0	1018	747	+0.42

YEAR 1984

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
172	151	90	550	55	27	0	550	27	0	145	27	+0.16
276	134	90	550	40	146	0	550	146	0	130	146	+0.53
126	135	90	550	41	-5	0	546	0	0	131	0	+0.00
410	112	90	546	19	301	5	550	296	0	109	296	+0.72
56	103	56	550	42	-42	0	508	0	0	98	0	+0.00
34	90	34	508	36	-36	42	472	0	0	70	0	+0.00
71	99	71	472	12	-12	78	459	0	0	83	0	+0.00
77	108	77	459	11	-11	91	448	0	0	88	0	+0.00
199	117	90	448	8	101	102	550	0	0	98	0	+0.00
28	142	28	550	102	-102	0	447	0	0	130	0	+0.00
42	151	42	447	31	-31	103	416	0	0	73	0	+0.00
308	159	90	416	7	211	134	550	78	0	97	78	+0.25
1799	1501	848		404				547	0	1252	547	+0.30

YEAR 1985

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
143	151	90	550	55	-2	0	548	0	0	145	0	+0.00
340	134	90	548	39	211	2	550	209	0	129	209	+0.61
408	135	90	550	41	278	0	550	278	0	131	278	+0.68
206	112	90	550	20	96	0	550	96	0	110	96	+0.47
124	103	90	550	12	22	0	550	22	0	102	22	+0.18
81	90	81	550	8	-8	0	542	0	0	89	0	+0.00
160	99	90	542	8	62	8	550	54	0	98	54	+0.34
30	108	30	550	70	-70	0	480	0	0	100	0	+0.00
36	117	36	480	39	-39	70	441	0	0	75	0	+0.00
38	142	38	441	26	-26	109	415	0	0	64	0	+0.00
16	151	16	415	12	-12	135	403	0	0	28	0	+0.00
147	159	90	403	1	56	147	459	0	0	91	0	+0.00
1729	1501	831		330				659	0	1161	659	+0.38

YEAR 1986

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
92	151	90	459	21	-19	91	439	0	0	111	0	+0.00
80	134	80	439	13	-13	111	427	0	0	93	0	+0.00
186	135	90	427	7	89	123	515	0	0	97	0	+0.00
277	112	90	515	15	172	35	550	137	0	105	137	+0.50
80	103	80	550	21	-21	0	529	0	0	101	0	+0.00
451	90	90	529	0	361	21	550	340	0	90	340	+0.75
99	99	90	550	8	1	0	550	1	0	98	1	+0.01
66	108	66	550	38	-38	0	512	0	0	104	0	+0.00
189	117	90	512	18	81	38	550	43	0	108	43	+0.23
159	142	90	550	47	22	0	550	22	0	137	22	+0.14
18	151	18	550	120	-120	0	430	0	0	138	0	+0.00
60	159	60	430	18	-18	120	412	0	0	78	0	+0.00
1757	1501	934		326				544	0	1260	544	+0.31

YEAR 1987

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
5	151	5	412	11	-11	138	402	0	0	16	0	+0.00
224	134	90	402	0	134	148	535	0	0	90	0	+0.00
152	135	90	535	36	26	15	550	11	0	126	11	+0.07
27	112	27	550	77	-77	0	474	0	0	104	0	+0.00
298	103	90	474	6	202	77	550	126	0	96	126	+0.42
135	90	90	550	0	45	0	550	45	0	90	45	+0.33
49	99	49	550	45	-45	0	505	0	0	94	0	+0.00
127	108	90	505	11	26	45	531	0	0	101	0	+0.00
25	117	25	531	72	-72	19	459	0	0	97	0	+0.00
26	142	26	459	41	-41	91	418	0	0	67	0	+0.00
72	151	72	418	8	-8	132	409	0	0	80	0	+0.00
586	159	90	409	4	492	141	550	351	0	94	351	+0.60
1726	1501	744		311				533	0	1055	533	+0.31

YEAR 1988

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
292	151	90	550	55	147	0	550	147	0	145	147	+0.50
99	134	90	550	40	-31	0	519	0	0	130	0	+0.00
142	135	90	519	32	20	31	539	0	0	122	0	+0.00
187	112	90	539	18	79	11	550	68	0	108	68	+0.36
191	103	90	550	12	89	0	550	89	0	102	89	+0.47
115	90	90	550	0	25	0	550	25	0	90	25	+0.22
58	99	58	550	37	-37	0	513	0	0	95	0	+0.00
25	108	25	513	56	-56	37	457	0	0	81	0	+0.00
332	117	90	457	9	233	93	550	140	0	99	140	+0.42
145	142	90	550	47	8	0	550	8	0	137	8	+0.06
319	151	90	550	55	174	0	550	174	0	145	174	+0.55
230	159	90	550	62	78	0	550	78	0	152	78	+0.34
2135	1501	983		423				729	0	1406	729	+0.34

YEAR 1989

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
367	151	90	550	55	222	0	550	222	0	145	222	+0.61
630	134	90	550	40	500	0	550	500	0	130	500	+0.79
283	135	90	550	41	153	0	550	153	0	131	153	+0.54
127	112	90	550	20	17	0	550	17	0	110	17	+0.14
213	103	90	550	12	111	0	550	111	0	102	111	+0.52
28	90	28	550	56	-56	0	494	0	0	84	0	+0.00
28	99	28	494	40	-40	56	454	0	0	68	0	+0.00
9	108	9	454	32	-32	96	422	0	0	41	0	+0.00
81	117	81	422	5	-5	128	417	0	0	86	0	+0.00

166	142	90	417	5	71	133	488	0	0	95	0	+0.00
188	151	90	488	32	66	62	550	4	0	122	4	+0.02
658	159	90	550	62	506	0	550	506	0	152	506	+0.77
2778	1501	866		399				1513	0	1265	1513	+0.54

YEAR 1990

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	SMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
255	151	90	550	55	110	0	550	110	0	145	110	+0.43
159	134	90	550	40	29	0	550	29	0	130	29	+0.18
82	135	82	550	48	-48	0	502	0	0	130	0	+0.00
192	112	90	502	14	88	48	550	41	0	104	41	+0.21
210	103	90	550	12	108	0	550	108	0	102	108	+0.52
262	90	90	550	0	172	0	550	172	0	90	172	+0.66
160	99	90	550	8	62	0	550	62	0	98	62	+0.39
18	108	18	550	81	-81	0	469	0	0	99	0	+0.00
167	117	90	469	11	66	81	535	0	0	101	0	+0.00
84	142	84	535	47	-47	15	488	0	0	131	0	+0.00
29	151	29	488	64	-64	62	424	0	0	93	0	+0.00
202	159	90	424	10	102	126	526	0	0	100	0	+0.00
1820	1501	933		389				522	0	1322	522	+0.29

44 YEAR AVERAGES

2232	1501	941		373				917	0	1315	917	+0.41

Summary of Monthly Recharge (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Recharge	Annual Rainfall
1947	189	0	507	0	12	197	36	0	0	0	0	115	1,056	2,425
1948	318	230	199	73	0	0	0	0	0	0	291	338	1,449	2,750
1949	54	0	210	23	0	0	0	0	49	11	0	152	499	1,848
1950	168	108	336	256	0	0	107	6	63	121	167	241	1,573	3,020
1951	110	147	327	19	14	24	0	0	133	0	0	0	775	1,894
1952	4	0	82	0	0	0	0	0	0	0	0	0	86	1,440
1953	0	0	83	190	0	0	0	0	0	0	0	0	273	1,281
1954	17	92	365	165	0	59	0	0	0	13	0	427	1,139	2,644
1955	0	37	254	0	20	303	224	130	74	110	79	30	1,260	2,708
1956	113	38	487	125	0	45	12	0	0	0	382	0	1,202	2,528
1957	575	361	0	145	0	49	59	0	0	0	0	123	1,312	2,638
1958	0	218	228	133	56	0	0	0	0	31	138	0	804	2,032
1959	0	0	459	121	27	11	0	0	293	114	0	0	1,025	2,341
1960	14	81	581	186	0	0	53	167	0	0	0	0	1,082	2,451
1961	314	0	667	34	74	0	0	18	5	0	61	263	1,436	2,893
1962	179	190	107	399	29	106	0	0	0	0	281	79	1,371	2,760
1963	0	279	229	90	100	0	0	35	0	0	0	0	733	2,070
1964	0	21	550	7	0	0	121	0	29	0	90	0	818	2,148
1965	173	131	197	94	104	0	0	0	0	52	0	0	751	1,983
1966	16	0	0	17	0	0	0	0	27	144	0	7	210	1,669
1967	864	181	83	328	138	7	0	0	0	112	0	0	1,714	2,954
1968	330	0	5	0	43	12	0	0	0	0	0	0	390	1,789
1969	0	87	154	157	0	0	0	0	0	6	0	0	404	1,610
1970	0	48	70	156	20	109	0	0	0	0	103	316	822	2,136
1971	28	285	59	141	268	0	0	0	38	69	24	304	1,217	2,657
1972	148	42	127	26	2	0	17	50	53	26	0	0	491	1,733
1973	0	262	263	194	0	0	292	3	83	0	174	158	1,428	2,918
1974	33	512	99	253	323	73	0	0	0	0	114	12	1,420	2,819
1975	350	214	173	10	0	57	202	122	0	0	292	117	1,537	2,962
1976	212	204	77	98	0	0	0	0	0	0	26	0	618	1,872
1977	82	167	363	0	0	0	73	21	0	0	0	0	706	1,766
1978	233	74	288	68	122	0	0	85	59	78	0	46	1,053	2,568
1979	0	78	265	160	107	198	0	0	0	187	4	2	1,001	2,428
1980	17	31	213	258	0	0	0	55	83	0	0	0	657	1,941
1981	0	279	182	100	212	0	0	0	0	0	0	0	773	2,128
1982	436	290	238	363	75	0	0	49	37	0	0	2	1,489	2,873
1983	28	88	350	0	0	0	0	0	0	0	0	281	747	1,765
1984	27	146	0	296	0	0	0	0	0	0	0	78	547	1,799
1985	0	209	278	96	22	0	54	0	0	0	0	0	659	1,729
1986	0	0	0	137	0	340	1	0	43	22	0	0	544	1,757
1987	0	0	11	0	126	45	0	0	0	0	0	351	533	1,726
1988	147	0	0	68	89	25	0	0	140	8	174	78	729	2,135
1989	222	500	153	17	111	0	0	0	0	0	4	506	1,513	2,778
1990	110	29	0	41	108	172	62	0	0	0	0	0	522	1,820

Appendix N

List of hydrogeological equipment

The Hydrogeology Unit of the Ministry of Lands, Survey and Natural Resources was provided with the following equipment during the course of the Master Plan study. Funds for the equipment were provided from the Master Plan study.

Item No	Item	Make/Model	Quantity
1.	Portable conductivity, salinity and temperature meter with 2m cable	TPS LC84	3
2.	Portable pH meter	TPS LC80	3
3.	Portable conductivity meter with 100 m cable	Beta 800	1
4.	PVC bailer	Islex	5
5.	Portable water depth probe (electric contact type) with 60m cable (note: 2 off 60m cables were modified on site to 1 off 40m cables and 1 off 80m cable	HS 67-814	
6.	Electronic data loggers (64 kb capacity) with environmental enclosures and software	Unidata 6003	5
7.	Electric pressure transducers		
	(a) 5m range, 10m cable	Unidata 6508C	1
	(b) 1m range, 15m cable	Unidata 6508A	4
	(c) 1m range, 25m cable	Unidata 6508A	1
8.	Tipping bucket raingauge	Unidata 6506A	5
9.	Barograph	Unidata 6522A	1
10.	Electrical resistivity equipment complete with cables, reels, probes, software and spare parts	ABEM SAS 300	1
11.	Electromagnetic equipment complete with data logger and software	Geonics EM34	1
12.	Automatic survey level, tripod (GSTO5) and two staffs (MYZOG)	Wild NA28	1
13.	Potable computer (386SX, 40 Mb hard disk) with maths co-processor and remote VGA colour monitor	Mitac 3030D	1
14.	Plotter (A3 size with8 pens)	Houston Instruments Image Maker HI1117E	1
15.	Digitiser tablet	Wintime KD-5000	1
16.	Software (a) Microsoft Works (b) dBaseIII+ (c) other software (yet to be ordered)		 1 1 1
17.	Chemical test equipment (yet to be ordered) (a) field kit for chloride tests (b) 1 litre brown glass bottles with caps (c) 28 g (1 oz) brown dropper bottle (d) 5 ml pipettes graduated in 0.1 ml (e) 100 ml porcelain mixing casseroles (f) 25 ml plastic measuring cylinder (g) glass stirring rods (h) silver nitrate (i) potassium chromate		 1 3 1 2 2 1 2 500g 250g
18.	Four wheel drive vehicle	Toyota Hilux Dual Cab	1

Suppliers' names, addresses and contact numbers are listed below for each item number:

1,2	TPS Pty Ltd	phone	(07)2088447
	4 Jamberoo Street	fax	(07)8084871
	Springwood		
	Brisbane QLD 4127		
	Australia		
3	CHK Engineering	phone	(02)8184555
	24 Fred Street	fax	(02)8107908
	Lilyfield NSW 2040		
	Australia		
4	Islex Pty Ltd	phone	(07)3768488
	PO Box 122	fax	(07)3762959
	Darra QLD 4076		
	Australia		
5	Hydrological Services Pty Ltd	phone	(02)6012022
	PO Box 322	fax	(02)6026971
	Liverpool NSW 2170		
	Australia		
6,7,8,9	Unidata	phone	(09)4571499
	3 Whyalla Street	fax	(09)4575224
	Willetton WA 6155		
	Australia		
10	Richard Foot Pty. Ltd.	phone	(02)4502133
	PO Box 245	fax	(02)4502569
	Terrey Hills NSW 2084		
	Australia		
11	Geoterrex	phone	(02)4383866
	13 Whiting Street	fax	(02)4375917
	Artarmon NSW 2064		
	Australia		
12	Leica Instruments Pty Ltd	phone	(02)8887122
	PO Box 21	fax	(02)8887526
	North Ryde NSW 2116		
13,14,15,16	PATCO	phone	21320
	Hala Taufa'ahau	fax	23120
	Nuku'alofa		
	Tongatapu		
	Kingdom of Tonga		
17	Not yet ordered		
18	Burns Philp Toyota	phone	23500
	Nuku'alofa		
	Tongatapu		
	Kingdom of Tonga		

Appendix O

Rainwater catchment analyses for islands other than Tongatapu

The analyses are summarised in the attached graphs which follow the format of Figure 5.52 for Tongatapu. The background to the analysis method is described in Section 5.6.

Attached are graphical summaries of Roof Area Factor v Days of Storage for:

(i) Ha'apai

(ii) Vava'u

(iii) Niuatoputapu, and

(iv) Niuafo'ou