SOPAC/EU EDF 8 Reducing the Vulnerability of Pacific APC States

Vulnerability of Groundwater in Tongatapu, Kingdom of Tonga

Groundwater Evaluation and Monitoring Assessment

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List of Abbreviations and Units

ADB	Asian Development Bank
ANU	Australian National University
AusAID	Australian Agency for International Development
AWS	automatic weather station
BTEX	benzene, toluene, ethyl benzene and xylene
BoM	Bureau of Meteorology (Government of Australia)
cm	centimetre
conc	concentration
CV	coefficient of variation (= standard deviation/mean)
DGPS	differential global positioning system
E	evaporation (mm/time period)
E_{pot}	potential evaporation (mm/time period)
EC	electrical conductivity (measure of salinity)
EDF	European Development Fund
EIS	Environmental Impact Statement
ET_a	actual evapotranspiration (mm/time period)
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
g	grams
GCM	Global climate model
GEF	Global Environment Facility
GHG	greenhouse gas
GIS	geographic information systems
GMW	groundwater monitoring well (near the Tapuhia Waste Management Facility)
GoT	Government of Tonga
GPS	global positioning system

Gt	gigatonnes
HYCOS	Hydrological Cycle Observing System
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
IWP	International Waters Project
IWRM	Integrated Water Resources Management
JICA	Japan International Co-operation Agency
Kg	kilogram (=1,000 grams)
kL	kilolitres (= 1,000 litres)
kL/day	kilolitres per day
km	kilometre
km^2	square kilometres
L	litres
LoD	limit of detection
L/day	litres per day
L/g	litres per gram (inverse concentration unit)
L/p/day	litres per person per day
L/s	litres per second
m	metre (= 1,000 mm)
m^3	cubic metre (=1,000 L)
MAFFF	Ministry of Agriculture, Food, Forestry and Fisheries
mbgl	metres below ground level
MDPE	medium density polyethylene
MFEP	Ministry of Finance and Economic Planning
meq/L	milliequivalents per litre
mg/L	milligrams per litre
ML	megalitre (= 1,000 kilolitres)
ML/day	megalitres per day
MLSNRE	Ministry of Lands, Survey, Natural Resources and Environment
mm	millimetre
MoF	Ministry of Finance
MoH	Ministry of Health
MoW	Ministry of Works
MSL	mean sea level
NDMO	National Disaster Management Office
NEMC	National Emergency Management Committee
NGO	Non Government Organisation
NIWA	National Institute of Water & Atmospheric Research (of New Zealand)
NMI	National Measurement Institute (Australian Government laboratory)
NWRC	National Water Resources Committee
NZAID	New Zealand’s International Aid & Development Agency
N/P	molar ratio of nitrogen to phosphorus (moles L^{-1}/moles L^{-1})
OCP	organochlorine pesticide
OPP	organophosphate pesticide
P	rainfall (mm/ time period)
PACC	Pacific Adaptation to Climate Change

PAH	polyaromatic hydrocarbons
PDO	Pacific Decadal Oscillation
PIC	Pacific island countries
PVC	polyvinyl chloride
PS	pump station
R	recharge rate (mm/time period)
R_c	correlation coefficient
R^2	coefficient of determination
RL	reduced (or relative) level
RWH	Rainwater harvesting
SCOPIC	Seasonal Climate Outlook Pacific Island Countries
SMB	salinity monitoring borehole
SOI	Southern Oscillation Index
SOPAC	Secretariat of the Pacific Islands Applied Geoscience Commission
SPCZ	South Pacific Convergence Zone
SPREP	Secretariat of the Pacific Regional Environment Programme
SRES	Special report of emission scenarios (IPCC)
SST	sea surface temperature
Std Dev	standard deviation
TBM	temporary benchmark
TEMPP	Tonga Environmental Management and Planning Project
TDS	total dissolved solids (mg/L)
TMS	Tonga Meteorological Service
ToR	Terms of Reference
TOP	Tongan Pa’anga
TPH	total petroleum hydrocarbons
TT	Tonga Trust (NGO)
TWB	Tonga Water Board
TWMF	Tapuhia Waste Management Facility
UN	United Nations
UNESCO	United Nations Educational. Scientific and Cultural Organisation
VWC	Village Water Committee
WA	Waste Authority
WHO	World Health Organisation
WMF	Waste Management Facility
μg/L	micrograms per litre
μS/cm	micro siemens per centimetre (unit of electrical conductivity, and used as an indicator of salinity; also shown in some publications as μmhos/cm)
<LoD	less than the limit of detection

Summary

Introduction

Tongatapu, the main island in the Kingdom of Tonga, is blessed with reliable rainfall, fertile soils and has an adequate supply of groundwater. There are, however, increasing demands on, growing threats to, and public concerns about its groundwater, which require wise management and use to ensure adequate supplies of safe freshwater for current and future generations, in accord with UN Millennium Goals and the Pacific Regional Action Plan on Sustainable Water Management.

Over the past 40 years, investigations in Tongatapu have identified a number of natural and human-related factors that increase or have the potential to increase the vulnerability of fresh groundwater sources. Some of these studies have suggested strategies to lessen impacts and improve resilience. This project builds on the considerable weight of those results as well as the depth of local expertise and the valuable, long-term record of monitoring. Our aim here is to summarise early work, to examine the current situation and to propose strategies to decrease the vulnerability of the groundwater resource and the water supply system. The overall goal of this project is to:

> *assist assessment of impacts on the aquatic environment and the planning and sustainable management of the finite water resources of Tongatapu*

In order to meet the project goal, the following project objectives were set.

1. Assess the institutional capacity and needs of organisations with responsibility for monitoring groundwater.
2. Assess the vulnerability of the groundwater resources of Tongatapu.
3. Review and analyse baseline groundwater monitoring data.
4. Conduct a survey of water quality in water supply wells and bores throughout Tongatapu.

This report presents the results and recommendations arising from consultations with personnel from relevant agencies of the Government of Tonga (GoT) and non-government organisations (NGOs) from groundwater investigations conducted on Tongatapu during between 21st July and 21 August 2007 and from 19th November to 13th December 2007 and from an extensive analysis of the extensive groundwater data bases.

Groundwater contained in Tongatapu's karst limestone aquifer is a valuable resource, particularly during dry seasons and periodic droughts. Unfortunately, the groundwater is of variable quality for drinking due to its mixing with underlying seawater and the impacts of overlying human settlements. There are, therefore, a range of natural, anthropogenic as well as institutional factors that contribute to the vulnerability of groundwater in Tongatapu. This study has assessed the main factors and their impacts on groundwater using: "snap shot" measurements of groundwater conducted during the study; the valuable data bases of monitoring results dating back to 1959 and a range of models and techniques to predict possible future situations.

Work carried out

The roles and responsibilities of organisations involved in the water sector, and particularly in groundwater monitoring were analysed together with the demographic pressures in Tongatapu. "Snap shot" measurements undertaken in this work designed to contribute to the assessment of impacts on groundwater are then described. To identify trends in groundwater impacts, these "snap shot" measurements were supplemented with data from the extensive MLSNRE and TWB data bases. A quality assessment of the MLSNRE data base was carried out to remove outliers and spurious measurements. The TWB data base was of high quality and required no culling of outliers. The project team were also able participated in measurements at the Waste Authority's Tapuhia Waste Management Facility which provided valuable information.

Groundwater recharge was estimated under the historic, variable climatic conditions. This was used to conservatively assess the sustainable groundwater yield, which was compared with current pumping rates. This information was used to suggest locations for future water supply schemes. Analyses of both meteorological and hydrological drought were carried out and the major influences driving drought and seasonal rainfall were identified. The potential impacts of climate change on rainfall, evaporation and groundwater recharge were estimated and the impacts of quarrying, and quarry filling on groundwater are examined. The uses and expansion of the MLSNRE GIS were considered and finally a description is presented of the training carried out throughout the project, the stakeholder workshop and the development of a Cabinet Briefing Note undertaken in the workshop as a way of summarising the project.

Principle findings

Institutional issues

The study found that the main threat to groundwater in Tongatapu is institutional. There is no legal basis for protecting groundwater from harmful activity or over use. The lead water resource Ministry, MLSNRE, has no statutory basis for protecting, regulating, monitoring or reporting on groundwater resources. There are also conflicting ministerial roles in the water sector and no incentives for collaboration. Currently, there is little obligation for Ministries to report collectively to the Government on the state of the nation’s water resources. The draft 2006 National Water Resources Bill addresses these issues. A National Water Resources Committee, with members drawn from key water agencies and non-government organisations, as specified in the draft 2006 Water Resources Bill, should be established as a matter of urgency. Once established, this Committee will report regularly to Cabinet on the condition and use of water resources and on priority issues in the sector and will improve coordination and cooperation between agencies and help focus aid donor projects.

There is a serious need for continued recruitment and training of staff in water resource management agencies. Water agencies are operationally poorly resourced to conduct groundwater monitoring, analysis, assessment, reporting and community consultation. There are few incentives for cooperation between Ministries with responsibilities in water. The establishment of a modest environmental water abstraction charge on all groundwater pumped in Tongatapu to be totally allocated to water resource monitoring and assessment would provide operational resources to carry out this vital function and incentives for cooperation.

Village Water Committees manage water supplies for villages in Tongatapu but are under-resourced and largely untrained for this important technical task. Ways of improving the management and delivery of water supplies at the village level are needed. Institutional reform of the water supply sector through the formation of a single Tongatapu Water Authority for both urban and rural Tongatapu would address this problem and improve service in most rural areas. Fua’amotu has already taken action in this direction.

Sustainable groundwater pumping

The sustainability of pumping from groundwater is uncertain since there is no accurate metering of the rate at which water is being pumped from groundwater in Tongatapu. It is estimated here that the total sustainable pumping rate for Tongatapu is between 54 and 72 ML/day. While the current extraction rate is uncertain, estimates suggest it could be as high as 13.4 ML/day or 19 to 25% of the sustainable yield. Approximately 10.7 ML/day, or 80% of this estimated total daily extraction, is sourced from the Liahona-Tongamai-Mataki’eua region due to the concentration of pumps at the Mataki’eua/Tongamai wellfield, while the remaining 20% is distributed over the rest of Tongatapu. This uneven distribution of pumping could be further exacerbated by proposals to increase the number of pumps at Mataki’eua/Tongamai to up to 60 and may create salinity problems in pumped water particularly during dry times. The household statistics show a dramatic increase in the number of household rainwater tanks since 1986, indicating a preference of rainwater for drinking.

The range of the maximum number of pumps, pumping continuously at rates of 216 to 260 m^3/day (2.5 to 3.0 L/s), that can be accommodated within the effective recharge zone of Tongatapu is between 210 and 330 pumps. It is concluded that all pumps should be metered and licensed to extract at a maximum of 3.0 L/s. To minimise upconing of the fresh/seawater interface it is desirable to have these pumps as evenly distributed as possible with spacing between pumps of 0.75 to 1 km. Spacing pumps closer than this will increase both local salinity of pumped groundwater, as observed at Mataki’eua/Tongamai wellfield.

Between half and two thirds of the water pumped from the Mataki’eua/Tongamai wellfield disappears as unaccounted-for losses. A large proportion of the good quality groundwater is therefore being pumped from Mataki’eua/Tongamai to be discharged from leaking pipelines into the polluted groundwater in Nuku’alofa were it discharges into the Lagoon or the ocean. Future water supply projects in Nuku’alofa should concentrate on reducing these losses.

Groundwater salinity

Mapping of the salinity of groundwater in village wells showed seawater intrusion causes increased groundwater salinity in the Hihifo, northern Lapaha (around Kolonga) Districts and the Mu’a villages. The water supply problems in the Hihifo region need to be addressed urgently. The freshest groundwater comes from the area around Fua’amotu and should be considered as a future water supply source, particularly in droughts. The current distribution of groundwater salinity in Tongatapu is similar to that mapped in the last survey in 1990. Water supply projects for the most saline areas and monitoring of their salinity should be of the highest priority. Where possible, water sourced from wells in areas with lower salinity groundwater should be used for supply.

The salinity of groundwater increases during droughts which are mostly related to El Niño events. The number of droughts in Tongatapu has increased in the period 1975 to 2007 compared with those from 1945 to 1975. The average duration of droughts which most affect groundwater is 14 months and the average time between droughts is 7 years. Droughts are highly correlated with ENSO events and sea surface temperatures, SSTs. It was found that wet season rainfalls were highly correlated with SST but dry season rainfalls were not.

Salinity of water from the Mataki’eua and Tongamai wellfield is highest in wells closer to the lagoon and depends on the rainfall over the past 12 to 18 months. Using the relation between rainfall and groundwater salinity, it was predicted that the groundwater salinity of the entire wellfield would exceed the salinity guideline limit for drinking water after four months without rain. Using the relationship between groundwater salinity and distance from the sea it was found that vertical wells within 0.75 km of the sea would exceed the salinity guideline if pumped continuously. During dry periods, the frequency of groundwater monitoring should be increased to improve management of wells. A new groundwater extraction scheme from government land at Fua’amotu should be initiated to mitigate the impacts of droughts and seawater intrusion.

Agricultural chemicals, heavy metals and nutrients

This study addressed the increasing concern about the quantity of agricultural chemicals used in Tongatapu and about leakage from septic tanks. Intensive sampling of 10 selected water supply wells across Tongatapu showed no detectable presence of harmful pesticides, petroleum products or most heavy metals. Elements that were detected were well below the World Health Organisation (WHO) guideline values for drinking water except for lead at the Tapuhia Waste Management Facility (TWMF). The absence of pesticides, petroleum products or heavy metals found in this study agrees with three groundwater surveys undertaken by the Waste Authority between April 2006 and July 2007 around the TWMF and a survey conducted ten years earlier in the mid 1990s.

Nutrients such as nitrate were present in every sample but were less than WHO guideline values except for one measurement at the TWMF. It was shown that nutrient levels have stayed remarkably constant since 1978. The nitrate in groundwater is attributed to leakage from septic tank and pit latrines, human and animal wastes rather than agriculture fertilisers.

Continued monitoring of nitrate in groundwater and strategies for reducing nitrate inputs are required because of the use of nitrogen fertilisers, leakage from septic tanks and the health impact of high concentrations of nitrate in drinking water on young babies. Continued use of hazardous agricultural chemicals requires continued monitoring of groundwater at selected sites. A data base showing where agricultural chemicals are being used across Tongatapu needs to be established to allow better targeting of sampling sites.

Faecal contamination

Indicators of bacterial contamination were found in 90% of the 19 water supply wells sampled and 24% of the wells had indicators of faecal contamination. Faecal contamination could be of human or animal origin and indicates that both the drilling of water supply wells away from faecal sources and treatment of all groundwater used for drinking in villages should be a priority. Control of leakage from septic tanks in and removing livestock from water source areas would decrease the threats to groundwater supplies. The study was not able to access the Ministry of Health microbiological water quality data base which is only available in hard copy record books.

Climate change

A suite of 23 coupled atmosphere-ocean global climate models, GCMs, run by CSIRO were used to predict possible changes to monthly rainfalls and potential evaporation for Tongatapu for 4 scenarios of future GHG emissions, SRES, through to near the end of the 21st century. These were then used to estimate GHG-related changes in recharge. The models predicted widely divergent future monthly rainfalls in Tongatapu for the SRES selected. Some predict increases in rainfall; others predict decreases under the same SRES. This is worrying since a small, relative low island embedded in a large ocean should be the simplest case. Here we have used the mean of all model predictions to arrive at a “consensus” value for the expected change in rainfall. These means have very large coefficients of variation, so limited confidence can be placed in them.

For the period 1990 to 2095, the predicted increases in mean annual rainfall lie between 0.2 and 1.3 mm/year. Mean wet season rainfall is predicted to increase by between 0.4 and 2.1 mm/year, while mean dry season rainfall is predicted to decrease by 0.1 and 0.8 mm/year. These predicted trends are exactly opposite to the very weak trends found in actual historic rainfall from 1945 to 2007. Annual rainfall has a decreased by 2.3 mm/year while that for the wet season has decreased by 3.2 mm/year, while dry season rainfall, increased by 0.7 mm/year.

Only 14 of the 23 GCMs can predict changes in potential evaporation. Their predictions for the 4 SRES scenarios give nearly an order of magnitude lower coefficient of variation in the mean predicted monthly potential evaporation than for predicted monthly rainfall. The mean predicted monthly changes in potential evaporation all increased with increasing time beyond the reference period 1975-2004, irrespective of season or SRES scenario. This seems to be a consequence of the predicted increase in global temperature with increased GHG emissions. The increased predicted ETs for the dry season were larger than those for the wet season. This differential increase in dry season ET over that for the wet season, coupled with predicted decreases in dry season rainfall, could increase seasonal differences in soil moisture and recharge.

Surprisingly, the predicted increasing trends in annual and wet and dry season ET between 1990 and 2095 are opposite to the trends in actual evaporation (ET_a) estimated using recharge Case 1 calculations for 1945 to 2006. For this period, estimated ET_a decreased for annual and wet and dry seasons. The magnitude of the decrease of dry season ET_a was less than that for the wet season. These trends are opposite to the predicted GSM trends, as was found for rainfall. Evaporation and its seasonal dependence appear more sensitive than rainfall to the expected impacts of increased GHG emissions. Monitoring of evaporation in Tongatapu should therefore recommence.

As a first approximation, the expected change in groundwater recharge resulting from continued GHG emissions has been estimated by assuming that the predicted percentage increases in potential evaporation also apply to ET_a. We have then used the observed mean rainfalls for the period 1975-2004 and the mean ET_a for the same period calculated for recharge Case 1 together with the simplified long-term water balance to estimate changes in annual groundwater recharge. These first-order estimates suggest recharge will decrease between 5 and 25% by 2095. The predicted increase in annual rainfall is offset by the predicted increase in evaporation, especially in the dry season which is coupled to the predicted decline in dry season rainfall.

When linear trends are fitted to the widely fluctuating annual Case 1 recharge estimates for 1945 to 2006, annual recharge was found to decrease close to the rate predicted for the high SRES scenario. The trends for the wet and dry season recharges, however, are opposite in sign to those predicted from the climate models with estimated wet season recharge decreasing and dry season recharge increasing. The coefficients of determination are very small indicating that the trends in the 1945-2006 recharge data are not significant.

Because recharge appears to be sensitive to climate change, it is important to monitor parameters indicative of recharge. The thickness of groundwater is clearly a sensitive parameter but one which is also influenced by the rate of withdrawal of groundwater and closeness to the sea. For this reason both profiles of salinity and pumping rates should be measured throughout Tongatapu. The predicted decrease in groundwater recharge rate with increasing GHG emissions, then it adds to the necessity that pumping should be licensed and monitored.

GCMs are not good at simulating changes to the hydrological cycle and are notoriously bad on rainfall, especially in the tropics. There are two basic reasons for this: (i) they generally do not simulate tropical convection very well, and (ii) they can not reproduce some the major modes of current climate variability, including El Niño- Southern Oscillation (ENSO). The predictions here should therefore be treated with caution.

Quarrying

Apart from the detailed measurements at the abandoned Tapuhia quarry now in use as the TWMF, no detailed measurements were made on either the hydraulic gradients around or the water quality resulting from quarries, mainly due to the absence of a groundwater monitoring borehole network. Because of this, we are unable to give recommendations on the safe distance between a quarry and a water supply well or wellfield. Nonetheless our observations and discussions with relevant agencies permit some general conclusions:

- Quarrying is largely unregulated.
- Current quarrying practice is to excavate material down to below the groundwater level. This exposes groundwater to direct evaporation losses and greatly increases the risk of groundwater contamination.
- Apart from the TWMF, there is no monitoring borehole network that can be used to determine the impacts of quarrying on groundwater hydraulic gradients or on the groundwater quality.
- Practices within quarries where the water table is exposed, such as disposal of industrial wastes and keeping of livestock, greatly increase the risk of groundwater contamination.
- Pre-existing lead and post-completion nitrate concentrations within monitoring boreholes around the TWMF warrant close attention and continued monitoring and reporting.
- Abandoned quarries could be used for locating infiltration galleries to produce lower salinity water from surface groundwater.

Each section in the report lists issues that are unresolved and require further work. Recommended actions are also suggested at the end of every section. These are collated following the 10 key recommendations.

Recommendations

Key Recommendations to decrease groundwater vulnerability

1. Enact the draft 2006 National Water Resources Bill. This will ensure protection of groundwater sources, provide a statutory basis for the lead water agency, control overuse and lessen the risk of pollution. National water policy and implementation plans should be introduced at the same time as the legislation.
2. Establish the broadly-based National Water Resources Committee, NWRC, specified in the draft 2006 Bill to better coordinate and provide a collaborative, reporting mechanism for government water agencies and a forum for NGOs.
3. Limit the number of pumps continuously extracting groundwater in Tongatapu to 210 pumps extracting water at a rate of no more that 3.0 L/s with design pump spacings of not less than 0.8 km.
4. Licence and meter all groundwater pumps and licence and train all groundwater bore drillers.
5. Reduce the high rates of leakage from domestic water reticulation systems
6. Undertake a study of the feasibility of developing alternate, safe groundwater sources for water supplies to Nuku'alofa, Hihifo, the Mua villages and Kolonga regions.
7. Develop a contingency plan to address the impacts of droughts on water supplies involving: early warning based on climate indices; voluntary and compulsory water restrictions; temporary decommissioning of pumps in more saline areas; and other instruments
8. Establish a network of salinity monitoring boreholes throughout Tongatapu to monitor the thickness of available fresh groundwater.
9. Monitor the field groundwater properties throughout Tongatapu at regular 3 month intervals and report annually to the NWRC. Establish two further rainfall sites in eastern and western Tongatapu. Recommence monitoring of potential and/or pan evaporation at Fua'amotu.
10. Ensure all quarries be limited in depth to leave 2 m of overburden above the water table to prevent direct contamination of and evaporation from the water table.

Collated recommendations made in sections throughout this report

Institutional

- Enacting the draft 2006 National Water Resources Bill. Passing the current draft 2006 National Water Resources Bill will address the lack of: protection of groundwater; statutory basis for MLSNRE; coordination of the water sector; reporting to GoT; controls on quarrying; information on groundwater extraction; and support for monitoring.
- Establishing the broadly based National Water Resources Committee, specified in the draft Bill to better coordinate and provide a reporting mechanism for government water agencies.
- Developing National Water Resources Policy and Plans. National recognition of the fundamental importance of water is essential for the future well-being of Tongans. National Water Policy and Plans together with National Legislation are important ways the GoT can provide leadership in an area vital to the lives and well-being of Tongans and to the development of Tongatapu. Clear policy directions and plans based on this policy can help coordinate government agency action, galvanise public participation and improve resource allocation and assistance down to the village level.
- Providing Tongan priorities for aid donors in the water sector. Having both a National Water Policy and Legislation will provide external aid donors with a clear indication of National priorities in the water sector. Monitoring water resource use and quality is clearly fundamentally important to the sustainable management of water resource management in Tonga and needs to be a priority.
- Introducing a modest environmental water abstraction charge for all water consumers to provide resources for vital water resource monitoring and assessment.
- Establishing a single Tongatapu Water Supply Authority to manage public urban and rural water supplies and their use and provide treated water to all communities in Tongatapu.

This would relieve the burden on Vacs, who must remain, however, actively engaged in water management.

- Regulating the quarrying industry to maximise protection of groundwater.
- Passing regulations for the mandatory licensing and training of drillers, the licensing of all pumped wells and the metering and reporting of the rate of groundwater pumped in all of Tongatapu (detailed in the draft Bill).
- Developing a database which shows the location of major uses of hazardous agricultural chemicals and fertilisers. These have the potential to pollute groundwater on Tongatapu. This measure will improve the effectiveness and efficiency of water quality monitoring.
- Installing additional SMBs throughout Tongatapu. The thickness of the freshwater lens is one of the critical indicators of the sustainability of water resource management in Tongatapu. At present SMBs are only around the Mataki'eua/Tongamai well field. In order to monitor the impact of management strategies on the fresh groundwater resource it is critical that SMBs be installed throughout Tongatapu as in Figure 15.
- Restricting free-ranging domestic animals to particular locations. Free ranging animals, particularly pigs pose a significant health risk to groundwater sources. Consideration should be given to reducing the threat posed by domestic animals.

Monitoring, data storage and analysis

Tongatapu

- It is strongly recommended that field monitoring of groundwater properties throughout Tongatapu be carried out at regular intervals of 3 months.
- It is recommended that as soon as data is collected it is entered into the database and compared with previous measurements.
- It is recommended that the database be critically analysed well by well to clean up the errors.
- It is strongly recommended that MLSNRE prepare an annual report based on analysis of the data base for presentation to government.
- The closest distance between individual wells and the sea or the lagoon should be recorded in the database.
- Several critical issues need to be addressed. These include the reason for the measurement, the use of the measurement and its reliability.
- When the reasons and use for the data have been identified, an analysis of data should be carried out to address these issues.
- Full analysis of data should be carried out annually and a report on the analysis presented to the appropriate authority.
- Confusion over the exact location of individual wells needs to be removed by geo-referencing and labelling wells and the database needs to be updated.
- Wells used for measuring water table depth, need to have the reference point for depth measurement accurately surveyed in relative to current mean sea level and to have the point marked clearly. This is needed so that the elevation of the water table in wells can be evaluated with precision. Groundwater elevation is one of the critical measures in the draft 2006 Water Resources Legislation.
- Instruments for measuring groundwater salinity, temperature and pH need to be calibrated against known standards prior to each field sortie.
- The data base contains no information about the volume of groundwater extracted each year in Tongatapu; efforts should be made to include estimates of groundwater extraction.
- Continuous logging of water table fluctuations in selected wells where water table elevation can be measured should be carried out over several months to a year to determine the tidal influence and groundwater recharge influence on water table elevation.

Mataki'eua/Tongamai

- It is strongly recommended that the monthly field monitoring of groundwater at Mataki'eua/Tongamai be continued.
- It is recommended that the groundwater database be critically analysed well by well to look for trends and to examine relationships with rainfall.
- The closest distance of individual wells from the sea or the lagoon should also be recorded in the database
- Full analysis of data should be carried out annually and a report on the analysis presented to the appropriate authorities.
- All wells should be geo-referenced and clearly labelled to avoid any confusion.
- Wells used for measuring the depth of the water table, need to have the reference point for depth measurement accurately surveyed relative to current mean sea level and to have the point marked clearly. This is needed so that the elevation of the water table in wells can be evaluated with precision. Groundwater elevation is one of the critical measures in the draft 2006 Water Resources Legislation.
- Continuous logging of the water table fluctuations in all wells where water table elevation can be measured should be carried out over several months to determine the tidal influence and groundwater recharge influence on water table elevation.
- The salinity of the wells closest to the lagoon is higher than those further away from the lagoon. In droughts, these wells may exceed acceptable limits and should be more closely monitored in dry times.
- Measurements of the salinity profiles in the SMBs within and adjacent to the Mataki'eua/Tongamai wellfield during this project suggest significant thinning of the lens due to pumping from the wellfield. Other monitoring bores should be drilling throughout Tongatapu. In addition, it may be advisable to also source water from other locations such as the International Airport at Fua'amotu or at Liahona.
- We were not able to access all data from the special SMBs. It is recommended that efforts be made to retrieve and analyse that data.
- Only a few pumps have working water meters and the main meter for overall supply to Nuku'alofa is inoperative. While estimates can be made of volume extracted from the wellfield, accurate measurements enable better management of the wellfield and are essential for improved estimates of leakage losses. It is recommended that all pumped wells be fitted with accurate flow meters and that these be checked and maintained on a regular basis.
- A study of the feasibility of using alternate groundwater sources for Nuku'alofa's water supply should be undertaken.

Tapuhia Waste Management Facility

- It is recommended that a multi-Ministry team, similar to that used by the Waste Authority at the TWMF, be formed from Ministries and agencies with responsibility for water and the environment to monitor groundwater throughout Tongatapu and other islands in the Kingdom.
- It is recommended that the Waste Authority ensure that monitoring data from the TWMF be incorporated into the MLSNRE national water resources database.
- It is recommended that the RLs of all monitoring boreholes be re-surveyed as accurately as possible.
- It is recommended that the piezometric head in all wells around the TWMF be monitored continuously for three months to enable accurate determination of flow directions.
- It is recommended that the Tongatapu map of groundwater wells be updated to include the location of all water supply wells.
- It is recommended that intensive chemical sampling for contaminants in the monitoring boreholes around the TWMF and in the public water supply wells closest to the TWMF be continued at least annually for the next 10 years.

- It is recommended that lead and nitrate levels be monitored in the monitoring boreholes around the TWMF every six months during operation of the facility.
- It is recommended that the influence of ponded water at the base of the TWMF on surrounding groundwater be examined.

Water quality

- The MoH use Colisure tests with the Quanti-tray system for screening village water supplies to provide a quicker indication of contamination and to enable more strategic targeting of water samples for full laboratory testing. This should also lessen the load on the hospital laboratory.
- The H_sS paper strip test not be used for the microbiological testing of public water supplies.
- The MoH hard copy database of the microbiological tests on well water samples be transferred to an electronic data.
- The data in the MoH microbiological database be analysed and a report prepared summarising the results.
- All groundwater pumping wells be fitted with flow meters to determine the volume of water extracted from wells.
- The performance of wells, which showed an increase in salinity between the drier period in 1991 and the average rainfall period in 2007, be analysed to determine the impact of pumping on salinity.
- All village wells and those at the TWMF be monitored every three months for salinity (EC), water level (where possible), pH, temperature, faecal indicators and nitrate.
- Selected village and Mataki'eua/Tongamai wells, and all monitoring wells at TWMF be monitored annually for nutrients, heavy metals, pesticides, herbicides and fungicides, petroleum products and hydrocarbons.
- The method of reporting of imports of agricultural chemicals and fertiliser be improved to include quantity and type of chemicals.
- Data be collected on the location of usage and application rates of agricultural chemicals and fertilisers.
- Data be collected on septic tanks and latrines with potential to influence water quality in village well.

Groundwater recharge and sustainable yield

- Groundwater salinity monitoring boreholes be established across Tongatapu.
- The RL of village wells, where water table elevation can be measured, be re-surveyed as accurately as possible.
- The Tongatapu well databases be examined to see if a spatial dependence of water table elevation on depth of soil can be established.
- That dependence of EC data in the Mataki'eua/Tongamai well and the Tongatapu village well databases on recharge be examined with a view to optimising the parameters in the WATBAL recharge model.
- The optimised WATBAL recharge model should be run every month. When the estimated recharge has been zero over a period of 8 months, the frequency of groundwater monitoring should be increased and a warning given to appropriate agencies.
- All groundwater supply pumps in Tongatapu should be licensed.
- The maximum pumping rate for any single groundwater supply pump in Tongatapu should be limited to 3.0 L/s (260 m^3/day) and this rate should be set as a licence condition.
- All water supply pumps must be fitted with a water meter and monthly reporting of the volume of water extracted should be a licence condition.
- The maximum number of licensed groundwater supply pumps for continuous operation in Tongatapu should be limited to 210 with a minimum design spacing of 0.8 km.
- Replacement of the defective main bulk water meter at Mataki'eua is a high priority.

- Reduction of water losses in the Nuku'alofa reticulation system should be made a high priority for donor funding.
- The impact of concentrating further pumps at Mataki'eua/Tongamai should be investigated.
- Also of high priority, the Fua'amotu and Liahona regions should be investigated as possible future water source areas.

Droughts, drivers of drought and climate change

- Two further rainfall measurements sites should be established in the eastern and western regions of Tongatapu to improve spatial coverage of the rainfall network.
- A contingency plan to address the impacts of droughts on water supply involving voluntary and compulsory water restrictions and other instruments should be developed for Tongatapu.
- Percentile analysis of rainfall over the past 12 months should be carried out at the end of each month using monthly rainfall data from the TMS. When the percentile ranking drops below 40% a warning should be issued to the Government about the possibility of a drought to follow.
- Groundwater recharge should be estimated at the end of each month using monthly rainfall from the TMS. When there are more than 8 consecutive months all with zero estimated recharge, the frequency of groundwater monitoring should be increased and a warning should be given to the government and the TWB. When there are more than 12 consecutive months of zero recharge consideration should be given to implementing the drought contingency plan.
- The relationship between long-term rainfall and long-term averages of climate indices should be further examined in order to predict long-term dry periods.
- The relationship between seasonal rainfall and recharge and climate indices and drivers should be further explored to improve prediction of impacts on groundwater.
- A critical examination of the 23 global atmosphere-ocean global climate models be undertaken with the aim of resolving the wide discrepancies in predictions of changes in rainfall in ocean-dominated regions.
- A thorough treatment of trends in measured rainfall and evaporation, or evapotranspiration, be carried out for Tonga and other small island situations to compare current trends with those expected from global climate models under various GHG emission scenarios.
- Monitoring of both potential evaporation and pan evaporation be recommenced in Tongatapu which will require installation and monitoring of a net solar radiometer and an evaporation pan at the Fua'amotu meteorological station.
- Further investigation of the measured trends in wet and dry season, as well as annual, evaporation be undertaken for accurate comparison of trends with those predicted from the models.
- More detailed investigations be carried out on the impact of the predicted changes in rainfall and evaporation on changes in groundwater recharge.
- In view of the prediction of up to 25% decrease in groundwater recharge by 2095, licensing of all groundwater pumps should be instituted as soon as practical and the sustainable groundwater yield under changing recharge be re-estimated.

Quarrying

- All quarrying and land mining in Tongatapu be regulated and monitored to ensure groundwater resources are not compromised by quarrying.
- The *2003 Environmental Impact Assessment (EIA) Act* be reviewed and modified if necessary to ensure that all new quarrying activities require consent through assessment of an EIS specifically detailing procedures for protecting groundwater.

- The draft 2006 Water Resources Bill be reviewed to ensure that it applies to and can control the impacts of quarrying on groundwater resources.
- The draft 2006 Water Resources Bill be submitted to parliament as soon as practical.
- The relevant regulating authorities review their capacity to assess EIS and regulate and monitor the impacts of quarrying.
- A groundwater monitoring borehole network be established in Tongatapu which can be used to asses the impacts of quarrying on groundwater hydraulic gradients and water quality.
- Research be undertaken to determine the safe minimum distance of quarries from water supply wells, boreholes and wellfields.
- The potential for constructing infiltration galleries as better quality water supply sources in abandoned quarries be considered.
- All quarries be limited in depth so as to leave 2 m of overburden above the water table.

Water Resources GIS, Workshops and Cabinet Note

- The multi-agency Tonga Water Resources Committee be established as soon as possible
- That a multi-agency water resources monitoring team be established as soon as possible
- That a high speed data link be set up between the Geology Section site and the main MLSNRE site
- That all water resources data from MLSNRE, MoH, TWB and the Waste Authority be entered into the water resources data base.
- The Cabinet Briefing Note be revised and sent to Cabinet.
- Future Workshops be organised with specific, practical outputs to foster cooperation and collaboration in the water sector.

1 Introduction

1.1 Vulnerability of Small Island States

The Barbados Conference on the Sustainable Development of Small Island States in 1994 helped raise awareness of both their fragility and vulnerability. This vulnerability arises from their remoteness, small land areas, rapid population growth, restricted capacity, limited resources and sensitivity to climate variability and change (Tula et al., 1979). Limited Gross Domestic Product, restricted trading opportunities and increasing urbanisation are straining traditional support mechanisms (Ward, 1999) and customary approaches to hazard reduction.

Many low small islands in the Pacific have maximum elevations less than one hundred meters above mean sea level (MSL) and are often less than ten kilometres wide. Surface water resources in many of these small islands are almost non-existent because the soils and regolith are highly permeable. Communities in these islands mainly depend on captured rainwater or unconfined groundwater stores. Fresh groundwater resources often exist as extremely vulnerable, shallow, thin freshwater lenses (typically of order 20 m thick) floating over and mixing with seawater (Underwood et al., 1992).

Urban and peri-urban island communities face water problems that are amongst the most critical in the world (Carpenter et al., 2002). Expanding human settlements and increasing demand, agricultural activities, spillages, leakages and waste disposal, frequent droughts, climate variability and seawater inundation of low-lying areas during storms and sea level rise as well as conflicts between traditional subsistence resource rights and the demands of urbanised societies are some of the difficulties (White et al., 1999a, Falkland, 2002). Urban atoll communities rapidly pollute shallow groundwater with industrial, agricultural, human and animal wastes so that water-borne diseases are often endemic and infant death rates due to water-borne diseases are tragically large.

The seriousness and wide spread occurrence of these issues led to the development of the 2003 *Pacific Regional Action Plan on Sustainable Water Management*, (SOPAC and ADB, 2003) which was endorsed by all Pacific island states and presented at the Third World Water Forum in Kyoto. The Plan called for broadly-based national water visions, design of capable institutions, national water action agenda and plans, empowerment of communities, and integrated investment plans. It recognised that both behavioural change and long-term collaboration were essential for improvement.

1.2 SOPAC/EDF8 Study of Groundwater in Tongatapu

The Secretariat of the Pacific Islands Geoscience Commission (SOPAC) under the European Union (EU) European Development Fund 8 (EDF8) has undertaken a project "*Reducing Vulnerability of Pacific APC Sates* (http://www.sopac.org/ISM). The overall project goal is to reduce the vulnerability in the Pacific ACP States through the development of an integrated planning and management system.

The SOPAC/EDF8 study described in this report has been conducted in the Kingdom of Tonga, which lies in the southwest Pacific Ocean on the boundary between the Australian and Pacific Plates (see Figure 1). Tonga has a total land area of 718 km^2 with 419 km of coastline spread over 172 islands, 36 of which are inhabited. The country's four island groups are spread over a north-south axis: Tongatapu and 'Eua (South), Ha'apai (central); Vava'u (north); Niuafo'ou and Niuatoputapu (far north). The first Tui Tonga, King George Tupou I, declared the kingdom's boundaries as longitudes 177° West and 173° West and latitudes 15° South and 23° 30′ South on 24th August 1887. In 2006, the estimated population of Tonga in 2006 was 101,991 which represents an increase of 4,207 people from the 1996 census population of 97,784.

This study is focused on the island of Tongatapu (see Figure 2), the Kingdom's main population centre in the southern most group of islands, which contains the capital Nuku'alofa. Tongatapu is the most populated island, with 70.6% of the nation's population in 2006. Tongatapu is a tilted, raised limestone island characterised by Pliocene and Pleistocene coral terraces unconformably overlying Miocene volcaniclastics (Furness, 1997). The limestone, which forms the unconfined aquifer, has a thickness of about 134 m around Nuku'alofa increasing to 247 m near Fua'amotu in the southeast (Lowe and Gunn, 1986). The maximum elevation of Tongatapu is 65 m above mean sea level (MSL) near Fua'amotu dipping down to sea level in the northwest. The island has a mantle of fine-grained, andesitic volcanic ash up to 5 m thick. This has produced extremely fertile and productive soils and agriculture is a fundamentally important activity.

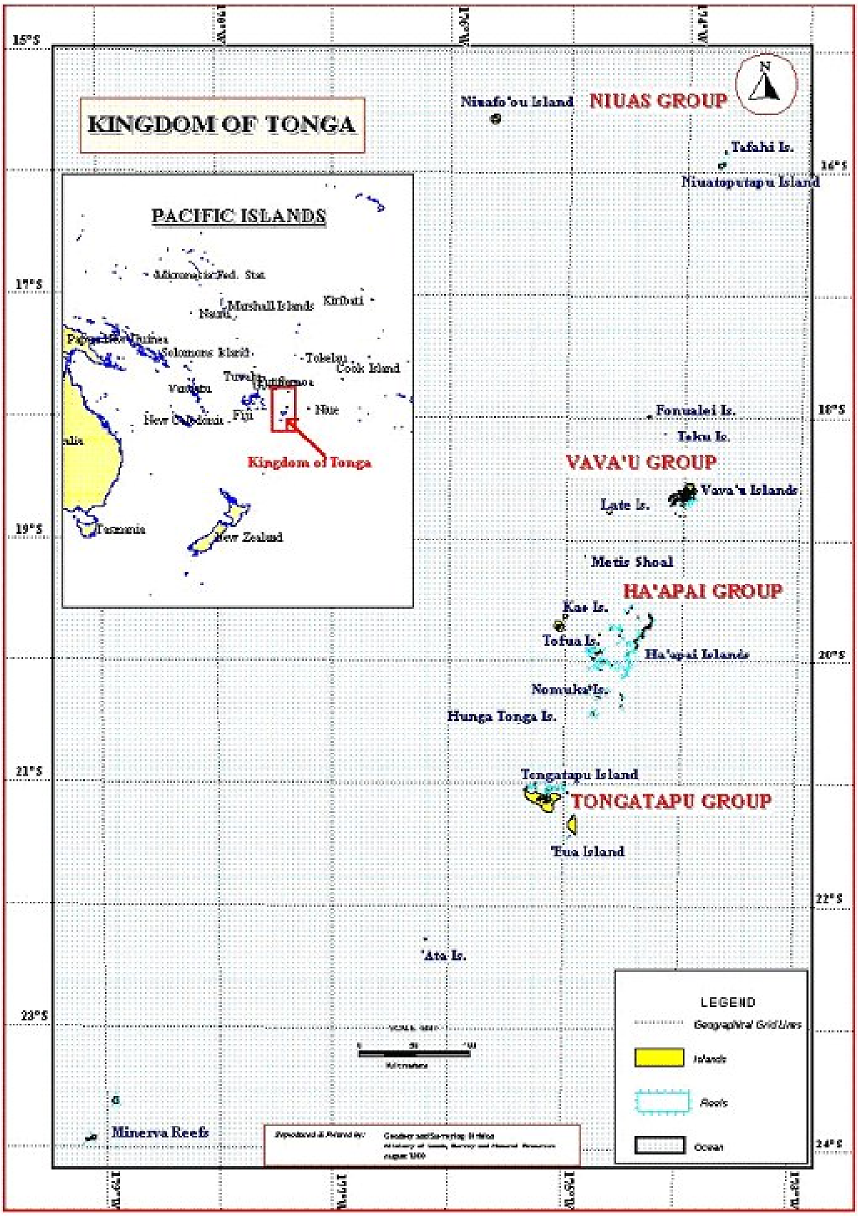

Figure 1 Map of the Kingdom of Tonga

The climate of Tonga is semi-tropical and is dominated by south-easterly trade winds. The climate in Tongatapu is heavily influenced by a large semi-permanent anticyclone centred in the eastern South Pacific between 90 and 100° W and 25 and 30° S. To the west is a more migratory anticyclone cell that moves eastward from the Australian-Tasman sea region. The South Pacific Convergence Zone (SPCZ) is sandwiched between these two high pressure regions and is an area of cyclonic circulation and semi-permanent cloud. During summer the SPCZ moves midway between Tonga and Samoa (Figure 1) resulting in a summer (December to April) wet season. In winter the SPCZ lies well to the north of Tonga and causes easterly to southeasterly winds. Cyclones are frequent in Tonga with on average of 1.3 cyclones per year.

Figure 2 **Tongatapu island, Tonga, tilts generally from the higher southeast around Fua'amotu to the low northwest around Kolovai**

Mean annual temperature in Tongatapu is 23°C and the mean annual rainfall in the capital Nuku'alofa (from 1945 to 2006) is 1,727 mm with a relatively small standard deviation of 423 mm. The five wet-season summer months of December to April have a mean combined rainfall of 962 mm which is 56% of annual mean rainfall (see Figure 3). There is a small orographic effect with mean annual rainfall in the higher southeast Fua'amotu region being about 9% higher than that at Nuku'alofa, almost at sea level. Annual rainfalls (see Figure 4) are correlated with El Niño Southern Oscillation events. Mean annual potential evaporation is around 1,460 mm (Furness 1997). Estimates of the mean annual groundwater recharge in Tongatapu vary between about 20 to 30% of annual rainfall with a value around 530 mm commonly accepted as a representative mean (Hunt 1979; Falkland 1992).

The hydraulic conductivities of the karst limestone aquifer are very large (of order 1,500 m/day). As a consequence large, elevated fresh groundwater mounds cannot develop as water is discharged relatively rapidly to the sea at the island's periphery or is mixed with the underlying seawater by diurnal tidal fluctuations. Consequently, the potentiometric surface of the shallow unconfined fresh groundwater lens in Tongatapu lies generally less than 0.6 m above MSL and the lens has a maximum freshwater thickness of about 12 m (Furness and Helu, 1993; Furness and Gingerich, 1993).

Potable freshwater in Tongatapu is sourced from three sources: rainwater harvesting; the fresh groundwater lens; or from imported bottled water. Fresh groundwater is hard because of high concentrations of bicarbonate from the limestone aquifer.

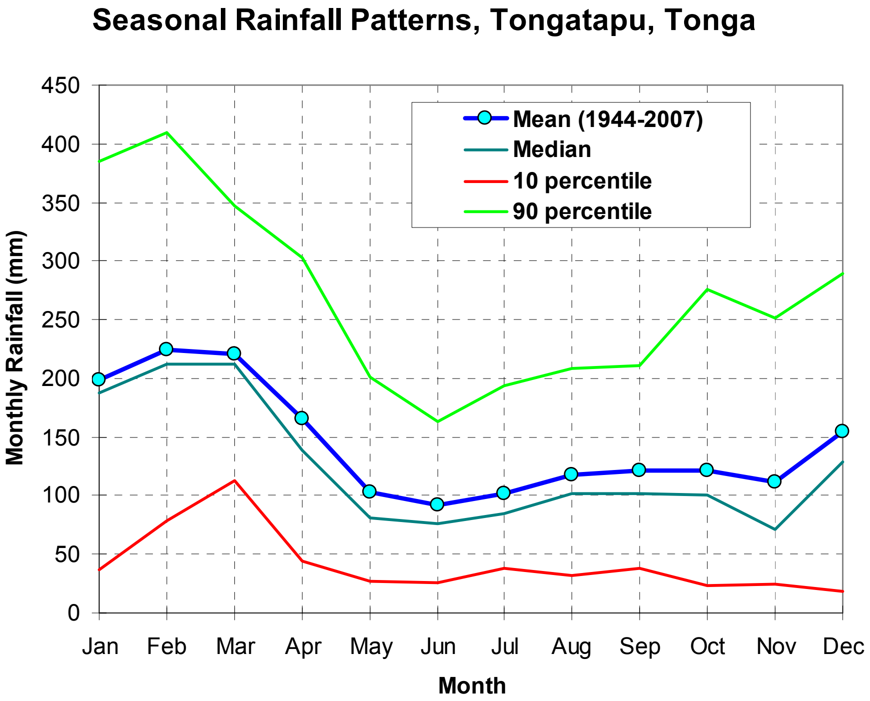

Figure 3 Mean monthly rainfall for Nuku'alofa Tongatapu for the period October 1944 to July 2007. Also shown are the median (50th percentile), 10th and 90 th percentile monthly rainfalls.

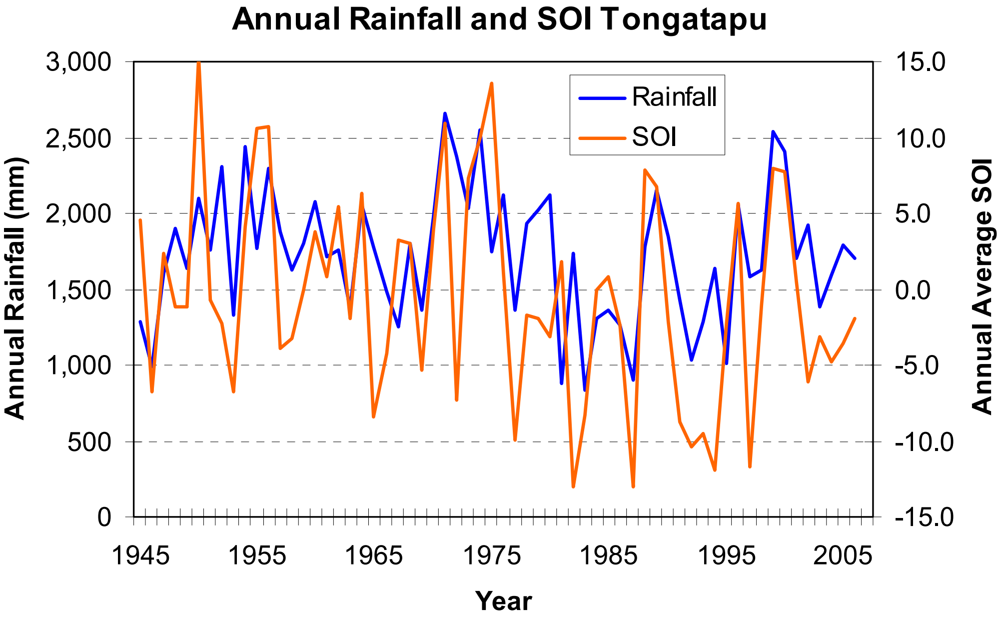

Figure 4 Variation of annual rainfall at Nuku'alofa, Tongatapu compared with the annual averaged Southern Oscillation Index (SOI). The correlation coefficient is 0.54.

Village reticulated water systems are supplied from local groundwater wells controlled by Village Water Committees (VWCs) under the Ministry of Health (MoH). Nuku'alofa's reticulation system is sourced from the Mataki'eua/Tongamai wellfield about 5 km southwest of the capital with a surface elevation around 20 m (Figure 5). The capital's water supply is managed by the Tonga Water Board (TWB), which also manages town water supplies in other islands in Tonga. The lead agency for water resource management is the Ministry of Land Survey, Natural Resources and Environment (MLSNRE).

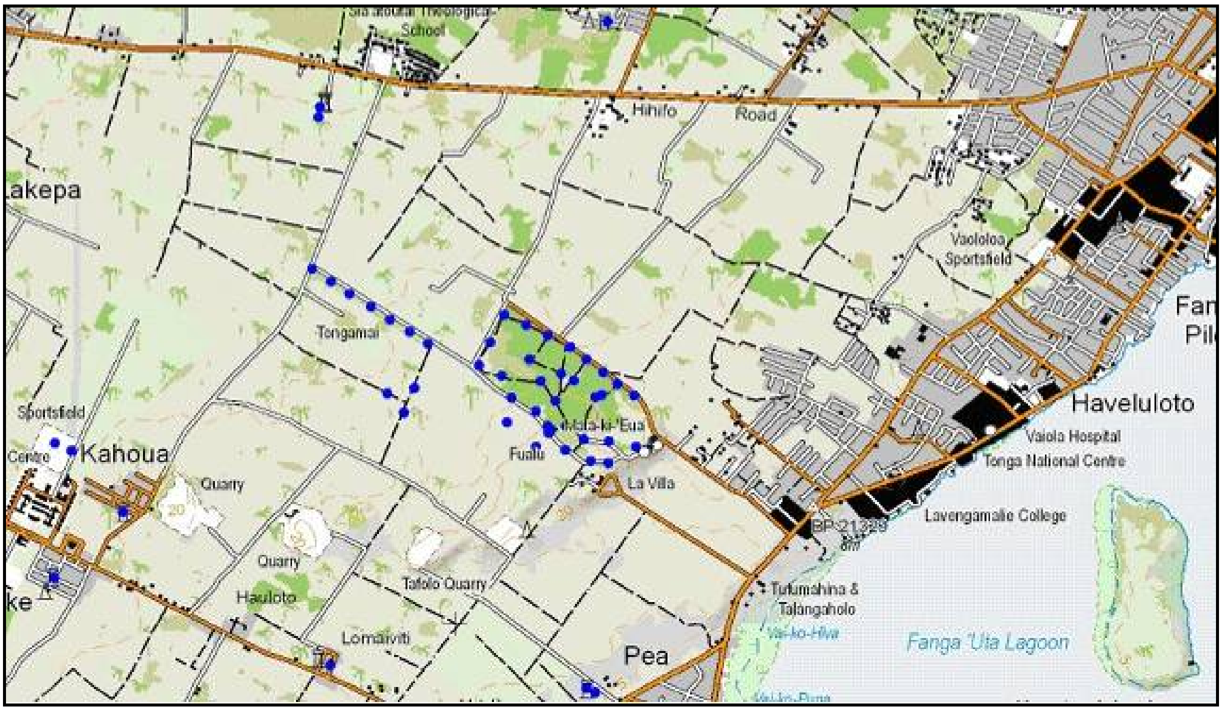

Figure 5 The Mataki'eua/Tongamai TWB wellfield which supplies Nuku'alofa to the northeast with water (wells and boreholes shown as blue dots). The proximities of the Fanga'uta Lagoon to the east and quarries to the southwest are evident.

1.3 Vulnerability of groundwater in Tongatapu

In the severe droughts of 1981 and 1983, where rainfall was about half the mean annual value, it was estimated that no groundwater recharge occurred (Falkland, 1992). This indicates that climate variability coupled with rates of groundwater extraction are fundamentally important in determining the vulnerability of the groundwater resource in Tongatapu.

Other key determinants of groundwater vulnerability in Tongatapu include both natural factors and those associated with human activities that impact on groundwater quality. Salinity, and concentrations of agricultural chemicals, nutrients, petroleum and heavy metal contaminations and the presence of human pathogens as well as the influence of uncontrolled quarrying of limestone down to the phreatic surface are of particular concern.

Monitoring the salinity of village groundwater wells across Tongatapu, has helped identify areas of Tongatapu which are prone to natural seawater intrusion (Furness and Helu, 1993; Furness, 1997), particularly in the northeast (Figure 6). These areas of brackish groundwater expand during droughts. Furness also presented evidence that suggests that the salinity of village wells has increased between 1965 and 1991 due to groundwater pumping.

Agriculture has intensified in Tongatapu over the past 25 years with an increase in production of crops for export such as squash pumpkin and vanilla beans. This had led to an expansion in the use of artificial fertilisers, pesticides and herbicides. There have been increasing concerns over the impacts of fertilisers and pesticides, on both groundwater and lagoon water quality. Pesticides have been detected in groundwater samples from some village wells and at some wells in the Mataki'eua/Tongamai wellfield (Chesher, 1984; Furness and Helu, 1993; van der Velde, 2006) as well as in Fanga'uta Lagoon, lagoon sediments and soil (Prescott *et al.*, 2001; van der Velde, 2006). In the groundwater, most were at concentrations well below the World Health Organisation (WHO, 2006) drinking water quality guidelines. In some of the shallow wells and in the lagoon, it is possible that contamination occurred through direct rinsing of spray equipment in the well or lagoon. Tests of pollution (nutrients, hydrocarbons, bacteriology and pesticides) at the Mataki'eua wellfield carried out in 1995 showed no evidence of pesticides or hydrocarbon compounds in the wells tested and samples showed relatively low levels of nutrients (Falkland, 1995).

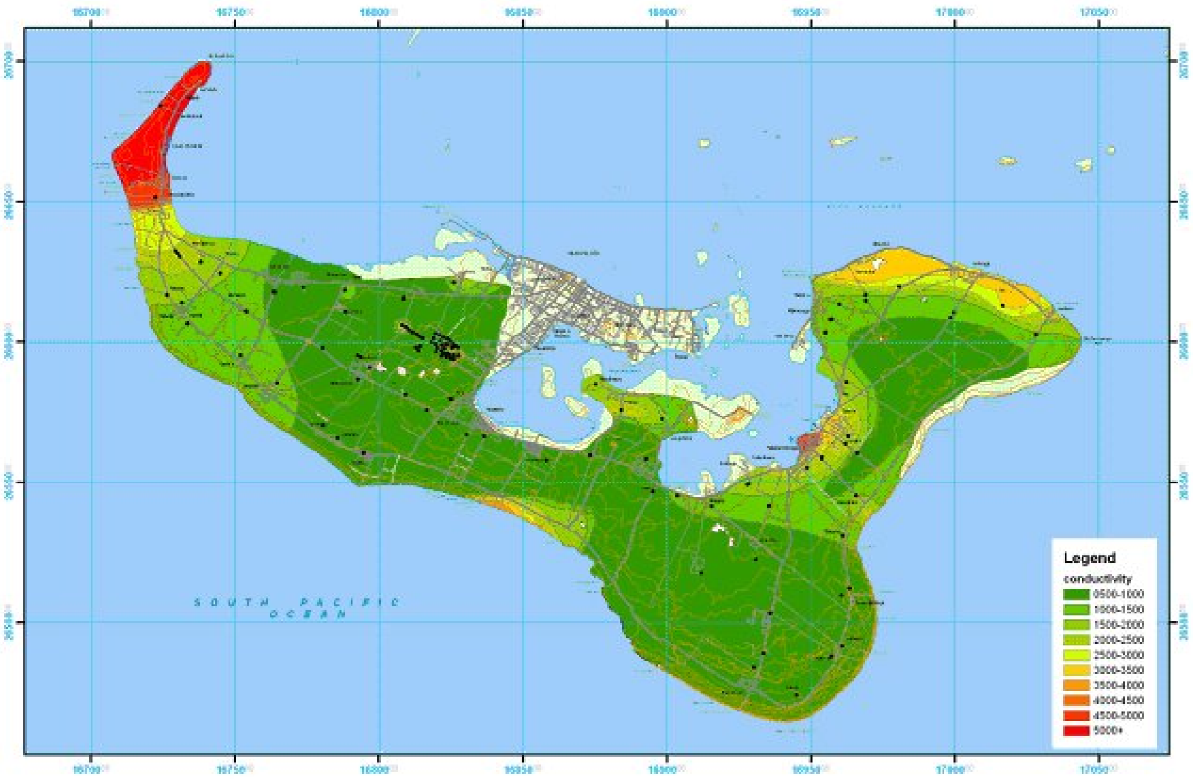

Figure 6 Groundwater salinity (EC) distribution map of Tongatapu in May 1990 showing areas prone to seawater intrusion and the freshest around Fua'amotu (GIS map produced by MLSNRE, after Furness and Helu, 1993)

Most sanitation systems in Tongatapu use septic tanks which tend to continuously leak or overflow in wet seasons. Contamination of the groundwater with human pathogens is therefore a significant risk, particularly to the young and infirm. Figure 7 contrasts the rates of infant mortalities due to water-borne diseases in Pacific nations and shows that these rates are high in Tonga.

Periodic testing of groundwaters in Tongatapu for indicator species of human waste contamination such as *E. coli* by MoH reveals episodic contamination of some local groundwaters by human or animal wastes. These constitute a considerable threat to groundwater quality in Tongatapu, especially in rural areas where village water supplies are not treated.

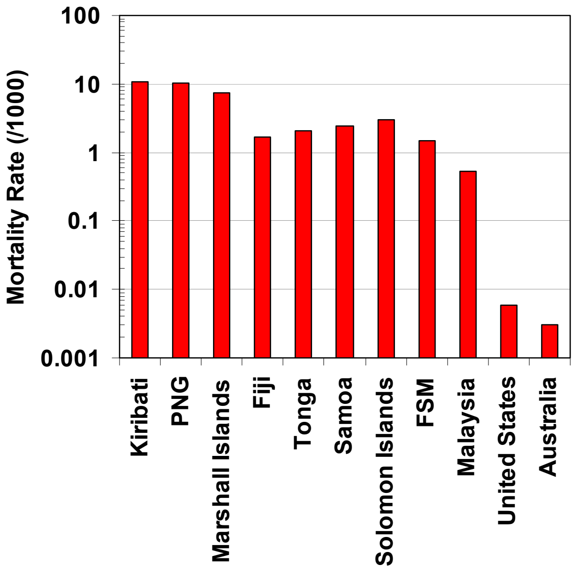

Figure 7 Comparison of infant (<5 yrs) mortality rates per 1000 due to diarrhoeal diseases for Pacific countries (WHO, 2005). Note the log scale.

1.4 Goal of this project

Over the past 40 years, groundwater studies in Tongatapu have identified the factors that contribute or have the potential to contribute to increasing the vulnerability of fresh groundwater resources. Some have developed strategies to lessen impacts and improve resilience. This project builds on the considerable weight of those results as well as the depth of local expertise. Our aim is to summarise early work, to examine the current situation and to propose strategies to decrease groundwater and water supply vulnerability. The overall goal of this project is to:

> *assist assessment of impacts on the aquatic environment and the planning and sustainable management of the finite water resources of Tongatapu*

1.5 Project objectives

In order to meet the project goal, the following project objectives were set.

1. Assess the institutional capacity and needs of organisations with responsibility for monitoring groundwater.
2. Assess the vulnerability of the groundwater resources of Tongatapu.
3. Review and analyse baseline groundwater monitoring data.
4. Conduct a survey of water quality in water supply wells and bores throughout Tongatapu.

This report presents the results and recommendations arising from consultations with personnel from relevant agencies of the Government of Tonga (GoT) and non-government organisations (NGOs) and from groundwater investigations conducted on Tongatapu during between 21st July and 21 August 2007 and from 19th November to 13th December 2007. The project was funded by the EU under the EDF8 project *Reducing the Vulnerability of Pacific APC States* which is administered by SOPAC. Additional support for the purchase of groundwater monitoring equipment was provided from SOPAC to the project under the Pacific-HYCOS project.

2 Outline of the Project

2.1 Terms of Reference

The full Terms of Reference (ToR) for the Tongatapu Groundwater Evaluation and Monitoring Assessment Report project are detailed in Annex A.

2.2 Activities

The ToR in Annex A specifies six main project activities:

(a) Baseline Water Resource Monitoring Data
(b) Assessment of Institutional Capacity for Groundwater Monitoring
(c) Vulnerability Assessment for Groundwater Resources
(d) Review Quarrying Activities and Potential Impacts on Water Resources
(e) Development of GIS Data Sets Suitable for Water Resources
(f) Final Deliverables.

A number of sub-activities within each activity are defined in the ToR (see Annex A).

There appears to be some implicit assumptions underlying the ToR. The first is that quarrying is a major threat to groundwater in Tongatapu. The second is that capability in Geographic information Systems (GIS) requires upgrading. There is also an implication that staff in the water agencies require training in many aspects of their responsibilities. Our study, described in the following sections, found that these implicit assumptions are unfounded.

2.3 Project team members

The project team consisted of:

- Ian White, Professor of Water Resources, ANU.
- Tevita Fatai, geologist / hydrogeologist.
- Tony Falkland, water resources specialist.

In Tonga, the team was very ably assisted by staff from MLSNRE, TWB, MoH, the Waste Authority (WA), the Tonga Meteorological Service (TMS) and the Ministry of Agriculture, Fisheries, Forestry and Food (MAFFF), Ministry of Finance and Economic Panning (MFEP) and the Tonga Trust (TT). The project was developed with guidance and timely assistance from staff at SOPAC in Suva. Two visits were made to Tonga by the Project Team, the first in July-August 2007 and the second in November-December 2007. Visit diaries are provided in Annex B, a list of the persons interviewed during the project is provided in Annex C and a summary of work undertaken is given in Annex D.

2.4 Objectives

After discussion with key stakeholders and a review of existing information, the activities and sub-activities were prioritised and rearranged into five objectives for Tongatapu:

(a) Evaluate information on groundwater resources
(b) Assess groundwater monitoring practices and needs
(c) Assess the groundwater vulnerability
(d) Provide a snapshot of groundwater quality
(e) Provide training in data collection, groundwater evaluation, monitoring and analytical techniques.

2.5 Project Work Plan

The project work plan, summarised in Table 1, was developed after consultation with SOPAC and key counterparts in Tongatapu.

Table 1 Summary of Project Work Plan

No.	Activities	Dates
1	Project initiation – contact SOPAC, Ministries in Tonga, review available data and reports.	1-18 July 2007
2	Project initiation – discussions with SOPAC, Suva	19-21 July 2007
3	First visit to Tongatapu - discussions with staff from MLSNRE, TWB, MoH, WA, TMS, MAFFF, MFEP and TT. Data collection - collect, collate and analyse existing data, Field investigations – pumping and well tests, salinity monitoring, pathogen sampling, intensive water quality sampling in village and TWB wells, inspect quarries, waste disposal facility, carry out TV interview on project.	21 July – 21 August 2007
4	Analysis of water quality samples, analysis of met. data, salinity, summarising previous results, reports on visit, salinity response to rainwater, droughts, summary of intensive water quality measurements.	23 August – 21 November 2007
5	Second visit to Tongatapu-collection of remaining data, GIS production of salinity map, planning, writing final report. Workshop-organising & planning.	21 November to 13 December 2007
6	Project workshop - invitees from MNLSNRE, TWB, MoH, WA, TMS, MAFFF and TT. Present report findings, discuss implications, identify future work and opportunities.	11-12 December 2007
7	Project completion, submit final reports, Cabinet Briefing Note to SOPAC.	16 December 2007

Details of the investigations carried out under this work plan together with findings and recommendations are provided in the subsequent sections of the report. The report is structured in the same sequence as the activities and sub-activities given in the ToR in Annex A. Selected photographs taken during the investigations are provided in this report.

2.6 Project outputs

The project outputs required by the ToR are:

(a) A Final Report which includes a comprehensive summary of all the major outcomes of the Project Activities. The Final Report shall be fully supported by comprehensive photographic records, a Manual on monitoring practice, a Manual on quality assurance for water resource data collection and archiving, and a Manual on best practice guidelines for protection of water resources from quarrying activities.

(b) A workshop in Nuku'alofa to present the primary elements identified during the groundwater evaluation & monitoring assessment to all key stakeholders. The workshop will include a single field trip to demonstrate pertinent site operational observations and emphasise conclusions and recommendations. The workshop should also seek to maximise the community awareness raising and media opportunities.

(c) A draft Cabinet Briefing Paper based upon Tongan Draft National Water Policy and assimilation of the results of the groundwater evaluation & monitoring assessment within the Final Report and key stakeholder feedback received during the workshop. The Cabinet Briefing Paper should not only emphasise the key conclusions and recommendations, but also make recommendations on improvements for national water resource monitoring.

We note here that the last required output involves a misconception. There is no Tongan Draft National Water Policy. A draft 2006 Draft National Water Resources Bill, based on elements proposed by Wilkinson (1985) is, however, currently under review. We have based our Cabinet Briefing Note on the draft 2006 Bill.

3 Water Monitoring, Institutional Issues and Demographics

In this section, the information sets necessary for the sustainable management of Tongatapu's groundwater resources are discussed; then the agencies with responsibilities in water are identified; followed by a brief overview of their responsibilities for water resource management and monitoring; and an analysis of the institutional issues affecting the vulnerability of groundwater in Tongatapu. A set of strategies for addressing these issues and reducing vulnerability is presented and demographic issues are discussed.

3.1 Key monitoring data

In the following assessment, the key information sets required for the efficient management and conservation of water resources in Tongatapu are:

- Rainfall data
- Evaporation data
- Groundwater monitoring data – salinity, water quality (including trace metals, nutrients, pesticides, herbicides, and petroleum products), piezometric level, pathogen levels.
- Rates of groundwater pumping and consumption
- Local sea level data
- Southern Oscillation Index (SOI) and sea surface temperature data (SST).

The important considerations about using these data sets for groundwater assessment are the availability of data, including the accessibility and the length of record, the quality of the data and the security of the data in terms of safe archiving.

3.1.1 Rainfall, evaporation and SOI

Rainfall records in Tongatapu have been collected discontinuously since 1881 (Thompson, 1986). The most continuous record is that for the meteorological station at Nuku'alofa from October 1944 and that record has been used in this work. It is noted, however, that recent data from this station are less reliable. Daily pan evaporation was collected at the weather station at MAFFF Vaini Agricultural Research Station from 1982 until 1989. Potential evaporation estimates (Thompson, 1986) are also possible from the climate records of wind speed, relative humidity, temperature and air pressure using the Penman equation (Penman 1948, 1956). Climate data for Tongatapu is also transmitted to the New Zealand organisation NIWA for archiving. Values of SOI dating back to 1876 and Niño SST from 1950 are available from the Commonwealth Bureau of Meteorology (BoM) web site

3.1.2 Groundwater data

Groundwater data on electrical conductivity (EC), pH and groundwater level has been collected with increasing frequency in Tonga since as early as 1958. Much of this has been summarised in reports, papers and theses (see e.g. Hunt, 1979; Chesher, 1984; Falkland, 1992; Furness and Helu, 1993; Furness, 1997; van der Velde, 2006). Indicator bacteria, coliforms and *E. coli.* And pathogen concentrations have been measured at selected wells since the 1970s. These have been recorded in a logbook by MoH staff but have not been transferred to an electronic database.

3.1.3 Pumping, consumption and leakage

Data on the total rate of pumping from the Mataki'eua/ Tongamai wellfield, exists from 1995 to about 2000 when the main production meter failed. Since this wellfield is operated 24 hours/day and the number of pumps and their approximate pumping rates are known, reasonable estimates can be made about current rates of pumping from this wellfield. Village water supply pumps operate intermittently and since they and private wells are not equipped with meters, there is no information on the total rate of groundwater extraction on Tongatapu. Household consumption of water has been measured monthly in Nuku'alofa even before 1995. Water meters have also been installed in some villages in the rest of Tongatapu, but consumption data is currently not available. The lack of meters in critical locations this means that it is difficult to currently assess leakage from the village supply systems in Tongatapu.

3.1.4 Groundwater data checking, analysis and reporting

In this study, we have reviewed the published information and, where possible, have updated those records by collecting information from relevant agencies. A critical issue identified in this study is that although water resources data is collected regularly, there is no data checking or analysis of data and no regular reporting of the state of the nation’s water resources including most of Tongatapu to the Government of Tonga. The TWB is statutorily obliged to report to the Board on water supply issues for Nuku’alofa.

3.2 Relevant agencies

Table 2 summarises the agencies involved with water resources monitoring in Tongatapu and their responsibilities.

Table 2 Agencies and their water resources monitoring responsibilities

Agency	Water resources monitoring responsibilities
Geology Section, Natural Resources and Environment Division, MLSNRE	Designated national lead water agency, water quality (salinity, pH, nutrients, pollutants), licensing of water wells, sustainable pumping rates.
Environment Section, Natural Resources and Environment Division, MLSNRE	Environmental impacts of development and extraction, lagoon water quality, biodiversity impacts, climate change impacts
GIS Section, Land Information and GIS Division, MLSNRE	Spatial representation and interpretation of data, mapping
TWB	Water quality of urban water supplies in Nuku’alofa, Neiafu on Vava’u and Pangai-Hihifo on Ha’apai and to villages on ‘Eua and selected villages in Tongatapu, water production volumes, water consumption data, payment for water use.
Public Health Section, MoH	Bacteriological quality of village water supplies, management of village water supplies, coordination of Village Water Committees, disease rates
TMS	Rainfall and climate monitoring, drought prediction
WA	Coordinates a multi-agency team to monitor groundwater quality around the Tapuhia Waste Management Facility
Village Water Committees	Water use and consumption, payment for water
MAFFF	Fertiliser, pesticide and herbicide imports for use on crops
MFEP	Coordination and monitoring of aid projects, capital and recurrent funding

3.3 Management and monitoring activities and responsibilities

Water resources in Tonga are currently managed by a number of government agencies. Some have specific and some have general monitoring responsibilities:

3.3.1 Geology Section, MLSNRE

The Geology Section of MLSNRE has been designated as Tonga’s lead national water resource agency. There is, however, no formal legal basis for this role. It is responsible for the monitoring and assessment of physical and chemical parameters, salinity, pH, temperature and water table elevations of the water resources throughout Tonga. The plan is to monitor 56 village water wells and bores across Tongatapu every 3 months. Recent resource limitations have decreased the frequency of measurement. There is also no formal requirement to report on the results of these measurements to GoT and there is no mandate to monitor the many private wells and bores. The Geology Section also advises on development and management of water resources, including permission to drill bores and install pumps. There appears to be no statutory basis for the latter functions. The quantity of groundwater extracted is not monitored outside TWB serviced urban centres. Water samples have been occasionally collected to assess for chemicals such as pesticides. These are sent to Australian or New Zealand laboratories for testing, which is expensive. Monitoring has been limited by available staff, lack of transport including fuel for transport, restricted operating budget and equipment.

A sea level recorder, located on the Queen Salote wharf, in Nuku'alofa provides a continuous record of sea level variations due to tidal, barometric, rainfall, and wind surge influences. The tidal and barometric fluctuations have been used to determine tidal lags and efficiencies at different locations within the groundwater lens when well loggers were installed. Currently the Geology Section has no well loggers to continuously measure groundwater levels. Tidal information is stored in the Geodesy section at the MLSNRE. The last major report on the results of water resource monitoring in Tonga by MLSNRE was published in 1993.

3.3.2 Public Health Section of the Environmental Health Division, MoH

The Public Health Section of the Environmental Health Division, MoH implements and maintains village water supply schemes, and for monitoring and surveillance of the biological quality of public water supply schemes. It also performs qualitative sanitary inspections of wells and households. Water samples are collected by Health Inspectors from suspected problem wells on a monthly basis. They are tested for the faecal indicator species faecal coliforms at the Ministry's laboratory at the Vaiola Hospital. Because of other responsibilities, the laboratory can only process 6 water samples for the MoH and one for TWB per month. There is no testing for specific pathogens such as protozoa or viruses. The MoH plans to assess each village water supply system approximately twice a year. MoH has the legal basis to order the closure of wells that are habitually contaminated.

3.3.3 Tonga Water Board, TWB

TWB is responsible for the planning, installation, operation and maintenance, and monitoring of public water supply systems in urban areas of Tongatapu, ‘Eua, Ha’apai and Vava’u and in a few village systems in Tongatapu. TWB provides technical assistance to some village water supply committees in rural areas. Supply is metered and billed at each household in the urban areas. The pH and salinity of production wells in the Mataki’eua/Tongamai wellfield and at selected sites throughout the Nuku’alofa distribution systems have been monitored regularly by the TWB since 1995. Tests on faecal coliforms and chlorine residual levels in the Nuku’alofa distribution are also carried out by the TWB in its laboratory in Nuku’alofa.

Up to 2002, TWB also periodically monitored the thickness of the freshwater lenses in 6 special salinity monitoring boreholes (SMBs) installed in and close to the Mataki’eua/Tongamai wellfield. This function should be now carried out by the Geology Section of MLSNRE and more salinity monitoring boreholes should be constructed throughout Tongatapu. At present, the volume of water extracted from the Mataki’eua/Tongamai wellfield cannot be accurately monitored as the main production meter is no longer functioning. Access to the important data collected by the TWB is limited.

3.3.4 Tonga Meteorological Service, TMS

TMS is responsible for operation and maintenance of the climatic stations in all island Groups, and collects data on daily rainfall, temperature, and cyclones. In Tongatapu, the number of rainfall stations maintained by the service has declined over the years so that now rainfall is recorded at only two sites, Nuku’alofa and Fua’amotu (see Figure 8 and Figure 9). Nuku’alofa was the main Tongatapu climate station until 1980 when the main station moved to Fua’amotu International Airport.

TMS also has access to SOI and SST data from the BoM website. Daily rainfall is currently being monitored at the Tapuhia Waste Management Facility, while shorter period rainfalls are currently being recorded at the Vaini Agricultural Research Station and data is available from MAFFF. The old weather station at Vaini has been abandoned. Because of the raised and tilted nature of Tongatapu, there is a small orographic effect and information on rainfall distribution is important for accurate estimation of groundwater recharge.

3.3.5 Ministry of Agricultural, Food, Forestry and Fisheries, MAFFF

MAFFF is responsible for promoting agricultural production and supervising use of fertilisers, pesticides and irrigation. They have no facilities for monitoring contamination of groundwater by pesticides or records of who is using irrigation systems. Their laboratory analyse water samples for nitrate concentrations. MAFFF's Vaini Research Centre currently has a tipping bucket rain gauge (Figure 10) and data from that is downloaded regularly. Soil water contents were also monitored as part of a PhD study until 2003 (van der Velde, 2006). The older weather station at Vaini is overgrown and abandoned.

Figure 8 Fua'amotu weather station, Tongatapu's main weather station

Figure 9 Nuku'alofa weather station, until 1980 Tongatapu's main weather station

3.3.6 Waste Authority, WA

The WA is responsible for the management of solid waste, which includes the new Tapuhia Waste Management Facility (TWMF) in an abandoned Government quarry near Vaini on Tongatapu (Figure 11). Effluent from this site is collected and treated in an aerated wastewater treatment plant. The treated effluent is dispersed by irrigation at the TWMF.

Groundwater at and near the TWMF is currently monitored in both specially drilled groundwater monitoring wells (GMWs) and in neighbouring village water supply wells to ensure leachate is not polluting groundwater. Because this involves testing for petroleum products, pesticides heavy metals and bacteria, monitoring is expensive. There are some doubts that testing will continue after the current aid project is completed. A very effective multi-agency team from MLSNRE, Ministry of Works (MoW), MoH and WA conducts the groundwater monitoring at the TWMF (Figure 12).

Figure 10 Tipping bucket rain gauge at the Vaini Agricultural Research Station, MAFFF

Figure 11 The TWMF located in an abandoned quarry near Vaini. Note the exposed water table at the base of the quarry.

Figure 12 Multi-agency monitoring team collecting groundwater samples from a bore near the Tapuhia waste facility for the WA

3.3.7 Ministry of Works, MoW

MoW used to operate a drilling rig for installation of water bores. It still has trained drillers but the drilling rig is now defunct. The only drilling rig in the country is an unlicensed, privately owned rig in poor state of repair (Figure 13). The absence of a government licensed and controlled drilling rig is a major concern.

Figure 13 Privately owned drilling rig, the only "operational" drilling rig in Tonga

3.3.8 Environment Section MLSNRE

The Environment Section in MLSNRE is responsible for assessing environmental impacts of development and extraction, Fanga'uta Lagoon water quality, biodiversity impacts and climate change impacts. MLSNRE established a National Monitoring Team to monitor water quality in Fanga'uta Lagoon because of concerns over pollution by groundwater discharge (Fakatava *et al*, 2000). This team had members drawn from MLSNRE, TWB, MAFFF, and the Tonga Visitors Bureau. The team was project-based and now appears to be defunct.

3.3.9 GIS Section MLSNRE

GIS section MLSNRE provides GIS services. Its system is modern, up-to-date and efficient. Unfortunately, the cost recovery policy currently in place means that the Unit charges other Sections and Divisions even within its own Ministry. MLSNRE cannot access its own data on the GIS server on-line because of the slow speed internet connection.

3.3.10 Ministry of Finance and Economic Planning, MFEP

MFEP is responsible for the co-ordination and monitoring of aid projects, the development of plans including those affecting the water sector. It also oversees capital and recurrent funding of water supply and water resource programs.

3.3.11 Village Water Committees, VWCs

VWCs operate and maintain village water supply systems. They generally employ on a part-time basis a local water technician and a plumber, A number of villages have installed household water meters to measure and charge for consumption. Village groundwater pumps are not supplied with water meters. Since these pumps do not operate continuously, unlike the TWB pumps at Mataki'eua/Tongamai, it is impossible for VWCs or MLSNRE to determine either the local or overall rates of groundwater extraction in Tongatapu. Moreover, since production and usage rates are unknown it is not possible to determine leakage rates that are known to be high (Figure 14)

Figure 14 Leakage from village water supply mains repaired with bicycle tubing (TWB photo)

There has been minimal routine community monitoring of quality water, although changes in taste, smell, colour or the presence of sediment generate complaints. Although TWB can provide technical support, many VWCs are in urgent need of training and resourcing. In many ways these VWCs, if properly resourced, provide a model for many parts of the world in community participation in water management.

3.3.12 Village Women's Groups

Village women's groups carry out community monitoring of household hygiene in neighbouring villages. Homes and villages are inspected and scored through assessment of the condition of toilets, bath houses and management of solid waste.

3.3.13 NGOs

NGOs ,such as Tonga Trust, are involved in community-based water schemes and are effective in mobilising communities. They have expressed particular concerns over pollution of groundwater especially by pesticides.

3.3.14 Householders

Householders manage their own rain harvesting systems, wells and connections to the reticulated supply. Sanitation and greywater disposal are also strictly a household concern. There are no reticulated sewerage or wastewater systems in Tongatapu. Instead, septic tank and soil absorption trenches are most commonly used. Most domestic septic tank systems leak. In dry periods appreciable absorption of pathogens occurs in the allophanic soils. In wet seasons, absorption is limited and groundwater contamination with pathogens can occur. Sewage discharges have been blamed for much of the increased nutrients inputs into Fanga'uta Lagoon (Fakatava *et al.*, 2000) The Public Health Unit of MoH has the statutory authority to order the closure of wells that are habitually contaminated.

3.4 Institutional issues affecting the vulnerability of groundwater

Some significant issues that have the potential to increase the vulnerability of groundwater in Tongatapu emerge from the summary of institutional responsibilities in water resource management and monitoring. The most significant are:

3.4.1 Lack of protection of freshwater sources

Draft National Water Resources legislation was proposed in 1985 (Wilkinson, 1985). It has been progressively modified over the intervening years, the latest being the completely revised draft 2006 Bill. The pressing need for the passage of national water legislation has been recognised for some time (ESCAP, 1990; Furness, 1991; PPK, 1992). Without the passage of this Bill, groundwater sources used for public water supply have no legal protection and are extremely vulnerable to contamination from a wide variety of land uses including quarrying, cropping and livestock production, waste disposal or the encroachment of settlements.

3.4.2 Lack of a statutory basis for MLSNRE activities in water resources

The Geology Section of MLSNRE has responsibilities such as the licensing of water wells for which it has no legal basis. There is no legal requirement for licensing drillers so that groundwater sources are vulnerable to inexperienced or careless drilling contactors who could salinise or pollute fresh groundwater. MLSNRE also has no legal responsibility to report to government on the condition of the nation’s water resources.

3.4.3 Lack of national drinking water standards

There are no national drinking water quality standards in Tonga. Regulations are governed by the Law of Tonga – Water Supply Regulations, 1963, which sets out the general regulations for the use of water sources and the formation of village water committees, and by the Act to deal with Public Health Services in Tonga – Water Supply Control, 1992. This latter Act specifies the function of officers from the MoH to carry out routine water quality tests, issue potable water certificates, and advise VWCs on the prevention of contamination and on technical issues relating to groundwater pumping and reticulation. The Act to Reconstitute and Empower the Tonga Water Board and for Related Purposes – 2001 sets down the formation, functions and powers of the TWB but does not define responsibility for the maintenance or monitoring of water quality (Kingston, 2004).

3.4.4 Lack of coordination in the water sector

There is currently no overall coordination and limited cooperation of agencies involved in the water sector and particularly in water quality monitoring (Kingston, 2004). The draft National Water Resources Bill specifies the establishment of a broadly-based National Water Resources Committee. One of the Committee’s important suggested functions is to promote coordination amongst government agencies having responsibilities relating to the water resource. The Fanga’uta Lagoon project and the Waste Management project set-up multi-agency monitoring teams that have worked effectively. These provide a model for a National Water Monitoring Team under and reporting to the proposed National Water Resources Committee. This team could be drawn from relevant agencies including MLSNRE, MoH, TWB, MoH and WA.

3.4.5 Lack of regular, routine reporting to Government

While the TWB has to formally report to its Board on the quality and quantities of water delivered to urban centres and income and expenditure associated with supply of water, there is no formal requirement for MLSNRE or MoH to provide GoT with a regular report on the condition of the nation’s water resources. This lack of a formal reporting requirement means that data is often not checked or analysed. There is no incentive for the pooling of data and neither the Ministries nor the GoT are fully informed about emerging water problems.

3.4.6 Lack of information on groundwater extraction

The lack of functioning water production meters both at the Tongamai/ Mataki'eua wellfield pumps and at village groundwater pumps means that the rate of groundwater extraction throughout Tongatapu can only be estimated approximately. This means that rates of extraction could exceed local estimated sustainable yields. Domestic meters have been installed in a limited number of villages throughout Tongatapu. Where installed, these can be used in conjunction with production meters to assess leakage losses in the reticulation system. There is consequently only imperfect estimation of leakage losses and therefore little incentive to reduce losses, which are believed to be substantial.

3.4.7 Lack of monitoring of private wells and bores

There are many private wells and bores throughout Tongatapu whose position is not recorded in the MLSNRE database and whose water quality and rates of groundwater extraction are not monitored. These should be licensed and monitored and there should be strict controls on the placement and construction of new bores and wells.

3.4.8 Lack of support for VWCs

In many ways, Tonga's VWCs present a model to the Pacific and indeed the rest of the world in real community participation in water resource management. However, there are major problems with VWCs. These are unpaid, voluntary organisations with little skills in water supply management. Because of the heavy demands on time there is a high turn-over rate in VWCs so that both continuity and training are problematic. Village water technicians who run pumps, repair distribution systems and maintain domestic plumbing are employed on low wages and are again largely untrained.

There is a significant need for VWCs to be adequately resourced in terms of skills and technical information and to involve them more in monitoring and protecting their water resources. Alternatively, the formation of a single authority to supply both urban and rural communities could be more and efficient and lessen the burden on VWCs (PPK, 1992).

3.4.9 Lack of controls on quarrying

At present, once a quarrying company is licensed, there are no further controls on quarrying. The quarrying company simply negotiates with a landholder or several landowners for permission to quarry their land. Once granted, quarrying may commence irrespective of how close it is to community water supply groundwater sources. Quarrying normally continues down to the water table (see Figure 11). This exposes the groundwater to both increased evaporation losses and increased risk of contamination.

3.4.10 Lack of a government-controlled drilling rig

Despite having the expertise, the GoT has no ability to drill water supply wells in Tonga. Currently wells are being drilled without approval of selected site and without licensing of the driller or of the borehole. If bores are drilled too deeply, there is the potential to salinise the groundwater and if drilling equipment is not cleaned thoroughly there is the potential to introduce micro-organisms into the aquifer.

3.4.11 Inadequate distribution of SMBs throughout Tongatapu

Currently, the seven special SMBs are clustered around the Mataki'eua/Tongamai wellfield. Until 2002, these were monitored by the TWB. There was limited recent information on the thickness of the freshwater lens at the wellfield until this current study. Earlier information was collected during the AusAID project in the 90s, when the salinity profiles were measured and brief summary reports were written on freshwater lens thickness and impacts of pumping. The thickness of freshwater available in the remainder of Tongatapu is poorly known as only limited data was available from the three earlier salinity monitoring boreholes at Kolonga, Fua'amotu and Liahona. Groundwater salinity profiles are vital for assessing the sustainability of groundwater and managing the groundwater resources in Tongatapu. It is recommended that another ten SMBs should be drilled across Tongatapu and that they be monitored every three months by the Geology Section of MLSNRE. The suggested positions of the additional 10 SMB's across Tongatapu and an additional 3 at Mataki'eua/Tongamai are shown in Figure 15.

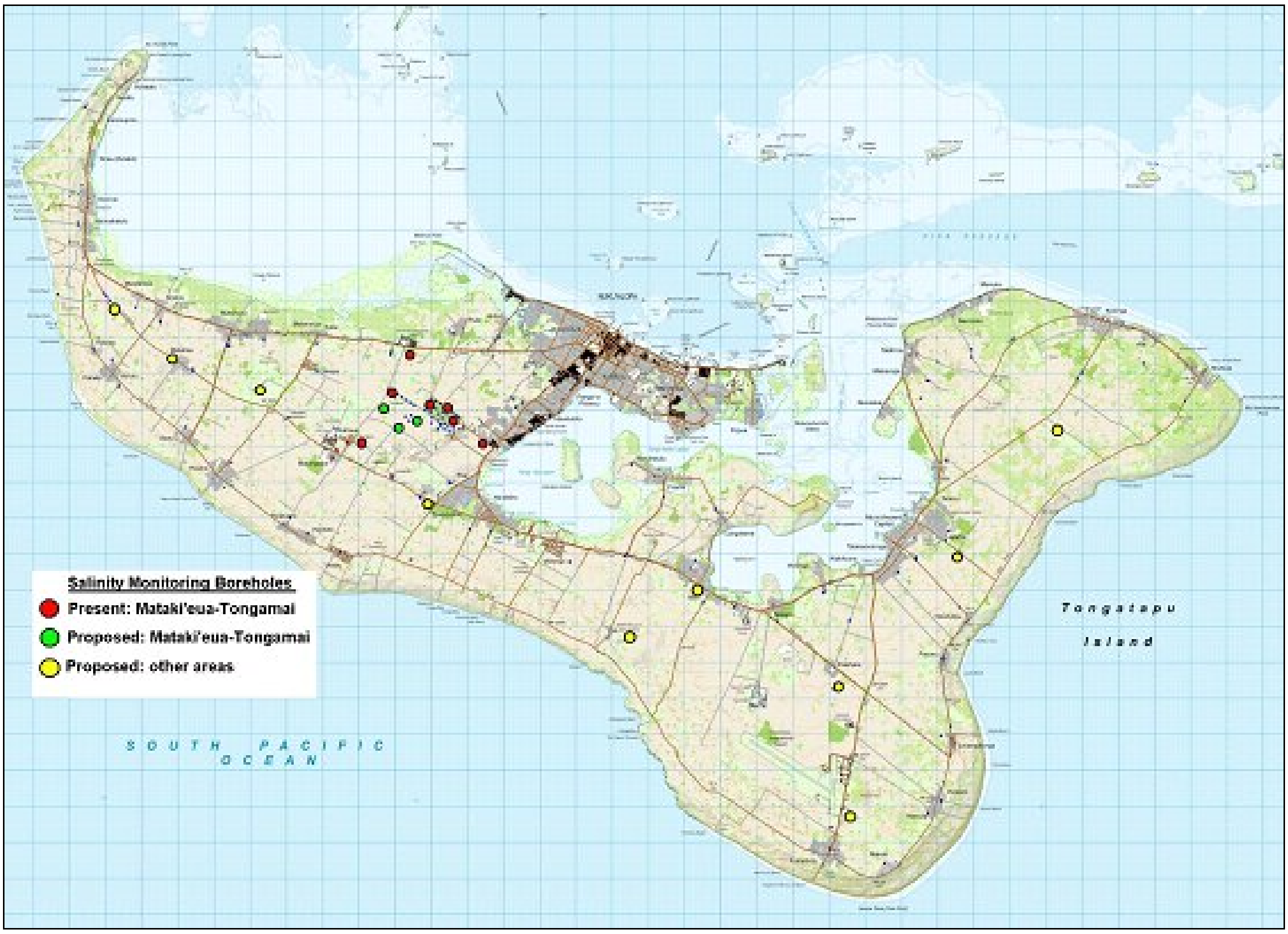

Figure 15 **Proposed location of 10 additional SMBs throughout Tongatapu and 3 more SMBs at Mataki'eua/Tongamai**

3.4.12 Lack of operational resources for monitoring groundwater

The decrease in frequency of monitoring of village wells throughout Tongatapu due to resource limitations, equipment and transport constraints points to a lack of recognition of the importance of this function. The absence of a requirement to regularly report monitoring results also underlines the lack of importance attached to monitoring.

3.4.13 Lack of spatial information on the use of agricultural nutrients and fertilisers

Partial statistics are available for the importation into Tonga of agricultural chemicals and fertilisers. Knowledge of the main locations of chemical and fertiliser use and rates of application of these chemicals in Tongatapu would greatly assist targeted monitoring of groundwater quality.

3.5 Demographics and the vulnerability of groundwater

Groundwater in small islands is especially vulnerable to overlying settlements and activities. It has been claimed that Tonga is also subject to a rapidly growing population with the number of people growing from around 20,000 in 1900 to around 100,000 in 2000 (van der Velde, 2006). The projected population of Tonga was expected to be 114,600 in July 2006 (Mafi and Crennan, 2007) with about 69% and 32% of the total population living in Tongatapu and Nuku'alofa respectively. In the past, Tongatapu and Nuku'alofa have experienced enhanced growth rates due to inward migration from outer islands to the main population centre. This has occurred in many small island countries in the Pacific (Ward, 1999). Figure 16 shows the population growth for the period 1956-2006. The actual total population in 2006 was only 101,991 with 70.6% and 33.6% of the total population living in Tongatapu and Nuku'alofa, respectively. The overall population statistics are also listed in Table 3 together with the projected population for 2009.

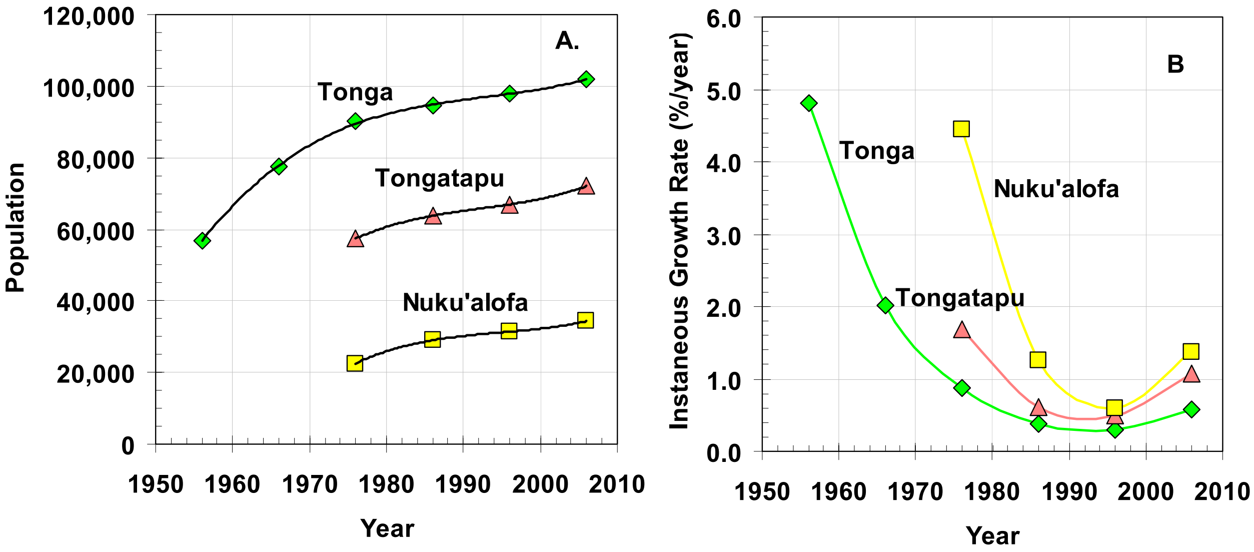

Figure 16 Population growth for Tonga, Tongatapu and Nuku'alofa A. Population numbers and B. Instantaneous rates of growth (Tonga Statistics Department)

It is clear that in the 1950's and 1960's, the population of Tonga was growing rapidly. Even in the 1970s and 1980s, the population growth in Tongatapu and Nuku'alofa was outstripping the growth in the Kingdom as a whole. The statistics in Figure 16 and Table 3, however, show a surprising slow down in the rate of increase in population numbers not only for Tonga as a whole, but for Tongatapu and Nuku'alofa, although they continue to increase at a faster rate than Tonga as a whole. This slow down appears not to be caused by a decline in fecundity but to expatriation to the United States, New Zealand and Australia. A noticeable increase in population growth rate occurred between 1996 and 2006 with the rate in Nuku'alofa being greater than that in both Tongatapu and the country as a whole.

While the population in Nuku'alofa is a major contributor to pollution of the shallow groundwater and therefore the Lagoon and northern sea coast, it is not a major threat to town water supplies since groundwater in Nuku'alofa is generally not used as a source of potable water. Instead, potable water is supplied by the TWB from the Mataki'eua/Tongamai wellfield. The more significant threat to local groundwater supplies comes from the approximately 48% of residents in Tongatapu who live outside Nuku'alofa or from agricultural activities, aggregate mining and raising stock.

Table 3 Population statistics for Tonga, Tongatapu and Nuku'alofa

Year	Tonga	Tongatapu	Nuku'alofa[†]
Population Numbers[‡]			
1956	56,838	-	-
1966	77,429	-	-
1976	90,085	57,411	22,561
1986	94,649	63,794	29,018
1996	97,784	66,979	31,404
2006	101,991	72,045	34,311

Instantaneous Growth Rates (%/year)[§]			
1956	4.72	-	-
1966	2.03	-	-
1976	0.90	1.39	3.76
1986	0.37	0.75	1.52
1996	0.23	0.24	0.11
2006	0.57	1.07	1.37
Discreet Growth Rates (%/year)*			
1956-66	3.62	-	-
1966-76	1.63	-	-
1976-86	0.51	1.11	2.86
1986-96	0.33	0.50	0.82
1996-06	0.43	0.76	0.93
Projected Population[#]			
2009	103310	73680	35260

[†] Assumed here to be the sum of populations in Kolofo'ou and Kolomotu'a Districts.
[‡] Data from Tonga Statistics Department (www.spc.int/prism/country/to/stats)
[§] Calculated from dp/dt for the curves in Figure 16A.
* Calculated from population numbers for each decade
[#] Estimated from discreet growth rates

Household activities and particularly waste disposal can pose a threat to groundwater. Table 4 provides details of household statistics for Tongatapu.

Several statistics stand out in Table 4. There was an increase of nearly 1,200 households in Tongatapu between 1996 and 2006 but the number of people per household continues to decline. There was a dramatic increase in the number of houses with rainwater tanks between 1986 and 2006, with 4.4% of all households having rainwater tanks in 1986 but nearly 76% in 2006. It would be interesting to examine if the rate of water-born diseases has correspondingly decreased. Between 1986 and 2006, the number of flush septic tank toilets has continued to increase whereas the number of manual flush septic tank toilets continued to decrease. The number of pit latrines also continues to decrease with less than 6% of households having pit latrines in 2006.

The 2006 census statistics reveal an interesting breakdown of sources for drinking and non drinking water (Table 5) in Tongatapu. There is clearly a strong preference for using rainwater over piped water for drinking which has obviously developed since 1986 when there were far fewer domestic rainwater tanks (Table 4).

Table 4 Selected Private Household Statistics for Tongatapu (Tongan Statistics Department, www.spc.int/prism/country/to/stats)

Statistic	**Year**		
	1986	1996	2006
No. Households	9,723	10,796	11,971
People/Household	6.6	6.2	6.0
Water Sources			
Piped	8,911	10,316	10,600
Own Tank	431	5,307	9,050
Own Well	157	216	227
Other	87	97	70
Not Stated	137	-	-

Latrines			
Flush septic	4,137	7,227	9,597
Manual flush septic	3,053	2,492	1,702
Pit	2,260	1,879	712
Other	34	41	28
No Latrine	43	50	2
Not Stated	196	-	-

Table 5 Comparison between Drinking and Non-Drinking Sources of Water in Tongatapu in 2006

Water Source	Drinking	Non-Drinking
Piped	2,297	10,600
Own Tank	9,050	1,199
Bottled	434	-
Own Well/*Boiled*	*125*	102
Other	64	70

Toilets pose a significant threat to local groundwater supply systems in Tongatapu whether septic tanks or pit latrines. Almost all of the septic tanks are of concrete block construction and they leak. The number of households in Tongatapu in 2007 can be estimated from the projected population in Table 3 and assuming that the number of people per household has further decreased to 6. This gives an estimated 11,800 households in Tongatapu, with 5,700 of these in Nuku'alofa and 6,100 outside Nuku'alofa. If we assume that each of these has a septic tank or pit latrine then there are potentially 6,100 individual sources of contamination from toilets of local groundwater supplies outside Nuku'alofa. There is no information on how many of these are down-gradient and how many are up-gradient of local water supply wells. It is important to identify toilets with the potential to contaminate local water supply wells.

In addition to the human wastes, many domestic animals are kept in close proximity to houses in Tonga. In 1996, Tonga had an estimated 80,823 pigs or an average of 108.2 pigs/km^2 or 0.83 pigs per person (Saville and Manueli, 2002). Using the values in Table 3 and Table 4 we can estimate the number of pigs in Tongatapu in other years. These are given in Table 6.

Table 6 Estimated number of domestic pigs in Tongatapu, Nuku'alofa and outside Nuku'alofa

Location	Statistic	1976	1986	1996	2006
Tongatapu	No. People	57,411	63,794	66,979	72,045
	No. Households[‡]	8,443	9,723	10,796	11,971
	No. pigs[§]	47,651	52,949	55,593	59,797
Nuku'alofa	No. People	22,561	29,018	31,404	34,311
	No. Households[‡]	3,318	4,397	5,065	5,725
	No. pigs[§]	18,726	24,085	26,065	28,478
Outside Nuku'alofa	No. People	34,850	34,776	35,575	37,734
	No. Households[‡]	5,125	5,326	5,731	6,246
	No. pigs[§]	28,926	28,864	29,527	31,319

[‡] Estimated 6.8, 6.4 and 6.2 people per household for 1976, 1986. and 1996 respectively.

[§] Number of pigs estimated by assuming 0.83 pigs/person (Saville and Manueli, 2002).

If it is assumed that each pig produces about half the amount of wastes of a human, then in 2006 Tongatapu had the equivalent of about 102,000 people while Nuku'alofa had about 48,500 people in terms of waste production.

3.6 Conclusions

This section has examined the roles and responsibilities of the various agencies and actors in the water sector in Tongatapu. It is clear from discussions with a wide range of organisations and individuals the Ministries' staffs are well trained, motivated and dedicated. There are a number of institutional factors which limit their ability to operate effectively. These are compounded by resource limitations which decrease the effectiveness of water management ministries, adding to the vulnerability of groundwater in Tongatapu.

At the time of the study, the lack of legislative protection of groundwater and the apparent absence of statutory powers for the lead water agency, MLSNRE, means that groundwater in Tongatapu remains exceptionally vulnerable. This lack of protection and institutional uncertainty over responsibilities pose one of the greatest threats to groundwater.

In most small island nations, a significant threat to groundwater is from pollution from human settlements, particularly from human and animal wastes. This often causes high incidents of water-borne diseases (Figure 7).

The high population growth rates in Tongatapu, part natural, part from inward migration, evident from the 1960s through the 1980s have slowed dramatically since the 1990s, lessening the potential threats to groundwater. None-the-less, because of the prevailing septic and pit sanitation systems and the number of free-ranging domestic animals, particularly pigs, contamination of groundwater supply sources remains a significant risk, particularly in areas where the water table is closer to the surface.

An interesting feature of the recent statistics on domestic water sources (Table 4) is the dramatic increase in the number of household rainwater tanks between 1986 and 1996 with a persistent increase to 2006. In 1986 the number of households with rain tanks was less than 5% of those connected to piped water. By 1996 that had grown to 51% and by 2006 it had further increased to 85%. This remarkable increase in rainwater harvesting reflects three possible factors: Tongatapu's generally reliable rainfall; the number of recent aid projects that have supported rainwater harvesting; and a community preference for rainwater. The statistics in 2006 for drinking versus non drinking water sources (Table 5) demonstrate the clear preference for drinking rainwater.

In the following recommendations, a number of strategies are suggested for addressing the institutional issues affecting the vulnerability of groundwater discussed above.

3.7 Recommendations: Strategies for decreasing vulnerability

There are some simple institutional strategies that have the potential to decrease the vulnerability of groundwater in Tongatapu. It is recommended that the GoT should consider:

- **Enacting the draft 2006 National Water Resources Bill.** Passing the current draft 2006 National Water Resources Bill will address the lack of: protection of groundwater; statutory basis for MLSNRE; coordination of the water sector; reporting to GoT; controls on quarrying; information on groundwater extraction; and support for monitoring.
- **Establishing the broadly based National Water Resources Committee,** specified in the draft Bill to better coordinate and provide a reporting mechanism for government water agencies.
- **Developing National Water Resources Policy and Plans.** National recognition of the fundamental importance of water is essential for the future well-being of Tongans. National Water Policy and Plans together with National Legislation are important ways the GoT can provide leadership in an area vital to the lives and well-being of Tongans and to the development of Tongatapu. Clear policy directions and plans based on this policy can help coordinate government agency action, galvanise public participation and improve resource allocation and assistance down to the village level.

- **Providing Tongan priorities for aid donors in the water sector.** Having both a National Water Policy and Legislation will provide external aid donors with a clear indication of National priorities in the water sector. Monitoring water resource use and quality is clearly fundamentally important to the sustainable management of water resource management in Tonga and needs to be a priority.
- **Introducing a modest environmental water abstraction charge** for all water consumers to provide resources for vital water resource monitoring and assessment.
- **Establishing a single Tongatapu Water Supply Authority** to manage public urban and rural water supplies and their use and provide treated water to all communities in Tongatapu. This would relieve the burden on VWCs, who must remain, however, actively engaged in water management.
- **Regulating the quarrying industry** to maximise protection of groundwater.
- **Passing regulations** for the mandatory licensing and training of drillers, the licensing of all pumped wells and the metering and reporting of the rate of groundwater pumped in all of Tongatapu (detailed in the draft Bill).
- **Developing a database which shows the location of major uses of hazardous agricultural chemicals and fertilisers**. These have the potential to pollute groundwater on Tongatapu. This measure will improve the effectiveness and efficiency of water quality monitoring.
- **Installing additional SMBs throughout Tongatapu**. The thickness of the freshwater lens is one of the critical indicators of the sustainability of water resource management in Tongatapu. At present SMBs are only around the Mataki'eua/Tongamai well field. In order to monitor the impact of management strategies on the fresh groundwater resource it is critical that SMBs be installed throughout Tongatapu as in Figure 15.
- **Restricting free-ranging domestic animals to particular locations.** Free ranging animals, particularly pigs pose a significant health risk to groundwater sources. Consideration should be given to reducing the threat posed by domestic animals.

4 Groundwater Sampling and Analysis

4.1 Outline

The key concerns in groundwater quality in Tongatapu are the encroachment of salinity, contamination from agricultural chemical and fertilisers, pollution from heavy metals and petroleum products and contamination by pathogens and nutrients from human and animal wastes. Studies over the past 40 years have reported the results of groundwater sampling conducted in Tongatapu (summarised in Falkland, 1992; Furness and Helu, 1993; Douglas Partners, 1993; 1996; Furness, 1997; van der Velde, 2006). These have shown that salinity encroachment in Tongatapu waxes and wanes with droughts and wet periods, that concentrations of agriculture chemicals, heavy metals and petroleum products are almost always below detection limits, that nutrients levels are below WHO guideline values, and that indicator species of human and animal wastes occur in water supply wells throughout Tongatapu from time to time.

Time series of salinity, chemical and pathogen concentrations provide a valuable way of identifying trends in encroachment and contamination and help identify potential “hotspots”. The groundwater sampling carried out in this project provides only a snapshot of the current state of groundwater. This could easily be altered by the next intense wet or dry period. When coupled to previous measurements it helps identify trends and may be useful for prioritising actions and management interventions.

The following sections describe the groundwater measurements that were carried out in this project.

4.2 Groundwater measurements in village wells

Field measurements were made on 14th and 15th August 2007 of the electrical conductivity (EC) and pH of water produced from 55 village wells and boreholes throughout Tongatapu. A portable temperature-compensated pH and EC meter (TPS WP81) was used. This meter was calibrated with EC and pH standards prior to use. The locations of the sites were determined using a hand-held GPS (Garman or Magellan Meridian Platinum) and are shown in Figure 17. Measurements were also made, where practical[1], of the depth to water table below ground surface using a Solinst TLC dipmeter with a 100 m tape. Where possible, measurements were made when the pump was operating. In wells where pumps were not operating, a well-rinsed one litre sampling bucket was used to collect samples (Figure 18). The wells together with their locations are listed in Annex E.

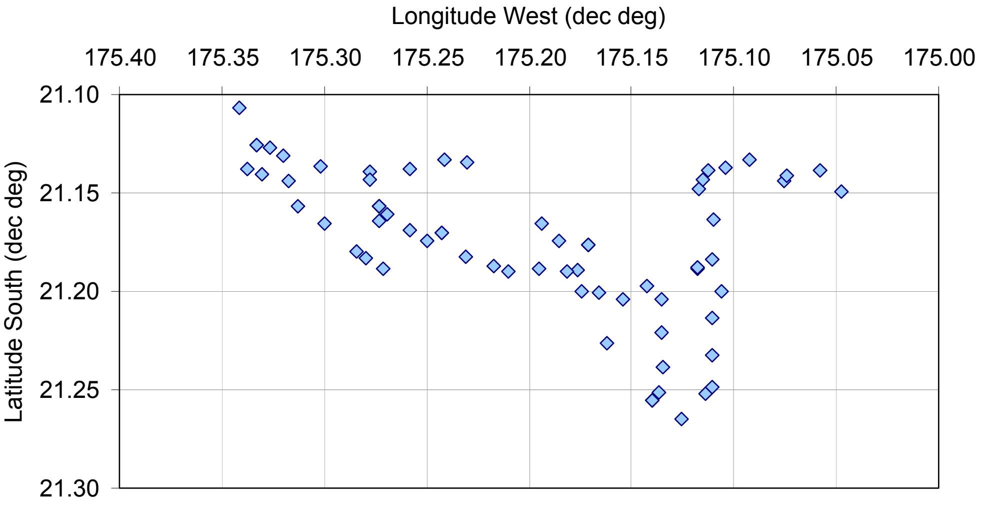

Figure 17 Location of the village wells in Tongatapu sampled for salinity

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[1] Measurements of the depth to watertable are only possible in dug wells. In drilled boreholes the pump has to be disassembled to make measurements.

Figure 18 Sampling the Fo'ui village well 151

4.3 Groundwater measurements in the TWB wellfield

Field measurements were made on 28th July and 10th August 2007 of the EC and pH of water produced from 31 of the 39 TWB wells and boreholes throughout the Mataki'eua/Tongamai wellfield. Some pump stations had missing pumps and others had no sample valve. These sites were not sampled. The portable pH and EC meter an EC meter (TPS WP84) or a Solinst TLC dipmeter were used for measurements. All instruments were calibrated with EC and pH standards prior to use. The locations of the sites (see Figure 5 and Annex F) were determined using a hand-held GPS (Garman or Magellan Meridian Platinum). Measurements were also made, where practical, of the depth to water table below ground surface using the Solinst TLC dipmeter. Where possible, measurements were made when the well or borehole was being pumped using the pump's water sample valve (Figure 19).

Figure 19 Sampling TWB well 131 in the Mataki'eua/Tongamai wellfield

4.4 Freshwater lens thickness in and around the TWB wellfield

Six salinity monitoring boreholes (SMBs) have been installed in and around the TWB's wellfield at Mataki'eua/Tongamai. Their location relative to the TWB pump stations is shown in Figure 20. SMBs are specially constructed boreholes (Falkland, 2002) to sample different depths through the freshwater lens with individual sampling tubes isolated from each other with bentonite packing. This borehole construction prevents tidal mixing of the groundwater that occurs in open boreholes (Figure 21 and Figure 22). The salinity profiles were determined on 2nd and 8th August 2007 by measuring the salinity down each tube using the Solinst TLC dipmeter (Figure 23).

The salinity at the bottom of each tube was taken to be the salinity at that depth as measured by the dipmeter tape. The EC sensor on the Solinst dipmeter was calibrated before and after measurements. The limit of freshwater was taken to be when the EC reached 2,500 μS/cm is adopted for an appropriate freshwater limit in island situations (Falkland, 2002).

4.5 Groundwater level and salinity logging at Mataki'eua well 117

An automatic logger (Greenspan CTD300) was placed in one of the TWB pumping wells at Mataki'eua, TWB well 117, at 13:45 on 2nd August 2007 to continuously record groundwater level, salinity and temperature fluctuations at a maximum of 10 minute intervals (Figure 24). Check measurements of EC, depth to water table and temperature were carried out using the Solinst TLC meter at the start, during and at the end of logging at 10:20 am 17th August 2007. Table 7 provides details of well 117. The well was being pumped during logging and the drawdown due to pumping was measured by stopping and re-starting the pump.

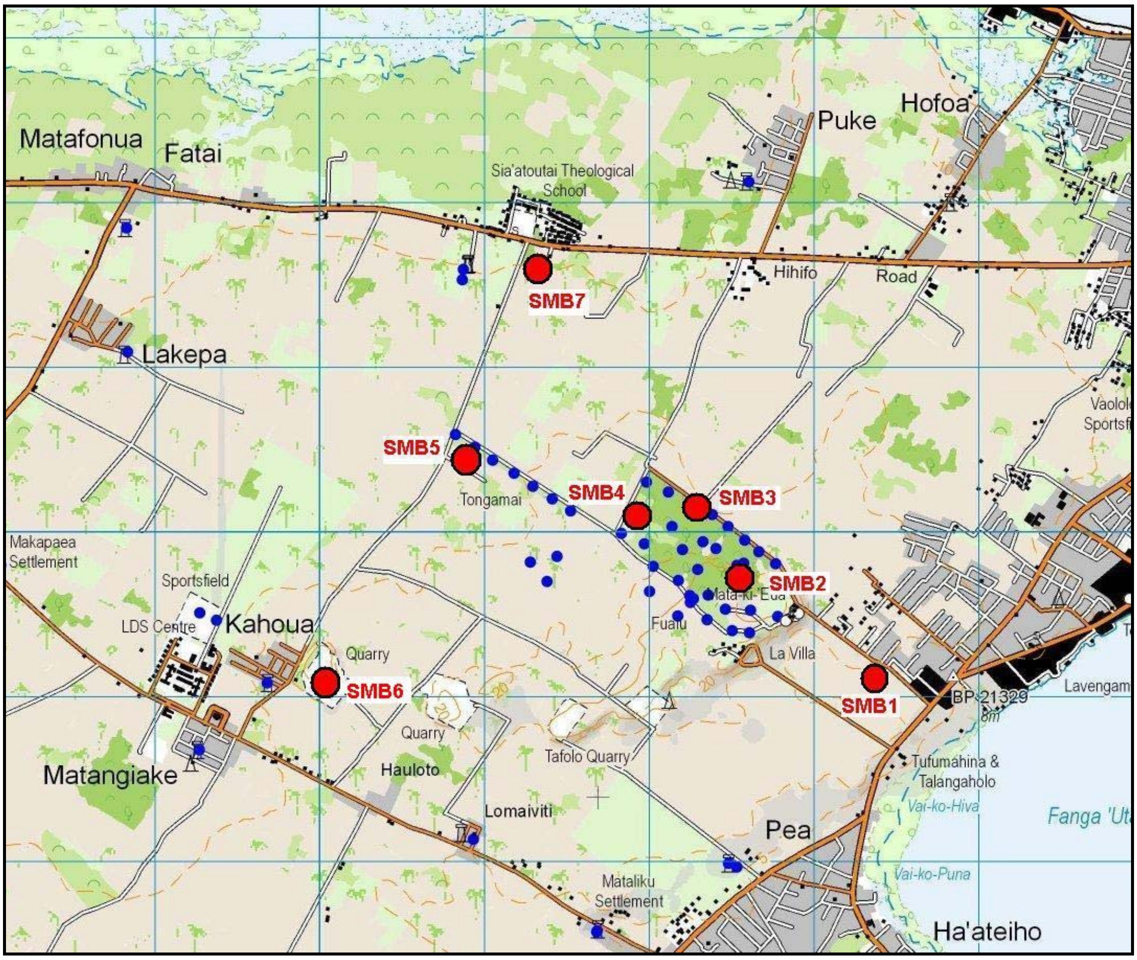

Figure 20 Location of the SMBs relative to the TWB pump stations in the Mataki'eua/Tongamai wellfield

Figure 21 SMB2 showing the tubes for sampling different depths through and beneath the freshwater lens in the Mataki'eua/Tongamai wellfield close to TWB pumping well 105

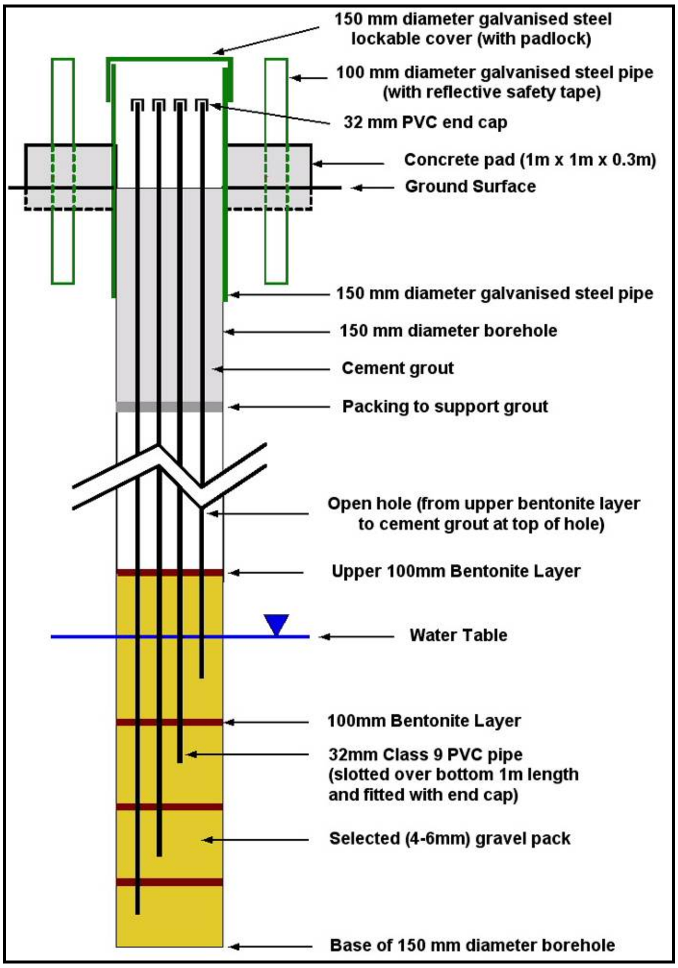

Figure 22 Cross-section through a salinity monitoring borehole

Table 7 Details of TWB well 117 chosen for continuous logging

Property	Value
Well No.	117
Type of Well	Open dug well
Location	TWB Wellfield Mataki'eua
Longitude West (dec deg)	175.246083
Latitude South (dec deg)	21.1500000
RL of well	12.74 m above MSL
Depth to Water table	12.105 m
Pumping Rate, 28 Jul 2007	376 KL/day
Pump Type	Electric submersible
Logging Commenced	13:45 on 2nd August 2007
Logging Terminated	10:20 am on 17th August 2007
Maximum Logging Interval	10 minutes

Figure 23 Measuring the thickness of the freshwater lens at SMB3 in the Mataki'eua wellfield using the Solinst TLC dipmeter

Figure 24 Placing the groundwater logger in Mataki'eua TWN pumping well 117

4.6 Groundwater measurements around the TWMF

During the field work in Tongatapu, the Waste Authority (WA) monitoring team conducted its third and final intensive sampling of monitoring boreholes around the TWMF near Vaini village (see Figure 11 and Figure 12). Our project team was invited to participate in this sampling on 31st July 2007 and took measurements of the water table depths using the Solinst dipmeter as well as measurements of EC of surface and bottom waters in the borehole. The EC and pH of bailed surface groundwater were also measured using the TPS WP81and TPS 84 EC meters or the Solinst TLC dipmeter. These had all been calibrated prior to use. The location of the TWMF is shown in Figure 25. The locations of the seven Tapuhia groundwater monitoring wells (GMWs) around the TWMF are shown in Figure 26 and their elevations are listed in Table 8. The TWMF water samples collected by the WA were analysed for contaminants.

Figure 25 TWMF (circled), northeast of Vaini village. Neighbouring village pumping wells are shown as blue dots.

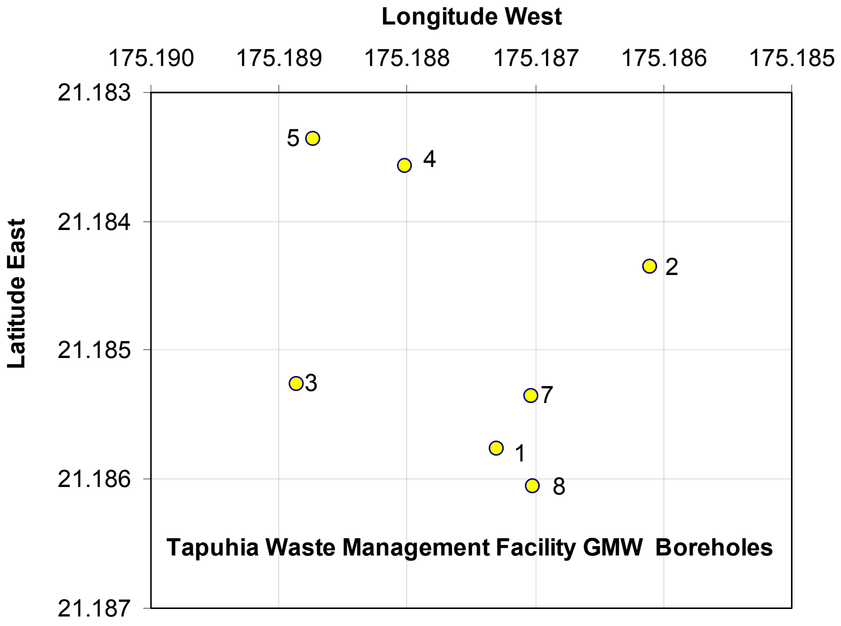

Figure 26 Location of the GMW boreholes around the TWMF

Table 8 Relative elevations of TWMF monitoring boreholes

Tapuhia Borehole	RL of Top of Pipe (m)	Height of Top of Pipe above ground (m)
GMW1	13.08	0.98?
GMW2	na	0
GMW3	13.036	??
GMW4	18.001	1.368
GMW5	13.512	0.948
GMW7	14.761	1.02
GMW8	13.476	0.995

Note: GMW6 has been destroyed

4.7 Testing wells for faecal indicator species

The contamination of water supplies by pathogens from human and animal wastes is a major concern in small island countries. Tongatapu has no reticulated sewerage or greywater systems. Instead, septic tanks and pit latrines are used. In wet weather particularly, these sanitation facilities have the potential to contaminate groundwater sources. In this project, we used two rapid, field techniques to test for the presence or absence of *E. coli* and total coliforms which are widely used as indicator species for faecal contamination.

The first method used the *Colisure* method (IDEXX Laboratories Inc, Maine USA). In this technique, 100 ml water samples were collected in sterile plastic sample bottles containing sodium thiosulfate to which a defined substrate containing nutrient indicator is added from a radiation sterilised snap-pack (Figure 175). The water turns yellow as the substrate dissolves (Figure 27). The sample is then incubated at 35°C and the results are read 24 and 48 hours after sampling. A red colour indicates the presence of total coliforms while a sample that fluoresces blue under a 365 nm UV light indicates the presence of *E. coli.* Samples that remain yellow are free from both (Figure 28). This test is strictly a test for the presence or absence of total coliforms and *E. coli.* The speed at which the indicator changes, however, does provide an estimate of the relative concentration.

Figure 27 **Testing a rainwater sample for faecal contamination. The *Colisure* substrate has just been added.**

Figure 28 **Results of *Colisure* test *Colisure* tests for the presence of *E. coli* (fluorescent blue), total coliforms (red), or their absence (yellow)**

The second method used was the H_2S Paper Strip Test (Allen and Geldreich, 1975; Manja *et al.,* 1982; WHO, 2002; Mosley and Sharp, 2005). In this test, 5 ml of water are added to a sterilised plastic container which contains a paper strip impregnated with a nutrient indicator. Samples are read over 3 days. Samples were scored according to the degree of colour change from clear to black (Figure 29):

- no colour change (-);
- water turned grey, possibility of bacteria (+);
- partly black, some faecal contamination present (++);
- paper strip and water noticeable black, very high risk of faecal contamination (+++);
- paper strip and water turn black overnight, high probability of bacterial present (++++).

Nineteen samples were collected from wells throughout Tongatapu and including the Mataki'eua/Tongamai wellfield (Figure 30). Where possible, water samples were collected from the sample taps on operating pumps. Care was taken to avoid contamination of samples. Table 9 lists the sample locations including the TWMF.

Figure 29 H_2S paper strip test for the presence of bacteria. Where the paper strip and water are black there is the very high risk of faecal contamination, partial black means some risk of contamination while the clear sample indicates no risk.

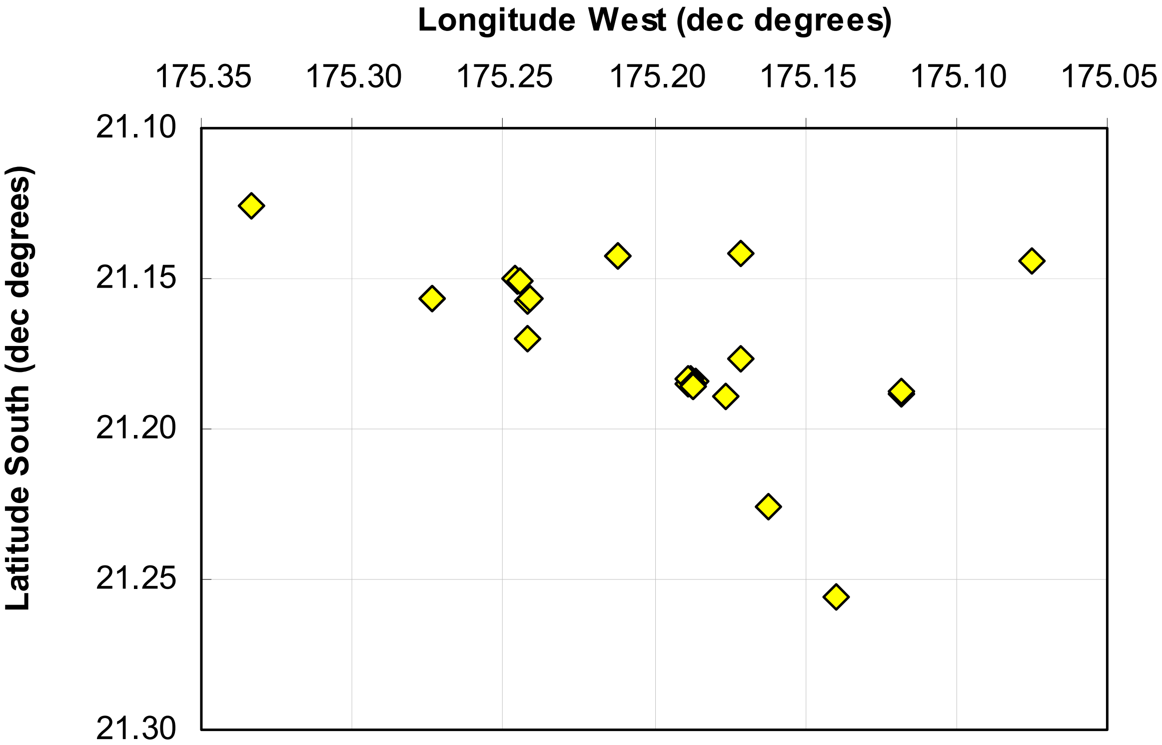

Figure 30 Location of water supply wells tested for faecal indicators in Tongatapu

4.8 Testing wells for agricultural and industrial contaminants

Ten water supply wells in Tongatapu were selected for intensive chemical analysis. Three wells in the Mataki'eua/Tongamai wellfield, 2 college and 5 village water supply wells were sampled on 7th August 2007. The well locations are listed in Table 9 and shown in Figure 31. Table 10 shows the data and time of sampling. Table 11 lists characteristics and comments on the selected sites.

Clean glass and polyethylene sample bottles were obtained from the Australian Government National Measurement Institute (NMI) together with two insulated sample containers and freezer packs. Samples were collected on the morning of 7th August 2007 and were immediately placed into the insulated containers with freezer packs. Where possible, samples were taken from the sample tap of operating pumps (Figure 32). For two wells, this was not possible and the wells were bailed (Figure 18). The insulated containers were delivered to the airfreight office in Nuku'alofa in the early afternoon were they were stored in a cold room overnight before shipping to New Zealand and then to NMI in Sydney. Analyses commenced on 14th August 2007. The compounds and species tested are listed in Annex G together with the detection limit and the analysis procedure used by NMI. In addition to the chemical sampling, field measurements of EC, pH and temperature were made using a calibrated TPS WP81 EC meter and the *Colisure* method was used to test for the presence or absence of faecal indicators.

Table 9 Water sources selected for faecal indicator testing

Location	Well No.	Location	
		Longitude (West) Decimal degree	Latitude (South) Decimal degree
Tapuhia WMF	GMW1	175.1873	21.1858
Tapuhia WMF	GMW2	175.1861	21.1844
Tapuhia WMF	GMW3	175.1889	21.1853
Tapuhia WMF	GMW4	175.1880	21.1836
Tapuhia WMF	GMW5	175.1887	21.1834
Tapuhia WMF	GMW7	175.1870	21.1854
Tapuhia WMF	GMW8	175.1870	21.1861
Rain water Geology		175.2120	21.1422
Mataki'eua wellfield TWB	115	175.2449	21.1507
Mataki'eua wellfield TWB	117	175.2461	21.1500
Boiled Rain Water Geology		175.2120	21.1422
TWB Tap Water FIH		175.1714	21.1418
Longoteme	GMW76	175.1714	21.1763
Fua'amotu	182	175.1395	21.2557
Tatakamotonga	21	175.1178	21.1883
Liahona	169	175.2734	21.1570
1. Kolonga	49	175.0753	21.1442
2. Tatakamotonga	20	175.1178	21.1879
3. Tupou College New Well		175.1620	21.2261
4. Vaini	218A	175.1766	21.1892
5. Pea	88	175.2424	21.1704
6. Liahona	169	175.2734	21.1570
7. Fo'ui	151	175.3332	21.1257
8. Mataki'eua TWB	115	175.2448	21.1506
9. Mataki'eua TWB	211	175.2423	21.1576
10. Mataki'eua TWB	104	175.2413	21.1565

Table 10 Water supply wells selected for intensive chemical testing

Site No.	Location	Well No.	Date sampled	Time sampled
1	Kolonga	49	7-Aug-07	9:12
2	Tatakamotonga	20	7-Aug-07	9:40
3	Tupou College	New Well	7-Aug-07	10:10
4	Vaini	218A	7-Aug-07	11:00
5	Pea	88	7-Aug-07	11:30
6	Liahona College	169	7-Aug-07	11:50
7	Fo'ui	151	7-Aug-07	12:10
8	Mataki'eua	115	7-Aug-07	12:50
9	Mataki'eua	211	7-Aug-07	13:05
10	Mataki'eua	104	7-Aug-07	13:20

Table 11 Characteristics and comments on wells selected for intensive sampling

Site no.	Type of Well	Pump	Operatin g	How Sampled	Comments
1	Drilled	Diesel	Just off	Tap	In agricultural area, considerable distance from village. Head tank was overflowing
2	Dug	Diesel	Yes	Tap	In agricultural area, at edge of town beside telecommunications tower, neighbouring village well 21 also operating
3	Drilled Feb 2007	Diesel	Yes	Tap	In school grounds, but neighbouring agricultural area, cattle pasture
4	Drilled	Diesel	Yes	Tap	Beside houses (septic tanks) and near rugby ground
5	Dug	Diesel	Yes	Bailed	Beside squash pumpkin fields. Pump off. TV report & interview carried out here.
6	Drilled	Electric	Yes	Tap	One of three pumps at end of rugby field in immaculately kept lawns neighbouring short pastures, no crops
7	Dug	Diesel	No	Bailed	East of Fo’ui. Short distance to water table. Surrounded by traditional crops. More saline area. Pump off
8	Dug	Diesel	Yes	Tap	TWB Pump, Beside SMB3
9	Drilled	Electric	Yes	Tap	TWB Pump, close to King's residence, La Villa.
10	Drilled	Diesel	Yes	Tap	TWB Pump, with copious oil spills and algae. In more saline area

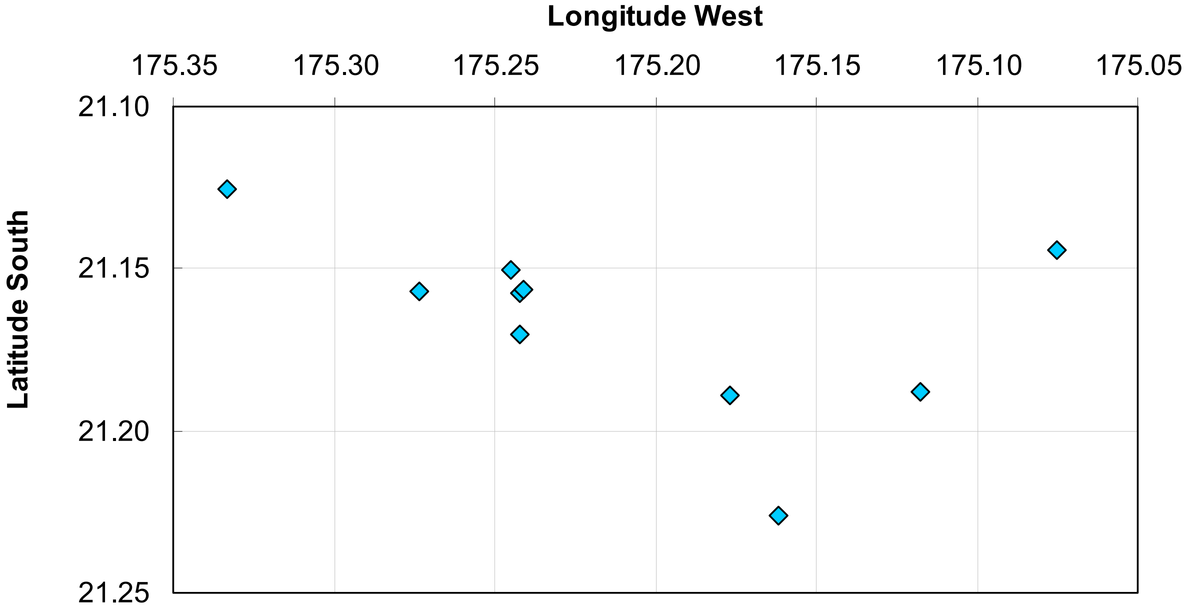

Figure 31 Location of the 10 intensively sampled water wells across Tongatapu

Figure 32 Sample point for the Kolonga village well 49

4.9 Intensive water quality sampling by other agencies

One week prior to our arrival in Tongatapu, a US army team working with Health Inspectors from the Public Health Section had carried out intensive sampling of water from house taps in Tongatapu for a range of biological and chemical species. The villages tested were Houma, Tokomololo, Lavangatonga and Tatakamotonga. In addition three urban sites were also tested: the Vaiola Hospital Kitchen; Seaview Restaurant; Tukutonga (old waste disposal site). In addition, rainwater tank samples from schools at Te'ekiu, Pelekale, and Telafo'ou, Unfortunately, the results of this study were unavailable.

The WA has conducted three intensive samplings at and around the Tapuhia WMF (Figure 25 and Figure 26) in February and May 2006 and during this study on 31st July 2007. The chemical species tested for were very similar to those listed in Annex G. The WA has very generously provided us with the results of these intensive sampling events.

The next section presents and discusses the results of the measurements described above and compares these measurements with previous measurements in Tongatapu.

5 Properties of Groundwater in Village Wells

5.1 Outline

The following sections give the results of the measurements of groundwater salinity (EC), pH, temperature and depth to water table or water table elevation above mean sea level (MSL) carried out in August 2007 in village wells throughout Tongatapu. This “snap shot” of groundwater properties is then compared with previous results of groundwater measurements carried out in Tongatapu since 1959.

5.2 Summary of field measurements, August 2007

An analysis of statistics of field measurements (depth to water table (WT), EC, temperature and pH) in 55 village wells and boreholes are given in Table 12. The coefficient of variation (CV) and the maximum and minimum values show large variation in the depth to water table across Tongatapu, consistent with the southeast-northwest tilt of the island. The variation in EC is smaller but has an almost four-fold difference between the minimum and maximum values in the southeast and northwest respectively. The variations in temperature and pH are much less as expected. The spatial distribution of salinity across Tongatapu is shown in Figure 33.

Table 12 Statistics of field measurements from 55 village wells and boreholes, 14th - 15th August 2007

Statistic	Depth to water table (m)	EC (µS/cm)	Temp (°C)	pH
Mean	**12.6**	**1,015**	**24.1**	**7.24**
Standard Deviation	13.3	314	0.9	0.27
CV (%)	106	30.9	3.6	3.7
Median	7.8	975	24.2	7.21
Maximum	62.2	2,101	26.7	7.73
Minimum	3.2	571	22.3	6.29
Number of Measurements	19	55	55	55

Comparison of the salinity distribution in May 1990 (Figure 6) with that in Figure 33 shows similar features. Both show significant groundwater salinity in the Hihifo northwest peninsula with some salinity intrusions around the Mu’a villages and in the northeastern peninsula around Kolonga. The lowest salinity water occurs at the highest point in the island around Fua’amotu. Saline intrusion appears slightly more extensive in 1990 than in 2007. These salinity distribution maps provide a useful way of identifying priority areas for addressing water supply problems. Clearly the Hihifo region has significant groundwater salinity levels.

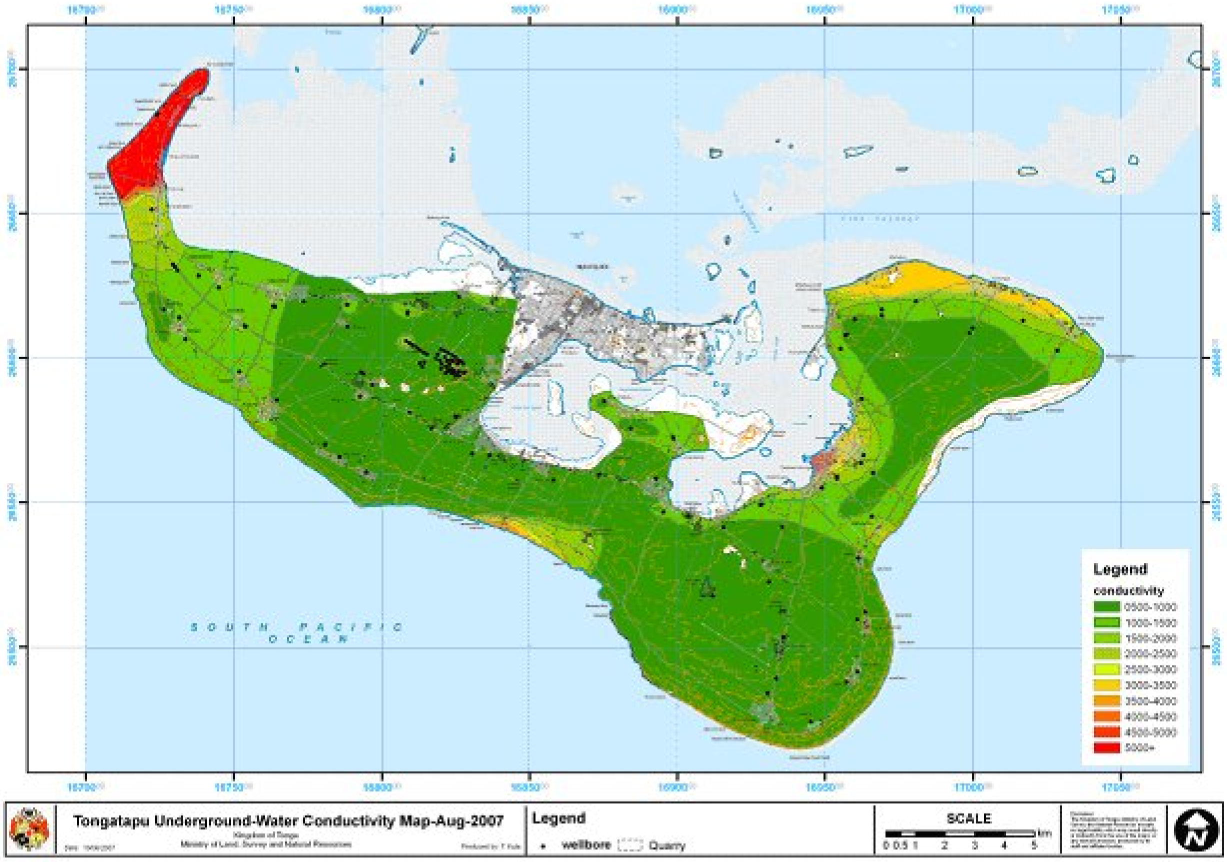

Figure 33 **Groundwater salinity (EC) distribution map of Tongatapu in August 2007 as measured in 55 pumping wells (GIS map produced by MLSNRE)**

5.3 Previous field measurements

The MLSNRE well monitoring database for Tongatapu is a record of field measurements of depth to water table, EC, temperature and pH of village wells dating back to 1959. Table 13 shows the statistics of all measurements, with outliers excluded, from 1959 to 2007.

Table 13 **Statistics of field measurement for village wells and boreholes, 1959 to 2007**

Statistic	Depth to water table (m)	EC (µS/cm)	Temperature (ºC)	pH
Mean	**11.8**	**1,259**	**24.9**	**7.39**
Standard Deviation	9.1	702	1.5	0.39
CV (%)	77	55.7	6.1	5.3
Median	8.3	1,060	25.0	7.38
Maximum	62.2	6,990	27.9	8.54
Minimum	1.4	314	21.0	6.45
No. of Measurements	1,169	2,043	1,446	1,213

Examination of the database reveals inconsistencies, with water table depths of zero, ECs as high as 13,000 µS/cm and as low as 52 µS/cm, pHs as high as 22.9 and as low as 0.7 and temperatures as high as 41.9ºC and as low as 13.3ºC. These extremes are physically impossible for water supply wells in Tongatapu. Extreme values were removed from the database. The values chosen for removal, the reasons for those limits and the number of values removed from the database are listed in Table 14. Also some dates, such as July 1996, show anomalous high values unexpected from the prevailing rainfall. These could be due to instrument calibration problems. It is also noted there may be some confusion over well numbers. Villages often have several wells and bores from which they can draw water. Villages often switch wells depending on circumstances or even abandon wells. Since most village well clusters are normally located over a relatively small area, this may not be a large problem.

Table 14 Values used to identify outliers in MLSNRE Tongatapu village well database

Parameter	Outliers	Outlier Statistics				Comments
		Number	%	Total number	Total %	
Depth to water table	Depth to water < 0.5m	0	0.0	0	0.0	No depths to groundwater in wells on Tongatapu should be less than 0.5m or greater than 65m (max elevation)
	Depth to water >65.0m	0	0.0			
EC	EC < 300 µS/cm	2	0.1	3	0.1	EC should not be lower than about 300 µS/cm or greater than about 10,000 µS/cm (if outside this range, checks are required)
	EC > 10,000 µS/cm	1	0.0			
Temp	Temp < 22ºC	187	10.2	399	21.9	Average temp in Tongatapu is 21.4ºC in July and 26.3ºC in February
	Temp > 28ºC	212	11.6			
pH	pH < 6.5	78	5.1	322	21.1	Reasonable range for limestone is 6.5 to 8.5
	pH > 8.5	244	16.0			

It is noted in for temperature and pH in Table 12 and Table 13 that the mean values are close to the medians, indicating these properties are normally distributed and have small CVs. Both EC and depth to water table appear not normally distributed.

With outliers removed, the database was then searched for wells with a long historic record of EC measurements. It was found that for one well the EC record extended back to 1959 while for another 24 wells the record dated back to a least the mid-1960. A further 10 wells had EC data starting in 1970 to 1980 while an additional 14 wells had data from the early 1990s, making a total of 51 wells with a sufficiently long record to examine trends with time. A simple linear trend was fitted to each of the individual wells for 3 periods, 1960s to 2007, 1970s to 2007 and 1990s to 2007 where data existed for those periods. Wells whose records terminated before 2007 were also included in the relevant periods. The results are summarised in Table 15.

All 25 of the wells whose records go back to the 1960s showed an increasing trend in EC over the period to 2007 with the mean trend being an increase of 13 µS/cm/year. The correlation coefficients of the trend lines, however, were extremely small as can be seen from the mean value of R^2 in Table 15. Only 5 wells had a correlation coefficient greater than 0.5. Out of the 35 wells with data extending back to the 1970s, 30 showed an increasing trend to 2007 and 5 showed a decreasing trend to 2007 with the mean trend being an increase of 9 µS/cm/year. Again the correlation coefficients were extremely small and only 4 wells had correlation coefficients greater than 0.5. A different situation arises for the 51 wells with sufficiently long records dating back to the early 1990s. Only 17 of these wells showed an increasing trend in EC with the remaining 34 wells showed a declining trend with the mean trend being a decrease in EC of 9 µS/cm/year to 2007. Again correlation coefficients were very small and only 4 wells had correlation coefficients exceeding 0.5.

Table 15 Temporal trends in EC data for individual wells in Tongatapu

Period	1960s to 2007	1970s to 2007	1990s to 2007
No. of Wells	25	35	51
No. of Positive EC Trends	25	30	17
No. of Negative EC Trends	0	5	35
No. of Wells with R>0.5	5	4	4
Mean Trend (µS/cm /year)	**13**	**9**	**-9**
Standard Deviation (µS/cm/year)	12	12	19
Mean R^2	0.147	0.087	0.072

The apparent trends in Table 15 warrant further analysis. Although the trend correlations for individual wells for the different periods are very weak for most of the wells, the consistency of the positive trends in all wells from the 1960's and most wells from the 1970s combined with the fact that two thirds of wells from the 1990s had a negative trend suggest a more detailed analysis is warranted. This analysis is provided below.

5.4 Trends in groundwater salinity

Figure 34 shows the plot of all salinity (EC) measurements in Tongatapu village water supply wells since 1959. It reveals some of the problems encountered in attempting to determine temporal trends in the salinity record. Firstly, there are only a few measurement periods prior to 1990 as well as a smaller number of measurements at each field sampling before 1990. Secondly, the scatter of the measurements between 1990 and 1998 is much higher than before or after this period. This means that relatively few high values could bias any analysis of mean salinity trends. It has already been mentioned that some measurements in the mid-1990s appear to be extremely and uncharacteristically high for water supply wells. Thirdly, there are no EC measurements between 2001 and 2003 due to instrument failures. All of these factors complicate analysis of temporal trends in salinity.

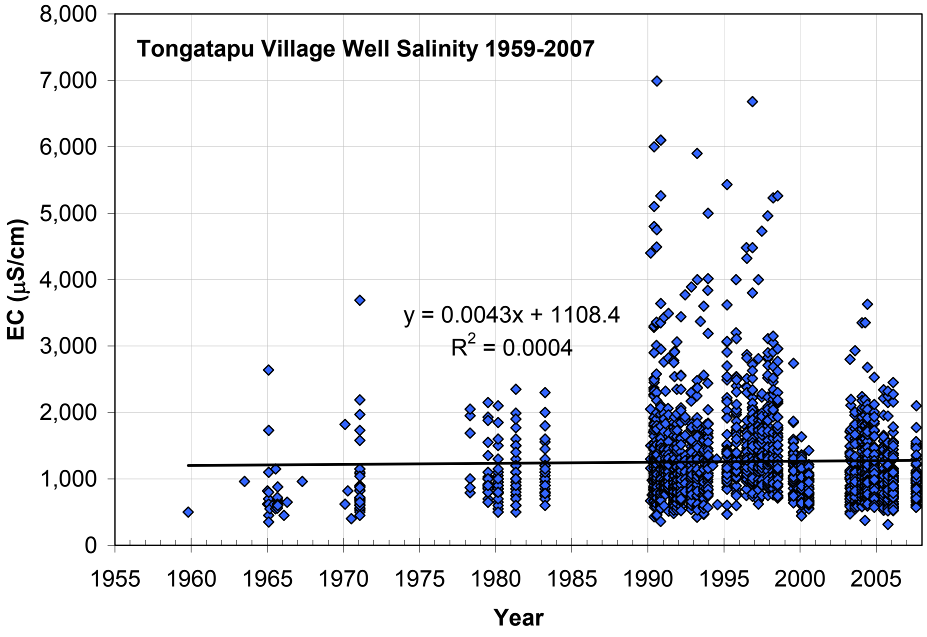

Figure 34 All groundwater EC measurements in Tongatapu village wells since 1959

In order to examine the trend of groundwater salinity in Tongatapu village wells, we have calculated the mean, geometric mean (log mean) and median of well measurements for all sampling periods involving more than 10 village wells. This average data is listed in Annex H for the period 1965-2007. Presenting the mean data as a log mean acknowledges the skewed distribution of the EC and places less emphasis on the few extreme high values of EC. Figure 35 shows the temporal trend in log mean EC from 1965 to 2007.

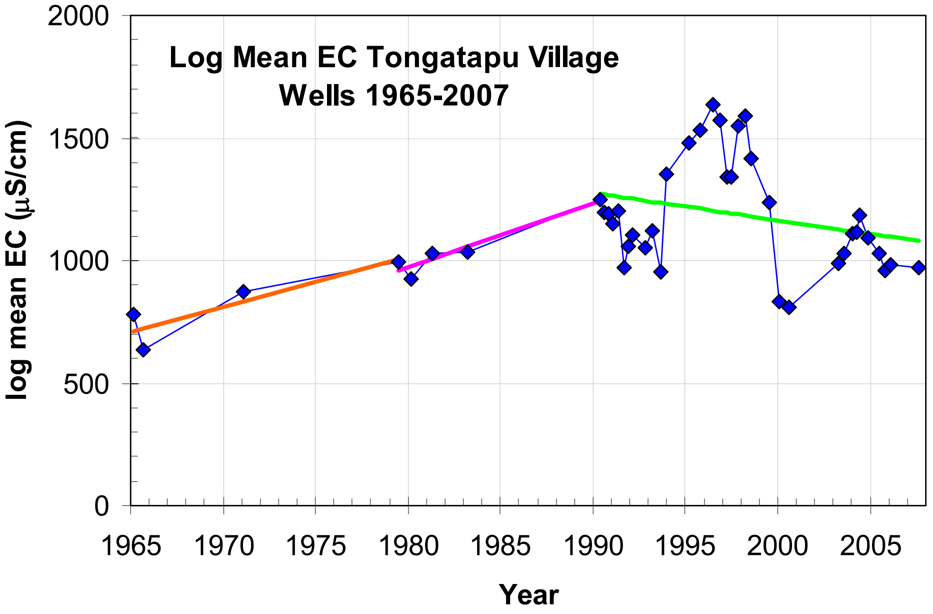

Figure 35 Temporal trends in log mean EC of Tongatapu village wells

There appear to be approximately three periods of trend in the log mean data: one from 1965 to 1979, the next from 1979 to 1990 and a final more complex period from 1990 to 2007. During the first two periods salinity increased while in the last period salinity appears to decline. Table 16 lists the value of the trends and R^2 for these periods.

Table 16 Trends in log mean EC for Tongatapu village wells for 3 periods between 1965 and 2007[2]

Period	Linear Trend (μS/cm/year)	Intercept (μS/cm)	R^2
1965-1979	20.5	-620	0.798
1979-1990	26.3	-1,131	0.918
1965-1990	19.7	-580	0.903
1990-2007	-11.2	2,282	0.074
1965-2007	7.9	400	0.117

The correlations for the trend in log mean EC are much higher for the two periods 1965 to 1979 and 1979 to 1990. Table 16 shows these two periods could easily be combined into a single period from 1965 to 1990 where there is a significant increase in the log mean EC of village wells. The period from 1990 shows a negative trend of similar magnitude to the mean trend for individual wells in Table 15. Again in Table 16, as in Table 15, the correlation coefficient is small and this negative trend is not significant due to the complex variation of EC in this period when more frequent EC measurements were taken.

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[2] In using these trend line values to estimate log mean EC for Tongatapu village wells using an XL spreadsheet the linear trend coefficient must be converted into μS/cm/day by dividing the values in Table 16 because of the date configuration used in XL.

Care must be taken in interpreting these trends; since the frequency of measurements prior to 1990 is much less than that after 1990. Also, the earlier measurements sampled fewer of the village wells than did those later (Annex H also lists the number of wells measured at each sampling date). It appears, however, that the log mean salinity of the Tongatapu village wells increased significantly during the period 1965 to 1990 but has not increased since then and may have slightly decreased. We will now explore the reasons for those changes.

5.5 Rainfall and groundwater salinity

One possible reason for the trends in log mean EC of the Tongatapu village wells listed in Table 16 could be different rainfall patterns and amounts over the period 1965 to 1990 and 1990 to 2007. van der Velde *et al.* (2006) found strong correlation with between groundwater EC in Mataki'eua/Tongamai wells and the previous 10 months SOI. To investigate the impact of rainfall patterns, the correlation between rainfall and log mean EC was investigated for a limited range of the complete record. The period chosen was the period from January 2000 to August 2007 during which the smallest number of wells measured was 42. Figure 35 shows that this period also has less scatter than the period from 1990 to 1999. This is also a period were we can expect that groundwater pumping was at a maximum in Tongatapu.

It was found that the negative correlation between EC and previous rainfall was a maximum if rainfall was summed over the previous 19 months. Figure 36 shows the correlation. The correlation between log mean *EC* (in μS/cm) and rainfall over the previous 19 months, $\left(\sum_{i=1}^{19} P_i\right)$ (in mm) is very strong with an R^2 = 0.942 (explains all but 5.8% of the variance) and follows the relation:

$$EC = 57015 \times \left(\sum_{i=1}^{19} P_i\right)^{-0.5124} \quad [1]$$

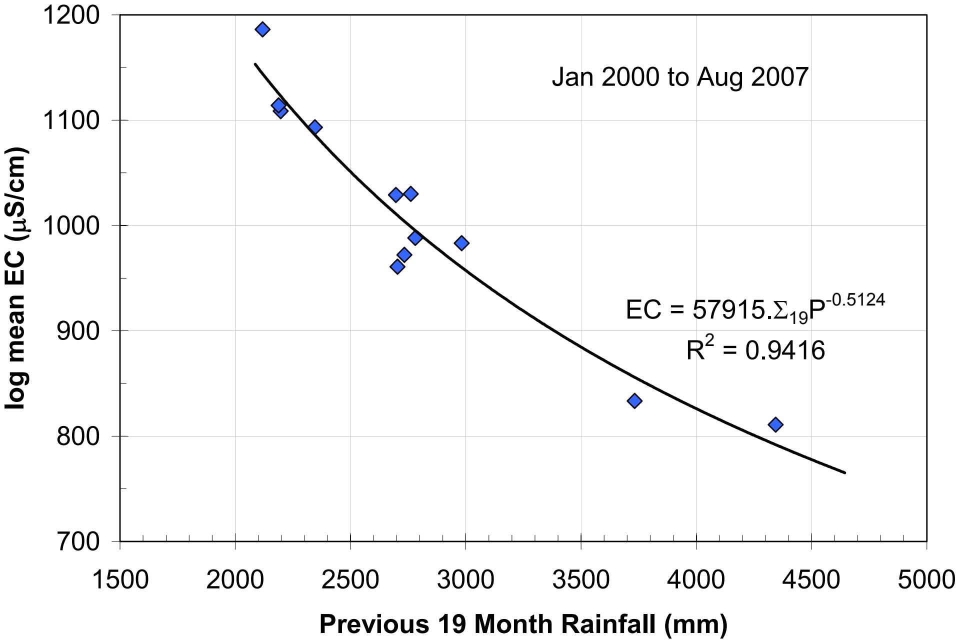

Figure 36 Correlation between log mean EC of Tongatapu village wells and rainfall over the previous 19 months

Equation [1] predicts that if the rainfall over the previous 19 months (including the month of the EC measurement) is less than 460 mm the log mean EC will exceed the drinking water limit of 2,500 μS/cm. To date, the lowest rainfall over a 19 month period is 1,317 mm which occurred in

December 1983 and is well above this limit. Unfortunately, no measurements of village well salinity were made between March 1983 and May 1990.

We can use equation [1] to predict the log mean EC of Tongatapu village wells. The comparison between predicted and measured log mean EC values (see Figure 37) shows excellent agreement for the calibration period January 2000 to August 2007. It is also clear that the measured log mean EC from May 1979 to March 1983 and some from October 1991 through to March 1992 agree quite well with predictions. The measured values in 1965 to 1971, however, fall well below the predicted values while the measured values from May 1990 to April 1991 and from March 1995 to June 1998 lie well above the predictions. There are several possible explanations for these differences. The first is that equation [1] is not applicable to other periods. If increased pumping had occurred from village wells in the period 2000 to 2007 and this had increased salinity then we might expect that measurements made in earlier periods, when village pumping was less than current rates, would fall below the mean values predicted from equation [1]. This may be the reason that measurements in 1965 fall below the predicted EC based on previous rainfall using equation [1]. This, however, does not explain why values measured in the periods 1990 to 1991 and 1995 to 1998, which are associated with an increased spread of EC data (see Figure 34), are much higher than predictions.

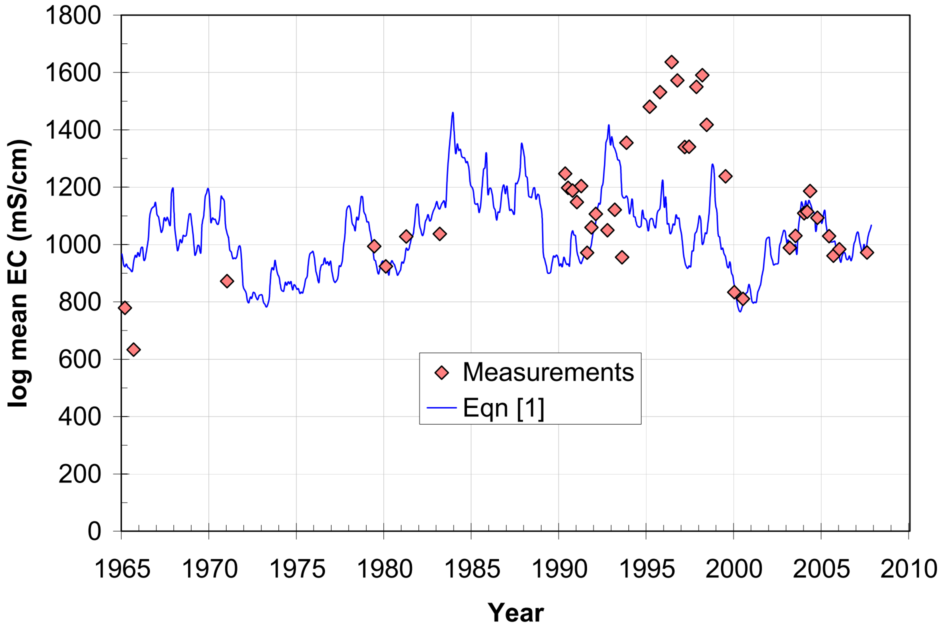

Figure 37 Comparison between the measured log mean EC of Tongatapu village wells and that predicted by equation [1]

An attempt was made to correlate the EC data from 1990 to 1999 with previous rainfall over various lengths of time. Unlike the period 2000 to 2007, correlation coefficients were very low and many were positive indicating that groundwater salinity increased when rainfall increased, which is physically counter-intuitive. The highest correlation coefficient (R) between EC and previous rainfall for the period 1990 to 1999 was found when rainfall was summed over 5 months prior to EC measurement but this had only a value of +0.1. This very low value of R indicates that the correlation explains only 1% of the observed variance (contrast Figure 38 with Figure 36).

Physically, it is reasonable to assume that groundwater EC should decrease as rainfall increases and that there should be a strong correlation between groundwater EC and rainfall as in Figure 36. The fact that there is no significant correlation between log mean EC and previous rainfall over any period for 1990 to 1999 suggests that there are technical problems with the high EC measurements during this period.

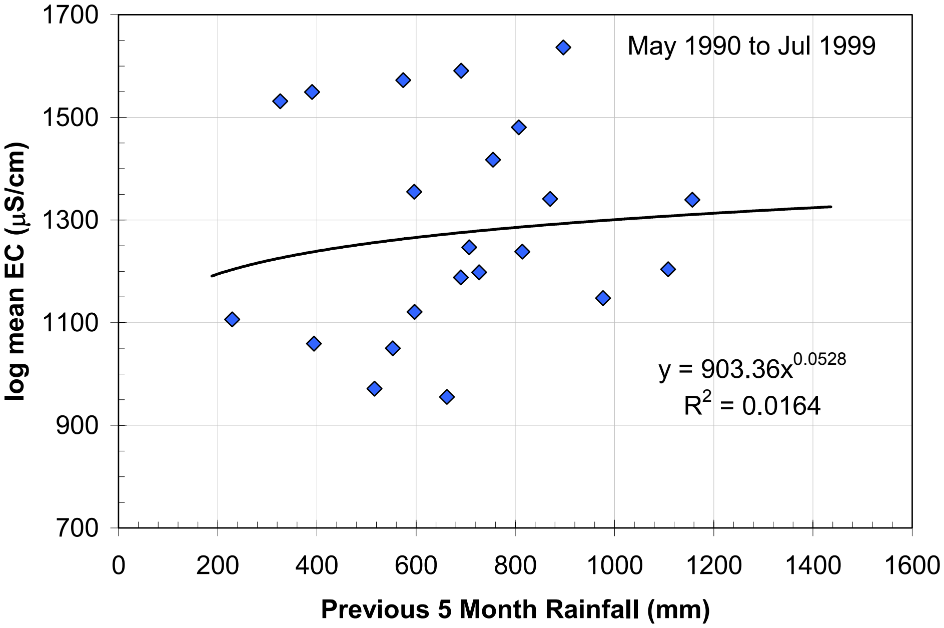

Figure 38 **The poor correlation between log mean EC and rain over the previous 5 months for 1990-1999**

Setting aside the period 1990 to 1999, the comparison between measured log mean EC and the values predicted from equation [1] suggest that salinity measurements in the period 1965 to 1971 are lower than in the period 2000 to 2007 and that this difference is not due to rainfall differences. Since the number of people in Tongatapu in 1965 to 1971 was about 70% of that in 2007, one possible explanation is that the increase in salinity is due to increased pumping. The results in Figure 37 suggest that this increase occurred between 1965 and 1979. Unfortunately, there is no information of the volume of water extracted by village wells.

5.6 Water table elevations

The MLSNRE database, from which outliers have been excluded (see section 5.3), also lists measurements of the depth to the water table for some of the Tongatapu village wells, including measurements made during August 2007. For a subset of these wells, the reduced (or relative) levels (RLs) (assumed above mean sea level, MSL[3]) of the reference position for measurement of water table depth are also listed. Using these RLs, the elevation of the water table relative to MSL can be estimated for these wells.

When the database was examined for water table depth, numerous problems were encountered. These included obvious transcription errors, apparent step changes in water table depth (perhaps due to changes in the reference point for depth measurement) and RLs of wells which gave negative values of depth to the water table, indicating water table elevations below MSL. Since EC measurements showed that the groundwater was still fresh, these values were excluded. In total, 30 wells had reliable RLs and records of water table depths some dating back to 1971. Table 17 summarises the mean RLs, depths to water table and water table elevations above MSL. Figure 39 shows the plot of all water table elevations in village wells since 1971.

The estimated mean water table elevation in Table 17, 0.41 m above MSL, is low for such a large “small” island as Tongatapu and reflects the large hydraulic conductivity of the aquifer. For some atolls only 1 km wide mean water table elevations are around 0.7 m above MSL. The water table elevations here are heavily reliant on the accuracy of the measurements of well RLs. By averaging over 30 wells and 409 individual measurements, the errors associated with this accuracy are reduced. Since some RLs in the database gave physically unrealistic, negative water table

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[3] It is assumed that these RLs are relative to MSL. Since MSL may have changed over the years it is important that these RLs are tied into current MSL.

elevations, it is recommended that all well RLs should be resurveyed and the reference point for water table depth measurement clearly marked. The data in Figure 39 shows that there has been no significant trend in water table height since 1971.

Table 17 Mean water table elevation for Tongatapu village wells with measured RLs for the period 1971-2007

Statistic	Well RL (m above MSL)	Depth to water table (m)	Water table elevation (m above MSL
Mean	**8.37**	**7.86**	**0.41**
Std Dev	5.17	4.44	0.18
CV (%)	62	56	44
Median	7.46	7.07	0.39
Maximum	26.10	25.80	1.03
Minimum	3.53	2.99	0.06
No. of Wells	30	No. of Measurements	409

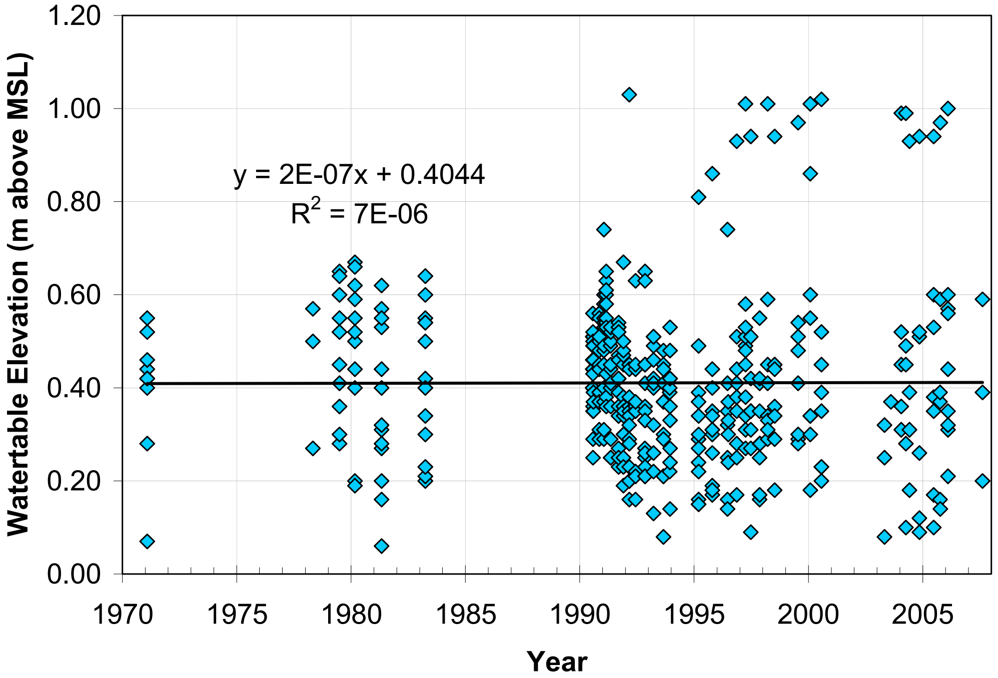

Figure 39 Temporal change in water table elevations in village wells since 1971

Hunt (1979) in his finite element study of piezometric heads of groundwater in Tongatapu estimated water table elevations that ranged from 0.5 m in the centre of the largest areas around Fua'amotu and Liahona to around 0.2 m at the edges. These estimates are in good agreement with the long-term mean in Table 17.

5.7 Factors affecting water table elevation

The mean water table elevation is a composite of temporal changes, rainfall recharge and discharge to the sea, tidal influences and impacts of groundwater pumping. Figure 40 compares the temporal changes in mean water table elevation with rainfall over the previous 3 months for the period 1971 to 2007. This rainfall period was found to give the maximum correlation between previous rainfall and mean water table elevation. There is an apparently slight linear trend for increasing water table elevation over the period although the correlation coefficient is very small (0.1) indicating no significant trend with time. Rainfall over the same period shows a slight decreasing linear trend with time (correlation coefficient, R = 0.09). It is noted that in the early 1990's when ECs were high (section 5.5) and rainfalls low, the mean water table elevation in Tongatapu was lower than current or previous values.

It is expected that water table elevation should depend on previous rainfall. Since groundwater salinity also depends on rainfall, it is anticipated that EC, on average, should decrease with increasing water table elevation. Figure 41A shows that mean water table elevation does increase with previous rain and Figure 41B shows that there is indeed a tendency for the log mean EC to decrease with increasing mean water table elevation, as expected.

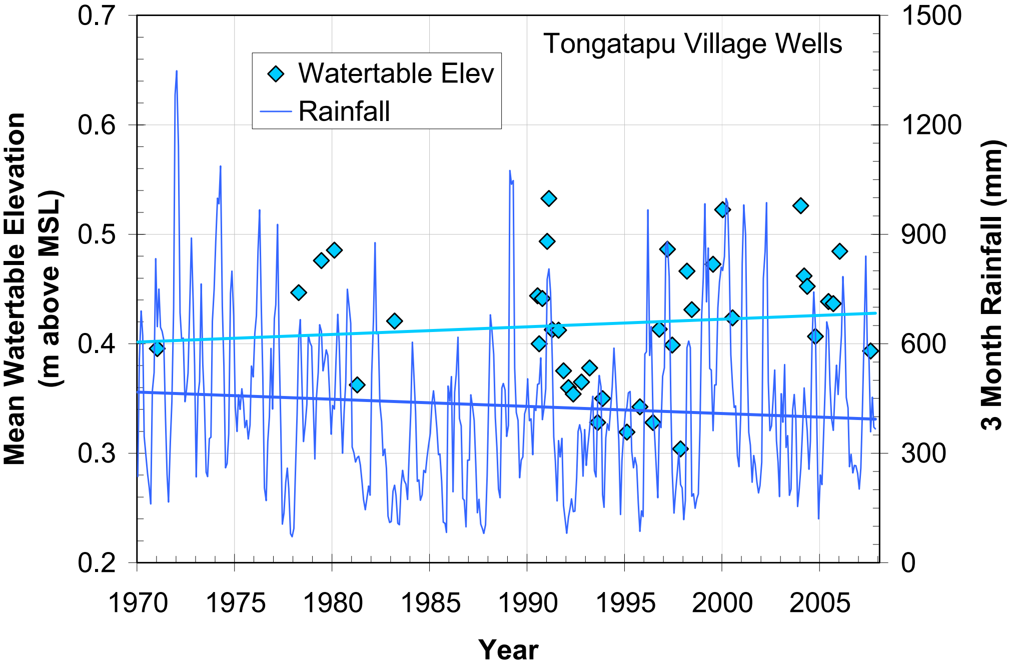

Figure 40 **Temporal changes in mean water table elevation of Tongatapu village wells compared with rainfall over the previous 3 months, 1971-2007**

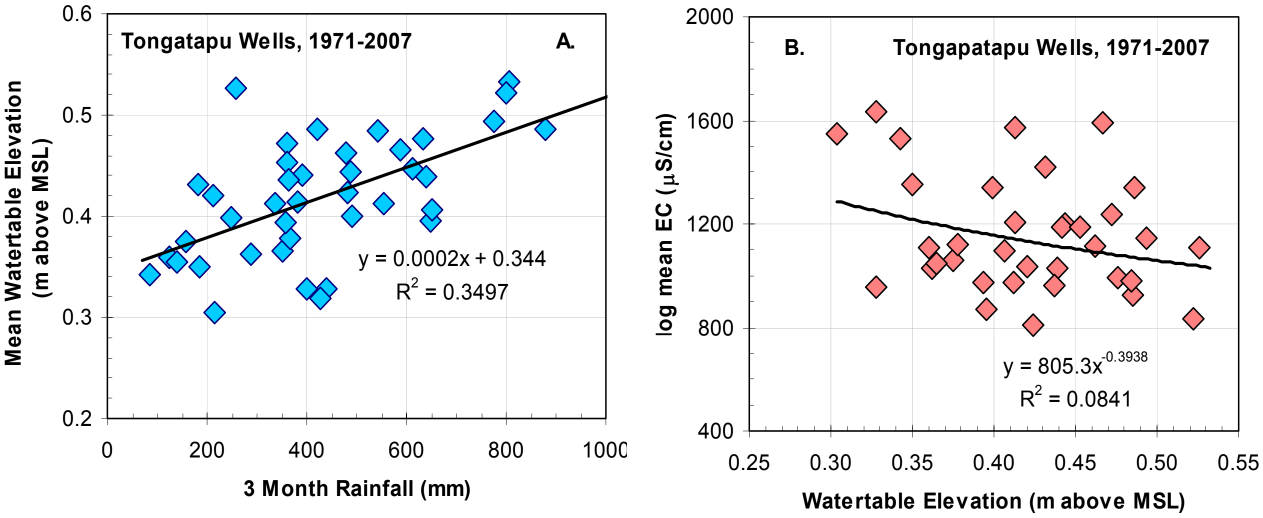

Figure 41 **Relationships between A. mean water table elevation and rainfall over the previous 3 months and B. log mean EC and water table elevation for 30 village wells**

The data for the mean water table elevation, *WT* (in m above MSL), can be fitted to the equation:

$$WT = 0.175 \times \left(\sum_{i=1}^{3} P_i \right)^{0.146} \qquad [2]$$

where $\left(\sum_{i=1}^{3} P_i \right)$ is the sum of the previous 3 months of rain (including the month of the water table measurement)[4]. The lowest 3 monthly total rainfall for Tongatapu is 59 mm which occurred in January 1946. Equation [2] predicts the water table elevation in Tongatapu then would have been about 0.32 m above MSL.

It is also known that water table elevation should increase with distance away from the sea or lagoon. While the MLSNRE database does not have distance from marine water as part of the database, it does have RL of the well. In Tongatapu, to a crude approximation, it is expected that positions with higher ground surface elevations will have a higher groundwater elevations. Figure 42 shows the apparent dependence of mean water table elevation for individual village wells on RL of the well. Contrary to expectations, the trend line shows a decrease with increasing surface elevation of the well. The R^2 value is, however, small showing no significant change with surface elevation. This probably reflects the accuracy of both the well RL and the measurement of depth to groundwater and emphasises the need for careful measurement of both.

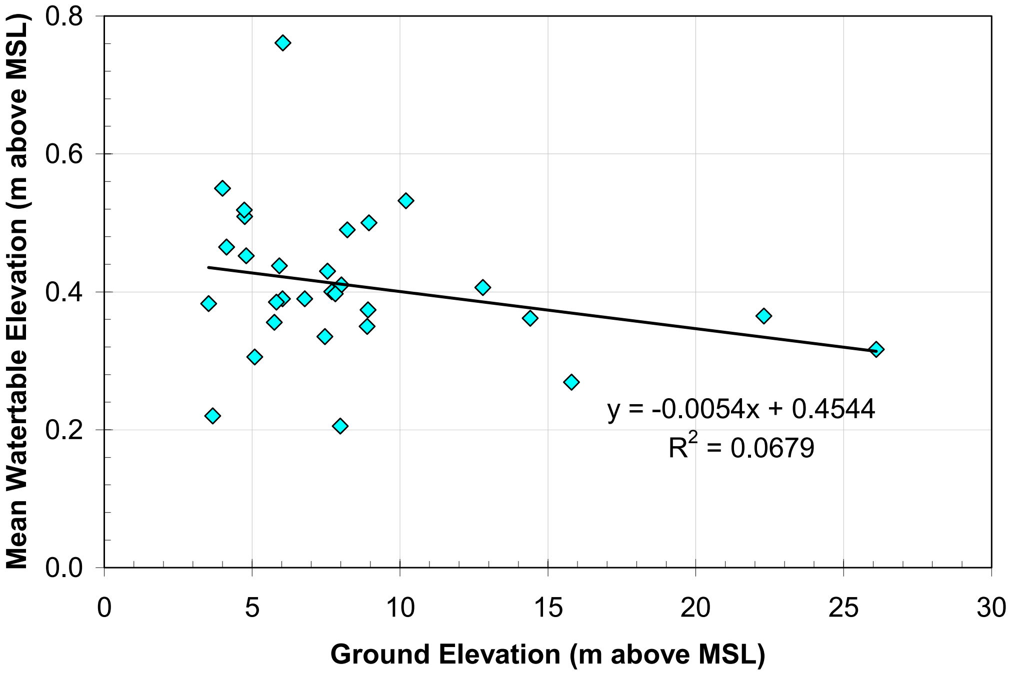

Figure 42 Relationship between mean water table elevation in Tongatapu village wells, averaged over time, on the RL of the well

Analyses were also carried out of the groundwater elevation of 9 individual wells with sufficiently long records of water table elevation. In general, the behaviour of the water table elevation in the individual wells was consistent with that of the mean water table elevation discussed above. Figure 43 and Figure 44 show the corresponding results for the Masilamea village well, well 68, where the correlation with rainfall was strongest for rainfall summed over the previous 4 months.

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[4] Since only monthly rainfall was available for this analysis, watertable measurements made before the 15 th of the month were assigned to the previous month of rainfall while measurements aon or after the 15th were assigned to the same rainall month as the watertable measurement.

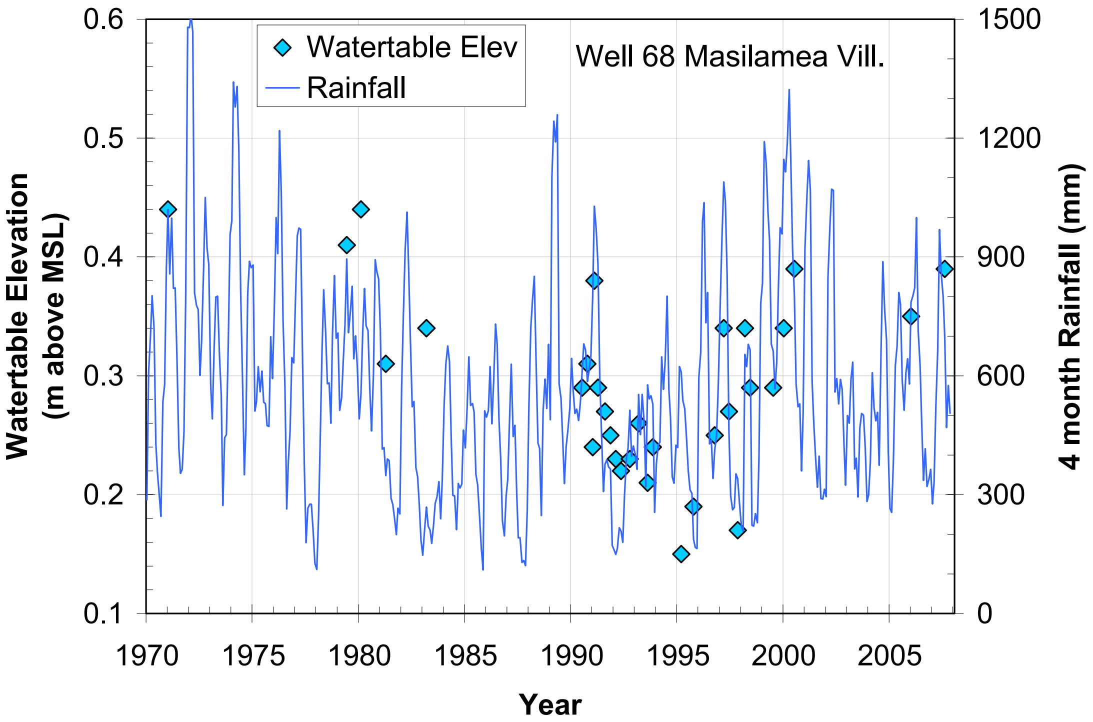

Figure 43 **Temporal changes in mean water table elevation of Masilamea village well 68 compared with rainfall over the previous 4 months, 1971-2007**

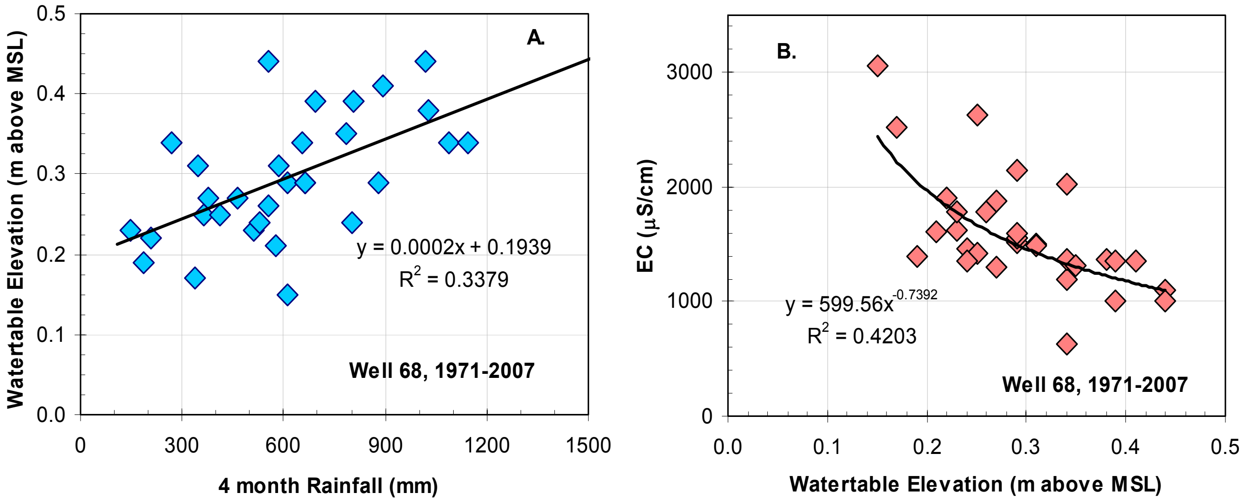

Figure 44 **Relationships between A. water table elevation and rainfall over the previous 4 months and B. EC and the water table elevation for the Masilamea village well 68**

5.8 Groundwater pH

The pH of rainwater in equilibrium with the atmospheric concentration of carbon dioxide (CO_2) is 5.65 at 25°C. For the system of solid calcite in water in equilibrium with air at the global atmospheric CO_2 concentration at one atmosphere pressure, the equilibrium pH is about 8.4 at 25°C. Groundwaters in contact with limestone aquifers can have a range of pH from about 6.5 to 8.4 depending on the concentration of CO_2 in the groundwater and on the dissolution and oxidation of other minerals (Hem, 1992). The pH results for Tongatapu village wells measured in August 2007 and summarised in Table 12 have a mean pH of 7.24 and span the range 6.29 to 7.73. The historic data from the culled MLSNRE database, as summarised in Table 13, have a mean pH of

7.39 and a range from 6.45 to 8.54. These ranges may reflect whether the sample has been taken from wells that are being pumped or from those that are stagnant where pHs would be expected to be closer to the atmospheric equilibrium value around 8.5.

When water percolates through soil, the partial pressure of CO_2 can be 10 to 100 times larger than the normal atmospheric partial pressure because of soil respiration (Hem, 1992). When this recharge water reaches limestone aquifers, calcites dissolve to higher solution concentrations than in equilibrium with atmospheric CO_2 and pH is lower than the atmospheric equilibrium value. If groundwater samples from limestone aquifers are stored, the pH may increase by up to one pH unit due to the precipitation of calcite or the evolution of CO_2 as the sample is stored under atmospheric conditions (Hem, 1992). For that reason, it is important to measure pH in the field at the time of groundwater sampling.

If we assume that the EC of the surface water is partly a reflection of the amount of calcite dissolved in groundwater and partly due to mixing and dispersion with underlying seawater, then we might expect that the groundwater pH may decrease as EC increases. The relation between pH and salinity in the Tongatapu village wells measured on 14th and 15th August 2007 is plotted in Figure 45.

While there is an apparent slight decreasing trend in pH with increasing EC, the R^2 value is very small and indicates the trend is not significant.

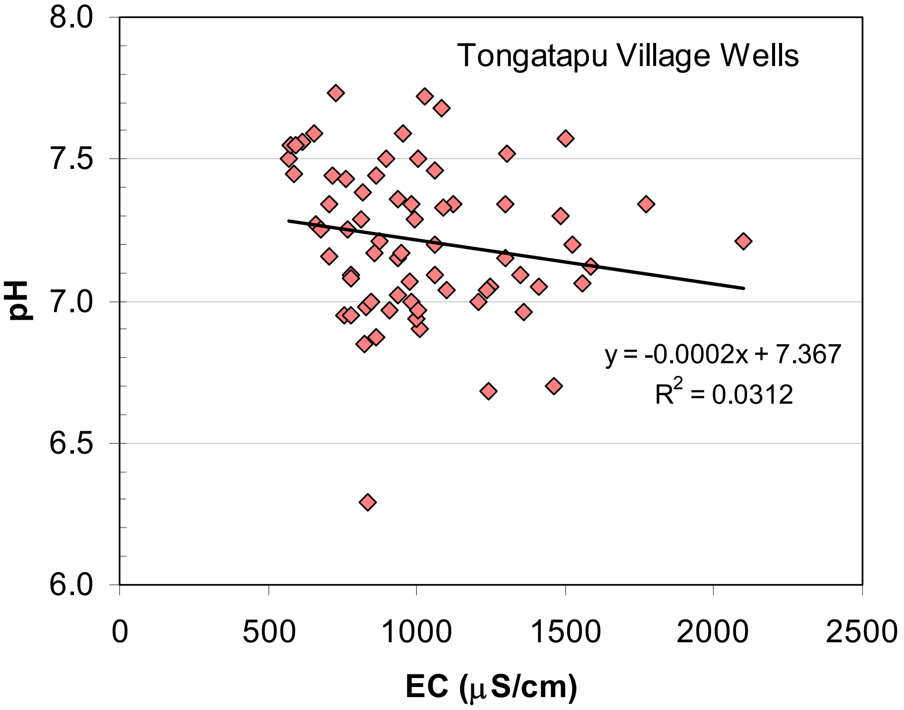

Figure 45 Dependence of pH of Tongatapu village wells on the EC of the wells on 14th and15th August 2007

5.9 Trends in groundwater pH

The culled MLSNRE database lists 1,213 measurements of pH in village wells since 1990 (see Table 13). Figure 46 shows the temporal trend in pH over the period 1990 to 2007. Some measurements in 1992 to 1998 appear high and may point to instrumental problems as does the gap in measurements between 1999 and 2003. The linear trend line indicates a slight decline in pH with time but the very small R^2 value indicates this trend is not significant. Figure 47 shows that there is also an apparent decline in pH with increasing well water EC but again the linear trend is not significant due to the scatter of results.

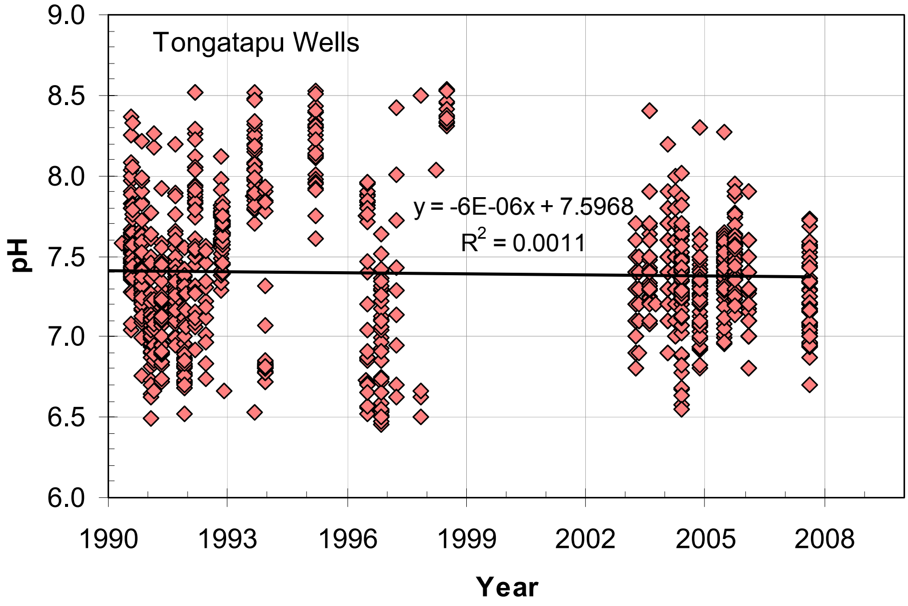

Figure 46 **Temporal trend in the pH of Tongatapu village wells, 1990-2007**

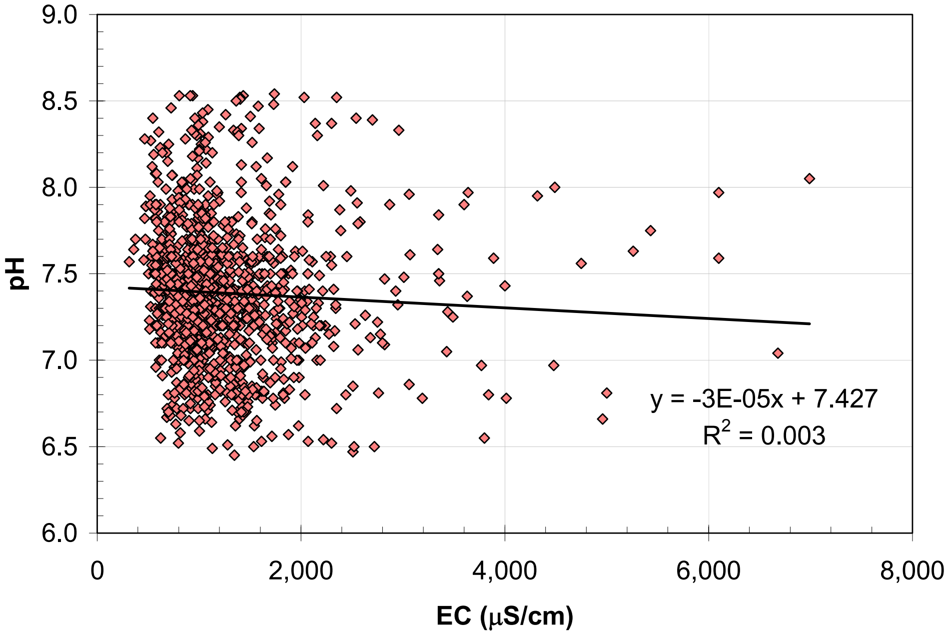

Figure 47 **Dependence of the pH of Tongatapu village well water on EC, 1990-2007**

5.10 Groundwater temperature

The mean groundwater temperature in Tongatapu should be the long-term mean atmospheric temperature. However, its actual value for any particular well will depend on the time of year, and on the depth of the groundwater beneath the surface. It is expected that there will be a gradient in temperature with depth. The mean groundwater temperature of the village wells in August 2007 was 24.1 ± 0.9°C (see Table 12). The gradient in groundwater temperature with depth to groundwater during the August 2007 measurements is plotted in Figure 48, which shows temperature increasing with depth as expected for measurements in the cooler months of the year. It is expected the gradient would be reversed in the warmer months of the year.

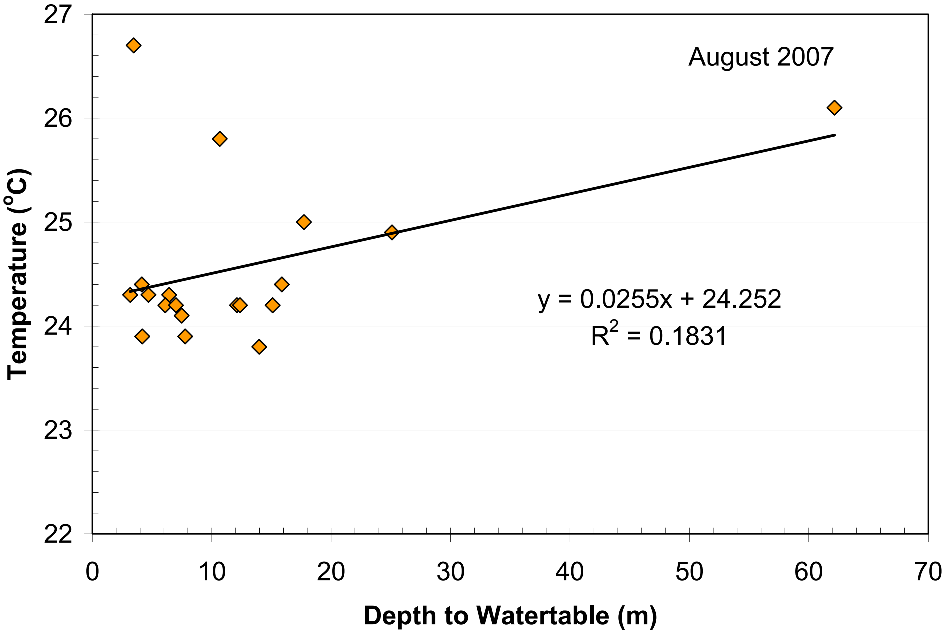

Figure 48 **Dependence of groundwater temperature on depth to water table, Tongatapu village wells, August 2007**

5.11 Trends in groundwater temperature

The MLSNRE database, from which outliers have been removed, lists 1,446 measurements of groundwater temperature in village wells since 1965 (see Table 13). These show a decreasing trend in groundwater temperature with time but with a low R^2 value. This trend, however, may be biased by the very few number of measurements made between 1965 and 1990. Most of the measurements were made since 1990 and Figure 49 shows the temporal trend in groundwater temperature over the period 1965 to 2007.

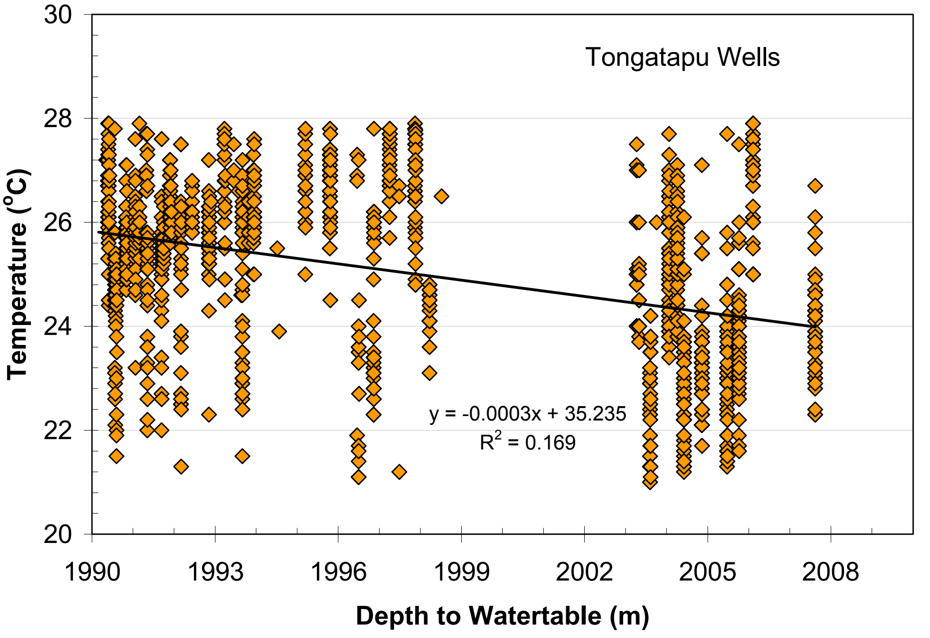

Figure 49 **Trend of groundwater temperature over time since 1990 for Tongatapu village wells**

The decreasing trend in groundwater temperature in Figure 49 is somewhat surprising since it shows a change in mean temperature of about 1.8°C over the 17 years. Examination of the results shows an increased frequency of measurements above 25.5°C in the early to mid 1990s. Since mean air temperatures have not increased by this amount in the same period it must be concluded that the apparent trend in groundwater temperatures in Figure 49 is due to instrumental uncertainties.

The above demonstrates that even with temperature measurements, periodic calibration of field instruments is required as well as their periodic checking against secondary standards.

5.12 Concluding comments and recommendations

The MLSNRE groundwater data base is a valuable record of both the spatial and temporal variability of groundwater properties and particularly salinity. In this project, the data base was analysed and physically impossible or spurious results were culled from the record. By comparing “snap-shot” measurements taken in this project in August 2007 with previous measurements in the culled version of the MSNRE database dating back to 1959 it was possible to summarise both the spatial distribution and trends in time of groundwater properties in village wells across Tongatapu

5.12.1 Spatial distribution and trends in EC

The spatial distribution of groundwater salinity in Tongatapu in August 2007 (Figure 33) is similar in pattern to that last mapped in May 1990 (Figure 6) but the extent of seawater intrusion appears less in August 2007 than in the early 1990s and clearly depends on the preceding rainfall.

Groundwater pumping to reticulated village water supply systems in Tongatapu commenced in 1961 (Furness and Helu, 1993). These authors suggested that the increase in groundwater salinity between 1965 and 1990 was due to increased extraction of groundwater in Tongatapu over this period. While there was no significant trend in the groundwater salinity of the combined individual village wells over the period 1965 to 2007, due to the scatter of data (Figure 34), there was a significant increase in the log mean EC of the village wells between 1965 and 1990 (Figure 35). There is, however, a suggested slight but not significant decrease in salinity between 1990 and 2007 despite an estimated almost 50% increase in groundwater extraction during this time.

Mean groundwater salinity was strongly dependent on rainfall over the preceding months (Figure 36). A simple EC-rainfall model (equation [1]) was fitted to the log mean EC for the period 2000 to 2007. This model predicted quite well previous EC measurements made in the 1980s and some in the early 1990s. It, however, predicted ECs greater than the mean values in 1965 and 1971. This suggests that the measured EC values were lower than those predicted by a model fitted to a period of higher pumping, because of the impact of pumping. The model predicted ECs that were much lower than the log mean of measured values during the period 1994 to1999. Data from 1990 to 1999 were found not to be significantly correlated with rainfall. There appear two possible explanations for this discrepancy. The first is that the high readings and increased scatter of data during the 1990s was due to instrumental problems. The second is that the increased salinity during the 1990s was caused by an increase in groundwater extraction, perhaps due to the irrigation of squash pumpkin.

5.12.2 Water table elevation

The impact of groundwater pumping can also be examined by measuring the elevation groundwater table above MSL. The MLSNRE data base lists groundwater elevation data for 30 village wells from 1971 onwards. The mean groundwater elevation from 1971 to 2007, 0.41 m above MSL is small for such a large small island. Some atolls in the Pacific with widths about 1 km have groundwater elevations of 0.7 m above MSL. This difference reflects the large hydraulic conductivities in the limestone aquifer in Tongatapu. The water table elevation was lower during the dry period from 1992 to 1995 but recovered after that. This is in contrast to the EC data which showed continuing high values during the mid to late 1990s.

The water table elevation data shows considerably variability because of the influence of rainwater recharge and tidal fluctuations as well as uncertainties over the RLs of the well. The long-term mean elevation for all village wells, 0.41 ± 0.18 m above MSL, agreed with the predictions of Hunt (1979) and there was no significant change in mean groundwater elevation in Tongatapu over the period 1971 to 2007 (Figure 39 and Figure 40). The groundwater elevation of both individual wells and the mean of all wells depended on previous rainfall, as expected, and groundwater EC correspondingly decreased as water table elevation increased. It was noticed that while groundwater EC appeared to depend on previous rainfall over the preceding 19 months, groundwater elevation showed a faster response to rainfall over only the last three to four months.

Groundwater elevation should depend on the distance of the groundwater from the sea. We used the RL of the well as an approximate surrogate of distance from the sea. The expected increase in water table elevation with RL of the well was not observed. This could be due to inaccuracies in the RL measurements. It is concluded that, within the scatter of data, no significant impact of groundwater pumping on groundwater elevation can be identified.

5.12.3 Groundwater pH

The groundwater pH data of village wells, measured since 1990, scatters over the range expected for waters in equilibrium with limestone aquifers. Values range from those for calcite in equilibrium with atmospheric carbon dioxide, around 8.5, to those in equilibrium with higher concentrations of carbon dioxide, around 6.5, presumably from recharge waters rich in CO_2. The actual values obtained will depend on whether the water is sampled from a well that is being pumped and whether the sample is exposed to the atmosphere for a significant length of time prior to sampling. The groundwater pH shows no significant trend with time. Both the “snap shot” measurements carried out in this project and the measurements recorded in the database suggest the pH may decrease with increasing salinity (EC) of the groundwater.

It is unclear what use can be made of the pH values of groundwater from the limestone aquifer in Tongatapu since samples may range anywhere from 6.5 to 8.5 depending on length of time of exposure of the sample to the air.

5.12.4 Groundwater temperature

The factors which control groundwater temperature are well known. The long-term mean groundwater temperature from 1965 to 2007, 24.9 °C (see Table 12) should equal the mean atmospheric temperature in Tongatapu. Analysis of the trend in groundwater temperature since 1990, when most of the measurements were conducted reveals a decrease in mean groundwater temperature of about 1.8 °C between 1990 and 2007. This seems highly unlikely and may be due to instrumental calibration problems.

As with groundwater pH it is unclear what use is to be made of the groundwater temperature data. If it is a check on global warming then instruments will have to be calibrated regularly against a known temperature standard.

5.12.5 Unresolved questions

The measurements and analyses carried out in this section have raised several unresolved questions. The EC data reveal that the groundwater salinity of Tongatapu village wells in the period 1965 to 1971 was lower than recent measurements. The difference does not appear to be due to differences in rainfall patterns and it is tentatively concluded that this is due to the impact of increased pumping over the period. Salinity data in the mid-1990s was significantly higher than expected from rainfall. It is unclear whether this is due to instrumental error or to increased groundwater extraction during this period. Somewhat surprisingly, the EC data was best correlated with long periods of previous rainfall.

Mean water table elevations for Tongatapu have a surprisingly low value of 0.41 m above MSL for such a large “small” island and suggest large hydraulic conductivity of the aquifer. Within the scatter of measurements, there is no significant trend in groundwater elevation with time over the period 1971 to 2007. Water table elevation was correlated with previous rainfall, although here the best correlation with mean groundwater elevation was with rainfall over the previous three months, much shorter than the period found for best correlation with EC measurement. The mean groundwater elevation did not show the expected increase with increasing RL of the wells. It is unclear whether this is due to the accuracy of the measurements of RL and water table depth.

The pH of groundwater appears to slightly decrease with increasing groundwater salinity as expected.

There appears to have been a decrease in groundwater temperature of about 1.8°C since 1990. One possible explanation for this is uncalibrated instruments.

We shall return to these questions when we examine groundwater at the Mataki'eua/Tongamai wellfield and at the Tapuhia Waste Management Facility.

5.12.6 Recommendations on data collection, storage and analysis

The data base maintained by the Geology Section of MLSNRE is an extremely valuable aid to the management and conservation of Tongatapu's groundwater resources. It, however, requires maintenance, analysis and above all the analysis of data needs to reported regularly to government. Despite the removal of outliers, the database still contains a number of anomalies and evidence of mis-transcribed data, erroneous and conflicting records and data giving physically impossible values. Analysis of the data has also suffered because of the irregular frequency of measurement and significant hydrological events such as the droughts in the 1980s where there were no measurements.

- It is strongly recommended that field monitoring of groundwater properties throughout be carried out at regular intervals of 3 months.
- It is recommended that as soon as data is collected it is entered into the database and compared with previous measurements.
- It is recommended that the database be critically analysed well by well to clean up the errors.
- It is strongly recommended that MLSNRE prepare an annual report based on analysis of the data base for presentation to government.
- The closest distance between individual wells and the sea or the lagoon should be recorded in the database.
- Several critical issues need to be addressed. These include the reason for the measurement, the use of the measurement and its reliability.
- When the reasons and use for the data have been identified, an analysis of data should be carried out to address these issues.
- Full analysis of data should be carried out annually and a report on the analysis presented to the appropriate authority.
- Confusion over the exact location of individual wells needs to be removed by geo-referencing and labelling wells and the database needs to be updated.
- Wells used for measuring water table depth, need to have the reference point for depth measurement accurately surveyed in relative to current mean sea level and to have the point marked clearly. This is needed so that the elevation of the water table in wells can be evaluated with precision. Groundwater elevation is one of the critical measures in the draft 2006 Water Resources Legislation.
- Instruments for measuring groundwater salinity, temperature and pH need to be calibrated against known standards prior to each field sortie.
- The data base contains no information about the volume of groundwater extracted each year in Tongatapu, efforts should be made to include estimates of groundwater extraction.
- Continuous logging of water table fluctuations in selected wells where water table elevation can be measured should be carried out over several months to a year to determine the tidal influence and groundwater recharge influence on water table elevation.

6 Measurements at the TWB Mataki'eua/Tongamai Wellfield

6.1 Outline

The Tonga Water Board's Mataki'eua/Tongamai wellfield is the most intensively pumped region in Tongatapu and supplies reticulated water to Nuku'alofa, the main population centre. This section describes measurements of groundwater salinity (EC), pH, temperature and water table fluctuations carried out during this project in July and August 2007. It then contrasts these measurements with previous measurements carried out at the wellfield and recorded in the TWB database.

6.2 Groundwater salinity, July-August 2007

Some of the boreholes at the Mataki'eua/Tongamai wellfield were not operating during our visit. Other pumps had no sample valves and it was not possible to obtain a groundwater sample. In some non-operational wells a sample was bailed from the well. In total, it was possible to measure the EC, pH and temperature of 31 of the 39 wells at the Mataki'eua/Tongamai wellfield. The statistics of the measurements are listed in Table 18. On average the water table is approximately 13 m below ground level. The EC of the groundwater has an almost 3-fold variation between maximum and minimum, less than that found for the entire island of Tongatapu (Table 12). The mean EC is slightly less than the mean EC of the whole island. The temperature and pH statistics are similar to those of the whole island and also show smaller variation than the EC. The distribution of salinity across the wellfield is shown in Figure 50.

Table 18 Field measurements statistics for 31 wells and boreholes at the Mataki'eua/Tongamai wellfield, July-August 2007

Statistic	Depth to water table (m)	EC (µS/cm)	Temp (°C)	pH
Mean	**13.59**	**961**	**23.5**	**7.06**
Standard Deviation	3.80	270	0.9	0.39
CV (%)	28.0	28.1	3.9	5.5
Median	12.74	890	23.7	6.99
Maximum	21.87	1,818	24.9	8.33[†]
Minimum	8.11	656	20.6	6.51
No. of measurements	39	No. sampled		31

[†] The maximum pH value was found with residual water stagnant in a non pumped pipeline.

It is clear that there is a decreasing gradient in salinity away from the southeast portion of the Mataki'eua/Tongamai wellfield. This area of the wellfield lies closest to Fanga'uta Lagoon. Figure 51 shows the relationship between groundwater salinity in individual pump stations in the wellfield and distance from the Lagoon. There is a strong inverse relationship with a correlation coefficient (R) of 0.65.

The data in Figure 51 is approximately fitted by the equation:

$$EC = 2034 \big/ D^{0.764} \qquad [3]$$

where D is the distance (km) to the lagoon.

Equation [3] predicts that water pumped continuously from vertical wells within 0.76 km of the lagoon would exceed the salinity EC guideline of 2,500 µS/cm. Figure 33 shows that this limit is reached in the north-western Hihifo peninsula and north-eastern region around Kolonga at distances from the sea around 0.75 km.

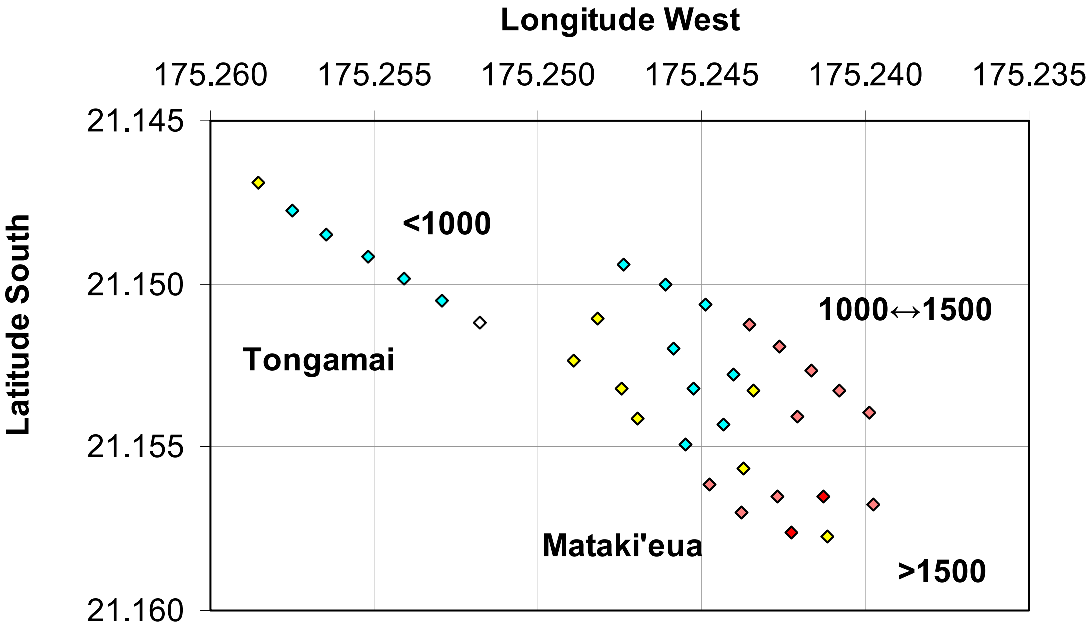

Figure 50 Distribution of salinity at the Mataki'eua/Tongamai wellfield

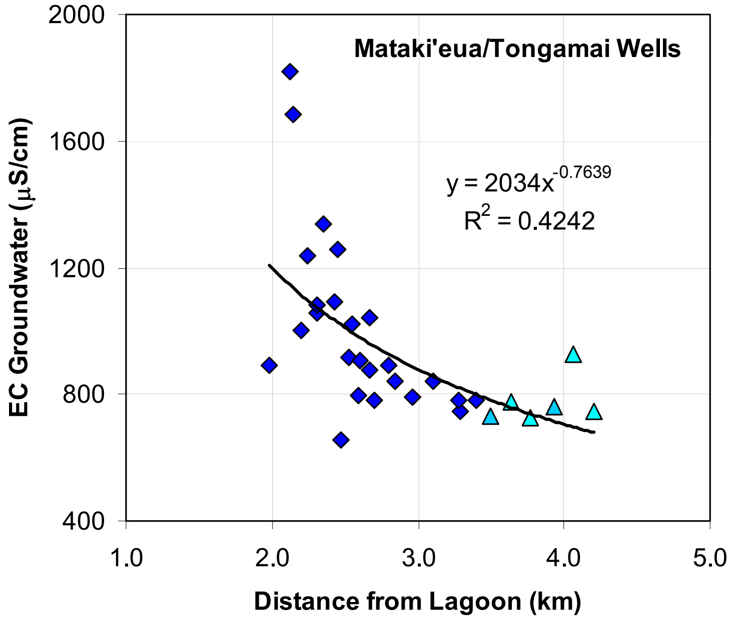

Figure 51 Relationship between EC of individual pumping wells at the Mataki'eua/Tongamai wellfield and distance from the well to Fanga'uta Lagoon. Wells in the Tongamai area are shown as light blue triangles.

This prediction does not mean that there is no thin freshwater lens in this 0.76 km region. Shallow, horizontal infiltration galleries installed in this region may be able to sustainably extract water whose salinity is below the nominal limit. Equation [3] is relevant to vertical wells penetrating through the groundwater by 2 m and pumping 24 hours per day, as at Mataki'eua/Tongamai. It predicts that such a well would extract water with an EC exceeding 2,500 μS/cm if it is within 0.76 km of marine waters. It may be that the groundwater salinity distribution map in Figure 33, determined using samples from vertical wells, may need to be modified to reflect the fact that pumped vertical wells penetrating the groundwater by 2 m located close to the coast usually produce water whose salinity exceeds the salinity limit because of upconing of the underlying freshwater/seawater interface.

6.3 Groundwater salinity profiles across Mataki'eua/Tongamai

The results of the measurements of salinity profiles on 8th August 2008 through the freshwater lens at the Mataki'eua/Tongamai wellfield using the salinity monitoring boreholes (SMBs) (Figure 20) are given in Annex I. Figure 52 shows the measured EC profiles and the freshwater limit of 2500 µS/cm.

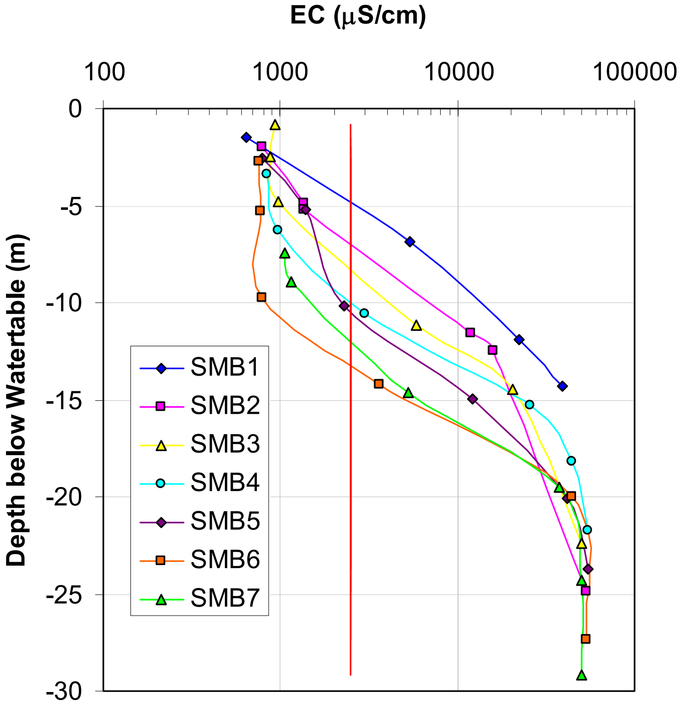

Figure 52 Profiles of EC measured through the freshwater lens at SMBs in and around the Mataki'eua/Tongamai wellfield on 8th August 2007. Also shown is the freshwater limit (red line).

There is considerable variation in the salinity profiles within and around the wellfield. There are four factors that can influence the thickness of the freshwater lens: distance from seawater; the amount of recent recharge; the amount of water abstraction; and the local hydrogeology (and therefore hydraulic conductivity) of the aquifer. The data in Figure 52 can be used to determine the spatial distribution of the thickness of the freshwater lens at the SMBs which is listed in Table 19 and plotted in Figure 53 as a function of the distance from SMB to the nearest seawater.

It is clear from Figure 53 that there is no simple relationship between the thickness of the freshwater lens and distance to the nearest seawater. If the data is grouped, as in Figure 53, into SMBs within the influence of the wellfield (SMB1, 2 and 3)[5], those SMBs that border onto the wellfield (SMB4 and 5) and those that are external to the wellfield (SMB6 and 7) then a pattern appears to emerge. The grouped values in Figure 53 suggest that the continuous extraction from the Mataki'eua wellfield is decreasing the thickness of the freshwater lens by between 3 and 5 m compared with locations removed from the wellfield. The possibility, however, that these differences are due to local differences in hydrogeology of the aquifer cannot be ruled out. Additional SMBs across Tongatapu are required to further investigate this vital issue.

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[5] SMB1 is not within the wellfield, however, it lies immediately downgradient of the whole Mataki'eua wellfield.

Table 19 **Thickness of freshwater in the SMBs in and around the Mataki'eua/Tongamai wellfield, August 2007**

SMB No.	Distance from Seawater (m)	Thickness of Freshwater (m)
SMB1	830	5.6
SMB2	1,886	7.2
SMB7	2,076	12.2
SMB3	2,479	8.4
SMB5	2,650	10.5
SMB4	2,824	10.2
SMB6	4,208	13.3
Mean		**9.6**
Std Dev		2.7

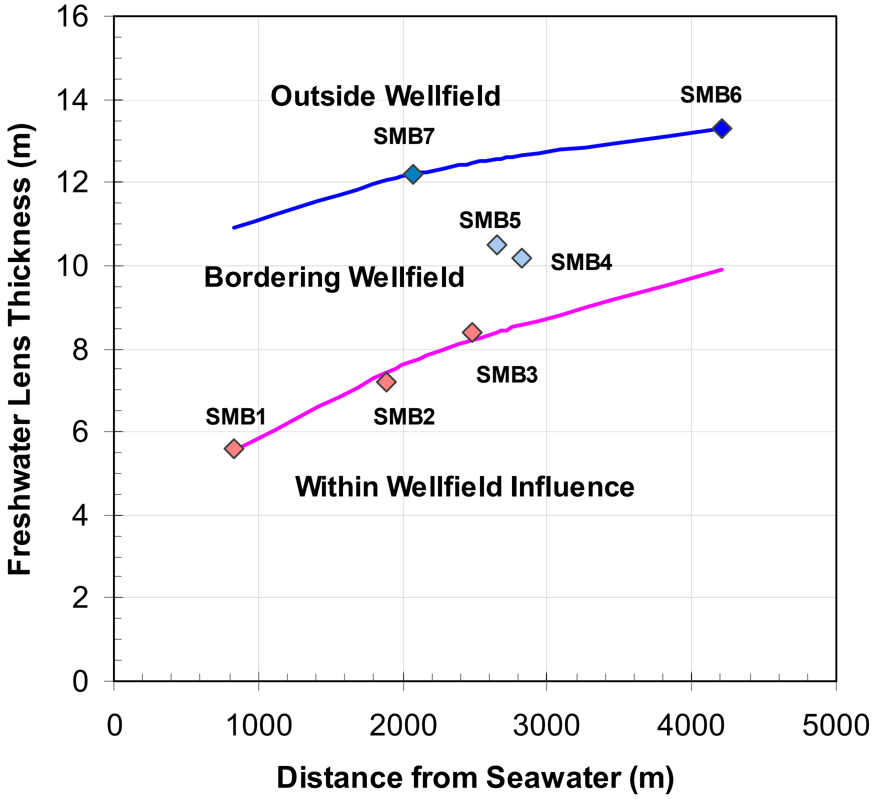


Figure 53 **The relation between thickness of freshwater in the salinity monitoring boreholes at Mataki'eua/Tongamai and distance from the nearest seawater**

6.4 Relationship between pH and salinity

The results from the village wells suggested that the pH of the groundwater may decrease as EC of the groundwater increases (sections 5.8 and 5.9). The relationship between pH and salinity in the TWB wells at Mataki'eua/Tongamai measured in July and August 2007 is plotted in Figure 54.

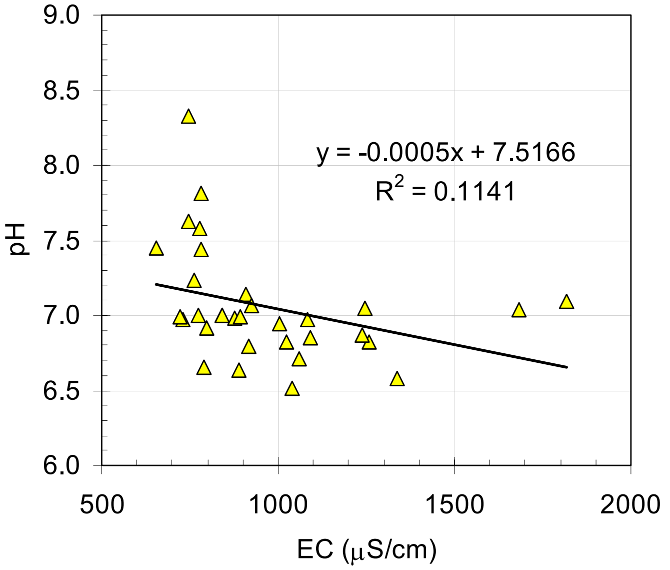


Figure 54 **Relationship between pH and EC for Mataki'eua/Tongamai wells sampled in July and August 2007**

There appears to be an overall slight decrease in the pH of the groundwaters in Tongatapu as salinity increases. However the trendline shown in Figure 54 for the Mataki'eua/Tongamai wells is not significant due to the scatter of results. The preponderance of measurements lie between 6.5 and 7.8 but one value in Tongamai of 8.33 was almost equal to the atmospheric equilibrium value. This sample came from residual stagnant water in the pipe coming from a well where the pump had failed. It also had a relatively low EC which may have been due to the precipitation of calcite. The difference between the mean pH of the village wells and that of the Mataki'eua/Tongamai wells is not significant.

6.5 Groundwater level and salinity logging at Mataki'eua well 117

Just prior to the placement of the groundwater logger into well 117, 94.4 mm of rain fell at Nuku'alofa. During the well logging period from 2nd to 17th August 2007 a further 34 mm of rain was recorded at Nuku'alofa, including 20.9 mm rainfall on 12th August (Figure 55). Table 20 gives the statistics of the water table elevation, groundwater salinity (EC) and temperature measured during the logging period.

Table 20 **Statistics from well logging at Mataki'eua well 117**

Statistic	Water table elevation (m above MSL)	EC (μS/cm)	Temp[†] (°C)
Mean	**0.556**	**723**	**24.99**
Standard deviation	0.033	13	0.01
CV (%)	5.9	1.8	0.04
Median	0.544	723	24.99
Maximum	0.645	796	25.08
Minimum	0.515	608	24.98
No. of Measurements	2,157		

[†] The groundwater logger was at a higher temperatures (around 26.6 °C) when first inserted in the well. It took approximately 65 minutes to cool down to groundwater temperature. The data recorded during the cooling-down phase was removed.

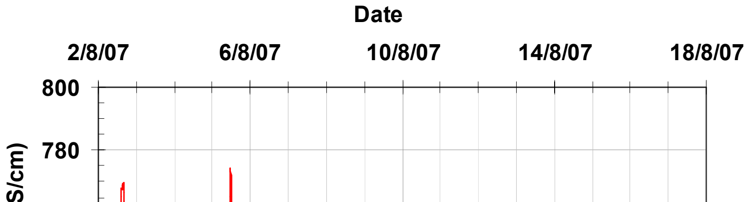


Figure 55 Record of groundwater EC (11 point moving average) and water table elevation at Mataki'eua well 117 and rainfall at Nuku'alofa for the period 2nd -17th August 2007

To estimate the tidal elevation we have assumed that the reference point used for depth measurement was at the RL of the well listed in Table 7. The maximum changes in the water table elevation, groundwater EC and temperature over the logging period were 0.13 m, 0.1 C and 188 μS/cm. The mean water table elevation, 0.556 m above MSL, is higher than the mean for village wells of 0.41 m (Table 17). The mean temperature of the groundwater in well 117 is about 0.9°C higher that that found in the August 2007 sampling of the village wells (Table 12) but is almost identical within error to the long term mean for village wells in Tongatapu (Table 13). It is noted that different instruments had been used for the measurements at well 117 (Greenspan CTD350 logger) and at the village wells (Solinst TLC meter) which may have caused the difference in mean temperatures of 0.9°C in August 2007. Neither instrument had been calibrated for temperature except in factory.

The continuous records of EC and water table elevation during the monitoring period are shown in Figure 55. The smoothed EC (11 point moving average) has three major peaks which appear due to the switching off and on of the electric submersible pump. The smaller diurnal variations correlate well with the tidal fluctuation of the groundwater which has a maximum tidal range of only 24 mm. The water table elevation fell by approximately 100 mm between the 2nd and 11th August. This decline appears to be due to groundwater discharge at the edge of the island due to the 94.4 mm rainfall event on 1st August, before the logger was installed.

When the tidal fluctuations in the water table elevation are smoothed using an approximately 24.5 hour (163 point) moving average, as in Figure 56, the response to rainfall can be seen more clearly. Firstly, the total of 6.7 mm rain which fell on 7th and 8th August caused a change in the rate of decline of the water table following the large rainfall on 1st August, equivalent to a rise in the water table of about 20 mm. Secondly, the 21.6 mm of rain recorded on 11th and 12th August 2007 caused an approximately 7 mm rise in water table. The difference in response is presumably due to the drying of the overlying soil in the period between rainfalls.

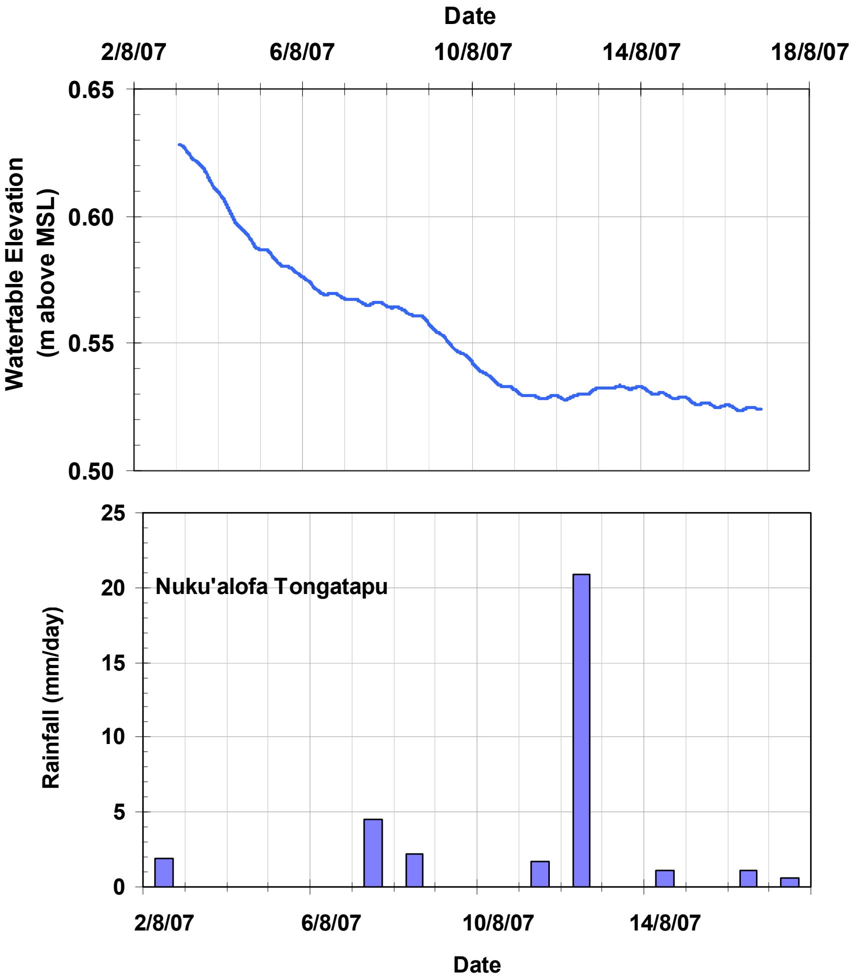


Figure 56 Smoothed (169 pt moving average) of the water table elevation at Mataki'eua well 117 showing the response to rainfall

If we assume that the 6.7 mm rainfall fell on a soil profile that was close to saturation then the porosity of the limestone aquifer is close to 0.3, a reasonable estimate. This means that the 7 mm rise following the 21.6 mm rainfall is equivalent to a recharge of about 2.1 mm, implying that 19.5 mm of rainfall was evapotranspired. This suggests that the evapotranspiration rate for the 4 days between rainfalls averaged 5 mm/day, a reasonable estimate.

The tidal efficiencies and lags estimated from the groundwater elevation fluctuations and the predicted tidal range for Nuku'alofa (National Tidal Facility, www.bom.com.au) are listed in Table 21. The mean tidal range over the period, 1.2 m, only produced a mean groundwater level change of 17 mm with a mean tidal efficiency of 1.5%. This suggests that the vertical hydraulic conductivity of the aquifer through which the tidal pressure signal is transmitted to the water table is relatively small.

6.6 Water table drawdown due to pumping

A test of the impact of pumping on the water table drawdown in well 117 was carried out on the 2nd August 2007 by monitoring the change in water table elevation when the pump was switched off at 16:33 and also when it was switched on at 16:40.

Table 21 Estimated tidal efficiencies and lags for well 117 for 2nd - 17th August 2007

Statistic	Sea level Low (m)	Sea level High (m)	Groundwater Low (m)	Groundwater High (m)	Tidal Efficiency (%)	Tidal Lag for Lows (hrs:mins)	Tidal Lag for Highs (hrs:mins)
Mean	**0.32**	**1.52**	**0.65**	**0.67**	**1.45**	**4:54**	**4:15**
Std Dev	0.05	0.06	0.02	0.02	0.39	0.02	0.01
CV (%)	15.6	3.7	3.6	3.3	27.3	9.4	7.3
Median	0.33	1.54	0.65	0.67	1.28	0.21	0.17
Maximum	0.41	1.56	0.69	0.71	2.14	0.23	0.20
Minimum	0.24	1.4	0.63	0.64	1.00	0.17	0.16

Simultaneous measurements of drawdown where conducted both manually and automatically using the well logger. Figure 57 shows the manually measured small rebound of the water table when the pump was switched off and then showing a drawdown of only 10 mm when pumping recommenced.

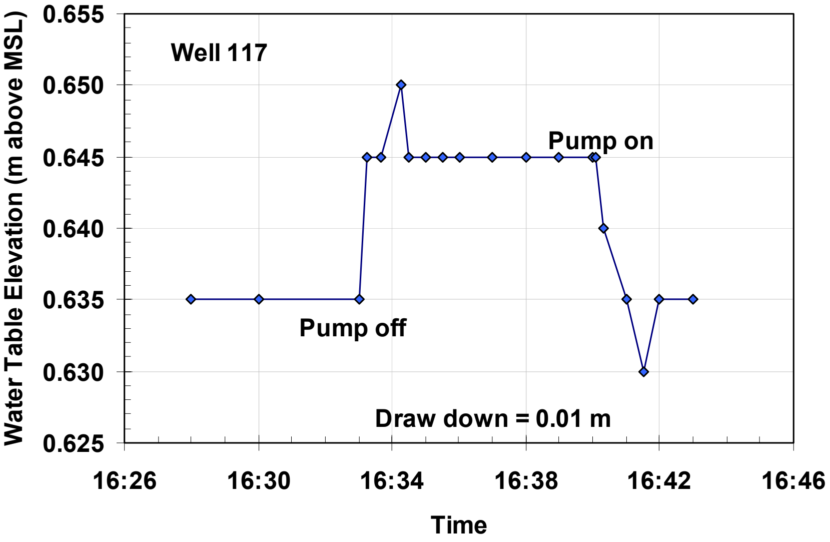


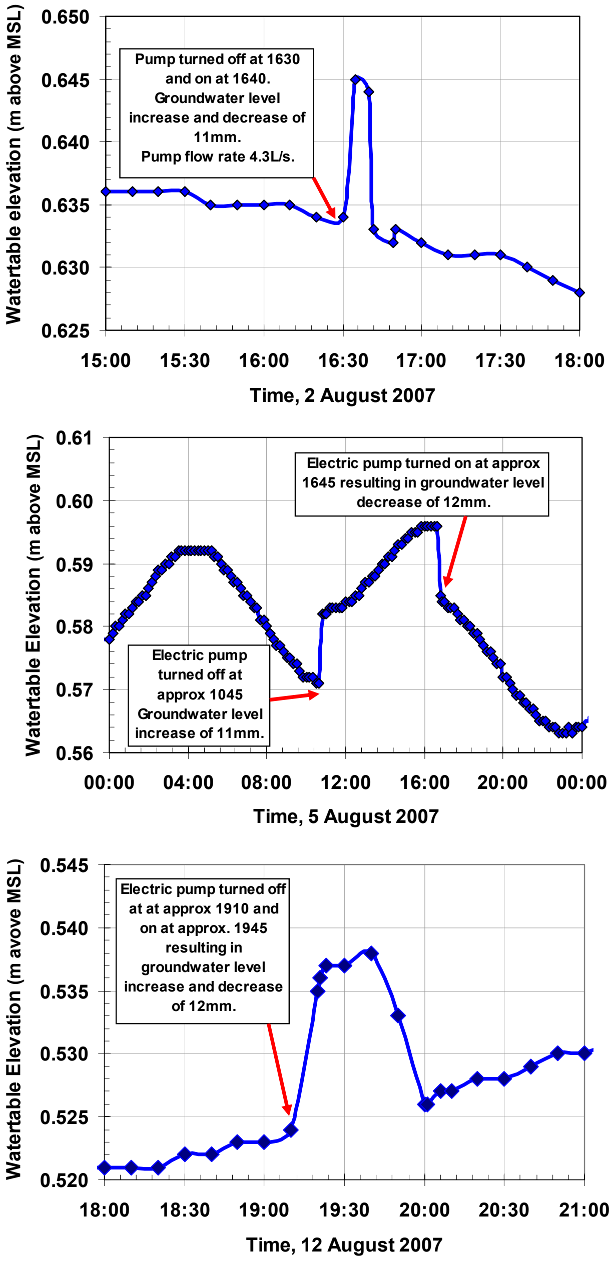
Figure 57 Manually measured rebound and drawdown of the water table elevation when the pump at Mataki'eua well 117 was switched off and on 2nd August 2007

The overshooting of the groundwater elevation when the pump is turned off and again when it is turned on is typical in groundwater systems and appears to be a hydraulic pressure reflection within the well.

Examination of the water table and EC record from the well logger also shows that the pump had been turned off (cause(s) unknown) at two other times during continuous logging of data on both the 5th and 12th August. Figure 58 shows the rebound and drawdown of the water table due to the switching off and on of the electric submersible pump, pumping at 4.3 L/s. Table 22 lists the measured rebounds and drawdowns and mean of all measurements, 11.5 ± 0.4 mm, again a very small drawdown. This drawdown is close to the manually measured value in Figure 58 reflecting the large horizontal hydraulic conductivity of the limestone aquifer and the diameter of the well (approximately 1 m).

Table 22 **Measured rebound and drawdown of the water table due to switching off and on the pump at Mataki'eua well 117**

Date	Water table Rebound (mm)	Water table Drawdown (mm)
2nd August 2007	11	11
5th August 2007	11	12
12th August 2007	12	12
Mean	**11.5**	
Std Dev	0.4	



Pump turned off at 1630 and on at 1640. Groundwater level increase and decrease of 11mm. Pump flow rate 4.3L/s.

Electric pump turned on at approx 1645 resulting in groundwater level decrease of 12mm.

Electric pump turned off at approx 1045 Groundwater level increase of 11mm.

Electric pump turned off at at approx 1910 and on at approx. 1945 resulting in groundwater level increase and decrease of 12mm.

Figure 58 **Rebound and drawdown of the water table measured by the well logger due to switching off and on the pump in well 117on 2nd, 5th and 15th August 2007**

6.7 Estimation of aquifer horizontal hydraulic conductivity

In the drawdown tests described in section 6.6, the water table responded rapidly to the switching on and off of the pump. Therefore, to a first approximation, we can use a simple steady state analysis to estimate the horizontal hydraulic conductivity, K, of the aquifer. For pumping rate Q, the hydraulic conductivity is given by (Smith and Wheatcraft, 1993)[6]:

$$K = \frac{Q}{2\pi\, L\, \Delta h_w} \ln\left(\frac{L}{r_w}\right) \qquad [4]$$

where L is the length of the well over which water is being extracted, Δh_w is the drawdown and r_w is the radius of the well. Here Q = 376 m^3/day, $L \approx 2$ m, $r_w = 0.5$ m, and $\Delta h_w = 0.0115$ m (Table 22). With these values, equation [4] suggests that $K \approx 3{,}600$ m/day. Hunt (1979), in his finite element study of groundwater in Tongatapu, assumed a value for K of almost 1,300 m/day. Falkland (1992) quotes values in the range 500 to 3,000 m/day with values of 1,500 to 2,000 m/day required to calibrate groundwater models.

6.8 Trends in groundwater salinity

The salinity (EC) data used in this analysis of the trend in EC came from the TWB database MATWELLS.XLS. Sporadic measurements of EC of groundwater pumped from wells in Mataki'eua date back to November 1966. Measurement frequency increased after August 1990 and became almost monthly after September 1995. Measurements from additional bores in the Tongamai section of the bore field commenced after September 1997, again at an almost monthly frequency. This data set represents one of the most comprehensive island groundwater salinity data sets available.

Two situations were analysed. In the first, the log means of measured EC data from the Mataki'eua/Tongamai wells were examined. In order to register a log mean EC value, the ECs from at least 10 wells were required so that a representative mean could be obtained. The EC data used in the second case came from measured EC values for water pumped from a single well, well 106, in Mataki'eua. This was chosen because it is one of the oldest wells, it shows a significant variation in EC and lies in a more saline region (1000<EC<1500 μS/cm) of the wellfield (Figure 50).

The mean of the 146 log mean EC values for the wellfield over the period November 1966 to August 2007 is 1,029±146 μS/cm, about 7% higher than the mean value for the July-August 2007 measurements at the wellfield in Table 18. The temporal trend in log mean EC data for the Mataki'eua/Tongamai wellfield from 1966 to 2007 is plotted in Figure 59A and the trends for the two periods 1966 to 1990 and 1990 to 2007 are shown Figure 59B. There is no significant overall trend with time flat for all the log mean data from 1966 to 2007. It can be seen in Figure 59B, however, that when the data is split into two periods a significant increasing trend is apparent from 1966 to 1990 followed by a decreasing trend from 1990 to 2007. The trend line coefficients and values of R^2 for both periods and the overall trend are given in Table 23.

While the value of R^2 for the period 1966 to 1990 in Table 23 for the Mataki'eua/Tongamai wells is not as large as that found for the village wells throughout Tongatapu in Table 16 (20.5 μS/cm/y), the trend coefficients and patterns are similar. In the period 1966 to 1990, the log mean EC increased and while in the period 1990 to 2007, a decrease in log mean EC occurred. There was no significant trend in log mean EC over the whole period, 1966 to 2007. As with the village wells, the question remains: is this caused by changes in the rainfall pattern?

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[6] Eqn [4] assumes that $L >> 2r_w$. Here $L \approx 4r_w$ and so the K calculated here is clearly approximate.

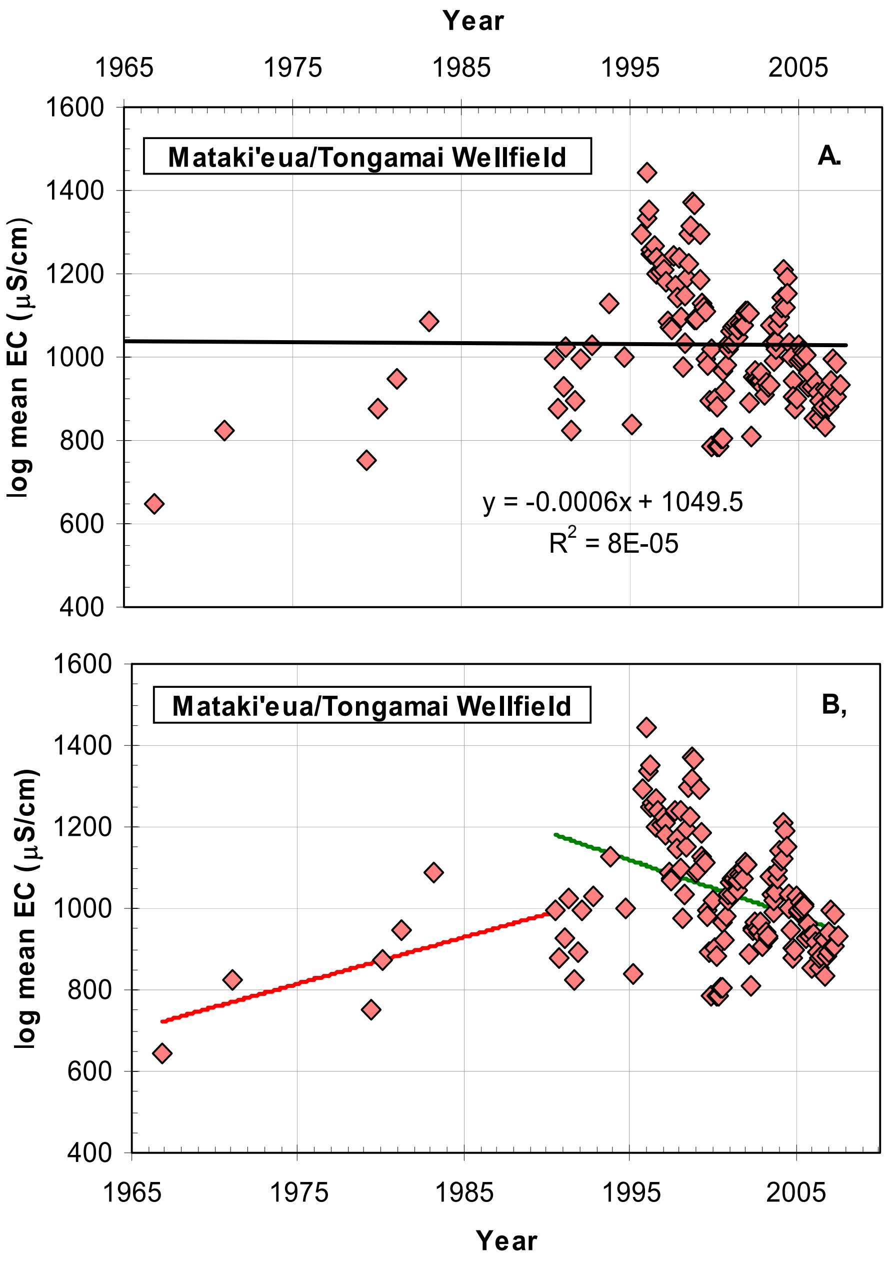

Figure 59 Temporal trend of log mean EC for Mataki'eua/Tongamai wells for the periods A. 1966-2007 and B. 1966-1990 and 1990-2007

Table 23 Trends in log mean EC for Mataki'eua/Tongamai wells for 2 periods between 1966 and 2007

Period	Linear Trend (µS/cm/year)	Intercept (µS/cm)	R^2
1966-1990	11.4	-39	0.473
1990-2007	-13.7	2,425	0.153
1966-2007	-0.2	1,050	8×10^{-5}

6.9 Trends in groundwater salinity of Mataki'eua well 106

The mean EC of the 145 measurements for Mataki'eua well 106 at from March 1971 to July 2007 was 1,160 ± 260 µS/cm. This is about 13% higher than the mean of the log means for all wells considered in the previous section. The standard deviation is about 80% higher than for all wells considered, indicating larger salinity variations at well 106. The overall trend in salinity in well 106 since 1971 is plotted in Figure 60A.

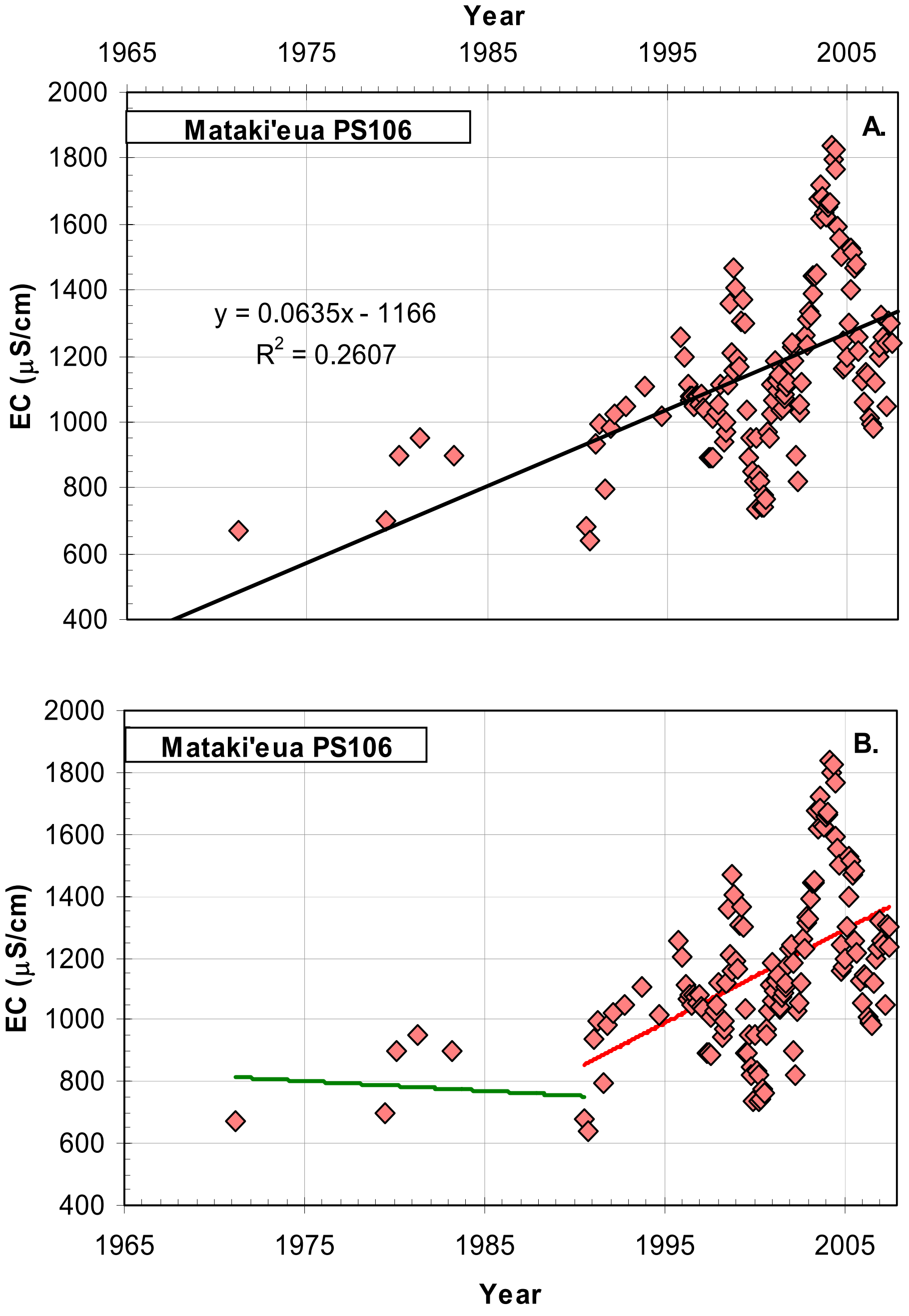

Figure 60 **Temporal trend of EC for Mataki'eua well 106 for the periods A. 1966-2007 and B. 1966-1990 and 1990-2007**

The linear increasing trend in EC has a correlation coefficient of 0.51. When the trends for the period 1971-1990 and 1990-2007 (Figure 60B) are examined, however, it is found that there is a slight decrease in the EC linear trend between 1971 and 1990 and a significant increase between 1990 and 2007. The trend line coefficients and values of R^2 for both periods and the overall trend are given in Table 24.

Table 24 Trends in EC for Mataki'eua well 106 for 2 periods between 1971 and 2007

Period	Linear Trend (μS/cm/year)	Intercept (μS/cm)	R^2
1971-1990	-3.2	1,040	0.027
1990-2007	30.1	-1,873	0.223
1971-2007	23.2	-1,166	0.261

The trend line behaviour for well 106 in Figure 60 and Table 24 differs from that for the log mean EC for the combined wells at the Mataki'eua/Tongamai wellfield (Figure 59 and Table 23) and for the log mean EC trends for village wells in Tongatapu (Figure 35 and Table 16). There is an overall increasing trend in EC in well 106 and that appears to have occurred mostly since 1990. An examination is now made of the influence of rainfall on the EC of wells at Mataki'eua/Tongamai.

6.10 Rainfall and groundwater salinity

As discussed in section 5.5, one possible reason for the trends in EC of the Mataki'eua/Tongamai wells listed in Table 24 could be different rainfall patterns and amounts over the period 1971 to 1990 and 1990 to 2007. To investigate this, the relation between rainfall and log mean EC was investigated for a limited time range of the complete record. The period chosen was from March 2002 to August 2007. The smallest number of wells measured in this period was 12 and the maximum number was 35. This is a period when groundwater pumping was at a maximum at the wellfield.

It was found that the negative correlation between EC and previous rainfall was a maximum if rainfall was summed over the previous 16 months. Figure 61 shows the relation between log mean EC and rainfall in the previous 16 months for the period 2002 to 2007 and Figure 62 shows the dependence of the correlation coefficient on the number of previous months of rainfall.

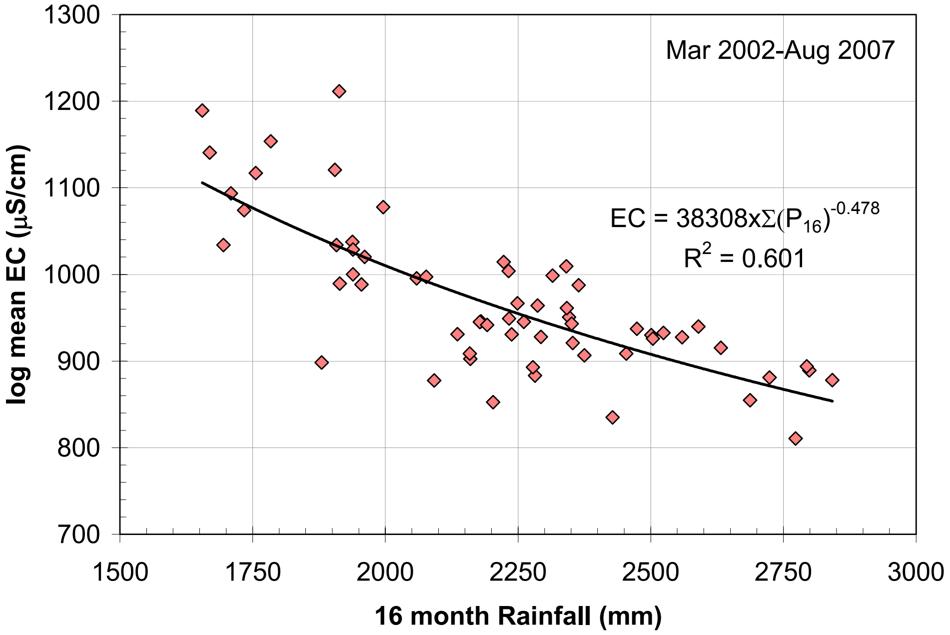

Figure 61 Relation between log mean EC of groundwater at the Mataki'eua/Tongamai wellfield and previous rainfall over the past 16 months

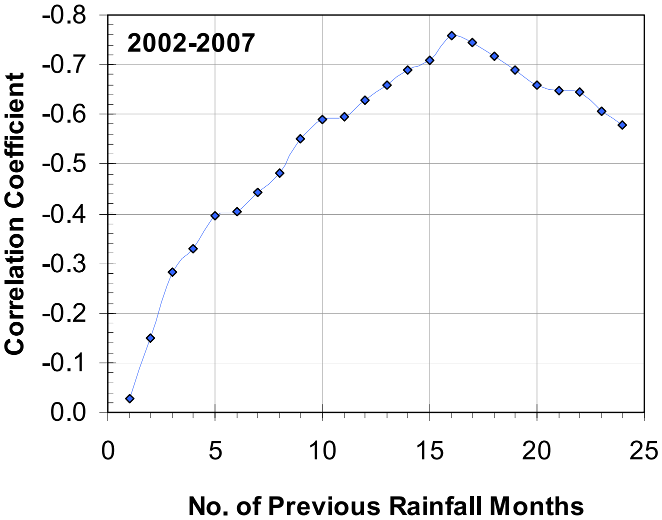

Figure 62 The relation between the correlation coefficient between log mean EC at the Mataki'eua/Tongamai wellfield and rainfall and the number of previous months of rainfall for the period 2002-2007

The correlation between log mean *EC* (in μS/cm) and rainfall over the previous 16 months, $\left(\sum_{i=1}^{16} P_i\right)$ (in mm) is reasonable with an $R^2 = 0.601$and follows the relation:

$$EC = 38308 \times \left(\sum_{i=1}^{16} P_i\right)^{-0.478} \qquad [5]$$

The similarity between the coefficients in equations [1] and [5], particularly the exponents, can be seen. Equation [5] can be used to predict the salinity at other times over the historic record of EC at the Mataki'eua/Tongamai wellfield. This prediction is shown in Figure 63.

Equation [5] can be seen to predict reasonably well the measured log mean EC for the period 1971 to the end of 1994. The initial measurement in 1966 falls well below the predictions. For most of the period 1995 to 1999 and from September 2000 to January 2002 the predictions under-estimate the log mean EC. This is similar to the findings for village wells throughout Tongatapu in section 5.5. It was also found for Mataki'eua/Tongamai wells that the correlation between log mean EC and rainfall for the period 1990 to 1999 was relatively poor, as in Figure 38, but the correlation for the period April 1996 to May 2000 was reasonably good and can be fitted, using rainfall over the previous 19 months to the equation:

$$EC = 70577 \times \left(\sum_{i=1}^{19} P_i\right)^{-0.524} \qquad [6]$$

with $R^2 = 0.668$. Although the exponents in equations [5] and [6] are similar, the number of months over which previous rainfall is summed is greater as is the leading constant in equation [6]. As shown in Figure 63, equation [6] over estimates the log mean EC in the periods 1966 to 1996 and 2003 to 2007.

The results for log mean EC at the Mataki'eua/Tongamai wellfield seem similar to those for the village wells (section 5.5). The earliest measurements in 1966 fall well below that expected from a relationship between rainfall and salinity based on current pumping. The measurements in the period 1995 to 2000 appear to be greater than expected from the relationship derived for the period 2002 to 2007. This could possibly be due to averaging the results of all wells so an examination was made of the results from one well, well 106.

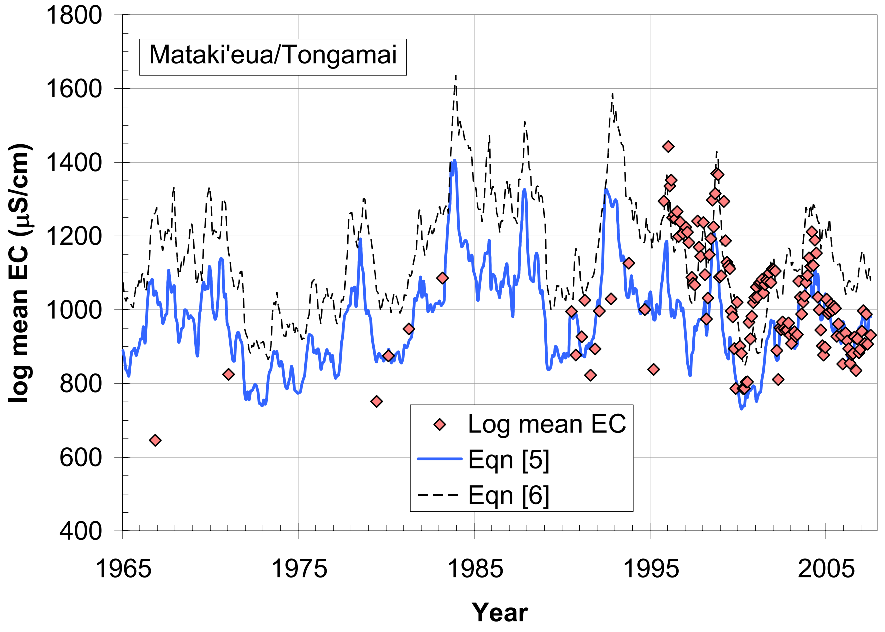

Figure 63 **Comparison between the log mean EC at the Mataki'eua/Tongamai wellfield and that predicted from equations [5] and [6]**

6.11 Rainfall and groundwater salinity in Mataki'eua well 106

To investigate the impact of differing rainfall patterns of the groundwater salinity in a single well, the relationship between rainfall and EC was investigated for a limited time range of the complete record. The period chosen was from January 2000 to August 2007. This is a period when groundwater pumping was at a maximum.

It was found for this period that the negative correlation between EC and previous rainfall was a maximum if rainfall was summed over the previous 16 months. Figure 64 shows the relation between the EC of the well and rainfall in the previous 16 months for the period 2000-2007.

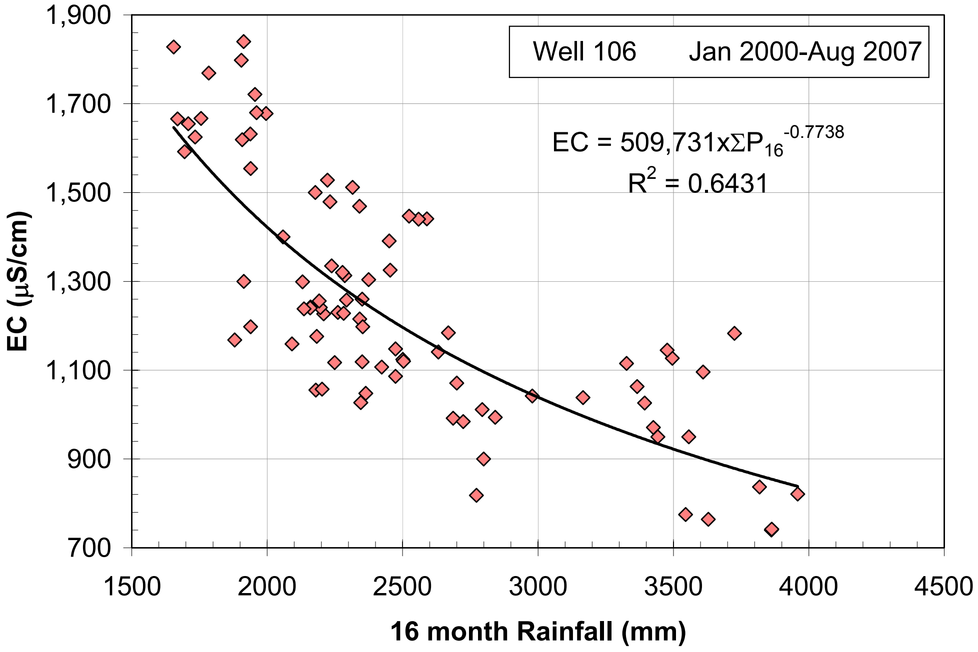

Figure 64 **Relation between the measured EC of Mataki'eua well 106 and previous rainfall over the past 16 months**

The correlation between EC (in μS/cm) and rainfall over the previous 16 months, $\left(\sum_{i=1}^{16} P_i\right)$ (in mm), is reasonable with an $R^2 = 0.643$ and follows the relation:

$$EC = 509731 \times \left(\sum_{i=1}^{16} P_i\right)^{-0.774} \qquad [7]$$

The coefficients in equation [7] are much higher than those in equations [1], [5], and [6]. Equation [7] can be used to predict the EC of well 106 from the rainfall at other times over the record. The predicted and measured EC are compared in Figure 65.

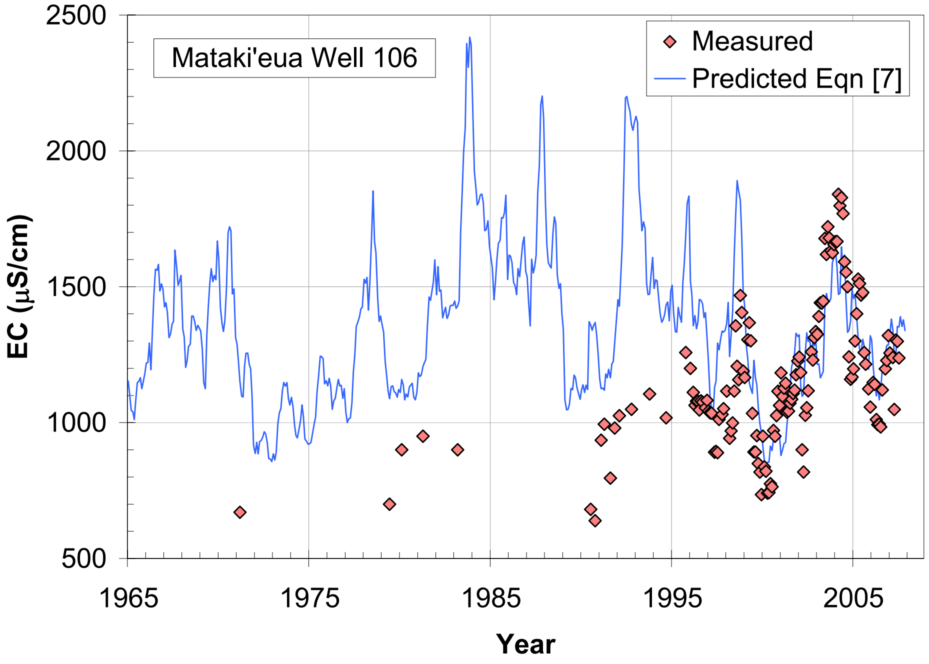

Figure 65 Comparison between the measured EC at Mataki'eua well 106 and that predicted from equation [7]

Figure 65 shows that equation [7] over-estimates the EC in the period 1971-1998, suggesting that the increasing trend in salinity in Figure 60 is not due to differing rainfall patterns.

The correlation between EC and rainfall for the period March 1995 to December 1999 was reasonably good and fitted the equation:

$$EC = 211003 \times \left(\sum_{i=1}^{19} P_i\right)^{-0.673} \qquad [8]$$

with $R^2 = 0.668$. Again, the 19 months over which previous rainfall is summed is greater than the 16 for the period 2000-7 as it was for the log mean data. The constants in equation [8] are smaller than in equation [7]. It can be seen here that well 106 behaves quite differently to the log mean behaviour for the whole wellfield.

6.12 Comparison of groundwater salinity at Mataki'eua/Tongamai and village wells

The log mean EC of the Tongatapu village wells has a similar relationship to rainfall to that for the log mean EC at Mataki'eua/Tongamai wells. Figure 66 shows the temporal relation between these log means ECs. For the periods 1966 to 1990 and 2000 to 2007, the two log mean ECs are in quite good agreement with the log mean EC for village wells being only on average 2.8% greater than that for Mataki'eua/Tongamai wells (see Figure 67). For the periods 1990 to 1997, the village well EC data are on average 24.5% greater than the Mataki'eua/Tongamai well EC data but some lie well above this (Figure 67). It can be argued that the wells sampled in the village well data set have a wider range of salinity that at the Mataki'eua/Tongamai wells and it might be expected that mean EC values would diverge during dry periods. The reason for the higher EC values in village wells than at the Mataki'eua/Tongamai wells during the mid-1990s warrants further analysis.

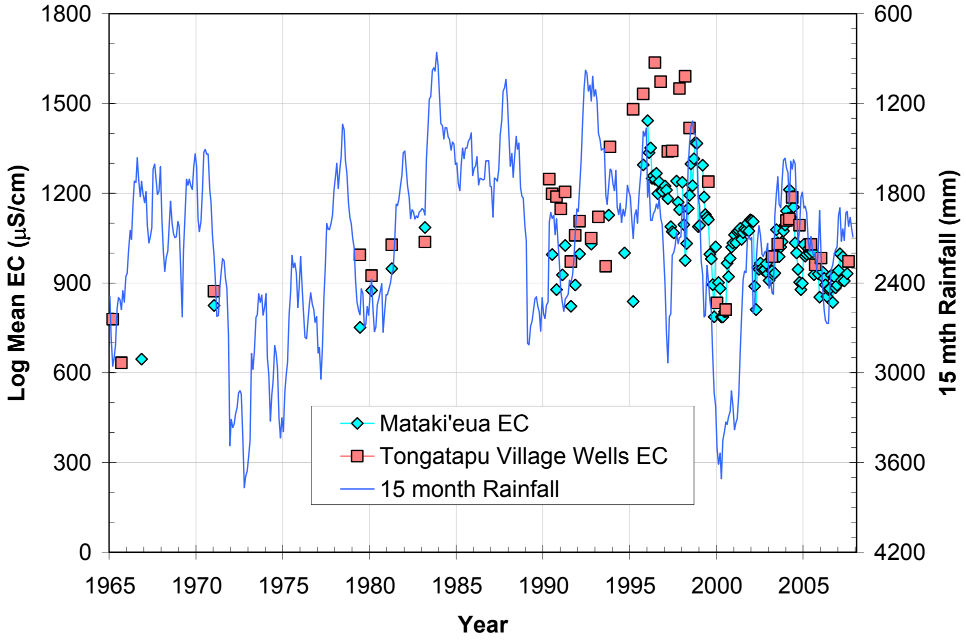

Figure 66 Comparison between the log mean EC of Tongatapu village wells and that of the Mataki'eua/Tongamai wellfield. Also shown is rainfall over the previous 15 months (plotted in reverse order).

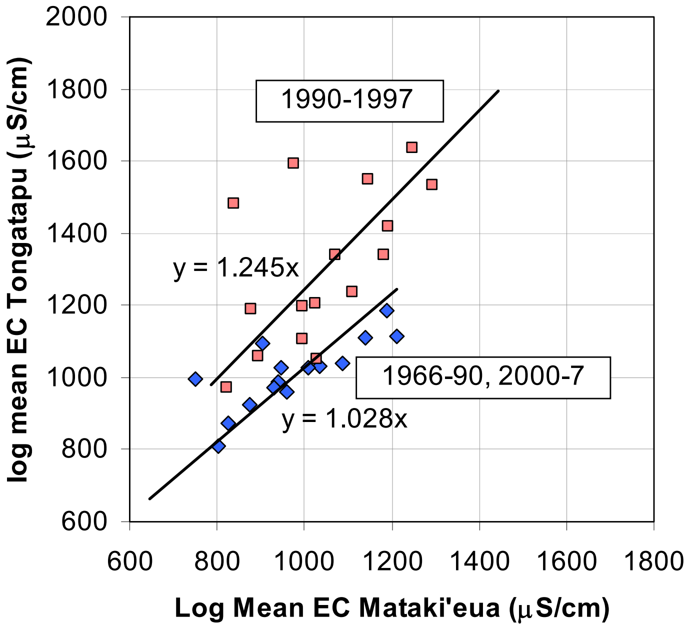

Figure 67 Relationships between the log mean ECs for Tongatapu village wells with that of the Mataki'eua/Tongamai wellfield for two different time periods

6.13 Impact of pumping on groundwater salinity

A critical issue in the management of the Mataki’eua/Tongamai wellfield is the influence of pumping on the salinity of the pumped groundwater. As we have seen in sections 6.8 to 6.11, that question is complicated by the variation in EC with variation in rainfall.

The supply of piped groundwater to Nuku’alofa commenced in 1966 from five hand-dug wells at Mataki’eua. By 1971, eight wells were operating (Furness and Helu, 1993) and by 1991, 31 dug and drilled wells had been installed at Mataki’eua and Tongamai. It has been estimated that in March 1991, 22 wells were operating with a combined production rate of 5.3 ML/day. From April to November 1995, the average combined production rate was 5.8 ML/day (Falkland, 1995). In August 2007, the estimated groundwater pumping rate was 8 ML/day. There has, therefore, been a 50% increase in groundwater pumping since 1991. The estimated groundwater pumping rates are listed in Table 25 and plotted in Figure 68.

Table 25 Estimated pumping rates and mean ECs at Mataki’eua/Tongamai wellfield

Year	No. Pumps operating	Pumping Rate (L/s)	Pumping Rate (ML/day)	Estimated log mean EC (μS/cm)	Estimated EC well 106 (μS/cm)
1966	5	15	1.30	646	
1968	6	18	1.56	670	
1971	8	24	2.07	825	670
1991	20	60	5.30	917	926
1995	22	66	5.80	1,145	1,259
1998	26	78	6.80	1,195	1,175
2007	31	93	8.04	948	1,231

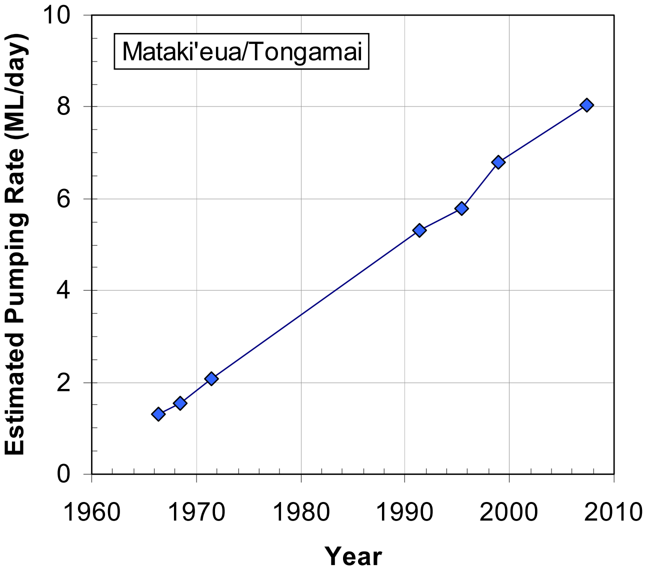

Figure 68 Estimated increase in pumping rate from the Mataki’eua/Tongamai wellfield

Although the increases in pumping rates in Figure 68 clearly occurred in an approximately stepwise progression, the overall trend appears as a linear increase in pumping rate with time. Table 25 summarises estimated pumping rates and log mean EC for groundwater at Mataki’eua/Tongamai for the years with pumping data. This enables the relationship between log mean EC and the pumping rate at Mataki’eua/Tongamai to be established (Figure 69).

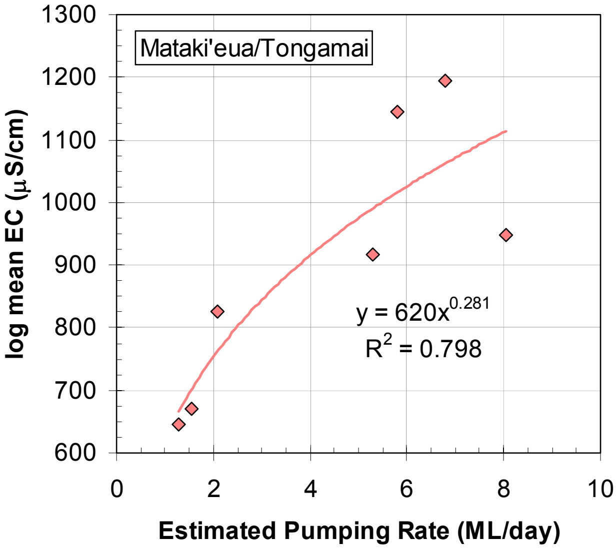

Figure 69 **Relationship between log mean EC of groundwater and the groundwater pumping rate at Mataki'eua/Tongamai wellfield**

The pumping rate, Q (ML/day), can be represented as the simple linear equation (with $R^2 = 0.998$):

$$Q = 4.514\times10^{-4}\times t_{1900} - 9.708 \qquad [9]$$

where t_{1900} is the number of days since 1st January 1900. The relation between log mean EC, $\overline{EC}_{\ln}(Q)$, on pumping rate, Q, can be fitted to ($R^2 = 0.798$):

$$\overline{EC}_{\ln}(Q) = 620\times Q^{0.281} \qquad [10]$$

Together, equations [9] and [10] give us a method of removing the trend in the log mean EC due to pumping by estimating a residual log mean EC, $\Delta\overline{EC}_{\ln}$ from the measured log mean EC, $\overline{EC}_{\ln}$,

$$\Delta\overline{EC}_{ln} = \overline{EC}_{ln} - \overline{EC}_{ln}(Q) = \overline{EC}_{ln} - 620\times\left[4.514\times10^{-4}\times t_{1900} - 9.708\right]^{0.281} \qquad [11]$$

If pumping is the cause of the trends in log mean EC discussed in section 6.8, then it is expected that the residual log mean ECs calculated using equation [11] should fluctuate about zero due to rainfall variations but have no significant trend with time. Figure 70 shows that this is indeed so for the period 1966 to the end of 1994, but not for the period 1995 to 2007 where the residual log mean EC decreases significantly with time despite an almost 41% increase in pumping rate over that time. The results in section 6.10 show that this decrease is not due to a marked change in rainfall.

It is concluded that the increasing trend in log mean EC of groundwater at the Mataki'eua/Tongamai wellfield between the start of systematic pumping operations in 1966 until the end of 1994 is due to pumping. The unexpected decreasing trend in mean salinity between 1995 and 2007 is not due to pumping since that has increased by nearly 41% in the period. Several suggestions can be advanced:

- Instrumental errors (this seems unlikely);
- Increased pumping in neighbouring areas perhaps for irrigation purposes during the late 1990s;
- Increased rainfall inputs to groundwater through the bottom of quarries neighbouring the wellfield in the period after 2000; and
- Introduction of lower salinity groundwater from the Tongamai section of the wellfield when five wells commenced operation in October-November 1997, a further two wells in September-October 2001 and a further four wells in February 2003.

The reason for the decline in the residual log mean groundwater EC at the wellfield is uncertain although the last point above appears to offer a rational explanation and is the most likely.

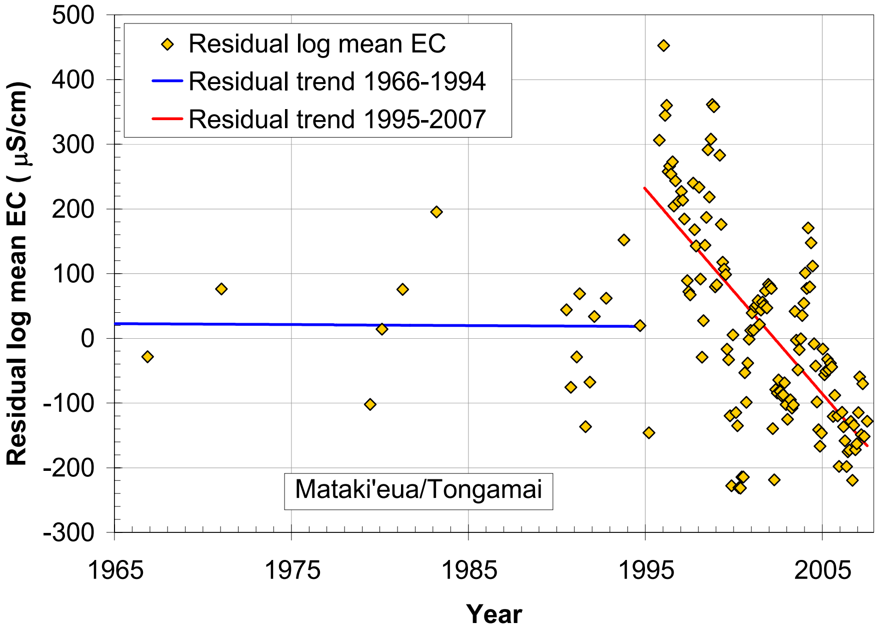

Figure 70 Residual log mean EC after the dependence of log mean EC on pumping rate has been removed (equation [11]) and the residual trends for 1966-1994 and 1995 to 2007

6.14 Impact of pumping on groundwater salinity of Mataki’eua well 106

Unlike the log mean data, Mataki’eua well 106 was found in section 6.9 to have an increasing salinity trend from 1971 to 2007 which was mostly attributable to a significant trend from 1990 to 2007. While the pumping rate from this individual well has probably remained reasonably constant since its installation, groundwater pumping in its neighbourhood has increased markedly since 1971. Well 106 lies in a more saline region (1000<EC<1500 µS/cm) of the wellfield (Figure 50), and it is expected that this region should demonstrate some impacts of pumping on groundwater salinity.

Table 25 also lists the mean EC for well 106 for the period 1971-2007 and these give a steeper dependence of EC on pumping rate, $EC(Q)$, (Figure 71) which can be represented by ($R^2 = 0.874$):

$$EC(Q) = 474 \times Q^{0.472} \qquad [12]$$

Again equations [9] and [12] provide a method of removing the trend in the EC of well 106 due to pumping, giving a residual EC, ΔEC from the measured EC, EC,

$$\Delta EC = EC - EC(Q) = EC - 474 \times \left(4.514 \times 10^{-4} \times t_{1900} - 9.708\right)^{0.472} \qquad [13]$$

Again, if pumping is the cause of the trends in EC of well 106 discussed in section 6.9, then it is expected that the residual ECs calculated using equation [13] should fluctuate about zero due to rainfall variations but have no significant trend with time. Figure 72 shows the trends in for the period 1971 to the end of 1994 ($R^2 = 0.104$), and for the period 1995 to 2007 ($R^2 = 0.071$). Neither of these linear trends or that for the total period 1971-2007 ($R^2 = 0.042$) are significant so that removing the trend due to pumping has removed the trends observed in Figure 60.

Figure 72 also shows the predicted variation in ΔEC due to rainfall estimated by fitting the residual data for 2002-2007 to rainfall over the previous 16 months ($R^2 = 0.874$). Apart from the data from 1990-1995, which appear to be problematic, the predictions fit reasonably well ($R^2 = 0.62$).

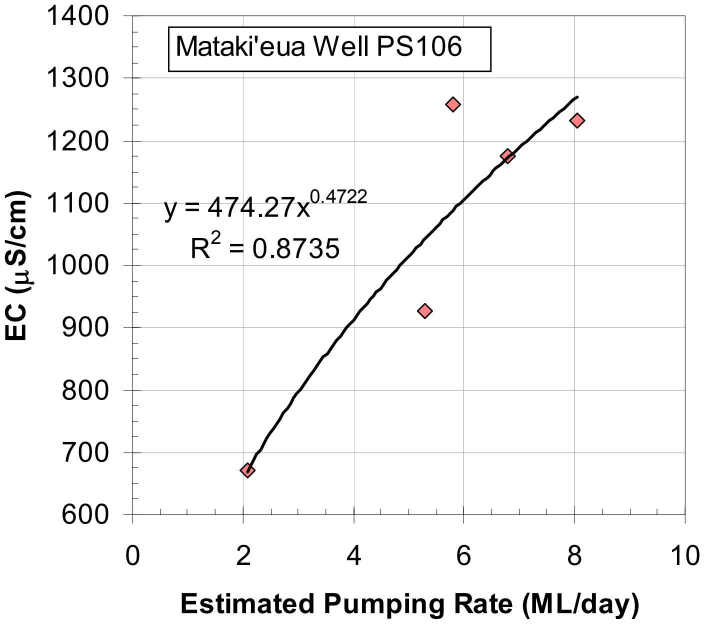

Figure 71 **Dependence of the EC of Mataki'eua well 106 on groundwater pumping rate from the Mataki'eua/Tongamai wellfield**

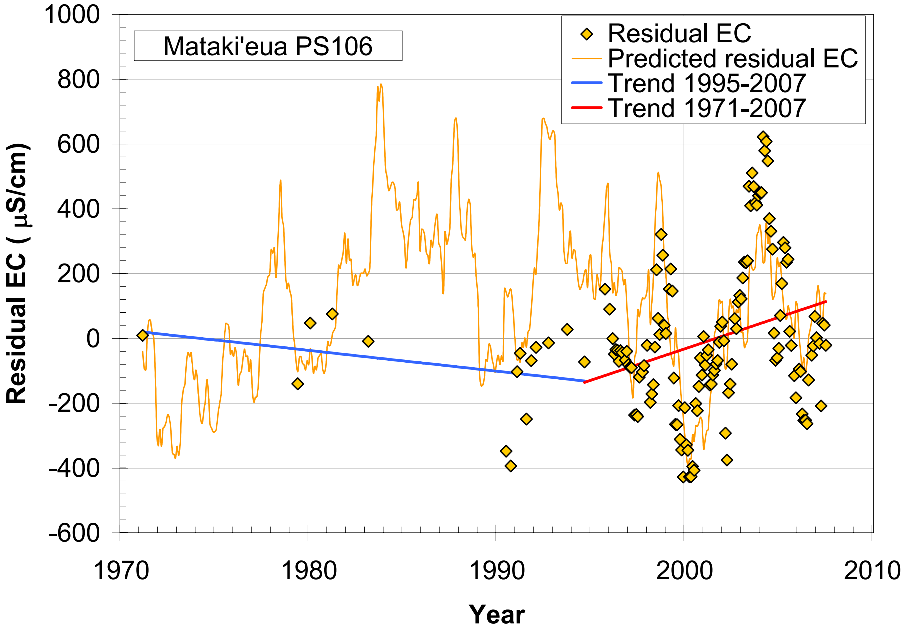

Figure 72 **Residual EC after the dependence of EC on pumping rate has been removed (equation [13]) and the trends in residual EC for 1966-1994 and 1995-2007. Also shown is the predicted residual EC estimating by fitting the data for 2002-2007.**

It is concluded here that the long-term increasing trend in groundwater salinity at Mataki'eua well 106 is due to the impact of pumping and it is recommended that the trends in all wells should be examined.

6.15 Estimated impacts of increased pumping

Under a loan scheme from Denmark, the TWB intends to install further wells in the Tongamai section of the wellfield to bring the total number of wells up to 60. It is intended to have up to 45 wells operating at any one time. We can use equations [10] and [12] to estimate the impacts of increased pumping on the salinity of the pumped water (Table 26). Two possible pump rates per well, 2.5 L/s (low) and 3 L/s (high), are assumed.

Table 26 Estimated impacts of increased pumping at Mataki'eua on the log mean EC of the wellfield and on the EC of well 106

No. Pumps operating	Low Pumping Rate (ML/day)	High Pumping Rate (ML/day)	Estimated log mean EC (μS/cm)		Estimated EC well 106 (μS/cm)	
			Low Rate	High Rate	Low Rate	High Rate
32	6.9	8.3	1,067	1,123	1,181	1,287
45	9.7	11.7	1,175	1,236	1,387	1,512
60	13.0	15.6	1,274	1,341	1,589	1,732

The results in Table 26 suggest that if 45 pumps are operating at Mataki'eua/Tongamai the log mean EC of extracted groundwater may increase by 10% while the EC of groundwater from well 106 may increase by nearly 18%. If all 60 pumps operate the log mean EC may increase by over 19% while the EC of water from well 106 may increase by nearly 35%.

It is emphasised that these estimates of increased salinity are dependent on the functional form assumed to fit the relation between EC and pumping rate. Had a linear fit been used in equations [10] and [12], larger expected increases in salinity due to increased pumping would have resulted. The power-law fits in equations [10] and [12] are somewhat conservative. The results here clearly indicate that increased pumping at Mataki'eua/Tongamai will result in increased salinity of the extracted groundwater. It may be worthwhile considering other groundwater sources, such as the area around Fua'amotu International Airport and Liahona, as alternative water supply sources for Nuku'alofa.

6.16 Concluding comments and recommendations

The TWB data base for the Mataki'eua/Tongamai wellfield, which supplies water to Tongatapu's main population centre, Nuku'alofa, is one of the most extensive records in any Pacific island countries. We have compared the "snap-shot" of measurements taken in this project in July and August 2007 with an analysis of measurements in the TWB database dating back to 1966. Some recommendations immediately follow from this analysis. The TWB database is an extremely valuable groundwater data set with almost monthly EC data from individual wells dating back to 1966. There is very little evidence of any anomalies in the EC database and it was not necessary to remove outliers or make corrections. Every effort should be made to preserve this database, to archive it and to share it with relevant authorities and agencies.

6.16.1 Spatial distribution of salinity

The "snapshot" monitoring of EC in the TWB wells at Mataki'eua/Tongamai in July and August 2007 revealed a significant inverse relationship between EC of individual wells and their distance from the lagoon (equation [1]). This relationship predicts that when continuously pumped vertical, 2 m deep wells are within 0.75 km from the coast, the EC will exceed the 2,500 μS/cm guideline value for freshwater. This distance is consistent with the groundwater salinity found in the Hihifo region of north-western Tongatapu and it may be that an equation similar to equation [1] is applicable more broadly in Tongatapu. This relationship means that the wells in Mataki'eua closest to the lagoon are the saltiest and should be monitored closely during droughts. The water from all wells is mixed before distribution, so that the impacts of more saline wells which exceed the EC aesthetic limit for freshwater of 2,500 μS/cm are mitigated. None the less it may be wise in droughts to cease pumping from some of the saltiest wells.

6.16.2 Thickness of the freshwater lens

The special SMBs locating within and near the Mataki’eua/Tongamai wellfield provide useful information on the thickness of the freshwater lens in the wellfield. In the August 2007 measurements, that thickness varied from 5.6 to 13.3 m, depending on the distance from seawater and on proximity to the wellfield. The measurements suggested (Figure 53) that the freshwater lens within the wellfield or down-gradient of it was up to 4.5 m thinner than that in wells bordering or removed from the wellfield when the wells are at a similar distance from seawater. This apparent thinning of the lens is consistent with the increasing trend in salinity observed in both the log mean EC of the wellfield as well as that for individual wells. This apparent finding is important and warrants further investigation.

6.16.3 Groundwater pH

The pH of the Mataki’eua/Tongamai wells measured in July and August 2007 again showed a decreasing trend with increasing groundwater salinity as with the village wells (Figure 54). Stagnant water from one non-operating well had a pH of 8.33, close to the expected limit for calcite dissolution in equilibrium with atmospheric CO_2 at 1 atmosphere pressure. The pH of water being pumped from the wells was on average about 1.3 pH units below this value, indicating that the partial pressure of CO_2 in the limestone aquifer is considerably greater than atmospheric CO_2 as expected from the organic-rich soils of Tongatapu.

6.16.4 Groundwater elevation and pump drawdown

The continuous well logger was placed in a well with an electric submersible pump at Mataki’eua for two weeks and recorded the recession phase of a significant 94.4 mm/day rainfall, which fell before the logger was installed, as well as tidally-forced variations in water table elevation and EC. During this recession phase, which lasted at least 10 days after the major rainfall, two small recharge events were recorded. These were used to estimate a mean evapotranspiration rate of 5 mm/day.

Operation of the electric submersible pump was interrupted on 3 occasions and the subsequent rebound and drawdown of the water table due to pumping was measured by the logger. The mean drawdown due to pumping at 376 m^3/day was only 11.5 mm and equilibrium was reached rapidly suggesting a large horizontal hydraulic conductivity. An approximate steady state analysis was used to estimate a horizontal hydraulic conductivity of 3,600 m/day, about twice previous estimates of the horizontal hydraulic conductivity in Tongatapu. These measurements should be repeated in other wells at Mataki’eua and Tongamai, where possible.

6.16.5 Temporal trends in groundwater salinity

A critical issue for management of the Mataki’eua/Tongamai wellfield is the impact of groundwater extraction on groundwater salinity. The supply of piped groundwater to Nuku’alofa has developed from 5 hand-dug wells at Mataki’eua commencing in 1966 to 39 wells and bores in 2007 with the last been completed in February 2003 in the Tongamai region. The pumping rate from the wellfield has increased from about 1.3 ML/day to approximately 8 ML/day in August 2007 with an estimated 50% increase in groundwater extraction since 1991.

Since the groundwater salinity is heavily influenced by antecedent rainfall, dis-entangling the impacts of rainfall and pumping on groundwater salinity is complex. We have been able to demonstrate that there have been increasing trends in the log mean EC of the wellfield due to pumping. Most of these increases occurred in the period from 1966 to the 1990s. The period from the mid 1990s to 2007 is complicated and shows a decrease in log mean EC over the period 1995 to 2007 despite a nearly 41% increase in pumping. We strongly suspect that this decrease is due to the progressive development of the lower salinity Tongamai portion of the wellfield (see Figure 50).

We have also examined the salinity trend in a single well, well 106, chosen because it was in the more saline portion of Mataki’eua. This well showed an increasing trend in salinity from commencement of pumping in 1971 through to 2007. Removal of the trend due to pumping produced residuals which had no significant trend in salinity. From this we conclude that increased pumping at Mataki'eua/Tongamai is increasing the salinity of the groundwater particularly in the area closest to the lagoon where the SMBs suggested thinning of the lens.

The planned development of the Tongamai section of the wellfield aims to increase the total number of wells in Mataki'eua/Tongamai to 60 with current plans to operate at least 45 of these. With 45 wells operating it is conservatively estimated that the log mean EC of the wellfield will increase by 9% and individual wells may increase salinity by 17%. If all 60 wells operate, it is estimated that the salinity of produced groundwater may increase by 17% with individual wells increasing by up to 35%. These estimates are believed to be conservative and it has been suggested that examination of possible alternate sources for groundwater such as the areas around the Fua'amotu International Airport and Liahona be carried out.

6.16.6 Unresolved questions

The measurements and analyses carried out in this section have raised several unresolved questions. The groundwater salinity data for Mataki'eua/Tongamai wells was correlated with distance from the lagoon. It is expected that, generally, the thickness of the freshwater lens is a function of distance from the coast. It would be useful to establish a relationship between thickness of the lens, the salinity of groundwater produced by wells and distance from the coast.

The SMBs in the Mataki'eua/Tongamai wellfield suggest that the freshwater lens within the wellfield is considerably thinner than in the monitoring wells bordering or removed from the wellfield. This needs to be further investigated as it is an important management issue.

It has been shown that the trend in log mean EC from 1966 to the 1990s is due to the increase in groundwater pumping over that time. However, the trend since 1995 is confused by the development of wells in the less saline Tongamai section of the wellfield and variations in rainfall. This confusion is removed if the EC of a single well is considered as done here for well 106. Ideally, the trends in all individual wells should be examined.

Continuous logging of one well at Mataki'eua for only two weeks revealed that the water table responds within about a day to rainfall, although discharge continues for at least 10 days after rainfall. The corresponding EC record does not show the same response and here it was compounded by spikes introduced when power to the electric submersible pump was turned off then on. The rebound and drawdown of the water table due to interruption of pumping was found to reach a new equilibrium quickly and was small, only 11.5 mm. This suggests large horizontal hydraulic conductivity, of order 3,600 m/day about twice previous estimates. From these measurements, the tidal lag was long and tidal efficiency was small suggesting that the vertical hydraulic conductivity is less that the horizontal conductivity. These measurements should be repeated, where possible, in other wells and for much longer periods to capture significant recharge events.

As was found for the Tongatapu village wells (section 5.5), both the log mean EC data as well as the EC data of an individual well was best correlated with long periods (up to 19 months) of previous rainfall. This needs to be investigated in more detail. There is also here, as there was for the Tongatapu village data, a suggestion that a slight decrease in pH occurs with increasing groundwater salinity.

Finally, the question of the impacts of increased pumping rates on groundwater quality at Mataki'eua/Tongamai needs to be investigated in more detail. Estimates have been made here of possible increases up to 35% in EC. This leads into the issue of exploring alternate groundwater sources in Tongatapu, particularly in areas where the freshwater lens is thicker and the salinity lower such as in the areas around the Fua'amotu International Airport and around Liahona.

6.16.7 Recommendations on data collection, storage and analysis

In this report we have only examined the log mean EC data and data from one individual well, well 106. It is fundamentally important that data for all wells are examined to look for trends in data and relations to rainfall.

- It is strongly recommended that the monthly field monitoring of groundwater at Mataki'eua/Tongamai be continued.

- It is recommended that the groundwater database be critically analysed well by well to look for trends and to examine relationships with rainfall.
- The closest distance of individual wells from the sea or the lagoon should also be recorded in the database
- Full analysis of data should be carried out annually and a report on the analysis presented to the appropriate authorities.
- All wells should be geo-referenced and clearly labelled to avoid any confusion.
- Wells used for measuring the depth of the water table, need to have the reference point for depth measurement accurately surveyed relative to current mean sea level and to have the point marked clearly. This is needed so that the elevation of the water table in wells can be evaluated with precision. Groundwater elevation is one of the critical measures in the draft 2006 Water Resources Legislation.
- Continuous logging of the water table fluctuations in all wells where water table elevation can be measured should be carried out over several months to determine the tidal influence and groundwater recharge influence on water table elevation.
- The salinity of the wells closest to the lagoon is higher than those further away from the lagoon. In droughts, these wells may exceed acceptable limits and should be more closely monitored in dry times.
- Analysis of measurements taken from the SMBs within and adjacent to the Mataki’eua/Tongamai wellfield during this project suggest significant thinning of the lens due to pumping from the wellfield. Other monitoring bores should be drilling throughout Tongatapu. In addition, it may be advisable to also source water from other locations such as the International Airport at Fua’amotu or at Liahona.
- We were not able to access all data from the special SMBs. It is recommended that efforts be made to retrieve and analyse that data.
- Only a few pumps have working water meters and the main meter for overall supply to Nuku’alofa is inoperative. While estimates can be made of volume extracted from the wellfield, accurate measurements enable better management of the wellfield and are essential for improved estimates of leakage losses. It is recommended that all pumped wells be fitted with accurate flow meters and that these be checked and maintained on a regular basis.
- A study of the feasibility of using alternate groundwater sources for Nuku’alofa’s water supply should be undertaken.

7 Measurements at the Tapuhia Waste Management Facility

During our field measurements in Tongatapu, we were fortunate to be invited to participate in the third and final groundwater monitoring event at the former quarry which had been re-developed as the Tapuhia Waste Management Facility (TWMF) for Tongatapu (section 3.3.6, Figure 11, Figure 25 and Figure 26).

7.1 Salinity distribution in groundwater around the TWMF

The field results obtained using the Solinst dipmeter to measure surface and bottom salinities in the monitoring boreholes around the TWMF are given in Table 27. The mean groundwater EC at the water table ('surface groundwater') is significantly less than the mean EC of water pumped from the village wells across Tongatapu (Table 12) or that from the Mataki'eua/Tongamai wellfield (Table 18). This is completely understandable since the wells for the latter two sets of measurements were extracting water over a depth of 2 m below the water table and from some quite saline areas (Figure 33) whereas the surface EC results in Table 27 are measured in unpumped boreholes from just below the water table.

Measurements of EC in the Tapuhia groundwater monitoring boreholes were also made by bailing surface water and measuring the EC, temperature and pH after 10 bailings with a TPH potable EC/ pH meter (WP81). A comparison of the mean results of the *in situ* values for surface water in Table 27 with those after bailing is given in Table 28.

The mean values of EC for the bailed surface water samples are slightly, but not significantly, greater than those for the *in situ* measurements and the median values are identical, within experimental error. Also, the standard deviations and range of values for both EC measurements are almost identical and together these results show that the *in situ* and surface measurements agree well.

Table 27 Results of field measurements of monitoring boreholes around the TWMF

Borehole No. / Statistic	RL Water table (m above MSL)	Depth to Water table below Ground (m)	At water table (surface)		RL Bottom of Borehole (m above MSL)	Depth to Bottom below Ground (m)	At Bottom	
			EC (µS/cm)	Temp (°C)			EC (µS/cm)	Temp (°C)
GMW1	0.369	12.37	647	24.9	-5.991	18.73	820	24.9
GMW2	n/a	13.43	750	24.7	n/a	17.71	693	24.5
GMW3	0.390	11.72	618	24.9	-6.239	18.35	1,130	24.9
GMW4	0.401	16.23	384	24.9	-6.209	22.84	1,019	24.9
GMW5	0.352	12.21	457	25.1	-6.688	19.25	1,034	24.9
GMW7	0.376	13.37	700	24.9	-5.289	19.03	706	23.5
GMW8	0.386	12.10	654	25.2	-7.774	20.26	7,971	24.9
Mean	**0.379**	**13.1**	**601**	**24.9**	**-6.37**	**19.45**	**1,910**	**24.6**
Std Dev	0.017	1.5	132	0.2	0.83	1.69	2,678	0.5
CV (%)	4.558	11.8	22.0	0.6	13.01	8.68	140	2.1
Median	0.381	12.4	647	24.9	-6.22	19.03	1,019	24.9
Max	0.401	16.2	750	25.2	-5.29	22.84	7,971	24.9
Min	0.352	11.7	384	24.7	-7.77	17.71	693	23.5

Table 28 Comparison of mean results of *in situ* and bailed water measurements of surface groundwater from the monitoring boreholes around the TWMF

Statistic	*In Situ* Surface		Bailed Surface Water		
	EC (μS/cm)	Temp (°C)	EC (μS/cm)	Temp (°C)	pH
Mean	**601**	**24.9**	**622**	**23.8**	**6.85**
Std Dev	132	0.2	129	0.4	0.19
CV (%)	22.0	0.6	20.7	1.7	2.8
Median	647	24.9	646	23.9	6.85
Max	750	25.2	740	24.3	7.22
Min	384	24.7	390	23.0	6.60

The mean EC from the unpumped TWMF monitoring bores (Table 28) is significantly less than that for the mean of the pumped village wells in Table 12 or that for the Mataki'eua/ Tongamai wellfield in Table 18. This is not surprising since these pumped wells draw water from up to 2 m below the water table whereas the results in Table 28 are from the surface groundwater just below the water table. This suggests that if pumped wells could be designed to draw water from shallower depths, the salinity of pumped water may be lower. The low values of EC found around the TWMF are similar to the lowest value found for the village wells at Fua'amotu.

7.2 Relationship between pH and salinity

The mean value of pH in Table 28 is lower than that of the 55 village water supply wells (Table 12), and significantly lower than the mean value for the village wells (Table 13). It is also lower than that at the Mataki'eua/Tongamai wellfield (Table 18). The relationship between EC and pH for the TWMF monitoring boreholes (Figure 73) again shows a decreasing trend in pH with increasing salinity which is here significant with an correlation coefficient of 0.76 (R^2=0.5764).

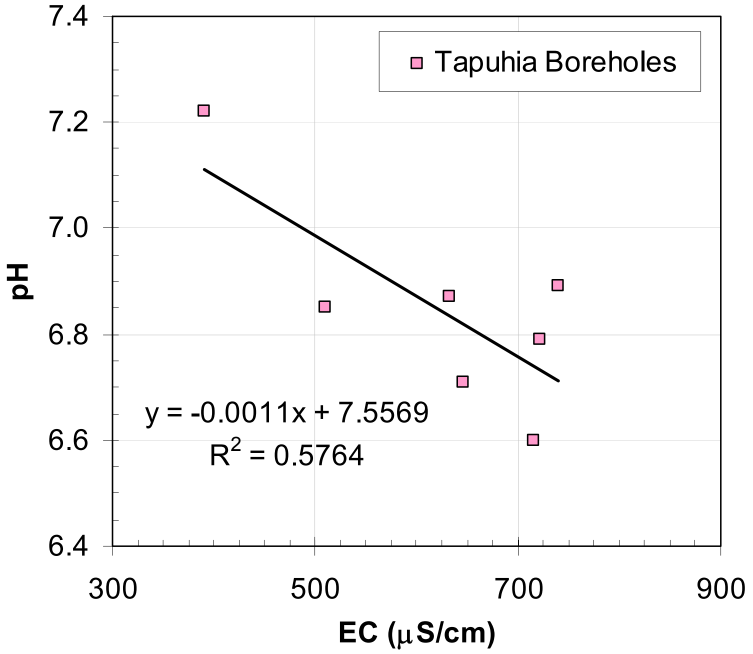

Figure 73 Dependence of pH on groundwater EC in the TWMF monitoring boreholes

The slope of the relationship between pH and EC in Figure 73 is five times that found for the combined village and Mataki'eua/Tongamai water supply wells. It is uncertain whether this difference in pH dependence on EC between that of the TWMF and that of the pumped groundwater in Tongatapu is due to: the fresher unpumped surface water at the TWMF site; the presence of the quarry and the disposal of wastes at TWMF increasing the dissolved CO_2; or to recent recharge. The difference is worth further investigation. It is important that pH in the TWMF monitoring boreholes be measured in the field as accurately as possible.

7.3 Approximate salinity profile of groundwater at the TWMF

Although the TWMF monitoring boreholes are open wells, and therefore not suitable for determining salinity profiles due to tidal mixing (Falkland, 1992), we can use all the boreholes to estimate an approximate salinity profile for the site. This estimation is based on the assumption that the *in situ* surface groundwater EC values in Table 27 give the approximate EC at the water table, while the ECs measured at the bottom of the well represent the EC of the general groundwater at the depth of measurement for each well. By agglomerating the data to represent the salinity profile of the entire site, an approximate profile of salinity (EC) at the site can be estimated as in Figure 74. This approximate profile gives the thickness of freshwater around the TWMF at about 6.5 to 6.9 m.

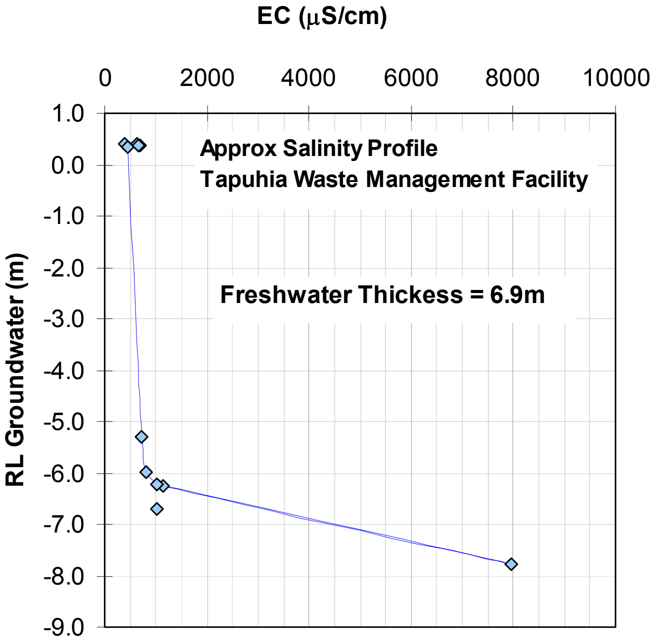

Figure 74 **Approximate salinity profile at TWMF from the results in Table 27**

The TWMF is about 1,000 m from the nearest lagoon water. The thickness of the TWMF freshwater is approximately 2.7 m less than the mean freshwater lens thickness estimated for SMBs within and around the Mataki'eua/Tongamai wellfield (Table 19 and Figure 53). This is no doubt due to the fact that the peninsula containing the TWMF is narrower than the width of the island at Mataki'eua./Tongamai. This emphasises the importance of having SMBs throughout Tongatapu.

7.4 Water table elevation and recharge to hydraulic conductivity ratio

The mean water table elevation for the TWMF boreholes in Table 27 is 0.38 ± 0.02 m above MSL. This value is consistent with the mean water table elevation of 0.41 ± 0.18 m found for village wells in Tongatapu (Table 17) and consistent with the elevations estimated by Hunt (1979).

The Dupuit-Forchheimer approximation for the steady state mean elevation of the freshwater lens water table above MSL, h_m (m), for an elongated island (UNESCO, 1991) is:

$$\left(\frac{h_m}{W}\right)^2 = \frac{R}{(1+\alpha)K}\left[\frac{x}{W} - \left(\frac{x}{W}\right)^2\right] \qquad [14]$$

where *W* (m) is the mean diameter of the island, *R* (m/y) is the mean annual recharge rate per unit area, *K* (m/y) is the mean hydraulic conductivity of the freshwater lens in the horizontal direction $\alpha = \rho_0/(\rho_s - \rho_0)$ with ρ_s, ρ_0 the densities (t/m^3) of sea and freshwater (≈ 37.1 for the South Pacific, Chapman, 1985) and *x* is the position across the elongated island starting from shore. The maximum value of h_m occurs at the centre ($x = W/2$) of the elongated island:

$$\left(\frac{h_m}{W}\right)^2 = \frac{R}{4(1+\alpha)K} \qquad [15]$$

The TWMF, although not in the centre of the peninsula on which it is located, appears to lie at the top of the groundwater divide (Figure 25) and it seems reasonable to assume that equation [15] is applicable there. Re-arranging equation [14], the ratio of mean annual recharge rate to the horizontal hydraulic conductivity is:

$$\frac{R}{K} = (1+\alpha)\left[\frac{2h_m}{W}\right]^2 \qquad [16]$$

If we assume that equation [14] can be applied to the peninsula within which the TWMF is located (Figure 25), with *W* ≈ 3,500 m and that the mean water table elevation in Table 27 is the long-term mean elevation, then equation [16] suggests $R/K \approx 1.8\times10^{-6}$, approximately twice the value estimated from Falkland (1992) for Tongatapu. If the long-term mean water table elevation for Tongatapu is used, 0.41 m, (Table 17) together with a mean island width of 5,500 m, equation [16] suggests that $R/K \approx 0.86\times10^{-6}$ approximately equal to the value estimated from Falkland (1992). If we assume that the recharge rate is relatively constant across Tongatapu, this implies that the hydraulic conductivity at the TWMF is about half that of the representative value for Tongatapu. Since hydraulic conductivities in karst limestones vary by several orders of magnitude, this small difference is not unexpected.

The estimate of *R*/*K* for the TWMF relies on the assumptions that equation [16] is applicable and that the value of h_m in Table 27 is the long-term equilibrium value. While the long-term mean value for Tongatapu is certainly a reasonable estimate of the long-term mean, it is by no means certain that this is so for the “snap shot” measurement for the TWMF in Table 27.

7.5 Direction of groundwater flow at Tapuhia

The measurements of water table elevation in Table 27 were made between 10:40 and 13:15 on 31st July 2007, so that we can assume to a first approximation that differences in water table elevation between wells were not predominantly due to differing tidal influence. The water table elevation data can therefore be used to estimate groundwater flow directions. The highest head occurred at GMW4 at the northern edge of the quarry. The lowest head occurred at the neighbouring GMW5, west-northwest of GMW4 and we infer that significant groundwater flow occurs in that direction. A less intense gradient is also evident from GW4 and GW3 towards GW1 and GW7 on the south-eastern edge of the quarry. GMW8, close to GMW1 and GMW7, appears anomalously high and may warrant re-surveying. It is important that GMW2 be re-surveyed to enable a better idea of flow direction in the north-easterly direction. The results here suggest that the TWMF lies on a divide with groundwater flowing towards the west-northwest and southeast towards Vaini.

7.6 Faecal indicators of contamination at the TWMF

The Colisure testing results for water samples bailed from monitoring boreholes around the TWMF and taken from two neighbouring pumped village water supply wells, one from the neighbouring town of Vaini, the other from more distant Longoteme (see Figure 25) are given in Table 29.

Table 29 Results of Colisure tests for *E. coli* and total coliform indicators at monitoring locations around the TWMF

Groundwater Monitoring Location	Measurement Date	Time of Measurement	Results
Tapuhia GMW1	31-Jul-07	11:15	E.Coli+ve
Tapuhia GMW2	31-Jul-07	12:40	Total Coliforms+ve
Tapuhia GMW3	31-Jul-07	11:30	Total Coliforms+ve
Tapuhia GMW4	31-Jul-07	12:10	E.Coli+ve
Tapuhia GMW5	31-Jul-07	13:15	Total Coliforms+ve
Tapuhia GMW7	31-Jul-07	10:40	Total Coliforms+ve
Tapuhia GMW8	31-Jul-07	11:50	Total Coliforms+ve
Longoteme well GMW76	5-Aug-07	14:40	Total Coliforms+ve
Vaini wellGMW218A	7-Aug-07	11:00	E.Coli+ve

All monitoring locations around the TWMF showed the presence of total coliforms which occur naturally in tropical island groundwaters (WHO, 1997). Two of the samples from the boreholes immediately adjacent to the TWMF, GMW1 and GMW4, showed the presence of *E. coli* contamination. The monitoring borehole, GMW2 is directly beside septic tank sullage drying beds at the TWMF. This borehole did not show any *E. coli* contamination. It is not certain if the *E. coli* found in the two boreholes is due to animals, birds or human sources. The village water supply well at Vaini, GMW218A, also showed the presence of *E. coli.* This was well adjacent to a septic tank latrine (Figure 75) and there is a possibility that this water may be contaminated with human waste.

Figure 75 Vaini water supply well, GMW218A, with neighbouring septic tank latrine

The Colisure test results merely show the presence or absence of faecal indicator species. Because they do not give any indication of the level of contamination they cannot provide a measure of the risk for human consumption. These results indicate that it is important to continue testing for indicator species at the TWMF and more generally in village water supply wells throughout Tongatapu.

7.7 Past intensive water quality sampling at the TWMF

Three intensive water quality testings have been carried out by the Waste Authority as part of the Tonga Solid Waste Management Project, on 8th February and 11th April 2006 and on 31st July 2007, during our field trip. We are extremely grateful to the project for the invitation to participate in the last sampling session and for making available the results of these samples.

The general chemical species and compounds for which testing was undertaken are listed in Table 30. The list is very similar to the compounds" tested for in this work during the intensive sampling of 10 water supply wells (Annex G).

7.7.1 Field and laboratory EC and pH

In the sampling undertaken on 31st July 2007, the mean EC of the laboratory measurements was 620 μS/cm, identical to the value found for the bailed water samples in Table 28. The mean pH in the laboratory, however, was 7.38, nearly 0.5 pH units greater than the value in Table 28. This increase in pH is expected because of supersaturation of field samples with respect to CO_2 (see section 5.8) and is the reason that pH should be measured accurately in the field when sampling waters from limestone aquifers (Hem, 1992).

Table 30 Chemical species and compounds tested in the intensive water analyses at the TWMF

EC	**pH**
Total Dissolved Solids	**Suspended Solids**
Alkalinity	**Fluoride**
Major Cations: Na, K, Ca, Mg	**Major Anions: Chloride, Sulfate, Total Cyanide**
Trace Metals	
Arsenic Cadmium Chromium Copper Lead	Manganese Nickel Zinc Iron Mercury
Nutrients	
Ammonia Nitrate Reactive Phosphorous	Nitrite NOX
Chemical Oxygen Demand	**Biochemical Oxygen Demand**
Organochlorine Pesticides	**Organophosphate Pesticides**
Polyaromatic Hydrocarbons (PAH)	**Benzene, Toluene, Ethyl Benzene, Xylene (BTEX)**
Total Petroleum Hydrocarbons (TPH)	
C6 - C9 Fraction C10 - C14 Fraction	C15 - C28 Fraction C29 - C36 Fraction

7.7.2 Major cations and anions

The mean concentrations (in mg/L) of major cations (sodium, Na; potassium, K; calcium, Ca; magnesium, Mg) and major anions (chloride, Cl; fluoride, F; bicarbonate, HCO_3; sulfate, SO_4) at the TWMF were not significantly different between the three samplings. The mean concentrations (mg/L) of major cations and anions for all monitoring wells and all samplings are given in Table 31 and the relative contribution of each ion (in meq/L) to the mean total dissolved salts at the TWMF is plotted in Figure 76.

Table 31 Mean concentrations of major ions at the TWMF over the 3 sampling periods

Statistic	Lab EC (µs/cm)	Na	K	Ca	Mg	Cl	HCO_3	SO_4
		Concentration (mg/L)						
Mean	**663**	**25.0**	**1.5**	**94.2**	**4.9**	**49.4**	**288**	**7.7**
Std Dev	85	6.7	0.5	10.4	1.4	12.5	38	1.6
CV (%)	12.8	26.7	33.7	11.1	28.0	25.4	13.3	20.9
Median	**676**	**27.0**	**2.0**	**97.0**	**5.0**	**51.5**	**296**	**8.0**
Max	804	35.0	2.0	108.0	8.0	67.5	342	12.0
Min	447	12.0	1.0	70.0	2.0	24.3	174	5.0

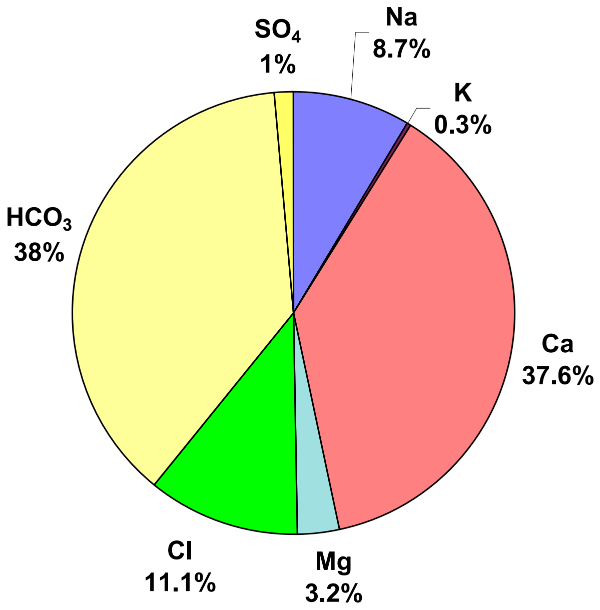

Figure 76 Relative contribution of major ions (in meq/L) to the total dissolved salt content in mean groundwater around the TWMF

Table 31 and Figure 76 demonstrate the dominance of Ca and HCO_3 from the dissolution of carbonates and secondary importance of Na and Cl from the dispersion of underlying seawater into the groundwater seawater. The charge of HCO_3 in meq/L is exactly balanced by that from Ca while Na + K + Mg balances the charge of Cl + SO_4. The overall dissolution of calcite is governed by:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \qquad [17]$$

The concentration of Ca in Table 31 is equivalent to the dissolution of calcite in equilibrium with carbon dioxide with a partial pressure of about 2×10^{-2} atmospheres (Hem 1992, Fig. 18), much higher than the normal atmospheric CO_2 partial pressure of 3.5×10^{-4} atmospheres. This arises because the groundwater system is partially closed with higher CO_2 concentrations due to soil respiration. Dienes *et al.* (1974) estimate CO_2 partial pressures of between 1.6 to 5×10^{-2} atmospheres for limestone groundwater systems in Pennsylvania. If seawater is diluted we expect the ratio of the major ions to chloride should remain essentially unchanged from those of undiluted seawater.

To illustrate the relative importance of carbonate aquifer dissolution and seawater dilution to the composition of major ions in the groundwater at Tapuhia, Table 32 compares the mean ion ratios (in mg/L) of the Tapuhia water samples with those for mean seawater (Hem, 1992) and for those for water discharging from a relatively pure limestone aquifer, the Tuscumbia Limestone, in Alabama, USA (Hem, 1992).

Table 32 Ratio of major ions in mean groundwater around the TWMF compared with those for seawater and groundwater from a relatively pure limestone aquifer (Hem, 1992)

Source	Na/Cl	K/Cl	Ca/Cl	Mg/Cl	HCO_3/Cl	SO_4/Cl	Ca/HCO_3	Ca/Mg
	Ratios of concentrations in mg/L							
Limestone Aquifer*	0.023†		6.0	0.45	19	0.40	0.32	13.3
Mean Seawater*	0.55	0.021	0.022	0.071	0.007	0.142	2.89	0.304
Mean Tapuhia Groundwater	**0.511**	**0.028**	**2.05**	**0.101**	**6.28**	**0.162**	**0.329**	**20.6**
Std Dev	0.087	0.009	0.67	0.024	2.19	0.053	0.028	5.7
Range	0.32-0.75	0.016-0.047	1.4-4.0	0.04-0.15	3.7-12.3	0.09-0.33	0.3-0.4	13-35

*Values calculated from Hem (1992) Tables 2 and 15.

† Value for [Na+K]/Cl

It is clear from the ratios in Table 32 that the main sources of Na, K, and SO_4 in the groundwater at Tapuhia are from diluted seawater. The source of Ca and HCO_3 is clearly dissolution of the limestone aquifer. Equation [17] predicts that dissolution of calcite should produce a Ca/HCO_3 ratio of 0.328 identical to that in Table 32. It can also be seen that while most of the Mg in the groundwater is sourced from groundwater dilution, a smaller portion comes from limestone dissolution. The relation between the composition of the groundwater and that of the supposed end members, seawater and rainwater in a limestone aquifer can be examined by plotting the ion ratios as a function of the reciprocal of the chloride concentration, 1/Cl (Figure 77).

For the ratios of concentrations of Ca, HCO_3 and Mg to Cl, Figure 77A, B, and C shows that the seawater ratios (at 1/Cl ≈ 0.053 L/g) appear to be one end member on a linear mixing line. For Mg/Cl the ratio given for limestone at recharge water chloride concentration (approximately 1/Cl ≈ 250 L/g) appears to be the other end member. In contrast, the ratio Ca/HCO_3 is essentially independent of chloride concentration and the ratio in seawater (2.89, Table 32) and is governed by the theoretical limit for the dissolution of calcite (equation [17]).

There is normally a very strong relation between EC and chloride for groundwater samples from Tongatapu (Furness and Helu, 1993). This is not the case for the Tapuhia samples (Figure 78). At all three samplings, groundwater monitoring well GMW3, at the south-western edge of the TWMF (Figure 26), had the highest chloride concentration while GMW5, outside the perimeter and to the west of the quarry, had the lowest chloride concentration. The results at GMW4 on the north side of the quarry were anomalous. Despite having the lowest chloride concentration, the EC at GMW5 was not the lowest. Rainwater collects in a pond at the bottom of the quarry used for waste disposal (Figure 11). The chloride concentrations suggest that the rainwater pond discharges to the west of the old quarry, a suggestion consistent with the hydraulic head measurements in section 7.5.

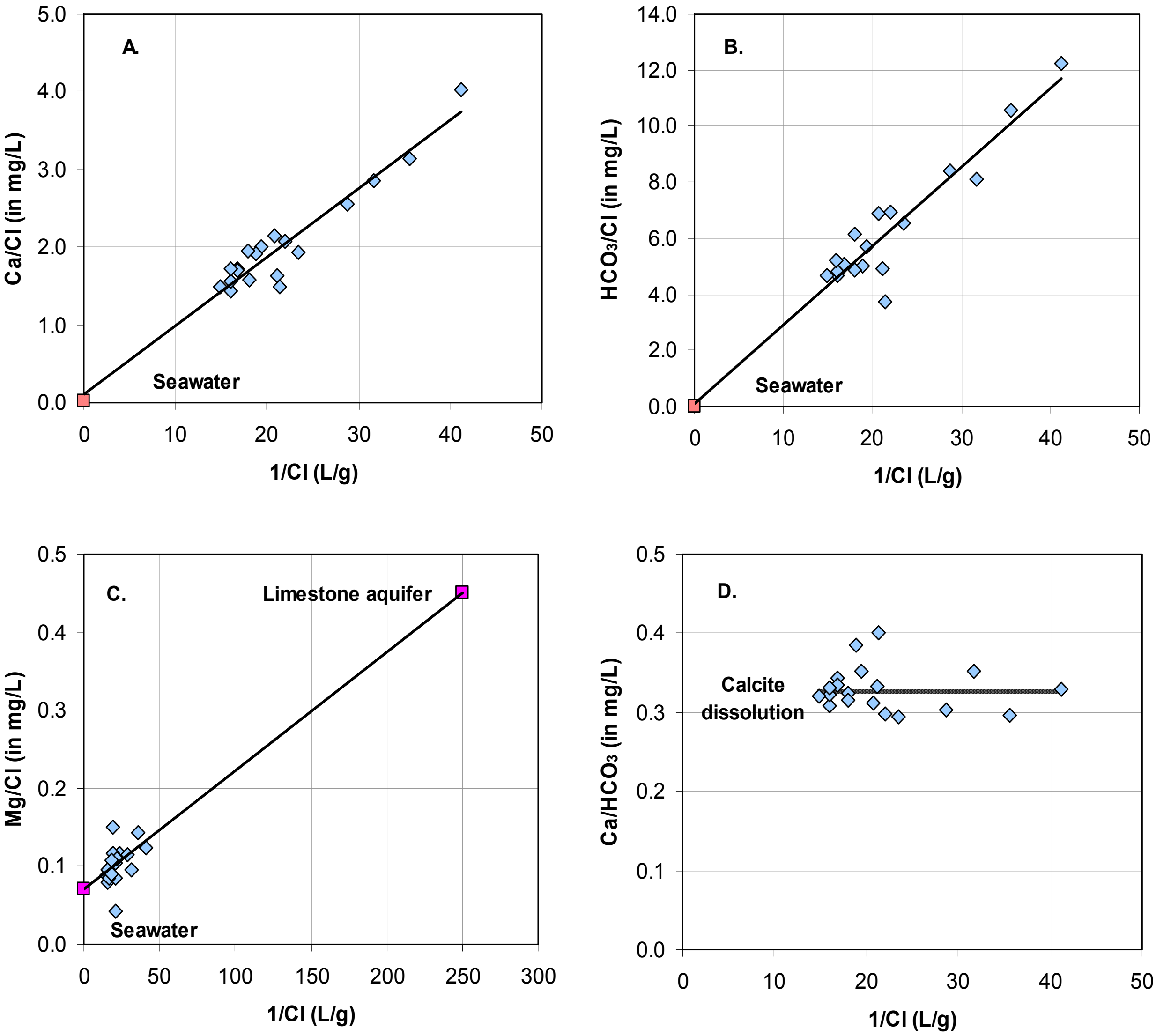

Figure 77 Major ion ratios for Tapuhia groundwater samples as a function of the reciprocal of the chloride concentration compared with expected seawater ratios (A, B), limestone in equilibrium with rainwater (C) and with calcite dissolution (D)

7.7.3 Relation between bicarbonate concentration and field pH

The overall equation for the dissolution of calcite, equation [5] is the sum of four individual reactions (Stumm and Morgan, 1992):

$$\begin{aligned} &CaCO_3(s) \leftrightarrow Ca^{2+} + CO_3^{2-} \\ &CO_3^{2-} + H^+ \leftrightarrow HCO_3^- \\ &CO_2(g) + H_2O \leftrightarrow H_2CO_3 \\ &H_2CO_3 \leftrightarrow H^+ + HCO_3^- \end{aligned} \qquad [18]$$

In equation [18] (*s*) and (*g*) refer to the solid and gas phases respectively. Some of the reactions in equation [18] involving bicarbonate [HCO_3^-] include the hydrogen ion [H^+] and so are pH dependent. For closed systems in which the total sum of the aqueous carbonate species (H_2CO_3, HCO_3^-, CO_3^{2-}) is constant it is expected at equilibrium, that the concentration of bicarbonate should be constant between about pH 6.3 and pH 10.3 (Stumm and Morgan, 1992). The dependence of bicarbonate concentration on the field measured pH at Tapuhia for the samples taken in July 2007 is plotted in Figure 79.

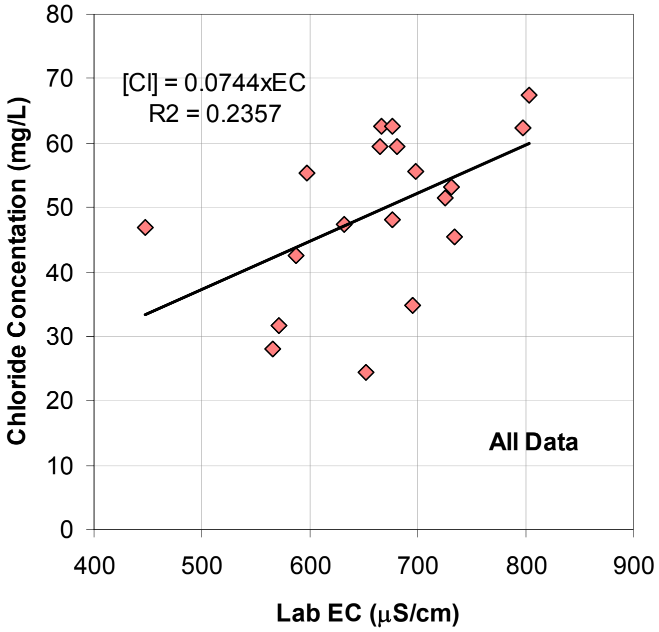

Figure 78 Relation between chloride concentration and EC determined in the laboratory for all water samples taken at Tapuhia on three sampling dates

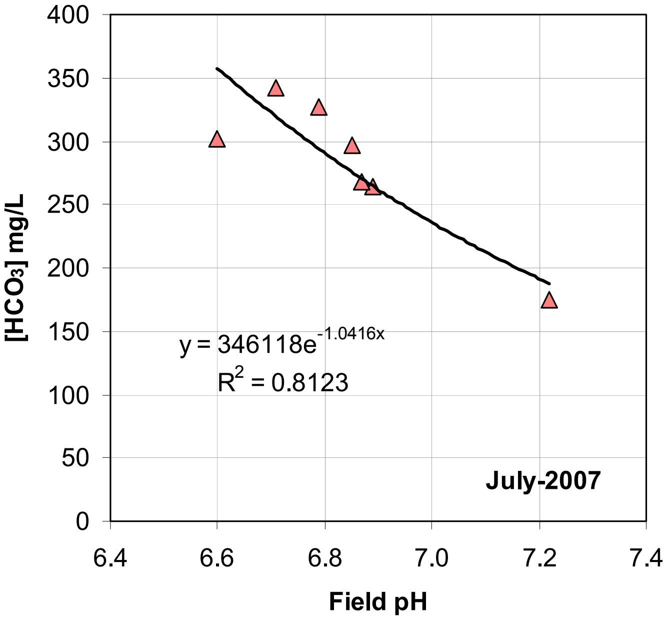

Figure 79 Dependence of bicarbonate concentration on the field measured pH for samples from the Tapuhia groundwater monitoring wells

A strong dependence of bicarbonate concentration on field measured pH can be seen with a correlation coefficient slightly greater than 0.9. The relation in the figure follows the equation:

$$\log[HCO_3]_{Wt} = 5.54 - 0.542 \times pH \text{ or} \quad [19]$$

$$\log[HCO_3]_M = 0.754 - 0.542 \times pH$$

where $[HCO_3]_{Wt}$ and $[HCO_3]_M$ are the bicarbonate concentrations in mg/L and moles/L respectively.

This dependence of bicarbonate concentration on pH could stem from non-equilibrium conditions, from the groundwater system being partially open or from different partial pressures of CO_2 in the recharge water.

To a first approximation, equation [19] can be used to estimate bicarbonate concentrations in groundwater samples from field measurements of pH taken at the time of water sampling.

7.8 Chemical contaminants

The three intensive analyses at Tapuhia at dates before and after the facility commenced operation have all shown that the concentrations of organochlorine and organophosphate pesticides, PAH, BTEX, TPH, total cyanide and mercury were all below the limits of detection (LoD).

All trace metals, with the exception of lead, were below the WHO (2006) guidelines for drinking water quality (Table 33). In all three samplings, the mean and all individual borehole concentrations of lead were above the WHO guideline limit of 0.010 mg/L for lead in drinking water. Table 33 shows the mean values for the three sampling dates for all heavy metals tested. The values are compared with the WHO (2006) guideline drinking water values.

Table 33 Mean concentrations of heavy metals from groundwater monitoring boreholes around the TWMF at three sampling times compared with WHO guideline values

Trace Metal	WHO (2006) guideline value (μg/L)	Mean concentrations (μg/L)		
		8th Feb 06†	11th Apr 06	31st Jul 07
Arsenic	10	<LoD	8	2
Cadmium	3	<LoD	0.4	0.2
Chromium	50	2.3	5.4	2.7
Copper	2000	4.2	13	6.2
Iron	None	444	4077	621
Lead	10	56	108	105
Manganese*	400	21	197	116
Mercury	6	<LoD	<LoD	<LoD
Nickel	70	<LoD	6.5	1.3
Zinc	None	145	203	167

† Wells GMW2 and GMW4 were not sampled in this round.

‡ The February and April 2006 samples were taken before the TWMF commenced in January 2007.

* The WHO guideline value for manganese is an aesthetic not health guideline.

The mean concentrations for lead exceed the WHO guideline value by between 5 and 10 times. It is not clear in there is any trend in lead concentration with time. The three mean lead concentrations have large CVs which suggest that they may not be significantly different. The median values are 6 to 7 times the guideline limit for drinking water and are similar although they suggest a slight increase in dissolved lead with time. This is further explored in Figure 80 where the results for individual monitoring wells are displayed for the three sampling times.

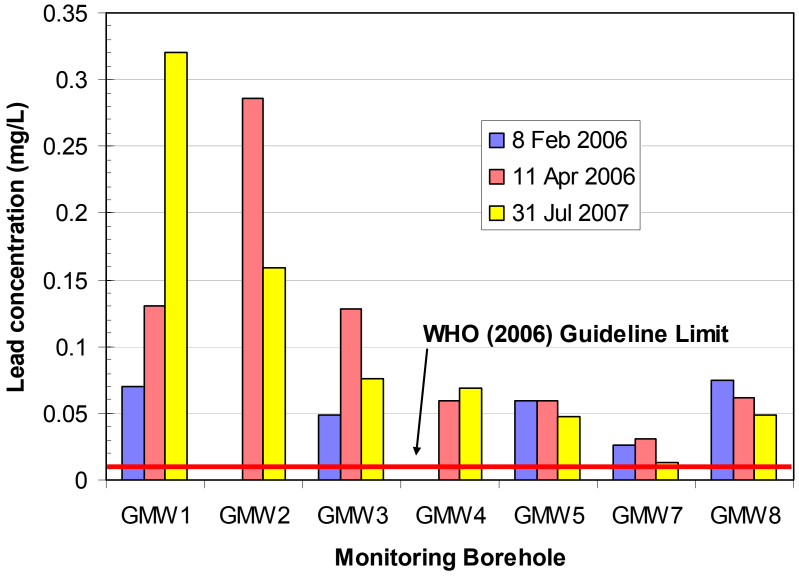

Figure 80 Lead concentrations in water samples from the individual monitoring boreholes around the TWMF

One monitoring borehole, GMW1, shows a consistent increase in lead concentrations despite both the February and April 2006 samples being taken before waste disposal at the site commenced. In contrast, GMW2 shows a corresponding decrease. The maximum concentrations of lead at both monitoring boreholes are at least 25 times higher that the WHO (2006) guideline limit for drinking water.

It is important to put these results in perspective. The 1958 WHO *International Standards for Drinking-water* recommended a maximum allowable concentration of 0.1 mg/L for lead, based on health concerns. This value was lowered to 0.05 mg/L in the 1963 International Standards. The tentative upper concentration limit was increased to 0.1 mg/L in the 1971 International Standards, because this level was accepted in many countries and water with this concentration had been consumed for many years without apparent ill-effects. In the first edition of the *Guidelines for Drinking-water Quality*, published in 1984, a health-based guideline value of 0.05 mg/L was recommended. The 1993 Guidelines proposed a health-based guideline value of 0.01 mg/L; because lead is a cumulative poison and there should be no accumulation of the body burden of lead. The lead concentrations in groundwater at Tapuhia are therefore at reasonably low concentrations but they warrant the continued monitoring of lead concentrations around the TWMF.

Figure 80 shows that there is significant groundwater concentration of lead at two sites, GMW1 and GMW2. It also suggests there may have been groundwater movement of dissolved lead from GMW2 to GMW1 between April 2006 and July 2007. If groundwater transport of lead were occurring between these wells, we would expect to see an increase in lead concentration at the intermediate well GMW7 and perhaps at the downstream well GMW8. No such increases in lead concentrations are evident in Figure 80.

7.9 Nutrients

The only other species of interest in the Tapuhia water quality samples are the nutrients, nitrate and phosphate. Nitrate in Tongatapu is sourced from fertilisers, leaking septic tanks, animal wastes and microbiological processes in the soil. The mean nitrate and phosphorus concentrations of the TWMF borehole samples for the three monitoring dates are listed in Table 34.

The mean nitrate concentration has increased from a mean of 6.8 mg/L for the two sampling periods before operations commenced at the facility to 18.4 mg/L (NO_3) after the start of operations. The two mean values before the TWMF commenced operation were identical within error.

Table 34 Mean concentrations of nutrients before and after commencement of the TWMF

Statistic	Nitrate concentration (mg/L of NO_3)			Reactive P concentration (mg/L of P)		
	Sampling Date			Sampling Date		
	8th Feb 06	11th Apr 06	31st Jul 07	8th Feb 06	11th Apr 06	31st Jul 07
Mean	**6.5**	**7.1**	**18.4**	**0.045**	**0.024**	**0.034**
Std Dev	3.8	4.6	27.6	0.041	0.011	0.032
CV (%)	59.3	64.2	150.2	90.3	47.4	94.1
Median	7.8	6.5	9.9	0.028	0.021	0.022
Max	11.2	13.2	80.6	0.114	0.047	0.092
Min	1.7	0.6	3.6	0.013	0.014	0.016

This apparent increase in the mean nitrate concentration for the 31st July 2007 is due to one borehole, GMW2, in which the nitrate concentration rose from 6 mg/L in April 2006 to over 80 mg/L in July 2007 (Figure 81). This latter value is greater than the WHO (2006) water quality guideline value of 50 mg/L introduced to protect against methaemoglobinaemia in bottle-fed infants. This borehole, as already mentioned, is right beside the septic tank sullage drying beds at the TWMF. The increased concentration of nitrate at this site warrants further monitoring.

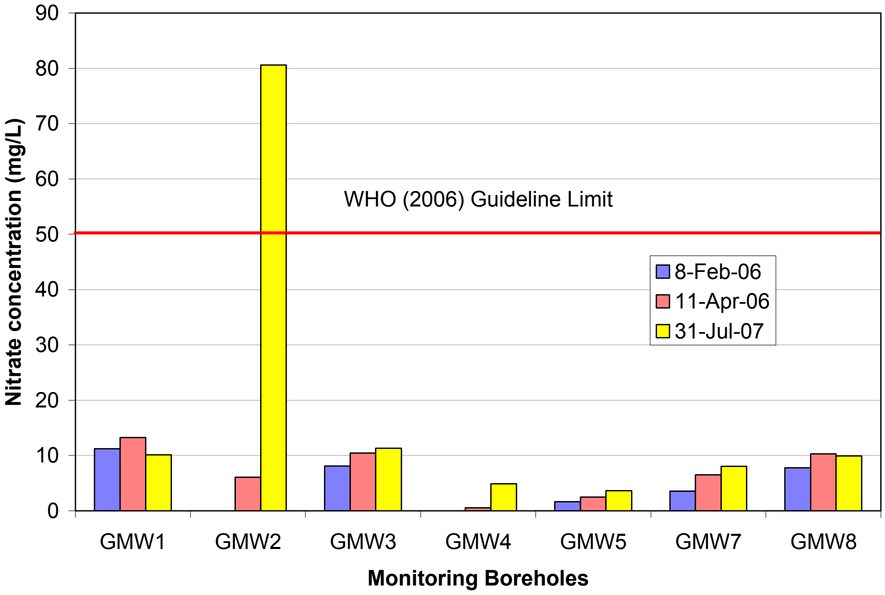

Figure 81 Nitrate concentrations in water samples from the monitoring boreholes around the TWMF

The mean phosphorus concentration from both sets of measurements in 2006 before the TWMF started operations was 0.033 ± 0.028 mg/L of P similar to the mean concentration in Table 34, 0.034 ± 0.032 mg/L after the TWMF commenced in January 2007. This then appears to be the background concentration of phosphorus in Tongatapu groundwater. The mean molar N/P ratio for the two 2006 measurements is 121 ± 71, well above the Redfield ratio (Stumm and Morgan, 1992), indicating a non microbial source of nitrogen.

7.10 Conclusions and recommendations

In this section, the results of field measurements and an examination of chemical analysis carried out at the TWMF have been presented. These lead to several conclusions and recommendations and conclusions.

7.10.1 Conclusions

The TWMF represents a bold solution to a difficult problem; waste disposal in a small island. Because the TWMF is located in a disused quarry, the risk of contaminating local groundwater is significant, and major efforts have been made to minimise this risk. One of the essential elements in managing operations there is the continued monitoring of groundwater in the immediate vicinity of the quarry and at village water supply wells in the area around the TWMF. The Waste Authority has assembled a multi-agency monitoring team that works exceptionally well. This team provides a model for groundwater monitoring throughout Tongatapu. It enables cooperation at the operational level, promotes the sharing of facilities and equipment and encourages the sharing of data and information.

The groundwater salinity in the monitoring boreholes around the facility is generally lower than that in pumped village wells in Tongatapu (section 5.2) and in the Mataki'eua/Tongamai TWB wellfield (section 6.2). This is hardly surprising since there appears to be no major groundwater pumping in the vicinity of the quarry and the GMWs sample the surface groundwater whereas the pumped wells withdraw water from the top 2 m below the water table.

The groundwater chemistry shows the predominance of carbonate dissolution products and a significant dependence of field pH on groundwater EC. The groundwater chemistry of the GMWs suggested some movement of rainwater ponded in the bottom of the quarry into groundwater to the west of the quarry may be occurring.

The "snap-shot" measurements here of piezometric heads in the GMWs suggest westward flow of groundwater, although this may have been influenced by tidal forcing of the piezometric head and was certainly hampered by the absence of a relative level for GMW2. Continuous monitoring of all seven GMWs immediately around the TWMF would provide a better idea of the groundwater flow directions.

Testing for the presence or absence of species indicating faecal contamination in all GMWs and two nearby village water supply wells showed the presence of total coliforms in all wells. Total coliforms occur naturally in tropical island groundwaters (WHO, 1997). Two of the samples from the boreholes immediately adjacent to the facility showed the presence of *E. coli* contamination. Monitoring borehole GMW2, directly beside septic tank sullage drying beds, however, showed no *E. coli* contamination. It is not certain if the *E. coli* found in two GMWs is due to animals, birds or human sources. One village water supply well at nearby Vaini also showed the presence of *E. coli.* This was adjacent to a latrine. These rapid field tests for presence or absence remove some of the burden of bacterial testing from the hospital laboratory.

Intensive groundwater sampling for contaminants and pollutants before and after the TWMF commenced operation showed that the concentrations of organochlorine and organophosphate pesticides, PAH, BTEX, TPH, total cyanide and mercury were all below the limits of detection. All trace metals, with the exception of lead, were also below the WHO (2006) guidelines for drinking water quality (see Table 33). In all three samplings, the mean and all individual boreholes concentrations of lead were above the WHO guideline limit of 0.010 mg/L for lead in drinking water. One monitoring borehole, GMW1, showed a consistent increase in lead concentrations despite two samples being taken in 2006 before waste disposal at the site commenced. In contrast GMW2 shows a corresponding decrease (see Figure 80). The maximum concentrations of lead at both monitoring wells are at least 25 times higher that the WHO (2006) guideline limit for drinking water. Reasons for these high values and the changes in concentration with time need to be investigated.

The mean nitrate concentration increased from a mean of 6.8 mg/L for the two sampling periods before operations commenced to 18.4 mg/L (NO_3) after the start of operations. This apparent increase in the mean nitrate concentration is due to one borehole, GMW2, in which the nitrate concentration rose from 6 mg/L in April 2006 to over 80 mg/L in July 2007 (Figure 81). This latter value is greater than the WHO (2006) water quality guideline value of 50 mg/L. This borehole, as already mentioned, is right beside the septic tank sullage drying beds at the TWMF. The increased concentration of nitrate at this site warrants further monitoring particularly to examine for migration of nitrate.

7.10.2 Recommendations

It is clear that the multi-Ministry monitoring team assembled by the Waste Authority works well and cooperatively together and presents a mechanism for sharing information and data. This is a good model for all groundwater monitoring in Tongatapu.

- It is recommended that a multi-Ministry team be formed from Ministries and agencies with responsibility for water and the environment to monitor groundwater throughout Tongatapu and other islands in the Kingdom.

The data being collected by the Waste Authority is important and valuable and adds to the knowledge base as a whole.

- It is recommended that the Waste Authority ensure that monitoring data from the TWMF be incorporated into the MLSNRE national water resources database.

"Snap-shot" measurements of piezometric head carried out in this project suggest that groundwater flow appears to be in a westerly direction. This conclusion may be influenced by the tidal dependence of piezometric head and by the accuracy of survey of the groundwater measurement height. Our conclusions may also have been biased by the fact that there is no RL for monitoring borehole GMW2.

- It is recommended that the RLs of all monitoring boreholes be re-surveyed as accurately as possible.
- It is recommended that the piezometric head in all wells around the TWMF be monitored continuously for three months to enable accurate determination of flow directions.

Two public water supply wells, well 328 and GMW29 lie to the southeast and are close to the TWMF. These wells are not shown on the Tongatapu map of wells (see Figure 25)

- It is recommended that the Tongatapu map of groundwater wells be updated to include the location of all water supply wells.

It had been originally planned that only three intensive chemical samplings, two before operations commenced and one after, be carried out from the monitoring boreholes around the TWMF.

- It is recommended that intensive chemical sampling for contaminants in the monitoring boreholes around the TWMF and in the public water supply wells closest to the TWMF be continued at least annually for the next 10 years.

The intensive chemical sampling of the TWMF monitoring boreholes showed generally the absence of major contaminants. There were two exceptions. Dissolved lead concentrations were above the WHO guideline limits for drinking both before and after commencement of operations, particularly in monitoring wells GMW2 and GMW3. In addition, nitrate levels in excess of WHO guidelines for drinking water were found in GMW2, adjacent to the sullage drying beds, after operations commenced. It is in important that these contaminants be tracked throughout operation of the facility.

- It is recommended that lead and nitrate levels be monitored in the monitoring boreholes around the TWMF every six months during operation of the facility.

The groundwater chemistry in the Tapuhia GMWs showed a lower salinity than generally in village wells in Tongatapu and at the Mataki'eua/Tongamai wellfield as well as unexpected chemistry t the west of the facility, suggesting inputs from ponded rainwater in the quarry base.

- It is recommended that the influence of ponded water at the base of the TWMF on surrounding groundwater be examined.

8 Intensive Groundwater Testing in Tongatapu

In this section, a report is given of the testing of groundwater samples throughout Tongatapu for the presence of faecal indicator species and other groundwater pollutants conducted as part of our field measurements. The data is then compared with previous measurements in Tongatapu.

8.1 Faecal indicators in groundwater samples

The results of the Colisure and H_2S paper strip tests (hereafter abbreviated to H_2S tests) for the presence of faecal indicators in groundwater and rainwater samples are shown in Table 35. The boiled rainwater sample was a blank and both tests showed that there was no faecal contamination in this sample. Also, in one instance, both tests showed that the groundwater sample from Liahona College water supply well 169 was negative. In duplicate tests of this well, the Colisure test again returned a negative test but the H_2S test returned an equivocal test with a (+) rating, indicating the possibility of bacteria present. Only 2 H_2S tests were unequivocally negative whereas 4 Colisure tests were negative.

Table 35 Comparison of tests for faecal indicators in groundwater and rainwater samples[7]

Site Sampled	Well Number	Date	Time	Colisure Result	H_2S Paper Strip Result
Mataki'eua	117	2-Aug-07	15:56	E.Coli+ve	+++
Boiled Rainwater		3-Aug-07	5:12	is -ve	is -ve
Tap Water Friendly Islander Hotel (groundwater from TWB reticulation system)	Various wells at Mataki'eua	3-Aug-07	5:22	Coliforms+ve	+++
Longoteme	GMW76	5-Aug-07	14:40	Coliforms+ve	+
Fua'amotu	182	5-Aug-07	15:40	Coliforms+ve	+
Tatakamotonga	21	5-Aug-07	18:10	Coliforms+ve	+++
Liahona	169	6-Aug-07	11:30	is -ve	+
Rainwater Geology		6-Aug-07	15:04	E.Coli+ve	+++
1. Kolonga	49	7-Aug-07	9:12	Coliforms+ve	++
2. Tatakamotonga	20	7-Aug-07	9:40	Coliforms+ve	+++
3. Tupou College	New Well	7-Aug-07	10:10	Coliforms+ve	+
4. Vaini	GMW218A	7-Aug-07	11:00	E.Coli+ve	+
5. Pea	88	7-Aug-07	11:30	Coliforms+ve	+++
6. Liahona	169	7-Aug-07	11:50	is -ve	is -ve
7. Fo'ui	151	7-Aug-07	12:10	Coliforms+ve	+++
8. Mataki'eua	115	2-Aug-07	14:00	E.Coli+ve	+++
9. Mataki'eua	211	7-Aug-07	13:05	Coliforms+ve	+
10. Mataki'eua	104	7-Aug-07	13:20	is -ve	+

Four of the (+++) rating H_2S results (very high risk of faecal contamination) corresponded to positive Colisure *E. coli* results but four others of the (+++) rating corresponded to only positive

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[7] Locations with numbers against them in Table 35 are the 10 sites chosen for intensive water quality testing

Colisure coliform results with no *E. coli* positives. It appears then that the H_2S test is very conservative suggesting faecal contamination in double the number of positive Colisure samples and in samples that may have naturally occurring rather that faecal coliforms. More worryingly, one of the lower H_2S ratings, (+), indicating the possibility of bacteria, corresponded to a positive Colisure *E. coli* test for the Vaini water supply well.

One of the lesser H_2S ratings (++), indicating some faecal contamination present, corresponded to a positive Colisure total coliform test for the Kolonga water supply well (Figure 32) while four of the lowest H_2S rating (+) results corresponded with four positive Colisure total coliform results. Again it is of concern that two of the lowest (+) H_2S results corresponded to negative Colisure results. The lack of consistency of the H_2S results is worrying.

The H_2S paper strip test (Manja *et al*., 1982) was introduced after it was observed that the presence of coliforms in water was also associated with hydrogen sulphide (H_2S) producing organisms (Allen and Geldreich, 1975). The test uses thiosulfate as a sulphur source and ferric ammonium citrate as an indicator. Sulfate-reducing enteric bacteria use the thiosulfate to produce H_2S which reacts with the ferric salt to produce a black insoluble ferrous sulphide precipitate (Mosley and Sharp, 2005). Its principle advantages are that it is cheap, very easy to use in the field since it does not require refrigeration or incubation or elaborate equipment, is easy to use by non-technical people and is therefore ideal for testing rural and isolated water supplies. For these reasons, it has been recommended for use in Pacific Island countries (Mosley and Sharp, 2005).

Clearly, the H_2S test here has over-estimated the risk of faecal contamination and under-estimated the number of negative results relative to the Colisure test, which has been adopted as a standard test in the USA. If we assume that the highest rating (+++) corresponds to the Colisure *E. coli* test and the next two ratings (++ and +) correspond to total coliforms then Figure 82 provides a pictorial summary of the results in Table 35.

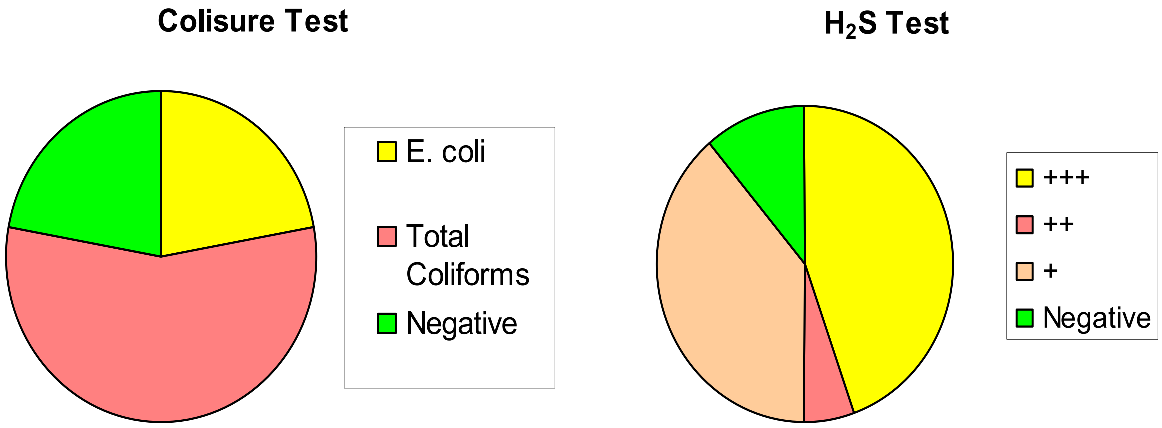

Figure 82 **Pictorial comparison of the distribution of results for the two faecal indicator tests of groundwater samples**

A report on the use of the H_2S test (WHO, 2002) did not recommend its use because of the possibilities of false positives from non-enteric, naturally-occurring sulfate-reducing bacteria, which seems to have occurred in this work. These false positives, here 11% of samples, and the over-estimation of the risk of faecal contamination by a factor of 2 strongly suggest that the standard, but more expensive, Colisure field test should be used where possible or the routine screening of the presence or absence of *E. coli* and total coliform indicators in public water supply systems.

The Colisure results in Table 35 provide some interesting results. Two of the four TWB water supply wells tested at Mataki'eua showed the presence of *E. coli.* These are of course upstream from the chlorination plant. One of the remaining TWB Mataki'eua wells had total coliforms while, surprisingly, the remaining well was free of both total coliforms and *E. coli.* The single tap water sample taken from the reticulation system showed the presence of total coliforms. This is not unexpected since the sample location is towards the end of the Nuku'alofa reticulation system with the potential for build-up of biofilms in the pipes. The sample of raw rainwater taken from the Geology rainwater tank also showed the presence of *E. coli* due probably to birds.

Excluding the rainwater samples and one of the duplicate Liahona samples, only two (8.3%) of the groundwater samples out of the total of 24 Colisure samples taken (Table 29 and Table 35) had no total coliforms or *E. coli*. The Liahona College sample came from a well in an immaculate rugby ground with little agriculture surrounding it (see Figure 83A). This suggests that, where possible, groundwater ought to be sourced from cleared, well-managed and protected areas. The Mataki'eua negative sample came from well 104 with diesel spills and ponded water on the soil surface which was heavily infested with algal blooms (see Figure 83B). Out of the total of 24 water samples, six (25%) returned positive *E. coli* tests. This is quite a high percentage, reflecting perhaps the impacts of neighbouring agriculture, particularly animals, and septic tank systems on neighbouring village water wells. This result indicates that disinfection of all pumped groundwater systems should be considered where practical.

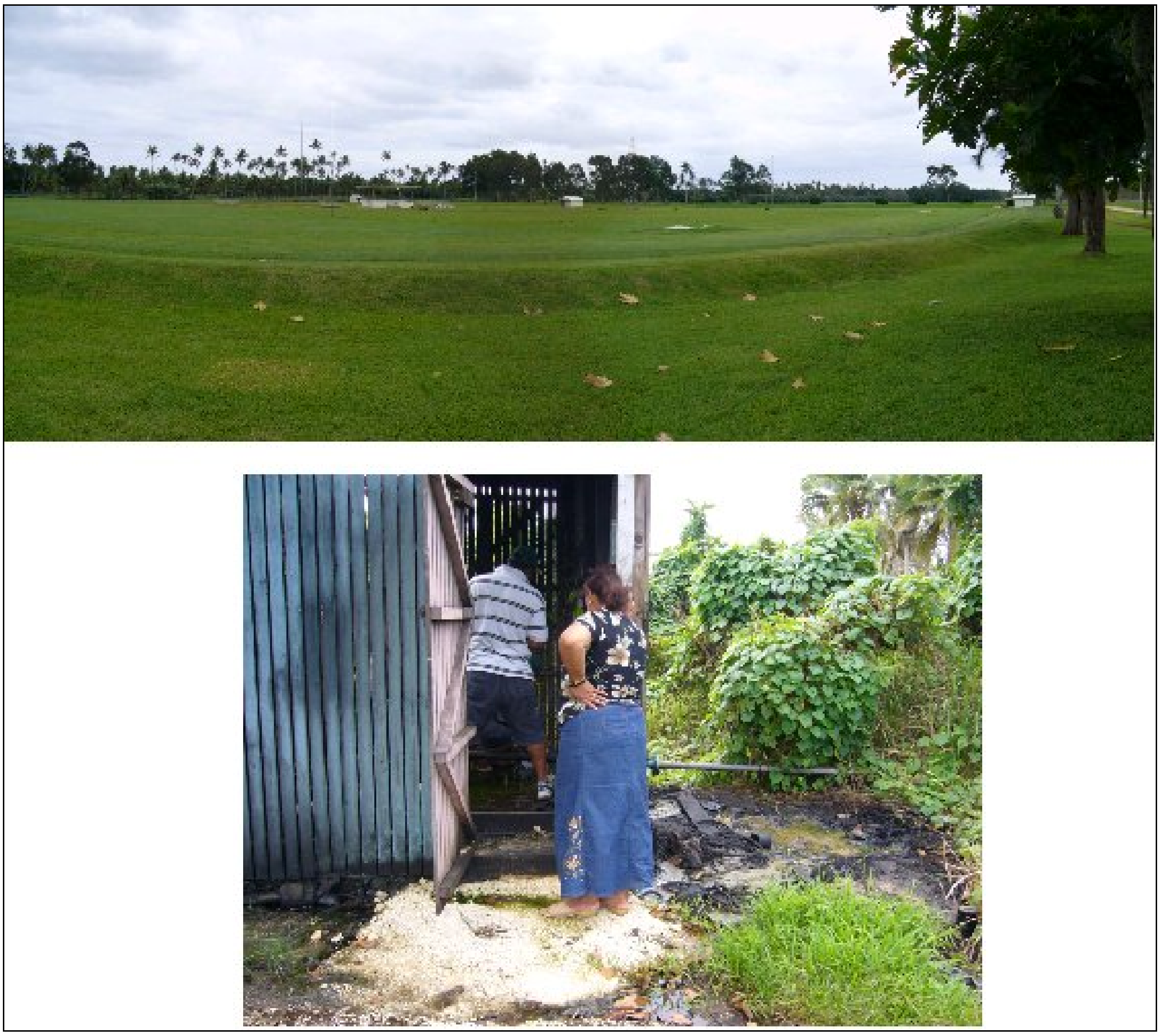

Figure 83 Only two groundwater samples had no *E, coli* and faecal coliforms absent at: A. Liahona College, PS 169 and B. Mataki'eua well 104

It is strongly recommended here that MoH use Colisure tests to screen village water supplies to provide a quicker indication of contamination and to enable more strategic targeting of water samples for full laboratory testing, which should also lessen the load on the hospital laboratory.

8.2 US Army survey of water quality, July 2007

Just prior to our field visit to Tongatapu in July 2007, a US Army team working with the Public

Health Section of the Environmental Health Division, MoH, conducted an intensive study of the water quality of 10 water supply systems connected with selected schools and villages. Rainwater tanks were also sampled. The project was in connection with the preparation of a Pandemic Preparation Plan. The water from domestic taps in rural villages tested were at Hofoa, Nukunuku, Houma, Tokomololo, Lavengatonga, Tatakamotonga and from three urban sites, the Nuku'alofa hospital kitchen, the Seaview Restaurant and at the old waste disposal site at Tukutonga. Rainwater from 3 general public schools at the villages of Te'ekiu, Pelehake and Talafa'ou were also tested. Some of the samples were apparently frozen. It was intended to test for faecal indicators, for pesticides, other organics and heavy metals (Dr Malachi 'Ake, Mr Te'efoto Mausia, MoH, Vaiola Hospital, private communication, 9th August, 2007). We heard later from the shipping agents that the samples had been impounded by US customs due to the failure to seek a quarantine clearance, resulting in a lengthy delay in analysis). To date, no results of these tests are available.

8.3 Comparison with previous measurements of faecal indicators

The Environmental Health Division, MoH has a record of faecal indicator species found in village water supply wells dating back to the 1970s. Unfortunately, this data is recorded in a book and is not available in electronic form. This data was not accessed for this study.

8.4 Intensive chemical sampling of 10 selected wells

8.4.1 Field measurements of EC and pH

The field measured EC and pH of the ten wells selected for intensive chemical sampling (see Table 10) are listed in Table 36.

Table 36 Field measurements of EC and pH in wells selected for intensive sampling

Site No.	Location	Well No.	Field Measurements		
			EC (μS/cm)	Temp (°C)	pH
1	Kolonga	49	910	25.0	6.94
2	Tatakamotonga	20	1,410	25.3	7.22
3	Tupou College	New Well	662	25.3	7.22
4	Vaini	218A	1,009	26.0	6.99
5	Pea	88	754	26.8	7.01
6	Liahona College	169	826	25.8	6.98
7	Fo'ui	151	1,239	25.0	6.86
8	Mataki'eua	115	848	26.9	7.36
9	Mataki'eua	211	1,720	26.4	7.36
10	Mataki'eua	104	1,650	25.3	7.40
		Mean	**1,103**	**25.8**	**7.13**
		Std Dev	380	0.72	0.20
		CV (%)	34.4	2.78	2.80
		Median	**960**	**25.6**	**7.12**
		Max	1,720	26.9	7.40
		Min	662	25.0	6.86

The mean EC for these 10 selected wells is slightly but not significantly higher that the means found for the 55 village wells (Table 12) and for the 31 Mataki'eua/Tongamai wells in the Mataki'eua/Tongamai wellfield (Table 18) and is higher that that at the TWMF boreholes. The mean pH of the selected wells lies between the mean pH for village and that for

Mataki'eua/Tongamai wells and the CVs of both properties are similar to the corresponding values in Table 12 and Table 18 . In terms of these parameters, the 10 wells chosen for intensive chemical sampling are therefore a reasonable representative sample of the village and Nuku'alofa water supply wells.

The mean pH in Table 36 is again higher than the equilibrium value of rainwater in equilibrium with air at atmospheric pressure and atmospheric CO_2 concentration at 25°C and lower than the equilibrium value of 8.4 for calcite in equilibrium with water under air at atmospheric pressure and atmospheric CO_2 concentration at 25°C. This agrees with the field measurements for all village wells, for the Mataki'eua/Tongamai wells and for the TWMF (Table 12, Table 18 and Table 27). This again points to higher dissolved CO_2 concentrations (and hence larger dissolved concentrations of calcium and bicarbonate) in the groundwater than expected from equilibrium with atmospheric concentrations of CO_2.

For these 10 samples, field measurements of EC and pH were made using two separately calibrated EC-pH meters (both TPS WP-81). The agreement between the meters, labelled A and B, is shown in Figure 84.

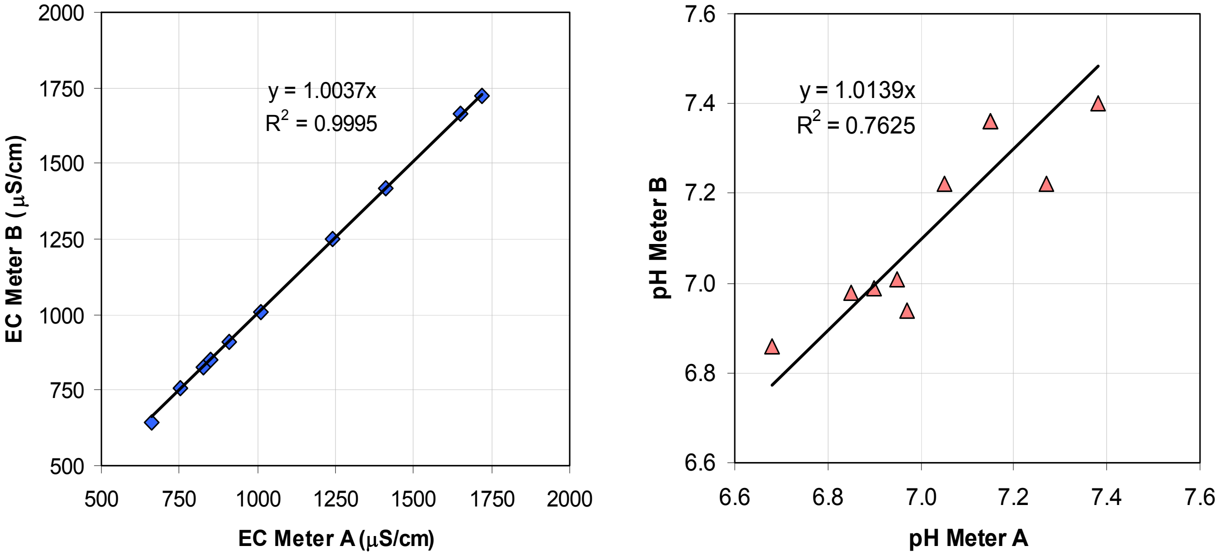

Figure 84 **Comparison of field EC and pH measurements for the 10 selected wells made with two separately calibrated EC-pH meters**

For EC, the agreement between both meters is excellent with a very high correlation coefficient (explaining 99.95% of the variance) and the slope of the comparison line differing by less than 0.4%. The means and standard deviations of the field EC for meters A and B were 1,103 ± 380 and 1,105 ± 386 μS/cm, respectively. For pH the agreement is less exact with a lower correlation coefficient (explaining 76.3% of the variance) and the slope of the comparison line differing by 1.4%. The means and standard deviations of the field pH for meters A and B were 7.13 ± 0.20 and 7.04 ± 0.20, respectively. The agreement between both instruments is good and we can be confident in these field measurements and on the representativeness of the wells chosen for intensive analysis.

8.4.2 Comparison of field and laboratory measurements of EC and pH

As part of the laboratory chemical analyses carried out on the water samples from the 10 selected wells, laboratory measurements were made of EC and pH. These are shown in Table 37. Also shown in Table 37 are total dissolved solids (TDS) calculated from the sum of the dissolved major cations and ions from the chemical analyses.

It can be seen that the mean laboratory EC is lower than the mean field EC and the mean laboratory pH is almost 0.4 greater than the field pH (Table 36). These results are consistent with the results found around the TWMF and reflect a change in water chemistry once the sample is exposed to the atmosphere (Hem, 1992).

Figure 85 shows the comparison between the field and laboratory measurement of EC and pH for the wells in Table 36 and Table 37.

Table 37 Laboratory measurements of EC, pH and TDS in wells selected for intensive sampling

Site No.	Location	Well no.	Laboratory Measurements		
			EC (μS/cm)	pH	Total Dissolved Solids (TDS mg/L)†
1	Kolonga	49	670	7.2	682
2	Tatakamotonga	20	1,100	7.4	781
3	Tupou College	New Well	630	7.5	483
4	Vaini	218A	980	7.4	673
5	Pea	88	590	7.4	473
6	Liahona College	169	830	7.4	527
7	Fo'ui	151	1,200	7.3	702
8	Mataki'eua	115	880	7.7	505
9	Mataki'eua	211	1,800	7.7	944
10	Mataki'eua	104	1,300	7.9	885
		Mean	**998**	**7.5**	**666**
		Std Dev	371	0.2	169
		CV (%)	37.2	2.8	25.3
		Median	**930**	**7.4**	**677**
		Max	1,800	7.9	944
		Min	590	7.2	473

† TDS here has been calculated from the sum of the dissolved major cations and anions.

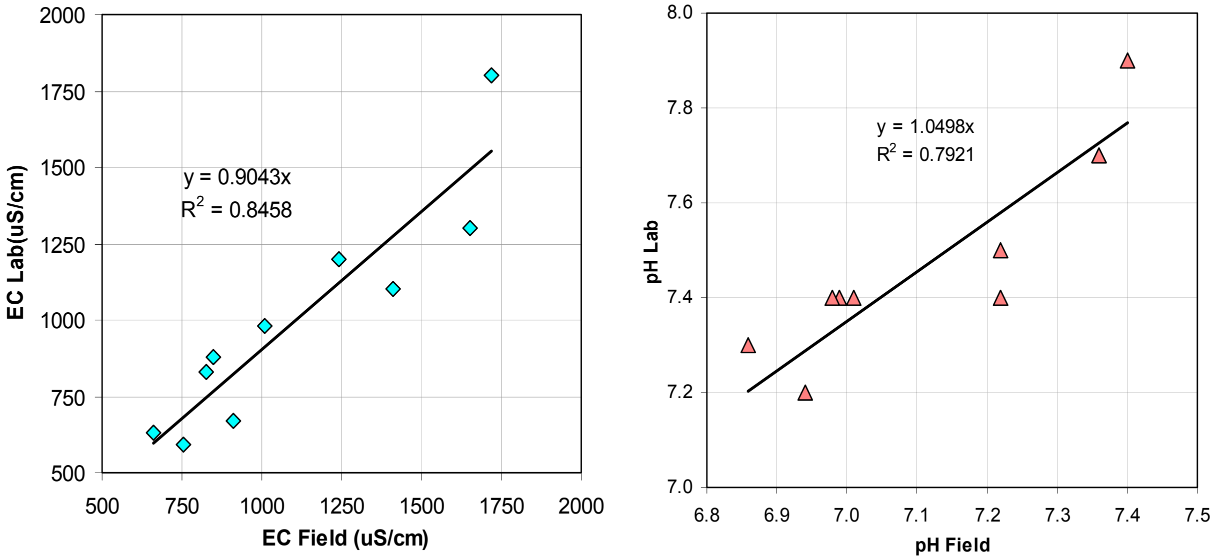

Figure 85 Comparison between laboratory and field measurements of EC and pH for the 10 selected water supply wells

Figure 85 shows that the laboratory EC values are on average about 10% lower than the field EC values and the laboratory pH values are about 5% higher than the field measurements. Since the two separate field measurements of EC and pH agreed well (Figure 84) we can be confident that these differences are real and point to a change in water chemistry after sampling.

8.4.3 Relation between TDS and EC

The total dissolved solids in Table 37 were estimated by summing the weights of major cations and anions found in the chemical analyses of the 10 samples. It is useful to relate this to the field measured EC as field measurements can then be used to estimate the TDS of groundwater from other locations in Tongatapu. The TDS is plotted against the field EC (Table 36) in Figure 86.

Although a linear plot fits the results in Figure 86 slightly better, the power law relation,

$$TDS = 4.292 \times EC^{0.721} \tag{20}$$

is preferred since it gives $TDS = 0$ mg/L when $EC = 0$ μS/cm.

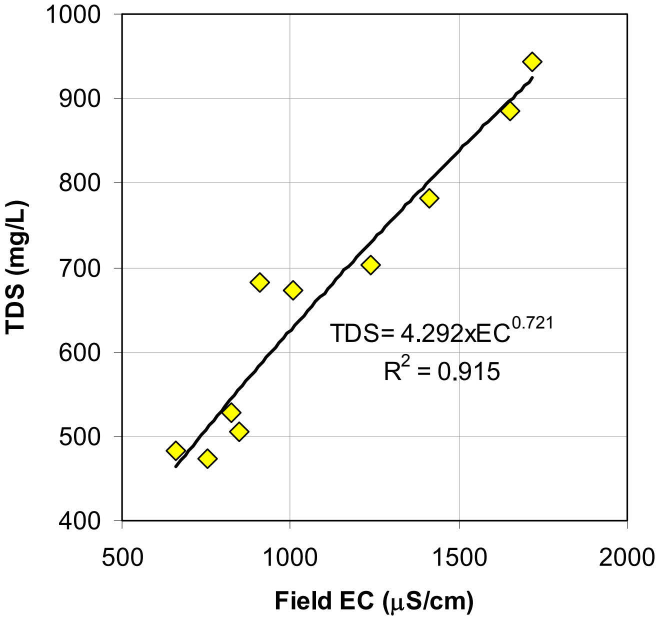

Figure 86 **Relation between TDS determined from the sum of the dissolved major ions and the field measured EC for the 10 selected wells**

8.4.4 Major cations and anions

The major ion composition in mg/L of the groundwater samples taken from across Tongatapu is listed in Table 38 and their relative contribution of their means in meq/L to the total dissolved salt content of mean groundwater in shown in Figure 87.

A comparison of Figure 87 with Figure 76 shows that the mean composition of the Tongatapu groundwater samples is more influenced by saline intrusion than the mean composition of the groundwater around the TWMF whose mean composition was dominated by calcite dissolution. This is consistent with the higher mean EC found for the 10 water supply well samples.

Only two of the major ion species in Table 38 have any health implications, nitrate, NO_3, and fluoride, F. For all wells tested, the concentrations of NO_3 and F are well below the WHO (2006) guideline values of 50 and 1.5 mg/L, respectively. Fresh volcanic ash is rich in F (Hem, 1992) and the ash-derived soils of Tongatapu may well be its source for groundwater.

The concentration of F in groundwaters containing Ca is often controlled by the formation of the mineral fluorite, CaF_2, whose solubility product at 25°C is approximately $10^{-10.58}$ $[\text{mole/L}]^3$ (Brown and Roberson, 1979). With the mean groundwater Ca concentration in Table 38, the concentration of F in equilibrium with fluorite would therefore be 2 mg/L, higher than that in Table 38. The concentration of F in Tongatapu groundwater does therefore not appear to be in equilibrium with fluorite.

Table 38 Major cations and anions in the 10 intensively sampled wells

Site No.	Location	Well no.	Cations (mg/L)				Anions (mg/L)					
			Na	K	Ca	Mg	Cl	F	HCO_3	SO_4	NO_3	CO_3
1	Kolonga	49	44	1.2	130	6.8	61	0.5	420	14	4.2	<5
2	Tatakamatonga	20	140	7.7	90	15	270	0.2	209	36	13	<5
3	Tupou College	New Well	25	1.2	96	4.1	31	0.2	309	5.2	12	<5
4	Vaini	218A	86	4.9	97	10	140	0.2	306	19	9.5	<5
5	Pea	88	32	1.2	90	4.9	53	0.2	278	7.8	5.3	<5
6	Liahona College	169	44	1.5	94	6.6	74	0.2	287	13	6.8	<5
7	Fo'ui	151	86	2.3	110	11	170	0.2	293	23	6.2	<5
8	Mataki'eua	115	42	1.5	91	6.3	76	0.2	269	12	6.5	<5
9	Mataki'eua	211	180	10	100	20	350	0.1	232	45	7	<5
10	Mataki'eua	104	170	11	92	18	320	0.1	217	51	6.6	<5
		Mean	**85**	**4.3**	**99**	**10.3**	**155**	**0.2**	**282**	**22.6**	**7.7**	**<5**
		Std Dev	59	3.9	12	5.6	118	0.1	60	16.0	2.9	
		CV (%)	69.0	92.1	12.6	54.8	76.7	52.4	21.4	70.8	37.2	
		Median	**65**	**1.9**	**95**	**8.4**	**108**	**0.2**	**283**	**16.5**	**6.7**	
		Max	180	11.0	130	20.0	350	0.5	420	51.0	13.0	
		Min	25	1.2	90	4.1	31	0.1	209	5.2	4.2	

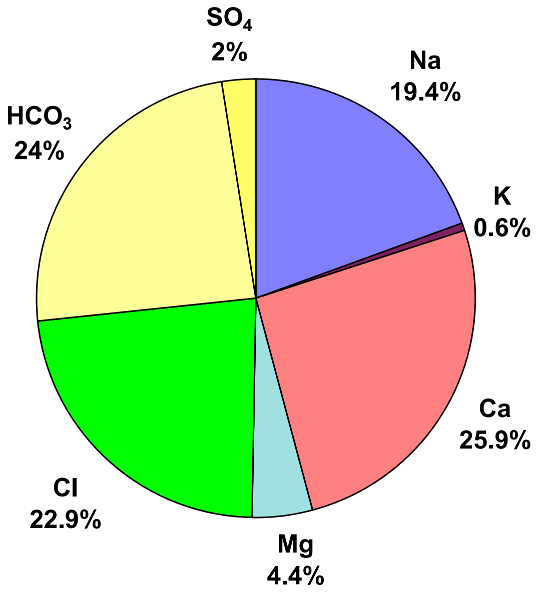

Figure 87 Relative contribution of major ions (in meq/L) to the total dissolved salt content of mean groundwater for the 10 selected wells

8.4.5 Relation between bicarbonate concentration and pH

At Tapuhia, a strong correlation was found between bicarbonate concentration and field pH. Figure 88 shows that the relation is not so strong for the 10 selected wells and only has a correlation coefficient of 0.67. The relationship in Figure 88 can be expressed as:

$$\log[HCO_3]_{Wt} = 4.54 - 0.295 \times pH \text{ or} \qquad [21]$$

$$\log[HCO_3]_M = -0.241 - 0.295 \times pH$$

Comparison with the results for Tapuhia in equation [19] shows that both the intercepts and the slopes of the relations in equation [21] are quite different.

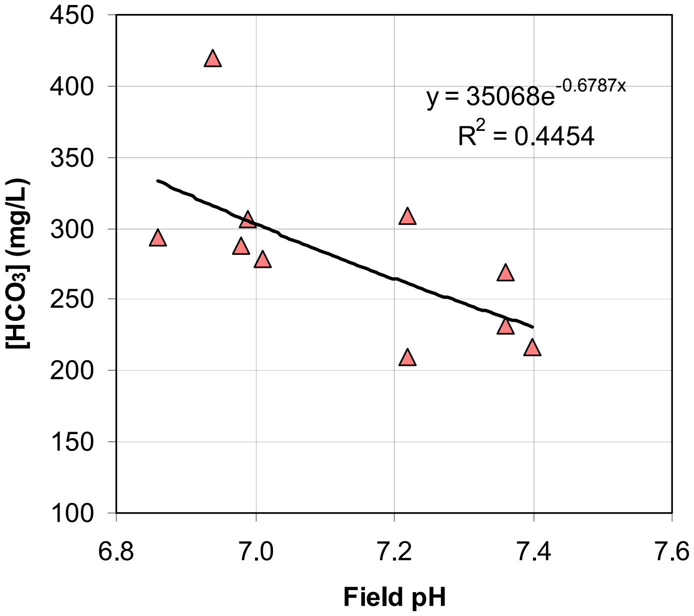

Figure 88 Relation between bicarbonate concentration and field pH for the 10 selected wells

A possible reason for this could be due to the fact that the groundwater system is not closed or that the partial pressure of CO_2 in recharge differs between locations. Some evidence for this can be seen from the Kolonga well, well 49 where the water table is only about 3.5 m below the soil surface and has by far the highest bicarbonate concentration. It would be interesting to test this idea by measuring the field bicarbonate concentrations and pH in wells with different depths to groundwater.

8.4.6 Relation between EC and chloride concentration

The data in Table 36 and Table 38 can be used to derive a relation between dissolved chloride ion and the field measured EC. The data is plotted in Figure 89.

The relationship found in Figure 89 with a strong correlation coefficient of 0.989 is:

$$[Cl] = 0.3156 \times EC - 193.5 \qquad [22]$$

where $[Cl]$ is the chloride concentration in mg/L and *EC* is the field EC of the water sample in μS/cm. A much weaker fit is found if EC measured in the laboratory is used.

The relation found by Furness and Helu (1993) can be transposed to:

$$[Cl] = 0.3199 \times EC - 173.74 \qquad [23]$$

The slopes of these relationships differ by only 1.3% while the intercepts differ by about 10%. It is not clear if Furness and Helu used field or laboratory EC data for their relationship. However, the relationships are useful for estimating chloride concentrations from field measured EC.

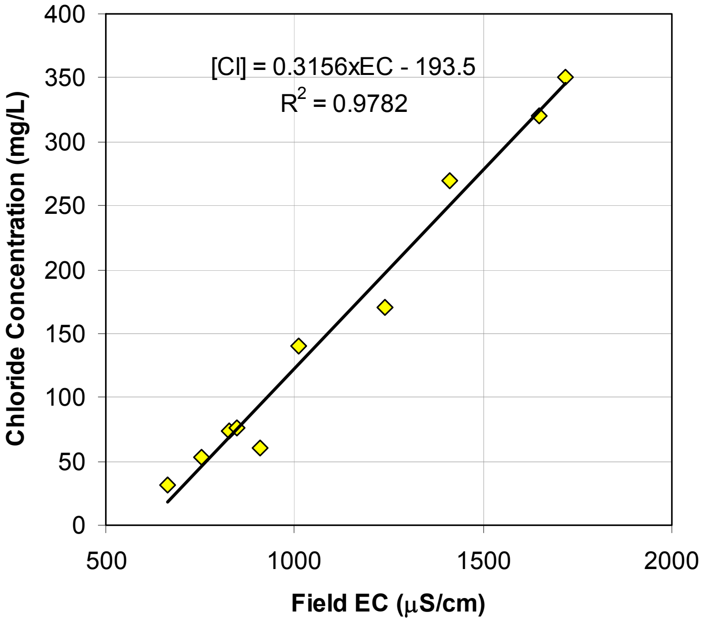

Figure 89 **Relation between chloride concentration and field EC for the 10 selected wells**

8.4.7 Relation between EC and concentrations of other major ions

The predominant source of chloride ion in fresh groundwater in Tongatapu is dispersion from underlying seawater. Since the concentration of chloride is strongly correlated with the field measured EC, it is likely that other ions, such as Na, K, Mg, and SO_4 are also correlated with EC. Figure 90 shows the correlation between the concentration of these ions and EC.

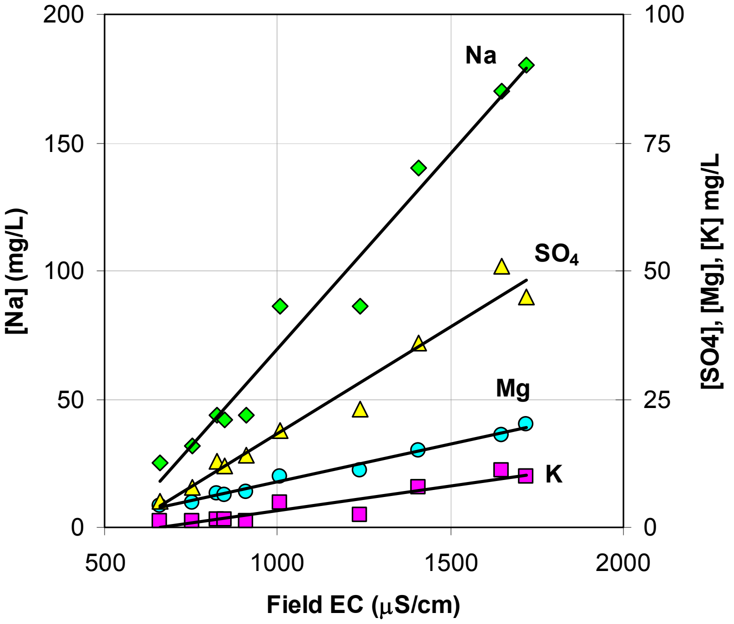

Figure 90 **Relationships between the concentration of major ions Na, K, Mg, and SO_4 and the field measured EC for the 10 selected wells**

The correlations in Figure 90 for some of the ions are as strong as that for chloride (Figure 89) and are therefore useful. The concentration data in the figure for species [X] (in mg/L) were fitted to the linear relation:

$$[X] = A \times EC - B \qquad [24]$$

with *EC* in μS/cm. Table 39 lists the values for the slope, A, and intercept, B, together with the value of R^2 for the major ion species.

Table 39 Values of parameters in fitting major ion concentrations (mg/L) to equation [24]

Major Ion [X]	A	B	R^2
Mg	0.0147	5.98	0.985
Cl	0.316	194	0.978
Na	0.152	83	0.971
SO_4	0.0414	23.1	0.967
K	0.0096	6.3	0.865
HCO_3	-0.097	-389	0.37
Ca	-0.0018	-101	0.0031
NO_3	0.0003	-7.4	0.0016

As expected, the major ions predominantly sourced from seawater, Mg, Cl, Na, SO_4, and K, all have strong correlations with EC while those sourced from carbonate dissolution, Ca and HCO_3 or from other sources, NO_3 have no significant correlation. Figure 91 shows that the Ca concentration is independent of EC. The independence of nitrate concentration on EC emphasises that the principal source of nitrate in groundwater does not come from the dispersion and mixing of seawater with fresh groundwater.

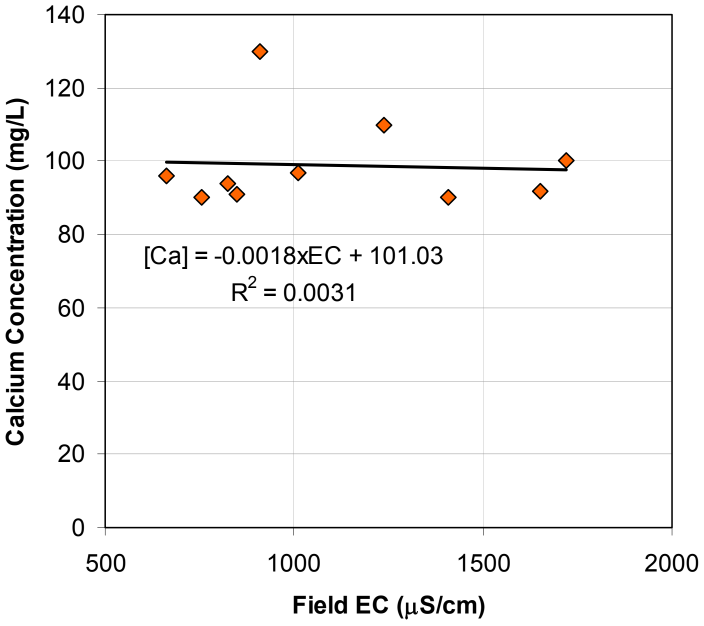

Figure 91 Independence of calcium concentration on the field determined EC

Equation [24], together with the parameter values in Table 39, provides a means of estimating the major ion concentrations of groundwater in Tongatapu for Na, K, Cl, Mg, and SO_4.

8.4.8 Ion ratios of groundwater samples

The ion ratios of the major ions provide a way of comparing the relative contributions of limestone dissolution and seawater dispersion and dilution to the composition of groundwater in Tongatapu. The comparison is based on the assumption that while dilution will change the concentration of dissolved species, the relative proportions expressed as a ratio ought to remain unchanged on dilution. Chloride is often considered a conservative species in dilute groundwater systems and is used as a standard against which to compare other species. The ratios of the major ions in seawater provide a characteristic signature which can be used to trace the influence of seawater.

Table 40 compares the mean ion ratios found for the 10 selected wells across Tongatapu with those for seawater and those for a relatively pure limestone aquifer (Hem, 1992).

It is clear from the ratios in Table 40 that the main sources of Na, K, Mg and SO_4 in the Tongatapu groundwater samples are from diluted seawater. The source of Ca and HCO_3 is clearly dissolution of the limestone aquifer. Equation [5] predicts that dissolution of calcite should produce a Ca/HCO_3 ratio of 0.328 similar within error to that in Table 40. The ratios for fluoride, F, and nitrate, NO_3, are much higher than those for seawater showing an additional source of these ions. For nitrate this appears to be anthropogenic and for fluoride it may be the volcanic-ash derived soils (Hem, 1992). The relation between the composition of the groundwater and that of the supposed end members, seawater and rainwater, in a limestone aquifer can be examined by plotting the ion ratios as a function of the reciprocal of the chloride concentration, 1/Cl (Figure 92).

For the ratios of concentrations of Ca and HCO_3 to Cl, Figure 92A and B shows that the seawater ratios (at 1/Cl $\approx 5.3\times10^{-5}$ L/mg) appear to be one end member on a linear mixing line. For Mg/Cl, (Figure 92C) there is again a good linear mixing line, but the Mg/Cl ratio at the seawater value of 1/Cl lies below that for seawater. The ratio Ca/HCO_3 (Figure 92D) is far removed from the ratio in seawater (2.89, Table 40) and the data scatters around the theoretical limit for the dissolution of calcite (equation [5]) except at higher chloride concentrations (lower 1/Cl) where the values of Ca/HCO_3 lie increasingly above this value.

Table 40 Mean ratios of major ions in Tongatapu groundwater compared with those for seawater and groundwater from a relatively pure limestone aquifer (Hem, 1992)

Source	Na/Cl	K/Cl	Ca/Cl	Mg/Cl	HCO_3/Cl	SO_4/Cl	F/Cl	NO_3/Cl	Ca/HCO_3	Ca/Mg
	Ratios of concentrations in mg/L									
Limestone Aquifer	0.023*		6.0	0.450	19.0	0.400	0.000	n/a	0.316	13.3
Mean Seawater	0.553	0.021	0.022	0.071	0.007	0.142	6.8E-05	1.6E-04	2.89	0.304
Mean Tongatapu	**0.596**	**0.026**	**1.16**	**0.081**	**3.6**	**0.157**	**0.003**	**0.093**	**0.359**	**12.5**
Std Dev	0.098	0.008	0.92	0.026	3.1	0.030	0.003	0.107	0.052	6.4
Range	0.51-0.81	0.014-0.039	0.29-3.1	0.06-0.13	0.7-10.0	0.13-0.23	0.0003-0.008	0.02-0.39	0.31-0.43	5-23.5

*Value for (Na+K)/Cl

8.4.9 Ion ratios of "end members"

The correlations between ion ratios and either 1/Cl or Cl concentration provide a way to estimate the mean ratios of the "end members" of the mixing line, the ratios in seawater and recharge water. Using relationships fitted to the ion ratio data, as in Figure 92, we can estimate the expected value of the various ion ratios in seawater (1/Cl $\approx 5.3\times10^{-5}$ L/mg). These are shown in Table 41 where they are compared with the values for mean seawater (Hem, 1992).

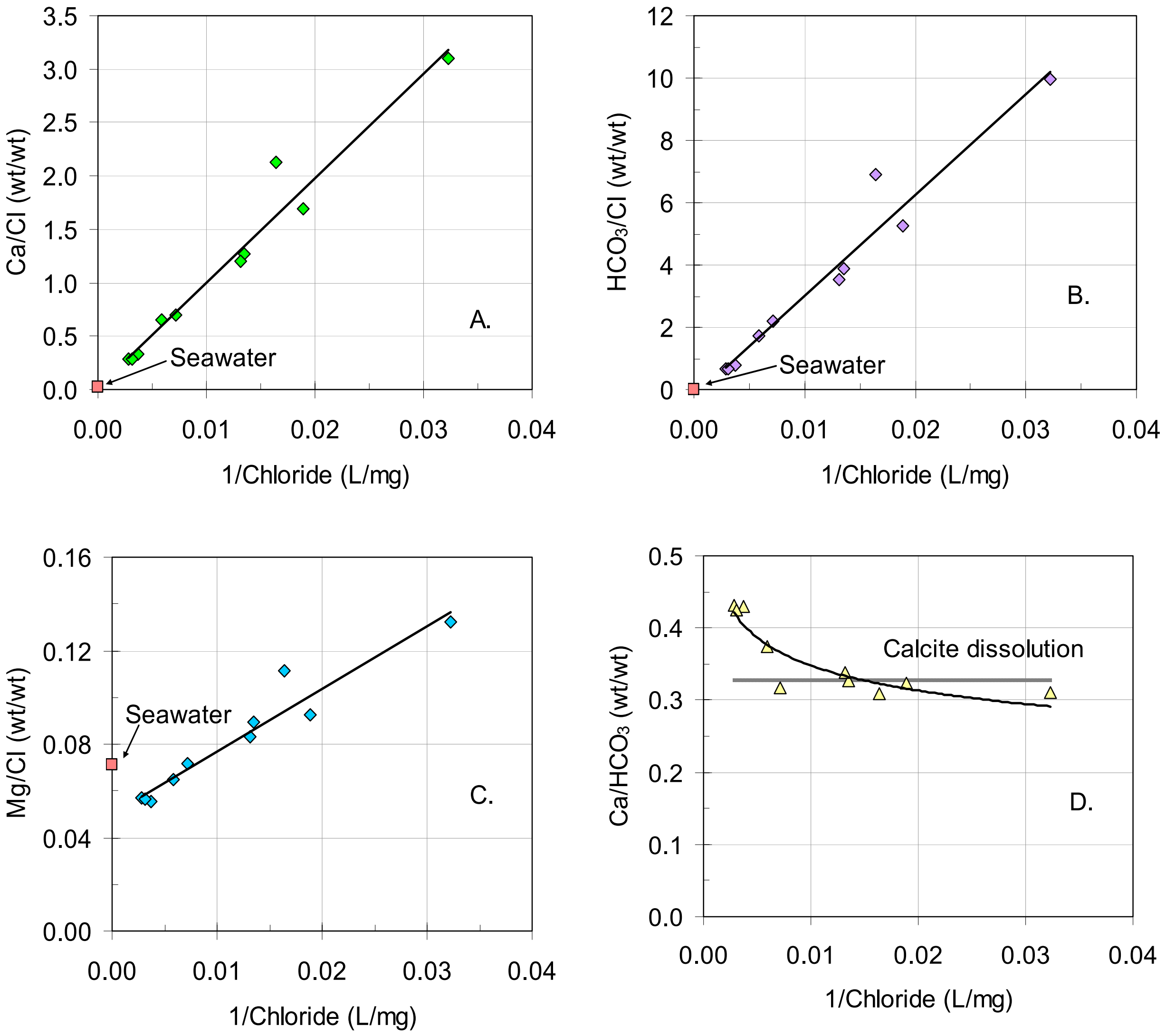

Figure 92 Major Ion ratios for Tongatapu groundwater samples as a function of the reciprocal of the chloride concentration compared with expected seawater ratios (A, B, C), and with calcite dissolution (D)

It can be seen that apart from F/Cl, NO_3/Cl and HCO_3/Ca the values of the ratios extrapolated to seawater chloride concentrations are very close to those expected for seawater. The strong relationships between the ion ratios and chloride concentration can also be extrapolated to recharge water concentration (Cl concentration approximately 4 mg/L). These ratios are also listed in Table 41.

If we assume that the concentration of chloride in the recharge water is 4 mg/L then the concentration of the major ions in the recharge as it first enters the limestone aquifer can be estimated from the extrapolated ion ratios for recharge water in Table 41. These estimated concentrations are shown in Table 42. These concentrations show that dissolution of calcite dominates the concentration of the recharge water as it enters the aquifer and has a high bicarbonate concentration. It is interesting to note that the bicarbonate concentration in the sample from Kolonga with the water table close to the soil surface is also elevated, indicating high dissolved CO_2 in the overlying soil water. The mean concentration of nitrate and fluoride in the recharge water is consistent with a soil water source of these ions.

Table 41 Values of ion ratios extrapolated to seawater and recharge water chloride concentrations using the relationships between ion ratios and chloride or reciprocal chloride concentrations. Extrapolated ratios are compared with seawater ratios (Hem, 1992)

Ion Ratio	Value at seawater chloride concentration		Extrapolated Value in Recharge Water
	Literature Value	Extrapolated Value	
Na/Cl	0.55	0.49	0.98
K/Cl	0.021	0.025	0.022
Ca/Cl	0.022	0.027	26
Mg/Cl	0.071	0.05	0.25
HCO_3/Cl	0.0075	0.0062	120
SO_4/Cl	0.14	0.14	0.23
F/Cl	6.8E-05	1.5E-05	0.14
NO_3/Cl	1.6E-04	5.1E-05	1.5
Ca/HCO_3	2.89	0.77	0.29
Ca/Mg	0.304	0.36	104

Table 42 Mean concentration of recharge water in Tongatapu first entering the limestone aquifer from the extrapolated ion rations in Table 41 and assuming the chloride concentration in recharge is 4 mg/L

Ion	Conc (mg/L)
Na	3.9
K	0.09
Mg	1.0
Ca	104
Cl	**4**
HCO_3	480
SO_4	0.9
F	0.6
NO_3	6.0

8.4.10 Estimation of all major ions from field measured EC

The relationship between ion concentrations and field measured EC, equation [12], together with the parameter values for the ions in Table 39 provide a means of estimating the Cl, Na, K, Mg and SO_4 concentrations, but not Ca and HCO_3 concentrations from field measured EC. The ion ratios to Cl relations for these two ions provide a way of estimating these remaining two species. These relations are:

$$[Ca] = 106.8[Cl]^{-0.017}$$
$$[HCO_3] = 622[Cl]^{-0.17} \qquad [25]$$

with the Cl concentration being estimated from the field measured EC, equations [22] or [23] and the parameter values in Table 39.

8.5 Comparison with previous measurements of major ions

In this section we compare the results of the chemical analyses carried out in this work in 2007 with previous findings in Tongatapu.

8.5.1 Trends in the chloride concentration of groundwater, 1965 – 2007

Furness and Helu (1993) provided a comparison of chloride concentration in 27 water supply wells across Tongatapu, including 5 Mataki'eua wells, in 1965, 1971 and 1991. They concluded that pumping of groundwater over the past 30 years had increased the chloride concentration of groundwater in Tongatapu. It is important in any assessment of pumping impacts on groundwater salinity that the impacts of pumping be separated from the impacts of variable rainfall. The EC data for Tongatapu water supply wells reported in section 5.2 and the relationship between EC and Cl concentration (equation [22]) provides a way of comparing the chloride concentrations measured in August 2007 with those reported in Furness and Helu (1993). Despite the passage of time, 21 of the 27 wells listed by them appear to be still in use. The comparison for these wells is given in Table 43 and the trends are shown in Figure 93.

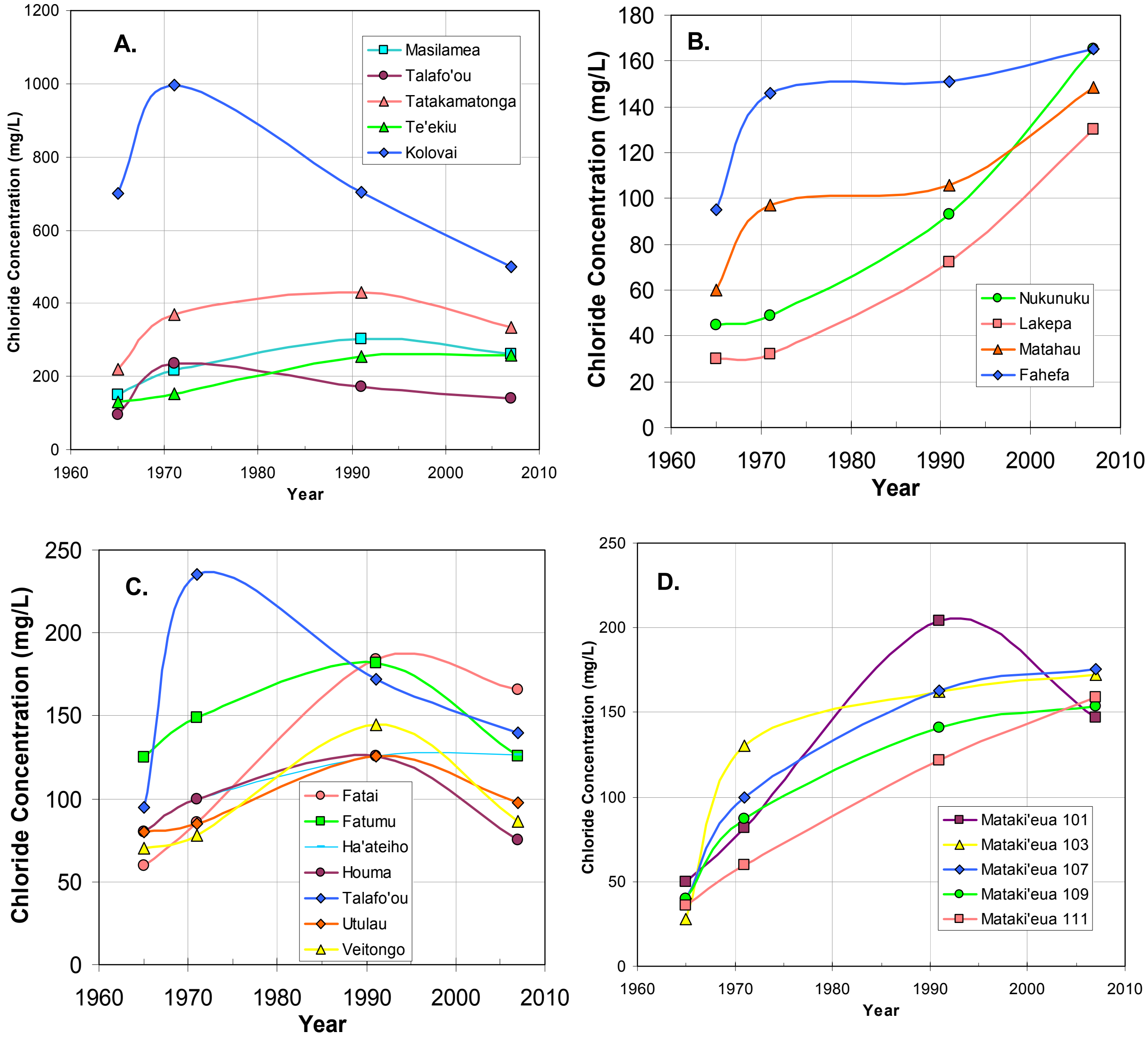

Figure 93 Chloride ion concentration trends in Tongatapu water supply wells from 1965 to 2007. A. Village wells with high but decreasing salinity., B. Village wells with increasing salinity, C. Village wells with lower and decreasing salinity and D. Mataki'eua wells

One difficulty in monitoring water supply wells in Tongatapu is that villages frequently have more than one well in their locality and periodically switch pumping between wells. Since wells are often not identified by number, It is unclear whether this is the case for the wells in Table 43 and Figure 93. Irrespective of the cause, the increase in salinity at these wells requires investigation.

Table 43 Trend in the chloride concentration of water supply wells in Tongatapu (data for 1965, 1971 and 1991 from Furness and Helu, 1993)

Village	Well No.	Chloride concentration (mg/L)				Change since 1991 (%)
		1965	1971	1991	2007	
Fahefa	157	95	146	151	165	9
Fatai	133	60	86	184	166	-10
Fatumu	14	125	149	182	125	-31
Fua'amotu Int.	9	-	20	35	22	-36
Ha'ateiho	175	80	100	126	126	0
Houma	165	80	100	126	75	-40
Kolovai	155	700	997	702	498	-29
Lakepa	134	30	32	72	130	81
Masilamea	68	150	218	302	261	-14
Matahau	147	60	97	106	148	40
Mataki'eua	101	50	82	204	147	-28
Mataki'eua	103	28	130	162	172	6
Mataki'eua	107	40	100	163	176	8
Mataki'eua	109	40	87	141	154	9
Mataki'eua	111	36	60	122	159	30
Nukunuku	144	45	49	93	165	77
Talafo'ou	61	95	235	172	140	-19
Tatakamatonga	19	220	369	429	334	-22
Te'ekiu	65	130	154	256	257	0.6
Utulau	161	80	85	126	98	-23
Veitongo	201	70	78	145	86	-40
Mean		**111**	**161**	**190**	**172**	**-10**
Std Dev		147	207	144	100	
CV (%)		132	129	76	58	
Geometric Mean		**77**	**109**	**157**	**147**	**- 6.5**
Maximum		700	997	702	498	
Minimum		28	20	35	22	
Number		20	21	21	21	

Examination of the data in Table 43 and Figure 93 shows that the mean and geometric mean[8] of the chloride concentration have decreased since 1991. Individually, 8 of the wells have increased in salinity since 1991 and a further 2 are essentially identical to measurements in 1991. Of those, 4 of the 5 wells at the Mataki'eua wellfield showed increases. The geometric mean of the Mataki'eua wells increased by 3.2% overall between 1991 and 2007. The geometric mean of the remaining 13

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[8] The standard deviations of the means in Table 43 are large indicating that the concentration data is not normally distributed. The geometric mean assumes the data is log normally distributed.

village water supply decreased by 9.3% overall between 1991 and 2007. Eleven village wells showed a decrease in salinity between 1991 and 2007. The information in Table 43 and Figure 93 helps identify wells that need further investigation. Wells at Lakepa (134), Nukunuku (144), Matahau (147), and Mataki'eua (111) all showed significant increases in salinity since 1991 while wells at Ha'ateiho (175) and Te'ekiu (65) were unchanged.

A critical issue concerning the observed increases in salinity in some of the wells is separating the influence of pumping from that of variable rainfall. Analysis of this is hampered by the lack of data on the month of the year in which measurements were taken. Here we simply use the annual rainfall in the year in which measurements were reported. Figure 94 shows the comparison between geometric mean chloride contents for the Mataki'eua and village water supply wells and the annual rainfall for Nuku'alofa since 1960.

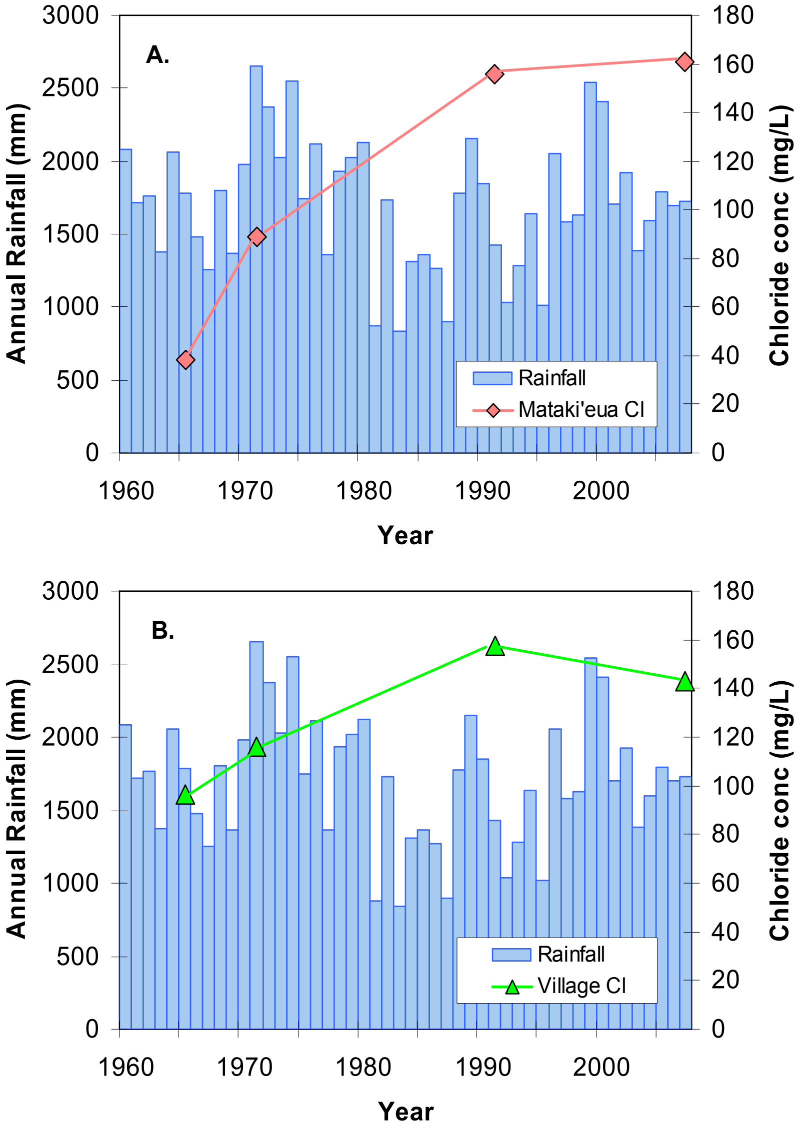

Figure 94 Comparison between the annual Nuku'alofa rainfall since 1960 and the geometric mean chloride concentration from A. Mataki'eua wells and B. village water supply wells listed in Table 43

The 1965 chloride samples were taken in a year that had annual rainfall in the 58th percentile of rainfalls since 1945. Those for 1971 were in the year with the highest rainfall on record (100th percentile) while samples taken in 1991 and 2007[9] were in the 27th and at least the 47th percentiles, respectively. The rainfall regimes when water samples were taken in 1965 and 2007 are therefore comparable and the significant increase in salinity that has occurred between 1965 and 2007 in all wells except that at Fatumu appears attributable to groundwater pumping, assuming that there is no analysis error in the early chloride estimations.

Even more remarkable is the increase in salinity between 1965 and the record rainfall year of 1971. Large increases in salinity between these two years are evident in many of the wells in Figure 93 and this is unexpected unless pumping increased dramatically in this period. The sampling in 1991 occurred in a drier year and the salinity in several of the wells in 1991 show maxima in this year. Furness and Helu (1993) concluded that the increase in salinity that occurred at this measurement was a result of groundwater pumping. The results here suggest that this is not universally true, since 1991 was a drier year. The comparison between 1991, a drier year and 2007, an average year, is however informative. Any salinity that is the same or shows an increase in salinity over that period is clearly due to pumping since increased rainfall should lower salinity. A total of 10 out of the 21 wells examined in Tongatapu show continued increases in salinity due to pumping since 1991.

Unfortunately the frequency of chloride concentration data for the wells throughout Tongatapu is too sparse in general to determine a relationship between chloride concentration and rainfall. Also village wells are unmetered so the relationship of salinity to volume of water pumped from the well cannot be determined. The TWB database does list a few wells in which chloride concentration was also determined during the drier period in 1986-7. The data for one well showing the relationship between chloride concentration and annual rainfall is shown in Figure 95.

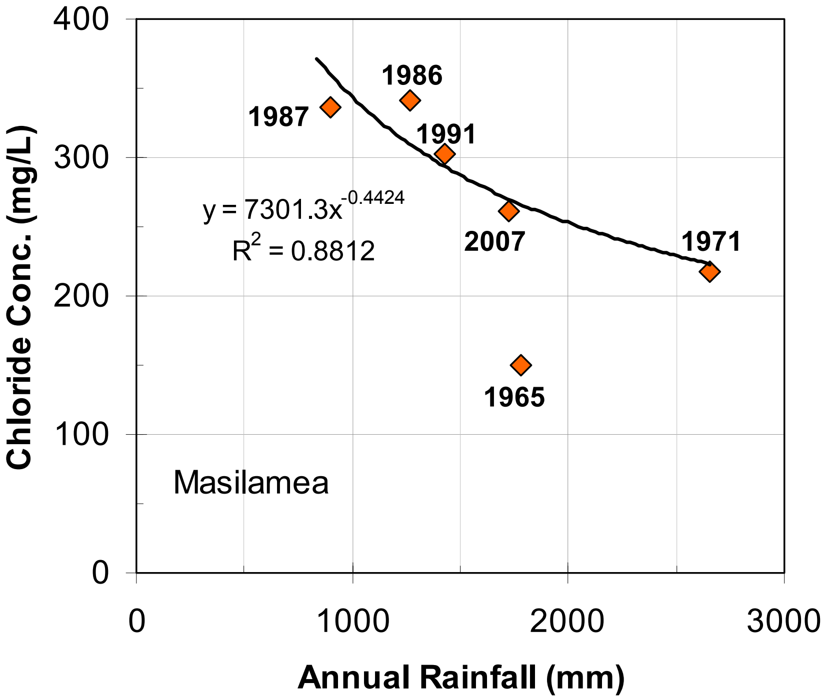

Figure 95 Relation between chloride concentration and annual rainfall for Masilamea village well 68

The 1965 chloride concentration lies well below the curve which fits well the data for other years. Again it must be concluded that either there was a major increase in pumping between 1965 and 1971 or the 1965 set of data is in error.

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[9] Rainfall for 2007 was only available up to November.

For the well at Masilamea, the data for 1971, 1986, 1987, 1991, and 2005 fit the approximate relationship:

$$[Cl] = 7301 \times P_{an}^{-0.442} \qquad [26]$$

where $[Cl]$ is the chloride concentration (mg/L) and P_{an} is the annual rainfall (mm). Equation [26], if extrapolated, predicts that if the annual precipitation dropped below 280 mm, the groundwater at this well in Masilamea would exceed the WHO (1971) *International Guidelines for Drinking Water* palatability limit of 600 mg/L.

The data presented in this section demonstrates the importance of regular systematic monitoring in order to manage the combined impacts of pumping and variable rainfall on groundwater salinity. Using the data, we have been able to identify wells in which there is a significant impact of pumping on salinity. These require careful investigation. The wells at Mataki'eua appear to show a continuing increasing salinity trend although the rate of increase is less than in the period 1965 to 1971. Information on groundwater salinity, however, is insufficient. It must be coupled with information on rainfall and on the rate of extraction of groundwater by pumping.

8.5.2 Comparison with previous major ion analyses

A search of the TWB database reveals limited numbers of major ion analyses of Tongatapu groundwater. A few wells were sampled in 1978, 1987 and 1992. Examination of the data reveals significant problems. Some analyses did not include bicarbonate, a major ion in Tongatapu groundwater. Other analyses found limited HCO_3 but more significant concentrations of carbonate and dissolved CO_2 which is not possible for the reported pHs at sampling. In earlier monitoring wells at Kolonga, Fua'amotu and Liahona wells, samples were taken at the top of the groundwater and saline bottom of the well. The charge balance between the anions and the cations in the bottom samples reveal major charge imbalance so these results were discarded. For the top samples, only two appeared to have reasonable values for bicarbonate concentrations. In order to compare the results in 2007 with the earlier measurements we have estimated the HCO_3 concentration from the charge balance equation for each sample:

$$[HCO_3]_w = 61.02 \times \{([Na]_m + [K]_m + 2 \times ([Ca]_m + [Mg]_m)) - ([Cl]_m + [NO_3]_m + 2 \times [SO_4]_m)\} \qquad [27]$$

where $[HCO_3]_w$ is the concentration of bicarbonate in mg/L and $[X]_m$ is the concentration of the major cations and anions in millimoles/L (mM/L). The results of past measurements of the major ion chemistry of Tongatapu are summarised in Table 44.

The mean pH in Table 44 is similar to that found in 2007 for the wells across Tongatapu (Table 36) while EC and concentrations of the major ions Na, K, Cl, and SO_4 are lower than those in Table 38 and the past mean calcium and bicarbonate concentrations are higher than found in this study in Table 38. The mean ion ratios from these past measurements are listed in Table 45 shows plots of the major ion ratios for the sites in Table 44 as a function of the reciprocal chloride concentration.

The mean ion ratios in Table 45 reflect again the predominant seawater origins of sodium, potassium and sulfate ions and the calcite weathering origins of the calcium and bicarbonate as found in this work in Table 40. The magnesium to chloride ion ratio is higher in these older measurements than in the 10 wells sampled in this work showing a contribution of limestone weathering as well as seawater to magnesium concentrations although seawater can still be seen as one end member (Figure 96). This is because the previous analyses in Table 44 include a low salinity sample from Fua'amotu that has ion ratios similar to those of the estimated recharge water in Table 42. The contribution of the two sources, seawater and aquifer dissolution, can be seen in the non-linear mixing curve for Ca/Mg in Figure 97 which also shows ratios from previous results as well as this work. Finally, the mean nitrate to chloride ratio from previous work is identical within error to that found in this work (Table 40) and reflects inputs of nitrate that are neither from seawater nor the limestone aquifer.

Table 44 Previous major ion analyses of Tongatapu groundwater

Date	Location	Well No.	pH	EC (μS/cm)	Cations (mg/L)				Anions (mg/L)			
					Na	K	Ca	Mg	Cl	HCO_3†	NO_3	SO_4
1/01/78	Fua'amotu Well	10	7.4	466	20	0.6	120	4	21	402	1.3	0
1/02/78	Hu'atolitoli Well		7.2	730	64	3	100	10	98	330	7.9	18
1/01/78	Kolonga Well		7.5	847	80	2.3	90	12	142	273	2.2	24.5
1/01/78	Liahona Well		7	848	100	2.2	150	14	106	515	1.1	20.6
1/02/78	Malapo Well		7.3	760	70	3	100	10	114	322	5.1	17
27/04/92	Kolofo'ou – PO	Retic.	7.2	1,100	78	2.2	130	11	150	386		14
1/01/78	Kolofo'ou TWB	Retic.	7.5	777	40	1	140	8.8	46	474	10.6	7
1/02/78	Tupou College Well		7.2	500	18	1	104	5	21	344	5.8	4
1/01/78	Vaini Farm		7.5	678	40	1.5	130	10	82	393	2.7	13.8
28/04/92	Mataki'eua	114	7.0	940	54	1.4	130	8	110	452		10
		Mean	**7.29**	**765**	**56**	**1.8**	**119**	**9.3**	**89**	**389**	**4.6**	**12.9**
		Std Dev	0.18	190	27	0.8	20	3.0	46	75	3.4	7.7
		CV (%)	2.5	25	48	46	17	33	52	19	74	59
		Median	**7.25**	**769**	**59**	**1.9**	**125**	**10**	**102**	**389**	**3.9**	**13.9**
		Max	7.50	1,100	100	3.0	150	14	150	515	11	24.5
		Min	7.00	466	18	0.6	90	4.0	21	273	1.1	0.0

† Pink shaded value from sum of HCO_3, CO_3, and CO_2 found in analysis, fawn shaded values calculated from charge balance equation [27].

Table 45 Mean ion ratios of past measurements in Tongatapu groundwater compared to seawater and groundwater from a limestone aquifer (Hem, 1992)

Source	Na/Cl	K/Cl	Ca/Cl	Mg/Cl	HCO_3/Cl	SO_4/Cl	NO_3/Cl	Ca/HCO_3	Ca/Mg
	Ratios of concentrations in mg/L								
Limestone Aquifer	0.023		6.0	0.450	19.0	0.400	n/a	0.316	13.3
Mean Seawater	0.553	0.021	0.022	0.071	0.007	0.142	1.6E-04	2.89	0.304
Mean Previous Samples	**0.695**	**0.024**	**2.13**	**0.129**	**7.0**	**0.155**	**0.094**	**0.309**	**14.6**
Std Dev	0.190	0.010	1.83	0.058	6.2	0.039	0.102	0.018	6.7
Range	0.49-0.95	0.013-0.048	0.63-5.7	0.07-0.24	1.9-19	0.091-0.19	0.01-0.28	0.29-0.34	7.5-30

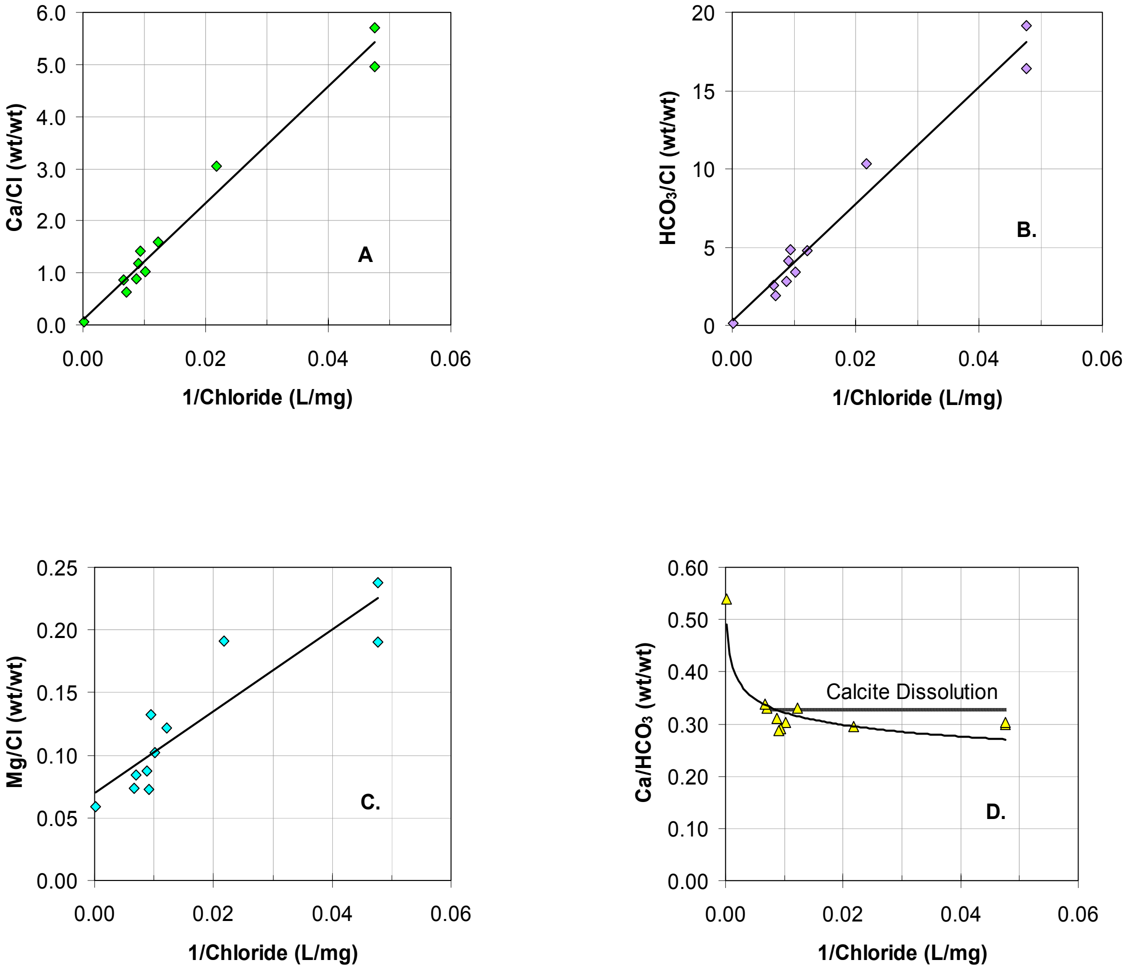

Figure 96 Major Ion ratios from previous groundwater analyses as a function of the reciprocal of the chloride concentration for, Ca, HCO3 and Mg (A, B, C), and for Ca/HCO3 compared with calcite dissolution (D)

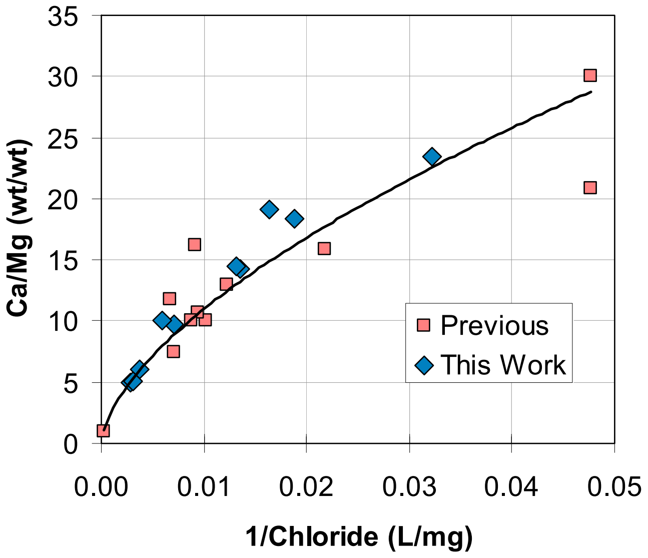

Figure 97 Non-linear mixing curve for Ca/Mg using ratios from previous and current work

It can be concluded that, despite problems with the previous analyses in determining the bicarbonate concentrations of samples, the results of the previous analyses are consistent with the results found in this work.

8.6 Pesticides, hydrocarbons and aromatics in sampled wells

The contamination of groundwater sources used for public water supply reticulation systems in Tongatapu by organochlorine pesticides (OCP) and organophosphate pesticides (OPP) is a major public concern because of the use of a range of pesticides in commercial crop production, particularly squash pumpkin, on the island. The use of diesel pumps to extract groundwater also carries the risk of the leakage of hydrocarbon fuels into groundwater wells. In addition, trace elements and metals sourced from domestic and industrial wastes, animal dips and industrial processes is always a potential threat. The presence of lead in monitoring boreholes around the TWMF at concentrations in excess of WHO (2006) drinking water guidelines for all three samplings (see section 7.8) emphasises the reality of this threat.

The full range of compounds for which chemical analyses were carried out for the 10 selected water wells is listed in Annex G. Table 46 summarises the results of analyses for pesticides, hydrocarbons and some of the trace elements. In this table, <LoD means “less than the limit of detection”.

Table 46 Results of chemical analysis for pesticides, hydrocarbons and some trace elements in the 10 selected wells

Species	Result of analyses
Organochlorine Pesticides (OCP)	<LoD* for all chemicals in all 10 wells
Organophosphate Pesticides (OPP)	<LoD for all chemicals in all 10 wells
Benzene, Toluene, Ethylbenzene, and Xylene (BTEX)	<LoD for all chemicals in all 10 wells
Total Petroleum Hydrocarbons (TPH)	<LoD for all chemicals in all 10 wells
Trace Elements	
Aluminium	<LoD in all 10 wells
Arsenic	<LoD in all 10 wells
Beryllium	<LoD in all 10 wells
Cadmium	<LoD in all 10 wells
Mercury	<LoD in all 10 wells
Selenium	<LoD in all 10 wells

*<LoD means less than the limit of detection

For most chemicals, the LoD was at least one order of magnitude smaller than the WHO (2006) guideline limits for drinking water. **Most of the chemical species of major concern examined here, the pesticides, BTEX, and TPH were all below the limit of detection in the 10 wells selected for intensive testing across Tongatapu**. This is in general agreement with the intensive groundwater sampling around the TWMF for pesticides, BTEX and TPH.

8.7 Trace elements in sampled wells

The trace metals arsenic, beryllium, cadmium, mercury and selenium were all below the limit of detection in the 10 wells selected for intensive testing. At the TWMF, mercury was also below the limit of detection and very low concentrations of arsenic and cadmium, all below WHO (2006) guideline values, were found in some monitoring boreholes (Table 33).

In the water samples from the 10 selected wells, other trace elements were found to be present in small concentrations. These are shown in Table 47 for each well and are compared with the WHO (2006) guideline limit for drinking water.

Iron and manganese were found in only one well each, nickel in two wells, lead in three, copper in 5 wells, chromium in 9 wells and zinc in all wells. Their concentrations were all well below WHO (2006) guideline values. Iron and manganese do not pose health problems but cause aesthetic taste and laundry problems in concentrations two orders of magnitude higher than the values in Table 47.

Zinc, found in all wells here and all monitoring bores around the TWMF, is an essential trace element found in virtually all food and potable water. Concentrations of zinc in groundwater normally do not exceed 50 µg/L but levels in reticulation systems can be much higher due to dissolution of zinc from pipes and fittings (WHO, 2006). One well in Table 47 at the Mataki'eua wellfield had a total zinc concentration of 260 µg/L. The WHO suggests that drinking-water containing zinc at levels above 3,000 µg/L may not be acceptable to consumers on aesthetic grounds.

Table 47 Concentrations of total trace elements in groundwater samples of the 10 selected wells

Site No.	**Location**	**Well no.**	**Iron (µg/L)**	**Manganese (µg/L)**	**Nickel (µg/L)**	**Lead (µg/L)**	**Copper (µg/L)**	**Chromium (µg/L)**	**Zinc (µg/L)**
1	Kolonga	49	<5	<1	1.1	1.8	2	<1	18
2	Tatakamotonga	20	<5	<1	<1	<1	<1	1.4	10
3	Tupou College	New Well	<5	<1	<1	<1	<1	1.6	8.8
4	Vaini	218A	<5	<1	<1	<1	9.2	1.7	25
5	Pea	88	13	<1	<1	<1	<1	2.5	15
6	Liahona College	169	<5	1.9	2.8	1.2	5	3.1	35
7	Fo'ui	151	<5	<1	<1	<1	<1	1.6	13
8	Mataki'eua	115	<5	<1	<1	<1	<1	2.3	7.9
9	Mataki'eua	211	<5	<1	<1	1.6	13	2	260
10	Mataki'eua	104	<5	<1	<1	<1	1.1	2	11
WHO (2006) Guideline Value (µg/L)*			**None**	**400**	**70**	**10**	**2000**	**50**	**None**
Mean			13	1.9	**2.0**	**1.5**	**7.3**	**2.0**	**43.6**
Std Dev					1.2	0.3	4.8	0.6	81.6
CV (%)					61.6	19.9	65.9	28.4	187.0
Median			13	1.9	**2.0**	**1.6**	**7.1**	**1.9**	**15.0**
Max					2.8	1.8	13.0	3.1	260.0
Min					1.1	1.2	2.0	1.4	7.9

* Shaded guideline value is an aesthetic not human health value.

It is possible that the chromium, copper, nickel and zinc found in samples listed in Table 47 all come from the dissolution of pipes or pump fittings. This can occur in either acid or alkaline conditions. Acid conditions are not possible with these groundwater samples from limestone aquifers, and the pH's measured here in freshly pumped groundwater were all close to neutral at pH's just greater than 7 (Table 12, Table 18, and Table 27). When exposed to the atmosphere, however, these waters can reach pH as high as 8.4 which may be sufficiently alkaline for dissolution of metals. It is emphasised, however, that all concentrations here are well below guideline or aesthetic values and pose no threat to health.

At the TWMF, mean lead concentrations were 5-10 times the WHO (2006) guideline value for lead. Lead was detected in all TWMF monitoring boreholes with two boreholes having lead concentrations over 25 times the guideline value. In Table 47, lead was found in only 3 of the

10 village wells tested. The mean concentration is less than 1/6 of the WHO (2006) guideline value and the maximum concentration 1.8 μg/L, found at Kolonga, is less than 1/5 of the guideline value. The lead concentrations at the TWMF can therefore not be attributed to background lead concentration in the general groundwater in Tongatapu, even though lead was detected at the TWMF before operation of the waste facility commenced. This finding warrants further investigation.

Comparison of the mean heavy metal concentrations for the July 2007 sampling at the TWMF site in Table 33 with those for the 10 selected wells in Table 47 reveals that the mean concentration of chromium, copper and nickel concentrations are very similar. These concentrations can then be considered background groundwater concentrations for Tongatapu. The mean concentrations of the remaining zinc, iron, manganese and lead at the TWMF site are 4, 48, 56, and 70 times respectively the mean concentrations in Table 47 for the 10 selected wells. Whether this is due to site differences between the peninsula on which the TWMF is located (Figure 25) and other locations in Tongatapu, or to the waste management facility itself, or the composition of the material used for the borehole casings, or other technical issues cannot be resolved here and requires additional investigation. It seems that the elevated lead concentrations cannot be due to the operation of the TWMF since the mean lead concentration in April 2006, before the facility commenced operation in January 2007 was identical to that in July 2007 after operation commenced. For manganese at the TWMF, it is noted that GMW2, adjacent to the septic tank sullage drying pads had manganese concentrations that exceeded the WHO (2006) aesthetic guidelines at both the April 2006 and July 2007 sampling dates. Again, this does not appear to be due to the operation of the facility.

In terms of the individual wells tested in Table 47, 6 different trace elements were found at the Liahona College well, 4 at the Kolonga well and Mataki'eua well 211, 3 at the Vaini and Pea wells and Mataki'eua well 104 and 2 (chromium and zinc) at the Tatakamotonga, Tupou College and Fo'ui wells and Mataki'eua well 114. The Liahona result is somewhat surprising given that it is in a well managed site (see Figure 83A) with no *E. coli* or total coliforms present. Again, it is noted that most of these trace elements may be due to the slight dissolution of well and pump materials and it is emphasised that all concentrations in Table 47 were well below WHO (2006) guideline values and do not constitute any health risk.

8.8 Nutrients

Nutrients, particularly nitrate and nitrite, are of concern in groundwater in Tongatapu due to the use of fertilisers in some cash crops, leakage from septic tank systems and contamination from animal wastes. There are two primary health concerns with nitrate levels in groundwater in Tongatapu. The first is the formation of algal booms in Fanga'uta Lagoon from the discharge of nitrate-rich groundwater into the lagoon (Zann *et al.*, 1984; Naidu *et al.*, 1991; Fakatava *et al.*, 2000), where nitrate concentrations as high as 520 μg/L have been reported recently, and impacts on the safety of harvested seafood have been suggested.

The second primary health concern regarding nitrate and nitrite is the formation of methaemoglobinaemia, the so-called "blue-baby syndrome" in bottle fed-fed infants. Nitrate is reduced to nitrite in the stomach of infants, and nitrite is able to oxidize haemoglobin to methaemoglobin, which is unable to transport oxygen around the body. The reduced oxygen transport becomes a problem when methaemoglobin concentrations reach 10% or more of normal haemoglobin concentrations. Methaemoglobinaemia, which appears to be exacerbated by gastrointestinal infections, causes cyanosis and, at higher concentrations, asphyxia. Older children and adults are less susceptible to methaemoglobinaemia (WHO, 2006).

Table 48 presents the results of the nutrient analyses undertaken for the 10 selected wells.

Nitrite was below the limit of detection in all wells. All wells had nitrate levels below the WHO (2006) guideline value for drinking water with the mean concentration being less than 1/6 of the guideline concentration. The highest concentrations of nitrate were at Tatakamotonga, Tupou College and Vaini while they were lowest at Kolonga. Total phosphorus concentrations were generally low, with the highest concentrations occurring in the three Mataki'eua wells. Phosphorus was undetectable in the groundwater sample from Kolonga. The low phosphorus concentrations in groundwater found at the 10 selected wells and at the TWMF boreholes are not surprising since the andesitic tephra soils have a high retention capacity for phosphorous (Chisholm, 1998).

Table 48 shows the molar ratio of nitrogen to phosphorus, N/P, for the samples. The N/P ratio for algae is 16 and this seems to control the N/P ratio for the ocean and for some freshwater bodies (Stumm and Morgan, 1996). The mean N/P ratio in Table 48 is 130, which is precisely the value found for Fanga'uta Lagoon by Zann *et al.* (1984) strongly suggesting that groundwater discharge into the lagoon controls the N/P ratio there. Thus, we would expect to see a gradient in the ratio between the mouth of the lagoon with more oceanic values closer to 16 and the interior portions of the lagoon around Pea and Vaini with values around 130. It is noted that with the N/P ratios in Table 48, the availability of phosphorus is probably limiting bacterial growth. An implication from this is that the use of phosphate fertilisers and phosphate detergents may need monitoring.

Mean nitrate concentrations found at the TWMF for the combined February and April 2006 measurements prior to the commencement of disposals at the facility was 6.8 ± 4.1 mg/L (Table 34), identical within error to the mean in Table 48. This suggests that a value of around 7 mg/L can be considered to be approximately the average background groundwater concentration of nitrate in Tongatapu.

Table 48 Results of nutrient analyses for the 10 selected wells

Site No.	Location	Well no.	Total Phosphorus (mg/L)	Nitrate as NO_3 (mg/L)	Nitrite as NO_2 (mg/L)	N/P (mole/mole)
1	Kolonga	49	<LoD	4.2	<LoD	
2	Tatakamotonga	20	0.04	13	<LoD	162
3	Tupou College	New Well	0.03	12	<LoD	200
4	Vaini	218A	0.02	9.5	<LoD	237
5	Pea	88	0.04	5.3	<LoD	66
6	Liahona College	169	0.04	6.8	<LoD	85
7	Fo'ui	151	0.02	6.2	<LoD	155
8	Mataki'eua	115	0.05	6.5	<LoD	65
9	Mataki'eua	211	0.05	7	<LoD	70
10	Mataki'eua	104	0.05	6.6	<LoD	66
WHO (2006) Guideline (mg/L)			None	50	3	
		Mean	**0.036**	**7.8**	**<LoD**	**130**
		Std Dev	0.012	3.0		68
		CV (%)	32.8	38.5		52.0
		Median	**0.04**	**6.8**		**120**
		Max	0.05	13.0		237
		Min	0.02	4.2		65

The mean reactive phosphate at the TWMF boreholes for the combined February and April 2006 prior to the commencement of disposals at the facility was 0.033 ± 0.028 mg/L again identical within error to the mean in Table 48. This also suggests that a value of around 0.035 mg/L can be considered to be the approximate average background groundwater concentration of phosphorous in Tongatapu. At the TWMF the mean molar N/P ratio before operations commenced was 121 ± 71, again in agreement with that in Table 48 and suggesting a mean molar N/P ratio of about 100-130 is characteristic of groundwater in Tongatapu.

One TWMP monitoring borehole, GMW2, close to the septic tank sullage drying beds, had a high nitrate concentration but unchanged low phosphorus concentration after operation of the facility commenced. This had a molar N/P ratio of 1,680, clearly showing the influence of introduced nitrate.

8.9 Faecal Indicators in the 10 selected wells

The results of tests for the presence of faecal indicators have already been presented in Table 35 and discussed in section 8.1. In summary, 2 of the 10 water supply samples were negative, two were positive for *E. coli* and the remaining 6 wells had total coliforms.

8.10 Comparison with previous tests in Fanga'uta Lagoon

The shallow Fanga'uta Lagoon system on the northern side of Tongatapu (Figure 2) receives groundwater discharge from a catchment that is estimated to be 80 km^2 (Zann *et al.*, 1984). The long term mean groundwater discharge into the lagoon should equal approximately the average groundwater recharge from rainfall in the contributing catchment. With an estimated average annual recharge of 528 mm/year (Falkland, 1992), this catchment would discharge on average 42 million cubic metres (m^3) per year or 116 ML/day of groundwater into the Lagoon[10]. The estimated volume of the Lagoon is 38 GL (Prescott *et al.*, 2001) which gives an average freshwater residence time of almost 330 days compared to an average tidal seawater turnover time of 23 days. The catchment contains both rural and urban areas and includes the Mu'a villages, Vaini, Folaha, Veitonga, Ha'ateiho, Pea, Haveluloto and other parts of Nuku'alofa adjacent to the lagoon including the old waste disposal site in the mangrove flats at Popua. The lagoon sediments, fish and shellfish therefore act as integrators of groundwater discharge, as well as any surface runoff, into the Fanga'uta Lagoon system.

8.10.1 Trace elements

Prescott *et al. (*2001) summarised some of the previous tests for trace metals, pesticides, nutrients and faecal indicators in the Fanga'uta Lagoon system. There appear to be no significant heavy, trace metal contamination in the lagoon sediments. Sediment analyses carried out as part of the Tonga Environmental Management and Planning Project (TEMPP) found cadmium in only one sample with a concentration just above the limit of detection and mercury was detected at very low concentrations. Copper was found at values above 10 ppm at only three sites probably associated with soil erosion. Lead concentrations were low in all sediments, while zinc, nickel and arsenic concentrations lay within ranges for unpolluted sediments (Morrison, 1999). Morrison and Brown (2003) found no evidence of trace metal contamination in shellfish and it seems safe to conclude that trace metal contamination is currently not a problem in the Lagoon system.

8.10.2 Pesticides

Sediment samples and shellfish from the Lagoon were collected in 1991 and tested for a range of OCPs (Harrison *et al.*, 1996). Pesticides were undetectable in the majority of samples however low concentrations of heptachlor and heptachlor epoxide, chlordane, DDT, DDE and dieldrin were found in some sediment and shellfish samples and a range or aroclor species were found in some sediments but not shellfish.

Lagoon sediment samples collected in February 1999 for pesticide analysis indicated the presence of chlorfluazuron (Atabron) and flusilazole (Punch) in low to very low concentrations and one sample was found to contain a small carbaryl (Sevin) residue but none of the tested samples contained any residue of dimethoate (Perfekthion) (Morrison, 2000). The presence of these low concentrations of a limited number of pesticides at a limited number of sites does not necessarily imply their source was groundwater discharge. There is the possibility that equipment used for pesticide spraying could have been rinsed in the Lagoon. In addition, the adjoining old Popua waste disposal site could be an important source of contaminants.

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[10] Precott *et al* (2001) cite that Zann *et al.* (1984) estimated the average freshwater input to the lagoon to be only 26 ML/day.

8.10.3 Nutrients

Fakatava *et al.* (2000)[11] summarised previous measurements of nutrients in the lagoon in 1981, (Zann *et al.*, 1984), 1988-89 (Naidu *et al.*, 1991) and 1992 (Aalbersberg *et al.*, 1992) and compared them with their results carried out from December 1998 to August 2000. In 1981 the maximum nitrate concentration found was 1.2 mg/L at a site near Vaini. In 1988-89 the maximum nitrate concentration was 12.8 mg/L at a lagoon site on the southern edge of Nuku'alofa. At Pea in this period, the maximum concentration was 8.8 mg/L while that at Mu'a and Vaini was 7.5 mg/L. These last two concentrations are comparable with those found here for groundwater undiluted with seawater (Table 48) as well as for groundwater at the TWMF. In the sampling period 1988-89, appreciable concentrations of nitrites and ammonia were also found. It was thought that these high values during this period were due to sewage discharge. During the 1998 to 2000 period the maximum nitrate concentration found was much lower at 0.52 mg/L at the lagoon site near Vaini. At the Pea and Mu'a lagoon sites, the maximum nitrate concentrations were 0.47 and 0.25 mg/L, respectively. These values were also associated with measurable levels of nitrite and ammonia.

In 1981 the maximum phosphorus[12] concentration was 0.06 mg/L at the Mu'a site while the maximum concentrations at Pea and Vaini were 0.04 mg/L and 0.02 mg/L. These concentrations are very similar to the mean groundwater phosphate concentration in Table 48 for the 10 selected wells. In 1988-89 the maximum phosphorous concentration was claimed to be 1.1 mg/L, just off the southern shore of Nuku'alofa. At Pea and Vaini the reported maximum values were 0.2 and >0.65 mg/L. These are extremely large values. The groundwaters sampled at Pea and Vaini (Table 48) had concentrations two orders of magnitude lower than these. In the 1998-2000 monitoring period, the reported maximum phosphorus concentration was 1.4 mg/L. again off the southern shore of Nuku'alofa and also at Pea while Vaini had a maximum concentration of 0.93 mg/L. During this sampling period the maximum N/P value was very low, 0.8.

In contrast to these very large values, the nitrate concentration in mean seawater is 3 mg/L and the mean phosphorus concentration is 0.09 mg/L (Hem, 1992). In Erakor Lagoon, Vanuatu, Kaly (1998) found lagoon water samples with maximum nitrate and phosphorus concentrations of 2.9 mg/L and 0.06 mg/L. respectively, close to mean seawater and with a N/P mole ratio of 100, similar to that found by Zann *et al.* (1984) in 1981. This is also similar to the groundwater values here in Table 48 and to those found in the TWMF monitoring boreholes before operations commenced (Table 34).

The very high phosphorus concentrations found in separate studies in the period from 1988 to 2000 raise several questions. What is the source of phosphorous? Groundwater samples within the Fanga'uta Lagoon catchment at Tatakamotonga, Vaini, Pea and Mataki'eua in this work had total phosphorus concentrations nearly 20 times lower than concentrations from the Lagoon. The locations of the wells sampled were in general, upstream of the major population centres and it may be that septic tank and greywater discharge from villages and particularly from Nuku'alofa and/or discharges from the old waste disposal site Popua are the sources of these elevated phosphorus values. Sullage drying beds used to be located on the northern side of Popua. At the TWMF, one monitoring well, GMW2, close to the new and improved sullage drying facility at Tapuhia had very high nitrate concentrations. It may be that the sullage drying beds near Popua coupled with septic tank discharge from areas of Nuku'alofa beside the Lagoon were the source of elevated nutrient levels. To examine this further would require measurement of nitrogen isotopes.

Falkland (1995) presented the results of 14 nutrient samples taken in the ocean and Lagoon, some opposite point source drain discharges, in 1995 (Figure 98). The mean values found are summarised in Table 49.

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[11] Fakatava *et al.* (2000) in their Table 9 have misreported the concentrations of nutrients found by Zann *et al* (1984). They list the units as μg/L but they should be mg/L. As listed, many of the claimed concentrations are over an order of magnitude lower than current detection limits.

[12] Fakatava *et al.* (2000) list values for phosphate. These have been converted here to phosphorus concentrations.

Table 49 Mean nutrient concentration of ocean and Lagoon samples taken in 1995 (Falkland, 1995)

Statistic	pH	EC (μS/cm)	Phosphate as P (mg/L)	Ammonia as N (mg/L)	Total Oxidised N as NO_3 (mg/L)	N/P
Mean	**8.1**	**30,721**	**0.28**	**2.69**	**0.74**	**48**
Std dev	0.5	22,051	0.70	8.81	0.68	30
CV (%)	5.9	72	248	327	92	63
Median	**8**	**37,300**	**0.04**	**0.09**	**0.38**	**45**
Max	9.4	54,800	2.00	32.0	1.95	100
Min	7.6	1,470	0.01	0.01	0.22	10

At the pHs sampled in Table 49, the predominant form of dissolved nitrogen is the ammonium ion.

The maximum phosphorus concentration measured in the outfall of a septic tank system beside the Dateline Hotel was 0.65 mg/L. This was also associated with a massive ammonia concentration of 32 mg/L but low levels of nitrate (0.3 mg/L). The mean phosphorus concentration in the remaining drains sampled was 0.011 mg/L so that septic tank and drain discharge do not seem to account for the elevated phosphorus concentrations in 1989-2000 which have been attributed to septic tank discharge.

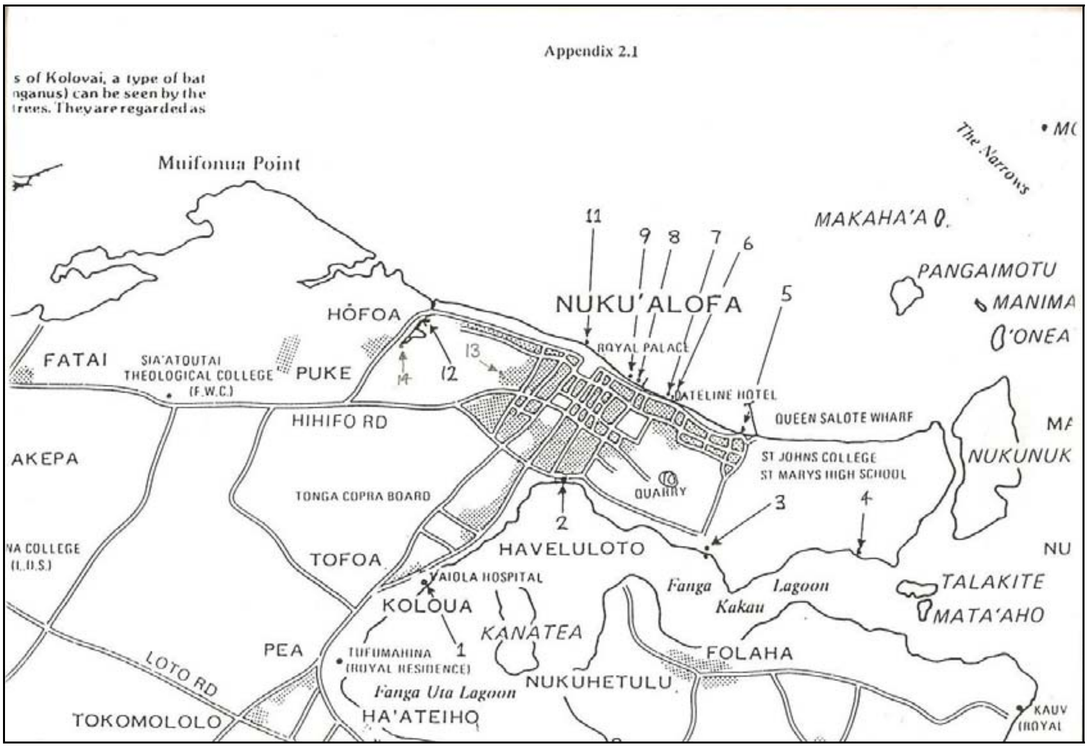

Figure 98 Location of ocean, lagoon and drain samples taken around Nuku'alofa in 1995 (Falkland, 1995)

The wells sampled in this work in Table 48 are mostly in rural areas, where agriculture predominates. It can be concluded confidently then that agriculture is not the source of phosphorus in the Lagoon. Continued monitoring and investigation of the sources of phosphorus in the Lagoon are required.

8.10.4 Faecal coliforms

Faecal coliforms were only examined during the 1992 and 1998-2000 monitoring periods with significant counts occurring in lagoon sites near Vaini and the southern side of Nuku'alofa. Cockles and clams tested during the latter monitoring period had no detectable *E. coli* or coliforms.

8.10.5 Relation to rainfall and groundwater discharge into the Lagoon

No attempt was made by Prescott *et al.* (2001) to relate the temporal changes of nitrate and phosphorus concentrations to the general rainfall patterns which would affect groundwater discharge. This is particularly important if septic tank discharge is the major source of nutrient inputs. In low rainfall periods septic tank discharge would be expected to make a greater contribution to nutrient concentrations in the Lagoon. Rainfall records show 1981 was a very dry year with annual rainfall of 874 mm, while 1989 had 2,154 mm and in 1999 and 2000 annual rainfall was very high at 2,540 and 2,408 mm, respectively.

8.11 Comparison with previous groundwater analyses in Tongatapu

8.11.1 Trace metals

The TWB database lists trace metal concentrations in mostly unspecified wells at Hu'atolitoli, Malapo (well 55), and Tupou College sampled on 1st February 1978 and for Vaiola Hospital (copper, iron and zinc only) sampled on 1st December 1978. The results are summarised in Table 50.

Table 50 Trace metal concentrations in 3 wells sampled in 1978 (from TWB database)

Trace Metal	Mean (μg/L)	Std Dev (μg/L)	CV (%)	Median (μg/L)	Max (μg/L)	Min (μg/L)
Arsenic	**<10**					
Cadmium	**<10**					
Chromium	**<10**					
Copper	**<10**					
Iron	**<10**					
Lead	**<10**					
Zinc	**93**	85	92	**75**	200	20

Arsenic, cadmium, chromium, copper, iron and lead concentrations were below the detection limit of 10 μg/L in all wells. Only zinc had a detectable concentration in all wells. The mean value of 93 ± 85 μg/L for zinc in 1978 compares with the mean of 175 ± 110 μg/L for the TWMF samples and 44 ±81 μg/L found for the 10 selected wells (Table 47). There has therefore been no dramatic increase in the concentration of zinc in the intervening 29 years.

Furness and Helu (1993) analysed 24 groundwater samples for heavy metals. No details of the wells tested or the results are presented, presumably because no heavy metals were detected. Instead they describe an accidental spill of arsenic, copper and chromium at a timber treated plant at Tokomololo in 1985 which led to the testing of 7 wells in the area for heavy metals. Although the soil was heavily contaminated, arsenic concentrations in the groundwater ranged from 0.2 to 0.6 μg/L while those for copper ranged from 0.8 to 40 μg/L, and those for chromium ranged from 0.5 to 2.6 μg/L (Furness and Helu, 1993). Groundwater concentrations were all below the WHO guideline limits. .From Table 47, arsenic was not detected in the 10 selected wells sampled in 2007 while the range for copper was smaller than reported for the spill site wells and the range for chromium was comparable to the spill site values and similar to that at the TWMF sites.

8.11.2 Pesticides

Chesher (1984) reported measurements of selected pesticides in 9 Mataki'eua wells (101-109) carried out in 1980. As van der Velde (2006) has pointed out, the concentration units quoted by Chesher are clearly in error and should be perhaps in μg/L rather than mg/L. Using that assumption, Table 51 presents the mean results of those tests. The mean values are compared with WHO (2006) guideline values for drinking water.

For three of the pesticides in Table 51, the mean concentrations were well below the WHO guideline values, while two are about 3 times the guideline value. Because heptachlor and its oxidation product heptachlor epoxide occur at some low concentrations in water samples (10^{-3}μg/L usually) no guideline value is given by WHO (2006) although a health value is mentioned. The results in Table 51 are somewhat surprising considering that relatively small amounts of pesticides were imported into Tonga prior to 1985. This combined with the fact that the heptachlor concentration in Table 51 is 100 times the expected largest concentration, together with the results of more recent groundwater analyses and the confusion over concentration units suggest that results of these 1980 measurements are doubtful and should be discounted as unreliable.

Table 51 Mean values of pesticide concentrations (assumed to be in μg/L) found for 9 water supply wells at the Mataki'eua wellfield in 1980 (Chesher, 1984)

Statistic	T Lindane	Heptachlor	T Aldrin	Endosulfan	T DDT
WHO (2006)* Guideline Value (μg/L)	2	0.03	0.03	20	1
Mean (μg/L)	**0.18**	**0.11**	**0.09**	**0.06**	**0.04**
Std Dev (μg/L)	0.12	0.10	0.03	0.04	0.02
CV (%)	65	85	35	61	47
Median (μg/L)	**0.15**	**0.16**	**0.085**	**0.06**	**0.04**
Max (μg/L)	0.4	0.23	0.13	0.1	0.07
Min (μg/L)	0.06	0.01	0.04	0.01	0.02
Number	9	9	6	5	6

* No guideline values are given for heptachlor or endosulfan. The shaded WHO guideline values are health values.

Water samples from different areas of Tongatapu were tested in 1989 for residues of two types of pesticides, carbofuran (9 samples) and oxamyl (3 samples). All samples were found to be free of residue within the limits of detection (Falkland, 1992). In 1991, tests were undertaken for five persistent pesticides in 24 wells on Tongatapu. Only three wells, listed in Table 52, showed trace amounts of pesticides with concentrations 25 to 50 times lower than WHO (1993) guidelines for drinking water.

While the wells in Table 52 do not exactly correspond to any of the wells tested here for pesticides (Table 10), the wells at Tatakamotonga and Liahona were very close to the ones sampled here. At Tatakamotonga and Liahona, no pesticides were detectable in this work

Six Mataki'eua wells and 2 village wells at Haulu were sampled on 25th August 1995 and tested for a very wide range of OCP and OPP compounds (Falkland, 1995). No pesticides were detected in any wells. In the same year, the WHO commissioned testing of 20 wells throughout Tongatapu, including wells tested in 1991, for OPP and OCP. No pesticides were found in any of the wells.

Table 52 Pesticide concentrations detected in a limited number of Tongatapu wells in 1991 (Furness and Helu, 1993)

Location	Well No	Pesticide	Concentration (μg/L)	WHO (1993) Guideline (μg/L)
Tatakamotonga	21	p,p-DDE	0.04	2
Houma	220	p,p-DDE	0.06	2
Liahona	170	p,p-DDE	0.08	2
		Hexachlobenzene	0.02	1

van der Velde (2006) tested water samples from 10 wells for 21 insecticides, herbicides and fungicides in 2002. He found only trace concentrations of 3 separate pesticides in 3 wells, 2 of which were open dug wells with relatively shallow water tables (177 and 35) which are listed in Table 53. It was claimed that the results in Table 53 demonstrate that "indeed there is transport of the applied chemicals through the soil" (van der Velde, 2006), although it was pointed out that the trace quantities of pesticides in the two open wells could have been contaminated by spray drift or by the washing of spray equipment.

The concentrations are so low[13], however, that one could also suspect the accuracy of the analysis. It is interesting to note that pesticides were detected in wells at Liahona in both the 1991 and 2003 samplings (Table 52 and Table 53). In the sampling conducted for this project, no OCPs or OPPs were found at Liahona which now sits in the middle of cleared rugby fields (Figure 83A) and was one of only two wells free from *E.coli* or total coliforms.

Table 53 Pesticide concentrations detected in a limited number of Tongatapu groundwater wells sampled in 2002 (van der Velde, 2006)[14]

Location	Well No	Carbaryl (μg/L)	Diazinon (μg/L)	Dieldrin (μg/L)
Kolonga	177	trace	<0.02	<0.01
Lapaha	35	<0.02	trace	<0.01
Liahona	168	<0.02	<0.02	0.01

The weight of evidence from this study, as well as that at the TWMF and the results of Furness and Helu (1993) and Falkland (1995) suggest that there is very little contamination of groundwater by pesticides in Tongatapu. The few pesticides that have been detected in a very limited number of wells by some of the studies are in concentrations just above the limit of detection and well below WHO (2006) guidelines for drinking water. There is clearly no discernible temporal trend in pesticide contamination which might be expected given the persistence of some compounds in the environment.

8.11.3 Imports of agricultural chemicals

To assess the potential risk to groundwater from pesticides, herbicides, fungicides and other agricultural chemicals, it is necessary to know how much of these materials are imported into Tonga, their application rate and where they are being used. van der Velde *et al.* (2007) found that

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[13] In Table 53, trace means the compound was detected at concentrations below the limit of detection. These must be regarded as doubtful (van der Velde, private communication, January 2008).

[14] van der Velde lists the wells tested by sample number with the actual well location and Tongan well number in an Appendix. The third well in the Appendix is identified as Tokomololo (MAFFF) 163. The Tongan village well database identifies well 163 as that at Ha'akame. In the text van der Velde uses a map to identify well locations. The third well is a pumped borehole located at Liahona.

the value of pesticides, fungicides and herbicides imported into Tonga increased 2.5 times from 1987 to 2003.

Table 54 shows the value (in Tongan Pa'anga, TOP) of these agricultural chemicals imported into Tonga between 2000 and 2007 (Foreign Trade Reports, Tonga Department of Statistics).

Table 54 Value of insecticides, fungicides and herbicides Imported into Tonga

Year	Value (TOP)			
	Insecticides	Fungicides	Herbicides	Total
2000	607,420	235,074	282,676	1,125,170
2001	512,537	242,667	99,775	854,979
2002	482,129	129,539	159,076	770,744
2003	665,449	425,417	369,991	1,460,857
2004	794,602	264,277	359,142	1,418,021
2005	543,892	159,078	511,168	1,214,138
2006	717,478	155,071	279,724	1,152,273
Mean	617,644	230,160	294,507	1,142,312

The results in Table 54 make no allowance for currency exchange rates and inflation and it is difficult to determine if there is an increasing or decreasing trend in the use of these agricultural chemicals. In terms of the value of agricultural chemicals, total imports appear relatively constant between 2000 and 2006.

It is recommended here that information be compiled on the weight of actual agricultural chemicals being imported and the location and application rates of their use.

8.11.4 Organics and petroleum products

Falkland (1995) reported the results of tests on water samples of 6 Mataki'eua wells and 18 village wells throughout Tongatapu for semi-volatile organics (detection limit 10 μg/L) and the same 6 Mataki'eua wells for volatile organics (detection limit 1 μg/L) including BTEX. One of the Mataki'eua wells (well 115) and one of the village wells (Kolonga well 49) were the same as tested here and two wells, Tatakamotonga well 21 and Tupou College well 33, were close to the wells sampled here. No semi-volatile or volatile organic, including BTEX were detected which agrees with the results found here and those at the TWMF.

8.11.5 Nutrients

The TWB database lists nitrate concentrations for water wells at Hu'atolitoli, Malapo (well 55), and Tupou College sampled on 1st February 1978. The mean value of these measurements was 6.3 ± 1.5 mg/L with a range from 1.3 to 7.9 mg/L.

Analysis of nitrate and phosphate levels on 9th September 1991 in 23 wells across Tongatapu indicated that heavy use of fertilisers had not seriously affected the groundwater. The nitrate (as NO_3) concentration ranged from <0.44 to nearly 17 mg/L (Furness and Helu, 1993) and had a mean of 7.4 ± 4.9 mg/L, all well below the WHO (2006) guideline limit for drinking water of 50 mg/L. These results are identical within error to the values found in this work (Table 48) and for the TWMF (Table 34). All phosphorus concentrations were less than 0.1 mg/L, again consistent with the findings of this work.

Falkland (1995) also reported values of nutrients from 6 Mataki'eua wells and 3 village wells. The means of these tests are given in Table 55. In this table, results are given as total oxidised nitrogen, NOX. The nitrite levels found in this work and in the groundwater samples from Tapuhia are very small. It is therefore reasonable to assume that the NOX concentrations in Table 55 are mainly nitrate. With this assumption, it can be seen that the nitrate levels in the 1995 tests are very similar to the results in this work (Table 48) and for the TWMF (Table 34). The mean phosphorus concentration in 1995 is also not significantly different from those in 2006 for the TWMF (Table 34) and the ones measured in this project in 2007 (Table 48). This shows that there has not been a significant increase in nutrient concentrations in groundwater accessed by water supply wells since 1995.

Table 55 Mean concentrations of nutrients in water supply wells sampled in August 1995 (Falkland, 1995)

Statistic	NOX (NO_3 mg/L)	Ammonia (N mg/L)	Phosphate (P mg/L)	N/P (mole/mole)
Mean	**6.3**	**0.03**	**0.044**	**79**
Std Dev	5.3	0.06	0.011	68
CV (%)	84.3	180.6	24.5	86.8
Median	**4.2**	**0.01**	**0.046**	**58**
Max	15.5	0.13	0.055	199
Min	1.8	0.002	0.019	16

The mean molar N/P ratio in 1995 was lower than those found in this study or at the TWMF. One of the N/P ratios in the 1995 measurements at a dug water supply well in Mataki’eua has a molar N/P ratio of 16, identical to the Redfield ratio for algae (Stumm and Morgan, 1996). This suggests that these wells should be sealed to prevent light penetration.

The TWB chemical database gives the results of nitrate analyses of water from 18 Mataki’eua wells sampled in March and July 1996. The mean nitrate concentration was 5.5 ± 2.5 mg/L while in March 1997 the mean nitrate concentration from 11 Mataki’eua wells was 6.9 ± 5.8 mg/L.

van der Velde (2005) measured nitrate and ammonia concentrations in groundwater samples taken from 10 wells, in groundwater seepage from a single site at the edge of the Fanga’uta Lagoon and in the Lagoon opposite the groundwater discharge site in 2002. His mean results, recalculated as nitrate concentrations, are given in Table 56.

Table 56 Mean concentrations of nutrients sampled in 2002 (van der Velde, 2006)

Source	Ammonia (N mg/L)		Nitrate (NO_3 mg/L)		Total N (NO_3 mg/L)	No. samples
	Mean	Std Dev	Mean	Std Dev		
Groundwater	0.07	0.06	6.4	4.7	6.7	39
Seepage	0.49	0.25	6.8	2.8	9.0	6
Lagoon	0.53	0.18	0.4	0.5	2.7	4

Again, it can be seen that within the large standard deviations in the nitrate values, the mean nitrate concentrations in groundwater found by van der Velde in 2003 are very close to the values found in Table 48 in this study and for the TWMF (Table 34). The mean nitrate concentration at the seepage site was also identical to the mean groundwater concentration but ammonia has increased suggesting a source of ammonia upstream of the seepage point. In the Lagoon, nitrate concentrations were low and most of the nitrogen present was ammonia, as was reported by Falkland (1995). The nitrate concentration in the lagoon in Table 56 is identical to that in the 1998-2000 monitoring of the Lagoon. If we estimate the total nitrogen concentration as nitrate (Table 56), then the mean concentration is close to the mean concentration of nitrate for seawater (Hem, 1992), as well as that found in Erakor Lagoon, Vanuatu (Kaly, 1998) and is much lower than the 1988/89 values reported for the Lagoon. Unfortunately, van der Velde did not report phosphorus concentrations.

8.11.6 Trends in groundwater nutrient concentrations

A critical question in examining the historic nutrient data is whether or not there has been an increasing trend in nutrient concentrations in groundwater. van der Velde (2006) showed that annual fertiliser imports into Tonga had increased dramatically from about 140 tonnes in 1988, to 2,250 tonnes in 1991 to a maximum of about 3,900 tonnes in 1994. Figure 99 shows the trends in dissolved nitrate since 1978 and phosphorus concentrations in groundwater since 1991. The values are also listed in Table 57.

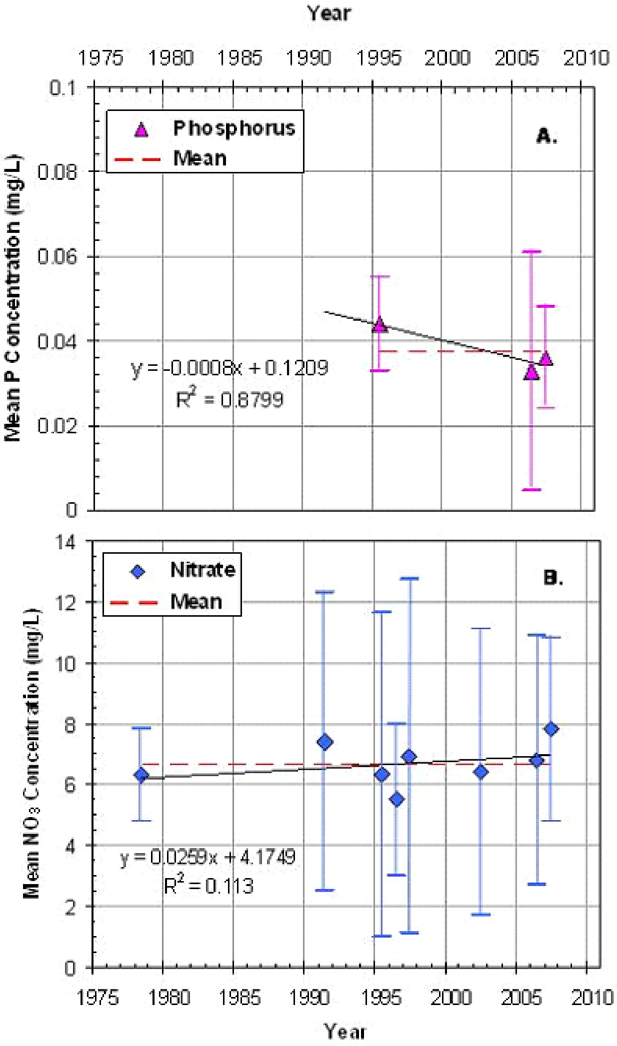

Figure 99 Trends in A. mean phosphorus and B. mean nitrate concentrations in groundwater in Tongatapu since 1978. Dashed lines are long-term means.

Table 57 Mean nitrate and phosphate concentrations in groundwater since 1978

Year	Nitrate Concentration (mg/L)			Phosphorus Concentration (mg/L)			Source
	Mean	St Dev	Median	Mean	St Dev	Median	
1978	6.3	1.5	5.8				TWB
1991	7.4	4.9	6.0				TWB
1995	6.3	5.3	4.2	0.044	0.011	0.046	Falkland (1995)
1996	5.5	2.5	4.9				TWB
1997	6.9	5.8	5.1				TWB
2002	6.4	4.7	**n/a**				van der Velde (2006)
2006	6.8	4.1	7.2	0.033	0.028	0.023	WA
2007	7.8	3	6.8	0.036	0.012	0.04	This study

There is no significant increase in nitrate over this period despite the large increase in fertiliser use. All previous measurements of nutrients in groundwater in Tongatapu support the findings of this study and that at the TWMF and suggest that the mean background concentrations of nitrate (as NO_3) and phosphorus (as P) in groundwater in Tongatapu are around 6.7 ± 0.7 and 0.038 ± 0.017 mg/L, respectively, with a mean N/P molar ratio of 85. There has not been a dramatic increase in these concentrations despite the increase in fertiliser use. Significant departures from these values would suggest sources or sinks of nutrients and it is important that monitoring of nutrients continue.

In section 8.4.4, it was shown that the ion ratios fell on simple mixing curves, mostly between those of seawater and recharge water just entering the aquifer. The inferred nitrate concentration of that recharge water was 6 mg/L (Table 42) close to the mean values above. At present, it cannot be determined if the source of the nitrate is from leaking septic tanks, agriculture or both. One way of more closely identifying the sources of nitrogen is to examine the isotopic signature of nitrogen in the groundwater at different locations throughout Tongatapu.

8.12 Fertiliser use in Tongatapu

van der Velde (2006) showed that, up to about 2000, the annual fertiliser imports into Tonga and the production of squash pumpkin for export were closely coupled. Table 58 provides details of the fertiliser imports into Tonga since 2000 and shows that the average annual total fertiliser imports into Tonga from 2000 to 2006 was about 2,400 tonnes. Figure 100 shows the increase in fertiliser imports since 1977 and the average since 1992.

Table 58 Weights of fertilisers imported into Tonga, 2000-2007 (Annual Foreign Trade Reports 2000-2006, Tonga Statistics Department)

Year	Amount (tonnes/year)					
	Animal or Vegetable-derived Fertilisers	Nitrogenous Fertilisers	Phosphatic Fertilisers	Potassic Fertilisers	Fertilisers: 2 or 3 of N, P, K	Total Fertiliser
2000	32	145	247	22	1,428	1,874
2001	649	71	360	21	997	2,098†
2002	551‡	310‡	419	22	1,775	30,77
2003	448	1097	396	24	1,232	3,197
2004	783	593	204	128	1,164	2,872
2005	590	61	117	116	1,682	2,566
2006	84	122	173	-	935	1,314
Mean	**448**	**343**	**274**	**56**	**1,316**	**2,428**
Std Dev	285	382	118	52	325	693

† van der Velde (2006) in Fig. 12.4 gives the total imports for 2001 as about 1,440 tonnes. It appears he overlooked the 649 tonnes of animal or vegetable derived fertiliser.

‡ The Annual Foreign trade Report for 2002 gives the import quantities of animal or vegetable-derived and nitrogenous fertilisers as a massive 9,451 and 84,810 tonnes, respectively. With the stated price this is equivalent to the ridiculously low prices of TOP33/tonne and TOP2/tonne respectively. We have used the average price/tonne for 2001 and 2003 to estimate the quantity from the value of the fertiliser.

There is no information on how much of this imported fertiliser is used in Tongatapu or on the composition of the fertilisers. We will assume, because of the “bush api” system of cultivation throughout Tonga, that the fertiliser use in Tongatapu is proportional to its population relative to the national population which was 68.5% in 1996 and an estimated at 69.7% in 2007 (Table 3). This leads to an estimate of the average annual total fertiliser use in Tongatapu, between 2000 and 2006, of about 1700 tonnes.

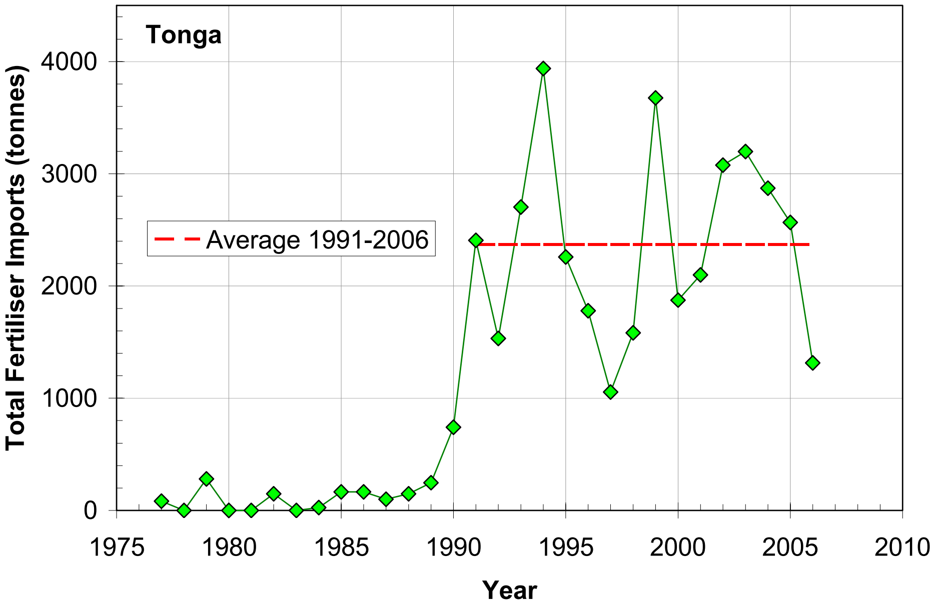

Figure 100 Annual total imports of fertilisers into Tonga (Annual Foreign Trade Reports 2000-2006, Tonga Statistics Department and van der Velde, 2006)

There is no information on the chemical composition of the fertiliser but we will assume that about half of the mean annual fertiliser use is equivalent to nitrate, or approximately 900 tonnes NO_3. There is also no information on the rate of application of fertiliser in different locations in Tongatapu so it will be assumed here that fertiliser is applied to 200 km^2 of Tongatapu's total area of 257 km^2 giving mean approximate annual fertiliser application rates of 45 kg NO_3 per hectare. We further assume that ⅔ of the NO_3 is taken up by the plant or lost to atmospheric emissions and soil adsorption giving about ⅓ of the NO_3 or 15 kg NO_3 per hectare available for annual recharge to groundwater.

van der Velde (2006) describes measurements of nitrate concentrations in repacked drainage flux meters buried 1 m below the soil surface in a squash pumpkin plot and found concentrations of equivalent to about 70 mg of NO_3/ha. The maximum groundwater concentration we have measured here (Table 48) was 13 mg of NO_3 /L. Using his measured drainage concentrations, with a fertiliser application rate of 62 kg of NO_3/ha, van der Velde estimated soil drainage fluxes of between 72 and 144 kg of NO_3/ha over the 100 day growing period. The difference between drainage rate and application rate he attributed to spatial heterogeneity, mineralisation from Guinea grass ploughed into the plot and the repacking of soil in the drainage flux meters. Both the application rate and the rate recharged to groundwater we have assumed is averaged out over the year and over all crops across an area of 200 km^2.

The mean annual recharge for Tongatapu is estimated to be 470 mm or 4.7 ML/ha. With an assumed 10 kg of NO_3/ha available annually for recharge, this suggests recharge concentrations around 3.2 mg/L, about half the mean observed, and a concentration equal to the mean seawater NO_3 concentration. If fertiliser applications were responsible for all the mean nitrate concentration of 6.7 mg/L found in groundwater it would require an annual recharge rate of 31.5 kg of NO_3/ha, or 70% of the assumed annual NO_3 application rate. Given the fact that the mean concentration of NO_3 in groundwater in 1978, prior to the massive increase in fertiliser imports commencing in 1990, is identical within error to that in 2007, it appears that there are either other sources of nitrate or denitrification reactions are removing nitrate from groundwater.

8.13 Domestic inputs of nutrients to groundwater

It was pointed out in section 3.5 that human waste disposal systems and the raising of domestic animals, particularly pigs, constitute potential threats to groundwater quality in Tongatapu. Here we will attempt to estimate waste inputs to groundwater from animal and human sources. Table 59 lists literature values (Feachem *et al.* 1983) for the assumed nutrient composition of human waste together with the calculated corresponding daily and annual outputs of nutrients per person.

It is interesting to note that the molar N/P of the annual output is only 2.8. This ratio is considerably lower than that found for groundwater from this work (Table 48), at the TWMF (Table 34) and from the mean results from 1978 to 2007 (section 8.11.6). The annual per capita nitrate output per person in Table 59 is slightly less than the 35 kg/person/year estimated for Wisconsin (Dillon, 1997). Here we have not taken into account any nutrients in greywater from washing or bathing.

The per capita nutrient output in Table 59 can be used together with the demographic data in Table 3 and the estimated number of pigs in Tongatapu in Table 6 to estimate the annual total human and animal waste outputs for Tongatapu as a whole and for the countryside outside Nuku'alofa since 1976 (Table 60). Nutrient production of a pig is taken to be ½ that of a human.

Table 59 Nutrient composition of human waste (Feachem e*t al.* 1983) and estimated daily and annual per capita outputs of nutrients

Source	Property	Value	Adopted Output
Faeces	Weight	0.08-0.2 Kg	0.2 kg
	Moisture Content	65-80%	70%
	% Nitrogen dry wt	5-7%	6%
	% Phosphorus (P_2O_5 dry wt)	3-5.4%	4%
	%Potassium (K_2O dry wt)	1-2.5%	2%
Urine	Volume	1-1.5 L	1.5 L
	Moisture Content	95%	95%
	% Nitrogen dry wt	15-19%	17%
	% Phosphorus (P_2O_5 dry wt)	2.5-5%	4%
	%Potassium (K_2O dry wt)	3-4.5%	4%
Daily Output/person		Nitrate	72 gm
		Total P	1.2 gm
		potassium	2.9 gm
Annual Output/Person		Nitrate	26.5 Kg
		Total P	0.43 Kg
		Potassium	1.1 Kg

There are two significant conclusions that can be drawn from Table 60. The first is that there has been only a small increase in output of nutrients from human and animal wastes in Tongatapu since at least 1976. The second is that the total annual nutrient output due to human and animal wastes in Tongatapu exceeds the mean (1991-2006) total annual fertiliser imports into all of Tonga. It is clear that the high groundwater nitrate concentrations prior to the rapid increase in fertiliser use in the early 1990s could easily be due to seepage from latrines, septic tanks and domestic animals.

To estimate the nutrient input to groundwater across all 257 km^2 of Tongatapu, we will assume that ½ of the nutrients from human and animal wastes is discharged into the groundwater through recharge[15]. This implies that ½ of the animal and human wastes are taken up by plants or lost to the atmosphere (for nitrogen compounds). Inputs of nutrients to groundwater used to source

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[15] This figure is higher than the ⅓ assumed for agricultural fertilizers because the nutrient drainage from human wastes via latrines and septic tanks occurs below the soil surface whereas fertilizers are surface applied.

village water supplies in Tongatapu, is estimated by assuming that villages outside Nuku'alofa also discharge ½ of the nutrients from wastes into groundwater over an area of 200 km^2. The concentration estimates in Table 61 are based on the assumption that these nutrients are carried into groundwater with the mean annual recharge of 0.47 m.

Table 60 Estimated annual nutrient outputs (tonnes) due to human and animal wastes

Year	Tongatapu (tonnes/year)				Outside Nuku'alofa (tonnes/year)			
	Nitrate	Total P	K	Total	Nitrate	Total P	K	Total
1976	2,145	35	85	2,265	1,302	21	52	1,375
1986	2,383	39	95	2,517	1,299	21	52	1,372
1996	2,502	41	100	2,642	1,329	22	53	1,403
2006	2,691	44	107	2,842	1,410	23	56	1,489

Table 61 Estimated nutrient concentrations in groundwater recharge in Tongatapu and in the village areas outside Nuku'alofa

Year	Tongatapu (mg/L)			Outside Nuku'alofa (mg/L)		
	Nitrate	Total P	K	Nitrate	Total P	K
1976	8.9	0.14	0.35	5.4	0.088	0.21
1986	9.9	0.16	0.39	5.4	0.088	0.21
1996	10.4	0.17	0.41	5.5	0.090	0.22
2006	11.1	0.18	0.44	5.8	0.095	0.23

It can be seen from Table 61 that the estimated contribution of animal and human wastes across all of Tongatapu to the recharge concentration of nitrate is higher than the mean groundwater concentration found between 1978 and 2007.

Almost none of the wastes discharged in Nuku'alofa would end up in groundwater accessed by the pumping systems surveyed in this study. Groundwater from Nuku'alofa containing seepage from septic tanks and animals is mainly discharged either into the sea or the Lagoon. If we examine only the nitrate inputs from settlements outside Nuku'alofa then Table 61 shows that the estimated nitrate concentration in recharge waters is only slightly less than the mean groundwater concentration found between 1978 and 2007 of 6.7 mg/L and very close to the estimated concentration of 6 mg/L In recharge water (Table 42). In addition the results in Table 61 offer an explanation for the elevated nitrate concentrations found in 1978 prior to the importation of large amounts of fertilisers.

The estimated total phosphorus concentration in groundwater recharge due to seepage from animal and human wastes outside Nuku'alofa is over 2.5 times the mean groundwater concentration found between 1995 and 2007. This is not unexpected. Detailed studies of a groundwater plume beneath a septic tank have shown that while nitrate is essentially a conservative tracer, phosphate movement is greatly attenuated due to soil adsorption (Robertson *et al.* 1989). The estimated potassium concentration in Table 61 due to seepage of human and animal wastes outside Nuku'alofa is substantially less than the mean of the 10 wells sampled in this study (Table 38) or in previous analyses of groundwater in Tongatapu (Table 44). The ion ratios however revealed that the source of potassium in the groundwater (Table 39 and Table 45) was predominantly from seawater.

The above results strongly suggest that seepage from human and animal wastes are a major contributor to the groundwater nitrate concentration observed in Tongatapu since 1978. This also suggests that groundwater nitrate concentrations should vary depending on location and the amount of recharge, and hence rainfall. A more detailed study of nitrate concentrations in Tongatapu, their relation to proximity of settlements, their variation with time and climate and their persistence is required.

These results raise questions on the maximum number of septic tanks that should be permitted in an area. Holzer (1975) estimated that one septic tank per 0.4 hectare in Eastern Connecticut would not cause the groundwater nitrate concentration to exceed 45 mg/L. The maximum population density, *n*, (people/ha) that will keep groundwater nitrate concentrations below this level is related to the annual recharge rate R (mm/year) (Dillon, 1997),

$$n < R/80 \qquad [28]$$

For Tongatapu, $R \approx 470$ mm/year so $n < 6$ persons/ha. The average population density in /ha spread uniformly across Tongatapu is 2.7 people/ha while the density outside Nuku'alofa is 1.8 people/ha. If we include the number of pigs, again as equivalent to half a person, these figures rise to 3.9 and 2.6 equivalent persons/ha less that the critical value of 6. It is clear, however, that this density is exceeded in certain areas and it is important to identify areas where the figure may be exceeded and where settlements may be impacting water supplies.

While the estimates of nitrate inputs to groundwater in sections 8.12 and 8.13 are based on a number of assumptions which need to be verified it seems that the explanation for the fact that the mean groundwater nitrate concentration has remained remarkably constant between 1978 and 2007 is due to the continued load of nutrients from animal and human wastes.

8.14 Concluding comments

The intensive chemical measurements and bacteriological testing undertaken in this study were compared them with previous measurements carried out in Tongatapu, including recent measurements at the TWMF (section 7). We have used the results to find answers to several important questions concerning groundwater in Tongatapu.

1. Is the groundwater used for domestic water supplies polluted because of the use of agricultural and industrial chemicals and the leakage of petroleum products?
2. Is the groundwater quality compromised through pollution from latrines and septic tanks?
3. Are nutrient concentrations in groundwater increasing due to agriculture, or inputs from human or animal wastes?
4. Is the chloride concentration of the groundwater increasing due to pumping or climate fluctuations?
5. Does mixing of groundwater with seawater influence groundwater quality?

8.14.1 Faecal indicators

Tests of water supply wells throughout Tongatapu for the presence of indicator species for faecal contamination using the Colisure test showed that, if the boiled rainwater blank and one of the duplicate Liahona samples are excluded, only two (8.7%) of the groundwater samples out of the total of 23 Colisure samples taken (Table 29 and Table 35) had no total coliforms or *E. coli*. The Liahona College sample came from a well in an immaculate rugby ground with little agriculture surrounding it. This suggests that, where possible, groundwater ought to be sourced from cleared well-managed and protected areas. The other negative sample at Mataki'eua came from a TWB well with diesel spills and ponded water on the soil surface, which was heavily infested with algal blooms (see Figure 83B).

Over 91% of 24 water samples, showed the presence of total coliforms. Total coliforms, which occur naturally in tropical island groundwaters (WHO, 1997), were found in all groundwater samples in Tapuhia. A further 6 samples, or 25%, returned positive *E. coli* tests. This is quite a high percentage, reflecting perhaps the impacts of neighbouring agriculture, particularly animals, and septic tank systems on village water wells. This result indicates that disinfection of water from all pumped groundwater systems should be carried out.

H_2S paper strip tests were also examined for their ability to show faecal contamination. These tests are much cheaper and easier to use by community groups than the Colisure tests and have been recommended for use in Pacific Island countries (Mosley and Sharp, 2005). The comparative tests carried out here revealed some worrying anomalies. Four of the (+++) rating (very high risk of faecal contamination) corresponded to only positive Colisure coliform results without *E.coli* positives. It appears then that the H_2S test is very conservative suggesting faecal contamination in double the number of positive Colisure samples and in samples that may have naturally occurring total coliforms rather than faecal coliforms. More worryingly, one of the lower H_2S ratings, (+), indicating the possibility of bacteria, corresponded to a positive Colisure *E. coli* test for the Vaini water supply well. Of even greater concern, two of the lowest (+) H_2S results corresponded to negative Colisure results. The lack of consistency of the H_2S results is worrying.

A report on the use of the H_2S test, (WHO, 2002) did not recommend its use because of the possibilities of false positives from non-enteric, naturally-occurring sulfate-reducing bacteria, which may have occurred in this study. The false positives here in 11% of samples, and the over-estimation of the risk of faecal contamination by a factor of 2 strongly suggest that the more expensive, Colisure field test, adopted in the US as a standard test, should be used where possible for the routine screening of the presence or absence of *E. coli* and total coliform indicators in public water supply systems.

It was not possible to compare these screenings with previous tests for faecal indicator species. The MoH database is contained in a hand-written book and was not available for this study. The TWB bacterial testing of the Mataki’eua/Tongamai wellfield was also not available for comparison.

8.14.2 Ph, EC and major ions

The pH and EC of water sampled in the field differed from measurements in the laboratory which may be due to the high partial pressure of CO_2 in the groundwater samples, which decreases on standing. This reveals the importance of measuring these parameters in the field at the time of sampling. A good relationship was established between the concentration of bicarbonate in the groundwater sample and the pH of the sample. A similarly good relationship was found between the chloride, sodium, potassium magnesium and sulfate concentration and the field EC of the sample. Similarly good relationships were found between calcium and bicarbonate and chloride concentrations. Together, these permit estimation of major ion composition of Tongatapu groundwater from field measured EC.

Examination of the ion ratios of the major ions in groundwater relative to chloride revealed that the major source of sodium, potassium and sulfate is from seawater. Calcium and bicarbonate are sourced from the dissolution of the limestone aquifer. Magnesium is sourced from both seawater and the dissolution of limestone. This analysis also showed that nitrate and fluoride came from neither seawater dilution nor limestone dissolution and both are clearly sourced from the soil. The analysis also permitted estimation of the composition of recharge water entering the limestone aquifer.

8.14.3 Salinity trends

We have compared the chloride concentrations found here with historic data from 1965 to 1991. The data in Table 43 and Figure 93 shows that both the mean and geometric mean of the chloride concentration have decreased since 1991. Some individual wells show increases some have remained the same and some have decreased between 1991 and 2007.

A critical issue concerning the observed increases in salinity in some of the wells is how to separate the influence of pumping from that of variable rainfall. Analysis of this is hampered by the lack of data on the month of the year in which measurements were taken. Here we used annual rainfall in the year in which measurements were reported to examine the relationship.

The 1965 chloride samples were taken in a year that had annual rainfall in the 58th percentile of rainfalls since 1945. Those for 1971 were in the year with the highest rainfall on record (100th percentile) while samples taken in 1991 and 2007[16] were in the 27th and at least the 47th percentiles, respectively. The rainfall regimes when water samples were taken in 1965 and 2007 are therefore comparable and the significant increase in salinity that has occurred between 1965 and 2007 in almost all wells appears attributable to groundwater pumping, assuming that

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[16] Rainfall for 2007 was only available up to November.

there is no analysis error in the early chloride estimations. In section 6.13, it was shown that the pumping at Mataki'eua had increased four-fold between 1966 and 1991.

The sampling in 1991 occurred in a drier year and the salinity in several of the wells in 1991 show maxima in this year. Furness and Helu (1993) concluded that the increase in salinity that occurred at this measurement was a result of groundwater pumping. The results here suggest that this is not universally true, since 1991 was a drier year. The comparison between 1991, a drier year and 2007, an average year, is however informative. Any salinity that is the same or shows an increase in salinity over that period is clearly due to pumping since increased rainfall should lower salinity. A total of 10 out of the 21 wells examined in Tongatapu show continued increases in salinity due to pumping since 1991.

Unfortunately, the frequency of salinity data for the wells throughout Tongatapu is too sparse in general to determine a general relationship between rainfall and salinity. Also village wells are unmetered so the relationship of salinity to volume of water pumped from the well cannot be determined. The TWB database does list a few wells in which chloride concentration was also determined during the drier period in 1986-7. The data for one well showed an excellent relationship between chloride concentration and annual rainfall except for the measurements in 1965 which fell well below the relationship. Again it must be concluded that the increase is either due to an increase in pumping between 1965 and 1971 or the 1965 set of data is in error.

The data presented in this section demonstrates the importance of regular systematic monitoring in order to manage the combined impacts of pumping and variable rainfall on groundwater salinity. Using the data, we have been able to identify wells in which there is a significant impact of pumping on salinity. These require careful investigation. The older wells at Mataki'eua closest to the lagoon appear to show a continuing increasing salinity trend although the rate of increase is less than in the period 1965 to 1971. Information on groundwater salinity, however, is insufficient. It must be coupled with information on rainfall and on the rate of extraction of groundwater by pumping

8.14.4 Pesticides, aromatics and hydrocarbons

Considerable concern has been expressed over agricultural and industrial contamination in Tongatapu. In this study the pesticides, BTEX, and TPH were all below the limit of detection in the 10 water supply wells selected for intensive testing across Tongatapu. This is in general agreement with the recent intensive groundwater sampling around the TWMF for pesticides, BTEX and TPH in 2006 and 2007.

The weight of evidence from this study, as well as that at the TWMF and the results of Furness and Helu (1993) and Falkland (1995), suggest that there is very little contamination of groundwater by pesticides, aromatics or hydrocarbons in Tongatapu. The few pesticides that have been detected in a very limited number of wells are in concentrations just above the limit of detection and well below WHO (2006) guidelines for drinking water. There is clearly no discernible temporal trend in pesticide contamination which might be expected given the persistence of some compounds in the environment.

8.14.5 Trace elements

The trace metals arsenic, beryllium, cadmium, mercury and selenium were all below the limit of detection in the 10 water supply wells selected for intensive testing across Tongatapu. Other trace elements were found to be present in small concentrations, which were well below the WHO (2006) guideline limit for drinking water.

At the TWMF boreholes, mean lead concentrations were 5-10 times the WHO (2006) guideline value for lead. Lead was found in only 3 of the 10 sleeted wells tested at a mean concentration less than 1/6 of the WHO (2006) guideline value.

Comparison of the mean heavy metal concentrations for the July 2007 sampling at the Tapuhia site in Table 33 with those for the 10 selected water supply wells in Table 47 reveals that the mean concentration of chromium, copper and nickel concentrations are very similar. These concentrations can then be considered background groundwater concentrations for Tongatapu. It is noted that most of these trace elements may be due to the slight dissolution of well and pump materials and it is emphasised that all concentrations in Table 47 were well below WHO (2006) guideline values and do not constitute any risk.

8.14.6 Nutrients

Nutrients, particularly nitrate and nitrite, are of concern in groundwater in Tongatapu due to the use of fertilisers, leakage from septic tank systems and contamination from animal wastes. There are two primary health concerns with nitrate levels in groundwater in Tongatapu. The first is the formation of algal booms in Fanga'uta Lagoon from the discharge of nitrate-rich groundwater which has potential impacts on the safety of harvested seafood. The second is that high nitrate concentrations can cause methaemoglobinaemia, the so-called "blue-baby syndrome" in bottle fed-fed infants.

Nitrite was below the limit of detection in all 10 wells tested. All wells had nitrate levels below the WHO guideline value for drinking water with the mean concentration being less than 1/6 of the guideline concentration. Total phosphorus concentrations were generally very low. The low phosphorus concentrations in groundwater found at the 10 selected wells and at the TWMF boreholes are not surprising since the andesitic tephra soils have a high retention capacity for phosphorous (Chisholm, 1998). Both mean nitrate and mean total P concentrations were very close to those found at the TWMF. At the TWMF, the mean molar N/P ratio before operations commenced was 121 ± 71, again in agreement with that in found at the 10 selected wells and suggesting a molar N/P ratio of about 100 to 130 is characteristic of groundwater in Tongatapu.

8.14.7 Trend in nutrients

Annual fertiliser imports into Tonga increased dramatically from virtually zero before 1988 to an average of almost 2,400 tonnes/year after 1991. There have been claims that this has had significant impacts on both groundwater nutrient concentrations and on the Fanga'uta Lagoon. We have compared mean nitrate concentrations from the results of this work in 2007 and the TWMF in 2006 prior to operations commencing with others dating back to 1978 and results for total P dating back to 1995. There is no significant increasing trend in nitrate between 1978 and 2007 and all total P values are equal within error. The mean nitrate and total phosphorus concentrations over this almost 30 year period are 6.7 ± 0.7 and 0.038 ± 0.017 mg/L respectively, with a mean N/P molar ratio of 85. This suggests that agriculture fertilisers are not the sole source of nitrate inputs to groundwater.

Estimations on the contribution of fertiliser to the groundwater were hampered by lack of information on the composition of the fertiliser and on the location of its use. In order for recharge from agricultural soils to be the sole source of nitrate in groundwater in Tongatapu would require an estimated 70% of the mean annual quantity of fertiliser imported into Tonga to be recharged into groundwater. This also does not explain the high nitrate concentration in 1978.

Estimates were also made of the contribution of nutrients in human and animal wastes disposed of in septic tanks, pit latrines and on the ground to groundwater concentrations. By assuming population numbers and the estimated number of pigs outside Nuku'alofa are a possible source it was shown that the concentration of nitrate in recharge water was close to the measured values and showed minimal variation between 1976 and 2007. Predicted total phosphorus concentrations from sewage discharge was about 2.5 times the long-term mean, pointing to loss of phosphorus through reactions in septic tanks and absorption in the volcanic derived soils. It is concluded that human and animal wastes constitute a significant source of nutrients supplied to Tongatapu groundwater.

8.15 Unresolved issues

It is important to develop a model for estimating the impact of pumping on the salinity of pumped water and to disentangle this from the influence of rainfall as in Figure 95. This will require regular monitoring of selected wells and recording of the volume of water pumped from the wells.

We have not been able to establish if some of the wells identified in this study as having *E. coli* present in pumped water, habitually have water quality problems. It is important that the MoH database on microbial tests of village wells and that of the TWB for Mataki'eua/Tongamai wells are analysed systematically and the results reported.

Our tests have shown the absence of significant pollutants such as BTEX, petroleum hydrocarbons and insecticides in groundwater. Many of these chemicals have limited solubility in water. Longer term tests need to be carried out using accumulators of these materials placed in water supply lines or head tanks.

We have suggested here that the human and animal wastes disposed in septic tanks or pit latrines are a major source of nitrate concentration in the groundwater of Tongatapu. Studies of the isotopic composition of the competing agricultural, human and animal potential sources should be carried out to more clearly delineate the relative risks posed by these sources.

A sanitary survey of all village wells needs to be carried out to determine possible sources of nutrients and bacteria from all septic tanks and latrines and animal enclosures.

8.16 Recommendations

It is recommended that:

- The MoH use Colisure tests with the Quanti-tray system for screening village water supplies to provide a quicker indication of contamination and to enable more strategic targeting of water samples for full laboratory testing. This should also lessen the load on the hospital laboratory.
- The H_sS paper strip test not be used for the microbiological testing of public water supplies.
- The MoH hard copy database of the microbiological tests on well water samples be transferred to an electronic data.
- The data in the MoH microbiological database be analysed and a report prepared summarising the results.
- All groundwater pumping wells be fitted with flow meters to determine the volume of water extracted from wells.
- The performance of wells, which showed an increase in salinity between the drier period in 1991 and the average rainfall period in 2007, be analysed to determine the impact of pumping on salinity.
- All village wells and those at the TWMF be monitored every three months for salinity (EC), water level (where possible), pH, temperature, faecal indicators and nitrate.
- Selected village and Mataki'eua/Tongamai wells, and all monitoring wells at TWMF be monitored annually for nutrients, heavy metals, pesticides, herbicides and fungicides, petroleum products and hydrocarbons.
- The method of reporting of imports of agricultural chemicals and fertiliser be improved to include quantity and type of chemicals.
- Data be collected on the location of usage and application rates of agricultural chemicals and fertilisers.
- Data be collected on septic tanks and latrines with potential to influence water quality in village well.

9 Groundwater Recharge

9.1 Overview

Rainfall recharge of the groundwater aquifer occurs across Tongatapu. An assessment of recharge is necessary in order to estimate the quantity of groundwater that can be extracted in a sustainable manner or the sustainable yield of the groundwater system. For aquifers in limestone islands, such as Tongatapu, which occur just above and below sea level, the fresh groundwater is in contact with seawater and only a fraction of the recharge can be safely extracted without compromising the quality of extracted water. Some recharging water is required to maintain the integrity of the freshwater zone by flushing salts from the base and the margins of this zone.

Groundwater recharge can be estimated by a number of methods. For Tongatapu, recharge was estimated using two methods as follows:

- A relatively simple empirical relationship between annual rainfall and annual recharge based on water balance studies on a number of islands.
- A more detailed water balance procedure using local rainfall and evaporation data and a knowledge of the island's vegetation and soil conditions.

Previous estimates of recharge have been made in a number of reports as outlined in Falkland (1992, section 5.1.6).

9.2 Empirical relationship between rainfall and recharge

A simple method based on a relationship between annual rainfall and recharge provides a reasonable first estimate of average recharge. UNESCO (1991) and Falkland (1992) provide such a graph using data from several limestone and coral islands, including Tongatapu (Figure 101).

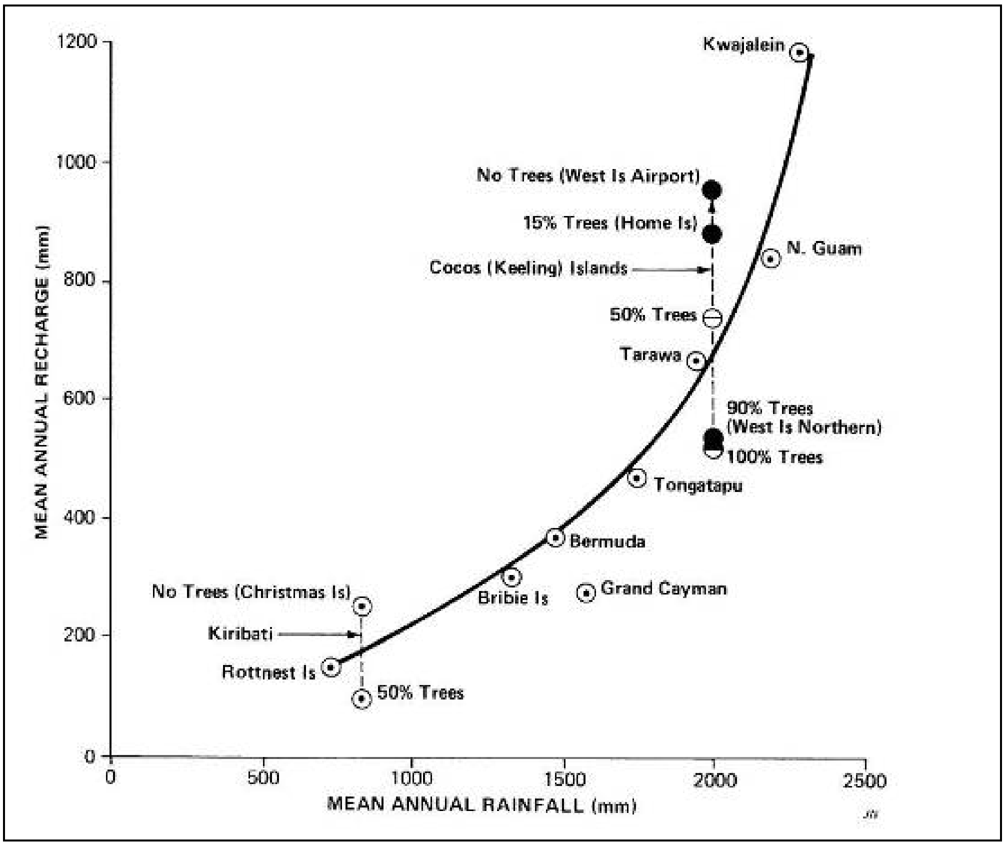

Figure 101 Relationship between annual rainfall and recharge for several islands (from UNESCO, 1991 and Falkland, 1992)

The data point for Tongatapu in Figure 101 is based on the average of estimated recharge of 25% to 30% of rainfall which was assumed to be 1,700 mm per year (from Hunt, 1978, 1979). This gives an estimated range for annual recharge of 425 mm to 510 mm or an average of about 470 mm.

If the same percentage recharge of 25 to 30% is applied to the annual average rainfall of 1,727 mm based on all data for Nuku'alofa from 1945 to 2006, the estimated average annual recharge would be slightly greater (about 430 mm to 520 mm with an average of about 480 mm).

9.3 Estimating recharge from the water balance

A water balance approach provides a more accurate estimation of groundwater recharge. Recharge is the net input to groundwater from rainfall after all evaporative and surface runoff losses have been deducted and soil moisture requirements have been met.

For an island like Tongatapu there is no significant surface runoff and recharge can be described by a water balance equation for a given time period *t*:

$$R = P - ET_a \pm dV \qquad [29]$$

where R = recharge to groundwater (mm/t)
P = rainfall (mm/t)
ET_a = actual evapotranspiration (mm/t)
dV = change in soil moisture store (mm/t).

Figure 102 shows the relationship between these parameters and others described below.

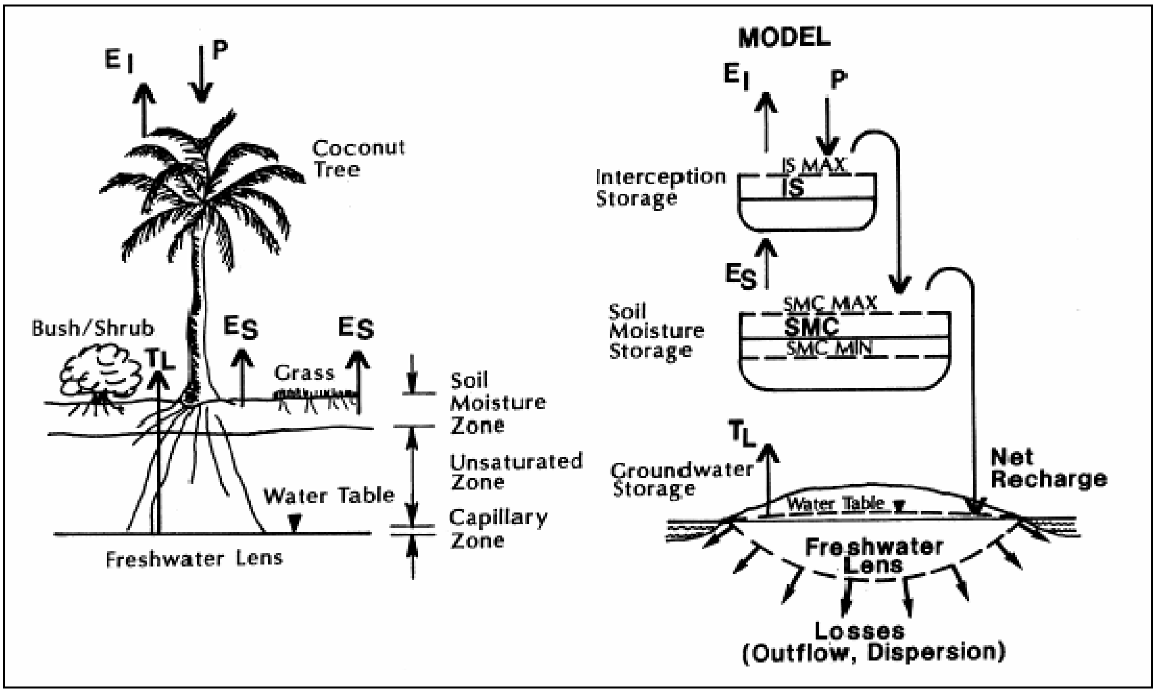

Figure 102 Water balance model for surface zone on a small island with no runoff (from Falkland & Woodroffe, 1997)

Actual evapotranspiration, ET_a, can be considered to comprise three components: evaporation from intercepted water on trees and other surfaces (E_I); evaporation and transpiration from the soil zone (E_S); and transpiration of deep-rooted vegetation directly from groundwater (T_L). It is normally assumed that the 'interception storage' is filled first before any excess rainfall enters the soil moisture zone and evaporation occurs from interception storage at the potential evaporation rate. Roots of shallow-rooted vegetation (grasses, bushes) and shallow roots of trees can obtain water from the soil moisture zone.

In the approach adopted here, vegetation types are assigned "crop factors" (Doorenbos & Pruitt, 1977) to compare their potential evaporation rate 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, E_{pot}, of the reference crop as derived from a recognised approach. The crop factor is a coefficient that is used to derive an adjusted potential evaporation of other crops from that of the reference crop.

Excess water from the soil moisture zone (SMZ) drains to the water table ("gross recharge" to the groundwater). Where water tables are relatively shallow, a further evaporative loss (T_L) can occur due to transpiration of trees whose roots penetrate to the water table. "Net recharge" is the excess water remaining in the groundwater after T_L is deducted from gross recharge. On low-lying islands such as atolls, where the groundwater is shallow, T_L can be a large proportion of evaporation losses. The depth to the water table under Tongatapu, however, varies from 1 to over 50 m, and there are very few trees on Tongatapu that have roots capable of penetrating to the water table and hence T_L can be disregarded.

9.4 Description of the recharge model

A computer program called WATBAL was used to simulate the water balance and derive recharge estimates. The main features of the WATBAL ‘model’ and the details and assumptions regarding input parameter are as follows:

- Monthly rainfall data and estimates of monthly evaporation were used and water balance calculations were conducted using a monthly time step. If possible, water balance calculations should be done using a daily time step for greater accuracy, as recommended by Chapman (1985). However, as daily rainfall data was not available in electronic form, it was decided to use the available monthly rainfall data. The use of monthly rainfall data in the model tends to slightly under-estimate the recharge. The degree of under-estimation of average annual recharge as a proportion of annual average rainfall is approximately 5-10% based on comparative studies.
- Monthly rainfall data from the Nuku’alofa climate station was used as this site had the longest record for Tongatapu (62 years from 1945 to 2006 with no missing data). Monthly data for November and December 2007 was not available in time for this analysis, so the data from 2007 was not included.
- Monthly potential evaporation estimates were obtained from Thompson (1986). Further details are provided in Falkland (1992).
- The model allows for interception by vegetation. A maximum value for the interception storage (ISMAX) is defined and it is assumed that this storage must be filled before water is made available to the soil moisture storage. Typical values of ISMAX are 1 mm per day (approximately 30 mm per month) for predominantly grassed areas and 3 mm per day (approximately 90 mm per month) for areas with substantial tree cover. A range of values were used in WATBAL to test the sensitivity of the results to variations in ISMAX from 30 to 90 mm/month.
- The model incorporates a soil moisture zone (SMZ) 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 any excess water drains to the water table. Above the field capacity, FC (the maximum moisture content that soil can retain), water is assumed to drain to the water table. Below the wilting point, WP (the minimum soil moisture required to sustain plants), no further evaporation or drainage is assumed to occur and plants may wilt or die.
- 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 thickness of the soils (and hence SMZ) is variable over Tongatapu from about 0.5 m in the east to about 6 m in the west (Cowie et al,

1991; van der Velde et al, 2005). The WATBAL model was used to test the sensitivity of the results to variations in SMZ from 1 m to 4 m.

- FC was assumed to be 0.55 (55%) and WP was assumed to be in range 0.35 – 0.40 (35% - 40%) based on soils studies in Tonga by the former New Zealand Department of Scientific and Industrial Research (DSIR) reports. van der Velde (2006) measured the water content over a range of soil water potentials for 5 soil layers at the Vaini Research Station. At a soil water potential of 0.1 kPa, approximating FC, the top 300 mm of the soil had a mean volumetric water content of 0.56 while at 1.5×10^3 kPa, approximating WP, the mean soil water content for the top soil was 0.44. Down to a depth of 1.2 m the mean FC and WP were higher at 0.68 and 0.52.
- The amount of evaporation from the SMZ is assumed to be related to the available soil moisture content. At WP, zero losses due to evaporation are assumed to occur from the soil. Maximum or potential evaporation is assumed to occur when the SMZ is at FC. 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 assumed to be half that of the potential rate.
- As mentioned above, it is assumed that no transpiration occurred directly from the water table as in most parts of Tonga tree roots are not long enough to reach the water table.
- It is assumed that the ‘crop factor’ for shallow-rooted vegetation is equal to 1.0. Deep rooted vegetation such as coconut and other trees are not considered as these are not prevalent in the makatea areas being considered for groundwater development.
- The crop factor for trees (predominantly 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 (DRVR) were estimated from photographs. This proportion varied from about zero to 0.3. Both values were used in WATBAL to test the sensitivity of the results to variations
- It is assumed that the parameter values apply to all of Tongatapu.

9.5 Results of analyses

Seven water balance analyses, or simulations, using the WATBAL program, were conducted (Case 1 to Case 7). Table 62 summarises the results of these water balance simulations for different combinations of ISMAX, SMZ, WP and DRVR values. The input data and the results of a sample water balance analysis (Case 1) are presented in Annex J. Monthly and annual values of the main water balance parameters are then shown, including the recharge (in mm) and the recharge ratio (recharge divided by rainfall) for each month of the analysis. Annex J provides a summary for the full 62-year period for Case 1.

Figure 103 and Figure 104 show comparisons between annual rainfall and recharge for, respectively, Case 1 and Case 4 (lowest recharge scenario). The relationships between average rainfall and average recharge for these two cases are shown in Figure 105 and Figure 106.

The mean monthly recharge is plotted in Figure 107 together with the 70th and 50th (median) percentiles for Case 1. It can be seen that, on average, most of the recharge takes place in January to April with relatively infrequent recharge from May to September and very infrequent recharge from October through December. The individual recharge estimates reveal, however, that significant recharge events can occur in all months. The longest consecutive period of zero recharge for Case 1 was 18 months from the beginning of September 1991 to the end of February 1993.

The mean 7 month dry season recharge, 172 mm, is almost half the mean 5 month wet season recharge, 393 mm for Case 1. The CV of the dry season mean, 99%, is larger than that of the wet season, 75%, reflecting the greater variability of dry season recharge.

Table 62 Summary of recharge estimates for various parameter values

Case	ISMAX (mm)	SMZ (m)	FC	WP	DRVR	Average Annual Recharge (mm)	Annual Recharge as proportion of Annual Rainfall		
							Average over 62 years (1945 – 2006)	Maximum (in 1971)	Minimum (in 1981 & 1983)
1	**90**	**1**	**0.55**	**0.40**	**0.3**	508	0.29	0.47	0
2	**90**	**4**	**0.55**	**0.40**	**0.3**	405	0.23	0.46	0
3	**90**	**1**	**0.55**	**0.35**	**0.3**	483	0.28	0.47	0
4	**90**	**4**	**0.55**	**0.35**	**0.3**	390	0.23	0.46	0
5	**90**	**2**	**0.55**	**0.35**	**0.3**	432	0.25	0.47	0
6	**60**	**1**	**0.55**	**0.40**	**0.3**	554	0.32	0.49	0
7	**30**	**1**	**0.55**	**0.40**	**0.0**	568	0.33	0.48	0

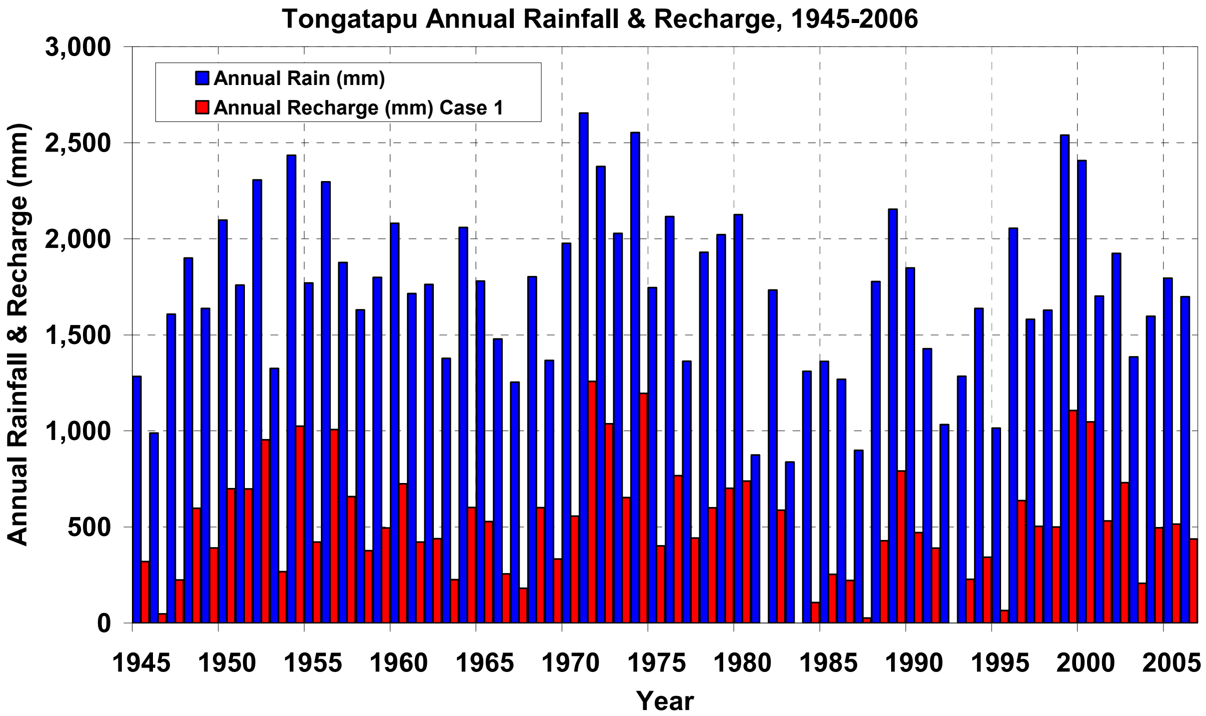

Figure 103 Annual rainfall & recharge, Case 1, 1945 - 2006

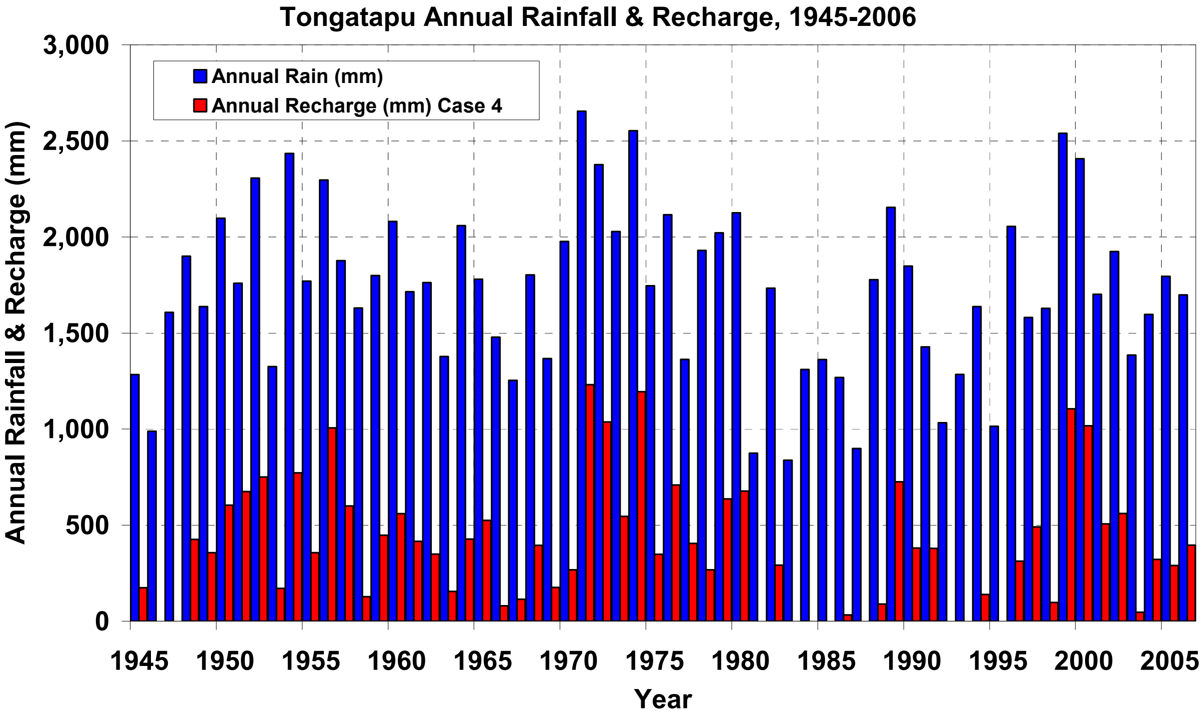

Figure 104 Annual rainfall & recharge, Case 4, 1945 - 2006

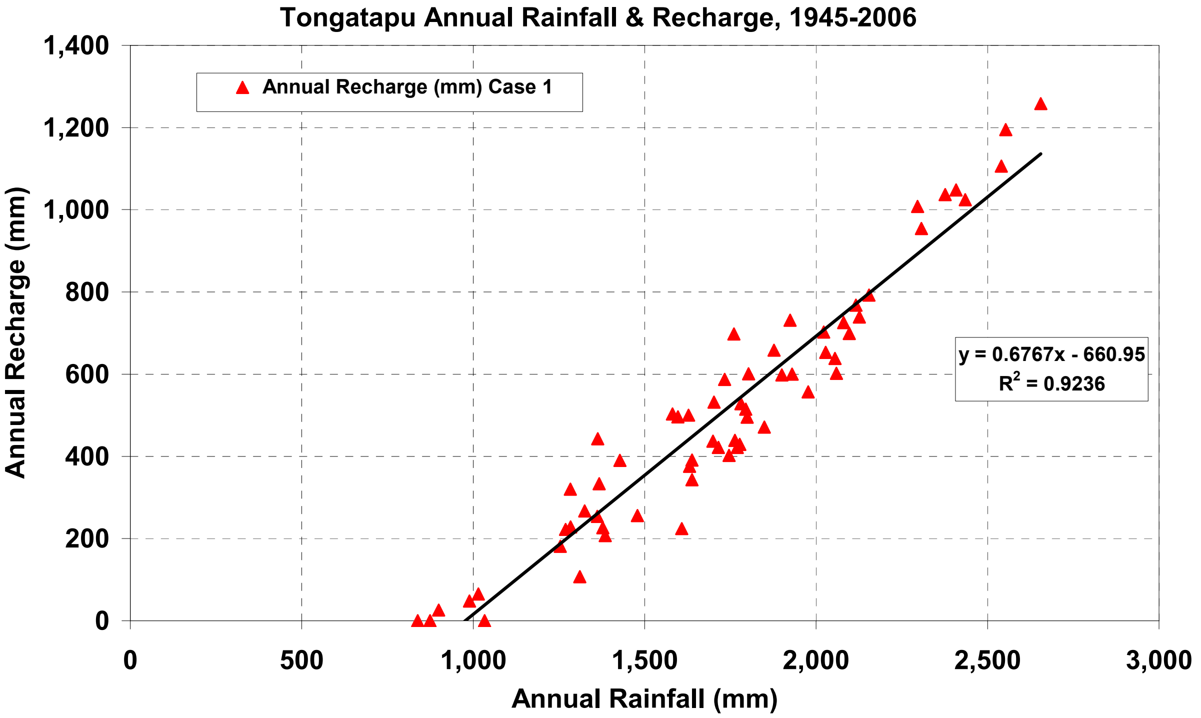

Figure 105 Annual rainfall versus recharge, Case 1, 1945 - 2006

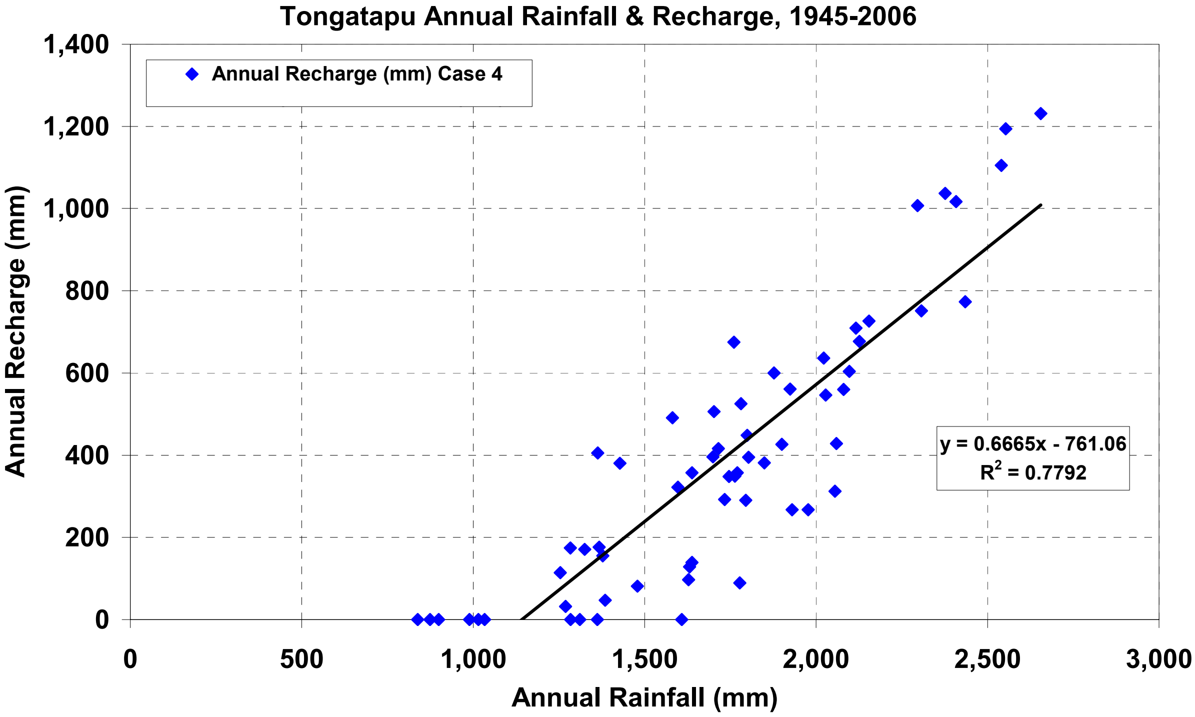

Figure 106 Annual rainfall versus recharge, Case 4, 1945 – 2006

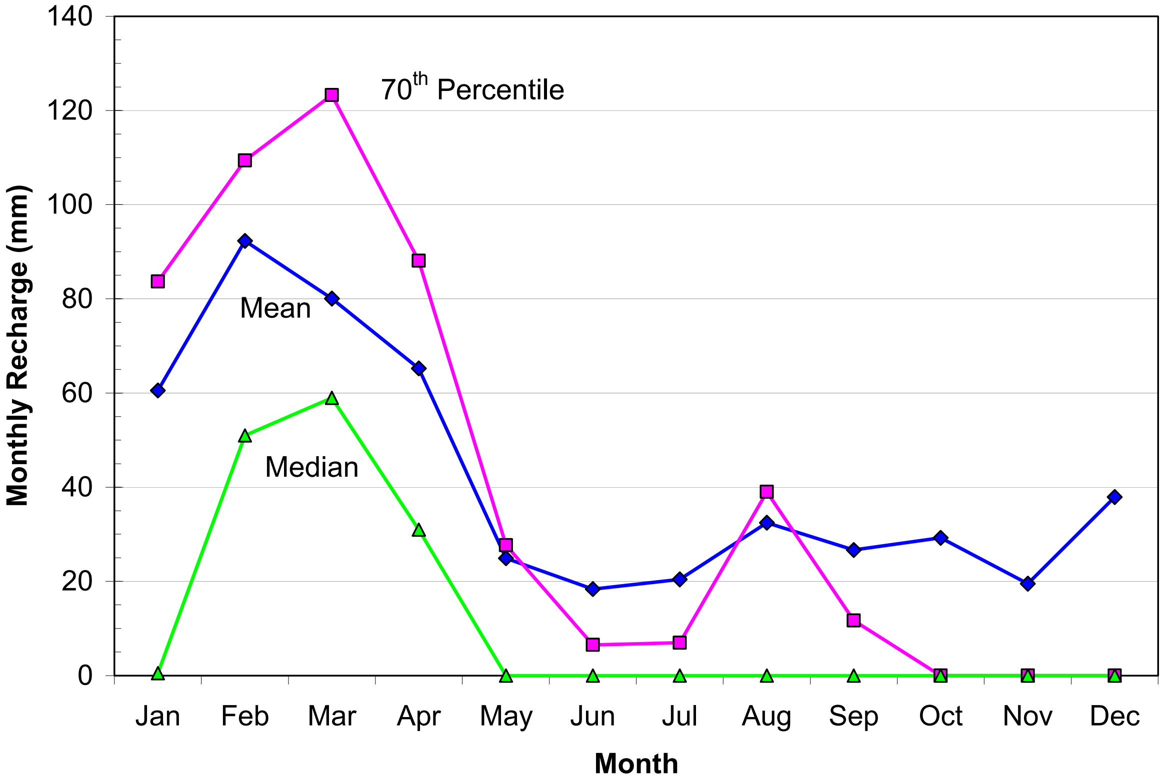

Figure 107 Mean, 70th and 50th (median) percentile monthly recharge for Case 1, 1945-2006

9.6 Discussion of results

From the results in Table 62 and in Figure 103 and Figure 104, the following observations are made:

- Calculated average annual recharge values vary from 405 mm to 568 mm (23% to 32% of average annual rainfall) according to the values of parameters selected.
- Changing various parameter values had differing effects on the recharge results, showing different sensitivity of the results. Some examples are:
    - Increasing SMZ from 1 m to 2 m (Cases 3 and 5) led to a 10% reduction in average annual recharge from 483 mm to 432 mm.
    - Further increasing SMZ from 1 m to 4 m (Cases 1 and 2) led to a 20% reduction in average annual recharge from 508 mm to 405 mm.
    - Decreasing WP from 0.40 to 0.35 (Cases 1 and 3) led to a 5% reduction in average annual recharge from 508 mm to 483 mm.
    - Decreasing ISMAX from 90 mm to 60 mm (Cases 1 and 6) led to a 9% increase in average annual recharge from 508 mm to 554 mm.
    - Further decreasing ISMAX from 90 mm to 30 mm (Cases 1 and 7) led to a 12% increase in average annual recharge from 508 mm to 568 mm.

Overall, the largest changes in recharge between the different cases were as a result of selecting different values of SMZ. Since Tongatapu has soil depth that varies between about 0.5 m in the east to about 6 m in the west (Cowie et al, 1991), recharge can also be expected to be spatially dependent. Using the results in Table 62, it can be estimated that recharge for a soil depth of 0.5 m would be about 570 mm compare with only about 380 mm for 6 m deep soil for Case 1. This may also help explain why the Hihifo region in the east of Tongatapu has such saline groundwater (see Figure 33).

There is considerable variation in recharge from year to year. The relationship between average annual rainfall and recharge is not linear as shown in Figure 105 (Case 1) and Figure 106 (Case 4). In particular, for Case 4, with the thickest estimate of SMZ, the data shows two significant non-linear features. Firstly, there is a range of annual rainfalls (from the lowest vale of 874 mm to just over 1,600 mm) where annual recharge was calculated as zero. Secondly, at annual rainfalls above about 2,300 mm the amount of recharge increases well above the line of best fit. This indicates a trend of an increasing proportion of rainfall that becomes recharge as annual rainfall increases (similar to the trend in Figure 101). In addition, the scatter in the data indicates that annual recharge is not only dependent on the magnitude of annual rainfall but also on the variability of the rainfall from month to month.

Figure 108 shows that the relationship between recharge and rainfall for Case 1 over every 12 month period between 1945 and 2006 is better fitted by a quadratic equation with a high correlation coefficient. We can use a quadratic relation to predict total recharge over the preceding 12 months from total rainfall over the preceding 12 months. To do this, we fit a quadratic to recharge (Case 1) - rainfall data over 12 months for a selected portion of the record and then fit it to the total record. Here we have chosen the period January 1965 to December 1980 and find the quadratic relation between total recharge over the previous 12 months $\sum_{i=0}^{11} R_i$ and rainfall over the previous 12 months $\sum_{i=0}^{11} P_i$:

$$\sum_{i=0}^{11} R_i = 1.761 \times 10^{-4} \times \left(\sum_{i=0}^{11} P_i \right)^2 + 3.71 \times 10^{-2} \times \sum_{i=0}^{11} P_i - 113 \qquad [30]$$

Figure 109 shows that this quadratic, derived for only the period January 1965 to December 1980, fits the estimated data from 1945 to 2006 remarkably well, explaining all but 5.8% of the variance

($R^2 = 0.942$). Equation [30] predicts that when the rainfall over the previous 12 months is less than about 700 mm, recharge over that 12 month period is, on average, zero.

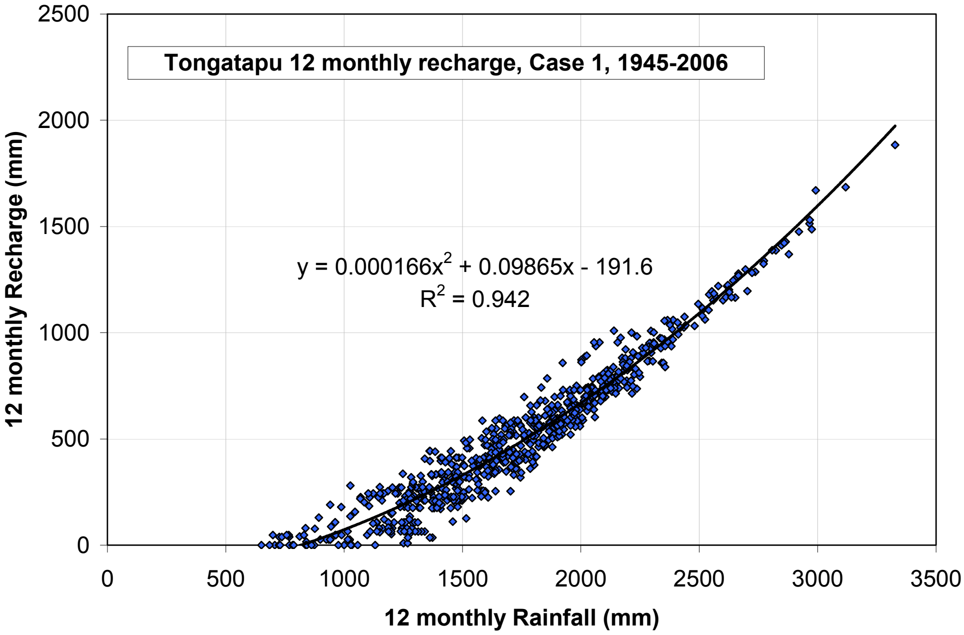

Figure 108 Non-linear relationship between recharge and rainfall for Case 1 and every 12 month period between 1945 and 2006

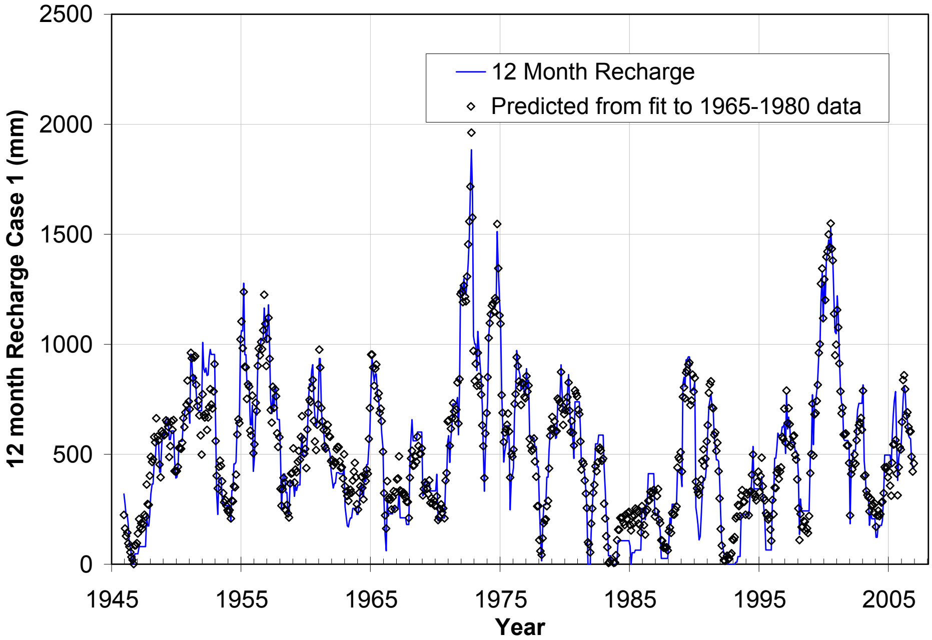

Figure 109 Comparison of 12 month recharge for Case 1 and that predicted from equation [30] fitted to recharge-rainfall data between 1965 and the end of 1980

Other observations arising from the recharge analyses are:

- Zero recharge occurred for nearly all cases in both 1981 and 1983. In some cases, other years also had zero recharge. For instance for Case 4, zero recharge also occurred in seven other years (1946, 1947, 1984, 1985, 1987, 1992 and 1993). In general, these years also had the lowest annual rainfalls.

- For Case 1, over the period 1946 to 2006 almost 58% of the months had zero recharge. Over this period, October was the month with the highest percentage of months with zero recharge (79%), followed by November (74%) and December (73%). For Case 1, the month with the lowest percentage of months with zero recharge was March (26%) followed by February and April (both 37%) as shown in Figure 110. Again for Case 1 for 1945-2006, the mean and median number of months each year with zero recharge is 7, with the maximum 12 months (1981, 1983 and 1992) and the minimum 2 months (1972 and 1999). A total of 11 dry seasons (May through October) out of the 62 dry seasons had no recharge over the 6 months, while 4 wet seasons (November through April) had no recharge.

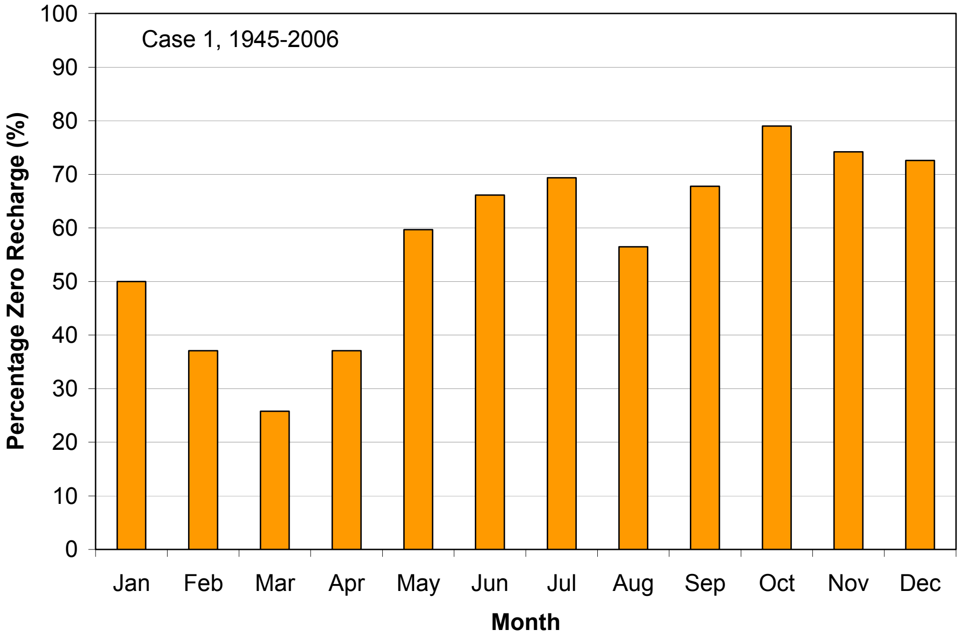

Figure 110 Percentage of months of the year with estimated zero recharge for Case 1 over the period 1945-2006

- The maximum recharge values occurred in all cases in 1971 (46 to 49% of average annual rainfall), corresponding to the highest annual rainfall.
- The lowest sequence of annual recharge occurred in the 1980s. This is particularly evident in Figure 104. The average annual recharge for the 7 year period from 1981 to 1987 for Case 4 was only 46 mm or 12% of the long-term annual average for this case. For Case 1, the average annual recharge for the same 7 year period was 171 mm or 34% of the long-term annual average recharge for this case. Again this illustrates the importance of the depth of the soil on recharge and on the fact that different areas of Tongatapu will experience different recharge rates. Further sequences of low recharge were experienced in the late 1940s and early 1990s. The longest sequence of estimated zero recharge (Case 1) was 18 months from September 1991 to February 1993, followed by 16 months zero recharge from September 1982 to December 1983, 14 months zero recharge from November 1980 to December 1981 and 13 months zero recharge from September 1945 to September 1946 . Figure 111 shows the frequency of occurrence of zero recharge periods of different durations for Case 1 from 1945 to 2006. Just less that half (48%) of the 123 periods of zero recharge had a duration of two months or less while 13 (10.6%) ran consecutively for more than 7 months.

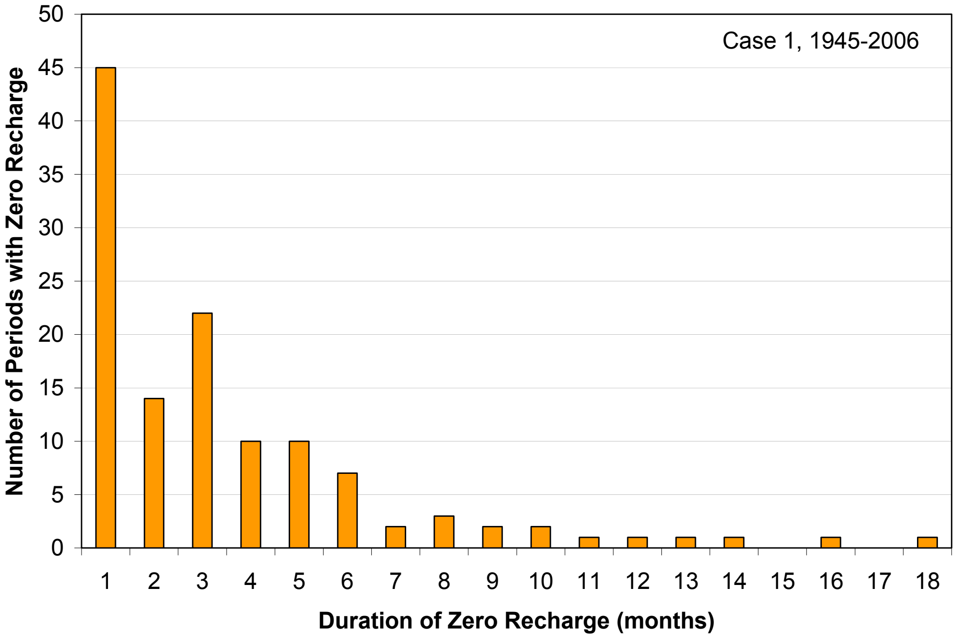

Figure 111 The frequency of occurrence of the number of consecutive months with zero recharge for Case 1

- Annual recharge in recent years 2004 to 2006 has been close to the long-term average.
- As expected, recharge predominantly occurs during the wet season and is most frequent during January through April. It is least likely to occur from October to December. Groundwater recharge, however, can take place in any month.

9.7 Conclusions, unsolved issues and recommendations

9.7.1 Conclusions

In order to estimate the sustainable yield of groundwater, the rate of groundwater recharge must be estimated. A monthly mass balance approach has been used here to estimate the groundwater recharge rate. The following conclusions regarding recharge are made from the above analyses and observations:

- A reasonable range of average annual recharge estimates for Tongatapu as a whole is about 430 mm - 520 mm or 25% - 30% of average rainfall. The variation is largely dependent on the thickness of soil cover and will vary spatially across Tongatapu. An average annual value of about 470 mm appears reasonable, but local recharge will depend on depth of soil cover.
- Because of the spatial variation of soil cover between east and west in Tongatapu, it is expected that recharge will be higher in the eastern part of the island than in the west where the soil cover is thicker. This makes the eastern part of the island, such as around Fua'amotu international Airport a more attractive water source for any expanded water supply scheme.
- The range of average annual recharge values is similar to that derived by Hunt (1978, 1979) as discussed in section 9.2. The upper end of the range is also very similar to the value of 528 mm or 30% of rainfall adopted from a water balance procedure in Falkland, 1992.
- If a full sequence of daily rainfall data in electronic form becomes available, the recharge estimation should be re-calculated using daily rainfall data. It is likely that the estimated recharge will be higher using daily rainfall data.

- The sequence of recharge is important for sustainable groundwater resources management. The very low recharge period in the 1980s is a critical period for estimating sustainable yield as indicated in the next section.
- There is a marked seasonality in groundwater recharge in Tongatapu with mean 7 month dry season recharge being almost half the mean 5 month wet season recharge and the dry season recharge has higher variability than the wet season recharge.

9.7.2 Unresolved issues

Several unresolved issues concerning recharge remain to be addressed.

- When a full sequence of daily rainfall data in electronic form becomes available, the recharge estimation should be re-calculated using daily rainfall data. It is likely that the estimated recharge will be higher using daily rainfall data.
- It is clear from the above analyses that recharge is spatially dependent in Tongatapu and that the elevation and thickness of the freshwater lens in Tongatapu should depend on location. The discussion in section 9.6 and equation [15] suggests that the mean water table elevation should vary by ±5% across Tongatapu for areas of equal island width. The database should be examined to determine if there is a spatial variation in water elevation consistent with soil cover.
- Both in this project in sections 5.5, 0, and 6.11 and in van der Velde (2006), groundwater salinity has been shown to depend on rainfall. More accurately, groundwater salinity should depend on recharge. An examination should be made of both the EC data from the Mataki’eua/Tongamai wells and the Tongatapu village wells for the variation of salinity with recharge with a view to optimising the parameters of the recharge model.

9.7.3 Recommendations

From the above discussion, it is recommended that:

- Groundwater salinity monitoring boreholes are established across Tongatapu.
- The RL of village wells, where water table elevation can be measured, be re-surveyed as accurately as possible.
- The Tongatapu well databases be examined to see if a spatial dependence of water table elevation on depth of soil can be established.
- That dependence of EC data in the Mataki’eua/Tongamai well and the Tongatapu village well databases on recharge be examined with a view to optimising the parameters in the WATBAL recharge model.
- The optimised WATBAL recharge model should be run every month. When the estimated recharge has been zero over a period of 8 months, the frequency of groundwater monitoring should be increased and a warning given to appropriate agencies.

10 Sustainable Groundwater Pumping in Tongatapu

10.1 Overview of groundwater yield

The sustainable yield of a groundwater aquifer can be defined as the maximum amount of water that can be extracted on a continuous basis, including during drought periods, without causing long-term depletion of the aquifer or adverse effects on the extracted water and on the environment. For freshwater aquifers on islands which are in contact with underlying seawater, as on Tongatapu, sustainable yield can be considered as the maximum amount of water that can be extracted on a continuous basis, while maintaining the salinity of the extracted water below the adopted freshwater limit of EC = 2,500 μS/cm (refer section 4.4).

The sustainability of freshwater aquifers depends on the amount of fresh groundwater in storage, the average recharge rate and the rate of and method of groundwater extraction. For continental groundwater systems, the sustainable yield can be close to the average recharge rate so that pumping can nearly equal the inflow to the groundwater system. For freshwater aquifers on small islands, however, not all recharge can be sustainably extracted, as some of the freshwater inflow mixes with saline water at the base of the freshwater zone. If all recharge was extracted, such aquifers would diminish as mixing with salt water continued until no freshwater is available.

The proportion of recharge to groundwater that can be sustainably extracted, the sustainable groundwater yield, is based on many factors including the distribution of the groundwater over the island and the methods of groundwater extraction (Waterhouse, 1984).

10.2 Preliminary estimates per unit area

Other small island studies (e.g. UNESCO, 1991) have indicated that approximately 20% to 50% of long-term average recharge to freshwater aquifers can be sustainably extracted. The sustainable yield as a proportion of average recharge increases as average annual recharge increases. For small islands with moderate rainfall, sustainable yield estimates are at the lower end of the range of percentage values above.

For Tongatapu, it is recommended that a conservative approach be adopted and that the sustainable yield should be in the range from 20% to 30% of average recharge. A similar approach was adopted in Falkland (1992) where a single estimate of 20% of average recharge was chosen.

Using the range of annual average recharge values of 430 mm - 520 mm (refer section 9.7), the range of sustainable yields in volume per unit area (mm) is 86 mm to 156 mm per year, equivalent to 5% - 9% of average annual rainfall. With these estimates, the average sustainable yield per unit area (hectare) is in the range 2,300 to 4,300 litres per hectare per day (L/ha/day) or 2.3 to 4.3 m^3/ha/day[17]. To be conservative, an average value of about 3 m^3/ha/day, equivalent to 110 mm per year, appears suitable, although a value of 4 m^3/ha/day could be used as a guide for the upper limit in the design of sustainable pumping systems. Our estimate of 3 m^3/ha/day is identical to that proposed in Falkland (1992).

In order to assess the validity of these preliminary estimates, further analyses of the impacts of droughts and possible pumping from the freshwater lenses were undertaken, as outlined below.

10.3 Impact of droughts on freshwater thickness

As mentioned previously, the average annual recharge in the 1980s was well below the long-term average recharge. In order to assess the impacts of the reduction in average annual recharge in this drought period (and possibly future drought periods), it is necessary to review the amount of storage in the freshwater aquifer(s) and the hydraulic residence times. The hydraulic residence time or turnover time of an aquifer[18] is a measure of the average time taken for fresh groundwater

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[17] Note 1m^3/ha/day = 1 kL/ha/day = 0.1 mm/day.

[18] Mean hydraulic residence time = volume of extractable water (m^3)/ mean inflow or outflow rate (m^3/day)

to move through the aquifer. The hydraulic residence time can be calculated by dividing the fresh groundwater thickness by the average annual recharge for the area investigated.

Measured values of the thickness of fresh groundwater in Tongatapu are only available in and around the Mataki'eua/Tongamai wellfield (sections 4.4 and 6.3). From monitoring of groundwater salinity profiles in the salinity monitoring boreholes SMB1 - SMB7 at and near the Mataki'eua/Tongamai wellfield between 1997 and 2007, the average freshwater zone (aquifer) thickness at the boreholes away from pumping influence (SMB6 and SMB7) is between 9 m and 14 m. For salinity monitoring boreholes close to or within the wellfield, the average freshwater zone thickness varied from about 5 m and 12 m. We note however, that this monitoring period does not include a major drought.

The minimum freshwater thickness in the aquifer for the boreholes beyond the influence of pumping was about 9 m in 1998. The actual depth of fresh groundwater that can be recovered from the aquifer is less than the thickness of fresh groundwater. This is because the aquifer consists of both groundwater and sediments/rock, mostly karst limestone. The actual groundwater thickness that can be recovered equals the fresh groundwater thickness multiplied by a factor called the specific yield which is the volume of freshwater released from the aquifer per unit surface area per unit decline in the water table height(dimensionless). The specific yield for the limestone formations on Tongatapu has been estimated to be between 0.3 and 0.4 so that 30-40% of the total thickness of a freshwater in aquifer is fresh groundwater can be extracted.

The minimum thicknesses of fresh groundwater that can be extracted at boreholes SMB6 and SMB7 is therefore 2.7 m, based on a conservative estimate for specific yield of 0.3. Using this groundwater thickness estimate and the average annual recharge of between 430 and 520 mm/year, the hydraulic residence time is between 5.2 and 6.3 years. Falkland (1992) estimated this time as 6.3 years, equal to the upper limit of the current estimates. Based on these calculations, the fresh groundwater aquifer should be able to withstand a number of years when much less than normal and even zero recharge occurs, such as occurred in the period 1981 - 1987. Unfortunately there were too few measurements of salinity during the decade 1980-1990 to verify this prediction in any detail (sections 5.4, 6.8, and 6.9).

The data from the salinity monitoring boreholes does not cover a period of extreme drought as occurred in the 1980s, so the effect of severely reduced recharge on groundwater aquifer thickness is not known. During such periods, there may be enhanced mixing between the fresh groundwater and underlying saline groundwater leading to a further reduction in the thickness of the aquifer. This factor can only be assessed after monitoring salinity profiles during significant periods of nil or negative recharge. This highlights the need for long-term monitoring and reporting of the groundwater resources throughout Tongatapu and indeed on other islands of the Kingdom of Tonga.

10.4 Impacts of pumping on freshwater thickness

An approximate method was employed to assess the impacts of long-term pumping on the fresh groundwater. This method uses an empirical relationship that was developed by Henry (1964) and applied to small islands by Mather (1975). The method is approximate since it assumes steady state conditions, uniform recharge and a sharp interface at the base of the freshwater lens. Better estimates of pumping impacts could be provided using a suitable groundwater flow model.

From steady state theory, the depth to the base of the freshwater aquifer is proportional to the square root of recharge (equation [15]). This relationship can be used to estimate changes in the long-term average depth to the base of the freshwater aquifer due to long-term decreases in available recharge caused by pumping. This approach assumes the effects of pumping are distributed across the total area of the aquifer whereby the volume of water extracted can reasonably be assumed to act as a reduction in the available recharge. We note that this gives a mean reduction in groundwater thickness. Concentrations of vertical wells are expected to produce upcoming of the local freshwater/seawater interface considerably greater than this mean reduction.

If pumping at a rate of 3 m^3/ha/day or 110 mm/year is applied across Tongatapu, the long-term mean reduction in fresh groundwater thickness can be estimated from the initial freshwater thickness and the square root of the ratio between initial and reduced recharge estimates. This pumping rate would effectively reduce the average annual recharge from 470 mm (section 9.5) to about 360 mm. The reduced recharge is then 76% of the original recharge. Using equation [15], the average fresh groundwater thickness during pumping would reduce to 87% of the original thickness. The reduction in thickness by about 13%, while significant, is not large. This would have the effect of reducing the average fresh groundwater thickness in the area of boreholes SMB6 and SMB7 from a minimum of 9 m to about 7.8 m.

If the maximum pumping rate of 4 m^3/ha/day or 145 mm/year was applied, the reduction in effective recharge would be 325 mm/year or 69% of the original. The corresponding reduction in mean freshwater thickness would be about 17%, from 9 m to 7.5 m, not much greater than that expected for a pumping rate of 3 m^3/ha/day. Even with this reduction in available fresh groundwater thickness, it is likely that fresh groundwater would remain after pumping at the nominated pumping rate over significant droughts provided wells are not concentrated in one location.

During the sampling of SMBs conducted during August 2007, it was noted that the thickness of the freshwater lens within the pumped wellfield at Mataki’eua/Tongamai was between 2 and 4 m thinner than the lens outside the influence of the bore field. The estimation above for only modest reductions in mean groundwater thickness is based on a model that assumes a sharp front between fresh and seawater at the base of the lens and assumes that the effect of pumping is distributed evenly over the entire island. It does not account for local upconing under concentration of wells such as occur in Mataki’eua/Tongamai as measured using the SMBs. Pumping clearly increases the width of the saline transition zone further decreasing the thickness of useable freshwater. Consequently, the above predictions of impacts on the reduction of mean water table thickness need to be treated cautiously since local effects may dominate under high density of pumps.

10.5 Estimate of sustainable yield for whole of Tongatapu

Based on the discussion in the above sections, island-wide estimates of sustainable yield for Tongatapu in volumetric terms can be made on the basis of the per unit area estimates multiplied by the area where recharge is effective.

Some 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. As noted in Falkland (1992), however, some areas of the island are not effective recharge zones for water supply wells. From observations of salinities in wells, it is apparent that the freshwater lens that is extractable from 2 m deep wells does not extend to within about 500 m of the ocean coastline on the outer edge of the island. This margin is one where freshwater is quickly discharged into and dispersed with seawater due to tidal mixing and other effects to produce a brackish groundwater in vertical wells beyond the freshwater limit. Near the lagoon, where finer sediments tend to decrease the aquifer permeability, fresh groundwater can be found within 100 m of open saline water. For this study, as in the Falkland (1992) study, only the area of the effective recharge zone, which is the area of the island underlain by a reasonable thickness of fresh groundwater, was included in the estimation of sustainable yield volumes. All island area within 500 m of the coastline and within 100 m of the lagoon and the area of Nuku’alofa were not considered. The resulting 'effective recharge zone' of the island is approximately 180 km^2 (18,000 ha) or 70% of the total island area.

Multiplying the range of per unit area of sustainable yields, 3 to 4 m^3/ha/day by this effective recharge zone area, the average sustainable yield for the whole of Tongatapu is therefore estimated to be in the range 54,000 - 72,000 m^3/day, or 54 - 72 megalitres per day (ML/day), for the whole of Tongatapu. A reasonable mean estimate is 60 ML/day.

Previous estimates of sustainable yield for the whole of Tongatapu have been made in a number of reports:

- Falkland (1992) estimated the sustainable yield at 52 ML/day.
- Lao (1979) derived a sustainable yield estimate of 61.8 ML/day. This was based on 20% of his estimated recharge. He also estimated sustainable yield on a 'regional' basis for the 3 areas:

o Liahona (west region)	25.4 ML/day (about 41% of total)
o Fua'amotu (southeast region)	23.2 ML/day (about 38% of total)
o Kolonga (east region)	13.2 ML/day (about 21% of total).

The estimate of the range of sustainable yields in this project covers the values found in these previous studies.

Assuming that the above listed regions cover 40%, 40% and 20%, respectively, of the Tongatapu effective recharge zone area, the following approximate sustainable yield estimates per region are made to the nearest 0.5 ML/day from the range of island wide sustainable yield estimates of 54 - 72 ML/day.

o Liahona region	21.5 – 29 ML/day
o Fua'amotu region	21.5 - 29 ML/day
o Kolonga region	11 – 14.5 ML/day.

More detailed work, beyond the scope of this study, is required to refine these estimates for these regions. It is interesting to note the salinity in the Fua’amotu region had the lowest salinity of all groundwaters sampled indicating higher recharge and a thicker freshwater lens than elsewhere in Tongatapu. This suggests, subject to further analysis, that the Fua’amotu region has the highest sustainable yield of the three regions.

10.6 Comparison with current groundwater extraction

Current groundwater extraction consists of concentrated pumping from the Mataki'eua/Tongamai wellfield for Nuku’alofa and more diffuse pumping from local village wells scattered across Tongatapu for village water supply. At the Mataki’eua/Tongamai wellfield, there are only a few operational flow meters at the pumps and the main flow meter on the supply pipeline from the storage tanks to Nuku’alofa has not been working for some time. Estimates are therefore made on the basis of past flow records and knowledge of the approximate number of pumps in service and their average flow rates. Based on this information, a current total pumping rate of 8 ML/day is made (see Section 6.15).

Figure 112 shows flow data from 1995 to 1998 (during the period of the AusAID funded Tonga Water Board Institutional Development Project). In 1998, the average daily groundwater production from the wellfield in Nuku’alofa was about 6.8 ML/day. This is consistent with the 2007 estimate of about 8 ML/day as some additional pumps have been installed since 1998 (see section 6.13).

The total estimated production from the Mataki'eua/Tongamai wellfield represents nearly 40% of the lower bound estimate of sustainable yield from the much larger Liahona, region which is a significant proportion. This production is also about 15% of the lower bound sustainable yield estimate of 54 ML/day for the whole island. Apart from its magnitude, the Mataki'eua/Tongamai wellfield production is concentrated in a reasonably small part of the whole Liahona region and could well be the reason for the estimated 2 to 4 m decrease in the thickness of the freshwater lens observed from the salinity monitoring boreholes (section 6.3). In section 6.15, mention was made of the proposed Danish project to increase the number of pumps in the Mataki’eua/ Tongamai wellfield to a total of 60 with a potential maximum extraction rate of 15 ML/day or 70% of the lower bound sustainable rate for the entire Liahona area. This extraction rate is expected to create increased salinity and further thinning of the freshwater lens at Mataki’eua/Tongamai and may create significant problems during droughts.

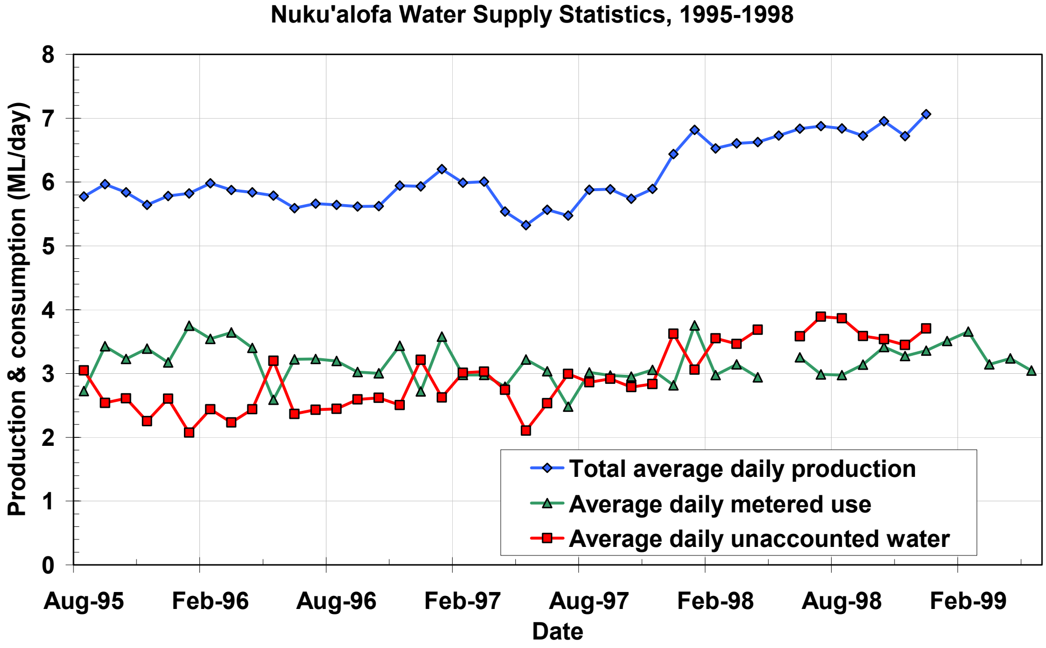

Figure 112 Average daily groundwater production and use for Nuku'alofa, 1995 - 1998

Current pumping from village and other wells (or "rural groundwater extraction") is more difficult to estimate as there are no flow meters installed on the pumps on these well. Estimates have been made elsewhere. Based on available information at the time, Falkland (1992) estimated that the total rural groundwater extraction was about 4.5 ML/day. Allowing for say a 20% increase since 1992, the estimated total current rural groundwater extraction is about 5.4 ML/day. For an estimated 60 village and other water supply systems on Tongatapu (other than the Mataki'eua/Tongamai wellfield), this flow represents about 90 m^3/day per village. These average flow rates appear reasonable but more information is required to estimate the actual flows with greater accuracy. The lack of data on volumes extracted shows the necessity of installing flow meters on all village and other water supply systems. Without proper measurement and assessment of pump flow, it is very difficult to manage the groundwater resources.

Using the population figures for 2006 for Nuku'alofa and rural Tongatapu (Table 3), the average daily per capita water supply in Nuku'alofa is approximately 240 L/p/day while that in rural Tongatapu villages is about 150 L/p/day. In Nuku'alofa, however, unaccounted for water in 1995-1998 was nearly ⅔ the total groundwater production, indicating that the amount of water actually available per capita in Nuku'alofa is only 80 L/p/day, which is similar to the rural per capita total usage. Information on unaccounted for water in village water supplies is not unavailable but is probably at least 50%. The unaccounted for water is the Nuku'alofa water supply is a particular problem since energy and money are being spent pumping good quality groundwater to Nuku'alofa where a high proportion of it leaks into unusable, polluted groundwater which discharges into the ocean or Lagoon.

As mentioned in Falkland (1992), a high proportion of the rural groundwater extraction takes place in the western Liahona region of the island. If it is assumed that 50% of the rural groundwater extraction takes place in this region, then 2.7 ML/day would be currently pumped from there. Combined with the production from the Mataki'eua/Tongamai wellfield, the estimated total production from the Liahona region is about 10.7 ML/day. This represents about 50% of the lower bound sustainable yield estimate for this region. If all of the proposed 60 wells at Mataki'eua/Tongamai are eventually in production, the extraction rate could be over 82% of the lower bound estimate of the sustainable yield for the Liahona region. We believe that this extraction rate will have significant impacts on the salinity of extracted water and on the thickness of the freshwater lens in this region.

For the areas of Tongatapu other than the western region, total current extraction is approximately 2.7 ML/day. This is about 8% of the lower bound sustainable yield for the rest of Tongatapu

(32.5 ML/day) and emphasises the fact that additional water extraction for Nuku'alofa should be sourced at some distance from the Mataki'eua/ Tongamai wellfield.

10.7 Area of influence of Mataki'eua/Tongamai pumping

Using the sustainable yield estimate of 3 to 4 m^3/ha/day above, an analysis can be made of the collective pumping rates in use at the Mataki'eua/Tongamai wellfield in 2007.

The area of influence of a pumping borehole on groundwater is considered to be circular. There have been no estimates on the area of influence of individual pumped wells in Tongatapu. In this project, we have measured the small drawdown of the water table within a pump well itself (Table 22). This information can be used to estimate the drawdown radius of a pumped well. Smith and Wheatcraft (1992) give the steady state flow to a fully penetrating well pumping at a rate of Q (m^3/s) in an unconfined aquifer as:

$$Q = \pi K \frac{h_0^2 - h_w^2}{ln(r_0 / r_w)} \qquad [31]$$

where $K =$ the hydraulic conductivity of the aquifer (m/s),

$h_0 =$ hydraulic head (m) at radius r_0 (m) from the well, and

$h_w =$ hydraulic head (m) within the well of radius r_w (m).

If we specify that r_0 is the radial position at which there is negligible drawdown, then r_0 is the radius of influence of the well. If Δh_w (m) is the drawdown in the well, equation [31] can be rearranged to give:

$$r_0 = r_w \, exp\left[\frac{\pi K \Delta h_w (2h_0 - \Delta h_w)}{Q}\right] \qquad [32]$$

In section 6.7 we estimated K from the drawdown, depth of penetration of the well, L, its radius, r_w, and pumping rate, Q, using equation [4]. We can substitute this expression for K in equation [32] to find:

$$r_0 = L.exp\left[\frac{2h_0 - \Delta h_w}{2L}\right] \qquad [33]$$

Using the values found for the pumped well 117 at Mataki'eua, $L \approx 2$ m, $h_0 = 0.556$ m, and $\Delta h_w =$ 0.0115 m (Table 22), we find $r_0 = 2.63$ m. This small radius of influence is due to the very large horizontal hydraulic conductivity of the aquifer. Essentially, the well is pumping over an effective area of only 22 m^2. The pumping rate for well 117 was 376 m^3/day or 17 m/day over the area of influence of the pump. This predicted zone of influence needs to be verified but it is noted that the estimated mean daily recharge is only 0.0013 m/day.

In order for well 117 to achieve the sustainable extraction rate of 3 to 4 m^3/ha/day within a collection of similar pumps it would need to be spaced 1.1 to 1.26 km from the next pump. Generally. the pumping rates of diesel pumps in Tongatapu are less than the submersible electric pump on well 117 and are usually between 2.5 and 3 L/s, or between 216 and 260 m^3/day. These rates require pumps to be spaced with a separation of between 0.83 and 1.05 km, in order to achieve the extraction rate of 3 to 4 m^3/ha/day for a wellfield[19].

The above information can be used to estimate the maximum number of pumps that can be used continuously on Tongatapu to stay within the sustainable groundwater yield. The effective recharge zone area on Tongatapu is 180,000 ha. For pumping rates of 2.5 to 3 L/s, the required area/pump to achieve the sustainable extraction rate is 54 to 86 ha/pump. That provides an estimate of between about 210 and 330 pumps pumping continuously. Collectively, these pumps would extract

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[19] Previous work has specified pump spacings of around 200 m.

between 54 and 72 ML/day as required (see section 10.5) but need to be spaced approximately 0.8 to 1 km apart in order to minimise upconing and salinity problems. Currently, most of the 58 village water supply wells in Tongatapu pump for only a few hours every day. Only about 32 of the wells at Mataki'eua/Tongamai pump continuously.

The approximate area covered by pumps at the Mataki'eua/Tongamai wellfield is 150 ha (see Figure 5). Water is extracted from there currently at a rate of about 8 ML/day, which is an areal rate of over 53 m^3/ha/day or between 13 to nearly 18 times the estimated sustainable yield of the wellfield area. It is clear that, because of the large hydraulic conductivity, the Mataki'eua/Tongamai wellfield is drawing water from an area around the wellfield equivalent to an area of between 2,000 and 2,700 ha since pumping has clearly been sustainable. Assuming a circular area of influence for the Mataki'eua/Tongamai wellfield, this is equivalent to a radius of influence of 2.5 to 2.9 km. The oldest wells at Mataki'eua are within 2.0 km (Figure 50 and Figure 51) of the Lagoon and it is therefore hardly surprising that these wells show an increasing salinity with increased pumping The installation of further pumping wells at Mataki'eua/ Tongamai would appear problematic.

10.8 Future wellfields for Tongatapu

Currently, water supplies for villages in Tongatapu are sourced from local wells located close to the villages. Many of these local wells are at risk from pollution, particularly from human and animal wastes, and, in the Hihifo region, village wells have very saline local groundwater. Nuku'alofa's water supply is currently sourced from the Mataki'eua/Tongamai wellfield whose approximate area of influence is shown in Figure 113.

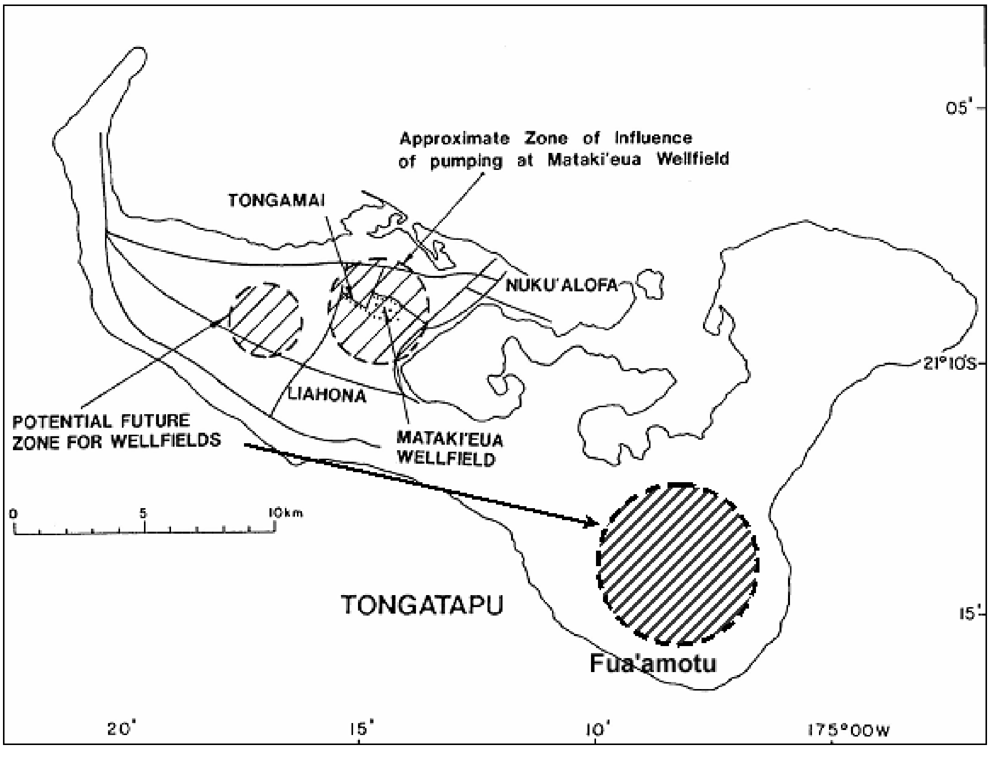

Figure 113 Tongatapu, showing the area of influence of the Mataki'eua/Tongamai wellfield and possible new wellfields at Liahona and Fua'amotu

Any new wellfields will have their own zone of influence, the size of which will be determined by the total pumping capacity. It is important that any new wellfield be beyond the current zone of influence at Mataki'eua/Tongamai. We have confirmed in this report that the western area of Hihifo has chronic groundwater salinity problems (Figure 33). The Liahona region has the potential to be developed as a water source area for the more saline, western portion of Tongatapu

The groundwater in the region of Fua'amotu International Airport has several advantages as a future water source for Nuku'alofa and for the Vaini and Tatakamotonga districts. While the cost of pipelines from this area will be significant, having a future water supply that is within government owned land, with lower salinity and is relatively remote from impacts of land use appear to be significant advantages. Detailed investigations of both the Liahona and Fua'amotu regions and more accurate estimates of sustainable yield would be required before these areas could be developed.

10.9 Conclusions and recommendations

A conservative estimate of the sustainable groundwater yield for Tongatapu has been derived assuming 20% of groundwater recharge. This means the estimated sustainable groundwater pumping rate is 3 m^3/ha/day with an upper limit of 4 m^3/ha/day. The lower rate has been selected here to ensure that a viable freshwater lens would be maintained throughout droughts as severe as any that have occurred in the past. When this areal pumping rate is applied to the effective recharge area of Tongatapu, a sustainable groundwater extraction rate of between 54 and 72 ML/day is found.

The absence of meters on village pumps and the failure of the bulk water meter at Mataki'eua mean that there is no accurate measure of groundwater extraction in Tongatapu. The estimate made here is that current extraction at the Mataki'eua/Tongamai wellfield is about 8 ML/day while village water pumping may be as high as 5.4 ML/day giving a current total estimated daily extraction of 13.4 ML/day or 19 to 25% of the sustainable yield. Approximately 10.7 ML/day, or 80% of this estimated total daily extraction, is sourced from the Liahona-Tongamai-Mataki'eua region due to the concentration of pumps at the Mataki'eua/Tongamai wellfield, while the remaining 20% is distributed over the rest of Tongatapu. This uneven distribution of pumping could be further exacerbated by proposals to increase the number of pumps at Mataki'eua/Tongamai to up to 60 and may create salinity problems in pumped water during dry times.

Between half and two thirds of the water pumped from the Mataki'eua/Tongamai wellfield disappears as unaccounted-for losses. A large proportion of the good quality groundwater is therefore being pumped from Mataki'eua/Tongamai to be discharged from leaking pipelines into the polluted groundwater in Nuku'alofa were it discharges into the Lagoon or the ocean. Future water supply projects in Nuku'alofa should concentrate on reducing these losses.

Using the mean measured drawdown of a single pump, it was estimated that the radius of influence around a pump was only about 2.6 m. This estimate needs to be verified as it implies considerable upconing of the fresh/seawater interface beneath pumps and especially under the concentration of pumps at Mataki'eua/Tongamai.

Based on the estimated areal sustainable groundwater extraction rate of 3 to 4 m^3/ha/day, the range of the maximum number of pumps, pumping continuously at rates of 216 to 260 m^3/day (2.5 to 3.0 L/s), that can be accommodated within the effective recharge zone of Tongatapu is between 210 and 330 pumps. To minimise upconing of the fresh/seawater interface it is desirable to have these pumps as evenly distributed as possible with spacing between pumps of 0.75 to 1 km. Spacing pumps closer than this will increase both local upconing, and as observed at Mataki'eua/Tongamai wellfield(see section 6.3) the salinity of pumped groundwater.

We have estimated that the Mataki'eua/Tongamai wellfield already has a radius of influence between 2.5 and 2.9 km. For this reason, it is concluded that the further concentration of pumping near Mataki'eua/Tongamai could be problematic. Instead the Fua'amotu region should be explored as a future water source for Nuku'alofa, Vaini, and Tatakamotonga districts and the area around Liahona be explored urgently as a source for future water supply to the saline Hihifo region.

10.9.1 Unresolved Issues

A conservative estimate of the sustainable yield for Tongatapu has been given here. More accurate estimates could be made with dynamic two-dimensional groundwater models, which allow for a diffuse fresh/seawater transition zone, using the historic rainfall record and a range of pumping scenarios.

An approximate estimate of the zone of influence of a groundwater pump based on the measured drawdown in the pump well has been estimated. Further tests of this need to be carried out throughout wells and particularly bores in Tongatapu. This will involve drilling piezometers around test wells. In addition, numerical modelling using measured values of well drawdown could be undertaken.

A caution on the concentration of pumping at Mataki'eua has been given here. Numerical modelling using dynamic two-dimensional groundwater models, which allow for a diffuse fresh/seawater transition zone interface should be undertaken to examine the impact of concentration of pumps.

It is has been concluded above that the Fua'amotu and Liahona regions be explored as possible future water source areas. Additional investigations, including the installation of SMBs will be required to fully asses these areas.

10.9.2 Recommendations

Based on the above considerations, the following recommendations are made:

- All groundwater supply pumps in Tongatapu should be licensed.
- The maximum pumping rate for any single groundwater supply pump in Tongatapu should be limited to 3.0 L/s (260 m^3/day) and this rate should be set as a licence condition.
- All water supply pumps must be fitted with a water meter and monthly reporting of the volume of water extracted should be a licence condition.
- The maximum number of licensed groundwater supply pumps for continuous operation in Tongatapu should be limited to 210.
- Replacement of the defective main bulk water meter at Mataki'eua is a high priority.
- Reduction of water losses in the Nuku'alofa reticulation system should be made a high priority for donor funding.
- The impact of concentrating further pumps at Mataki'eua/Tongamai should be investigated.
- Also of high priority, the Fua'amotu and Liahona regions should be investigated as possible future water source areas.

11 Droughts

11.1 Overview

The goals of this study are to facilitate the planning and sustainable management of the fresh groundwater resources of Tongatapu in the Kingdom of Tonga, to aid in the identification of trends and threats so that corrective actions can be taken, and to enable sound planning for any future development and use of Tongatapu's groundwater resources. Evaluation of the occurrence of droughts and their impacts on Tongatapu's groundwater resources are vitally necessary for the assessment of threats to the islands water resources and their ability to supply the population centre of Nuku'alofa, village communities, agriculture and industry. It is also required for the prediction of climate change risks and impacts, estimation of sustainable groundwater yields and in the planning of mitigation strategies to address land use changes, water quality trends and contamination issues.

In this section, we examine the occurrence of hydrological droughts in Tongatapu. Agricultural drought, which is concerned with the soil water store, is of central importance to crop production in Tongatapu, however, groundwater resources respond to changing rainfall patterns over a longer time-scale than does soil water. Here, we therefore concentrate on hydrologic drought appropriate to the groundwater stores in Tongatapu.

11.2 Rainfall variation in Tongatapu and ENSO events

Falkland (1992) comprehensively summarised of rainfall in Tongatapu from 1947 to 1990. For that period he reported a mean annual rainfall of 1,770 mm at the Nuku'alofa weather station on the northern side of the island, just above mean sea level. This mean had a small coefficient of variation (CV) of only 0.24, indicating that annual rainfall in Nuku'alofa is relatively reliable.

For the period 1951-1980, the mean annual rainfall in Nuku'alofa was 1,888 mm (Thompson, 1986) while from 1981 to 1990, the mean annual rainfall was only 1,406 mm. The El Niño Southern Oscillation (ENSO) phenomenon, a feature of the climate of the Pacific Ocean, has a marked effect on rainfall patterns in Tonga (van der Velde, 2006). The major ENSO events in 1982/83 and 1986/87 caused extensive droughts throughout the kingdom and had a major influence on the lower rainfalls which extended from 1981 to 1990 (Falkland, 1992). Spennemann (1989) reviewed incomplete rainfall records data from 1888 to 1987 and concluded that the drought in 1982 was the longest on record. The hydraulic residence time or turnover time of the freshwater lens in Tongatapu (depth of freshwater lens divided by the recharge rate) has been estimated to be six years (see section 6.3) and, under natural conditions, can probably withstand quite long droughts. With pumping, turnover time is reduced and the lens may be more vulnerable to drought under increased pumping.

Rainfalls in coral islands in the Pacific are usually significantly correlated to variations in central and eastern Pacific sea surface temperatures and ENSO events (Falkland, 1983, Evans *et al.,* 1998). This variability results in periods of sometimes over 12 months with small, infrequent rainfalls followed by periods of high rainfalls. During extended low rainfall periods, the unique hydrogeology of coral islands, and the continual erosion of their freshwater lenses can severely limit freshwater availability, and has sometimes forced the expatriation of islanders.

The major drought throughout the central Pacific from 1998 to around 2000 resulted in rainwater tanks running dry, dramatic increases in salinity in domestic wells, the death of some trees, die-back in others and an increasing demand for potable, reticulated water in many small island nations and even led to a least one declaration of a national State of Disaster. This declaration highlighted the need for appropriate quantitative measures of the severity of droughts (Falkland, 1999) or a drought index for coral islands which takes into account the different sources of water used for domestic supplies. This report uses a systematic approach (White *et al.,* 1999b) for assessing the severity of prolonged hydrologically significant dry periods and for providing warning of their onset,

In this section, an examination is carried out on the occurrence, severity and duration of droughts as evidenced in the historic rainfall record in Tongatapu. This study has access to some 16 more years of monthly rainfall than was available to Falkland (1992). We adopt here a different approach to that used by van der Velde (2006)[20] who was primarily concerned with agricultural drought.

11.3 Defining drought

Drought, like "bad weather" is a relative term. It is generally associated with a sustained period of significantly lower soil moisture and water supply than the normal levels to which the local environment and society have adapted. The relative nature of drought, the fact that a low rainfall period in a tropical environment can be the equivalent of a high rainfall period in a semi-arid environment, makes the definition of drought difficult (Smith *et al.*, 1992) as well as complicating the identification of its onset and its conclusion. Only abnormally dry conditions, which lead to a lack of sufficient water to meet normal requirements, should be recognised as drought (Gibbs, 1975).

Emphasis on droughts has usually centred on their impacts on crop and animal production. However, there are broader issues which go beyond agriculture, such as potable water supply, which require different approaches. Consequently, there are at least four common definitions for drought based on meteorological, agricultural, hydrologic and economic considerations (Rasmussen *et al.,* 1993).

11.3.1 Meteorological or climatological drought

Meteorological or climatological drought is an interval of time during which the supply of moisture at a given place cumulatively falls below the climatologically appropriate moisture supply. This sort of drought has been defined as a prolonged abnormal moisture deficiency (Palmer, 1965). In areas with marked seasonal dry periods, the interval of time over which supply of moisture is considered has to be long enough to cover wet and dry seasons.

11.3.2 Agricultural drought

Agricultural drought is an interval of time when soil moisture cannot meet the evapotranspiration demand for crop initiation, to sustain crops and pastures or supply water for livestock or irrigated crops. With this definition, crops with different water demands and water-use strategies, such as deep-rooted trees and shallow-rooted grasses experience onset of drought at differing times (Rasmussen *et al.,* 1993).

11.3.3 Hydrologic drought

Hydrologic drought is an interval of time of below-normal stream flow or recharge, or depleted reservoir or groundwater storage. Because of the residence time for water in different storages, hydrological drought can lag behind and extend beyond regions of meteorological drought. It can be also influenced by land use changes, particularly those which alter runoff, infiltration and ultimately deep drainage.

11.3.4 Socio-economic drought

Socio-economic drought is the impact of physical processes on human economic activities as a result of drought, such as returns from crop sales. It occurs when demand for an economic good (e.g. water, food, forage, fish and hydropower) exceeds supply due to a deficit of water as a result of the weather.

The sequence of drought impacts is first felt in systems with short water residence times. Thus topsoil water storage, typically of order 100 mm, upon which dryland crops and pastures depend, is the first depleted. Rainwater tanks and shallow surface storages such as farm dams generally follow. Systems which rely on large surface water reservoirs and deep groundwater systems are

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[20] van der Velde (2006) describes drought as "a deficiency of rain over an extended period". While perhaps applicable to the agricultural context, this makes no allowance for tropical situations with normally dry seasons.

the most robust. When droughts break, systems with the smallest water residence time recover first.

11.4 Drought in coral islands

The unique hydrology of coral islands means that they are sensitive to extended dry periods. Their small areas limit any surface harvesting and storage of water. Additionally, the high permeability of their soils and aquifers means that runoff collection is limited to impermeable surfaces, artificial rainwater catchments and constructed surface storages, such as rainwater tanks of limited capacity (Falkland, 2002). The main water storage is usually thin fresh groundwater lenses floating over seawater. The tidally-forced mixing of the freshwater with seawater thins the freshwater lens further and creates a brackish water transition zone (Wheatcraft and Buddemeier, 1981) and the lens is constantly discharging to the sea at the islands coast.

The most important factors that determine the thickness of freshwater in the lens are (Falkland and Woodroffe, 1997):

- Rainfall amount and distribution;
- The type and distribution of surface vegetation and soils;
- Size of the island, particularly the width from sea to lagoon;
- Permeability and porosity of the geological aquifer formation;
- Tidal range; and
- Methods of groundwater extraction and the quantity of water extracted by pumping.

For water supply and irrigation systems, drought in coral islands is intimately connected with the continued viability of the fresh groundwater storage.

To a first approximation, for a uniform aquifer, the relationship between the maximum thickness of freshwater (actually the depth from the water table to the midpoint of the saline transition zone) in the centre of a lens, H_m, is related to the island width, W and the recharge rate, R, the hydraulic conductivity of the lens K_0, and the density of sea and freshwater, ρ_s and ρ_0 respectively, through (Chapman, 1985):

$$\begin{aligned}\frac{H_m}{W} &= \frac{1}{2}\left(\frac{\rho_S\ R}{(\rho_S - \rho_0)K_0}\right)^{1/2} \\ &= \frac{1}{2}\left((1+\alpha)\frac{R}{K_0}\right)^{1/2}\end{aligned} \tag{34}$$

where $\alpha = \rho_0 / (\rho_S - \rho_0)$.

The karst limestone in Tongatapu has very high horizontal aquifer hydraulic conductivities, typically 1,000 m/day or more (see section 6.7). This means that freshwater discharges rapidly to the surrounding sea at a high rate and that seawater can more easily mix with freshwater. With typical values for island width, recharge and hydraulic conductivity, equation [34] predicts that the freshwater lenses in Tongatapu should be of order 10 m thick, which accords with an observed maximum thickness in this work of around 14 m (Figure 53).

The high permeability of the volcanic soils of Tongatapu and the depth of the water table mean that, in the absence of irrigation, shallow-rooted crops, such as vegetables, which do not tap into the groundwater, experience agricultural drought within a few days without rain. In Tongatapu, agricultural droughts are of considerable concern because of the widespread reliance on home-produced crops (Furness, 1991a). Here our concern is with the limited quantities of drinking and irrigation water for human survival and we shall concentrate therefore on meteorological and hydrological drought.

11.5 Quantitative estimation of droughts

A central problem in identifying droughts is how to compare dry periods at different times and in different locations, particularly in areas with marked wet and dry seasons such as Tongatapu. One way of doing this is to use drought indices which are designed to remove these spatial and temporal dependencies. The most frequent use of drought indices is in farming situations where decisions are required on crop planting, irrigation, stocking densities and providing support or drought relief to farmers and communities who rely on cropping or grazing.

There are a number of existing indices which are largely irrelevant to coral islands. Indices such as: the surface water supply index, which is mountain-water dependent and incorporates mountain snow pack; the crop moisture index, introduced to measure the impact of short-term moisture conditions on a developing crop (Palmer, 1968); the national rainfall index, developed to compare spatial and temporal variability of precipitation on a continental scale (Gommes and Petrassi, 1994); and dependable rains, an index for agricultural production planning which is the amount of rain that occurs statistically in four out of every five years (Le Houérou *et al.,* 1993) are irrelevant to hydrologic drought in Tongatapu. In addition, percent of normal rain, the actual precipitation divided by the long-term (30 year) mean rain and expressed as a percentage is not considered here because of its unrealistic assumption of a normal distribution for rain, and the fact that spatial comparisons are not possible (Willeke *et al.,* 1994).

Water balance calculations of the relevant water storages (Chapman, 1985), are the best approach for considering hydrological droughts and their impacts. Water balances are used in estimating the probability of failure, the reliability and critical drawdown of surface water storage reservoirs (McMahon, 1993). These appear appropriate for groundwater supplies in coral islands. At their simplest, these water balances over a time period t can be expressed as:

$$\textit{Change in storage} = \textit{sum of inputs} - \textit{sum of outputs} \qquad [35]$$

When the decrease in storage during dry times reduces the storage volume to a critical level, a drought is frequently declared and procedures are adopted to conserve the remaining water. In order to use the water balance approach for drought declarations, the storage volume, critical storage (volume below which problems arise), as well as the water inputs and outputs need to be known. Outputs are the demand for or extraction of water together with natural losses such as evaporation or evapotranspiration and discharge.

In Tongatapu, there are three sources of water for domestic consumption: rainwater catchments, a few private domestic wells, and reticulated water drawn from groundwater reserves. In order to define droughts unambiguously, information on the size of storages, critical storage volumes, inputs and outputs are required. Storage, demand values and natural losses for rainwater and domestic water wells are usually poorly known. The inputs for both rainwater and groundwater storages are directly related to rainfall, because of negligible surface runoff for groundwater, and are therefore better known, although the areas of rainwater catchments for rainwater collection are, in general, poorly characterised. The outputs consist of the demand, rate of extraction, leakages and natural losses due to evaporation, as well as for groundwater outflow and mixing losses. These outputs are often only approximately known for major groundwater sources used for reticulation systems (Falkland, 2002; White *et al.,* 2002). In Tongatapu, there is limited information on the rate of groundwater extraction, because of the absence of meters on village pumps and the failure of the bulk supply meter at Tongatapu. In addition, the time period over which water balances need to be estimated depend on the capacity of the storages and the residence time of water in them. These are not well-characterised for rainwater or domestic water wells.

The time period over which water balances should be calculated depends on the residence time of water in the storage which is estimated from (Chapman, 1985):

$$\textit{Residence time} = \textit{volume of storage/ inflow or outflow rate(demand)} \qquad [36]$$

Neither the volumes of storage nor demands are known for rainwater tanks and domestic wells. For the groundwater system in Tongatapu we have estimated here a residence time of approximately 6 years (see section 10.3). The water balance for the groundwater store in Tongatapu over a time period *t* is:

$$R = T_i + GD + D + Q \pm dS \qquad [37]$$

where R = recharge to groundwater
T_i = direct transpiration losses from the groundwater
GD = groundwater discharge around at the coastal fringe
D = dispersion losses at the base of the lens
dS = change in aquifer storage.

The mean depth of groundwater in Tongatapu means that T_i is negligible and equation [37] becomes:

$$R = GD + D + Q \pm dS \qquad [38]$$

Over long periods the change in aquifer storage is also negligible and equation [38] is simplified to:

$$R = GD + D + Q \qquad [39]$$

While we can estimate *R* (section 9), *Q* is only known approximately and *GD* and *D* are unknown. In general, only one of the components of the water balance, rainfall, is known for the sources of domestic water on coral islands. White *et al.* (1999b) reviewed available drought index methods for assessing droughts and concluded that the rainfall decile method, used as standard in Australia, was the most appropriate method for assessing meteorological or hydrological droughts in coral islands.

The treatment of the variability of rainfall is the key to the analysis of meteorological drought (Smith *et al.,* 1992). The statistics of rainfall provide a method for deciding the occurrence and severity of droughts. The monthly or annual decile method (Gibbs and Maher, 1967) provides a method of examining meteorological drought which enables comparisons of rainfalls between different locations and different times. It is a non-parametric method that makes no assumptions about stationarity or normality of rainfall distributions.

11.6 Rainfall deciles

Rainfall deciles rank the rainfall over the period of interest in terms of the relative quantity of rain that fell in that period compared with the total distribution of all recorded rainfalls over the same period. The total quantity of rain, TP_n, for an *n* month accumulation period is just:

[40]

Here is the rainfall for the current month, P_{-i} is the rainfall for the previous *i* th month (-1 is the previous month and so on). The ranking of rainfall against the total record is expressed as a percentile of the total distribution. Thus rainfalls in the lowest 10th percentile, or lowest decile, are in the lowest 10% of all recorded rainfalls. Because this ranking is relative to the total distribution of rainfall over the time period of interest at a location, it is relative to the climatologically appropriate moisture supply at that location, as required by the definition of meteorological drought.

Rainfall deciles are a non-parametric measure of drought since they are calculated without any assumptions about how rainfall is distributed in time. Rainfall in Tongatapu shows large variability seasonally as well as annual variability over the period of record (see Figure 3 and Figure 114).

Deciles directly provide a normalised measure of dry and also wet conditions that can be compared between different sites and times. Rainfall deciles have a much higher spatial coherence than actual monthly rainfall totals. This is because deciles are essentially normalised departures from average conditions and are related to broad scale synoptic patterns (Smith *et al.,* 1992). The decile method is used in the Australian Drought Watch System and forms the basis for declaring drought and providing drought relief (White and O'Meagher, 1995). The classifications used in this system are listed in Table 63.

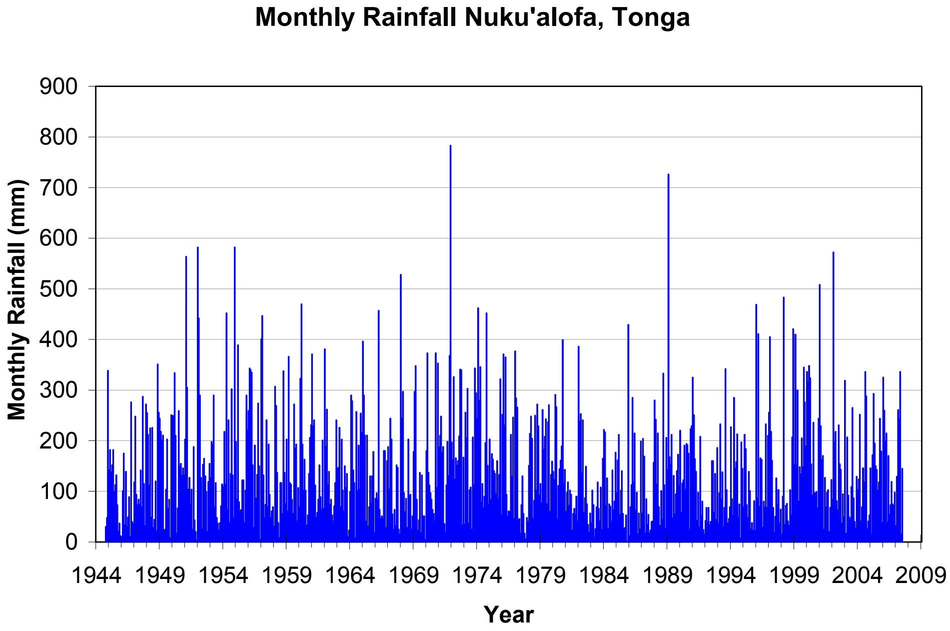

Figure 114 **Variation of monthly rainfall at Nuku'alofa. The seasonality of rainfall and the episodic, extremely high rainfalls over the period are evident.**

Table 63 **Classification system for the decile method used in Australia**

Decile	Percentile Range (%)	Climate Classification
	100	Highest of record
10	90 to <100	Very much above average
8-9	>70 to <90	Above average
4-7	>30 to <70	Average
2-3	>10 to <30	Below average
1	>0 to <10	Very much below average
	0	Lowest on record

The strengths of the decile method are:

- It recognises that different time scales are needed for different water storages.
- Non-parametric method, does not assume any rainfall distribution.
- Does not require transformation of data.
- Can be used for comparison between locations.
- Simple to calculate (in an EXCEL spreadsheet using the percentrank function).
- Meaning is clear and easily understood by non-specialists.

The main weaknesses of the decile method, also inherent in other drought indices approach, are:

- Requires long rainfall record (>30 years)
- Used mainly in Australia
- Ignores demand and losses.

When the time over which rainfall is totalled increases to 12 months or more, the coefficient of variation decreases and the distribution of longer-term rainfall approaches a near normal distribution with the mean and median values lying closer together. Also, by summing rainfalls over periods of 12 months or more, the effect of seasonality of rainfall is removed. In the decile method, droughts are identified where rainfall totals over a given period lie in the bottom 10% of all rainfalls on record.

11.7 Appropriate time periods for summing rainfall for deciles

Choosing an appropriate period of time over which to sum monthly rainfalls in coral islands depends on the water storage system of concern. For water sources in coral islands, we can be prescriptive. The appropriate time period should be related to the average residence time of water in rainwater tanks, domestic wells or reticulation groundwater reservoirs in question. This, in turn, depends on storage capacity and on the demand and discharge. The large freshwater lens which supplies the reticulation systems on Tongatapu is the storage of interest (Falkland, 1992, White et al., 1999 b).

The major freshwater lens that store water for the reticulated water supplies in Tongatapu has been characterised (Hunt, 1979; Lao, 1979; Kafri, 1989; Falkland, 1992). The thickness of the major freshwater lens has been monitored at selected sites around Mataki'eua/Tongamai since 1990. Data and experience in other Pacific islands (White et al.1999b), suggests that a rainfall summation period of between 6 to 60 months is appropriate for the major freshwater lens in Tongatapu.

11.8 Seasonality of rainfall

If the rainfall in a particular location has marked seasonality, care must be taken in applying the decile method. For example, a location with a 6 month dry period each year cannot be classified as in regular drought each year because the definition of meteorological drought is based on the concept of departures from a climatologically appropriate moisture supply for any given location. Drought in this context is defined as a prolonged, abnormal moisture deficiency. Regular, seasonal dry periods cannot be considered abnormal.

Mean rainfall in Tongatapu shows a generally wet period from December to April with a dry period from May to November (see Figure 3). The mean wet season rainfall is 962 mm, nearly 25% larger than the mean dry season monthly rainfall of 770 mm. It is noted, however, that the seasonality of rainfall can shift sometimes with the wet season starting in October or as late as February. The difference between the mean and median rainfalls in Figure 3 and the spread between the 10th and 90th percentile monthly rainfalls (rainfalls being in the lowest 10% and highest 90%) show that the monthly rainfall distribution is slightly skewed.

In order to handle seasonal rainfalls summed over less than about 12 month periods, the rainfall for the month in question summed over the preceding months has to be compared with that of all rainfalls for only the particular month in question, not the total population of all monthly rainfalls. A disadvantage of this procedure is that the number of rainfalls against which the comparison is made is reduced by a factor of twelve. This means that, in order for rainfall seasonality to be included, a minimum of at least 30 years of rainfall records are required. Here we use the seasonal method to examine rainfalls summed over 6 months.

The non-parametric decile method makes no assumption on the form of rainfall distribution and is easy to calculate. In addition, it provides a direct, easily understood ranking of the actual rainfall, providing immediate information on whether the rainfall for the period in question is above normal, above or below normal, or extremely wet or dry.

11.9 Duration of droughts

The decile method provides a way of identifying the start, duration and end of a drought. Here we identify severe droughts as periods when the rainfall summed over a specified number of previous months falls to at or below the 10th percentile level. The start of the drought is identified as the date at which the percentile for the rainfall summation period first drops below the 40th percentile level on its way to below 10th percentile. The end of the drought is identified as the date at which the percentile again reaches the 40th percentile after climbing back from the 40th percentile. The duration of the drought is then just the difference between the start and end dates. Selection of the 40% is based on the fact that this percentile represents a departure from as well as a return to near-average conditions and appears to work well in other coral islands (White et al., 1999b).

11.10 Calculation of deciles

We follow Smith *et al*., (1992) and calculate 6, 12, 18, 24, 30 and 60 month deciles on a month by month basis. This differs from the annual rainfall deciles proposed by Gibbs and Maher (1967). For 6 month rainfall periods, for each month of the year the rainfall for the preceding 6 months up to and including the month in question is summed for the 63 years of records. Each month is then ranked in percentiles against all rainfall totals for that particular month. For the longer period rainfalls, for each month of the entire rainfall record (754 consecutive months), the rainfall for the preceding 12, 18, 24, 30, and 60 months up to and including the month in question is totalled over the full sequence of months. This is then ranked in percentile terms against the rainfall totals for each sequence of months, totalled over the same period, over the whole rainfall record. Ranking can be done conveniently using the PERCENTRANK function in EXCEL spreadsheets. As the totalling period becomes longer, variations tend to be smoothed and the coefficient of variation of rainfall over the summation period decreases.

The decile data is then used to identify major droughts for a range of rainfall summation periods by identifying rainfalls which lie below the 10th percentile (0.1 decile). The onset of drought is identified as the month when the rainfall first fell below the 40th percentile (0.4 decile) before falling below the 10th percentile. The end of the drought was identified as the month when the rainfall percentile first rose above the 40th percentile on its return from below the 10th percentile level. The duration of the drought was taken as period between the onset and end of the drought. The time between droughts was taken as the time between the minimum percentiles (below 10th percentile) in each separate drought. For some droughts the rainfall percentile rose above 10% for appreciable periods but did not rise above the 40th percentile. These were included as a continuation of the drought. The number of droughts in the period January 1951 and end of October 2007 were recorded as were the mean time between droughts and the mean duration of droughts.

11.11 Characteristics of rainfall in Tongatapu

11.11.1 Nuku’alofa monthly and annual rainfall

The monthly and annual rainfall statistics for Nuku’alofa, Tongatapu, the weather station with the longest continuous rainfall record, is listed in Table 64 for the period October 1944 to July 2007. Monthly rainfalls are plotted in Figure 3 and Figure 114.

The mean annual rain in Table 64 is slightly less than the 1,770 mm found by Falkland (1992) for the period 1947 to 1990. The standard deviation of annual rainfall in Table 64 is slightly higher than that found by Falkland of 425 mm and increases the coefficient of variation (CV) slightly from the his value of 0.24 to 0.25 in Table 64. This CV is significantly lower than that found in coral islands in the central Pacific (UNESCO, 1991; White et al., 1999b) and indicates a relatively reliable annual variation.

The mean monthly rainfalls in Table 64 and Figure 3 show an average wetter season from December to April followed by a May to November drier season. The CVs for the months of October, November and December are 0.88 - 0.92 and are larger than those for the dry season (0.59 - 0.66) and appear to indicate a variable starting time for the wet season. November and December have the lowest minimum monthly rainfalls of 2 and 3 mm. December also has the highest maximum monthly rainfall of 783 mm. March, in the wet season, has the most reliable monthly rainfall with a CV of 0.44, half that of October, November and December.

Table 64 Monthly and annual rainfall statistics for Nuku'alofa, Tongatapu for the period October 1944 to July 2007

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean (mm)	198.4	224.1	220.4	165.6	102.4	92.1	100.2	117.9	121.1	121.3	110.8	153.9	**1,727**
SD (mm)	138.5	143.0	97.4	105.8	67.3	61.5	58.7	78.7	80.3	106.3	97.9	142.0	**432**
CV %	70	64	44	64	66	67	59	67	66	88	88	92	**25**
Maximum (mm)	582.0	726.0	483.0	457.0	336.0	243.0	259.0	342.0	341.0	452.0	368.0	783.0	**2655**
Minimum (mm)	10.0	15.0	39.0	9.0	17.0	8.0	18.0	17.0	11.0	8.0	2.0	3.0	**838**
Median (mm)	187.0	212.0	212.0	139.0	81.0	76.0	84.0	102.0	100.5	99.0	71.0	129.0	**1753**
10th percentile (mm)	37.0	78.2	112.2	44.0	27.4	25.6	38.6	32.0	38.3	23.4	24.0	18.8	**1256**
90th percentile (mm)	385	409	346	302	201	163	185.8	208.9	211.5	275.6	252.4	289.6	**2306**
No. Years	63	63	63	63	63	63	63	62	62	63	63	63	**62**

11.11.2 Spatial variation in rainfall

There are two rain gauges currently maintained by TMS, one downtown in Nuku'alofa, just above mean sea level (MSL) at the former main weather station, the other at the current main weather station at Fua'amotu International Airport close to the highest part of the island. Because Tongatapu's topography is subdued we expect relatively little spatial variation in rainfall. The island rises 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 in the Fua'amotu region, approximately 500 m inland from the coastline in the south-eastern corner of the island. Falkland (1992) found that monthly rainfall at Nuku'alofa was highly correlated with that at Fua'amotu. For the annual data for 1980 to 1990, we find:

$$P_{Nuku'alofa} = 0.916 \times P_{Fua'amotu} \qquad [41]$$

where $P_{Fua'amotu}$ = annual rainfall (mm) at Fua'amotu and $P_{Nuku'alofa}$ = annual rainfall (mm) at Nuku'alofa. The correlation coefficient (R_c) for equation [41] is 0.90.

Table 65 compares the annual rainfall statistics for each site for the period January 1994 to end of July 2007. It can be seen for this period the mean annual rainfall at Nuku'alofa is 94% that at Fua'amotu, while the standard deviations are almost identical. It is generally expected that annual rainfall on average increases by about 10% per 100 m rise in elevation. The difference in rainfall in Table 65 is consistent with the 50-60 m difference in elevation between the weather station sites.

Figure 115 shows the correlation between monthly rainfalls at the two stations. The relation is:

$$P_{Nuku'alofa} = 0.896 \times P_{Fua'amotu} \qquad [42]$$

with a strong correlation (R_c = 0.88).

Figure 116 shows the double mass plot for the two sites. No major departures from linearity are evident, although there seems to be a slight departure at the end of the plot starting around April 2006 with Nuku'alofa rainfalls lying increasingly below the trend line.

Table 65 Comparison of annual rainfall statistics for Tongatapu's two Meteorology Bureau rain gauges for the period January 1994 to end of July 2007

Location	Nuku'alofa	Fua'amotu
Mean (mm)	**1,767**	**1,876**
SD (mm)	402	401
CV	0.23	0.21
Maximum (mm)	2,540	2,592
Minimum (mm)	1,015	1,147
Median (mm)	1,699	1,868
10th percentile (mm)	1,424	1,548
90 th percentile (mm)	2,337	2,486
No. Years	13	13

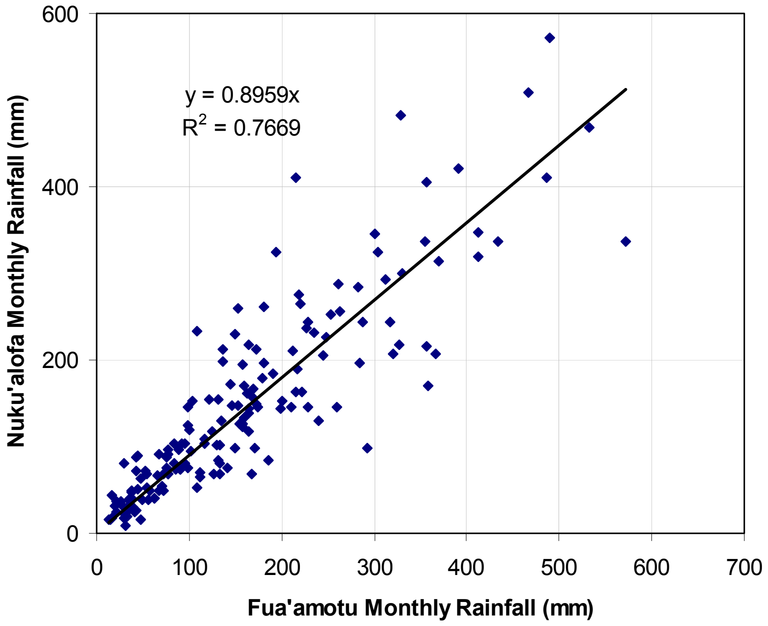

Figure 115 Correlation between monthly rainfalls at Nuku'alofa and Fua'amotu

Despite the limited spatial coverage, it is clear that there is a slight topographic variation in rainfall in Tongatapu with higher elevations receiving higher rainfalls, consistent with a 10% rise per 100 m rise in elevation. The higher elevations may also have smaller coefficients of variation of annual rainfall. Since the mean elevation of wells at the Mataki'eua/Tongamai wellfield is approximately 14 m above MSL, we can use the above to suggest that the mean annual rainfall at the wellfield should be about 1.4% higher than that at Nuku'alofa or about 1,750 mm.

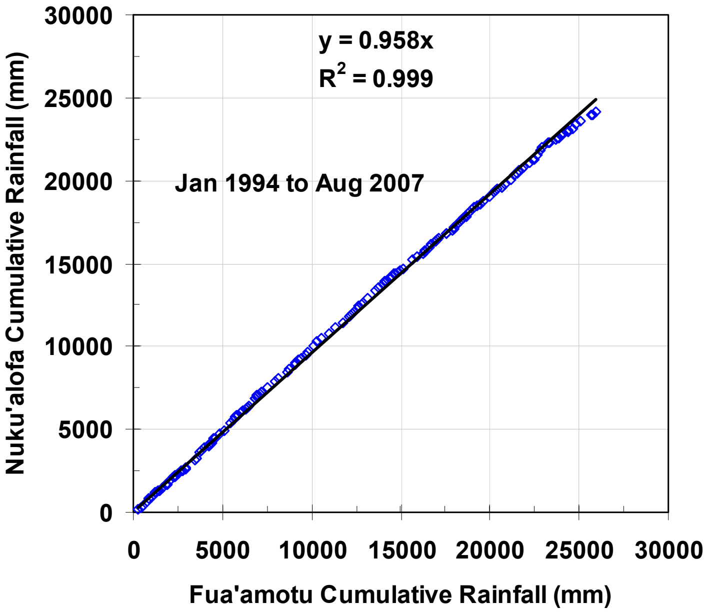

Figure 116 Double mass plot between cumulative rainfalls at Nuku'alofa and Fua'amotu

11.12 Meteorological droughts

11.12.1 Rainfall over summation periods from 6 to 60 months

Figure 117 and Figure 118 show the rainfalls summed over the previous 6 and 18 months for rainfall at Nuku'alofa. For rainfalls summed over 6 months, a clear seasonality in rainfall is evident in Figure 117. Somewhat surprisingly, this seasonal signature is also evident in rainfall summed over longer periods, particularly that for 18 month rainfalls shown in Figure 118 and also for 30 month rainfalls (not shown here). Normally longer time periods than 12 months remove seasonal signatures.

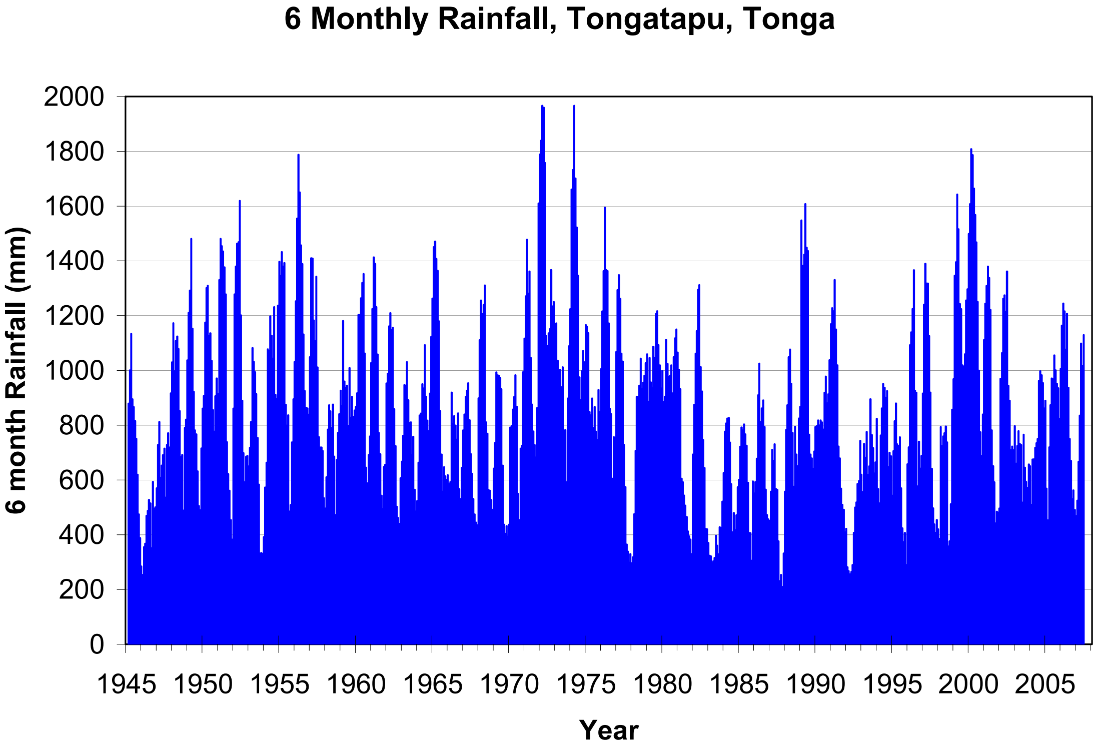

Figure 117 Rainfall summed over the previous 6 months

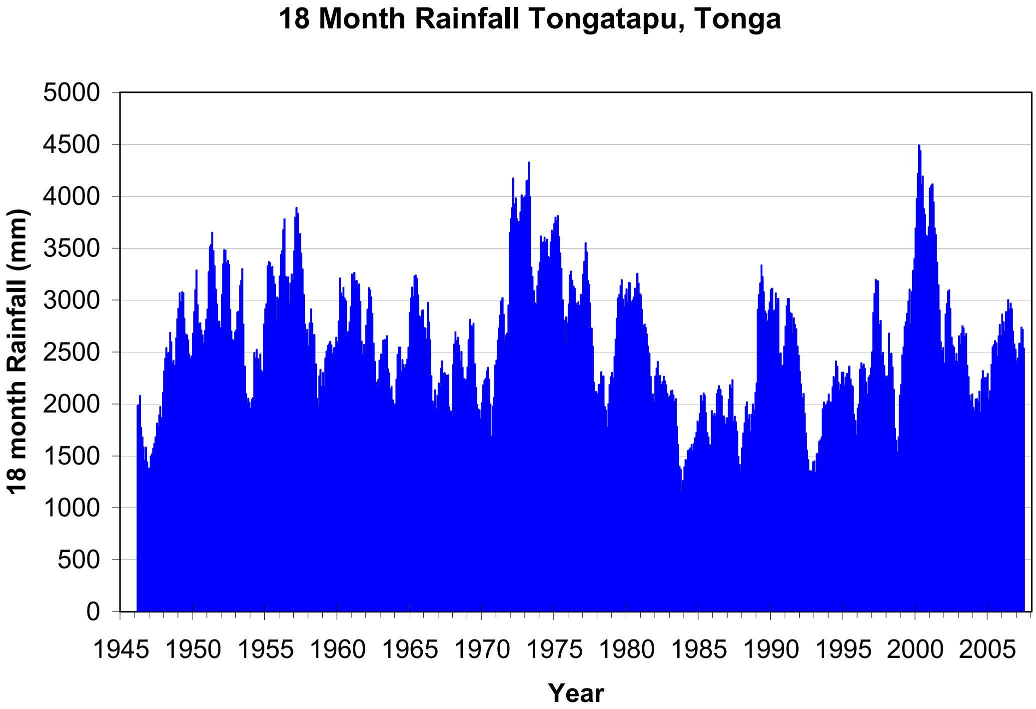

Figure 118 **Rainfall summed over the previous 18 months**

The data indicates a strong seasonal signal with period between about 9 and 13 months being particularly pronounced in the period 1948 until 1972. Longer time scale periodic rainfall signals are also evident in Figure 117 to Figure 119. For these, the period seems to be a little over 3½ years except for the mid-1970s, where major rainfall extended over about 7½ years. The significant dry period over 6 years from the end of 1982 to the beginning of 1989 is also evident. For the longest period rainfall, 60 months shown in Figure 119, smaller period events are replaced by four major wet periods from 1952 to 1962, from the beginning of 1972 to the beginning of 1983 (the wettest period), from 1987 to the end of 1995 and from the beginning of 1999 to the beginning of 2007. The only three major dry periods at this time scale occurred in the early 1970s, and in the mid 1980s. and mid 1990s.

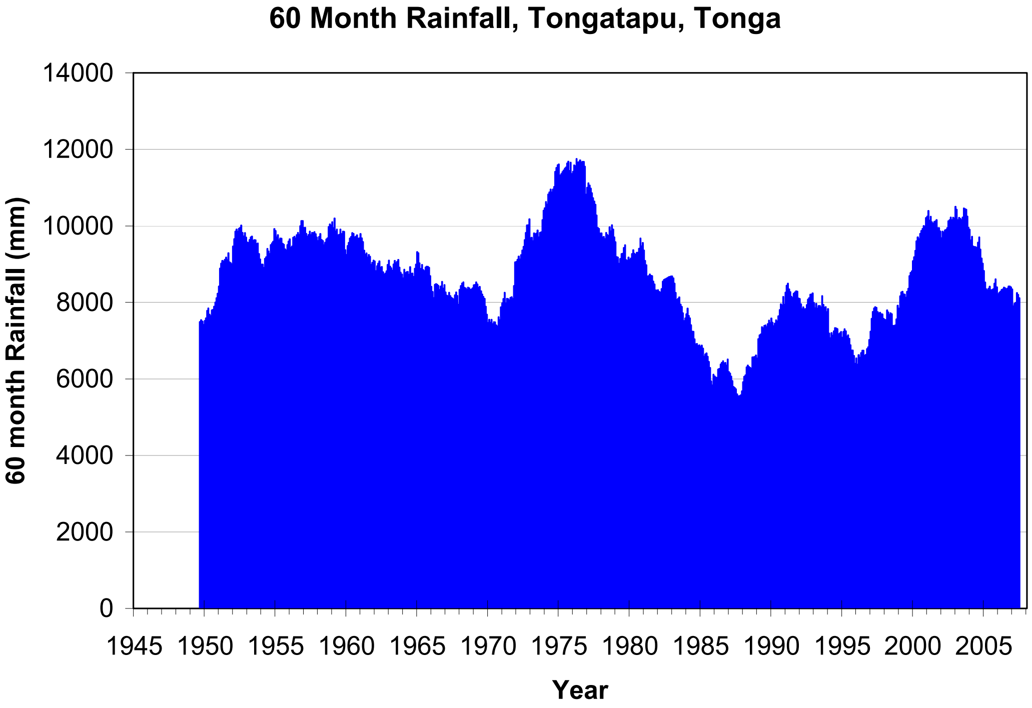

Figure 119 **Rainfall summed over the previous 60 months**

van der Velde (2006) identified two components of the inter-annual variation coupled to ENSO events of 3.3 and 4.9 years. It can be seen in Figure 118 that there appears to be a distinct change in these inter-annual events before and after about 1972.

11.12.2 Rainfall statistics for different rainfall summation periods

The rainfall statistics for Tongatapu, summed over periods ranging from 1 to 60 months are given in Table 66. The variability of rainfall, seen in the CV, decreases as the rainfall summation period increases, as expected.

Table 66 Rainfall statistics for Tongatapu, for different summation periods from October 1944 to July 2007

Parameter	Rainfall Summation Period (months)[1]						
	1	6	12	18	24	30	60
No. of data points	754	749	743	737	731	725	695
Lowest rain(mm)	2	210	651	1,152	1,871	2,451	5,551
Highest rain (mm)	783	1,967	3,327	4,490	5,324	6,885	11,756
Median rain in period (mm)	117	835	1,713	2,566	3,437	4,299	8,756
Mean rain in period (mm)	**144**	**864**	**1,728**	**2,598**	**3,468**	**4,341**	**8,721**
Standard Deviation (mm)	111	327	454	616	718	846	1,286
CV (%)	**77**	**38**	**26**	**24**	**21**	**19**	**15**
Mode (mm)	69	782	1,819	2,475	3,267	4,044	9,706
10th percentile rain (mm)	31	455	1,186	1,865	2,529	3,208	7,032
90th percentile rain (mm)	290	1,318	2,296	3,374	4,527	5,567	10,151
No. of droughts <10th percentile	-	**19**	**9**	**7**	**3**	**3**	**2**
Average time between droughts (mth)	-	**41**	**86**	**103**	**274**	**277**	**101**
CV (%)	-	88	73	91	88	86	-
Range of times between droughts (mth)	-	9 to149	21 to 234	34 to 284	104 to 444	109 to 444	-
Average duration of droughts (mth)	-	**11**	**22**	**29**	**69**	**72**	**98**
CV (%)	-	76	85	93	18	12	5
Range of durations of droughts (mth)	-	4 to 42	10 to 68	8 to 82	60 to 77	63 to 80	94 to 101

[1] The rainfall summation period is the number of preceding months over which rainfall has been totalled

For rainfalls summed over 12 month periods, the ratio of the highest to lowest 12 month rainfall is just over 5. In some central Pacific coral islands, this ratio is as high as 40 (White et al., 2007).

The number of droughts, less than 10th percentile, experienced in the past 63 years in Tongatapu decreases as the rainfall summation period increases. It ranges from 19 for the seasonally adjusted 6 month rainfalls to just 2 for rainfalls summed over 60 months. Over the same rainfall periods, the average time between droughts ranges from close to 3½ to nearly 36 years. The average duration of droughts variations from just under 1 year to 8 years, increasing with rainfall summation period. For the shorter rainfall periods relevant to the groundwater lens in Tongatapu (12 to 18 months), the maximum length of a prolonged drought was 8 years during the 1980s. The

CVs for both the length of time between droughts and the duration of droughts show that the occurrence and duration of droughts in Tongatapu are irregular with significant variation in both.

11.12.3 Decile analysis of droughts

Figure 120 to Figure 125 show the decile rankings of rainfall over the previous 6, 12, 18, 24, 30 and 60 months in Tongatapu, corresponding to the rainfalls over these periods. The red line in these figures corresponds to the lowest 10th percentile and the green line is the 40th percentile used here to identify the start, duration and end of droughts.

It is clear from these figures and particularly Figure 121 to Figure 125 that there have been several large cycles of rainfall in Tongatapu. The periods from the early 1950s to 1965, from 1972 to 1982 and from the end of 1999 to the beginning of 2007 have all been long-term wetter periods. The 1940s represented a dry period, although we are hampered here because of the lack of a continuous rainfall record throughout the 1940s. From 1966 to the beginning of 1972 there was a shorter drier period. This was followed by a prolonged dry period from mid-1983 to mid-1989. The driest period for all rainfall summation times from 12 to 60 months occurred during this prolonged dry period in the 1980s. It is noted from Figure 125 that Tongatapu appears to be entering another long-term drier period in terms of rainfall over 60 months. Superimposed on these long-term events there is also a shorter-term cyclic behaviour, most noticeable in Figure 123 and in the period 1947 to 1971. These shorter-term cycles of wetter periods separated by a brief drier period appear to occur every 4½ to 5 years but were interrupted by the longer, wetter period in the mid-1970s and the long dry period in the 1980s. Table 67 lists the start and end date, duration, month of lowest rainfall and the ranking and value of the lowest rainfall as well as time between droughts for Tongatapu from the decile analysis.

It is noted in both Table 67 and Figure 120 to Figure 125, that there were many fewer droughts in the 38-year period 1945 to 1982 than in the 25-year period 1983 to 2007. It has been shown that the salinity of water produced from the freshwater lens at the Mataki'eua/Tongamai wellfield and throughout Tongatapu is most strongly correlated with the amount of rainfall that fell over the preceding 12 to 18 months (van der Velde, 2006; White *et al.* 2007b). For these shorter rainfall periods, it can be expected that the droughts that affect the thickness of the freshwater lenses occur on average between 7 and 9 years, but have high variability and will last on average about 22 to 29 months. Examining the lowest totals of rainfall that fell in these dry periods in Table 67 shows annual rainfalls on average of around 900 to 1,000 mm with the lowest 12 month rainfall close to 650 mm.

Falkland (1992) estimated that there was no recharge on Tongatapu during 1981 and 1983 when annual rainfall was 874 and 838 mm, respectively. The results presented in Figure 108 suggest on average about 800 mm of rain is required over 12 months for some recharge to occur. From the results in Table 67, we expect, in general, some small groundwater recharge to occur during some of the 10th percentile droughts in Tongatapu over 12 to 18 month periods but that this will be insufficient to meet the losses from the freshwater lens. It is vitally important that groundwater extraction rates during droughts are managed, demand is controlled and monitoring is carried out to ensure that a viable freshwater lens continues to persist over these dry periods.

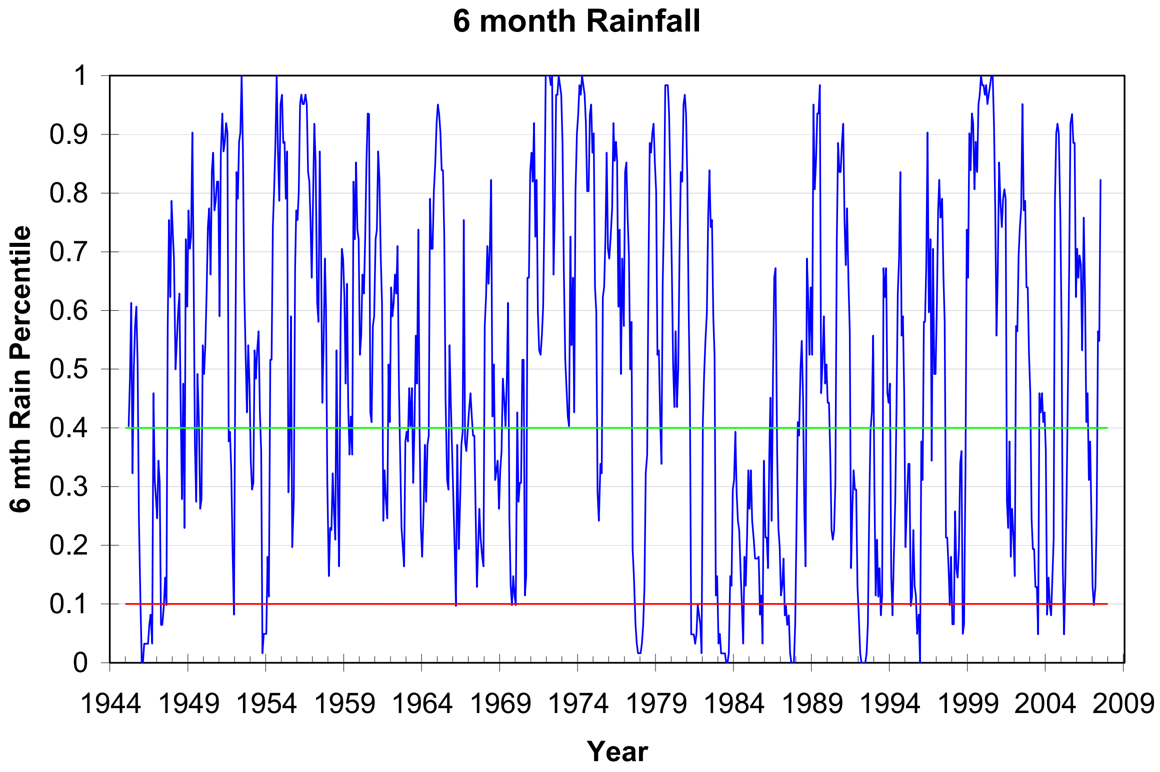

Figure 120 Decile ranking of rainfalls over the previous 6 months. These have been seasonally adjusted to account for Tongatapu's wet and dry seasons.

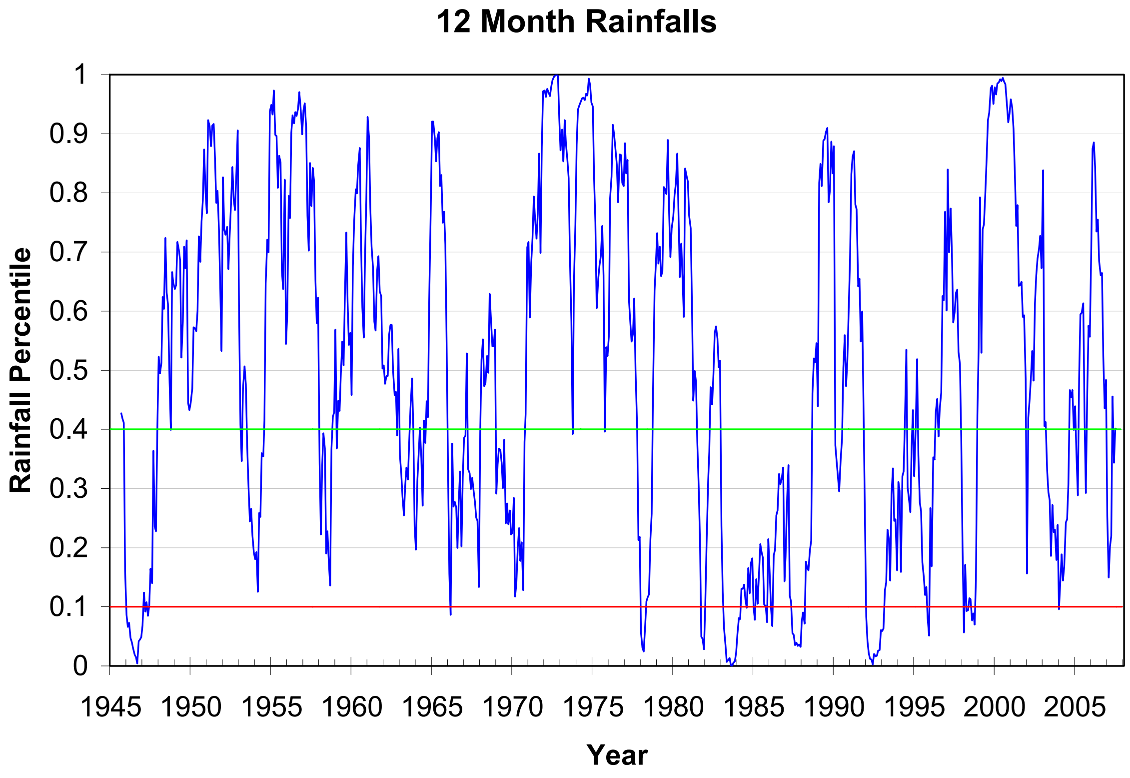

Figure 121 Decile ranking of rainfalls over the previous 12 months

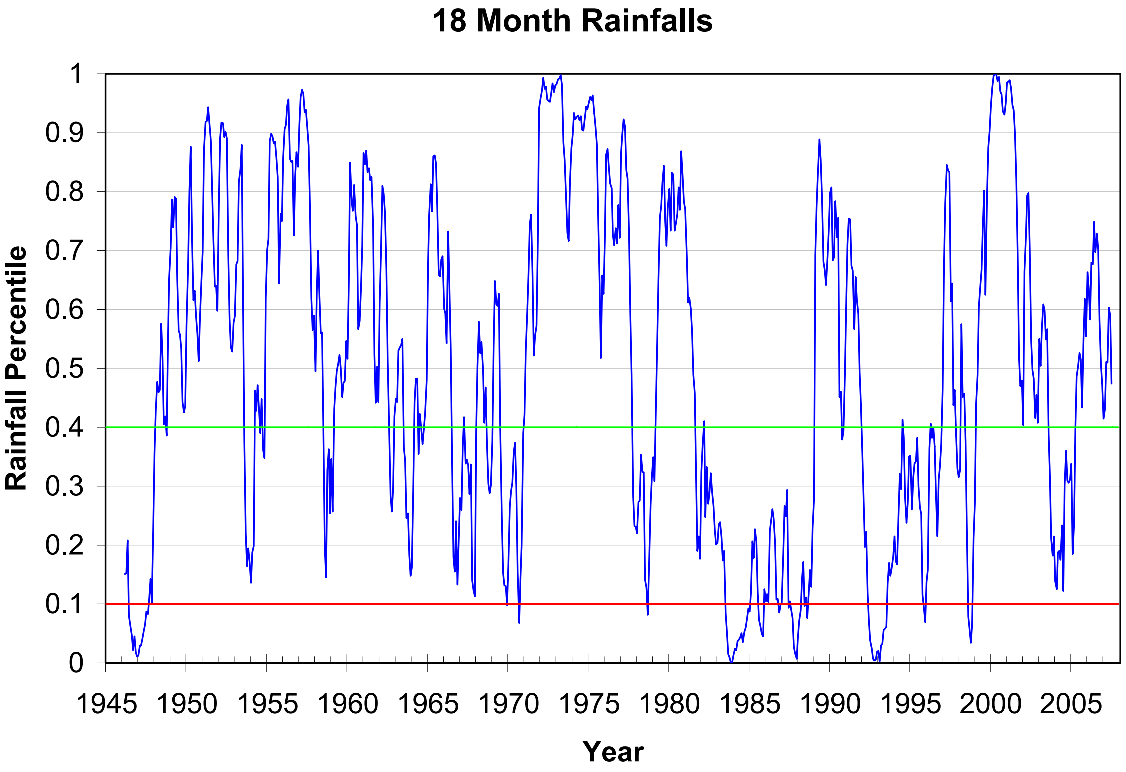

Figure 122 Decile ranking of rainfalls over the previous 18 months

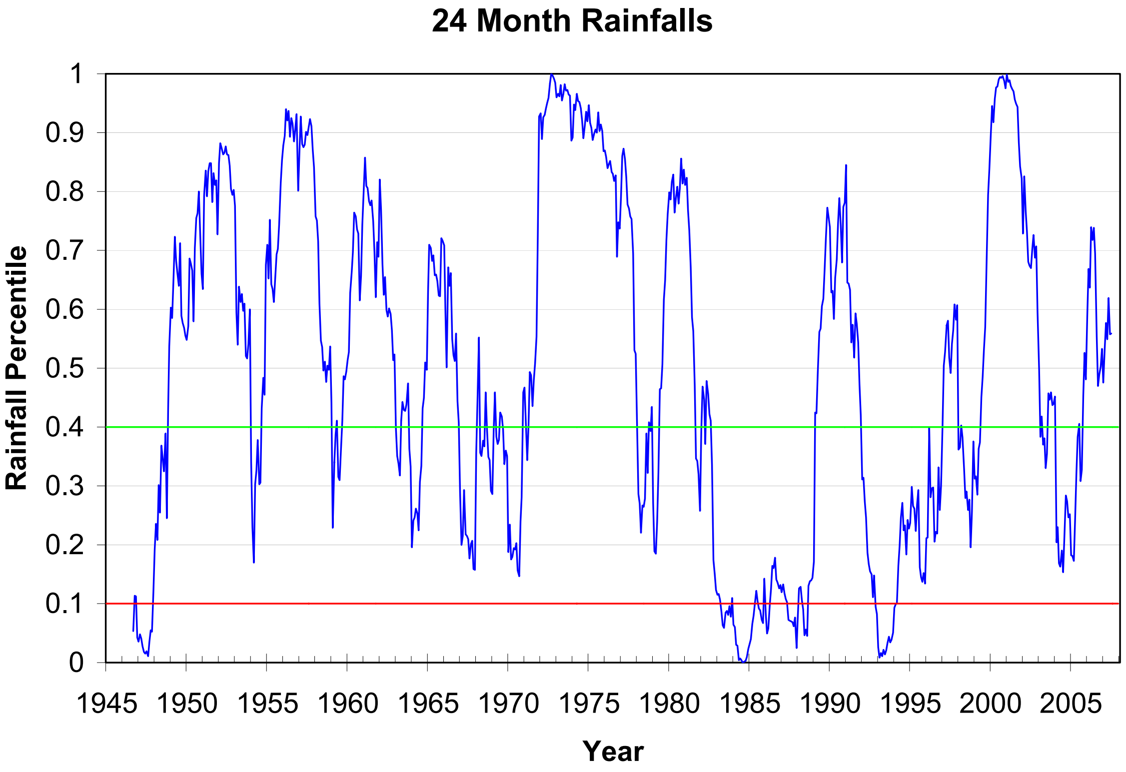

Figure 123 Decile ranking of rainfalls over the previous 24 months

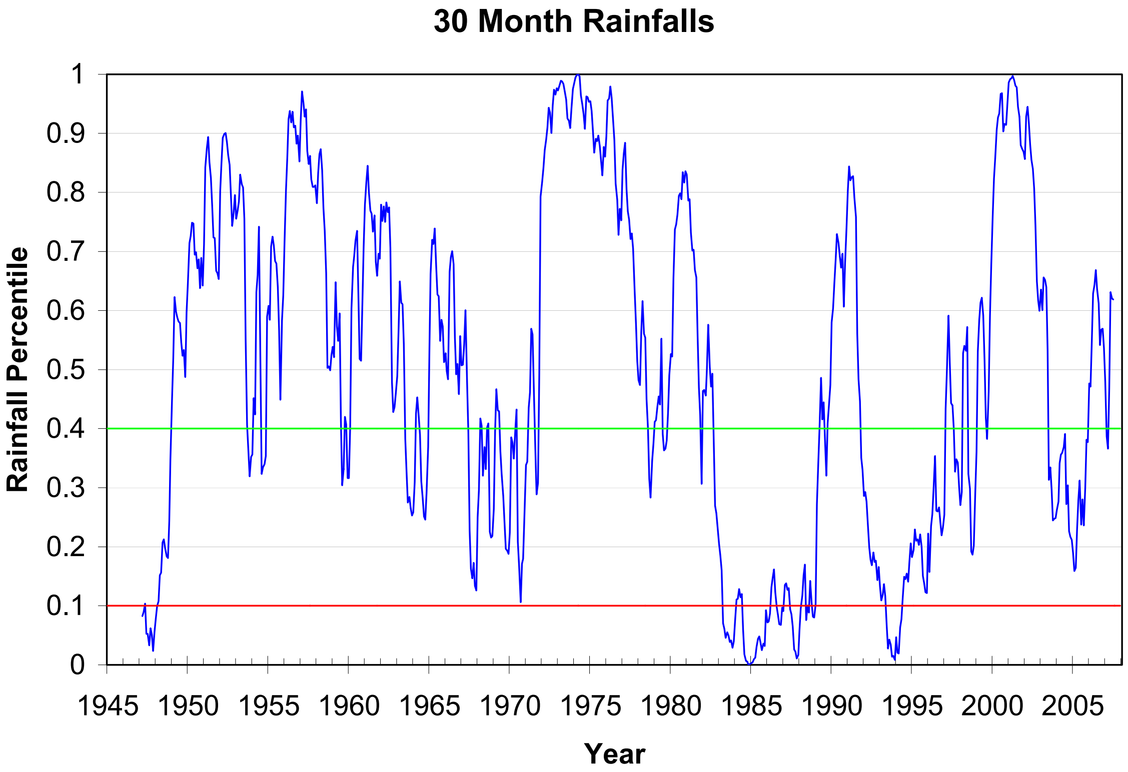

Figure 124 **Decile ranking of rainfalls over the previous 30 months**

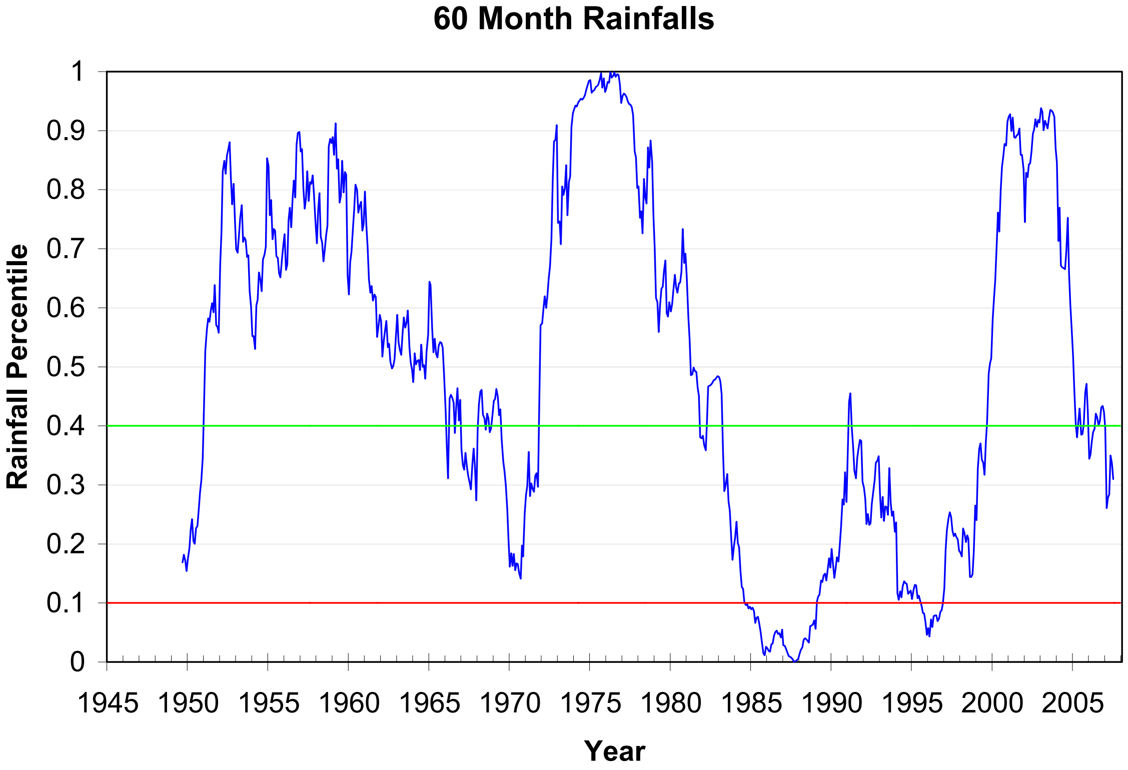

Figure 125 **Decile ranking of rainfalls over the previous 60 months**

Table 67 Meteorological droughts for different rainfall periods in Tongatapu

Rainfall Summation Period (mths)	Start Date (<40%)	End Date (>40%)	Duration (mths)	Date of Lowest	Lowest Percentile (%)	Lowest Rainfall (mm)	Time between Droughts (mths)
6[1]	Nov-45	Oct-46	11	Feb-46	0.0	254	
	Nov-46	Sep-47	10	Apr-47	6.5	609	14
	Aug-51	Jan-52	5	Dec-51	8.2	383	56
	Aug-53	Apr-54	8	Oct-53	1.6	332	22
	Dec-65	Sep-66	9	Mar-66	9.7	593	149
	Aug-69	Feb-70	6	Oct-69	9.8	404	43
	Jul-77	Jul-78	12	Jan-78	1.6	297	99
	Apr-81	Jan-82	9	Dec-81	1.6	330	47
	Nov-82	May-86	42	Jul-83	0.0	397	19
	Oct-86	Feb-88	16	Sep-87	0.0	231	50
	Jul-91	Nov-92	16	Mar-92	0.0	268	54
	Jan-93	Aug-93	7	Jun-93	8.1	619	15
	Feb-94	Jun-94	4	Mar-94	8.1	515	9
	Dec-94	Mar-96	15	Dec-95	0.0	290	21
	Aug-97	Dec-98	16	Sep-98	4.9	358	33
	Jan-03	Aug-03	7	Jul-03	4.8	518	58
	Jan-04	Aug-04	7	May-04	8.1	718	10
	Feb-05	Jun-05	4	Mar-05	4.8	453	10
	Oct-06	May-07	7	Feb-07	4.8	**525**	23
		Mean	**11**			**426**	**41**
		Std Dev	**9**			**142**	**36**
		CV (%)	**76**			**33**	**88**
		Median	**9**			**397**	**28**
12	Dec-45	Dec-47	24	Sep-46	0.4	707	
	Jan-66	Mar-67	14	Mar-66	8.6	1151	234
	Nov-77	Oct-78	11	Mar-78	2.4	841	144
	Jul-81	May-82	10	Dec-81	2.8	874	45
	Jan-83	Sep-88	68	Sep-83	0.0	651	21
	Dec-91	Jan-94	25	May-92	1.1	757	104
	Apr-95	May-96	13	Dec-95	5.1	1,015	43
	Dec-97	Dec-98	12	Feb-98	5.7	1,026	26
	Apr-03	Sep-04	17	Jan-04	9.6	1,169	71
		Mean	**22**			**910**	**86**
		Std Dev	**18**			**190**	**73**
		CV (%)	**85**			**21**	**85**
		Median	**14**			**874**	**58**
18	-	Feb-48		Jan-47	1.2	1,382	
	Aug-69	Jan-71	17	Sep-70	6.8	1,688	284
	Oct-77	Mar-79	17	Sep-78	8.2	1,773	96
	Apr-82	Feb-89	82	Nov-83	0.0	1,152	62
	Jan-92	Jul-94	30	Feb-93	0.3	1,339	111
	Aug-94	Apr-96	20	Dec-95	6.9	1,702	34
	Jun-98	Feb-99	8	Oct-98	3.4	1,541	34
		Mean	**29**			**1,511**	**103**
		Std Dev	**27**			**228**	**94**
		CV (%)	**93**			**15**	**91**

		Median	**19**			**1,541**	**79**
24	-	Nov-48		Aug-47	1.1	2,034	
	Sep-82	Feb-89	77	Aug-84	0.0	1,871	444
	Jan-92	Jan-97	60	Apr-93	1.1	2,034	104
		Mean	**69**			**1,980**	**274**
		Std Dev	**12**			**94**	**240**
		CV (%)	**18**			**5**	**88**
		Median	**69**			**2,034**	**274**
30	-	Jan-49		Nov-47	2.3	2,812	
	Sep-82	May-89	80	Nov-84	0.0	2,451	444
	Nov-91	Feb-97	63	Dec-93	0.8	2,726	109
		Mean	**72**			**2,663**	**277**
		Std Dev	**12**			**189**	**237**
		CV (%)	**17**			**7**	**86**
		Median	**72**			**2,726**	**277**
60	Apr-83	Feb-91	94	Sep-87	0.0	5,551	
	Apr-91	Sep-99	101	Feb-96	4.3	6,378	101
		Mean	**98**			**5,965**	**101**
		Std Dev	**5**			**585**	
		CV (%)	**5**			**10**	
		Median	**98**			**5,965**	**101**

[1] The data for 6 month rainfalls were analysed for each month of the year in order to account for Tongatapu's seasonal rainfall. With this analysis the lowest 0th percentile occurs for each month of the year.

11.12.4 Wet and dry season meteorological droughts

We have also used a similar analysis to that for rainfalls over less than 12 months to examine the variability of rainfall over the wet and dry seasons shown in Figure 126.

In this analysis, the total rainfall for each 5 month wet season (December -April) and each 7 month dry season (May to November) is compared with all other wet or dry season rainfalls, respectively. The percentiles are plotted in Figure 126 where it can be seen that the temporal variability of both seasons differs substantially.

The correlation between wet and dry season percentiles is weak (correlation coefficient, $R_c = 0.171$). Table 68 lists the characteristics of meteorological droughts for the wet and dry seasons. The correlation between wet and dry season percentiles improves ($R_c = 0.253$) if the dry season is correlated with wet seasons three years previously as plotted in Figure 127. While in Figure 127 the correlation is far from perfect, it does suggest a linkage between the dry season rainfall percentile in one year and the wet season rainfall percentile 3 years previously.

The lowest wet season rainfall occurred in 1992 while the lowest dry season rainfall was in 1997. Both wet and dry seasons have had 5 major droughts between 1944 and 2007. However, for wet seasons the period between 1946 and 1981 was remarkably free of major droughts while for dry seasons there were three droughts in this period. Wet and dry season droughts only coincide in any one year in the 1980's and from 1982 to 1988 there were three consecutive wet seasons and five consecutive dry seasons that fell below the 10th percentile level. In the 1990s, two wet season and one dry season droughts occurred. The 1991 wet season drought persisted for 4 wet seasons. Average duration of wet and dry season droughts was two seasons with an average of 12 years between wet season droughts and 11 years for dry seasons. The average is however somewhat misleading since for wet seasons the time between droughts varied between 2 and 35 years.

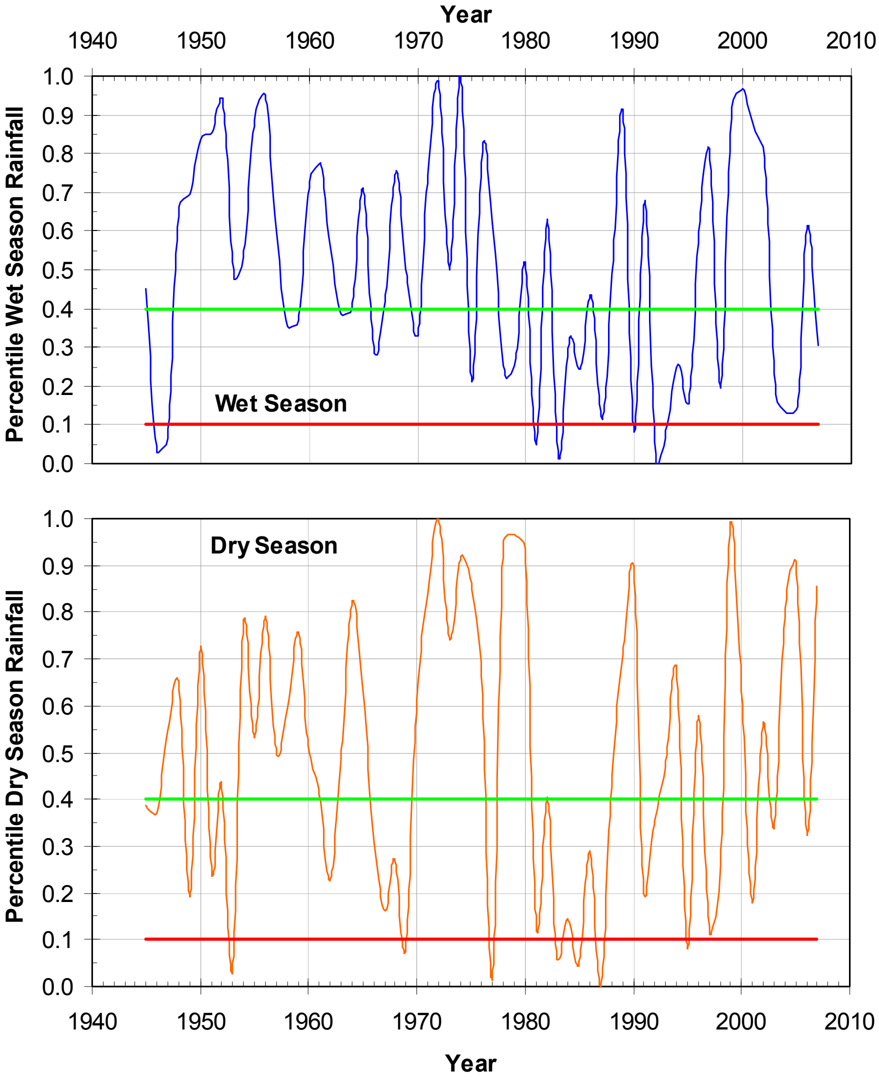

Figure 126 **Decile rankings of wet and dry season rainfalls for Tongatapu**

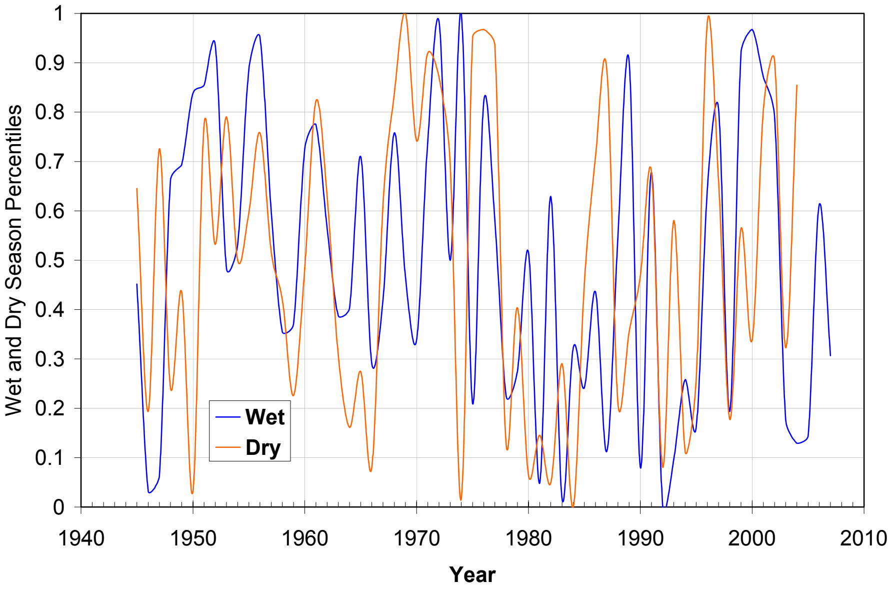

Figure 127 **Correlation between dry season rainfall percentiles and those for wet seasons 3 years previously**

Table 68 Wet and dry season meteorological droughts in Tongatapu

Season	Start Year (<40%)	End Year (>40%)	Duration (Seasons)	Year of Lowest	Lowest Percentile (%)	Lowest Rainfall (mm)	Time between Droughts (Years)
WET	1945	1948	3	1946	3.2	331	
	1980	1982	2	1981	4.8	491	35
	1982	1986	4	1983	1.6	278	2
	1989	1991	2	1990	8.1	627	7
	1991	1996	5	1992	0.0	232	2
		Mean	**3.2**			**392**	**11.5**
		Std Dev	**1.3**			**164**	**15.8**
		CV (%)	**41**			**42**	**138**
		Median	**3.0**			**331**	**4.5**
		Number	**5**				
DRY	1952	1954	2	1953	3.2	403	
	1965	1970	5	1969	8.1	455	16
	1976	1978	2	1977	1.6	345	8
	1982	1988	6	1987	0.0	295	10
	1994	1996	2	1995	8.1	455	8
		Mean	**3.4**			**391**	**10.5**
		Std Dev	**1.9**			**70**	**3.8**
		CV (%)	**57**			**18**	**36**
		Median	**2.0**			**403**	**9.0**
		Number	**5**				

11.13 Hydrological droughts in Tongatapu

Hydrologic drought is an interval of time of below-normal stream flow, or depleted reservoir or groundwater storage (section 11.3.3). We do not have complete information on groundwater storage throughout Tongatapu due to the absence of salinity monitoring boreholes across the island. We do, however, have estimations of the groundwater recharge in Tongatapu (section 9) which we can use in an analogous fashion to stream flow to estimate hydrological drought in Tongatapu. We shall examine the percentiles for recharge events calculated only for Case 1 in Table 62 summed over varying lengths of time.

11.13.1 Characteristics of recharge for different summation periods

Table 69 lists the characteristics of recharge for summation periods from 1 to 60 months for Case 1 in Table 62.

The period of recharge calculation differs slightly from that for rainfall in Table 66. The non-linear dependence of recharge on rainfall suggests that some differences should occur between the meteorological droughts in Table 66 and the hydrological droughts in Table 69. This can be seen in the number of droughts that fall below the 10th percentile level. For the 6 month summation period there were 19 meteorological droughts compared with 21 hydrological droughts; for 12 month summation period there were 9 meteorological droughts compared with 8 hydrological droughts; for the 18 month summation period there were 7 meteorological droughts compared with 6 hydrological droughts; for the 24 month summation period there were 3 meteorological droughts compared with 6 hydrological droughts; for the 30 month summation period there were 3 meteorological droughts compared with 4 hydrological droughts; while for the 60 month summation period there were 2 meteorological droughts compared with 1 hydrological drought. Some, but not all of these differences, reflect the slight difference between the time periods over which rainfall and recharge was considered.

Table 69 Recharge statistics for Tongatapu for different summation periods from January 1945 to December 2006

Parameter	Recharge Summation Period (months)[1]						
	1	6	12	18	24	30	60
No. of data points	744	739	733	727	721	715	685
Lowest recharge(mm)	0	0	0	0	57	107	609
Highest recharge (mm)	633	1,119	1,884	2,212	2,502	3,330	4,893
Median recharge (mm)	0	214	483	731	968	1,240	2,457
Mean recharge (mm)	**42**	**255**	**511**	**768**	**1,027**	**1,287**	**2,606**
Standard Deviation (mm)	77	227	328	440	523	611	952
CV (%)	**182**	**89**	**64**	**57**	**51**	**47**	**37**
Mode (mm)	0	0	0	107	587	587	2,082
10th percentile recharge (mm)	0	0	107	228	419	517	1,331
90th percentile recharge (mm)	144	567	948	1,355	1,761	2,220	3,764
No. of droughts <10th percentile	-	**21**	**8**	**6**	**6**	**4**	**1**
Average time between droughts (mth)	-	**36**	**84**	**137**	**137**	**270**	**-**
CV (%)	-	80	93	56	38	52	-
Range of times between droughts (mth)	-	7 to 107	23 to 237	34 to 246	57 to 419	107 to 440	-
Average duration of droughts (mth)	-	**11**	**20**	**37**	**37**	**64**	**187**
CV (%)	-	75	61	80	90	41	-
Range of durations of droughts (mth)	-	3 to 37	7 to 40	13 to 82	7 to 77	38 to 91	-

[1] The rainfall summation period is the number of preceding months over which rainfall has been totalled

The average time between droughts depends on the summation period. For the 6 month summation period there was, on average, 36 months between droughts but with a range from 7 to 107 months while for the 12 month summation period major hydrological droughts occur every 84 months but have a range from 23 to 237 months. For the 30 month summation period, the average time between major droughts was 270 months with a range of 107 to 440 months. As with the meteorological droughts, the period from 1945 to 1980 had far fewer droughts than the period from 1980 to 2007.

The average duration of hydrological droughts varied from 11 months for the 6 month summation period to 187 months for the 60 month summation period which corresponded to the dry period from August 1983 to February 1999. Again, durations of droughts varied widely. For example, for the 12 month summation period, the duration of droughts varied between 7 to 40 months with the longest drought being from February 1983 to June 1986.

11.13.2 Decile analysis of hydrological droughts for Case 1

Table 70 identifies hydrological droughts for recharge summation periods from 6 to 60 months.

Table 70 Hydrological droughts for different recharge periods in Tongatapu

Recharge Summation Period (mths)	Start Date (<40%)	End Date (>40%)	Duration (mths)	Date of Lowest	Lowest Percentile (%)	Lowest Recharge (mm)	Time between Droughts (mths)
6[1]	Jan-46	Sep-47	20	Feb-Sep 46, Aug 47	0.0	0	
	Oct-53	Apr-54	6	Dec 53-Jan 54	0.0	0	91
	Aug-62	Aug-63	12	Nov-62	0.0	0	107
	Nov-65	Aug-66	9	Mar-66	10.0	3	40
	Sep-66	Jan-68	16	Oct-Dec 67	0.0	0	20
	Sep-69	Feb-70	5	Sep 69-Jan 70	0.0	0	24
	Mar-70	Oct-70	7	Aug-70	9.8	13	9
	Aug-77	May-78	9	Sep 77-Feb 78	0.0	0	87
	Apr-81	Jan-82	9	Apr 81-Dec 81	0.0	0	45
	Nov-82	Dec-85	37	Feb 83-Feb 85	0.0	0	28
	Dec-86	Feb-88	14	Dec 86-Dec 87	0.0	0	42
	Jul-91	Aug-93	25	Feb 92-Feb 93	0.0	0	62
	Feb-94	Jul-94	5	Feb-Mar 94	0.0	0	18
	Dec-94	Jan-96	13	Jan-95	0.0	0	11
	Aug-97	Mar-98	7	Oct 97-Feb 98	0.0	0	35
	Sep-98	Dec-98	3	Sep-Nov 98	0.0	0	10
	Jul-01	Feb-02	7	Oct 01-Jan 02	0.0	0	37
	Feb-03	Oct-03	8	Jul-03	0.0	0	20
	Jan-04	Aug-04	7	Feb-04	0.0	0	7
	Mar-05	Jun-05	3	Mar-05	0.0	0	13
	Oct-06			Dec-06	0.0	0	21
		Mean	**11**			**1**	**36**
		Std Dev	**8**			**3**	**29**
		CV (%)	**75**			**378**	**80**
		Median	**8**			**0**	**26**
12[2]		Apr-48	>28	Aug-Sep 46	0.0	0	
	Jan-66	Jan-68	24	Mar-66	6.4	61	237
	Jan-78	Aug-78	7	Mar-78	2.7	16	144
	Aug-81	Apr-82	8	Oct-Dec 81	0.0	0	44
	Feb-83	Jun-86	40	Aug-Dec 83, Feb 85	0.0	0	23
	Dec-86	Sep-88	21	Jun-Dec 87	3.0	26	47
	Dec-91	Jun-94	30	Aug 92-Feb 93	0.0	0	62
	Apr-95	Mar-96	11	Jul-Dec 95	7.4	65	34
		Mean	**20**			**21**	**84**
		Std Dev	**12**			**28**	**78**
		CV (%)	**61**			**132**	**93**
		Median	**21**			**8**	**47**
18		Nov-48	>29	Feb-Aug 47	2.5	80	
	Jul-66	Feb-68	19	Oct-Dec 67	7.9	211	246
	Aug-69	Feb-71	18	Sep-70	7.4	211	34
	Apr-82	Feb-89	82	Nov-Dec 83	1.0	39	158
	Feb-92	Jun-96	52	Feb-93	0.0	0	111
	Aug-03	Sep-04	13	Jul-04	7.2	199	137
		Mean	**37**			**123**	**137**
		Std Dev	**30**			**95**	**77**
		CV (%)	**80**			**77**	**56**
		Median	**19**			**140**	**137**

24		Jan-49	>25	Aug-47	0.1	80	
	Feb-54	Sep-54	7	Mar-54	10.0	419	79
	Nov-66	Mar-68	16	Feb-67	9.0	392	155
	Sep-82	Feb-89	77	Aug 84-Feb 85	0.8	107	213
	May-91	Feb-97	69	Apr-93	0.0	57	101
	Feb-04	Jun-05	16	Jul-04	8.8	376	135
		Mean	**37**			**239**	**137**
		Std Dev	**33**			**173**	**52**
		CV (%)	**90**			**73**	**38**
		Median	**16**			**242**	**135**
30		Apr-49	>22	Aug-47	2.9	306	
	Jan-66	Mar-69	38	Nov-Dec 67	5.7	440	243
	Oct-82	May-90	91	Feb-85	0.0	107	207
	Nov-91	Feb-97	63	Feb-Mar 94	1.8	228	108
		Mean	**64**			**270**	**186**
		Std Dev	**27**			**140**	**70**
		CV (%)	**41**			**52**	**38**
		Median	**63**			**267**	**207**
60	Aug-83	Feb-99	187	Aug 87-Dec 87	0.0	609	
		Mean					
		Std Dev					
		CV (%)					
		Median					

[1] The data for 6 month recharges were analysed for each month of the year in order to account for Tongatapu's seasonal rainfall. With this analysis, the lowest 0th percentile occurs for each month of the year.

[2] For the 12 month recharges, there are four 12 month periods with zero recharge hence the multiple 0th percentiles

The drought which occurred in the mid-1940s was clearly a severe drought. Unfortunately, the available data do not span this whole period so the analysis in Table 70 cannot provide full details of this drought except for the 6 month summation period. For the 6 month summation period, 19 out of the 21 severe hydrological droughts had zero recharge. The longest duration for these was the 37 month drought from November 1982 to December 1985 with the 25 month drought from July 1991 to August 1993 being the second longest. For the 12 month summation period, 4 out of the 8 severe droughts had zero recharge. Again, the longest drought was the 40 month drought from February 1983 to June 1986 with the 30 month drought from December 1991 to June 1995 being the second longest. For the 18 month summation period, there was still one severe drought where there was zero recharge and the drought lasted 52 months from February 1992 to June 1996. The longest drought for this summation period was the second most severe drought which lasted for 82 months from April 1982 to February 1989. Finally, for the very long 60 month recharge summation period only one major drought is apparent, the period from August 1983 to February 1999, which encompasses the two severe droughts identified for shorter summation periods.

11.13.3 Wet and dry season hydrological droughts

The wet and dry season recharge percentiles are plotted in Figure 128. Again it can be seen that there were no wet season hydrological droughts between 1947 and 1981, but significant wet season hydrological droughts are evident between 1981 and 1992. For the dry season there are no severe droughts before 1968, then droughts occurred fairly regularly between then and 2001.

Although there are similarities to the wet and dry season rainfall percentiles in Table 68 and Figure 126, details of wet and dry season hydrological, recharge droughts in Table 71 and Figure 128 reveal some differences. Although the average duration of wet and dry season recharge droughts are equal at 2 seasons, the number of dry season droughts is significantly greater (8) than the number of wet season droughts (5). As a consequence, the average time between severe dry season droughts is less than half (5 years) of that between wet season droughts (12 years).

Four years, 1981, 1983, 1987 and 1992, had both wet and dry season hydrological droughts in the same year. Apart from these, however, the correlation between wet and dry season hydrological droughts is weak (R_c = 0.165). As for meteorological droughts, a stronger correlation (R_c = 0.268) was found between the recharge percentiles for dry seasons with those for the wet season 3 years previously. A slightly stronger correlation, however, was found between the recharge percentiles for the wet season and the dry season 5 years previously. This and the obvious difference in the wet and dry season recharge percentiles in Figure 128 point to different climate drivers of wet and dry season droughts in Tongatapu.

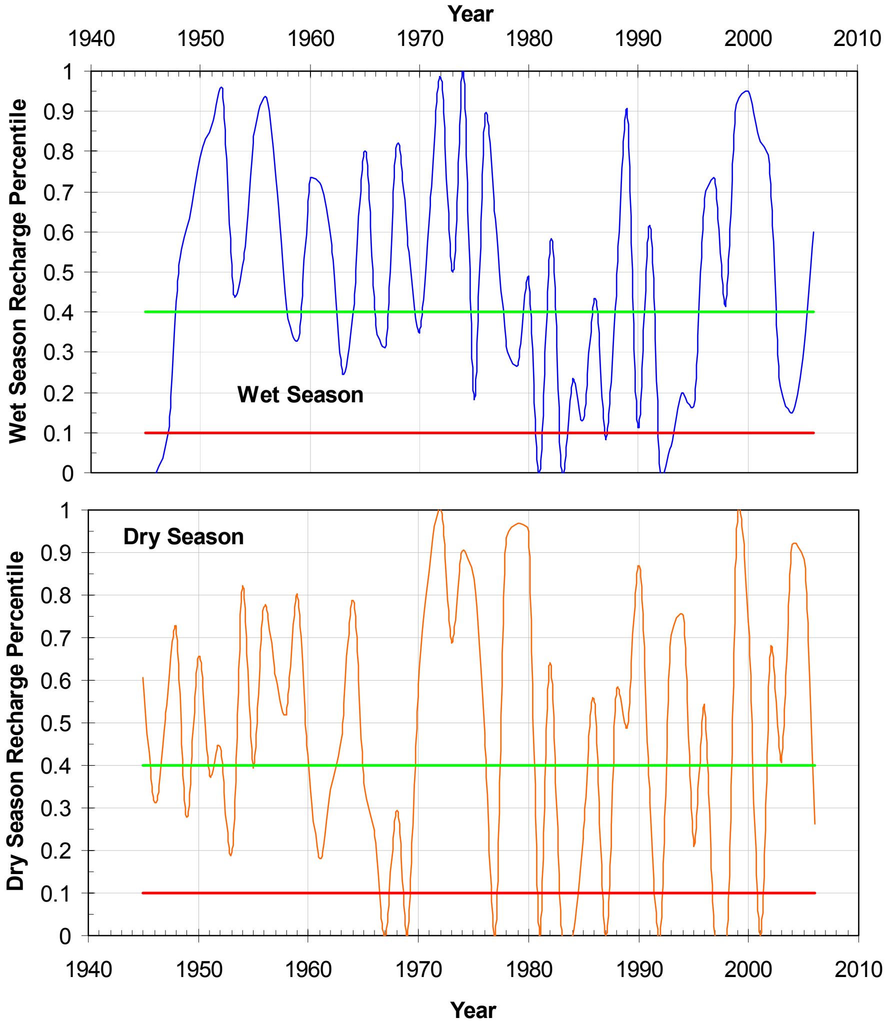

Figure 128 Recharge percentiles for wet and dry seasons for Tongatapu

Table 71 Wet and dry season hydrological droughts in Tongatapu

Season	Start Year (<40%)	End Year (>40%)	Duration (Seasons)	Year of Lowest Percentile	Lowest Percentile (%)	Lowest Recharge (mm)	Time between Droughts (Years)
WET		1948	>2	1946	0.0	0	
	1981	1982	1	1981	0.0	0	35
	1983	1986	3	1983	0.0	0	2
	1986	1987	1	1987	8.3	26	4
	1992	1996	4	1992	0.0	0	5
		Mean	**2.3**			**5**	**11.5**
		Std Dev	**1.5**			**12**	**15.7**
		CV (%)	**67**			**224**	**137**
		Median	**2.0**			**0**	**4.5**
		Number	**5**				
DRY	1965	1970	5	1967	0.0	0	
	1977	1978	1	1977	0.0	0	10
	1981	1982	1	1981	0.0	0	4
	1983	1986	3	1983	0.0	0	2
	1987	1988	1	1987	0.0	0	4
	1991	1993	2	1992	0.0	0	5
	1997	1999	2	1997	0.0	0	5
	2001	2002	1	2001	0.0	0	4
		Mean	**2.0**			**0**	**4.9**
		Std Dev	**1.4**				**2.5**
		CV (%)	**71**				**51**
		Median	**1.5**			**0**	**4.0**
		Number	**8**				

11.14 Conclusions and recommendations

11.14.1 Meteorological and hydrological droughts

Tongatapu is blessed by relatively reliable rainfalls having high mean annual rainfall with a relatively low coefficient of variability. Nonetheless, past droughts have had significant impacts on crop production and water resources. This report has concentrated on meteorological and hydrological droughts and has used a quantitative, non-parametric method, the decile (or percentile) method, to examine the severity, duration and frequency of past droughts over time periods, varying from 6 to 60 months, long enough to have an influence on fresh groundwater resources. The decile method has the advantages that it does not need to transform rainfall data to a normal distribution, provides an easily understood ranking of drought severity and identification of the start and end of droughts and is used as standard throughout Australia.

A comparison between the two currently daily monitored rainfall stations at sea level, Nuku'alofa, and at about 60 m above mean sea level, Fua'amotu, shows the expected orographic effect with monthly rainfalls at the higher Fua'amotu station being on average approximately 10% higher than those at Nuku'alofa, while the double mass plot showed the cumulative rainfall at Fua'amotu is over 4% higher than that at Nuku'alofa. The double mass plot was close to linear showing no major relative changes in behaviour between the two sites.

The frequency of severe meteorological droughts (total rainfall in a given period falling below the 10^{th} percentile level) decreases as the time period increases over which rainfall is summed. For 60 month rainfall periods since 1945, there have only been two major dry periods, one starting in April 1983 and the other starting in April 1991.On average these dry periods persisted for about 8 years and could be expected to significantly impact on groundwater resources. During the 1980's there was minimal monitoring of groundwater resources in Tongatapu greatly improved monitoring occurred during the 1990s (see section 6.12) which showed an increase in the salinity of village wells in the mid 1990's.

Probably the two rainfall summation periods of most relevance to Tongatapu groundwater are 12 and 18 months. For the 12 month rainfalls there were 9 severe droughts since 1945 with the most severe drought having its maximum impact in September 1983. On average, these droughts occurred every 86 months and lasted for 22 months although there is a wide range in both frequency and duration. For 18 month rainfall, there were 7 severe droughts since 1945 with the most severe drought having its maximum impact in November 1983. On average, these droughts occurred every 103 months and lasted for 29 months, although again there is a wide range in both frequency and duration.

In the examination of hydrological drought, one recharge case, Case 1 in Table 62, was taken as representative. It was found that there were slight differences in the number of droughts for different periods over which recharge is summed between hydrological and meteorological drought with generally fewer hydrological than meteorological droughts. There were periods of at least 18 months where no estimated recharge occurred. Again, the frequency of severe hydrological droughts (total recharge over a given period falling below the 10th percentile level) decreases as the time period increases over which recharge is summed. For 60 month recharge periods, since 1945, there has been only one major drought, which started in August 1983 and ended in February 1999. During this approximately 15½ year period it was estimated that total recharge was only 609 mm. It is somewhat surprising that while the groundwater salinity in village wells in Tongatapu peaked during this period, those at Mataki'eua did not.

For the two recharge summation periods probably of most relevance to groundwater in Tongatapu, 12 and 18 months, there were 8 and 6 severe droughts respectively since 1945. For the 12 month period, the five most severe droughts, all having zero recharge, had their maximum impacts in August-September 1946, October-December 1981, August-December 1983, February 1985 and August 1992-February 1993. The average duration of the severe (<10th percentile) hydrological droughts was 20 months and they occurred on average every 7 years. For the 18 month summation period, the worst drought since 1945 had its maximum impact in February 1993 when there was an estimated zero recharge for 18 months. For this recharge period the average duration of droughts was 37 months and they occurred on average nearly every 11½ years although again there is a wide range in both frequency and duration.

11.14.2 Wet and dry season droughts

Because of the importance of the wet (December to April) and dry seasons (May to November) in Tongatapu, and the predominant contribution of wet seasons to recharge, an examination was made of wet and dry season droughts. It was found that there were no wet season hydrological droughts between 1947 and 1981, but significant wet season hydrological droughts occurred between 1981 and 1992 with a total of 5 wet season droughts for the period 1945-2006. For the dry season there are no severe droughts before 1968, then droughts occurred fairly regularly between then and 2001, with a total of 8 droughts for the period 1945-2006. For the wet season these droughts occurred in 1946, 1981, 1983, 1987, and 1992. All had an estimated recharge of zero except 1987 where the recharge was 26 mm. The median duration of wet season droughts was two seasons with a median time of 4½ years between wet season droughts. There were 8 dry season droughts which occurred in 1967, 1977, 1981, 1983, 1987, 1992, 1997 and 2001. All these had an estimated recharge of zero and had a median duration of 1.5 seasons and a median time of 4 years between dry season droughts. The 4 years 1981, 1983, 1987 and 1992 were clearly problematic as they had both severe wet and dry season droughts within the same year.

The analyses presented in this section show that droughts with the potential to impact on groundwater resources are a relatively frequent event in Tongatapu and contingency plans should be developed to reduce the risk of significant impacts.

11.14.3 Unresolved Issues

Annual rainfall in Tongatapu is quite reliable with a low coefficient of variability. Since the 1980s, however, there have been two decades of significantly lower rainfall. During these decades there were 3 extended periods; 14 months from November 1980 to December 1981; 16 months from September 1982 to December 1983 and 18 months from September 1991 to January 1993; where it is estimated there was zero recharge (for Case 1).

There was only sparse monitoring of the groundwater salinity during the 1980s but this improved during the 1990s. Monitoring during the 1990s showed an increase in salinity in village water supply wells in Tongatapu but not a major increase in salinity at the Mataki'eua wellfield. This appears to suggest that the groundwater in Tongatapu is able to withstand at least 18 months of zero recharge with only minimal increase in groundwater salinity. This suggestion, however, has to be viewed with caution. The estimated groundwater pumping rate from the Mataki'eua/Tongamai wellfield was only about 4 ML/day in the early 1980s which had increased to about 5.5 ML/day during the dry periods of the early 1990s. Currently, the groundwater extraction rate from the wellfield is estimated to be 8.0 ML/day. It is by no means certain that under this increased pumping regime the groundwater system would be able to withstand 18 months of zero recharge without significant increases in salinity.

11.14.4 Recommendations

Based on the above considerations, the following recommendations are made:

- Consideration should be given to establishing two further rainfall measurements sites in the eastern and western regions of Tongatapu to improve spatial coverage of the rainfall network.
- A contingency plan to address the impacts of droughts on water supply involving voluntary and compulsory water restrictions and other instruments should be developed for Tongatapu.
- Percentile analysis of rainfall over the past 12 months should be carried out at the end of each month using monthly rainfall data from the TMS. When the percentile ranking drops below 40% a warning should be issued to the Government about the possibility of a drought to follow.
- Groundwater recharge should be estimated at the end of each month using monthly rainfall from the TMS. When there are more than 8 consecutive months all with zero estimated recharge, the frequency of groundwater monitoring should be increased and a warning should be given to the government and the TWB. When there are more than 12 consecutive months of zero recharge consideration should be given to implementing the drought contingency plan.

12 Drivers of Droughts in Tongatapu

12.1 Overview

The strong periodic nature of droughts in Tongatapu point to oceanographic drivers of extreme conditions such as the Southern Oscillation Index (SOI), the Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (IPO), and the normalised sea surface temperatures (SST) in the central Pacific (Niño 1, 2, 3, 4 and 3.4 regions). These have been shown to be tightly coupled to climates and groundwater in Pacific island countries (Hay *et al.,* 1993, van der Velde *et al.*, 2006, White *et al.,* 2007). Here we will examine the correlations between these indices of ocean temperature, surface atmospheric pressure, rainfall and recharge in Tongatapu.

12.2 SOI

12.2.1 SOI and droughts

Figure 129 shows the correlation between the SOI averaged over the previous 12 months and the cumulative rainfall over the previous 12 months at Nuku'alofa. While there is a general correlation between major peaks and troughs in rainfall and major La Niña and El Niño events in Figure 129, it is clear that some features of the rainfall and the magnitude of the events sometimes do not correspond with features in the SOI. As the period increases over which rainfall is summed and the SOI is averaged, the correlation between cumulative rainfall and SOI improves (Table 72). In addition, some features appear to be lagged between the rainfall and SOI maxima and minima. Table 73 shows that the maximum correlation occurs when rainfall is correlated with the SOI of approximately 3 months previous. This means that there is a 3 months lead in being able to approximately predict droughts from the SOI.

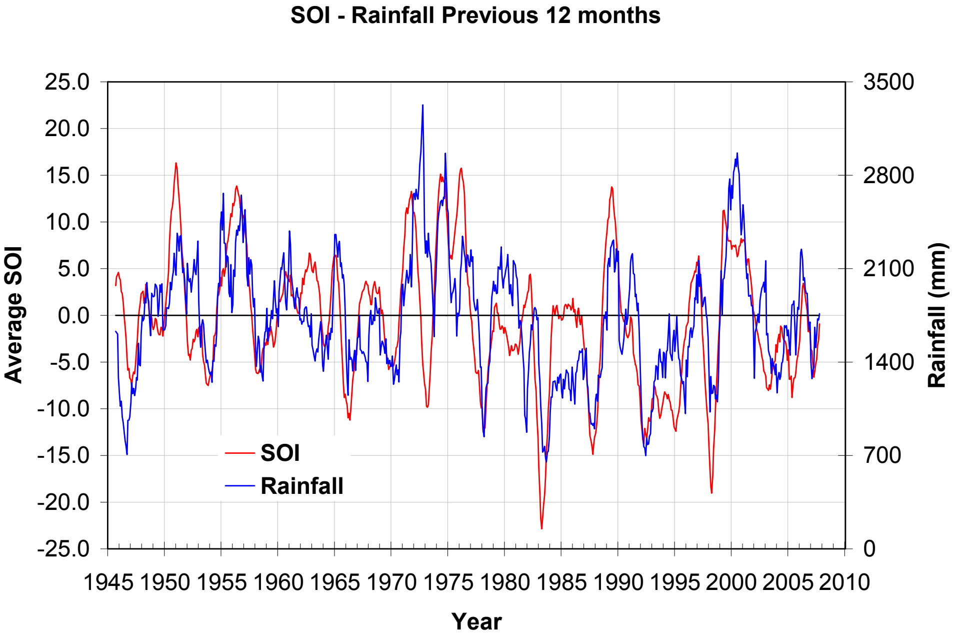

Figure 129 Correlation between the cumulative rainfall in Nuku'alofa and the average SOI over the previous 12 months

The relation between the rainfall over the previous 12 months, $\sum_{12} P_t$ and the average SOI over 12 months starting 3 months previously, $\overline{SOI}_{t-3}$ is:

$$\sum_{12} P_t = 1749 + 44 \times \overline{SOI}_{t-3} \qquad [43]$$

Equation [43] accounts for 46% of the observed variance. For the historical Nuku'alofa rainfall data since 1945 and the SOI data over the same period, equation [43] predicts a maximum 12 month rainfall of close to 2,500 mm compared with an actual maximum rainfall in the period of 3,327 mm.

Table 72 Correlation between cumulative rainfall and average SOI over a range of time periods

Cumulative Rainfall or Averaging Period (mths)	Correlation Coefficient
12	0.624
18	0.654
24	0.724
30	0.742
60	0.821
120	0.864

Table 73 Maximum correlation between cumulative rainfall and average SOI over a range of time periods and the lag at which maximum correlation occurs

Cumulative Rainfall or Averaging Period (months)	Rainfall Lag (months)	Correlation Coefficient
12	3	0.679
18	3	0.691
24	2	0.738
30	2	0.751
60	4	0.840
120	2	0.866

12.2.2 SOI and seasonal rainfall

The November to April wet season in Tongatapu is of major interest for crop production, irrigated agriculture and groundwater recharge, since failure of the wet season can have significant social and economic consequences and because much of the mean annual recharge occurs during the wet season (see Figure 107). In this section, an analysis is carried out between the wet and dry season rainfalls and the average wet and dry season SOIs.

While there are some discrepancies, Figure 130 shows that the average wet season SOI is quite strongly correlated with the average preceding dry season SOI[21], so that there is inter-seasonal persistence in the SOI going from dry season to the next wet season.The total wet season rainfall is, however, poorly correlated with the total preceding dry season rainfall ($R_c = 0.080$, see Table 74). In addition, the average dry season SOI is only poorly correlated with the average preceding wet season SOI ($R_c = 0.235$) indicating that the persistence in SOI does not extend beyond the wet season.

Figure 131 demonstrates a strong relationship between the total wet season rainfall and the average SOI for that wet season. This, of course, does not enable forecast of wet season rainfall. This strong relationship does not carry over to the dry season rainfall. The correlation between total dry season rainfall is weak (Figure 132). It appears then that while the total wet season rainfall is correlated to the average wet season SOI, the total dry season rainfall is not well correlated with

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[21] Note, the wet season for the year 1982 is the wet season that starts in November 1981 and runs to April 1982. The dry season for 1982 is the dry season that starts in May 1982 and runs to October 1982.

the average dry season SOI, suggesting that the seasonal linkage going from dry to wet season in the PDO does not carry through to seasonal rainfall.

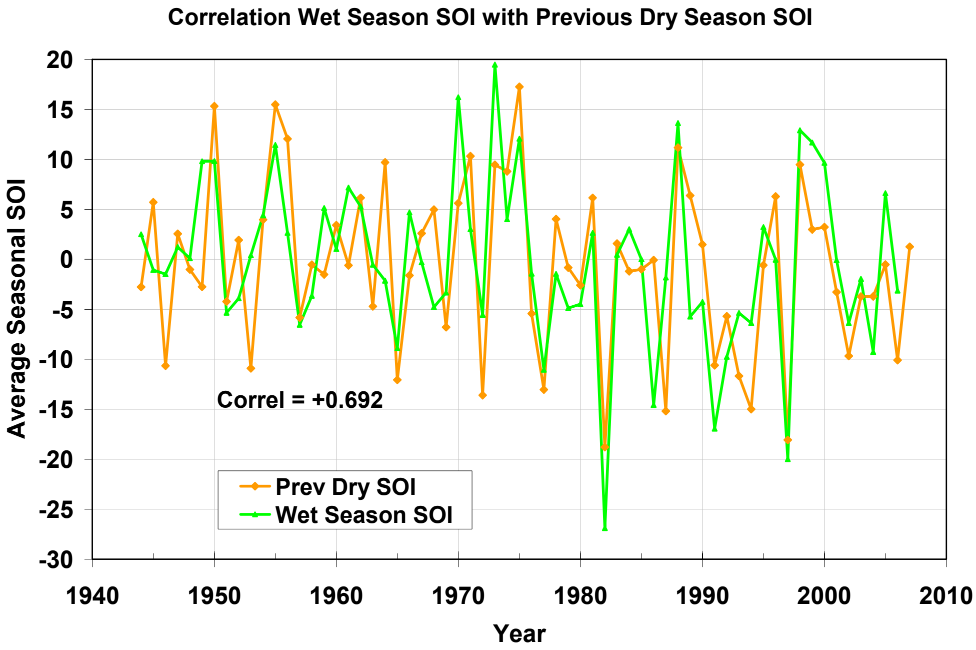

Figure 130 Correlation between average SOI of the wet season (Nov-Apr) and average SOI for the previous dry season (May-Oct)

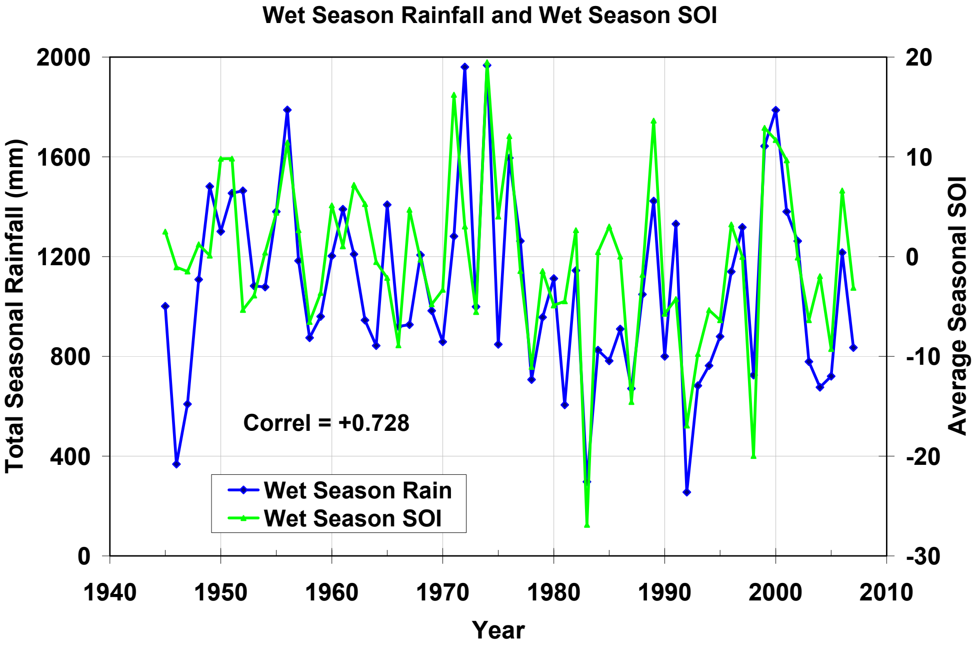

Figure 131 Correlation between total wet season rainfall and average SOI for that wet season

Because of the quite strong relationship between the average wet season SOI and the average previous dry season SOI, it is useful to examine the relationship between the total wet season rainfall and the average previous dry season SOI. Figure 133 shows that there is a good correlation between the total wet season rainfall and the average previous dry season SOI. This provides some possibility for predicting the important total wet season rainfall, $\sum_{Apr}^{Nov} P$ in Tongatapu from the average SOI for the preceding May to October dry season $\overline{SOI}_{Pr\,evMay-Oct}$:

$$\sum_{Nov}^{Apr} P = 1091 + 26.9 \times \overline{SOI}_{Pr\,evMay-Oct} \qquad [44]$$

Equation [44] only explains 37% of the observed variance in the total wet season rainfall. Table 74 summarises the correlations found in the examination of total wet and dry season rainfalls.

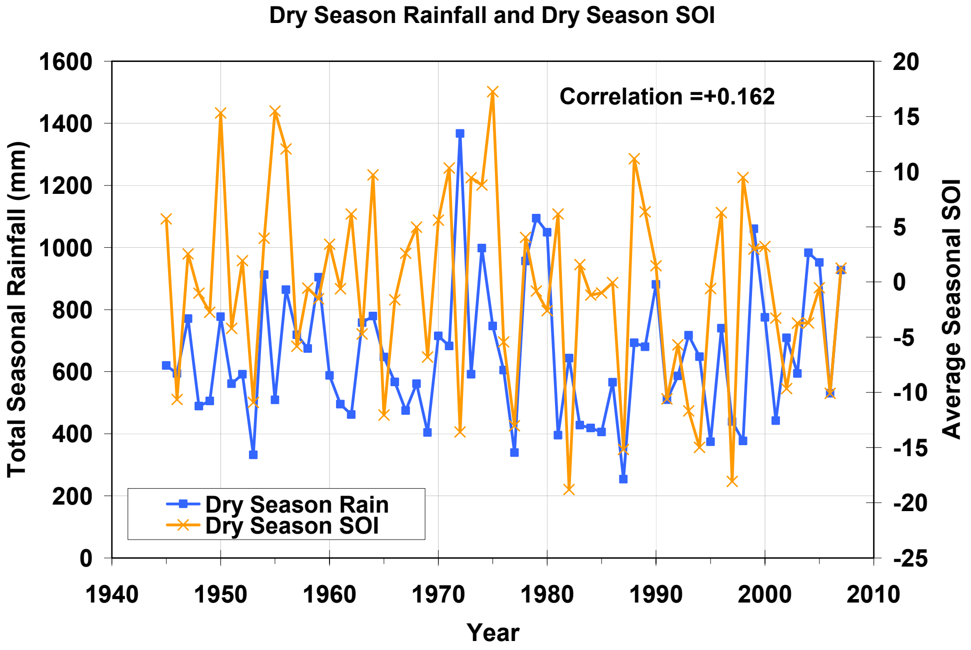

Figure 132 Correlation between total dry season rainfall and average SOI for that dry season

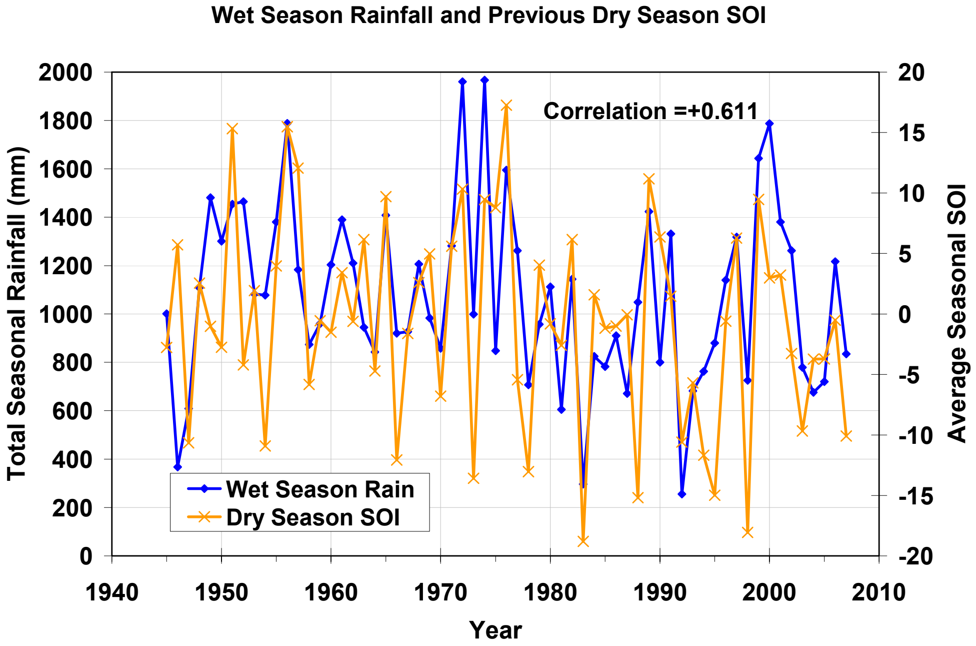

Figure 133 Correlation between total wet season rainfall and average SOI of the previous dry season

Table 74 Correlations between wet and dry season rainfalls and average SOIs

Correlates	Correlation Coefficient
Nov-Apr SOI (wet) and preceding May-Oct SOI (dry)	0.692
May-Oct SOI (dry) and preceding Nov-Apr SOI (wet)	0.235
Nov-Apr Rain (wet) and preceding May-Oct Rain (dry)	0.080
May-Oct Rain (dry)and preceding Nov-Apr Rain (wet)	0.235
Nov-Apr Rain (wet) and Nov-Apr SOI (wet)	0.728
Nov-Apr Rain (wet) and preceding May-Oct SOI (dry)	0.611
May-Oct Rain (dry) and May-Oct SOI (dry)	0.162
May-Oct Rain (dry)and preceding Nov-Apr SOI (wet)	0.227

12.3 PDO

12.3.1 PDO and droughts

The term "Pacific Decadal Oscillation" (PDO) was introduced in 1996 to describe a long-lived El Niño-like pattern of Pacific climate variability, involving atmosphere-ocean interaction as exemplified in both SST and sea level atmospheric pressure (SLP) observed in the northern Pacific (Mantua *et al* (1997). The PDO differs from the El Niño/Southern Oscillation (ENSO) in two key characteristics. The first is that PDO "events" persisted for 20 to 30 years in the 20th century, while typical ENSO events persisted for 6 to 18 months. The second is that the climatic fingerprints of the PDO are most visible in the Northern Pacific, with secondary signatures in the tropics, whereas the opposite is the case for ENSO.

There is evidence of just two full PDO cycles in the 20th century (Zhang *et al.*, 1997). "Cool" (negative PDO index) PDO regimes prevailed from 1890-1924 and 1947-1976, while "warm" (positive PDO index) PDO regimes dominated from 1925-1946 and from 1977 through to at least the mid-1990's (Mantua *et al.*, 1997). In the cool, negative PDO phase, northern hemisphere wintertime (December through February) SST in the northern Pacific above latitude 20° N and in the southern Pacific below latitude 20° S are warmer than in the central Pacific while in the warm, positive phase the reverse is the case. The SST effects appear more pronounced in the northern than southern Pacific. The PDO appears to have dominant periodicities of 15 to 25 years, and 50 to 70 years. At present, the factors which cause the PDO are not understood. From a social perspective, the PDO shows that “normal” climate conditions are able to vary over time periods of the same order as a human life-span.

The time history of the leading empirical orthogonal functions (EOFs) of the mean November to March SST anomalies for the Pacific Ocean to the north of 20° N latitude is used as an index for the state of the PDO and the data set is available from http://jisao.washington.edu/data_sets/pdo/. Figure 134 shows the negative correlation between the SOI and the PDO both averaged over the previous 12 months. The maximum negative correlation (R_c = -0.536) occurs when the PDO lags behind the SOI by 2 months. Because the PDO is a longer, more persistent time scale phenomena, Figure 135 displays the negative correlation between SOI and PDO averages over the previous 120 months. For these longer time periods the correlation improves, but the maximum negative correlation (R_c = -0.650) still occurs when PDO lags behind SOI by 2 months.

Since PDO is negatively correlated with SOI, it is expected that rainfall over different periods in Tongatapu will also be correlated with PDO. Again, because of the longer persistence of the PDO, it is expected that the correlation will be better for longer rainfall intervals. Table 75 shows that the negative correlation between average PDO and cumulative rainfall does indeed increase as the averaging period is increased. The correlations are, however, smaller in absolute terms than those found between rainfall and SOI over the same periods. The lag between rainfall and PDO at which the maximum correlation occurs in Table 75 also shows no consistent trend varying between -2 and +3 months for averaging periods up to 60 months and being as high as 22 months for 120 months.

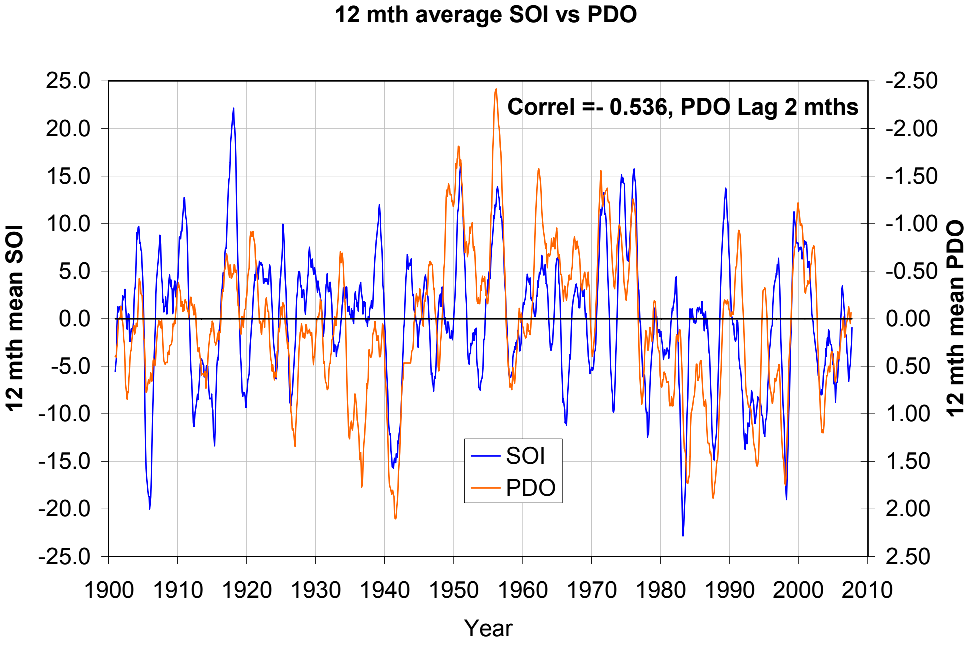

Figure 134 Correlation between the SOI and the PDO, both averaged over the previous 12 months with PDO lagged behind SOI by 2 months

As expected, higher than normal rainfall in Tongatapu is correlated with the negative phase of the PDO when the SST in the southern Pacific below 20° S is warmer than usual, and prolonged drier periods correspond to the positives phases of the PDO when SST in the southern Pacific is cooler than normal.

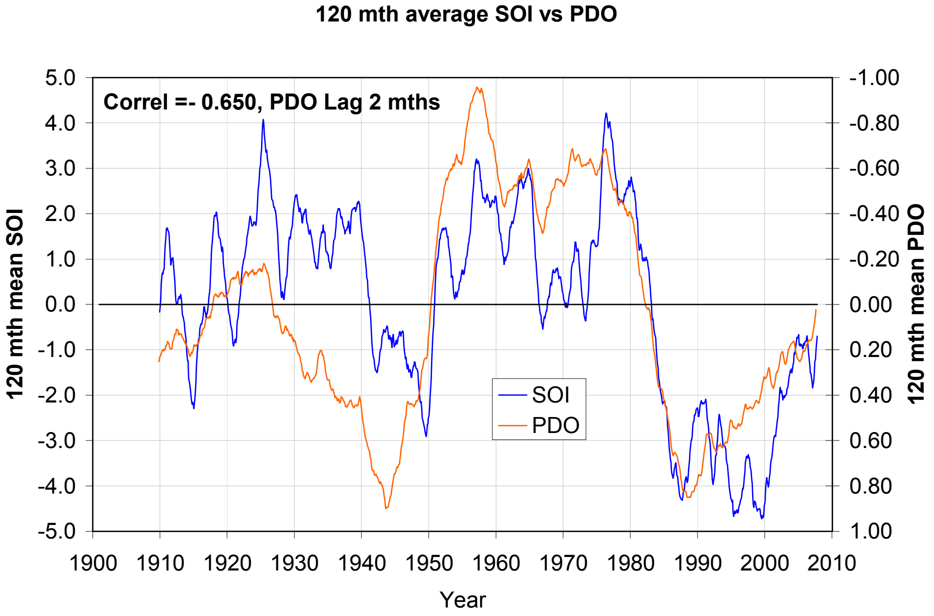

Figure 135 Correlation between the SOI and PDO, both averaged over the previous 120 months with PDO lagged behind SOI by 2 months

Table 75 Maximum negative correlation between cumulative rainfall and average PDO over different periods and the lag at which that correlation occurs

Cumulative Rainfall or Averaging Period (mths)	Rainfall Lag (mths)	Correlation Coefficient
12	2	-0.563
18	1	-0.597
24	-2	-0.657
30	-1	-0.673
60	3	-0.713
120	22	-0.820

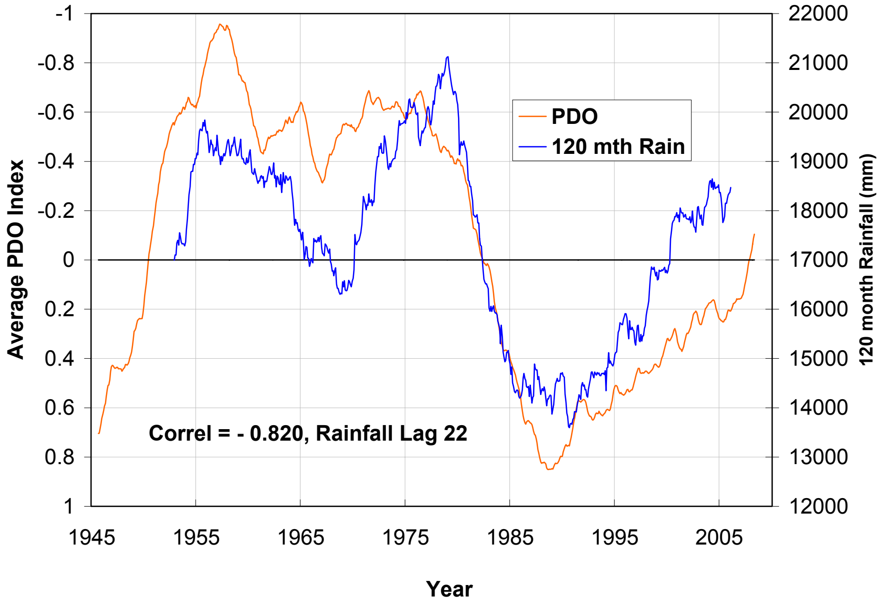

Figure 136 Correlation between the lagged cumulative rainfall over the previous 120 months and the average PDO over the same period

12.3.2 PDO and seasonal rainfall

The principal time period of interest for the PDO is the northern hemisphere winter period from November to April, which approximately corresponds with the November to April wet season in Tongatapu. Since the “cool” negative phase of the PDO corresponds to warmer SST in latitudes above 20° N and below 20° S it might be expected that these correspond to higher rainfall wet seasons in Tongatapu.

Figure 137 shows the dry season (May-October) average PDO for the period 1945 to the end of 2007 and compares it with the following wet season (November- April) average PDO. It can be seen that the wet season PDO is strongly positively correlated with the previous dry season PDO (R_c = +0.769) so that there is also an inter-seasonal persistence in the PDO in going from dry to wet season. It is noticeable in Figure 137 that the average PDOs for both total seasonal rainfalls in the period 1945 to 1978 are predominately negative, while from 1978 to 1997 they are predominantly positive. These correspond to relatively wetter and drier periods, respectively, in Tongatapu. In addition, the correlation between the average dry season PDO and the preceding wet season PDO is also reasonable (R_c = +0.537)

To investigate this further, Figure 138 shows that the total dry season rainfall is only weakly negatively correlated with the average wet season PDO (R = -0.134). The dry seasons from 1945 to 1977 had no correlation (R_c = +0.053) with the corresponding PDO compared with weak correlation for the period 1978 to 2007 (R_c = -0.345) as is evident in Figure 138.

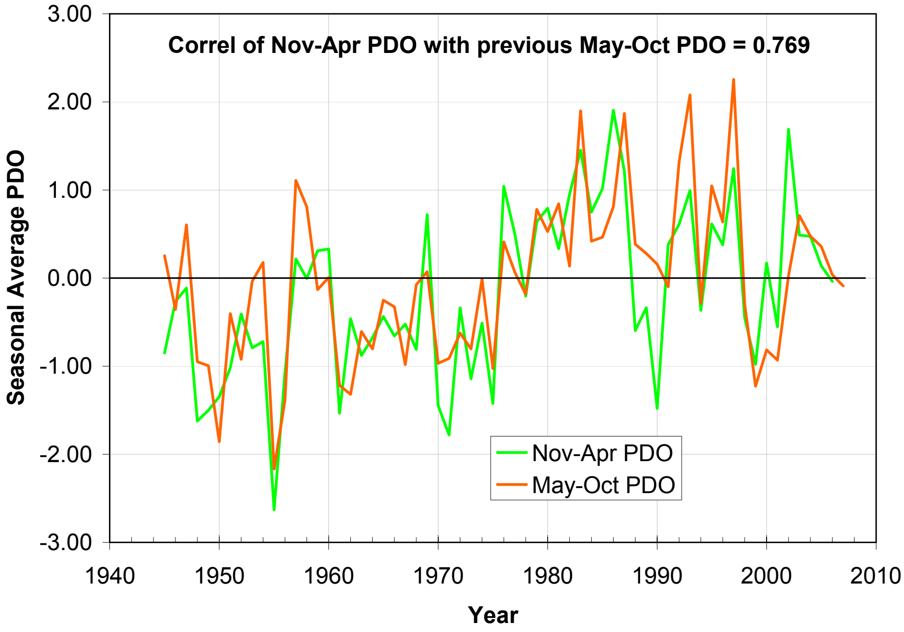

Figure 137 Correlation between average PDO for wet season (Nov– Apr) and average PDO for the previous dry season (May – Oct)

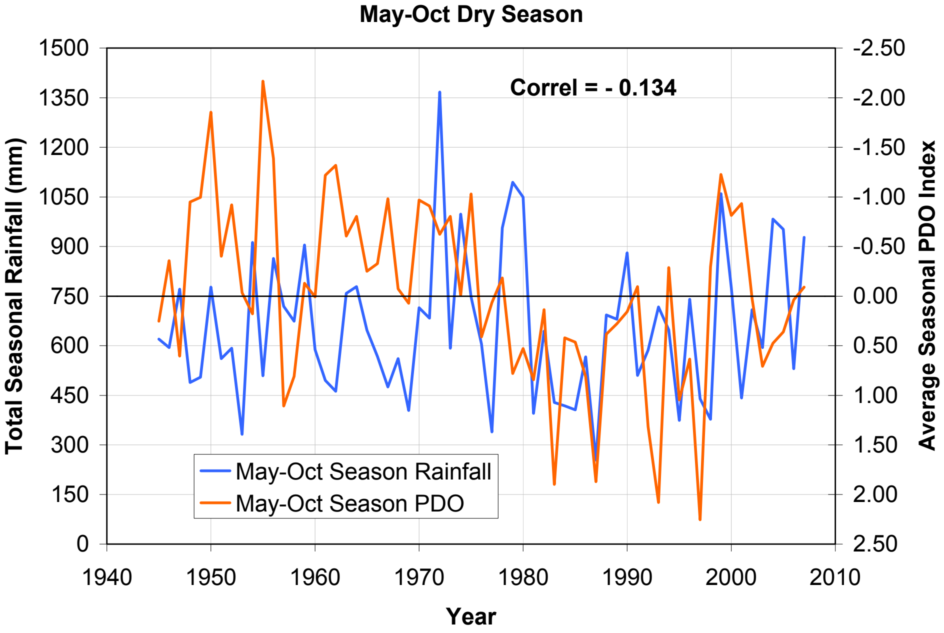

Figure 138 Correlation between total dry season rainfall and average PDO for same period

In contrast to the dry season, the total wet season rainfall shows a stronger negative correlation (R_c = -0.603) with the average wet season PDO (Figure 139). Correlations of total wet season rainfall with average wet season PDO for the period 1945-1977 (R_c = -0.509) and 1978-2007 (R_c = -0.592) were closer. So it appears that the total wet season rainfall is linked to the average PDO for the same season while the dry season is not, as was found with the SOI.

Because the average wet season PDO is closely coupled to the previous average dry season PDO, the total wet season rainfall should also be negatively correlated with the average dry season PDO. This is shown to be so in Figure 140 (R_c = 0.50). This provides some possibility for predicting the important total wet season rainfall, $\sum_{Apr}^{Nov} P$ in Tongatapu from the average PDO index for the preceding dry season $\overline{PDO}_{Pr\ evMay-Oct}$:

$$\sum_{Nov}^{Apr} P = 1068 - 203 \times \overline{PDO}_{Pr\ evMay-Oct} \qquad [45]$$

Equation [45], however, only accounts for 25% of the variance in total wet season rainfall. Table 76 summarises the correlations found in this examination of wet and dry season rainfall and PDOs.

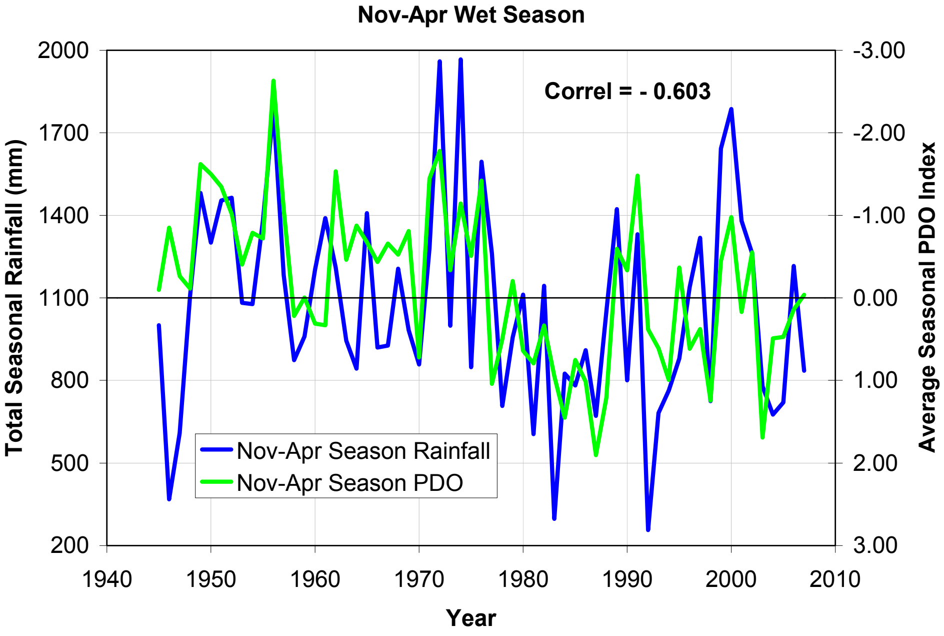

Figure 139 **Correlation between total wet season rainfall and average PDO for same period**

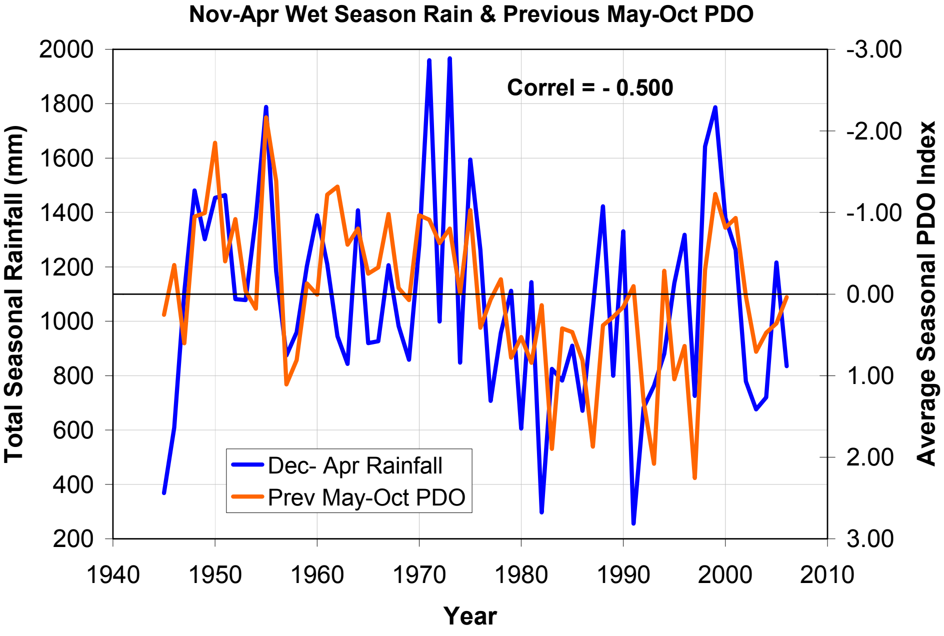

Figure 140 **Correlation between the total wet season rainfall and the average PDO for previous dry season**

Table 76 Correlations between wet and dry season rainfalls and average PDO indices

Correlates	Correlation Coefficient, R_c
Nov-Apr PDO and preceding May-Oct PDO	+0.769
May-Oct PDO and preceding Nov-Apr PDO	+0.537
Nov-Apr Rain and Nov-Apr PDO	-0.603
Nov-Apr Rain and preceding May-Oct PDO	-0.500
May-Oct Rain and May-Oct PDO	-0.134
May-Oct Rain and preceding Nov-Apr PDO	-0.274

12.4 Niño SST anomalies

12.4.1 Niño SST anomalies and droughts

Surface sea temperatures from the central Pacific region have been used in a variety of climate predictions. The region has been divided into 4 Niño SST zones (Figure 141). The combined Niño regions 1+2 span the area 0°S to10°S and 90°W to 80°W; Niño 3 spans the equatorial region 5° N to 5°S and 150 W to 90°W; Niño 4 covers the region 5°N to 5°S and 160°E to 150°W. The composite Niño 3.4 covers the central Pacific equatorial region from 5 N to 5°S and 170°W to120°W. Values of both weekly and monthly SST and SST anomaly[22] data are available from January 1950 to the present and can be accessed at http://www.cpc.ncep.noaa.gov/data/indices/.

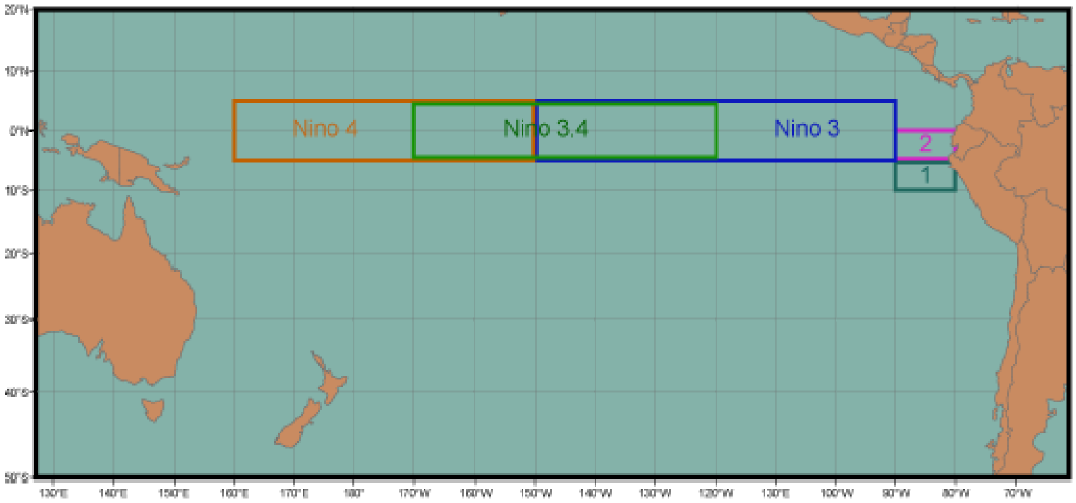

Figure 141 Location of the Niño regions in the equatorial Pacific Ocean (NOAA)

Figure 142 shows the annual average Niño SSTs in the 4 regions. The Niño SST anomaly data, presented as the mean of the previous 12 months, is plotted in Figure 143 where the large temperature anomalies that occurred in Niño 1+2, 3 and 3.4 in 1983 and 1998 are evident.

The correlation between total rainfall over the previous 12 months and the average Niño SST anomaly over the previous 12 months was examined for each of the 4 Niño regions for different lags between total rainfall and SST anomaly. Table 77 lists the correlation coefficients and lags at which the maximum negative correlations occurred.

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[22] On 1st August 2001 the base period used to calculate monthly Niño region anomalies was changed from (1961-1990) to (1971-2000). This change has caused some small variations in the Niño region anomalies.

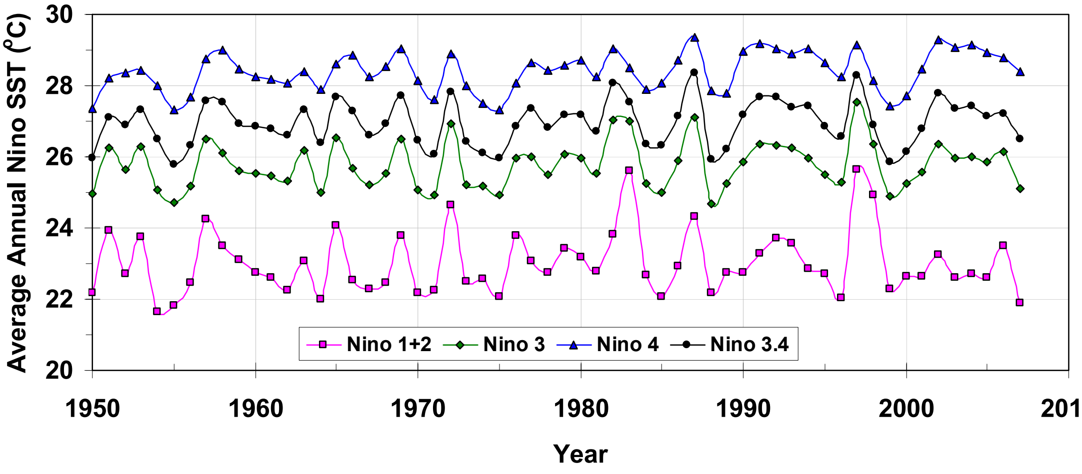

Figure 142 Annual average SSTs for the 4 Niño regions since 1950

Table 77 Maximum correlations between total rainfall and the average SST anomalies over the previous 12 months and the lag at which those correlations occurred.[23]

Niño Region	Rainfall Lag (months)	Correlation Coefficient
1+2	3	-0.429
3	3	-0.580
3.4	3	-0.639
4	3	-0.618

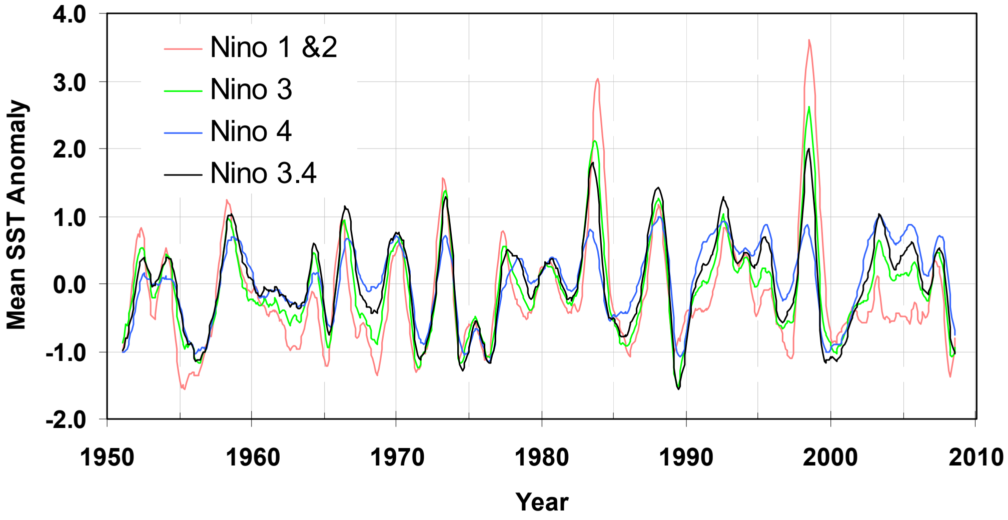

Figure 143 Mean SST anomalies for the previous 12 months for the 4 Niño regions

The maximum negative correlation between rainfall in Tongatapu and SST anomaly for all Niño regions occurred when rainfall lagged behind the SST by 3 months. The correlation of 12 month rainfalls in Tongatapu with average 12 month SST anomalies was weakest for the Niño 1+2 region,

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[23] There are no significant differences in correlations or lags when the actual average SST are used instead of SST anomalies.

as expected. Niño regions 3 and 4 had higher correlations while the highest correlation was with the composite, central Pacific Niño 3.4 region.

The correlation between 12 month total rainfall and the lagged average 12 month SST anomaly for the Niño 3.4 region is plotted in Figure 144. It can be seen that while some peaks coincide others do not suggesting a variable lag between rainfall and SST anomaly. The relation between the rainfall over the previous 12 months, $\sum_{12} P_t$ and the average Niño 3.4 anomaly over 12 months starting 3 months previously, $\overline{SST}_{t-3}$ is:

$$\sum_{12} P_t = 1764 - 502 \times \overline{STT}_{t-3} \qquad [46]$$

Equation [46] accounts for 38% of the observed variance.

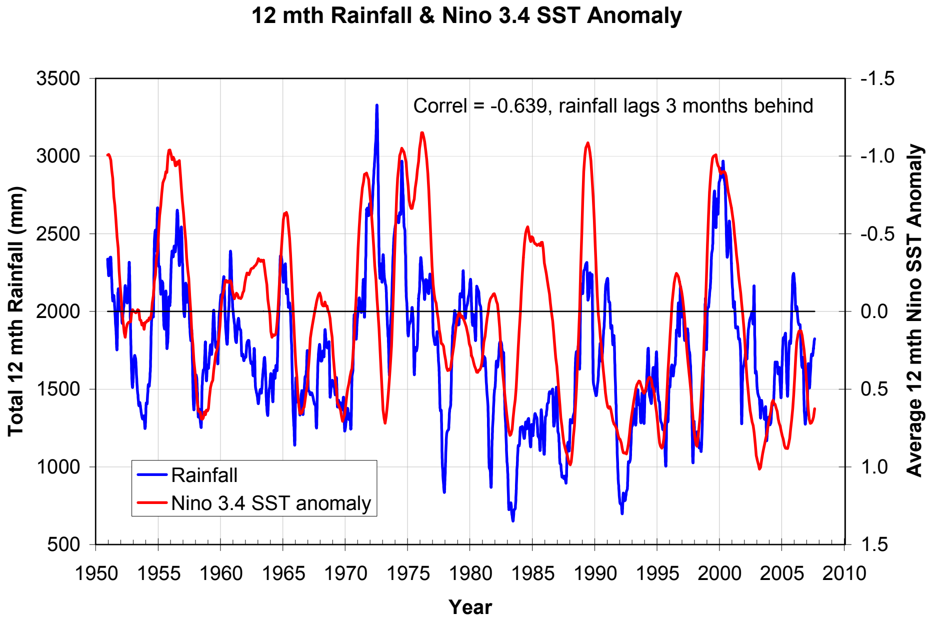

Figure 144 Correlation between 12 month total rainfall and the average 12 month Niño 3.4 SST anomaly 3 months previously

12.4.2 Niño sea SST anomalies and seasonal rainfall

In this section, the relation between Niño region SST anomalies and seasonal rainfall in Tongatapu is examined. Because it has been shown in section 12.4.1 that the maximum correlation between rainfall and SST anomaly occurs for the Niño 3.4 region, we shall only examine the correlation between wet (November - April) and dry season (May - October) rainfalls and the SST anomalies in the Niño 3.4 region.

For the Niño 3.4 region, Figure 145 shows the strong correlation between the average wet and average dry season SST anomalies (R_c = 0.885). As with the other climate indices, the correlation between the average dry season SST anomalies and those for the preceding wet season are weak (R = 0.123). This again illustrates the apparent disconnect that occurs between the end of the wet season and the start of the dry season.

The linear regression between the wet season and dry season for the SST is the strongest of the three climate indices and indicates persistence in SST anomaly. Linear regression of the data in Figure 145 gives a relation between the average wet and previous dry season SSTs for the period 1950-1977:

$$\overline{SST}_{Nov-Apr} = (1.13 \pm 0.10) \times \overline{SST}_{Pr\,evMay-Oct} + (0.05 \pm 0.06) \qquad [47]$$

with R_c = 0.917, accounting for all but 16% of the observed variance.

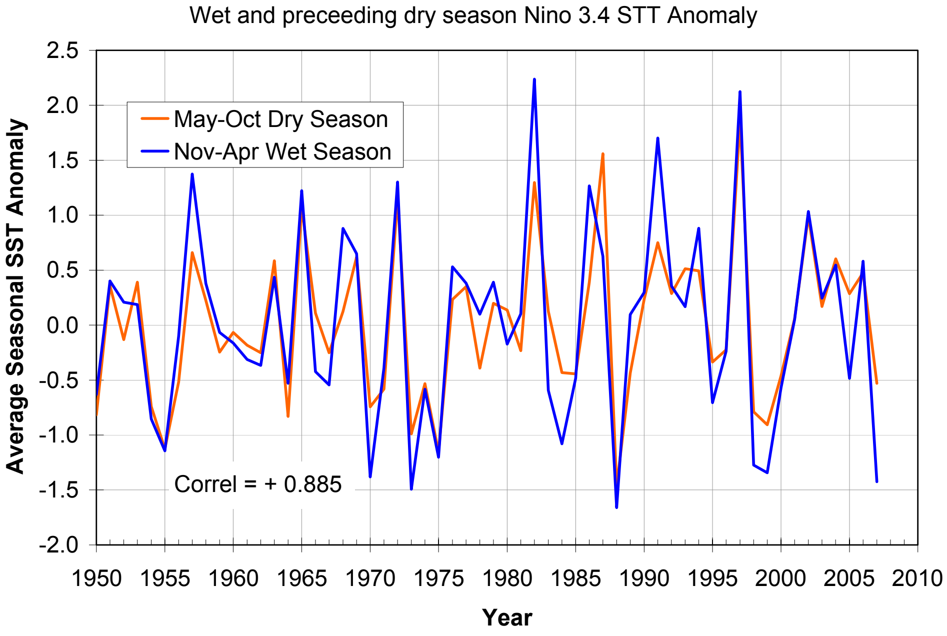

Figure 145 Correlation between the wet season average Niño 3.4 SST anomaly and that for the preceding dry season

Again it is found that the negative correlation between total wet season rainfall in Tongatapu and the average Niño 3.4 SST anomaly for the same wet season is reasonable (R_c = -0.681) but that between the total dry season rainfall and the average Niño 3.4 SST anomaly for the same dry season is weak (R_c = -0.115). These results suggest that we should again see a reasonable correlation between total wet season rainfall and the average Niño 3.4 SST anomaly for the previous dry season. Figure 146 shows this to be the case (R = -0.664). The correlation between the total dry season rainfall and the average preceding wet season Niño 3.4 SST is, however ,much weaker (R_c = -0.219).

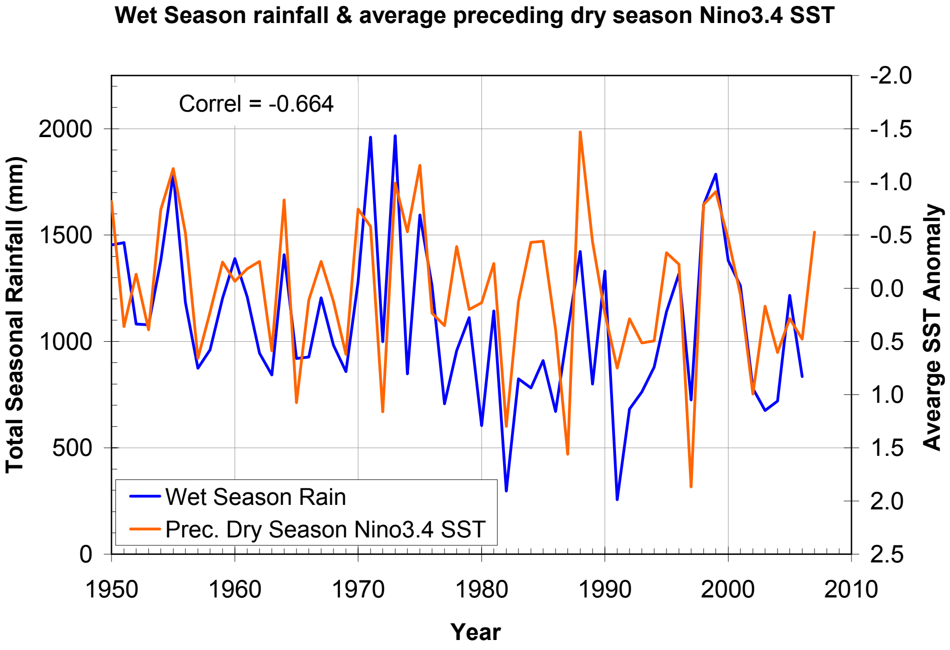

Figure 146 Correlation between the total wet season rainfall and the average preceding dry season Niño 3.4 SST

Figure 146 provides some possibility for predicting the important total wet season rainfall, $\sum_{Apr}^{Nov} P$ in Tongatapu from the average Niño 3.4 SST index for the preceding May to October period $\overline{SST}_{PrevMay-Oct}$:

$$\sum_{Nov}^{Apr} P = 1090 - 351 \times \overline{SST}_{PrevMay-Oct} \quad [48]$$

Equation [48], however, accounts for only 44% of the variance in total wet season rainfall. Table 78 summarises the correlations found in this examination of wet and dry season rainfall and SSTs.

12.5 Wet Season Rainfall and Combined Climate Indices

In sections 12.2.2, 12.3.2 and 12.4.2 it has been found that the total dry season (May - October) rainfall is poorly correlated with either the same dry season climate indices (SOI, PDO or Niño 3.4 SST) or with the preceding wet season climate indices. This is in sharp contrast with the total wet season (November - April) rainfall which has a stronger correlation with both the same wet season climate indices and with the preceding dry season climate indices. Because wet season rainfall is important for groundwater recharge (see section 9.6), we shall concentrate here on the relation between total wet season rainfall and linear combinations of the three climate indices. To find the strongest relationships we have carried out multiple regressions between total wet season rainfall and various combinations of the three climate indices, SOI, PDO and SST both for the same wet season and the preceding dry season.

Table 78 Correlations between wet and dry season rainfalls and average Niño 3.4 SST indices

Correlates	Correlation Coefficient, R_c
Nov-Apr SST (wet) and preceding May-Oct SST (dry)	0.885
May-Oct SST (dry) and preceding Nov-Apr SST (wet)	0.123
Nov-Apr Rain (wet) and preceding May-Oct Rain (dry)	0.095
May-Oct Rain (dry)and preceding Nov-Apr Rain (wet)	0.263
Nov-Apr Rain (wet) and Nov-Apr SST (wet)	-0.681
Nov-Apr Rain (wet) and preceding May-Oct SST (dry)	-0.664
May-Oct Rain (dry) and May-Oct SST (dry)	-0.115
May-Oct Rain (dry)and preceding Nov-Apr SST (wet)	-0.219

For the period 1950 to 2007[24], the strongest correlation between total wet season rainfall and a single climate index averaged over the same wet season occurs when the SOI is used as the climate index. The linear regression[25,26] found for total wet season rainfall is:

$$\sum_{Nov}^{Apr} P = (1100 \pm 32) + (32.2 \pm 3.7) \times \overline{SOI}_{Nov-Apr} \quad [49]$$

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[24] This period was chosen because Niño SST anomaly values are only available from 1950 onwards.

[25] Standard error estimates of the regression coefficients are included in the parentheses.

[26] We have also used the square root of the rainfall data to normalise it. This does not significantly change the correlations.

with an $R^2 = 0.584$ ($R_c = 0.764$) . When two climate indices are used, each averaged over the same wet season, the strongest correlation is found when both SOI and PDO are used as the climate indices:

$$\sum_{Nov}^{Apr} P = (1082 \pm 29) + (24.5 \pm 4.0) \times \overline{SOI}_{Nov-Apr} - (126 \pm 37) \times \overline{PDO}_{Nov-Apr} \quad [50]$$

with an improved $R^2 = 0.657$ ($R_c = 0.811$). When all three climate indices are used the regression equation is:

$$\sum_{Nov}^{Apr} P = (1082 \pm 30) + (24.5 \pm 8.5) \times \overline{SOI}_{Nov-Apr} - (126 \pm 38) \times \overline{PDO}_{Nov-Apr} - (0.3 \pm 79) \times \overline{SST}_{Nov-Apr} \quad [51]$$

but with an identical $R^2 = 0.657$ ($R_c = 0.811$). In other words, the addition of the average wet season Niño 3.4 SST anomaly data to the SOI and PDO has not improved the correlation. This does not mean that the Niño 3.4 SST is unimportant, rather that its impact is probably already incorporated with the PDO and SOI impacts.

When we examine the relation between total wet season rain and the previous dry season climate indices for the period 1950 to 2007, the strongest correlation between total wet season rainfall and a single climate index averaged over the previous dry season occurs when the Niño 3.4 SST anomaly is used as the climate index. The linear regression[27] found for wet season rainfall is:

$$\sum_{Nov}^{Apr} P = (1090 \pm 37) - (351 \pm 53) \times \overline{SST}_{PrevMay-Oct} \quad [52]$$

with an $R^2 = 0.441$ ($R_c = 0.641$). The relation found for the SOI has only a slightly lower $R^2 = 0.437$:

$$\sum_{Nov}^{Apr} P = (1100 \pm 37) + (28.0 \pm 3.3) \times \overline{SOI}_{PrevMay-Oct} \quad [53]$$

When two climate indices are used, each averaged over the same previous dry season, the strongest correlation is again found when both SOI and PDO are used as the climate indices:

$$\sum_{Nov}^{Apr} P = (1096 \pm 36) + (22.9 \pm 4.8) \times \overline{SOI}_{PrevMay-Oct} - (95 \pm 44) \times \overline{PDO}_{PrevMay-Oct} \quad [54]$$

with an $R^2 = 0.481$ ($R_c = 0.694$). When Niño 3.4 SST anomaly and PDO are used the $R^2 = 0.479$ ($R_c = 0.692$) is only slightly less. When all three climate indices are used the regression equation is:

$$\sum_{Nov}^{Apr} P = (1093 \pm 36) + (12.6 \pm 9.2) \times \overline{SOI}_{PrevMay-Oct} - (84 \pm 45) \times \overline{PDO}_{PrevMay-Oct} - (151 \pm 117) \times \overline{SST}_{PrevMay-Oct} \quad [55]$$

with an increased $R^2 = 0.497$ ($R_c = 0.705$).

For the total dry season rainfall, the maximum correlation occurred when all three average dry season indices are used but with a very small $R^2 = 0.041$ ($R_c = 0.202$). When the relation between total rainfall and the average previous wet season climate indices are examined, the strongest correlation is again found when all previous wet season climate indices are used but again with a small $R^2 = 0.097$ ($R_c = 0.311$). This confirms that fact that while the wet season rainfall is linked to the climate indices, that for the dry season is not.

Figure 147 compares the actual total wet season rainfall with that predicted from equations [54] and [55].

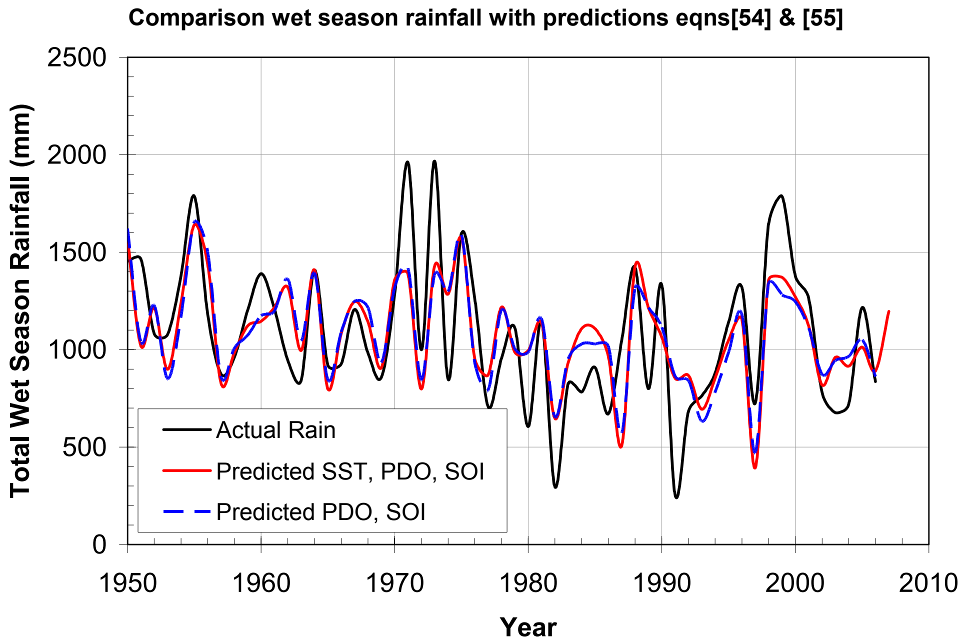

Figure 147 Comparison between the actual total wet season rainfall and that predicted from the previous dry season average climate indices using equations [54] and [55]

It can be seen that while the predictions of both equations [54] and [55] are close to each other they under-estimate the magnitude of the wet season rainfalls for wet seasons starting in November 1971, 1973 and 1999 and do not predict the severe wet season droughts starting in November 1981 and 1990. This is hardly surprising since the R^2 values indicate these equations explain just less than 50% of the variance at best.

12.6 Wet Season Recharge and Combined Climate Indices

A brief examination was made of the relationship between total wet and total dry season recharge and the average seasonal climate indices. As with seasonal rainfall, the total dry season recharge was poorly correlated with average dry season or the average previous wet season climate indices. The correlation is stronger for the total wet season recharge and the average wet season climate indices with the strongest correlation being with average wet season SOI ($R_c = 0.642$). When the average previous dry season climate indices are used, the correlation between the total wet season recharge and the average previous dry season climate indices is slightly less, with the strongest absolute correlation being for the average previous dry season Niño 3.4 SST anomaly ($R = -0.567$). When all average dry season climate indices are combined the regression equation found is:

$$\sqrt{\sum_{Nov}^{Apr} R} = (17.1 \pm 0.9) + (0.34 \pm 0.24) \times \overline{SOI}_{Pr\,evMay-Oct} - (1.9 \pm 1.2) \times \overline{PDO}_{Pr\,evMay-Oct} - (1.7 \pm 3.1) \times \overline{SST}_{Pr\,evMay-Oct} \qquad [56]$$

with $R_c = 0.605$. Here the square root of total wet season recharge is used because wet season recharge is not normally distributed. Figure 148 shows the comparison between the total wet season recharge predicted from equation [56] using all the average previous dry season climate indices and the estimated seasonal recharge for Case 1.

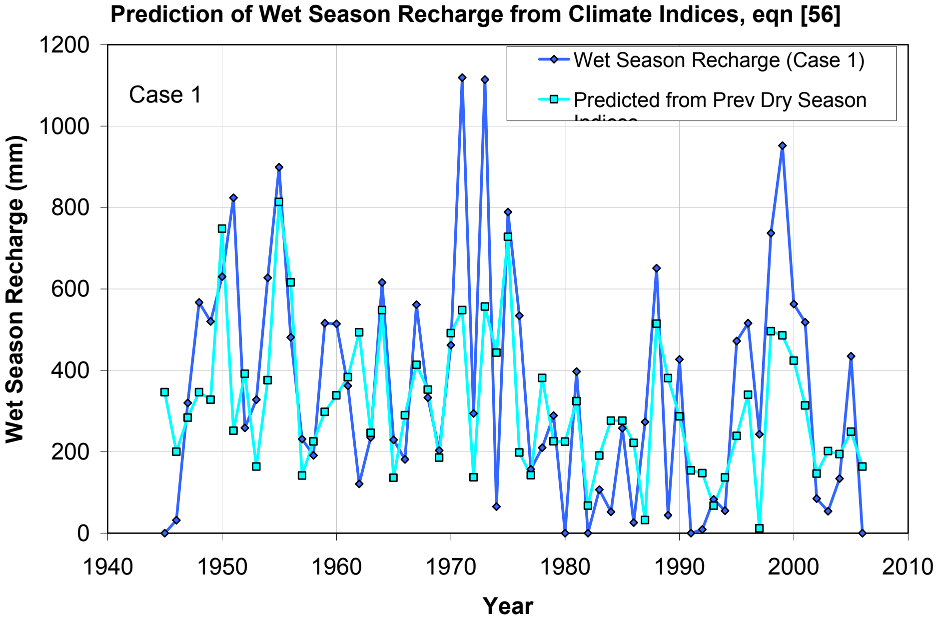

Figure 148 Comparison of total wet season recharge predicted from equation [56] and the average previous dry season climate indices and the estimated wet season recharge for Case 1

It can be seen in Figure 148 that equation [56] grossly under-estimates the wet season recharge that occurred in the wet years 1971, 1973 and 1999. Over the period 1945 to 2006, the cumulative total wet season recharge estimated from equation [56] is 11% less than that calculated for Case 1.

12.6.1 The break in autocorrelation between seasonal climate indices

The correlation found above between total wet season rainfall and the average climate indices of the previous dry season showed reveal good correlations. In contrast to this, the total dry season rainfall is poorly correlated with the average previous wet season climate indices or any linear combination of them. These results are unexpected. They indicate that while total wet season rainfall is correlated with the average 6 month climate indices, the total dry season rainfall is not. This seems to suggest that dry season rainfall is governed by factors other than regional SSTs. This also suggests there is a break in autocorrelation between different 6 month seasons of the climate indices.

To explore this further, we have examined the autocorrelation between the averages of two succeeding 6 month periods or seasons of the climate indices with the first season, season 1, starting in different months of the year and season 2, starting 6 months later. We have examined the autocorrelation between season 2 and the preceding season 1 and between season 1 and the preceding season 2. Figure 149 illustrates the autocorrelations for the Niño 3.4 SST anomaly from 1950 to 2007. It is clear that the correlation between the two 6 month seasons, season 2 and the preceding season 1, is at a maximum when season 2 starts in November and season 1 starts in May, corresponding to the wet and preceding dry seasons in Tongatapu, respectively, and is a minimum when season 2 starts in May and season 1 starts in the preceding November, corresponding to the dry and preceding wet seasons in Tongatapu. We therefore see a seasonal “disconnect” in the Niño 3.4 SST anomaly. Similar results are found for the SOI. The seasonal disconnect occurs but is not nearly as marked in the PDO.

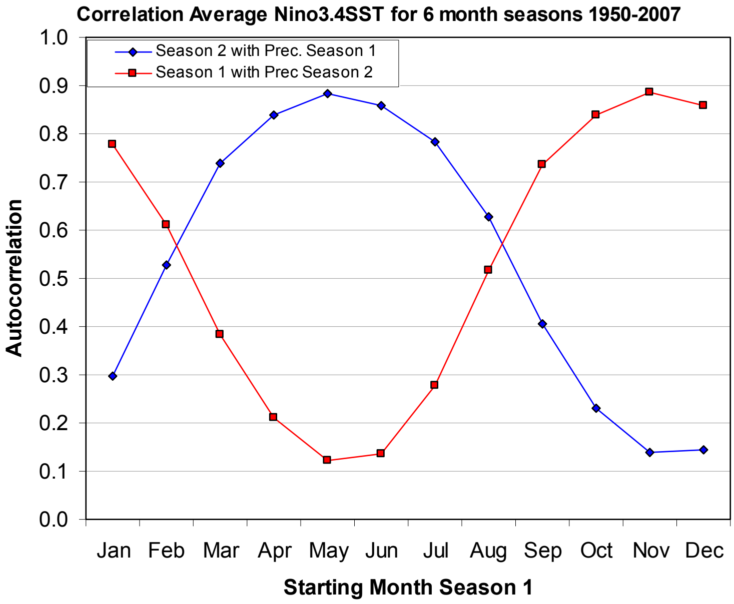

Figure 149 Autocorrelation between seasonal averaged values of the Niño 3.4 SST anomaly for two successive 6-month seasons. The correlations are shown between season 2 and the preceding season 1 as well as between season 1 and the preceding season 2

The relation found between the total wet (November through April) and total dry (May through October) season rainfalls and the average 6 month Niño 3.4 SST anomaly starting at different lags between -12 and +24 months[27] is plotted in Figure 150.

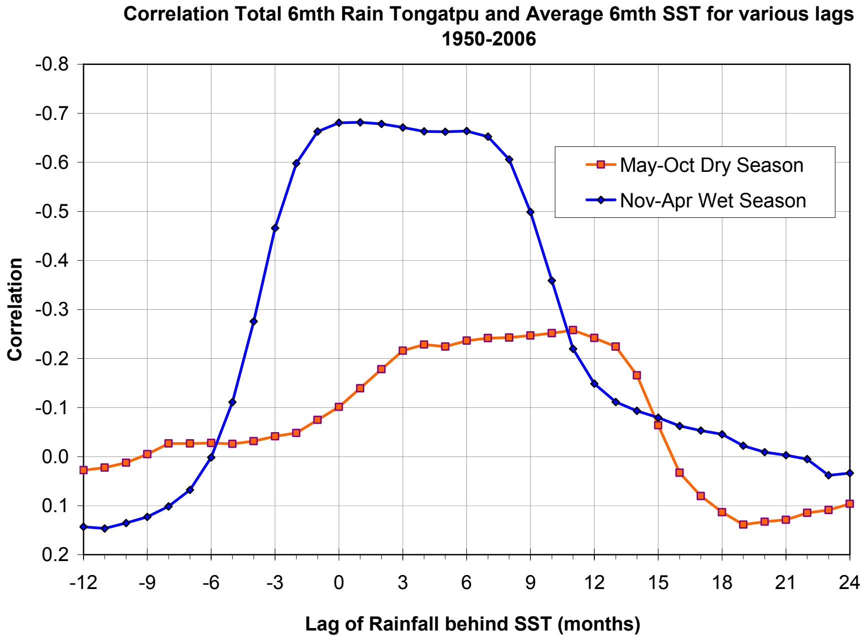

Figure 150 Correlations between total wet (Nov-Apr) and dry (May-Oct) season rainfalls and 6 month average Niño 3.4 SST anomaly for various lags between the starting month of rainfall and SST

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[27] A positive lag means the starting month for the 6 month total rainfall lags behind the starting month for the 6 month average SST, while a negative lag means that the rainfall starting month precedes the starting month of the average SST. A lag of zero means that total 6 month rainfall and 6 month average SST both start at the same month.

It is clear that there is a broad plateau of good correlation between total 6 month wet season rainfall and average SST starting with a lag of -2 months (starting month of rainfall total precedes starting month of SST average by 2 months) and extending to a lag of +8 months. A similar, but much weaker correlation plateau exists for the dry season extending from a lag of +3 to +13 months. Similar results are found for the SOI but smaller differences are found for the PDO.

12.7 Conclusions and recommendations

12.7.1 Drivers of drought in Tongatapu

The correlations between rainfall in Tongatapu and the climate indices of the SOI, PDO and Niño SST anomaly have been examined here. In general, the correlation is positive for SOI and negative for PDO and Niño SST anomaly (data only from 1950) and is also strongest for SOI, followed by Niño Region 3.4 SST anomaly and then PDO. As the time periods increase over which rainfall is summed and over which the indices are averaged is increased so the absolute value of the correlation increases. In general, the maximum absolute correlation is found when the rainfall period lags 3 months behind the SOI and the Niño 3.4 SST anomaly period. For the PDO, the lag is both positive and negative and for the 120 month summation and averaging period, the maximum absolute value of correlation occurs when rainfall lags 22 months behind the average PDO period, providing a means of estimating variations in long-term rainfall from the average PDO index.

An unexpected result was found when the correlations between total seasonal rainfall and seasonal averaged climate indices were examined for a wet season taken as November to April and a dry season taken as May to October. A reasonably good correlation was found between the total wet season rainfall and the average wet season climate indices, with SOI given the highest correlation. The total dry season rainfall, however, was poorly correlated with the average corresponding dry season climate indices.

The wet season correlation improved when total wet season rain is compared to a linear combination of the average SOI and PDO for the same wet season, but inclusion of the average Niño 3.4 SST anomaly did not improve the correlation. The correlation between total dry season rain and a linear combination of all average dry season climate indices was still very weak.

An examination of the correlation between total wet season rainfall and the average climate indices of the previous dry season showed that the good correlation persisted and was strongest when Niño 3.4 SST was used as the average dry season climate index; although the correlation was very slightly less when the average previous dry season SOI was used. A linear combination again of average dry season SOI and PDO improved this correlation and there was a slight improvement when all climate indices were used.

It has been shown that the autocorrelation in the average 6 month SST or SOI indices starting in November has a maximum autocorrelation with the previous average 6 month season starting in May. The autocorrelation is a minimum when the average 6 mth period starting in May is compared with the 6 mth season starting the previous November. This indicates a “resetting” of the SST at the start of the dry season in May. This carries over to total wet season rainfall, where a very broad, reasonably strong correlation is found with average SST or SOI indices up to 8 months prior to the wet season. Total dry season rainfall, however, showed a much weaker correlation with SST or SOI.

The analyses presented in this study show that droughts, as expected, are related to the drivers of climate in the South Pacific, as measured by the climate indices SOI, PDO and Niño 3.4 SST. It has also been shown, however, that there is a complex relation between seasonal rainfall in Tongatapu and SOI, PDO and Niño 3.4 SST with wet season rainfall having a significant correlation to these climate indices but the dry season rainfall having a poor correlation. Because of the importance of recharge during the wet season for water resources, this complex relationship requires further examination.

12.7.2 Unresolved Issues

The prolonged dry periods revealed by rainfalls summed over 120 month periods that occurred in the 1980s and 1990s appear to be correlated and lag about 22 months behind 120 month averages of the PDO. This appears to provide a warning system for identifying the onset of dry periods and this relationship should be examined more closely.

It is clear that wet season recharge is a very important component of groundwater recharge in Tongatapu. It has been shown here that there is a reasonable relationship between wet season rainfall and the average climate indices SOI, PDO and SST in both the same wet season and the previous dry season but this is not the case for dry season rainfall. There appears to be a resetting of the autocorrelation of climate indices at the start of the dry season in May. The complex relationship between seasonal rainfall and climate indices warrants further attention.

12.7.3 Recommendations

Based on the above considerations, the following recommendations are made:

- The relationship between long-term rainfall and long-term averages of climate indices should be further examined in order to predict long-term dry periods.
- The relationship between seasonal rainfall and recharge and climate indices and drivers should be further explored to improve prediction of impacts on groundwater.

13 Climate Change

13.1 Climate excursions over the past 400,000 years

As has been demonstrated in the preceding Section 12, the surrounding ocean exerts a strong influence on the climate in small islands such as Tongatapu and is responsible for the generally warm, year-round temperatures on the island (Ali *et al.*, 2001). As shown in section 12.1 and elsewhere (Hay *et al.,* 1993), rainfall variations in Tongatapu are coupled to variations in the climate indices, SOI, PDO or Niño SST anomalies which are tied to sea surface temperature (SST). The appearance of cyclones is also coupled to these indices. Changes therefore in global atmospheric temperature and corresponding increases in mean SST are expected to have major impacts on climate and especially rainfall and the frequency of extreme events (IPCC, 1998). The current observed rises in global atmospheric temperature, linked to the increasing atmospheric concentrations of greenhouse gases (GHGs) such as CO_2, CH_4 and N_2O, therefore, have the potential to change climatic conditions.

During the past 400,000 years, palaeoclimate records show at least 4 periods of slow cooling of global temperature over about 100,000 years followed by rapid temperature rises (IPCC, 1998). These so-called “whipsaw” temperature excursions correspond to periods of slow sea level fall, by up to 120 m below current mean sea level, followed by rapid sea level rises with maximum levels of up to about 10 m above present MSL (Hansen *et al.,* 2007). It is these sea level rises associated with rapid global warming that are seen as the major threat to small island nations, and particularly those with very low lying islands (Ali *et al.,* 2001). While in Nuku’alofa, many of the services and economic activities and other northern parts of Tongatapu are low-lying, most of the major groundwater source areas (see Figure 113) are situated above the projected maximum sea level rise expected from global warming. In addition to physical and economic impacts, global warming has major implications for public health (McMichael, 1993). In terms of its vulnerability to sea level rise alone, Tonga has been rated as “severe” (Pernetta, 1988).

The palaeoclimate data shows that the Earth’s climate is remarkably sensitive to global forcings with slight changes in solar insolation, leading to albedo ‘flips’ between ice and water as ice sheets melt and rapid increases in the release of GHGs, principally CO_2, CH_4 and N_2O, causing “whipsawing” of the entire planet between climate states (Hansen *et al.,* 2007). It has been claimed that current emissions of GHGs place the Earth perilously close to a dramatic climate change that could run out of control (Hansen *et al.,* 2007). For this reason, this section examines the predicted consequences for rainfall, evaporation and groundwater in Tongatapu.

13.2 Past sea surface temperature excursions and current trends

In tropical regions, over these approximately 100,000 year cycles of global cooling and warming, the typical SST swings, recorded in the composition of microscopic, shelled organisms, has been 3-4°C (Hansen *et al.,* 2007). These temperature excursions are predicted to have had major impacts on climate in small island nations with the general expectation that warmer SSTs would be associated with higher annual rainfalls and more frequent and more severe cyclones (IPCC, 1998).

In the period from 1880 to 2003, It has been estimated that average annual temperature in the Tonga region may have risen by about 0.6 to 1.0°C (Hansen *et al.,* 2007) although other estimates suggest that in the Pacific islands, the increase in average annual temperature has been less than 0.5°C since 1900 (Ali *et al.,* 2001). Within the region, there has been a steady increase in temperature to the south of the South Pacific Convergence Zone, an area that includes Fiji and Tonga, since the 1880s (Salinger *et al.*, 1995).

Reliable annual rainfall data in Tongatapu extends back only to 1945. A trend line fitted to the annual rainfall series in Figure 4 shows an average decrease in Nuku’alofa rainfall over that period of 2.3 mm/year. The R^2, however, of this trend line is 0.0096 (R_c = 0.098) indicating that this trend is not significant. This is consistent with analyses of rainfall in other Pacific Islands when large inter-annual and inter-decadal variations swamp any significant trends ((Ali *et al.,* 2001). As was demonstrated in section 12.1 and shown previously (Hay *el al.,* 1993, Salinger *et al.*, 1995), these swings are correlated with variations in the SOI, PDO or Niño SST anomaly. Since the late 1970s, the long-period rainfall in Tongatapu has shown an increasing frequency of drier periods (Figure 4 and Figure 118) and severe hydrological droughts (Table 70).

The annual number of tropical cyclones for the Southwest Pacific cyclone belt over the past 50 years has high inter-annual and sub-decadal variations with no evident long-term overall trend (Ali *et al.,* 2001). This illustrates one of the real problems in recognising climate trends in the Pacific. The instrumental record is generally too short for reliable identification of significant trends.

13.3 Predicting the possible impacts of future climate change

In order to assess how increasing anthropogenic emissions of carbon dioxide and other GHGs will affect future global and regional climate, coupled global atmosphere-ocean models have been developed around the world (IPCC, 2001a). These aim to simulate how the world's atmosphere and oceans would respond to a range of possible future emissions of GHGs and aerosols over the next century. The IPCC's Third Assessment Report (IPCC 2001a, b) suggests that there are 20 to 30 models around the world that appear to give plausible predictions of the sensitivity of global mean temperature and rainfall to increasing GHG emissions. Most global climate models suggest that global mean surface air temperatures can be expected to rise in the future as GHG emissions continue to increase (Ali *et al.*, 2001).

Current atmosphere-ocean global climate model simulations are necessarily carried out at a coarse horizontal scale. This unfortunately means that many small island states in the Pacific fall within a single grid box. This severely constrains the ability of the models to predict climate change scenarios for small island nations. Nonetheless, because the climate of these islands is influenced by the surrounding ocean, and the oceans are expected to warm in the future, but more slowly than land masses, small island states are also likely to experience moderate warming (Pittock *et al.*, 1995) and rainfall increases.

In order for climate models to project possible future climate change, it is necessary to estimate the probable range of rates of emissions of GHGs that can be expected. The range of emission rates will depend on future human responses to global warming and the reaction of the earth system to those responses. In order to overcome this problem, the IPCC (2000), in its Special Report on Emission Scenarios (SRES), developed a range of greenhouse emission scenarios to cover the expected range of responses. These scenarios ranged from the expected highest to the lowest scenario, with intermediate scenarios representing such strategies as SRES A1FI, incorporating intensive fossil fuel use and SRES B1, a scenario incorporating the adoption of clean technologies. Figure 151 shows the expected anthropomorphic contribution to GHG emission to the year 2100, given in gigatonnes (Gt) of equivalent carbon per year (Hadley Centre, 2003) and Table 79 lists the characteristics of the SRES scenarios in the figure.

It can be seen that if there is a greater than two-fold difference in the total amount of CO_2 emitted between the A1F1 and B1 scenarios for approximately the same projected world population over the period 1900 to 2100. Under the full range of scenarios, the coupled models suggest that global atmospheric temperatures could rise by about 1 to 9°C with corresponding sea level rises of about 0.1 to 0.9 m (IPCC, 2001a) by 2100.

Hansen *et al.* (2007) dispute the predictions of the IPCC (2001a, 2007), which foresee little or no contribution to twenty-first century sea-level rise from the melting Greenland and Antarctic ice sheets. They believe IPCC analyses and projections do not properly account for the non-linear physics of wet ice sheet disintegration, ice streams and eroding ice shelves, nor do they see them as consistent with the palaeoclimate evidence for the absence of a discernable lag between ice sheet forcing and sea-level rise. They conclude that the change in the albedo between ice and wet ice, the albedo "flip", over large portions of ice sheets in combination with warming of the nearby ocean and atmosphere, would produce multiple positive feedbacks leading to eventual non-linear ice sheet disintegration, producing a situation which Hansen *et al.* (2007) describe as "imminent peril". They believe that climate forcing of this century under "business as usual" GHG emissions would dwarf natural forcings of the past million years, and may probably exceed climate forcing of the middle Pliocene, when the planet was not more than 2–3°C warmer and sea level 25 ± 10 m higher than at present. The timescale for such an event is difficult to predict in such a non-linear problem. Hansen *et al.* (2007) could find no evidence of millennial lags between forcing and ice sheet response in palaeoclimate data. They conclude an ice sheet response time of centuries seems probable, but could not rule out large changes on decadal time-scales once wide-scale surface melt is underway. With GHGs continuing to increase, they concluded the planetary energy imbalance provides ample energy to melt ice corresponding to several metres of sea level per century.

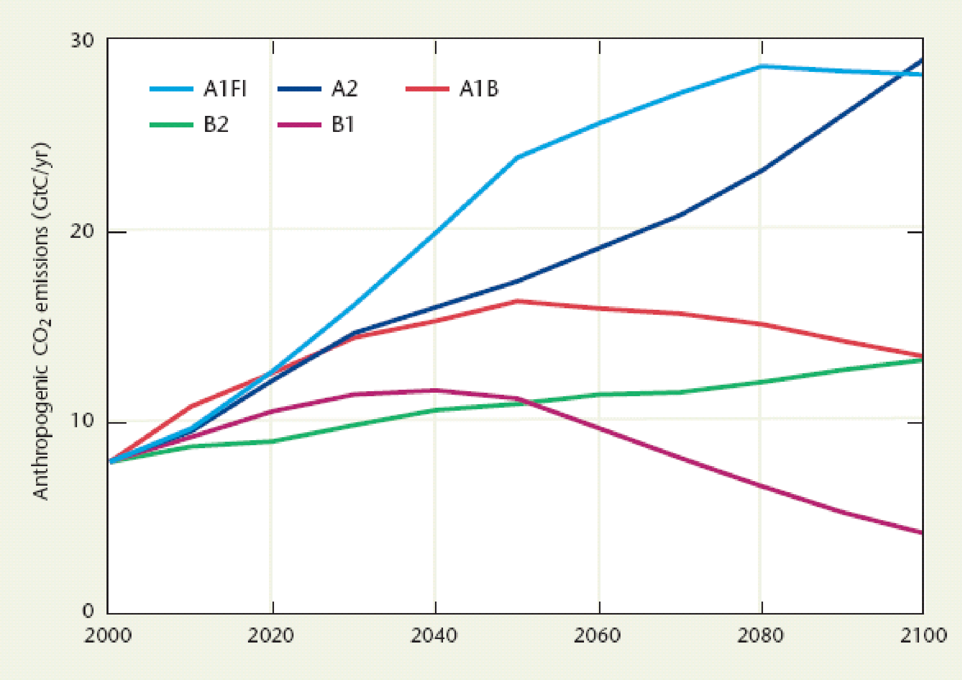

Figure 151 Projected anthropomorphic emissions of greenhouse emissions for a range of SRES scenarios (Hadley Centre, 2003)

Table 79 Characteristics of the SRES scenarios in Figure 151 (Hadley Centre, 2003)

SRES Scenario	Increase in GNP 1990-2100 (Trillion $US)	Population by 2100 (billion)	Total CO_2 Emissions 1900-2100 (Gt Carbon)
A1FI	505	7.14	2190
A2	225	15.07	1860
A1B	510	7.06	1500
B2	215	10.42	1160
B1	310	7.05	980

13.4 Estimated changes in rainfall over the 21st century

In view of the importance of possible changes in climate caused by GHG emissions we asked CSIRO to provide estimates of the range of changes to rainfall and evaporation in Tongatapu over the next century relative to the 1975-2004 period for 12 months of the year for the following 4 global warming SRES scenarios (Table 79):

1. Highest values for the SRES scenarios
2. Best estimate values for the A1FI scenario
3. Best estimate values for the B1 scenario
4. Lowest values for the SRES scenarios

The analysis used the WCRP CMIP3 database of model output at PCMDI (Meehl *et al.,* 2007) and "pattern scaling" (Whetton *et al.,* 2005) to generate the results. Twenty three separate atmosphere-ocean global climate models were used to generate predictions of percentage changes in monthly rainfall relative to the mean rainfall for the period 1975-2004. Table 80 compares the mean rainfall for this period with that for the full period of reliable rainfall record between 1945 and 2007. The shorter rainfall period 1974-2004 has a higher frequency of significant droughts than the full rainfall record 1945 to 2007 (see section 11.12). As a consequence, some months in the shorter period have mean rainfalls that are over 11% smaller than those of the full record. Generally, the wet season for the shorter period has lower mean rainfall than that for the full record, while the dry season for the shorter period has higher rainfalls than the full record. The mean annual total rainfall for 1975 to 2004 is 6.6% less than that for 1945 to 2004 and appears to reflect a generally positive phase of the PDO (see e.g. Figure 136).

Table 80 Comparison between the mean and median rainfalls for the period 1975-2004 used in the climate predictions with values for 1945-2007

Period	**Rainfall (mm)**			
	1945-2007		**1975-2004**	
	Mean	**Median**	**Mean**	**Median**
Jan	198.4	187.0	186.1	148.0
Feb	224.1	212.0	205.5	156.5
Mar	220.4	212.0	198.2	190.5
Apr	165.6	139.0	150.6	137.5
May	102.4	81.0	102.6	83.0
Jun	92.1	76.0	93.7	84.0
Jul	101.2	84.0	100.5	84.5
Aug	118.2	102.0	130.7	112.0
Sep	120.9	102.0	111.6	91.0
Oct	122.8	102.0	97.9	58.5
Nov	112.1	72.0	101.1	68.0
Dec	150.9	126.0	141.1	136.0
Annual	**1,727**	**1,746**	**1,620**	**1,633**

The complete range of the 23 global circulation model predictions for the 4 SRES scenarios for 2020, 2050 and 2095 are given in Annex K. Table 81 summarises the mean and other statistics of the model predictions for the percentage changes in mean monthly rainfall from the period 1975-2004 (Table 80).

It is immediately obvious from both the differences between the predicted maximum and minimum values of the changes in rainfall as well as the large coefficients of variation in Table 81 that there is a wide discrepancy between the predictions of the 23 atmosphere-ocean models. Some suggest increases in rainfall while others suggest decreases for the same case. The average CV across all months, all SRES scenarios and all years is a very high 322%, with little variation between scenarios or years. For one case the CV is higher than 700%. The CVs for the individual months show a consistent pattern and values, irrespective of year or SRES scenario. The average CV for May is the highest (657%), followed by February (612%) and June (570%) while the lowest is for August (138%), followed by March (151%) and January (154%). This consistency suggests underlying structural difficulties in the models.

Table 81 Statistics of predicted changes in rainfall for 4 SRES scenarios for the 2020, 2050 and 2095

Year	**SRES**	**Statistic**	**Change in Rainfall from Mean Monthly Rain 1975 – 2004 (%)**											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2020	**Low**	**Mean**	**1.6**	**0.5**	**0.5**	**1.5**	**0.5**	**-0.4**	**-1.2**	**-1.2**	**-0.8**	**-0.7**	**0.7**	**1.9**
		Std Dev	2.8	2.9	1.6	2.1	2.8	2.2	2.0	1.6	1.7	2.2	2.8	3.0
		CV %	173	601	305	144	591	554	166	137	218	320	405	161
		Median	**2.0**	**0.0**	**1.0**	**1.0**	**0.0**	**-1.0**	**-1.0**	**-1.0**	**-1.0**	**-1.0**	**1.0**	**3.0**
		Max	7	6	4	5	6	4	3	1	3	5	7	6
		Min	-5	-4	-3	-1	-6	-4	-5	-4	-3	-4	-5	-4
	B1	**Mean**	**3.1**	**0.8**	**1.0**	**2.6**	**0.7**	**-0.7**	**-2.2**	**-2.0**	**-1.3**	**-1.2**	**1.3**	**3.4**
		Std Dev	4.7	5.3	2.8	3.9	5.0	3.9	3.7	2.9	3.0	4.2	5.1	5.4
		CV %	154	642	295	151	713	597	168	140	223	362	389	158
		Median	**4**	**1**	**1**	**2**	**0**	**-1**	**-2**	**-2**	**-1**	**-2**	**2**	**5**
		Max	12	11	7	8	11	7	5	3	5	10	12	12
		Min	-9	-8	-5	-3	-10	-7	-10	-8	-6	-6	-8	-7
	A1FI	**Mean**	**2.9**	**0.8**	**0.8**	**2.5**	**0.7**	**-0.6**	**-2.1**	**-1.9**	**-1.3**	**-1.0**	**1.2**	**3.1**
		Std Dev	4.4	4.8	2.6	3.6	4.5	3.7	3.5	2.6	2.8	3.9	4.7	5.0
		CV %	153	619	315	144	697	604	167	140	207	375	397	159
		Median	**3**	**1**	**1**	**2**	**0**	**-1**	**-2**	**-2**	**-1**	**-2**	**2**	**5**
		Max	11	10	6	8	10	6	4	2	5	9	11	11
		Min	-8	-7	-5	-2	-9	-7	-9	-7	-6	-6	-8	-6
	High	**Mean**	**6.0**	**1.7**	**1.7**	**5.0**	**1.5**	**-1.3**	**-4.3**	**-4.0**	**-2.9**	**-2.4**	**2.6**	**6.6**
		Std Dev	9.3	10.2	5.6	7.7	9.7	7.6	7.4	5.5	5.9	8.1	9.8	10.6
		CV %	155	585	320	154	656	585	170	137	204	340	384	160
		Median	**7**	**2**	**2**	**4**	**0**	**-2**	**-5**	**-3**	**-3**	**-4**	**4**	**10**
		Max	24	21	13	17	21	13	9	5	10	19	23	23
		Min	-17	-15	-10	-5	-20	-14	-19	-15	-12	-12	-16	-14
2050	**Low**	**Mean**	**3.6**	**0.9**	**1.0**	**3.0**	**0.9**	**-0.9**	**-2.6**	**-2.3**	**-1.6**	**-1.3**	**1.6**	**3.8**
		Std Dev	5.4	6.1	3.3	4.7	5.7	4.6	4.3	3.3	3.4	4.8	5.9	6.2
		CV %	152	669	329	155	626	525	168	139	209	353	377	162
		Median	**4.0**	**1.0**	**1.0**	**2.0**	**0.0**	**-1.0**	**-3.0**	**-2.0**	**-2.0**	**-2.0**	**3.0**	**6.0**
		Max	14	13	8	10	12	8	5	3	6	11	14	13
		Min	-10	-9	-6	-3	-12	-9	-11	-9	-7	-7	-10	-8
	B1	**Mean**	**5.9**	**1.7**	**1.7**	**4.9**	**1.5**	**-1.3**	**-4.3**	**-4.0**	**-2.8**	**-2.4**	**2.5**	**6.6**
		Std Dev	9.1	10.1	5.6	7.6	9.6	7.6	7.3	5.5	5.8	8.1	9.7	10.3
		CV %	155	597	320	154	646	564	170	138	206	339	393	156
		Median	**7**	**2**	**2**	**4**	**0**	**-2**	**-5**	**-3**	**-3**	**-4**	**4**	**10**
		Max	23	21	13	16	20	13	9	5	10	19	23	22
		Min	-17	-15	-10	-5	-20	-14	-19	-15	-12	-12	-16	-13
	A1FI	**Mean**	**9.7**	**2.8**	**2.8**	**8.2**	**2.4**	**-2.1**	**-6.9**	**-6.5**	**-4.5**	**-3.9**	**4.2**	**10.7**
		Std Dev	14.8	16.6	8.9	12.3	15.6	12.3	11.8	8.8	9.6	13.0	15.9	16.8
		CV %	152	596	320	150	654	579	171	136	214	332	380	158
		Median	**12**	**3**	**3**	**7**	**0**	**-4**	**-7**	**-5**	**-4**	**-7**	**7**	**16**
		Max	38	34	21	27	34	21	14	8	17	30	37	36
		Min	-27	-25	-16	-8	-32	-23	-31	-24	-20	-20	-26	-22
	High	**Mean**	**15.7**	**4.3**	**4.5**	**12.9**	**3.7**	**-3.5**	**-11**	**-10**	**-7.1**	**-6.0**	**6.7**	**17.0**
		Std Dev	23.7	26.7	14.4	19.6	24.9	19.7	19.0	14.2	15.1	21.0	25.4	26.9
		CV %	151	614	321	152	665	559	170	137	212	347	379	158
		Median	19	4	5	10	-1	-6	-12	-9	-7	-11	11	26
		Max	61	55	34	42	54	34	23	13	27	49	59	58
		Min	-43	-40	-26	-13	-51	-37	-49	-39	-31	-32	-42	-35

Year	SRES	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2095	Low	**Mean**	**5.9**	**1.7**	**1.7**	**4.9**	**1.5**	**-1.3**	**-4.3**	**-4.0**	**-2.8**	**-2.4**	**2.5**	**6.6**
		Std Dev	9.1	10.1	5.6	7.6	9.6	7.6	7.3	5.5	5.8	8.1	9.7	10.3
		CV %	155	597	320	154	646	564	170	138	206	339	393	156
		Median	**7**	**2**	**2**	**4**	**0**	**-2**	**-5**	**-3**	**-3**	**-4**	**4**	**10**
		Max	23	21	13	16	20	13	9	5	10	19	23	22
		Min	-17	-15	-10	-5	-20	-14	-19	-15	-12	-12	-16	-13
	B1	**Mean**	**9.7**	**2.8**	**2.8**	**8.2**	**2.4**	**-2.1**	**-6.9**	**-6.5**	**-4.5**	**-3.9**	**4.2**	**10.7**
		Std Dev	14.8	16.6	8.9	12.3	15.6	12.3	11.8	8.8	9.6	13.0	15.9	16.8
		CV %	152	596	320	150	654	579	171	136	214	332	380	158
		Median	**12**	**3**	**3**	**7**	**0**	**-4**	**-7**	**-5**	**-4**	**-7**	**7**	**16**
		Max	38	34	21	27	34	21	14	8	17	30	37	36
		Min	-27	-25	-16	-8	-32	-23	-31	-24	-20	-20	-26	-22
	A1FI	**Mean**	**21.8**	**6.0**	**6.3**	**18.0**	**5.2**	**-4.9**	**-15**	**-14**	**-10.**	**-8.3**	**9.3**	**23.7**
		Std Dev	32.9	36.9	19.9	27.3	34.6	27.4	26.1	19.6	21.0	29.0	35.3	37.4
		CV %	151	611	316	152	663	563	169	136	211	348	382	158
		Median	**26**	**6**	**7**	**14**	**-1**	**-8**	**-16**	**-12**	**-10**	**-15**	**16**	**36**
		Max	85	77	47	59	75	47	32	18	37	68	82	81
		Min	-60	-55	-36	-18	-71	-52	-68	-54	-44	-44	-59	-49
	High	**Mean**	**35.0**	**9.6**	**10.0**	**28.9**	**8.3**	**-7.7**	**-25**	**-23**	**-16**	**-13**	**14.9**	**37.9**
		Std Dev	52.7	59.2	31.9	43.6	55.3	43.8	41.9	31.7	33.5	46.4	56.5	59.8
		CV %	151	616	318	151	666	573	169	138	210	349	380	158
		Median	**42**	**9**	**11**	**23**	**-2**	**-13**	**-26**	**-19**	**-15**	**-24**	**25**	**57**
		Max	137	122	75	94	119	75	51	29	59	108	131	130
		Min	-96	-88	-58	-29	-113	-83	-108	-86	-70	-70	-94	-78

The mean monthly predictions in Table 81 are plotted in Figure 152 which shows that the rainfall in the wet season (November to April) is expected to increase, while that in the dry season (May to October), will decrease relative to the mean for 1975 to 2004 and that the changes are expected to intensify as time progresses. Surprisingly, the mean results suggest a disproportionate increase in April rainfall and no change in rainfall between May and June and October and November.

The marked difference in the predicted behaviour of the wet and dry seasons is of particular interest given that we have shown in this report that the wet and dry season rainfalls in Tongatapu appear to be driven by different factors. Estimates of the change in mean wet and dry season and annual rainfall due to GHG emissions can be made using the mean monthly rainfalls for the period 1975 to 2004. Here, this mean rainfall will be identified by the middle year of this period, the year 1990. These estimates are shown in Figure 153 which illustrates the marked difference between the predictions for changes in the seasonal rainfall over the 21st century. For the higher GHG emission scenarios, the effects are clearly non-linear. By the year 2095, it is expected that the mean wet season rainfall will increase by between 4 and 22%, while the expected decrease in mean dry season rainfall is between 2 and 13%, giving a range of increases in mean annual rainfall of between 1 and 8%compared with the means for the period 1975-2004.

Given the current variability of annual rainfall, such relatively modest increases will be difficult to discern. The wet season rainfall, however, is expected to change more significantly and it might be possible to discern changes there. The predicted increasing trends in annual rainfall lie between 0.2 and 1.3 mm/year and for wet season rainfall between 0.4 and 2.1 mm/year. The predicted decrease in dry season rainfall lies between 0.1 and 0.8 mm/year. When the actual rainfall record from 1945 to 2007 is examined (section 13.2), the linear trend in annual rainfall **decreases** by 2.3 mm/year while that for the wet season **decreases** by 3.2 mm/year. The linear trend for dry season rainfall, however, **increases** by 0.7 mm/year. These linear trends are exactly opposite to the mean trends predicted by the climate models, although the maximum coefficient of determination (R^2) of the linear trends to the measured rainfalls is only 0.025 (R_c = 0.158), indicating the observed trends are not significant.

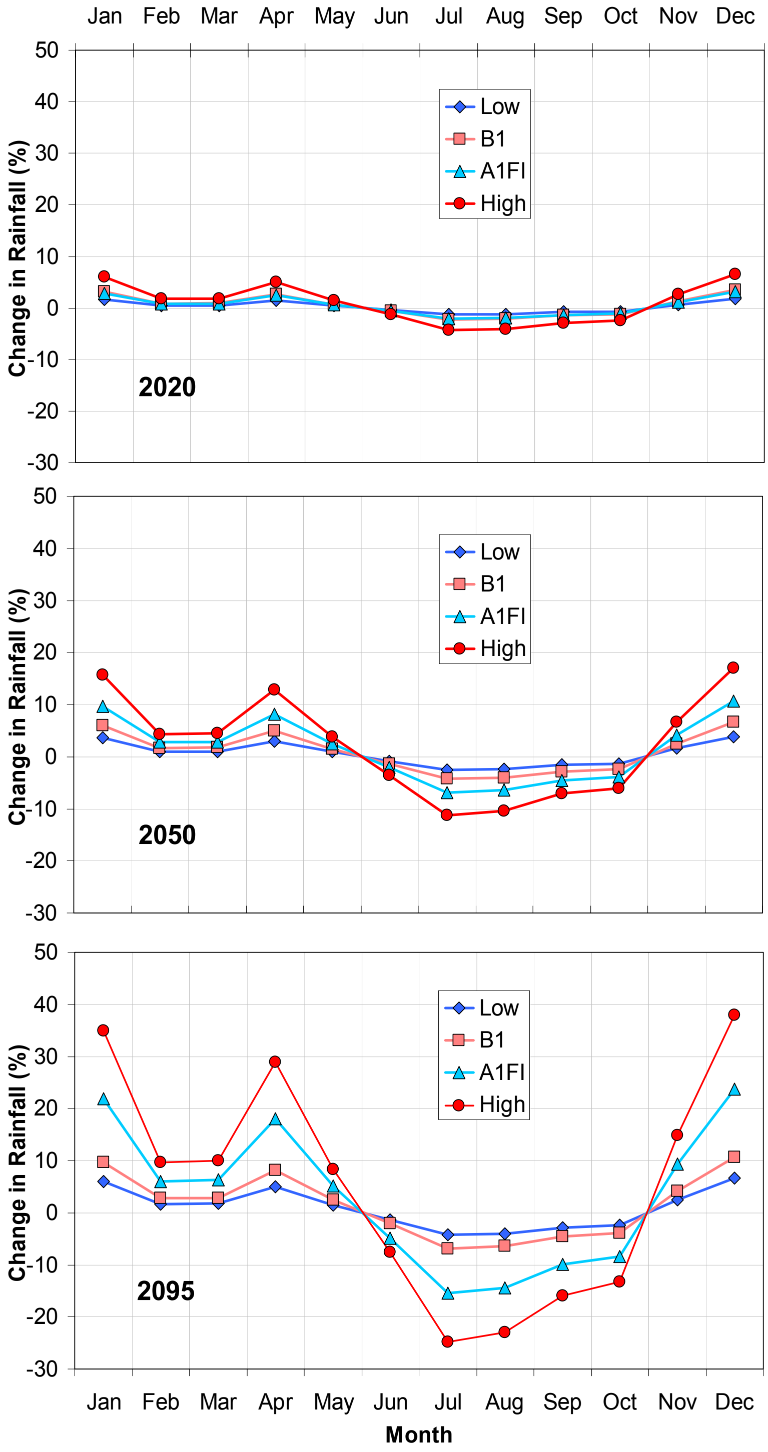

Figure 152 Mean predictions from 23 atmosphere-ocean models of the percentage change in rainfall in Tongatapu for 4 SRES scenarios for the years 2020, 2050 and 2095

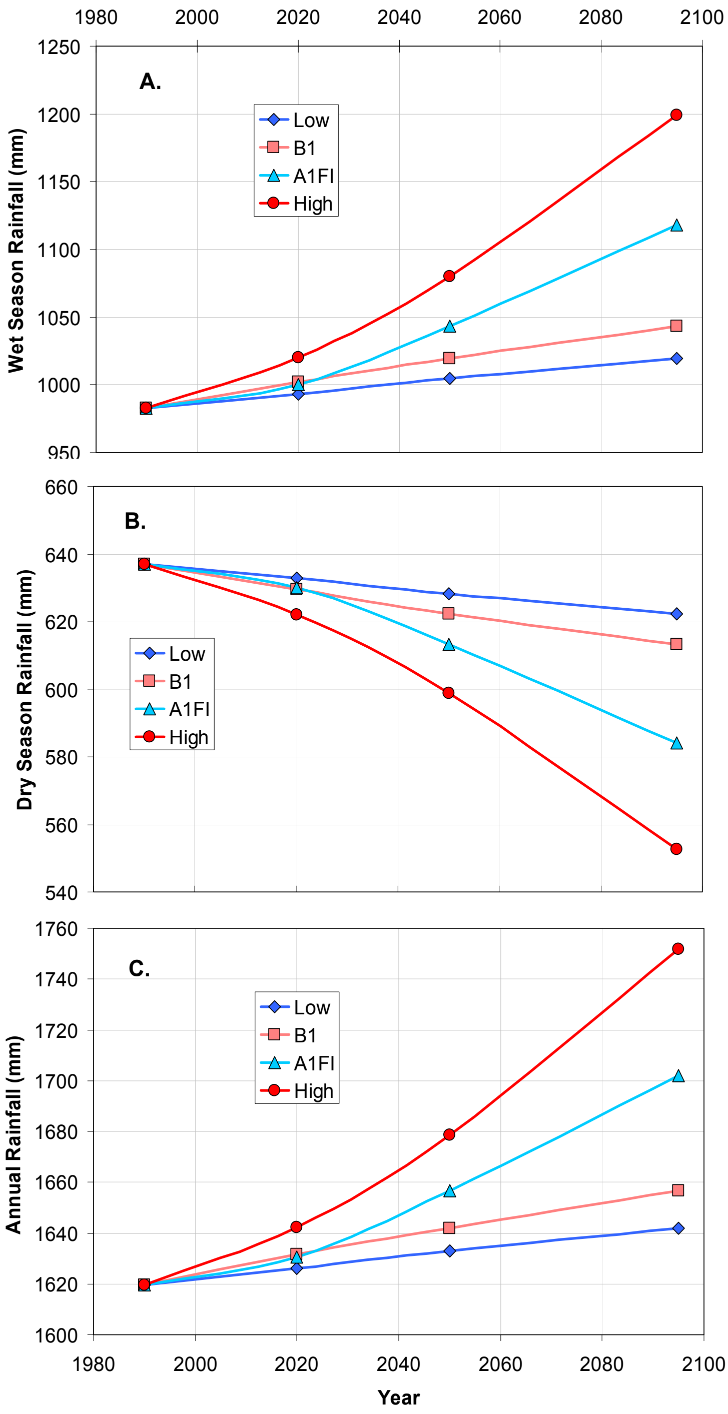

Figure 153 Predicted changes in mean rainfall: A. wet season, B. dry season, and C. annual; over the 21st century due to GHG emissions for 4 SRES scenarios. The reference mean rainfall for 1975-2004 is represented by the year 1990.

13.5 Estimated changes in evaporation over 21st century

Evaporation is an equally important component of the water balance but it is only available in 14 of the 23 atmosphere-ocean global circulation models used for rainfall. CSIRO has provided estimates from these models of the range of changes to potential evaporation in Tongatapu over the next century relative to the 1975-2004 period for all 12 months of the year for the same 4 global warming SRES scenarios listed in section 13.4. Table 82 lists the estimated monthly and annual potential evaporation, E_{pot}, for Tongatapu (Thompson, 1986). Thompson (1986) does not provide the period of record used for these estimates.

Spasmodic measurements were made of pan evaporation, E_{pan}, at the Vaini Experimental Station between 1982 and 1989. As well, estimates of actual evapotranspiration, ET_a, are also made in the water balance estimation of recharge (section 9.2). The mean monthly and annual values of the pan measurements and the estimates of ET_a for Case 1 of the recharge estimates (Table 62) are compared with the E_{pot} in Table 82. On average, the monthly E_{pan} measurements are 1.24 times greater than the potential evaporation estimates while the mean monthly estimated ET_a for Case 1 is 0.86 of the potential evaporation. The monthly ratios between E_{pan} and E_{pot} and between ET_a and E_{pot} vary with the time of year.

The monthly variation of E_{pot}, E_{pan} and ET_a estimated for Case 1 are also plotted in Figure 154 where it may be noted that the estimated ET_a lies only slightly below E_{pot} for the mainly dry season months of April through August while the estimated ET_a peaks towards the end of the wet season (March) and at the end of the dry season (October). The maximum differences between estimated ET_a and E_{pot} occur for the wet season months of November through January.

Table 82 Monthly and annual values of potential evaporation for Tongatapu compared with pan evaporation and estimated actual evapotranspiration for recharge Case 1

Month	Mean Potential Evaporation, E_{pot} (mm)	Mean Pan Evaporation, E_{pan}, 1982-9 (mm)	Mean Estimated Actual ET_a, Case 1 1945-2006 (mm)	E_{pan}/E_{pot}	ET_a/E_{pot}	ET_a/E_{pan}
Jan	164	179	119	1.09	0.73	0.67
Feb	137	162	118	1.18	0.86	0.73
Mar	139	140	124	1.01	0.89	0.89
Apr	108	136	102	1.26	0.95	0.75
May	89	115	85	1.30	0.95	0.73
Jun	77	93	72	1.21	0.94	0.78
Jul	85	117	81	1.38	0.96	0.69
Aug	96	127	89	1.32	0.93	0.70
Sep	116	161	102	1.39	0.88	0.64
Oct	144	181	118	1.26	0.82	0.65
Nov	152	196	107	1.29	0.70	0.55
Dec	154	187	104	1.22	0.67	0.55
Mean	**122**	**150**	**102**	**1.24**	**0.86**	**0.69**
Std Dev	**30**	**33**	**17**	**0.11**	**0.10**	**0.09**
Annual	**1,530**	**1,780**	**1,222**	**1.16**	**0.80**	**0.69**

The complete range of the 14 global circulation model predictions for the 4 SRES scenarios for 2020, 2050 and 2095 are given in Annex L. Table 83 summarises the mean and other statistics of the model predictions for the percentage changes in mean monthly potential evaporation from the period 1975-2004.

The differences between the predicted maximum and minimum values of the changes in potential evaporation as well as the coefficients of variation in Table 83 are markedly smaller that for those for predicted rainfall in Table 81. The CVs in Table 83 are almost an order of magnitude smaller than those for rainfall. This is not unexpected, since the dominant driver for potential evaporation is solar radiation, which should be model-independent. The maximum CV in Table 83 is 66% while the minimum is 21%. The mean CV across all SRES scenarios and years is 39%, independent of SRES and year.

Table 83 Statistics of predicted changes in potential evaporation for 4 SRES scenarios for the 2020, 2050 and 2095

Year	**SRES**	**Statistic**	**Change in Potential Evaporation from Mean Monthly PE 1975 - 2004 (%)**											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2020	**Low**	**Mean**	**0.7**	**0.8**	**1.0**	**1.2**	**1.5**	**1.6**	**1.4**	**1.2**	**1.0**	**1.0**	**0.9**	**0.7**
		Std Dev	0.4	0.4	0.3	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.3
		CV %	65	60	28	36	24	22	22	35	44	39	44	46
		Median	**0.6**	**0.8**	**1.0**	**1.3**	**1.5**	**1.6**	**1.4**	**1.2**	**0.9**	**0.9**	**1.0**	**0.7**
		Max	1.3	1.4	1.5	1.6	2	2.1	2	2	1.8	1.6	1.4	1.3
		Min	0.1	-0.2	0.4	0.4	0.7	0.8	1	0.5	0.3	0.4	0	0
	B1	**Mean**	**1.2**	**1.3**	**1.8**	**2.1**	**2.7**	**2.8**	**2.5**	**2.2**	**1.7**	**1.8**	**1.6**	**1.3**
		Std Dev	0.8	0.8	0.5	0.8	0.7	0.6	0.6	0.8	0.7	0.7	0.7	0.6
		CV %	64	60	27	36	24	22	22	36	43	39	46	45
		Median	**1.1**	**1.4**	**1.8**	**2.4**	**2.6**	**2.75**	**2.4**	**2.2**	**1.6**	**1.6**	**1.75**	**1.25**
		Max	2.4	2.5	2.6	2.9	3.6	3.8	3.6	3.6	3.1	2.9	2.6	2.2
		Min	0.2	-0.4	0.7	0.7	1.3	1.4	1.8	0.8	0.5	0.8	-0.1	0
	A1FI	**Mean**	**1.1**	**1.2**	**1.7**	**1.9**	**2.5**	**2.6**	**2.3**	**2.0**	**1.6**	**1.6**	**1.5**	**1.2**
		Std Dev	0.7	0.8	0.4	0.7	0.6	0.6	0.5	0.7	0.7	0.6	0.7	0.6
		CV %	63	60	27	36	25	23	21	37	44	38	46	46
		Median	**1**	**1**	**2**	**2**	**2**	**3**	**2**	**2**	**1**	**2**	**2**	**1**
		Max	2	2	2	3	3	4	3	3	3	3	2	2
		Min	0	0	1	1	1	1	2	1	0	1	0	0
	High	**Mean**	**2.3**	**2.7**	**3.5**	**4.1**	**5.3**	**5.5**	**5.0**	**4.2**	**3.4**	**3.5**	**3.1**	**2.6**
		Std Dev	1.5	1.6	1.0	1.5	1.3	1.2	1.1	1.5	1.4	1.3	1.4	1.2
		CV %	66	60	28	36	24	22	22	36	43	39	45	46
		Median	**2**	**3**	**4**	**5**	**5**	**5**	**5**	**4**	**3**	**3**	**3**	**2**
		Max	5	5	5	6	7	8	7	7	6	6	5	4
		Min	0	-1	1	1	3	3	4	2	1	2	0	0
2050	**Low**	**Mean**	**1.4**	**1.6**	**2.1**	**2.4**	**3.1**	**3.3**	**2.9**	**2.5**	**2.0**	**2.1**	**1.8**	**1.5**
		Std Dev	0.9	0.9	0.6	0.9	0.8	0.7	0.6	0.9	0.8	0.8	0.8	0.7
		CV %	66	61	27	36	24	22	22	37	43	39	47	46
		Median	**1.3**	**1.7**	**2.2**	**2.7**	**3.0**	**3.3**	**2.8**	**2.5**	**1.8**	**1.9**	**2.0**	**1.4**
		Max	3	3	3	3	4	4	4	4	4	3	3	3
		Min	0	-1	1	1	2	2	2	1	1	1	0	0
	B1	**Mean**	**2.3**	**2.6**	**3.4**	**4.0**	**5.2**	**5.4**	**4.9**	**4.1**	**3.3**	**3.4**	**3.0**	**2.5**
		Std Dev	1.5	1.6	0.9	1.4	1.3	1.2	1.1	1.5	1.4	1.3	1.4	1.2
		CV %	66	60	27	36	25	22	22	36	43	39	45	46
		Median	**2**	**3**	**4**	**5**	**5**	**5**	**5**	**4**	**3**	**3**	**3**	**2**
		Max	5	5	5	6	7	7	7	7	6	6	5	4
		Min	0	-1	1	1	3	3	4	2	1	2	0	0
	A1FI	**Mean**	**3.7**	**4.3**	**5.6**	**6.6**	**8.4**	**8.9**	**8.0**	**6.8**	**5.4**	**5.6**	**4.9**	**4.1**
		Std Dev	2.4	2.5	1.5	2.4	2.1	2.0	1.7	2.4	2.3	2.1	2.2	1.9
		CV %	66	60	27	36	24	22	22	36	43	38	45	45
		Median	**3**	**5**	**6**	**7**	**8**	**9**	**8**	**7**	**5**	**5**	**5**	**4**
		Max	8	8	8	9	11	12	11	11	10	9	8	7
		Min	1	-1	2	2	4	5	6	3	2	3	0	0
	High	**Mean**	**6.0**	**6.8**	**9.0**	**10.5**	**13.5**	**14.2**	**12.7**	**10.8**	**8.7**	**9.0**	**7.9**	**6.6**
		Std Dev	3.9	4.1	2.5	3.8	3.3	3.2	2.8	3.9	3.7	3.4	3.6	3.0
		CV %	65	60	27	36	25	22	22	36	43	38	46	45
		Median	6	7	9	12	13	14	12	11	8	8	9	6
		Max	12	13	13	15	18	19	18	18	16	15	13	11

		Min	1	-2	3	4	7	7	9	4	2	4	0	0
Year	**SRES**	**Statistic**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2095	**Low**	**Mean**	**2.3**	**2.6**	**3.4**	**4.0**	**5.2**	**5.4**	**4.9**	**4.1**	**3.3**	**3.4**	**3.0**	**2.5**
		Std Dev	1.5	1.6	0.9	1.4	1.3	1.2	1.1	1.5	1.4	1.3	1.4	1.2
		CV %	66	60	27	36	25	22	22	36	43	39	45	46
		Median	**2.1**	**2.75**	**3.55**	**4.5**	**5.05**	**5.35**	**4.7**	**4.2**	**3.05**	**3.1**	**3.3**	**2.35**
		Max	4.6	4.8	5	5.6	6.9	7.4	6.9	7	6	5.6	4.9	4.3
		Min	0.3	-0.8	1.3	1.4	2.5	2.7	3.5	1.6	0.9	1.5	-0.1	0
	B1	**Mean**	**3.7**	**4.3**	**5.6**	**6.6**	**8.4**	**8.9**	**8.0**	**6.8**	**5.4**	**5.6**	**4.9**	**4.1**
		Std Dev	2.4	2.5	1.5	2.4	2.1	2.0	1.7	2.4	2.3	2.1	2.2	1.9
		CV %	66	60	27	36	24	22	22	36	43	38	45	45
		Median	**3**	**5**	**6**	**7**	**8**	**9**	**8**	**7**	**5**	**5**	**5**	**4**
		Max	8	8	8	9	11	12	11	11	10	9	8	7
		Min	1	-1	2	2	4	5	6	3	2	3	0	0
	A1FI	**Mean**	**8.3**	**9.5**	**12.5**	**14.6**	**18.8**	**19.7**	**17.6**	**15.0**	**12.0**	**12.4**	**10.9**	**9.1**
		Std Dev	5.4	5.7	3.4	5.3	4.6	4.4	3.8	5.4	5.2	4.8	5.0	4.2
		CV %	65	60	27	36	25	22	22	36	43	39	46	46
		Median	**8**	**10**	**13**	**17**	**18**	**19**	**17**	**15**	**11**	**11**	**12**	**9**
		Max	17	17	18	20	25	27	25	25	22	20	18	16
		Min	1	-3	5	5	9	10	13	6	3	6	0	0
	High	**Mean**	**13.2**	**15.2**	**20.0**	**23.4**	**30.1**	**31.5**	**28.2**	**24.0**	**19.2**	**19.9**	**17.5**	**14.6**
		Std Dev	8.7	9.1	5.4	8.4	7.4	7.0	6.1	8.7	8.3	7.7	8.0	6.7
		CV %	66	60	27	36	24	22	22	36	43	39	46	45
		Median	**12**	**16**	**20**	**26**	**29**	**31**	**27**	**24**	**18**	**18**	**19**	**14**
		Max	27	28	29	33	40	43	40	41	35	33	29	25
		Min	2	-5	8	8	15	16	20	9	5	9	-1	0

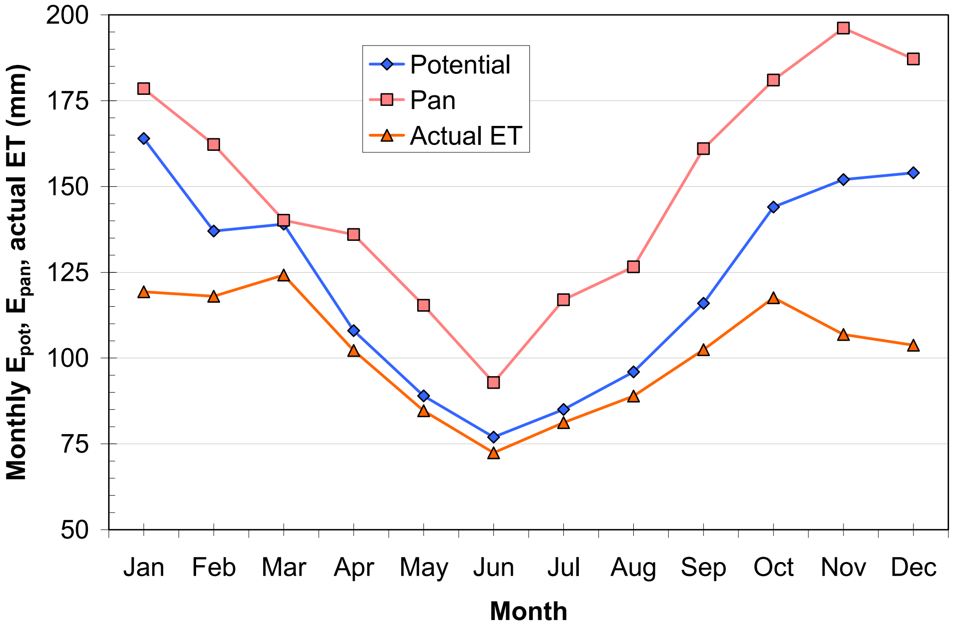

Figure 154 Estimated mean monthly values of potential and pan evaporation compared with estimated actual evapotranspiration for recharge Case 1

The summer months in Table 83 have the highest CV, with January having the highest mean CV (65%), followed by February (60%) and December (46%). The lowest CVs occur in late autumn and early winter with June and July the lowest (22%) followed by May (25%). The constant mean CV between scenarios and years suggests a structural consistency between models.

Unlike the predicted changes in rainfall, all predicted changes in potential evaporation due to increasing GHG emissions are positive, irrespective of SRES scenario and year, probably reflecting the predicted increasing trend in global temperature. For 2020, the range of mean annual change for the various SRES scenarios varies from 0.2 to 0.9%; for 2050 from 2.2 to 10%; and for 2095, from 4 to over 21%, the last being a substantial change in potential evaporation. Currently, neither pan nor potential evaporation is monitored on Tongatapu, so it is difficult to investigate any trends in potential or pan evaporation. The spasmodic annual pan evaporation data from the Vaini experimental station for the period 1982 to 1989 show fluctuations ranging from +9.5 to -12.5% about the mean with no consistent trend.

Figure 155 shows the predicted positive percentage change in potential evaporation for the three years 2020, 2050 and 2095 and for the 4 SRES scenarios.

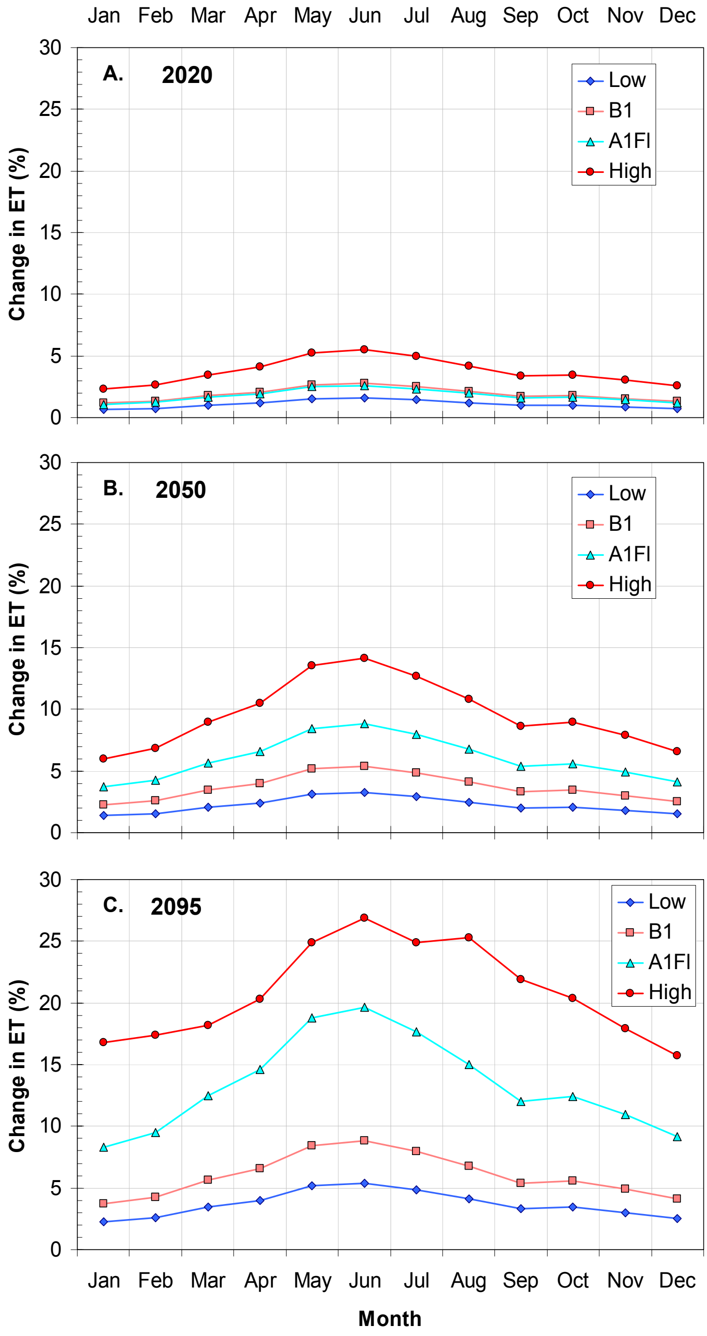

Figure 155 Mean predictions of the percentage change in potential evaporation in Tongatapu for 4 SRES scenarios for the years A. 2020, B. 2050, and C. 2095 from 14 atmosphere-ocean models

It can be seen that the maximum percentage increase in potential evaporation is expected between June and July at the start of the dry season. We will assume here that ET_a (Table 82) is also increased by the same mean percentages as in Table 83 and Figure 155. With this assumption, the predicted changes in mean ET_a due to GHG emissions based on the mean ET_a estimated for Case 1 for 1975-2004 is given in Figure 156. Again we have represented the mean ET_a for 1975-2004 as the year 1990.

It can be seen for the higher GHG emission scenarios, the effects are again non-linear. By the year 2095, it is expected that the mean wet season ET_a will increase by between almost 3 to 17%, while the expected increase in mean dry season ET_a is higher at between 4 to almost 25%, giving a range of increases in mean annual ET_a of between nearly 4% to almost 21% over that for the period 1975-2004.

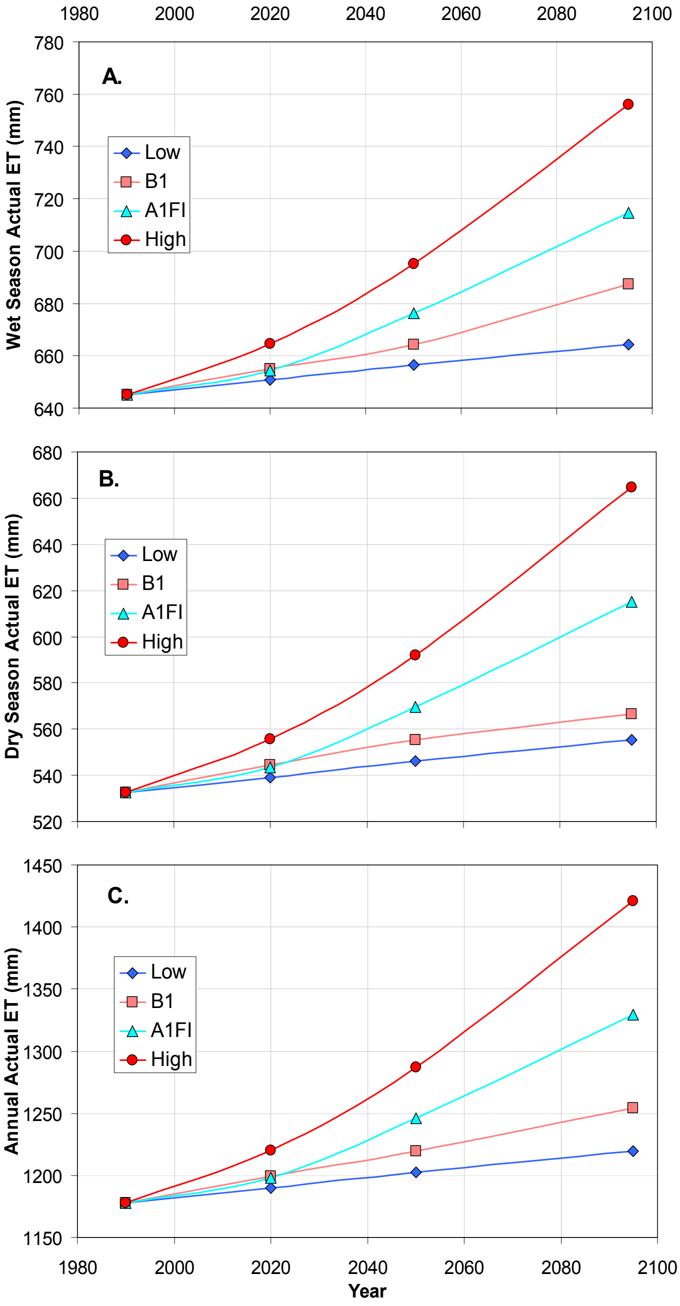

Figure 156 Predicted changes in mean ET_a for recharge Case 1 for: A. wet season; B. dry season; C. annual; over the 21st century due to GHG emissions for 4 SRES scenarios. Reference mean ET_a for 1975-2004 is represented by the year 1990.

The variability of annual ET_a is less than that for rainfall, as expected and the relatively modest increases predicted in annual ET_a may be difficult to discern. The predicted percentage change in dry season ET_a is expected to be more than the percentage change of either annual or wet season ET_a and it might be possible to discern changes in dry season ET_a, which is currently not monitored in Tongatapu. The predicted increasing trends in annual ET_a lie between 0.4 and 2.3 mm/year. The predicted trend for the wet season ET_a is between 0.2 and 1.1 mm/year while, for the dry season, the predicted increase lies between 0.2 and 1.3 mm/year. When the estimated ET_a for recharge Case 1 from 1945 to 2006 is examined, the linear trend in ET_a decreases by 1.3 mm/year while that for the wet season decreases by 1.0 mm/year while the dry season decreases by 0.2 mm/year. These are exactly opposite to the mean trends predicted by the climate models although the maximum coefficient of determination of the linear trends to the estimated ET_a for Case 1 is only 0.025 ($R_c = 0.158$), indicating the observed trends are not significant.

The predicted changes in ET_a for Tongatapu differ from those for rainfall in that both wet and dry season ET_a are expected to increase, whereas only the dry season rainfall was expected to decrease. The climate change predictions therefore suggest that groundwater recharge during the dry season will decrease. We shall now examine the predicted impacts on recharge. It appears from the above analysis that daily measurements of either potential or pan evaporation in Tongatapu would be valuable is assessing the impacts of climate change.

13.6 Estimated changes in groundwater recharge over 21st century

The information in sections 13.4 and 13.5 can be used to estimate the changes in monthly recharge to groundwater expected from the atmosphere-ocean global circulation models. Rather than re-run the water balance model with the range of changes for rainfall and ET_a predicted from the climate models, the simple procedure used here is to assume that for long periods such as a full wet or dry season or for annual recharge we can neglect the soil storage term in equation [29] and simplify the water balance to:

$$R = P - ET_a \qquad [57]$$

Using equation [57] and the information in Figure 153 and Figure 156 we can estimate the predicted change in annual recharge expected for Tongatapu due to climate change as a result of enhanced GHG emissions. Table 84 presents the estimated change in mean annual recharge for Tongatapu for the 4 SRES scenarios up to 2095. These results are also plotted in Figure 157.

Table 84 Estimated changes in total annual groundwater recharge for Tongatapu predicted for 21st century for 4 SRES scenarios

Year	Total Annual Recharge (mm)			
	Low	B1	A1FI	High
1990	444	444	444	444
2020	436	432	433	422
2050	430	423	411	392
2095	423	403	373	331

The estimated annual recharge in Figure 157 is predicted to **decrease** through the 21st century by between 5 and 25% due to climate change, or between about -0.2 to -1.1 mm/year between 1990 and 2095. The predicted increase in rainfall in the wet season results in a slight increase in wet season recharge but this is offset by the predicted decrease in dry season rainfall and the increase in evapotranspiration whose effect is most pronounced at the end of the dry season in October. The estimated increase in wet season recharge is between +0.7 and +1.5 mm/year while the dry season recharge decreases by -0.8 to -2.6 mm/year. Fitting linear trends to the widely fluctuating recharge data calculated for Case 1 for 1945 to 2006 reveals for annual recharge a decline of -1.2 mm/year, for wet season recharge a decline of -2.4 mm/year while dry season recharge has an increasing linear trend of +0.9 mm/year. While the annual recharge trend is consistent with that predicted for the highest SRES scenario the signs of the wet and dry season recharge trends are opposite to those predicted. We also caution that the highest coefficient of determination for these trends was only 0.022 (R_c = 0.148), indicating that the trends are not significant.

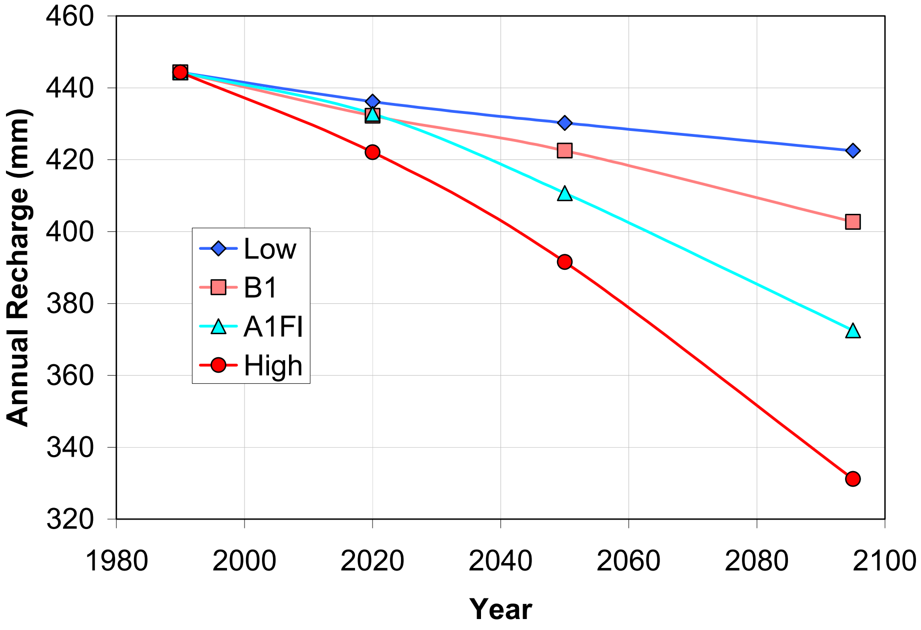

Figure 157 Estimated mean groundwater recharge in Tongatapu for 4 SRES scenarios for the 21st century

13.7 Conclusions and recommendations

The results from a suite of coupled atmosphere-ocean global climate models run by CSIRO were used to predict possible changes to monthly rainfalls and potential evaporation for Tongatapu for 4 SRES scenarios of future GHG emissions through to near the end of the 21st century.

13.7.1 Predicted changes in rainfall

The 23 GCMs give widely divergent predictions for predicted future monthly rainfalls in Tongatapu under a range of GGG emission scenarios. Some models predict increases in rainfall while others predict decreases under the same scenarios. This is worrying since the case of a small relative low island embedded in a large ocean should be the simplest possible case. Here we have used the mean of all 23 model predictions to arrive at a “consensus” value for the expected change in rainfall. As can be seen in Table 81, the mean values are associated with very large coefficients of variation, so limited confidence can be placed in these mean monthly values.

The mean predictions suggest that there will an increase in the seasonal differences in rainfall in Tongatapu. Mean wet season (November through April) rainfall is expected to increase by between 4 and 22% by 2095, while the mean dry season rainfall is expected to decrease by between 2 and 13% from the mean seasonal rainfall for the period 1975-2004. Together these contribute to an expected increase in mean annual rainfall of between 1 to 8% over the mean annual rainfall for 1975-2004. Such relatively modest increases will be difficult to discern within the current variability of annual rainfall. Predicted increases and decreases of seasonal rainfall for the higher GHG emission scenarios were non-linear.

For the period 1990 to 2095, the predicted increases in mean annual rainfall lie between 0.2 and 1.3 mm/year, while for wet season rainfall the predicted increase is between 0.4 and 2.1 mm/year. The predicted range of decreases in dry season rainfall lies between 0.1 and 0.8 mm/year. The actual rainfall from 1945 to 2007 has a linear trend **decreasing** by 2.3 mm/year while that for the wet season **decreases** by 3.2 mm/year. The linear trend for dry season rainfall, however, **increases** by 0.7 mm/year. These linear trends are exactly opposite to the mean trends predicted by the climate models for the period 1990-2095, but the coefficients of determination of these trends in the recorded rainfall indicate the observed trends are not significant. The model estimates discussed here provide no information on expected changes in the variability of rainfall.

13.7.2 Predicted changes in evaporation

Only 14 of the 23 coupled atmosphere-ocean GCMs can predict changes in potential evaporation. The predictions of these 14 models for the 4 SRES scenarios show nearly an order of magnitude lower coefficient of variation in the mean predicted monthly potential evaporation than for predicted monthly rainfall.

The means of the predicted monthly changes in potential evaporation all increased with increasing time beyond the reference period 1975-2004, irrespective of season or SRES scenario. This seems to be a consequence of the predicted increase in global temperature with increased GHG emissions. The increases predicted for the dry season were larger than those for the wet season. This differential increase in dry season potential evaporation over that for the wet season, coupled with the expected decreases in wet season rainfall, could further heighten the seasonal differences in soil moisture and recharge. The rates of increase in potential evaporation for the higher GHG emission scenarios were again non-linear.

Surprisingly, the predicted increases in annual and wet and dry season ET between 1990 and 2095 were not evident in the values of actual evaporation (ET_a) estimated using recharge Case 1 calculations for the period 1945 to 2006. For this time period, the estimated ET_a has a decreasing linear trend for annual as well as wet and dry seasons, and the magnitude of the rate of decrease of dry season ET_a was less than that for the wet season. Although the coefficients of determination for these linear trends are very small, the trends are opposite to the predicted trends as was found for rainfall.

It would seem that evaporation and particularly its seasonal dependence is more sensitive to the expected climate change due to increased GHG emissions. In estimating recharge in this work, we have assumed the monthly cycle of potential evaporation is unchanged with time so that our estimations of recharge are biased by this assumption. It would seem from this, that there is a need for recommencing monitoring of evaporation in Tongatapu.

13.7.3 Estimated changes in recharge

As a first approximation, the expected change in groundwater recharge resulting from continued GHG emissions has been estimated by assuming that the predicted increases in potential evaporation also apply to ET_a. We have then used the observed mean rainfalls for the period 1975-2004 and the mean ET_a for the same period calculated for recharge Case 1 together with the simplified long-term water balance to estimate changes in annual groundwater recharge. These first-order estimates suggest recharge will decrease between 5 and 25% by 2095. The predicted increase in annual rainfall is offset by the predicted increase in evaporation, especially in the dry season which is coupled to the predicted decline in dry season rainfall. Again, for the higher SRES scenarios, the estimated rate of change of recharge is non-linear.

When linear trends are fitted to the widely fluctuating annual Case 1 recharge estimates for 1945 to 2006, the rate of decrease of annual recharge is close to that predicted for the high SRES scenario. The trends for the wet and dry season recharges, however, are opposite in sign to those predicted from the climate models with estimated wet season recharge decreasing and dry season recharge increasing. Again, it is noted that the coefficients of determination are very small indicating that the trends in the 1945-2006 recharge data are not significant.

Because recharge appears to be sensitive to climate change, it is important to monitor parameters indicative of recharge. The profile of groundwater salinity is clearly a sensitive parameter but one which is also influenced by the rate of withdrawal of groundwater. For this reason both profiles of salinity and pumping rates should be measured throughout Tongatapu. If the groundwater recharge rate is declining with increasing GHG emissions, then pumping should be licensed and monitored and conservative estimates need to be adopted on the safe rate of groundwater withdrawal.

13.7.4 Cautionary note

A note of caution needs to be added here about the above predictions. Rainfall is a key driver of the recharge process. The general lack of agreement between the 23 climate models, resulting in very large coefficients of variation in the mean monthly predictions of expected rainfall under a range of GHG emission scenarios, means that these projections of future changes in rainfall and recharge must be treated with extreme caution.

"GCMs (used to here predict the impacts of green-house gas emission scenarios on future climates) are not good at simulating changes to the hydrological cycle and are notoriously bad on rainfall, especially in the tropics. There are two basic reasons for this: (i) they generally do not simulate tropical convection very well, and (ii) they can not reproduce some the major modes of current climate variability, including El Niño- Southern Oscillation (ENSO). Although the major American model at the US National Center for Atmospheric Research (NCAR) now apparently starts to simulate something that looks like ENSO." (Steffen[28], private communication, 23 February 2009). Since it has been clearly demonstrated here (Section 12) that ENSO is a key driver of wet season rainfall in Tongatapu, the rainfall predictions here must be viewed as highly uncertain.

13.7.5 Unresolved issues

The predictions on the impact of increased emissions of GHGs in this section have raised a number of issues that need to be resolved.

- The wide discrepancies between model predictions on the impact of a range of SRES scenarios on rainfall in a small, relatively low island surrounded by a large ocean are of concern. This should be the simplest possible case. A critical examination is required of the models and their performance before more reliable estimates can be made.
- A major prediction of the models was the change in seasonal behaviour in rainfall with wet season (November through April) rainfall increasing while dry season (May through October) rainfall is expected to decrease in the long-term. This appears to emphasise the radically different behaviour of wet and dry season rainfall in Tongatapu noted in section 12.7.1.
- The linear trends in measured annual, wet and dry season rainfalls for the period 1945 to 2006 are at odds with the climate model predictions for the period 1990 to 2095. The coefficients of determinations of these linear tends are very small indicating that these trends are not significantly different from no trend in rainfall. The identification of a trend in data that is subject to considerable variability and coupled to major sea surface temperature fluctuations is difficult and further work is required on this. It is clear, however, that the continued monitoring of rainfall in Tongatapu is critical.
- The fact that only 14 of the 23 atmosphere-ocean climate models used for rainfall prediction were suitable for predicting changes in potential evaporation is of concern. Evaporation is a key component of both the hydrologic cycle and the earth's energy balance and it would seem that models not able to explicitly treat evaporation may be considered unsuitable for climate predictions.
- For potential evaporation, the models predicted that both wet and dry season evaporation would increase with time and with higher rates of green house gas emissions. The dry season potential evaporation, however, was expected to increase at a higher rate that the wet season.
- The linear trends in estimated actual evaporation from Case 1 recharge estimation for 1945-2006 were also at odds with those predicted by the 14 models for annual, wet and dry season evapotranspiration. Again, the coefficients of determination of the linear trends were too small to suggest that these trends are significant. It is also noted that the ET_a estimated in the recharge calculations assumed that the distribution of monthly potential

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[28] Professor Will Steffen is Executive Director of the Australian National University's Climate Change Institute.

evaporation over the year does not change from year to year. Any change in estimated ET_a is driven by the change in measured monthly rainfall.

- The first order estimation of the expected change in annual, as well as wet and dry season recharge over the 21st century relied on a simplified water balance and the prediction of changes in rainfall and evaporation. These suggested that annual recharge would decrease by up to 25% by 2095. This decrease resulted from an increase in wet season rainfall being more than offset by increase in wet season ET_a and the predicted decline in dry season rainfall and the disproportionate increase in dry season ET_a. Further detailed estimates of recharge under the SRES scenarios are needed.
- The decreasing trend in estimated annual recharge for Case 1 for 1945 to 2006 was consistent with that predicted for the climate change models for the high emission scenario but that for the individual wet and dry season was not. This warrants further study.
- Regular measurements of evaporation used to be carried out in Tongatapu. The sensitivity of evaporation to climate change suggests that it would be worthwhile recommencing measurements of solar radiation and pan evaporation. .

13.7.6 Recommendations

In view of the conclusions of this section and the unresolved issues identified above it is recommended that:

- A critical examination of the 23 global atmosphere-ocean global climate models be undertaken with the aim of resolving the wide discrepancies in predictions of changes in rainfall in ocean-dominated regions.
- A thorough treatment of trends in measured rainfall and evaporation, or evapotranspiration, be carried out for Tonga and other small island situations to compare current trends with those expected from global climate models under various GHG emission scenarios.
- Monitoring of both potential evaporation and pan evaporation be recommenced in Tongatapu which will require installation and monitoring of a net solar radiometer and an evaporation pan at the Fua'amotu meteorological station.
- Further investigation of the measured trends in wet and dry season, as well as annual, evaporation be undertaken for accurate comparison of trends with those predicted from the models.
- More detailed investigations be carried out on the impact of the predicted changes in rainfall and evaporation on changes in groundwater recharge.
- In view of the prediction of up to 25% decrease in groundwater recharge by 2095, licensing of all groundwater pumps should be instituted as soon as practical and the sustainable groundwater yield under changing recharge be re-estimated.

14 Quarrying and Groundwater

14.1 Overview

Tongatapu is dotted with both active and abandoned limestone quarries, used principally for aggregate extraction. The predominant quarrying practice is to remove and stockpile or sell the soil overburden then excavate limestone down to the water table, whose depth depends on the quarry's location within Tongatapu's tilted landform. This practice poses potential risks to groundwater because of the increased ease of groundwater contamination and increased evaporation losses through direct atmospheric exposure of the water table in ponds at the base of quarries.

Quarries of special concern are those in the vicinity of water supply wells and especially those close to water source area for Nuku'alofa, the Mataki'eua/Tongamai wellfield (see Figure 5 and Figure 158). There, four quarries are within 1.6 km from the nearest well, with the closest two between 0.75 to 1.1 km away and the groundwater is exposed in one of them (see Figure 159).

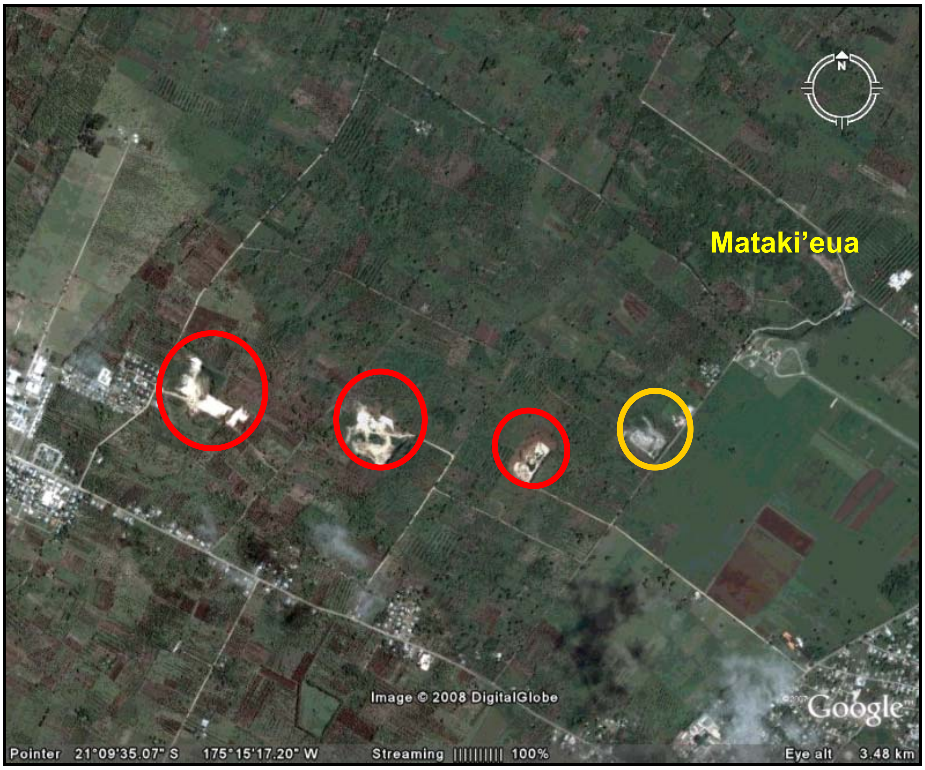


Figure 158 Quarries close to the Mataki'eua/Tongamai wellfield. Active quarries at Kahoua, Hauloto and Tafolo (left to right) are circled in red, an inactive or partially active quarry in yellow. The closest quarry is 0.75 km from the nearest TWB well (Google Earth).

In our brief visits, time did not permit a detailed on-ground exploration of all quarries in Tongatapu. Instead we focussed on three representative quarries for inspection and measurements. These were the abandoned Tapuhia government quarry, now converted to a waste management and disposal facility (see section 7), the Royco Industries Kahoua Quarry near Tongamai and the Malapo Quarry on the way to the Fua'amotu Airport. A brief description of our observations at these quarries will be given followed by a discussion of the institutional issues surrounding quarrying and our recommendations for improved management to protect groundwater resources from impacts.

Figure 159 Aerial view of the Tafolo quarry close to water wells in Mataki'eua. The quarry on the right is within 0.75 km of the nearest well, while that at Tafolo on the left is within 1.1 km. Note the exposed water table in the lower left of the Talofa quarry.

14.2 Tapuhia Waste Management Facility

The Tapuhia Waste Management Facility (21°11'03" S, 175°11'13" W), which has been described in detail in section 7 (see also Figure 11 and Figure 25), is approximately 0.8 km from the nearest water supply well for the village of Vaini (Figure 160) which lies to the southwest of the TWMF. The groundwater is clearly exposed at the base of the Facility (Figure 11 and Figure 161). Spot measurements of hydraulic head suggested that the general groundwater flow at the time of measurement was towards the west, but it was recommended (see section 7.10.2) that the influence of the ponded water at the base of the old quarry should be examined.

Figure 160 TWMF in an abandoned quarry (circled) and the village of Vaini in lower right (Google Earth)

Figure 161 Groundwater exposed at the base of the TWMF being used to wash front-end loader

Although the TWMF is a “state-of-the-art” facility, there were two issues which measurements suggested could be problems. The first was the concentrations of lead in the monitoring boreholes which exceeded the WHO guidelines. The presence of lead pre-dates commencement of use of the site as a waste management facility with one borehole showing an increase in lead concentrations after disposal commenced and one showing a decrease. Both wells had 25 times the WHO guideline concentration for lead. The other was the dramatic increase in dissolved nitrate in the monitoring borehole (GMW2) closest to the sullage disposal beds and waste truck wash-down area (Figure 162) that occurred after operations commenced. While the sullage drying beds are well constructed and drainage is designed to be contained, the concentrations in the monitoring well were in excess of the WHO guidelines and are a potential threat to groundwater. It was recommended that the fate of this nitrate should be closely monitored.

Figure 162 Groundwater monitoring borehole GMW2 beside the sullage drying beds and waste truck wash-down area at the TWMF

The multi-agency monitoring team set up by the Waste Authority provides a good model for groundwater monitoring in Tongatapu in general.

14.3 Royco Industries Kahoua Quarry

The Royco industries Kahoua Quarry (21°09'38" S, 175°15'56" W), on the left of Figure 158, is about 1.6 km southwest from the nearest well at the Mataki'eua/Tongamai wellfield and about 0.7 km southeast of the water supply wells at Liahona School (Figure 163). A general view of the quarry is shown in Figure 164. It has been excavated down to the groundwater (Figure 165). The pond in the bottom of the quarry had been recently refreshed with rainwater and had an EC of 206 μS/cm on 28th July 2007. The salinity monitoring borehole SMB6 is located in the bottom of this quarry (Figure 166) and its shallowest tube had an EC of 620 μS/cm at a depth below ground surface of about 4 m on the same day.

The base of the quarry is littered with industrial refuse, not all derived from quarrying (Figure 167 and Figure 168). In addition, part of the base of the quarry was being used for raising pigs with numerous penned and roaming pigs (Figure 169). Disposal of industrial waste and the raising of pigs at the bottom of quarries, without proper structuring of the site, have significant potential to contaminate the exposed groundwater in the quarries.

14.4 Malapo Quarry

The Malapo Quarry (21°12'37" S, 175°09'07" W) is located approximately equidistant, at 1.2 km, from two villages and also from Tupou College (Figure 170). Because of the general tilt of Tongatapu, the water table is relatively deep at this location. Nonetheless, the quarry has been excavated in parts down to the groundwater (Figure 171). Figure 172 shows the significant depth of the quarry. It was not possible to enter this quarry to measure the salinity of the groundwater.

The lack of general groundwater monitoring bores across Tongatapu means that it is not feasible to determine groundwater flow direction from the quarries or their impacts of groundwater quality. The three quarries examined here show that current quarrying practices constitute a significant risk to groundwater resources and practices need to be both improved and regulated.

Figure 163 Distance between the Kahoua Quarry and the nearest water supply well at Liahona School. The distance of the line between the red points is 0.7 km.

Figure 164 General view of the Kahoua Quarry from the road entrance

Figure 165 Groundwater exposed at the base of the Kahoua Quarry

Figure 166 Salinity monitoring borehole SMB6 in the middle of industrial refuse in the Kahoua Quarry

Figure 167 Industrial mining refuse at the base of the Kahoua Quarry

Figure 168 Industrial refuse at the base of the Kahoua Quarry

Figure 169 Pig pens at the base of the Kahoua Quarry

Figure 170 Malapo Quarry situated about 1.2 km northeast of water supply wells at Tupou College (lower left) [Google Earth]

Figure 171 General view of the eastern arm of Malapo Quarry. Groundwater can be seen in the centre of the photo.

Figure 172 General view of the western arm of Malapo Quarry

14.5 Regulation of quarrying

There is currently no legislation or regulations to control the specific impacts of quarrying on the groundwater resource. As was pointed out in section 3.4, the absence of a National Water Resources Act means that groundwater is legally unprotected in Tonga. The draft Water Resources Bill 2006, yet to be passed by parliament, specifically addresses the issue of contamination of groundwater resources. Under Part III *Powers of the Ministry over the Water Resource* it specifies:

> “**8.** (1) In order to meet the objectives stated in section 7, the Minister shall have the power to:
>
> ... … … … …
>
> (f) declare any area to be a water source protection zone on the recommendation of the Committee, and determine that the designated area shall be managed in accordance with a management plan approved by the Committee to apply to the water source protection zone;
>
> (g) otherwise regulate and control the use of water, and any activity that may affect the quality of water or the quantity of water supply;
>
> (h) give notice to persons to cease activities or practices having a detrimental affect on the quality of water or the quantity of the water resource, including the power to require the removal of any structure or thing having such an impact;
>
> (i) arrange for the removal of any structure or thing not having been removed in accordance with a notice given under paragraph (h), and to recover the cost from the person in default; and
>
> (j) require that certain matters relating to the water resource be considered in the assessment of environmental impacts of proposed developments required under the *Environment Impact Assessment Act 2003.”*

The draft Bill specifies significant fines and/or imprisonment for contravening these regulations.

Under Part IV *Regulating the Taking of Water* the draft Bill details:

> “**12.** (1) Environmental standards relating to –
>
> (a) the taking of water; and
>
> (b) any activity that may affect water quality or the integrity of any water source, including waste management operations and any commercial enterprise;
>
> may be prescribed by the Minister and the Department of Environment (within the Ministry) shall be responsible for the monitoring and enforcement of the approved standards.”

There is a clear intent within the draft Bill to protect water resources that are sourced for public use from contamination.

Currently, there are a few pieces of legislation which are relevant to the ownership and use of living and non-living natural resources in Tonga, including limestone aggregate. These are covered in several statutes and Laws of Tonga such as the

- *1903 Land Act*
- *1969 Petroleum Mining Act*,
- *1970 Continental Shelf*

These provide for land acquisition processes and for pollution prevention during exploration or mining. All natural land and sea resources are the property of the Crown in Tonga and government agencies are responsible for managing those resources. A mineral resource whether from land or the sea, falls under the responsibility of the Minister of Lands and the (*Land Act, 1903 s. 2*).

The 1988 edition of the *Land Act* contains the following section pertinent to quarrying.

SECTION 22 - Land (Quarry) Regulations

Made by His Majesty in Council

G. S. 3/85

1. These Regulations may be cited as the Land (Quarry) Regulations.
2. No person shall allow his tax allotment to be used as a quarry.
3. The quarrying on and removal from a tax allotment of stone of any description is hereby prohibited.
4. Any person who offends against these regulations shall be liable to a penalty not exceeding $100.

This undated regulation appears to have been made in 1985. It makes no mention of the impact of quarrying on water resources.

The *2003 Environmental Impact Assessment* (EIA) *Act* covers development activities that require licensing. However, land on which quarrying takes place is generally owned by land owner or estate owners. In current practice, it appears that initiation of quarrying involves private negotiations between the land owner or owners and the quarry operator. Once agreement has been reached, there seems to be no impediments to quarrying proceeding irrespective of potential groundwater or other impacts, and regardless of proximity to water wells and boreholes. In essence quarrying is currently unregulated despite the Land (Quarry) Regulations.

There is a clear need to regulate quarrying in order to protect public and private groundwater sources, to improve practices in the quarrying industry and to monitor and report on the impacts of quarrying. The draft Water Resources Bill provides that protection.

14.6 Protecting groundwater sources from quarrying

One simple way of improving regulation of quarrying would be to ensure that all quarrying and land mining activities in Tonga fall under the 2003 Environmental Impact Assessment Act so that all quarrying and mining activities are required to submit an Environmental Impact Statement (EIS), which details planned operations, including protection of groundwater, for approval prior to commencement of quarrying or mining. By specifically including protection of groundwater in the requirements for an EIS, this would raise awareness of the issue in the quarrying and mining sector.

In some countries, however, EIS's have been less effective due to capacity limitations in the regulating authority, failure to comply with the conditions of the EIS by the developer and failure to monitor the development and operations by the regulator. Those issues would need to be specifically addressed in Tonga.

Another problem with the EIS process is that it only applies to new developments so that existing quarries would need to be covered by another instrument. The draft Water Resources Bill 2006 offers the possibility of providing that instrument through Part III 7(1) (f) to (j) and Part IV 12(1) (a) and (b) quoted above. It is important that the relevance of the draft Bill to protecting groundwater from adverse impacts of quarrying be reviewed as some specific regulations may be required including best practice guidelines. It is also important that the Bill be submitted to parliament as soon as possible.

14.7 Improving quarrying and monitoring practices

From our relatively brief examination of current quarrying practices in Tongatapu, a number of improved practices can be suggested. These include:

- Determine the appropriate maximum depth for quarrying in each quarry location so as not to intersect the groundwater surface (MLSNRE). Our suggestion here is that quarrying should cease at a level 2 m above the local groundwater surface.
- Ongoing monitoring of quarry activities (MLSNRE).
- No washing of equipment or aggregate within the quarry.

- No disposal of wastes on the site unless special protective measures have been put in place to contain leachate.
- No raising of livestock on site.
- Construct appropriate, non-polluting sanitation facilities on-site for quarry workers.
- Install groundwater monitoring boreholes within the quarry and external to the quarry with regular monitoring and reporting of water level and water quality results by MLSNRE to appropriate authorities.

It is strongly recommended that quarrying activity be limited to the zone 2 m above the water table to lower the risk of contamination and lessen direct evaporation losses of groundwater.

14.8 Improving existing quarries

As our brief examination revealed, many existing quarries have partly exposed the groundwater surface at the base of the quarries. This increases the risk of groundwater contamination and increases local direct evaporation losses from the exposed water table. To lessen these risks we recommend:

- All existing quarries in which the water table is exposed be backfilled to a depth of 2 m above the water table with clean soil.
- Install monitoring boreholes in existing and abandoned quarries.

14.9 Potential to use abandoned quarries as freshwater sources

Abandoned quarries do offer a potential advantage for water supplies. One of the problems in Tongatapu is that the depth of overburden above the groundwater means that vertical boreholes or wells have been used to extract groundwater. While these have generally been limited to a 2 m depth below the water table, there is a gradient of salinity even within the top 2 m of the groundwater lens. This was clearly illustrated by our measurements in the Kahoua Quarry where the exposed groundwater at the surface had an EC of 206 µS/cm, while groundwater in the nearby monitoring borehole at depth of about 4 m had an EC of 620 µS/cm on the same day. During pumping from vertical wells, upconing tends to mix underlying seawater with the overlying freshwater, making the pumped groundwater more saline than the surface groundwater.

In low small islands, a technique used to skim off the fresher groundwater from close to the surface of the water table, is to use long, horizontal infiltration galleries (UNESCO, 1991) such as that shown in Figure 173.

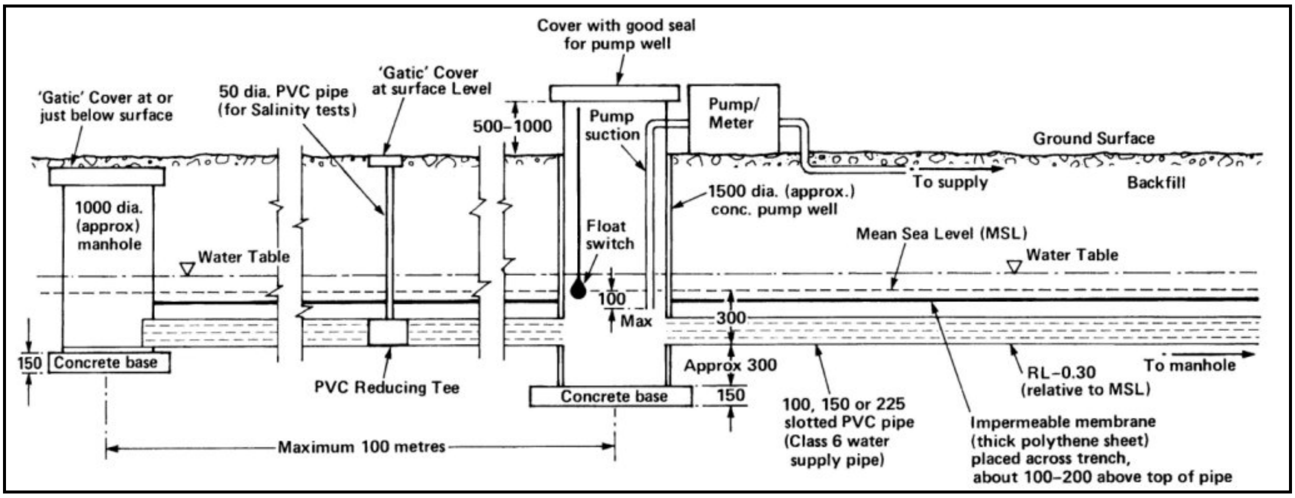


Figure 173 Schematic diagram of an infiltration gallery designed to skim off fresh groundwater from close to the surface of the water table

Because of the length of the horizontal extraction zone of up to 300 m, infiltration galleries have minimal drawdown and upconing (White *et al*, 2007) and minimize the salinity of the extracted water. The general depth of overburden in Tongatapu means that it is usually not possible to install infiltration galleries. Abandoned quarries, however, offer the potential to install galleries at their base which should be capable of delivering lower salinity water than from the vertical boreholes and wells.

14.10 Conclusions and recommendations

The examination of quarries in this work was necessarily brief and did not involve an exhaustive examination of all quarries in Tongatapu. Apart from the detailed measurements at the abandoned Tapuhia quarry now in use as the TWMF (see section 7) no detailed measurements were made on either the hydraulic gradients around or the water quality resulting from quarries, mainly due to the absence of a groundwater monitoring borehole network. Because of this, we are unable to give recommendations on the safe distance between a quarry and a water supply well or borehole or a water supply wellfields. Nonetheless our observations and discussions with relevant agencies permit some general conclusions:

- Quarrying is largely unregulated.
- Current quarrying practice is to excavate material down to below the groundwater level. This exposes groundwater to direct evaporation losses and greatly increases the risk of groundwater contamination.
- Apart from the TWMF, there is no monitoring borehole network that can be used to determine the impacts of quarrying on groundwater hydraulic gradients or on the groundwater quality.
- Practices within quarries where the water table is exposed, such as disposal of industrial wastes and keeping of livestock, greatly increase the risk of groundwater contamination.
- Pre-existing lead and post-completion nitrate concentrations within monitoring boreholes around the TWMF warrant close attention and continued monitoring and reporting.

14.10.1 Unresolved issues

There are five main unresolved issues that this study has raised:

- Does the *2003 Environmental Impact Assessment (EIA) Act* require modification in order to require all new quarrying activities to submit an EIS specifically detailing procedures for protecting groundwater for approval prior to commencement of quarrying?
- Does the regulating authority have the capacity to both assess EISs and to monitor compliance by the quarrying operator?
- Does the draft 2006 Water Resources Bill require modification to specifically regulate impacts of existing quarries on groundwater sources?
- What are the impacts of quarrying on groundwater hydraulic gradients and on water quality?
- What is the safe distance between a quarry and a water supply well or borehole or water supply wellfields?

14.10.2 Recommendations

The above conclusions and unresolved issues lead to the following recommendations:

- All quarrying and land mining in Tongatapu be regulated and monitored to ensure groundwater resources are not compromised by quarrying.
- The *2003 Environmental Impact Assessment (EIA) Act* be reviewed and modified if necessary to ensure that all new quarrying activities require consent through assessment of an EIS specifically detailing procedures for protecting groundwater.

- The draft 2006 Water Resources Bill be reviewed to ensure that it applies to and can control the impacts of quarrying on groundwater resources.
- The draft 2006 Water Resources Bill be submitted to parliament as soon as practical.
- The relevant regulating authorities review their capacity to assess EIS and regulate and monitor the impacts of quarrying.
- A groundwater monitoring borehole network be established in Tongatapu which can be used to asses the impacts of quarrying on groundwater hydraulic gradients and water quality.
- Research be undertaken to determine the safe minimum distance of quarries from water supply wells, boreholes and wellfields.
- The potential for constructing infiltration galleries as better quality water supply sources in abandoned quarries be considered.
- All quarries be limited in depth so as to leave 2 m of overburden above the water table.

15 GIS for Water Resources

15.1 Existing MLSNRE GIS

The ToR for this project required that the consultant:

(a) Identify all existing data sets in Agencies and Departments that are suitable for inclusion in development of a GIS for water resource management and assessment;

(b) Where appropriate, transfer knowledge to local counterparts in applications of GIS for water resource management.

There appears to be an assumption in these ToR that local understanding of the use of and applications GIS was limited in Tonga. We found that not to be the case. Land and land ownership and leasing is fundamentally important in Tonga. The MLSNRE has excellent GIS coverage detailing property boundaries throughout Tonga. In addition, the MLSNRE GIS has the position of many of the water wells throughout Tonga, as well as results for the 1990 and our 2007 survey of groundwater salinity distribution in Tongatapu. The maps in this report showing the salinity distribution in May 1990, Figure 6, and in August 2007, Figure 33 , were both produced by the GIS section of MLSNRE. Also the maps in Figure 2, Figure 5, Figure 20 and Figure 25 were produced from the MLSNRE GIS. Staffs at the GIS section of MLSNRE and the TWB were extremely proficient at manipulating the GIS and were fully aware of the potential uses of GISs in natural resource management. There are 2 systems in use: ArcGIS & MapInfo (GIS Section and Tonga Water Board. The GIS section has the necessary skills to provide training to other agencies in the use of GIS.

15.2 Data Sets for Inclusion into a Water Resources GIS

In examining what data sets are necessary for inclusion into a water resources GIS data base it is important to determine what the uses for such a system. There is little point in constructing an extensive GIS merely for the sake of having one. It must serve a practical need. There are 12 water resource management questions which a water resources GIS could potentially answer.

1. What is the location and depth of all wells and monitoring boreholes in Tongatapu?
2. How is the salinity distribution across Tongatapu changing with time?
3. How is the distribution of water quality due to faecal indicators, nutrient, and other hazardous chemical across Tongatapu changing with time?
4. How is the thickness of the fresh groundwater lens across Tongatapu changing with time?
5. How is the elevation of the groundwater table (above MSL) across Tongatapu changing with time?
6. How is the rate of groundwater extraction changing with time across Tongatapu?
7. What is the location and depth of all wells and monitoring boreholes at the TWB Mataki’eua/Tongamai well field?
8. How is the salinity distribution at the TWB Mataki’eua/Tongamai well field changing with time?
9. How is the distribution of water quality due to faecal indicators, nutrient, and other hazardous chemical at the TWB Mataki’eua/Tongamai well field changing with time?
10. How is the thickness of the fresh groundwater lens at the TWB Mataki’eua/Tongamai well field changing with time?
11. How is the elevation of the groundwater table (above MSL) at the TWB Mataki’eua/Tongamai well field changing with time?
12. How is the rate of groundwater extraction changing with time across the TWB Mataki’eua/Tongamai well field?

Questions 7 to 12 are clearly a subset of the first 6 questions.

The location of a majority of village wells across Tongatapu and all wells at Mataki’eua/Tongamai are recorded on the MLSNRE GIS. Some public wells were found not to be recorded in the system.

Every effort should be made to record the location and depth of all wells, both public and private, on the GIS.

The existing MLSNRE well monitoring database for Tongatapu contains a record of field measurements of depth to water table, EC, temperature and pH of village wells dating back to 1959. The GIS results of the EC measurements have been plotted for May 1990 in Figure 6, and for August 2007 in Figure 33. The ability to examine the changing distribution of salinity in Tongatapu is a very useful management tool. Efforts should be made to download all measurements from the database onto the GIS so that temporal and spatial changes in groundwater EC can be displayed. The WA's GMB water quality data base around the TWMF also could be added to this.

Bacterial water quality testing, undertaken by the MoH, is available only as hardcopy. Efforts should be made to transfer this to an electronic data base in order to examine the persistence of faecal contamination of wells in Tongatapu. Some early measurements of nutrient concentrations are available in the TWB data base, while other measurements are in reports or papers. It is important to incorporate all measurements of nutrients in groundwater, including those in the monitoring boreholes at the TWMF into a Tongatapu data base. Displaying the results in a GIS will assist in identifying "hot spots". It is also important to include in the water quality GIS information on the location of major users of nutrients and agricultural chemicals.

Information on the change in time and space of the thickness of the freshwater lens in Tongatapu is critical to good management. Unfortunately, SMBs are only located in and around the Mataki'eua wellfield. The GMBs around the TWMF can be used also to provide an approximate salinity profile at Tapuhia. During this study we were unfortunately not able to access the TWB data base of SMB results. It is our strong recommendation that 13 additional SMBs are drilled throughout Tongatapu and the results of monitoring in all SMBs, including those at Mataki'eua/Tongamai, be incorporated into a GIS data base.

The water table elevation above MSL provides valuable information on both the impacts of climate variability and pumping on the freshwater lens. In a sense, however, this information is also available in the EC distribution data as well as thickness of the freshwater lens. Unfortunately, many new boreholes drilled for village water supplies do not allow easy measurement of water table elevation without having to dismantle the pumping system. This means that only limited measurements of water table elevation can be made across Tongatapu and at Mataki'eua/Tongamai. While this information would be useful, it is recognised that currently it is not feasible to obtain it for all wells monitored in Tongatapu.

Knowing how the rate of extraction of groundwater by pumping systems varies across Tongatapu is very important for the management of the groundwater system. Currently, the total water extracted in Mataki'eua/Tongamai can only be estimated as the main water production meter has failed. In addition, the majority of village water supply systems in Tongatapu are not fitted with pumps.

The TWB data base for the Mataki'eua/ Tongamai well field is one of the most extensive in the Pacific. It is important that data from the TWB data base also be added to the MLSNRE and MoH data bases in a GIS to construct a comprehensive water resources GIS which can track both the temporal and spatial variability of Tongatapu's groundwater resources to enable better management.

It is recommended that the following data bases be entered into the combined Water Resources GIS for Tongatapu.

1. The location, elevation above MSL and depth of all water wells in Tongatapu (a majority to this information is available on the MLSNRE and TWB well monitoring data bases but will need to be upgraded to include all wells in Tongatapu).
2. EC data from the long term MSL well monitoring data base, the WA's GMB data base and the extensive TWB Mataki'eua/Tongamai data base should be added together to get a comprehensive set of data on the spatial and temporal variability of the salinity of pumped groundwater in Tongatapu.

3. Available data on water table elevation above MSL from the MLSNRE and TWB well monitoring data bases should be added to the GIS.
4. Freshwater lens salinity profile data from the SMBs around Mataki'eua should be released to the MLSNRE by TWB for entry into the water resources GIS.
5. All data on faecal indicators, nutrients and other hazardous chemicals from the MoH, TWB and WA's GMB data bases as well as reports and papers be collated and added to the GIS. This will involve digitising the MoH records and data from reports and publications.

15.3 Barriers to the Development of the Water Resources GIS

There is a real lack of operational resources for the GIS section of MLSNRE and that constrains their activities. Another barrier to developing and maintaining the Water Resources GIS is the due to the physical separation between the GIS section in the main MLSNRE site and the Geology section in its separate remote site. Electronic connections at the Geology section site are by dial up modem. This is far too slow to enable updating and manipulation of a GIS. Because of this any entry of data by Geology section staff has to be carried out by the staff driving to the main MLSNRE/ This is inefficient and time consuming. The establishment of a high speed link between the main MLSNRE site and the Geology site would greatly speed up the development and maintenance of the Water Resources GIS.

Some of the data required to address the water management questions posed in section 15.2 are still in hard copy form, either in record books, reports or papers. In order to be entered into a GIS, these need to be transferred to electronic data bases.

The limited cooperation between MLSNRE, TWB and MoH means that there is a significant barrier to the sharing of data. The model adopted by the WA authority of a joint Ministry monitoring team (see Figure 12) is a very effective method of promoting cooperation and data sharing. Part V of the draft 2006 Water Resources Bill for Tonga describes the establishment of a Tonga Water Resources Committee made up of senior representatives drawn from MLSNRE, MoH, TWB and the WA. Establishment of this committee who provide a further stimulus for cooperation and the development of a Water Resources GIS

15.4 Conclusions

It was found that the MLSNRE has a sophisticated GIS capability and that staff are fully aware of the potential uses for a Water Resources GIS and are capable of training other agencies in the use of GIS. Some of existing MLSNRE well monitoring data base has already been entered into the GIS. Two factors delaying further development of a groundwater resources GIS are the limited resources available for this task and the lack of a high-speed electronic data link to the Geology section building.

The existing data bases in various Ministries that could be usefully incorporated into a national water resources GIS had been identified in section 15.2 above. There is a considerable amount of important information suitable for the water resources GIS, that is either in hard copy or is not available for sharing. This is a significant barrier to the creation of a comprehensive and practically useful data base. The setting up of a high speed data transfer link between the Geology section site and the main MLSNRE site would greatly increase the efficiency of the further development of a water resources data base.

15.5 Recommendations

It is recommended that:

- The multi-agency Tonga Water Resources Committee be established as soon as possible
- That a multi-agency water resources monitoring team be established as soon as possible
- That a high speed data link be set up between the Geology section site and the main MLSNRE site
- That all water resources data from MLSNRE, MoH, TWB and WA be entered into the water resources data base.

16 Training, Project Workshop and Cabinet Briefing Note

As part of the ToR for this project, other activities were undertaken which included carrying out training in groundwater assessment, conducting a workshop for a range of stakeholders in Tonga at the end of the field work and the preparation of a draft Cabinet briefing paper at the end of the workshop.

16.1 Training in procedures

During the course of this project, training sessions were held on all aspects of the project from instrument calibration to archiving of handwritten data (Figure 174 to Figure 179).

Figure 174 Training Session on EC and pH meter calibration (MLSNRE)

Figure 175 Training session on testing for the presence of faecal indicators in water

Figure 176 Training session on data storage and analysis (TWB)

Figure 177 Training session on salinity monitoring boreholes

Figure 178 Training session on installation of a well-logger at Mataki'eua wellfield

Figure 179 Training session on electronic archiving of handwritten data (TMS)

16.2 Workshop 11-12 December 2007

The terms of reference (TOR) for the SOPAC/ EU EDF8 Project on *Tongatapu Groundwater Evaluation and Monitoring Assessment, Kingdom of Tonga* specify that one of the main final deliverables of the project was to be a workshop. The ToR specifies the task as:

> *Organise and conduct a workshop (not exceeding 2-days total duration) in Nuku'alofa to present to all key stakeholders the primary elements identified during the groundwater evaluation & monitoring assessment. The workshop should include a single fieldtrip to demonstrate pertinent site operational observations and emphasise conclusions and recommendations. The workshop should also seek to maximise the community awareness raising and media opportunities.*

The workshop was held on the 11-12 December 2007 in the Conference Room, Environment Section of the Ministry of Lands, Survey, Natural Resources and Environment (MLSNRE) in Vuna Road Nuku'alofa, Tongatapu. The two salinity maps (Figure 6 and Figure 33), produced by the GIS section of MLSNRE were printed out in large format and were used as a focus for the workshop (Figure 180). There was great interest in them.

Figure 180 TWB General Manager Saimone Helu and Chief Engineer Quddus Fielea beside salinity distribution maps at the workshop

16.2.1 Attendance at the Workshop

Twenty five people attended the workshop drawn from government agencies, non-government organisations, international consulting, a regional organisation and the external members of the project team (Figure 181). Attendees were drawn from the following organisations:

- MLSNRE: Geology, Environment and GIS sections
- The Tonga Water Board
- The Ministry of Health, Environmental Health Division
- Ministry of Works, National Disaster Unit
- Ministry of Food, Fisheries and Forestry, Forestry Division
- Waste Authority
- Tonga Trust
- Tonga Association of Non-Government Organisations, TANGO
- Solid Waste Management Project
- Coffey International Development
- SOPAC.

The only invitee that could not send a representative was the Tonga Meteorological Service due to understaffing on the days of the workshop. Key representatives from the Geology and Environment sections of MLSNRE were unable to attend the workshop on the second day due to the pressures of preparing the IWRM Demonstration Concept Project for the SOPAC GEF project. In the authors' view this demonstrates a problem occurring in many small island states. They have limited staff in the water sector who already have significant local work commitments and who are being swamped with the plethora of bilateral and regional projects currently existing in the Pacific.

Figure 181 Some of the workshop participants

16.2.2 Workshop Aims

Given the TOR, the aims of the workshop were to:

1. Present the main findings of the project
2. Discuss the conclusions and recommendations and provide feedback
3. Identify and prioritise needs
4. Discuss future strategies
5. Prepare a Cabinet Briefing Note
6. Demonstrate some field techniques
7. Build relationships.

16.2.3 Workshop Program

The original workshop agenda was modified as the workshop progressed because of the amount of discussion and interest in the results and recommendations. The general structure of the workshop was built around the project TOR and is given in Table 85:

16.2.4 Project goal, objectives and ToRs

The overall project goal, objectives derived from the TOR and the TOR were presented and discussed:

Project Goal

To assist assessment of impacts on the aquatic environment, the planning and sustainable management of the finite groundwater resources of Tongatapu.

Project Objectives

1. Evaluate information on groundwater resources
2. Assess groundwater monitoring practices and needs and groundwater vulnerability
3. Provide a snapshot of groundwater quality
4. Provide training in data collection, groundwater evaluation, monitoring and analytical techniques.

Project ToR

1. Examine baseline water resource monitoring data
2. Assess institutional capacity for groundwater monitoring

3. Assess vulnerability of groundwater resources
4. Review quarrying and potential impacts on groundwater
5. Identify GIS data sets for water resource management
6. Produce specified outputs
    - Report
    - Manuals on monitoring, quality assurance for data and protection of water resources from quarrying activities
    - Workshop
    - Cabinet Briefing Paper.

Table 85 Workshop program

Day 1 Tuesday 11th, 0930 – 1530

Department of Environment Conference Room, Vuna Road

Time	Session	Person
0930 - 0940	Opening of Workshop	'Asipeli (Dep Sec MLSNRE)
0940 - 0950	Introduction	Ian
0950 - 1010	Session 1. Baseline Water Resource Monitoring Data	Tevita & Tony
1010 - 1030	**Morning Tea**	
1030 - 1100	Session 2. "Snapshot" of Groundwater Quality (during project period)	Ian
1100 - 1140	Session 3. Groundwater Vulnerability & Mitigation of Risks	Tevita, Ian & Tony
1140 - 1200	Discussion of morning sessions	Saimone (TWB)
1200 - 1300	**Lunch**	
1300 - 1330	Session 4. Institutional Capacity	Tevita & Ian
1330 - 1340	Session 5. GIS	Tony & Taniela (GIS Section, MLSNRE) & Quddus (TWB)
1340 - 1400	Session 6. Pacific HYCOS inputs to Tonga	Peter Sinclair, SOPAC
1400 - 1420	Session 7. Discussion & Future Directions	Kelepi (Geology Unit MLSNRE)
1420- 1450	**Afternoon Tea**	
1450 - 1520	Sessions 8. Conclusions & Recommendations	Tevita, Ian & Tony
1520-1530	Closing	'Asipeli

Day 2 Wednesday 12th, 0930 – 1530

Time	Session	Person
0930 - 1040	Review of Project Findings & Revision of Cabinet Briefing Note	Ian & Workshop Participants
1040 - 1100	**Morning Tea**	
1100-1230	Guidelines for Water Monitoring & Database	Tony & Workshop Participants
1230 - 1300	Guidelines for Protection of Groundwater from Quarrying Activities	Tevita & Workshop Participants
1300 - 1320	Discussion	
1320 - 1400	**Lunch**	
1400 – 1530	Field Trip to salinity monitoring borehole	

In the general discussion on the above items, it was pointed out by Tongan participants that the project was incomplete in that it did not look at water use by individual households, firms and other users. Profligate use is an important consideration in the vulnerability of groundwater. An opinion was also expressed that the project was incomplete in that it only looked at Tongatapu, and not all the inhabited islands of Tonga.

16.2.5 Baseline water resources monitoring data

Analysis was presented of the monitoring data going back to 1959. It was concluded that:

- There is a reasonable amount of baseline monitoring data
- Frequency of monitoring of village wells needs to be regular (3 months)
- Frequency of monitoring at salinity monitoring boreholes needs to be regular (3 months)
- Monitoring at the Tapuhia Waste Management Facility should be ongoing – frequency to be discussed (annual?)
- Very little data from private wells. Need to be added to monitoring program
- Checking (processing) of data needs to be improved for village water supply wells
- Results need to be regularly reported.

16.2.6 "Snapshot" of groundwater quality

It was concluded that:

- Groundwater salinity in northwest and northeast of Tongatapu (see Figure 6 and Figure 33) and at the lagoon side of Mataki'eua is problematic– should be monitored intensively in droughts (frequency 1 month). These maps also identify sites of the highest priority for water resource development
- Need more salinity monitoring boreholes across Tongatapu to expand monitoring of impacts of groundwater pumping
- No evidence of agricultural (pesticides), petroleum or heavy metal pollution of groundwater
- Nitrates are below World Health Organisation Guidelines for Drinking Water but should continue to be monitored because of septic tanks and fertiliser use
- Faecal contamination of groundwater a significant risk – all village water supplies should be treated.

16.2.7 Groundwater vulnerability

The study found that groundwater in Tongatapu was vulnerable because:

- Groundwater has no legal protection – absence of enacted water legislation & national water policy
- Lead agency, MLSNRE, has no statutory basis for its role in water resource management
- Water agencies act as "silos" (even within Ministries) – limited cooperation or information sharing.
- Insufficient information on the volume of groundwater extracted
- No licensing needed for groundwater drilling or well construction
- Inevitable droughts & impacts of groundwater salinity
- No government-controlled drilling rig
- Leaking septic tanks
- Continued use of agricultural chemicals
- Quarries excavated into the groundwater (symptomatic of no legal protection)
- Restricted number of water samples that MoH Laboratory can process
- Limited analysis or reporting of monitoring data
- Village Water Committees are important but struggling and either need support, training and strengthening or else being replaced by a single water authority for urban and rural areas in Tongatapu.

There was considerable discussion of these issues as some are highly controversial.

16.2.8 Institutional capacity

It was concluded that:

- Relevant institutions have well trained staff
- Important data sets exist – but more analysis needed
- There is a lack of operational resources to carry out responsibilities
- Work is mainly project based and not strategic
- There is limited formal requirement for reporting results of monitoring
- Capacity would be strengthened by increased cooperation between agencies
- There are limited incentives for cooperation
- Funding opportunities exist – an environmental water abstraction fee to fund monitoring

In the discussion, it was pointed out that there was not a philosophy of continued recruitment and training of staff. The last staff member recruited in the Geology Section of MLSNRE was 11 years ago!

16.2.9 Draft Cabinet Briefing Note

As part of the discussion on institutional capacity, a draft version of the Cabinet Briefing Note to encapsulate the findings and recommendations of the study was produced and discussed. Key elements were:

- Tongatapu is blessed with fertile soils, reliable rain rains and good groundwater.
- The SOPAC/EU EDF8 project aimed to assess the vulnerability of water resources in Tongatapu
- Groundwater in Tongatapu is vulnerable to natural and human influences and needs to be well managed and protected
- The study found that the Hihifo, Kolonga and Mu'a regions have salinity problems which depend on long wet and dry periods.
- An intensive sampling of water supply wells across Tongatapu showed no detectable presence of pesticides, petroleum products or heavy metals. Nutrients were less than WHO drinking water guideline values. Indicators of Faecal contamination were found in 23% of the wells sampled
- Currently there is no national water resource legislation to protect groundwater and to provide a statutory basis for management
- The study concluded that the passage of the draft 2006 National Water Resources Legislation would greatly decrease the vulnerability of groundwater.
- The establishment of a small water resources abstraction fee would help fund monitoring and management of the nation's water resources.

These were criticised by some participants as being not hard-hitting enough and that the urgency of the situation needed to be emphasised.

16.2.10 GIS

This session had presentations from the GIS Section MLSNRE and the TWB. It was concluded that:

- Two systems – ArcGIS & MapInfo are used in relevant agencies (GIS Section and Tonga Water Board)
- Both GIS Section and Tonga Water Board have experienced users of GIS
- GIS Section has skills to analyse data and produce maps (e.g. conductivity maps for Tongatapu)
- GIS Section has skills to train other sections within MLSNRE (e.g. Geology Section) and other agencies (e.g. Tonga Water Board)

There appeared to be an implication in the TOR for this project that there were limited skills in GIS in Tongatapu. This is far from the case. The problem is the lack of operational resources.

16.2.11 Pacific HYCOS

The presentation by SOPAC explained that the Pacific Hydrological Cycle Observing System (HYCOS) will provide equipment and training for monitoring of water resources to enable improved decision making for development and protection of freshwater resources. For Tonga the following needs had been identified:

- Information and resource sharing between water resource users and managers. Encourage the exchange of information through shared activities.
- Targeted data collection and information products, focus on information needs of stakeholders, water quality – salinity and microbiology, usage data, changes in storage, rainfall.
- Elevation data for well heads in main well field.
- Capacity building to assist with development of information products existing data sets and additional information in both TWB and MLSNRE.

There was animated discussion on the urgent need in Tongatapu for a government-controlled drilling rig.

16.2.12 Review of results and refinement of Cabinet briefing note

The Cabinet Briefing Note was used as the vehicle to review the results of the project and to refine its conclusions and recommendations. There was detailed discussion of every point made in the Briefing Note and many excellent recommendations and suggestions were given.

16.2.13 Guide to groundwater monitoring or groundwater assessment

The items covered in this presentation were:

- Background information
- Data collection
- Data processing
- Data analysis
- Reporting.

The important parameters that need to be measured were identified as:

Water quantity:

- Rainfall
- Evapotranspiration
- Groundwater salinity
- Groundwater level
- Quantity of water extracted.

Water quality:

- Groundwater salinity
- Biological quality
- Chemical quality.

Two types of measurement frequency were identified:

- Regular (either monthly or every 3 months)
- Periodic (annual or lesser frequency)

Several questions were raised:

- pH and temperature have been deleted. Are they required?
- Tonga Water Board wells: frequency of regular monitoring of some or all could be reduced to once every 3 months (subject to further analysis of data)
- Transfer Public Health Unit, MoH, microbial data from record book(s) to a database

- How often should potential pollutants at Tapuhia Waste Management Facility be measured?

These generated considerable discussion. There was a feeling that because pH and temperature had always been measured they should be continued to be measured. These parameters had never been used in any way. Groundwater is Tongatapu is highly buffered and any variations in pH in the past have been due to instrument malfunction or lack of calibration.

There is no information on the thickness of the freshwater lens throughout Tongatapu as salinity monitoring boreholes are only in and around the Mataki'eua/Tongamai well field. It was recommended that 10 new SMBs be drilled across Tongatapu and an extra 3 in Mataki'eua/Tongamai (Figure 15).

16.2.14 Guidelines for the protection of groundwater resources

It was pointed out that there is no direct existing Legislation or Act to control quarrying activities even close to groundwater production wells. The suggested best practice guidelines for quarrying included:

- Formulation of a new act and/or amendment of related existing acts/legislations to clearly address and identify the control and management of quarrying activities
- Determine appropriate depth for quarrying (MLSNRE)
- Avoid dumping of rubbish on the site
- Avoid raising livestock on site, (especially existing quarries which the water table has been exposed)
- Use appropriate sanitation facilities onsite
- Backfill exposed water table (2 meters) with soil to avoid direct evaporation.
- Consider reusing of old quarry site for village water supply by using infiltration gallery methodology (i.e. given water table is very near and can be easily excavated)
- Ongoing monitoring of quarry activities (MLSNRE)
- Groundwater monitoring boreholes must be drilled and ongoing monitoring of water quality (EC, WL etc.) be undertaken by line ministries/agencies.
- Regular Reporting to appropriate authority or authorities on monitoring results
- Conduct EIS prior to opening of new quarry site

16.2.15 Field trip to SMB7

The field trip for persons interested was to SMB7, which lies to the northwest of the Mataki'eua/Tongamai well field close to the Sia'atoutai Theological School. The salinity profile there was measured (Figure 182) using the Solinst TLC dipmeter bought under the Pacific HYCOS project.

16.2.16 Media coverage of workshop

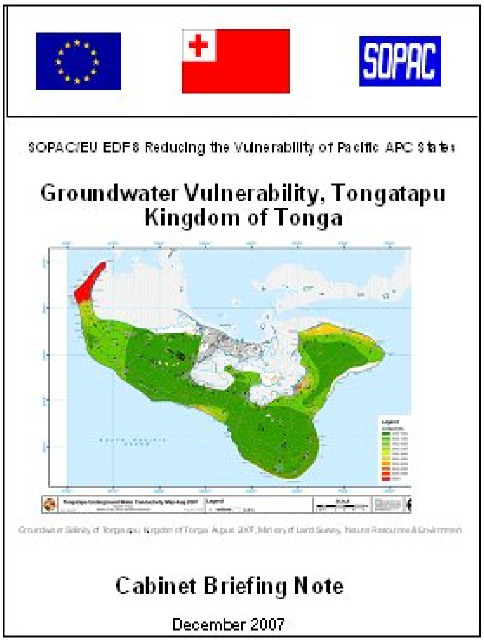
The Geology Section MLSNRE arranged for television coverage of the workshop by Tonga Television. Part of a session of the Workshop and an interview on the main findings and recommendations of the project were video recorded by Tonga Television on 11 December 2007. These were broadcast on the night of 11 December and more fully on 15 December.

This coverage complements previous TV coverage of the project during our previous visit when part of the intensive water quality sampling of village wells and an interview was recorded on 7 August 2007.

Figure 182 Measuring SMB7 salinity profile using the Solinst meter bought under HYCOS

16.3 Cabinet Briefing Note: Findings and Recommendations

The Cabinet Briefing Note had been refined and improved during the workshop. The final revision encompassed the findings of the project and the very helpful feedback, comments and suggestions during the workshop. The front piece used for the Cabinet Briefing Note is shown in Figure 183 and text of the briefing note follows below.



SOPAC/EU EDF8 Reducing the Vulnerability of Pacific APC States

Groundwater Vulnerability, Tongatapu
Kingdom of Tonga

Groundwater Salinity of Tongatapu, Kingdom of Tonga, August 2007, Ministry of Land Survey, Natural Resources & Environment

Cabinet Briefing Note

December 2007

Figure 183 The front piece of the Cabinet Briefing Note

Results

This briefing note presents the **results and recommendations** of a SOPAC/EU EDF8 project on the **monitoring and assessment of the vulnerability of Tongatapu's groundwater resources** conducted by a team from the Ministry of Lands, Survey, Natural Resources and Environment, the

Tonga Water Board and the Australian National University. This briefing note was developed during a project workshop in Nuku'alofa which drew on the broad experience of a wide range of Tongan government agencies and non-government organisations on 11-12 December 2007.

Tongatapu is blessed with reliable rainfall and fertile soils but has **groundwater of variable quality** for drinking. There are **increasing demands** on, **growing threats** to, and **public concerns** about its groundwater, which **require wise management and use** to ensure adequate supplies of safe freshwater for current and future generations, in accord with UN Millennium Goals and the Pacific Regional Action Plan on Sustainable Water Management.

The team found that **natural, human and institutional factors** all add to the **vulnerability** of groundwater in Tongatapu. **Strategies to decrease this vulnerability** and protect Tongatapu's vital groundwater resource are **needed urgently**.

1. Mapping of the salinity of groundwater in village wells (see front piece) showed **seawater intrusion** causing increased **groundwater salinity** in the Hihifo, northern Lapaha (around Kolonga) Districts and the Mu'a villages salinises local groundwater. The **water supply problems** in the Hihifo region need to be addressed urgently. The freshest groundwater comes from the area around Fua'amotu. The government land there should be considered as a **future water supply source**, particularly in droughts. The current distribution of groundwater salinity in Tongatapu is similar to that mapped in the last survey in 1990. Water supply projects for these saline areas and the monitoring of their salinity should be of the highest priority. Where possible, water sourced from wells in areas with lower salinity groundwater should be used for supply.
2. The salinity of groundwater increases during droughts which are mostly related to El Niño events. The **number of droughts in Tongatapu has increased** in the period 1975 to 2007 compared with those from 1945 to 1975. The average duration of droughts which most affect groundwater is 14 months and the average time between droughts is 7 years. Salinity of water from the Mataki'eua and Tongamai wellfield depends on the rainfall over the past 12 to 18 months. Using the relation between rainfall and groundwater salinity, it was predicted that the groundwater salinity of the entire wellfield would **exceed the salinity guideline** limit for drinking water after **four months without rain**. During dry periods, the frequency of groundwater monitoring should be increased to improve management of wells. A new groundwater extraction scheme from government land at Fua'amotu should be initiated to mitigate the impacts of droughts and seawater intrusion.
3. There is increasing concern about the quantity of **agricultural chemicals** used in Tongatapu and about **leakage from septic tanks**. Intensive sampling of 10 selected water supply wells across Tongatapu showed **no detectable presence** of harmful **pesticides, petroleum products or most heavy metals**. Elements that were detected were well below the World Health Organisation (WHO) guideline values for drinking water. Nutrients such as nitrate were present in every sample but were less than WHO guideline values. Continued monitoring of nitrate in groundwater and strategies for **reducing nitrate inputs** are required because of the use of nitrogen fertilisers, leakage from septic tanks and the health impact of high concentrations of nitrate in drinking water on young babies. The absence of pesticides, petroleum products or heavy metals found in this study agrees with three groundwater surveys undertaken by the Waste Authority between April 2006 and July 2007 around the Tapuhia Waste Management Facility and a survey conducted ten years earlier in the mid 1990s. Continued use of hazardous agricultural chemicals requires **continued monitoring of groundwater** at selected sites. A data base showing where agricultural chemicals are being used across Tongatapu needs to be established to allow better targeting of sampling sites.
4. Indicators of **bacterial contamination** were found in 90% of the 19 water supply wells sampled and 24% of the wells had indicators of **faecal contamination**. Faecal contamination could be of human or animal origin and indicates that both the drilling of water supply wells away from faecal sources and **treatment of all groundwater** used for drinking in villages should be a priority. Control of leakage from septic tanks in and removing livestock from water source areas would decrease the threats to groundwater supplies.
5. The **sustainability of pumping from groundwater** is uncertain since there is **no accurate measure** of the rate at which water is being pumped from groundwater in Tongatapu. It is

critical to know the pumping rate. If it exceeds the groundwater recharge rate then pumping is unsustainable. All groundwater pumps should be metered and licensed.

6. There is **no legal basis for protecting groundwater** resources from harmful activity or over use. The lead water resource Ministry also has **no statutory basis** for protecting, regulating or reporting on groundwater resources. It is urgent that the draft 2006 National Water Resources Bill be debated and enacted into Law. Development of a Water Resources Policy and a National Water Resource Plan to implement that Policy would also provide clear guidance to government agencies and the community and provide a framework for sustainable water management and use.
7. Drilling of water wells is a technical operation that requires trained and licensed drillers in order to prevent damage to groundwater through contamination or salinisation. All **drillers** and all **pumped water supply wells** should be **licensed**.
8. A **National Water Resources Committee**, with members drawn from key water agencies and non-government organisations, as specified in the draft 2006 Water Resources Bill, should be established as a matter of urgency. Currently there is little obligation for Ministries to report collectively to the Government on the **state of the nation's water resources**. Once established, this Committee will report regularly to Cabinet on the condition and use of water resources and on priority issues in the sector and will **improve coordination and cooperation** between agencies.
9. There is a serious need for **continued recruitment and training of staff** in water resource management agencies. Water agencies are **operationally poorly resourced** to conduct groundwater monitoring, analysis, assessment, reporting and community consultation. There are **few incentives for cooperation** between Ministries with responsibilities in water. The establishment of a **modest environmental water abstraction charge** on all groundwater pumped in Tongatapu to be totally allocated to water resource monitoring and assessment would provide operational resources to carry out this vital function and incentives for cooperation.
10. **Village Water Committees** manage water supplies for villages in Tongatapu but are **under-resourced** and **largely untrained** for this important technical task. Ways of improving the management and delivery of water supplies at the village level are needed. Institutional reform of the water supply sector through the formation of a **single Tongatapu Water Authority** for both urban and rural Tongatapu would address this problem and improve service in most rural areas. Fua'amotu has already taken action in this direction.
11. The external members of the study team express their **deep appreciation** for the help, support and generous hospitality given to them by the government, its agencies and the community in Tongatapu and the support of the EU and SOPAC.

Strategies for addressing the above issues are given in the following recommendations.

Recommendations

1. Enact the Draft 2006 Water Resources Bill to protect and better manage Tonga's water resources.

2. Establish the National Water Resources Committee (detailed in the Bill) to improve coordination of and cooperation between government agencies, to advise Government on priorities, and to report regularly to government and the community on the state and use of the Kingdom's water resources.

3. Develop and announce National Water Resources Policy to provide clear direction to government agencies, the community and international aid, donor and loan organizations.

4. Develop a National Water Resources Plan (detailed in the Bill) to implement Government water resources policy.

5. Introduce a modest environmental water abstraction charge for all water consumers to provide resources for vital water resource monitoring and assessment.

6. Establish a single Tongatapu Water Authority to manage public water supplies and their use and provide treated water to all communities in Tongatapu, to relieve the burden on Village Water Committees.

7. Develop drought contingency plans for urban and rural water supplies to areas including planning for the development of government land at Fua'amotu as a water source area.
8. Use the salinity distribution map to identify priority areas for the augmentation and improvement of water supplies, particularly in Hihifo District.
9. Pass regulations for the mandatory licensing and training of drillers, the licensing of all pumped wells and the metering and reporting of the rate of groundwater pumped in all of Tongatapu (detailed in the Bill).
10. Develop strategies for decreasing leakage from septic tanks, drainage of nitrogen fertilisers into groundwater and the removal of animals from water supply sources areas.
11. Develop a data base which shows where hazardous agricultural chemicals, that have the potential to pollute groundwater, are being used on Tongatapu to improve the effectiveness of monitoring.

Acting on these recommendations will **decrease the vulnerability** of groundwater in Tongatapu, **increase community confidence** in the safety and management of groundwater and **establish Tonga's leadership** in groundwater management amongst island states in the Pacific Region.

16.3.1 Help with the workshop

This workshop would not have taken place without the help of staff from MLSNRE and TWB. We are very grateful to MLSNRE for hosting this workshop and to its Deputy Secretary, 'Asipeli Palaki, for participating in the workshop. We would like to thank Tonga Rugby and its coach, Quddus Fielea (also, at the time, Chief Engineer, Tonga Water Board) for providing the data projector used in this workshop and to express our great appreciation to ‘Apai Moala and Akapai Vailea of the Geology Section for wonderful logistic assistance with the workshop and to Taniela Kula of the GIS Section for producing the marvelous salinity distribution maps.

16.4 Conclusions

The training sessions undertaken throughout this work with a range of agencies were highly successful, due to the good level of background training of the Ministry staff involved and their enthusiasm. Participation in the monitoring at the TWMF with the WA multi-agency monitoring team demonstrated to us the strengths of a collegiate approach to water monitoring and training and is one that could be emulated throughout Tonga.

The project workshop was equally successful with a very good number of participants drawn from a wide range of ministries and organisations. Discussion was lively and constructive. One issue raised in the workshop was the absence of new government appointments in water resources over the past 11 years. The workshop was an excellent vehicle for bringing together different organisations within the water sector to exchange ideas in a collegial way.

The joint production by Workshop participants of the Cabinet Briefing Note on the results of the study was a very useful way of producing a practical output from the Workshop and one which summarised the study. The Note's 11 recommendations are focused and if implemented should decrease the vulnerability of groundwater in Tongatapu.

16.5 Recommendations

It is recommended that:

- The Cabinet Briefing Note be revised and sent to Cabinet.
- Future Workshops be organised with specific, practical outputs to foster cooperation and collaboration in the water sector.

17 Conclusions

This work has been a broad ranging study of the vulnerability of groundwater and groundwater monitoring and assessment in Tongatapu, Kingdom of Tonga. It is clear that Tongatapu is blessed with reliable rainfall through both wet and dry seasons. This reliable and generally adequate rainfall in combination with its fertile soils and warm temperatures means that agricultural produce is usually abundant. These natural advantages are recognised and greatly appreciated by GoT and its people.

Groundwater contained in Tongatapu's karst limestone aquifer is a valuable resource, particularly during dry seasons and periodic droughts. Unfortunately, the groundwater is of variable quality for drinking due to its mixing with underlying seawater and the impacts of overlying human settlements. There are, therefore, a range of natural, anthropogenic as well as institutional factors that contribute to the vulnerability of groundwater in Tongatapu. This study has tried to assess the main factors and their impacts on groundwater in turn using both "snap shot" measurements of groundwater conducted during the study and the considerable data bases of monitoring results dating back to 1959.

The study started with an analysis of the roles and responsibilities of organisations involved in the water sector, and particularly in groundwater monitoring. It also analysed the demographics of Tongatapu. The "snap shot" measurements undertaken in this work to assess impacts on groundwater were then described. To identify trends in groundwater impacts, these "snap shot" measurements were supplemented with data from the extensive MLSNRE and TWB data bases. A quality assessment of the MLSNRE data base was carried out to remove outliers and spurious measurements. The TWB data base was of high quality. The project team were also able to participate in measurements at the TWMF which provided valuable information.

Assessments were made of groundwater recharge under variable climatic conditions and the sustainable groundwater yield was estimated. Locations for future water supply schemes were identified. Analyses of both meteorological and hydrological drought were undertaken and the major influences driving drought were identified. The potential impacts of climate change on future rainfall, evaporation and groundwater recharge were considered and the impacts of quarrying, and post quarry filling on groundwater were examined. The uses and expansion of the MLSNRE GIS were discussed and finally a description is presented of the training carried out throughout the project, the stakeholder workshop and the development of a Cabinet Briefing Note undertaken in the workshop to summarise the project.

Conclusions are given at the end of each section and are collated under their section headings in the following.

17.1 Responsibilities, Institutions and Demographics

It is clear from discussions with a wide range of organisations and individuals that the Ministries' staffs are well trained, motivated and dedicated. There are, however, hampered by a number of institutional factors which limit their ability to operate effectively. These are compounded by resource limitations which decrease the effectiveness of water management ministries, adding to the vulnerability of groundwater in Tongatapu.

At the time of the study, the lack of legislative protection of groundwater and the apparent absence of statutory powers for the lead water agency, MLSNRE, means that groundwater in Tongatapu remains exceptionally vulnerable. This lack of protection and institutional uncertainty over responsibilities pose one of the greatest threats to groundwater.

In most small island nations, a significant threat to groundwater is from pollution from human settlements, particularly from human and animal wastes. This often causes high incidents of water-borne diseases (Figure 7).

The high population growth rates in Tongatapu, part natural, part from inward migration, that were evident from the 1960s through 1980s have slowed dramatically since the 1990s, lessening the potential threats to groundwater. None-the-less, because of the prevailing septic and pit sanitation systems and the number of free-ranging domestic animals, particularly pigs, contamination of water supply systems remains a significant risk, particularly in areas where the water table is closer to the surface.

An interesting feature of the recent statistics on domestic water sources (Table 4) shows a dramatic increase in the number of household rainwater tanks between 1986 and 1996 with a persistent increase to 2006. In 1986 the number of households with rain tanks was less than 5% of those connected to piped water. By 1996 that had grown to 51% and by 2006 it had further increased to 85%. This remarkable increase in rainwater harvesting possibly reflects three factors: Tongatapu's generally reliable rainfall; the number of recent aid projects that have supported rainwater harvesting; and a community preference for rainwater. The statistics in 2006 for drinking versus non drinking water sources (Table 5) demonstrate the clear preference for drinking rainwater.

17.2 Groundwater properties and water quality in village wells

The MLSNRE groundwater data base is a valuable record of both the spatial and temporal variability of groundwater properties and particularly salinity. In this project, the data base was analysed and physically impossible or spurious results were culled from the record. By comparing "snap-shot" measurements taken in this project in August 2007 with previous measurements in the culled version of the MSNRE database dating back to 1959 it was possible to summarise both the spatial distribution and trends in time of groundwater properties in village wells across Tongatapu

17.2.1 Spatial distribution and trends in EC

The spatial distribution of groundwater salinity in Tongatapu in August 2007 (Figure 33) is similar in pattern to that last mapped in May 1990 (Figure 6) but the extent of seawater intrusion appears less in August 2007 than in the early 1990s and clearly depends on the preceding rainfall.

Groundwater pumping to reticulated village water supply systems in Tongatapu commenced in 1961 (Furness and Helu, 1993). These authors suggested that the increase in groundwater salinity between 1965 and 1990 was due to increased extraction of groundwater in Tongatapu over this period. While there was no significant trend in the groundwater salinity of the combined individual village wells over the period 1965 to 2007, due to the scatter of data (Figure 34), there was a significant increase in the log mean EC of the village wells between 1965 and 1990 (Figure 35). There is, however, a suggested slight but not significant decrease in salinity between 1990 and 2007 despite an estimated almost 50% increase in groundwater extraction during this time.

Mean groundwater salinity was strongly dependent on rainfall over the preceding months (Figure 36). A simple EC-rainfall model (equation [1]) was fitted to the log mean EC for the period 2000 to 2007. This model predicted quite well previous EC measurements made in the 1980s and some in the early 1990s. It, however, predicted ECs greater than the mean values in 1965 and 1971. This suggests that the measured EC values were lower than those predicted by a model fitted to a period of higher pumping, because of the impact of pumping. The model predicted ECs that were much lower than the log mean of measured values during the period 1994 to1999. Data from 1990 to 1999 were found not to be significantly correlated with rainfall. There appear two possible explanations for this discrepancy. The first is that the high readings and increased scatter of data during the 1990s was due to instrumental problems. The second is that the increased salinity during the 1990s was caused by an increase in groundwater extraction, perhaps due to the irrigation of squash pumpkin.

17.2.2 Water table elevation

The impact of groundwater pumping can also be examined by measuring the elevation groundwater table above MSL. The MLSNRE data base lists groundwater elevation data for 30 village wells from 1971 onwards. The mean groundwater elevation from 1971 to 2007, 0.41 m above MSL is small for such a large small island. Some atolls in the Pacific with widths about 1 km have groundwater elevations of 0.7 m above MSL. This difference reflects the large hydraulic conductivities in the limestone aquifer in Tongatapu. The water table elevation was lower during the dry period from 1992 to 1995 but recovered after that. This is in contrast to the EC data which showed continuing high values during the mid to late 1990s.

The water table elevation data shows considerably variability because of the influence of rainwater recharge and tidal fluctuations as well as uncertainties over the RLs of the well. The long-term mean elevation for all village wells, 0.41 ± 0.18 m above MSL, agreed with the predictions of Hunt (1979) and there was no significant change in mean groundwater elevation in Tongatapu over the period 1971 to 2007 (Figure 39 and Figure 40). The groundwater elevation of both individual wells and the mean of all wells depended on previous rainfall, as expected, and groundwater EC correspondingly decreased as water table elevation increased. It was noticed that while groundwater EC appeared to depend on previous rainfall over the preceding 19 months, groundwater elevation showed a faster response to rainfall over only the last three to four months.

Groundwater elevation should depend on the distance of the groundwater from the sea. We used the RL of the well as an approximate surrogate of distance from the sea. The expected increase in water table elevation with RL of the well was not observed. This could be due to inaccuracies in the RL measurements. It is concluded that, within the scatter of data, no significant impact of groundwater pumping on groundwater elevation can be identified.

17.2.3 Groundwater pH

The groundwater pH data of village wells, measured since 1990, scatters over the range expected for waters in equilibrium with limestone aquifers. Values range from those for calcite in equilibrium with atmospheric carbon dioxide, around 8.5, to those in equilibrium with higher concentrations of carbon dioxide, around 6.5, presumably from recharge waters rich in CO_2. The actual values obtained will depend on whether the water is sampled from a well that is being pumped and whether the sample is exposed to the atmosphere for a significant length of time prior to sampling. The groundwater pH shows no significant trend with time. Both the “snap shot” measurements carried out in this project and the measurements recorded in the database suggest the pH may decrease with increasing salinity (EC) of the groundwater.

It is unclear what use can be made of the pH values of groundwater from the limestone aquifer in Tongatapu since samples may range anywhere from 6.5 to 8.5 depending on length of time of exposure of the sample to the air.

17.2.4 Groundwater temperature

The factors which control groundwater temperature are well known. The long-term mean groundwater temperature from 1965 to 2007, 24.9 °C (see Table 12) should equal the mean atmospheric temperature in Tongatapu. Analysis of the trend in groundwater temperature since 1990, when most of the measurements were conducted reveals a decrease in mean groundwater temperature of about 1.8 °C between 1990 and 2007. This seems highly unlikely and may be due to instrumental calibration problems.

As with pH it is unclear what use is to be made of the temperature data. If it is a check on global warming then instruments will have to be calibrated regularly against a known temperature standard.

17.3 Groundwater properties and water quality at Mataki’eua/Tongamai

The TWB data base for the Mataki’eua/Tongamai wellfield, which supplies water to Tongatapu’s main population centre, Nuku’alofa, is one of the most extensive records in any Pacific island countries. We have compared the “snap-shot” of measurements taken in this project in July and August 2007 with an analysis of measurements in the TWB database dating back to 1966. Some recommendations immediately follow from this analysis. The TWB database is an extremely valuable groundwater data set with almost monthly EC data from individual wells dating back to 1966. There is very little evidence of any anomalies in the EC database and it was not necessary to remove outliers or make corrections. Every effort should be made to preserve this database, to archive it and to share it with relevant authorities and agencies.

17.3.1 Spatial distribution of salinity

The "snapshot" monitoring of EC in the TWB wells at Mataki'eua/Tongamai in July and August 2007 revealed a significant inverse relationship between EC of individual wells and their distance from the lagoon (equation [1]). This relationship predicts that when continuously pumped vertical, 2 m deep wells are within 0.75 km from the coast, the EC will exceed the 2,500 μS/cm guideline value for freshwater. This distance is consistent with the groundwater salinity found in the Hihifo region of north-western Tongatapu and it may be that an equation similar to equation [1] is applicable more broadly in Tongatapu. This relationship means that the wells in Mataki'eua closest to the lagoon are the saltiest and should be monitored closely during droughts. The water from all wells is mixed before distribution, so that the impacts of more saline wells which exceed the EC aesthetic limit for freshwater of 2,500 μS/cm are mitigated. None the less it may be wise in droughts to cease pumping from some of the saltiest wells.

17.3.2 Thickness of the freshwater lens

The special SMBs locating within and near the Mataki'eua/Tongamai wellfield provide useful information on the thickness of the freshwater lens in the wellfield. In the August 2007 measurements, that thickness varied from 5.6 to 13.3 m, depending on the distance from seawater and on proximity to the wellfield. The measurements suggested (Figure 53) that the freshwater lens within the wellfield or down-gradient of it was up to 4.5 m thinner than that in wells bordering or removed from the wellfield when the wells are at a similar distance from seawater. This apparent thinning of the lens is consistent with the increasing trend in salinity observed in both the log mean EC of the wellfield as well as that for individual wells. This apparent finding is important and warrants further investigation.

17.3.3 Groundwater pH

The pH of the Mataki'eua/Tongamai wells measured in July and August 2007 again showed a decreasing trend with increasing groundwater salinity as with the village wells (Figure 54). Stagnant water from one non-operating well had a pH of 8.33, close to the expected limit for calcite dissolution in equilibrium with atmospheric CO_2 at 1 atmosphere pressure. The pH of water being pumped from the wells was on average about 1.3 pH units below this value, indicating that the partial pressure of CO_2 in the limestone aquifer is considerably greater than atmospheric CO_2 as expected from the organic-rich soils of Tongatapu.

17.3.4 Groundwater elevation and pump drawdown

The continuous well logger was placed in a well with an electric submersible pump at Mataki'eua for two weeks and recorded the recession phase of a significant 94.4 mm/day rainfall, which fell before the logger was installed, as well as tidally-forced variations in water table elevation and EC. During this recession phase, which lasted at least 10 days after the major rainfall, two small recharge events were recorded. These were used to estimate a mean evapotranspiration rate of 5 mm/day.

Operation of the electric submersible pump was interrupted on 3 occasions and the subsequent rebound and drawdown of the water table due to pumping was measured by the logger. The mean drawdown due to pumping at 376 m^3/day was only 11.5 mm and equilibrium was reached rapidly suggesting a large horizontal hydraulic conductivity. An approximate steady state analysis was used to estimate a horizontal hydraulic conductivity of 3,600 m/day, about twice previous estimates of the horizontal hydraulic conductivity in Tongatapu. These measurements should be repeated in other wells at Mataki'eua and Tongamai, where possible.

17.3.5 Temporal trends in groundwater salinity

A critical issue for management of the Mataki'eua/Tongamai wellfield is the impact of groundwater extraction on groundwater salinity. The supply of piped groundwater to Nuku'alofa has developed from 5 hand-dug wells at Mataki'eua commencing in 1966 to 39 wells and bores in 2007 with the last been completed in February 2003 in the Tongamai region. The pumping rate from the wellfield has increased from about 1.3 ML/day to approximately 8 ML/day in August 2007 with an estimated 50% increase in groundwater extraction since 1991.

Since the groundwater salinity is heavily influenced by antecedent rainfall, dis-entangling the impacts of rainfall and pumping on groundwater salinity is complex. We have been able to demonstrate that there have been increasing trends in the log mean EC of the wellfield due to pumping. Most of these increases occurred in the period from 1966 to the 1990s. The period from the mid 1990s to 2007 is complicated and shows a decrease in log mean EC over the period 1995 to 2007 despite a nearly 41% increase in pumping. We strongly suspect that this decrease is due to the progressive development of the lower salinity Tongamai portion of the wellfield (see Figure 50).

We have also examined the salinity trend in a single well, well 106, chosen because it was in the more saline portion of Mataki’eua. This well showed an increasing trend in salinity from commencement of pumping in 1971 through to 2007. Removal of the trend due to pumping produced residuals which had no significant trend in salinity. From this we conclude that increased pumping at Mataki’eua/Tongamai is increasing the salinity of the groundwater particularly in the area closest to the lagoon where the SMBs suggested thinning of the lens.

The planned development of the Tongamai section of the wellfield aims to increase the total number of wells in Mataki’eua/Tongamai to 60 with current plans to operate at least 45 of these. With 45 wells operating it is conservatively estimated that the log mean EC of the wellfield will increase by 9% and individual wells may increase salinity by 17%. If all 60 wells operate, it is estimated that the salinity of produced groundwater may increase by 17% with individual wells increasing by up to 35%. These estimates are believed to be conservative and it has been suggested that examination of possible alternate sources for groundwater such as the areas around the Fua’amotu International Airport and Liahona be carried out.

17.4 Groundwater quality at Tapuhia Waste Management Facility

The TWMF represents a bold solution to a difficult problem; waste disposal in a small island. Because the TWMF is located in a disused quarry, the risk of contaminating local groundwater is significant, and major efforts have been made to minimise this risk. One of the essential elements in managing operations there is the continued monitoring of groundwater in the immediate vicinity of the quarry and at village water supply wells in the area around the TWMF. The WA has assembled a multi-agency monitoring team that works exceptionally well. This team provides a model for groundwater monitoring throughout Tongatapu. It enables cooperation at the operational level, promotes the sharing of facilities and equipment and encourages the sharing of data and information.

17.4.1 Salinity

The groundwater salinity in the monitoring boreholes around the facility is generally lower than that in pumped village wells in Tongatapu (section 5.2) and in the Mataki’eua/Tongamai TWB wellfield (section 6.2). This is hardly surprising since there appears to be no major groundwater pumping in the vicinity of the quarry and the GMWs sample the surface groundwater whereas the pumped wells withdraw water from the top 2 m below the water table.

The groundwater chemistry shows the predominance of carbonate dissolution products and a significant dependence of field pH on groundwater EC. The groundwater chemistry of the GMWs suggested some movement of rainwater ponded in the bottom of the quarry into groundwater to the west of the quarry may be occurring.

17.4.2 Groundwater elevation and flow

The “snap-shot” measurements here of piezometric heads in the GMWs suggest westward flow of groundwater, although this may have been influenced by tidal forcing of the piezometric head and was certainly hampered by the absence of a relative level for GMW2. Continuous monitoring of all seven GMWs immediately around the TWMF would provide a better idea of the groundwater flow directions.

17.4.3 Faecal indicators

Testing for the presence or absence of species indicating faecal contamination in all GMWs and two nearby village water supply wells showed the presence of total coliforms in all wells. Total coliforms occur naturally in tropical island groundwaters (WHO, 1997). Two of the samples from the boreholes immediately adjacent to the facility showed the presence of *E. coli* contamination. Monitoring borehole GMW2, directly beside septic tank sullage drying beds, however, showed no *E. coli* contamination. It is not certain if the *E. coli* found in two GMWs is due to animals, birds or human sources. One village water supply well at nearby Vaini also showed the presence of *E. coli.* This was adjacent to a latrine. These rapid field tests for presence or absence remove some of the burden of bacterial testing from the hospital laboratory.

17.4.4 Groundwater pollutants

Intensive groundwater sampling for contaminants and pollutants before and after the TWMF commenced operation showed that the concentrations of organochlorine and organophosphate pesticides, PAH, BTEX, TPH, total cyanide and mercury were all below the limits of detection. All trace metals, with the exception of lead, were also below the WHO (2006) guidelines for drinking water quality (see Table 33). In all three samplings, the mean and all individual boreholes concentrations of lead were above the WHO guideline limit of 0.010 mg/L for lead in drinking water. One monitoring borehole, GMW1, showed a consistent increase in lead concentrations despite two samples being taken in 2006 before waste disposal at the site commenced. In contrast GMW2 shows a corresponding decrease (see Figure 80). The maximum concentrations of lead at both monitoring wells are at least 25 times higher that the WHO (2006) guideline limit for drinking water. The reasons for these high values and the changes in concentration with time need to be investigated.

17.4.5 Groundwater nutrients

The mean nitrate concentration increased from a mean of 6.8 mg/L for the two sampling periods before operations commenced to 18.4 mg/L (NO_3) after the start of operations. This apparent increase in the mean nitrate concentration is due to one borehole, GMW2, in which the nitrate concentration rose from 6 mg/L in April 2006 to over 80 mg/L in July 2007 (Figure 81). This latter value is greater than the WHO (2006) water quality guideline value of 50 mg/L. This borehole, as already mentioned, is right beside the septic tank sullage drying beds at the TWMF. The increased concentration of nitrate at this site warrants further monitoring particularly to examine for migration of nitrate.

17.5 Extensive sampling of Tongatapu groundwater quality

The intensive chemical measurements and bacteriological testing undertaken in this study were compared them with previous measurements carried out in Tongatapu, including recent measurements at the TWMF (section 7). We have used the results to find answers to several important questions concerning groundwater in Tongatapu.

1. Is the groundwater used for domestic water supplies polluted because of the use of agricultural and industrial chemicals and the leakage of petroleum products?
2. Is the groundwater quality compromised through pollution from latrines and septic tanks?
3. Are nutrient concentrations in groundwater increasing due to agriculture, or inputs from human or animal wastes?
4. Is the chloride concentration of the groundwater increasing due to pumping or climate fluctuations?
5. Does mixing of groundwater with seawater influence groundwater quality?

17.5.1 Faecal indicators

Tests of water supply wells throughout Tongatapu for the presence of indicator species for faecal contamination using the Colisure test showed that, if the boiled rainwater blank and one of the duplicate Liahona samples are excluded, only two (8.7%) of the groundwater samples out of the total of 23 Colisure samples taken (Table 29 and Table 35) had no total coliforms or *E. coli*. The Liahona College sample came from a well in an immaculate rugby ground with little agriculture surrounding it. This suggests that, where possible, groundwater ought to be sourced from cleared well-managed and protected areas. The other negative sample at Mataki'eua came from a TWB well with diesel spills and ponded water on the soil surface, which was heavily infested with algal blooms (see Figure 83B).

Over 91% of 24 water samples, showed the presence of total coliforms. Total coliforms, which occur naturally in tropical island groundwaters (WHO, 1997), were found in all groundwater samples in Tapuhia. A further 6 samples, or 25%, returned positive *E. coli* tests. This is quite a high percentage, reflecting perhaps the impacts of neighbouring agriculture, particularly animals, and septic tank systems on village water wells. This result indicates that disinfection of water from all pumped groundwater systems should be carried out.

H_2S paper strip tests were also examined for their ability to show faecal contamination. These tests are much cheaper and easier to use by community groups than the Colisure tests and have been recommended for use in Pacific Island countries (Mosley and Sharp, 2005). The comparative tests carried out here revealed some worrying anomalies. Four of the (+++) rating (very high risk of faecal contamination) corresponded to only positive Colisure coliform results without *E.coli* positives. It appears then that the H_2S test is very conservative suggesting faecal contamination in double the number of positive Colisure samples and in samples that may have naturally occurring total coliforms rather that faecal coliforms. More worryingly, one of the lower H_2S ratings, (+), indicating the possibility of bacteria, corresponded to a positive Colisure *E. coli* test for the Vaini water supply well. Of even greater concern, two of the lowest (+) H_2S results corresponded to negative Colisure results. The lack of consistency of the H_2S results is worrying.

A report on the use of the H_2S test, (WHO, 2002) did not recommend its use because of the possibilities of false positives from non-enteric, naturally-occurring sulfate-reducing bacteria, which may have occurred in this study. The false positives here in 11% of samples, and the over-estimation of the risk of faecal contamination by a factor of 2 strongly suggest that the more expensive, Colisure field test, adopted in the US as a standard test, should be used where possible for the routine screening of the presence or absence of *E. coli* and total coliform indicators in public water supply systems.

It was not possible to compare these screenings with previous tests for faecal indicator species. The MoH database is contained in a hand-written book and was not available for this study. The TWB bacterial testing of the Mataki'eua/Tongamai wellfield was also not available for comparison.

17.5.2 Ph, EC and major ions

The pH and EC of water sampled in the field differed from measurements in the laboratory which may be due to the high partial pressure of CO_2 in the groundwater samples, which decreases on standing. This reveals the importance of measuring these parameters in the field at the time of sampling. A good relationship was established between the concentration of bicarbonate in the groundwater sample and the pH of the sample. A similarly good relationship was found between the chloride, sodium, potassium magnesium and sulfate concentration and the field EC of the sample. Similarly good relationships were found between calcium and bicarbonate and chloride concentrations. Together, these permit estimation of major ion composition of Tongatapu groundwater from field measured EC.

Examination of the ion ratios of the major ions in groundwater relative to chloride revealed that the major source of sodium, potassium and sulfate is from seawater. Calcium and bicarbonate are sourced from the dissolution of the limestone aquifer. Magnesium is sourced from both seawater and the dissolution of limestone. This analysis also showed that nitrate and fluoride came from neither seawater dilution nor limestone dissolution and both are clearly sourced from the soil. The analysis also permitted estimation of the composition of recharge water entering the limestone aquifer.

17.5.3 Salinity trends

We have compared the chloride concentrations found here with historic data from 1965 to 1991. The data in Table 43 and Figure 93 shows that both the mean and geometric mean of the chloride concentration have decreased since 1991. Some individual wells show increases some have remained the same and some have decreased between 1991 and 2007.

A critical issue concerning the observed increases in salinity in some of the wells is how to separate the influence of pumping from that of variable rainfall. Analysis of this is hampered by the lack of data on the month of the year in which measurements were taken. Here we used annual rainfall in the year in which measurements were reported to examine the relationship.

The 1965 chloride samples were taken in a year that had annual rainfall in the 58th percentile of rainfalls since 1945. Those for 1971 were in the year with the highest rainfall on record (100th percentile) while samples taken in 1991 and 2007[29] were in the 27th and at least the 47th percentiles, respectively. The rainfall regimes when water samples were taken in 1965 and 2007 are therefore comparable and the significant increase in salinity that has occurred between 1965 and 2007 in almost all wells appears attributable to groundwater pumping, assuming that there is no analysis error in the early chloride estimations. In section 6.13, it was shown that the pumping at Mataki'eua had increased four-fold between 1966 and 1991.

The sampling in 1991 occurred in a drier year and the salinity in several of the wells in 1991 show maxima in this year. Furness and Helu (1993) concluded that the increase in salinity that occurred at this measurement was a result of groundwater pumping. The results here suggest that this is not universally true, since 1991 was a drier year. The comparison between 1991, a drier year and 2007, an average year, is however informative. Any salinity that is the same or shows an increase in salinity over that period is clearly due to pumping since increased rainfall should lower salinity. A total of 10 out of the 21 wells examined in Tongatapu show continued increases in salinity due to pumping since 1991.

Unfortunately, the frequency of salinity data for the wells throughout Tongatapu is too sparse in general to determine a general relationship between rainfall and salinity. Also village wells are unmetered so the relationship of salinity to volume of water pumped from the well cannot be determined. The TWB database does list a few wells in which chloride concentration was also determined during the drier period in 1986-7. The data for one well showed an excellent relationship between chloride concentration and annual rainfall except for the measurements in 1965 which fell well below the relationship. Again it must be concluded that the increase is either due to an increase in pumping between 1965 and 1971 or the 1965 set of data is in error.

The data presented in this section demonstrates the importance of regular systematic monitoring in order to manage the combined impacts of pumping and variable rainfall on groundwater salinity. Using the data, we have been able to identify wells in which there is a significant impact of pumping on salinity. These require careful investigation. The older wells at Mataki'eua closest to the lagoon appear to show a continuing increasing salinity trend although the rate of increase is less than in the period 1965 to 1971. Information on groundwater salinity, however, is insufficient. It must be coupled with information on rainfall and on the rate of extraction of groundwater by pumping

17.5.4 Pesticides, aromatics and hydrocarbons

Considerable concern has been expressed over agricultural and industrial contamination in Tongatapu. In this study the pesticides, BTEX, and TPH were all below the limit of detection in the 10 water supply wells selected for intensive testing across Tongatapu. This is in general agreement with the recent intensive groundwater sampling around the TWMF for pesticides, BTEX and TPH in 2006 and 2007.

The weight of evidence from this study, as well as that at the TWMF and the results of Furness and Helu (1993) and Falkland (1995), suggest that there is very little contamination of groundwater

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[29] Rainfall for 2007 was only available up to November.

by pesticides, aromatics or hydrocarbons in Tongatapu. The few pesticides that have been detected in a very limited number of wells are in concentrations just above the limit of detection and well below WHO (2006) guidelines for drinking water. There is clearly no discernible temporal trend in pesticide contamination which might be expected given the persistence of some compounds in the environment.

17.5.5 Trace elements

The trace metals arsenic, beryllium, cadmium, mercury and selenium were all below the limit of detection in the 10 water supply wells selected for intensive testing across Tongatapu. Other trace elements were found to be present in small concentrations, which were well below the WHO (2006) guideline limit for drinking water.

At the TWMF boreholes, mean lead concentrations were 5-10 times the WHO (2006) guideline value for lead. Lead was found in only 3 of the 10 selected wells tested at a mean concentration less than 1/6 of the WHO (2006) guideline value.

Comparison of the mean heavy metal concentrations for the July 2007 sampling at the Tapuhia site in Table 33 with those for the 10 selected water supply wells in Table 47 reveals that the mean concentration of chromium, copper and nickel concentrations are very similar. These concentrations can then be considered background groundwater concentrations for Tongatapu. It is noted that most of these trace elements may be due to the slight dissolution of well and pump materials and it is emphasised that all concentrations in Table 47 were well below WHO (2006) guideline values and do not constitute any risk.

17.5.6 Nutrients

Nutrients, particularly nitrate and nitrite, are of concern in groundwater in Tongatapu due to the use of fertilisers, leakage from septic tank systems and contamination from animal wastes. There are two primary health concerns with nitrate levels in groundwater in Tongatapu. The first is the formation of algal booms in Fanga'uta Lagoon from the discharge of nitrate-rich groundwater which has potential impacts on the safety of harvested seafood. The second is that high nitrate concentrations can cause methaemoglobinaemia, the so-called "blue-baby syndrome" in bottle fed-fed infants.

Nitrite was below the limit of detection in all 10 wells tested. All wells had nitrate levels below the WHO guideline value for drinking water with the mean concentration being less than 1/6 of the guideline concentration. Total phosphorus concentrations were generally very low. The low phosphorus concentrations in groundwater found at the 10 selected wells and at the TWMF boreholes are not surprising since the andesitic tephra soils have a high retention capacity for phosphorous (Chisholm, 1998). Both mean nitrate and mean total P concentrations were very close to those found at the TWMF. At the TWMF, the mean molar N/P ratio before operations commenced was 121 ± 71, again in agreement with that in found at the 10 selected wells and suggesting a molar N/P ratio of about 100 to 130 is characteristic of groundwater in Tongatapu.

17.5.7 Trend in nutrients

Annual fertiliser imports into Tonga increased dramatically from virtually zero before 1988 to an average of almost 2,400 tonnes/year after 1991. There have been claims that this has had significant impacts on both groundwater nutrient concentrations and on the Fanga'uta Lagoon. We have compared mean nitrate concentrations from the results of this work in 2007 and the TWMF in 2006 prior to operations commencing with others dating back to 1978 and results for total P dating back to 1995. There is no significant increasing trend in nitrate between 1978 and 2007 and all total P values are equal within error. The mean nitrate and total phosphorus concentrations over this almost 30 year period are 6.7 ± 0.7 and 0.038 ± 0.017 mg/L respectively, with a mean N/P molar ratio of 85. This suggests that agriculture fertilisers are not the sole source of nitrate inputs to groundwater.

Estimations on the contribution of fertiliser to the groundwater were hampered by lack of information on the composition of the fertiliser and on the location of its use. In order for recharge from agricultural soils to be the sole source of nitrate in groundwater in Tongatapu would require an estimated 70% of the mean annual quantity of fertiliser imported into Tonga to be recharged into groundwater. This also does not explain the high nitrate concentration in 1978.

Estimates were also made of the contribution of nutrients in human and animal wastes disposed of in septic tanks, pit latrines and on the ground to groundwater concentrations. By assuming population numbers and the estimated number of pigs outside Nuku'alofa are a possible source it was shown that the concentration of nitrate in recharge water was close to the measured values and showed minimal variation between 1976 and 2007. Predicted total phosphorus concentrations from sewage discharge was about 2.5 times the long-term mean, pointing to loss of phosphorus through reactions in septic tanks and absorption in the volcanic derived soils. It is concluded that human and animal wastes constitute a significant source of nutrients supplied to Tongatapu groundwater.

17.6 Rate of groundwater recharge

In order to estimate the sustainable yield of groundwater, the rate of groundwater recharge must be estimated. A monthly mass balance approach has been used here to estimate the groundwater recharge rate. The following conclusions regarding recharge are made:

- A reasonable range of average annual recharge estimates for Tongatapu as a whole is about 430 mm - 520 mm or 25% - 30% of average rainfall. The variation is largely dependent on the thickness of soil cover and will vary spatially across Tongatapu. An average annual value of about 470 mm appears reasonable, but local recharge will depend on depth of soil cover.
- Because of the spatial variation of soil cover between east and west in Tongatapu, it is expected that recharge will be higher in the eastern part of the island than in the west where the soil cover is thicker. This makes the eastern part of the island, such as around Fua’amotu international Airport a more attractive water source for any expanded water supply scheme.
- The range of average annual recharge values is similar to that derived by Hunt (1978, 1979) as discussed in section 9.2. The upper end of the range is also very similar to the value of 528 mm or 30% of rainfall adopted from a water balance procedure in Falkland, 1992.
- If a full sequence of daily rainfall data in electronic form becomes available, the recharge estimation should be re-calculated using daily rainfall data. It is likely that the estimated recharge will be higher using daily rainfall data.
- The sequence of recharge is important for sustainable groundwater resources management. The very low recharge period in the 1980s is a critical period for estimating sustainable yield as indicated in the next section.
- There is a marked seasonality in groundwater recharge in Tongatapu with mean 7 month dry season recharge being almost half the mean 5 month wet season recharge and the dry season recharge has higher variability than the wet season recharge.

17.7 Sustainable groundwater yield

A conservative estimate of the sustainable groundwater yield for Tongatapu has been derived assuming 20% of groundwater recharge. This means the estimated sustainable groundwater pumping rate is 3 m^3/ha/day with an upper limit of 4 m^3/ha/day. The lower rate has been selected here to ensure that a viable freshwater lens would be maintained throughout droughts as severe as any that have occurred in the past. When this areal pumping rate is applied to the effective recharge area of Tongatapu, a sustainable groundwater extraction rate of between 54 and 72 ML/day is found.

The absence of meters on village pumps and the failure of the bulk water meter at Mataki’eua mean that there is no accurate measure of groundwater extraction in Tongatapu. The estimate made here is that current extraction at the Mataki’eua/Tongamai wellfield is about 8 ML/day while village water pumping may be as high as 5.4 ML/day giving a current total estimated daily extraction of 13.4 ML/day or 19 to 25% of the sustainable yield. Approximately 10.7 ML/day, or 80% of this estimated total daily extraction, is sourced from the Liahona-Tongamai-Mataki'eua region due to the concentration of pumps at the Mataki'eua/Tongamai wellfield, while the remaining 20% is distributed over the rest of Tongatapu. This uneven distribution of pumping could be further exacerbated by proposals to increase the number of pumps at Mataki'eua/Tongamai to up to 60 and may create salinity problems in pumped water during dry times.

Between half and two thirds of the water pumped from the Mataki'eua/Tongamai wellfield disappears as unaccounted-for losses. A large proportion of the good quality groundwater is therefore being pumped from Mataki'eua/Tongamai to be discharged from leaking pipelines into the polluted groundwater in Nuku'alofa were it discharges into the Lagoon or the ocean. Future water supply projects in Nuku'alofa should concentrate on reducing these losses.

Using the mean measured drawdown of a single pump, it was estimated that the radius of influence around a pump was only about 2.6 m. This estimate needs to be verified as it implies considerable upconing of the fresh/seawater interface beneath pumps and especially under the concentration of pumps at Mataki'eua/Tongamai.

Based on the estimated areal sustainable groundwater extraction rate of 3 to 4 m^3/ha/day, the range of the maximum number of pumps, pumping continuously at rates of 216 to 260 m^3/day (2.5 to 3.0 L/s), that can be accommodated within the effective recharge zone of Tongatapu is between 210 and 330 pumps. To minimise upconing of the fresh/seawater interface it is desirable to have these pumps as evenly distributed as possible with spacing between pumps of 0.75 to 1 km. Spacing pumps closer than this will increase both local upconing, and as observed at Mataki'eua/Tongamai wellfield(see section 6.3) the salinity of pumped groundwater.

We have estimated that the Mataki'eua/Tongamai wellfield already has a radius of influence between 2.5 and 2.9 km. For this reason, it is concluded that the further concentration of pumping near Mataki'eua/Tongamai could be problematic. Instead, the Fua'amotu region should be explored as a future water source for Nuku'alofa, Vaini, and Tatakamotonga districts and the area around Liahona should be explored urgently as a source for future water supply to the saline Hihifo region.

17.8 Meteorological and hydrological droughts

Tongatapu is blessed by relatively reliable rainfalls having high mean annual rainfall with a relatively low coefficient of variability. Nonetheless, past droughts have had significant impacts on crop production and water resources. This report has concentrated on meteorological and hydrological droughts and has used a quantitative, non-parametric method, the decile (or percentile) method, to examine the severity, duration and frequency of past droughts over time periods, varying from 6 to 60 months, long enough to have an influence on fresh groundwater resources. The decile method has the advantages that it does not need to transform rainfall data to a normal distribution, provides an easily understood ranking of drought severity and identification of the start and end of droughts and is used as standard throughout Australia.

A comparison between the two currently daily monitored rainfall stations at sea level, Nuku'alofa, and at about 60 m above mean sea level, Fua'amotu, shows the expected orographic effect with monthly rainfalls at the higher Fua'amotu station being on average approximately 10% higher than those at Nuku'alofa, while the double mass plot showed the cumulative rainfall at Fua'amotu is over 4% higher than that at Nuku'alofa. The double mass plot was close to linear showing no major relative changes in behaviour between the two sites.

The frequency of severe meteorological droughts (total rainfall in a given period falling below the 10th percentile level) decreases as the time period increases over which rainfall is summed. For 60 month rainfall periods since 1945, there have only been two major dry periods, one starting in April 1983 and the other starting in April 1991.On average these dry periods persisted for about 8 years and could be expected to significantly impact on groundwater resources. During the 1980's there was minimal monitoring of groundwater resources in Tongatapu greatly improved monitoring occurred during the 1990s (see section 6.12) which showed an increase in the salinity of village wells in the mid 1990's.

Probably the two rainfall summation periods of most relevance to Tongatapu groundwater are 12 and 18 months. For the 12 month rainfalls there were 9 severe droughts since 1945 with the most severe drought having its maximum impact in September 1983. On average, these droughts occurred every 86 months and lasted for 22 months although there is a wide range in both frequency and duration. For 18 month rainfall, there were 7 severe droughts since 1945 with the most severe drought having its maximum impact in November 1983. On average, these droughts occurred every 103 months and lasted for 29 months, although again there is a wide range in both frequency and duration.

In the examination of hydrological drought, one recharge case, Case 1 in Table 62, was taken as representative. It was found that there were slight differences in the number of droughts for different periods over which recharge is summed between hydrological and meteorological drought with generally fewer hydrological than meteorological droughts. There were periods of at least 18 months where no estimated recharge occurred. Again, the frequency of severe hydrological droughts (total recharge over a given period falling below the 10th percentile level) decreases as the time period increases over which recharge is summed. For 60 month recharge periods, since 1945, there has been only one major drought, which started in August 1983 and ended in February 1999. During this approximately 15½ year period it was estimated that total recharge was only 609 mm. It is somewhat surprising that while the groundwater salinity in village wells in Tongatapu peaked during this period, those at Mataki’eua did not.

For the two recharge summation periods probably of most relevance to groundwater in Tongatapu, 12 and 18 months, there were 8 and 6 severe droughts respectively since 1945. For the 12 month period, the five most severe droughts, all having zero recharge, had their maximum impacts in August-September 1946, October-December 1981, August-December 1983, February 1985 and August 1992-February 1993. The average duration of the severe (<10th percentile) hydrological droughts was 20 months and they occurred on average every 7 years. For the 18 month summation period, the worst drought since 1945 had its maximum impact in February 1993 when there was an estimated zero recharge for 18 months. For this recharge period the average duration of droughts was 37 months and they occurred on average nearly every 11½ years although again there is a wide range in both frequency and duration.

17.8.1 Wet and dry season droughts

Because of the importance of the wet (December to April) and dry seasons (May to November) in Tongatapu, and the predominant contribution of wet seasons to recharge, an examination was made of wet and dry season droughts. It was found that there were no wet season hydrological droughts between 1947 and 1981, but significant wet season hydrological droughts occurred between 1981 and 1992 with a total of 5 wet season droughts for the period 1945-2006. For the dry season there are no severe droughts before 1968, then droughts occurred fairly regularly between then and 2001, with a total of 8 droughts for the period 1945-2006. For the wet season these droughts occurred in 1946, 1981, 1983, 1987, and 1992. All had an estimated recharge of zero except 1987 where the recharge was 26 mm. The median duration of wet season droughts was two seasons with a median time of 4½ years between wet season droughts. There were 8 dry season droughts which occurred in 1967, 1977, 1981, 1983, 1987, 1992, 1997 and 2001. All these had an estimated recharge of zero and had a median duration of 1.5 seasons and a median time of 4 years between dry season droughts. The 4 years 1981, 1983, 1987 and 1992 were clearly problematic as they had both severe wet and dry season droughts within the same year.

The analyses presented in this study show that droughts with the potential to impact on groundwater resources are a relatively frequent event in Tongatapu and contingency plans should be developed to reduce the risk of significant impacts.

17.9 Drivers of droughts in Tongatapu

The correlations between rainfall in Tongatapu and the climate indices of the SOI, PDO and Niño SST anomaly have been examined here. In general, the correlation is positive for SOI and negative for PDO and Niño SST anomaly (data only from 1950) and is also strongest for SOI, followed by Niño Region 3.4 SST anomaly and then PDO. As the time periods increase over which rainfall is summed and over which the indices are averaged is increased so the absolute value of the correlation increases. In general, the maximum absolute correlation is found when the rainfall period lags 3 months behind the SOI and the Niño 3.4 SST anomaly period. For the PDO, the lag is both positive and negative and for the 120 month summation and averaging period, the maximum absolute value of correlation occurs when rainfall lags 22 months behind the average PDO period, providing a means of estimating variations in long-term rainfall from the average PDO index.

An unexpected result was found when the correlations between total seasonal rainfall and seasonal averaged climate indices were examined for a wet season taken as November to April and a dry season taken as May to October. A reasonably good correlation was found between the total wet season rainfall and the average wet season climate indices, with SOI given the highest correlation. The total dry season rainfall, however, was poorly correlated with the average corresponding dry season climate indices.

The wet season correlation improved when total wet season rain is compared to a linear combination of the average SOI and PDO for the same wet season, but inclusion of the average Niño 3.4 SST anomaly did not improve the correlation. The correlation between total dry season rain and a linear combination of all average dry season climate indices was still very weak.

An examination of the correlation between total wet season rainfall and the average climate indices of the previous dry season showed that the good correlation persisted and was strongest when Niño 3.4 SST was used as the average dry season climate index; although the correlation was very slightly less when the average previous dry season SOI was used. A linear combination again of average dry season SOI and PDO improved this correlation and there was a slight improvement when all climate indices were used.

It has been shown that the autocorrelation in the average 6 month SST or SOI indices starting in November has a maximum autocorrelation with the previous average 6 month season starting in May. The autocorrelation is a minimum when the average 6 mth period starting in May is compared with the 6 mth season starting the previous November. This indicates a “resetting” of the SST at the start of the dry season in May. This carries over to total wet season rainfall, where a very broad, reasonably strong correlation is found with average SST or SOI indices up to 8 months prior to the wet season. Total dry season rainfall, however, showed a much weaker correlation with SST or SOI.

The analyses presented in this study show that droughts, as expected, are related to the drivers of climate in the South Pacific, as measured by the climate indices SOI, PDO and Niño 3.4 SST. It has also been shown, however, that there is a complex relation between seasonal rainfall in Tongatapu and SOI, PDO and Niño 3.4 SST with wet season rainfall having a significant correlation to these climate indices but the dry season rainfall having a poor correlation. Because of the importance of recharge during the wet season for water resources, this complex relationship requires further examination.

17.10 Impacts of climate change

The results from a suite of 23 coupled atmosphere-ocean global climate models run by CSIRO were used to predict possible changes to monthly rainfalls and potential evaporation for Tongatapu for 4 SRES scenarios of future GHG emissions through to near the end of the 21st century.

17.10.1 Predicted changes in rainfall

The 23 GCMs give widely divergent predictions for predicted future monthly rainfalls in Tongatapu under a range of GHG emission scenarios. Some models predict increases in rainfall while others predict decreases under the same scenarios. This is worrying since the case of a small relative low island embedded in a large ocean should be the simplest possible case. Here we have used the mean of all 23 model predictions to arrive at a “consensus” value for the expected change in rainfall. As can be seen in Table 81, the mean values are associated with very large coefficients of variation, so limited confidence can be placed in these mean monthly values.

The mean predictions suggest that there will an increase in the seasonal differences in rainfall in Tongatapu. Mean wet season (November through April) rainfall is expected to increase by between

4 and 22% by 2095, while the mean dry season rainfall is expected to decrease by between 2 and 13% from the mean seasonal rainfall for the period 1975-2004. Together these contribute to an expected increase in mean annual rainfall of between 1 to 8% over the mean annual rainfall for 1975-2004. Such relatively modest increases will be difficult to discern within the current variability of annual rainfall. Predicted increases and decreases of seasonal rainfall for the higher GHG emission scenarios were non-linear.

For the period 1990 to 2095, the predicted increases in mean annual rainfall lie between 0.2 and 1.3 mm/year, while for wet season rainfall the predicted increase is between 0.4 and 2.1 mm/year. The predicted range of decreases in dry season rainfall lies between 0.1 and 0.8 mm/year. The actual rainfall from 1945 to 2007 has a linear trend **decreasing** by 2.3 mm/year while that for the wet season **decreases** by 3.2 mm/year. The linear trend for dry season rainfall, however, **increases** by 0.7 mm/year. These linear trends are exactly opposite to the mean trends predicted by the climate models for the period 1990-2095, but the coefficients of determination of these trends in the recorded rainfall indicate the observed trends are not significant. The model estimates discussed here provide no information on expected changes in the variability of rainfall.

17.10.2 Predicted changes in evaporation

Only 14 of the 23 coupled atmosphere-ocean GCMs can predict changes in potential evaporation. The predictions of these 14 models for the 4 SRES scenarios show nearly an order of magnitude lower coefficient of variation in the mean predicted monthly potential evaporation than for predicted monthly rainfall.

The means of the predicted monthly changes in potential evaporation all increased with increasing time beyond the reference period 1975-2004, irrespective of season or SRES scenario. This seems to be a consequence of the predicted increase in global temperature with increased GHG emissions. The increases predicted for the dry season were larger than those for the wet season. This differential increase in dry season potential evaporation over that for the wet season, coupled with the expected decreases in dry season rainfall, could further heighten the seasonal differences in soil moisture and recharge. The rates of increase in potential evaporation for the higher GHG emission scenarios were again non-linear.

Surprisingly, the predicted increases in annual and wet and dry season ET between 1990 and 2095 were not evident in the values of actual evaporation (ET_a) estimated using recharge Case 1 calculations for the period 1945 to 2006. For this time period, the estimated ET_a has a decreasing linear trend for annual as well as wet and dry seasons, and the magnitude of the rate of decrease of dry season ET_a was less than that for the wet season. Although the coefficients of determination for these linear trends are very small, the trends are opposite to the predicted trends as was found for rainfall.

It would seem that evaporation and particularly its seasonal dependence is more sensitive to the expected climate change due to increased GHG emissions. In estimating recharge in this work, we have assumed the monthly cycle of potential evaporation is unchanged with time so that our estimations of recharge are biased by this assumption. It would seem from this, that there is a need for recommencing monitoring of evaporation in Tongatapu.

17.10.3 Estimated changes in recharge

As a first approximation, the expected change in groundwater recharge resulting from continued GHG emissions has been estimated by assuming that the predicted increases in potential evaporation also apply to ET_a. We have then used the observed mean rainfalls for the period 1975-2004 and the mean ET_a for the same period calculated for recharge Case 1 together with the simplified long-term water balance to estimate changes in annual groundwater recharge. These first-order estimates suggest recharge will decrease between 5 and 25% by 2095. The predicted increase in annual rainfall is offset by the predicted increase in evaporation, especially in the dry season which is coupled to the predicted decline in dry season rainfall. Again, for the higher SRES scenarios, the estimated rate of change of recharge is non-linear.

When linear trends are fitted to the widely fluctuating annual Case 1 recharge estimates for 1945 to 2006, the rate of decrease of annual recharge is close to that predicted for the high SRES scenario. The trends for the wet and dry season recharges, however, are opposite in sign to those predicted from the climate models with estimated wet season recharge decreasing and dry season recharge increasing. Again, it is noted that the coefficients of determination are very small indicating that the trends in the 1945-2006 recharge data are not significant.

Because recharge appears to be sensitive to climate change, it is important to monitor parameters indicative of recharge. The profile of groundwater salinity is clearly a sensitive parameter but one which is also influenced by the rate of withdrawal of groundwater. For this reason both profiles of salinity and pumping rates should be measured throughout Tongatapu. If the groundwater recharge rate is declining with increasing GHG emissions, then pumping should be licensed and monitored and conservative estimates need to be adopted on the safe rate of groundwater withdrawal.

17.10.4 Cautionary note

A note of caution needs to be added here about the above predictions. Rainfall is a key driver of the recharge process. The general lack of agreement between the 23 climate models, resulting in very large coefficients of variation in the mean monthly predictions of expected rainfall under a range of GHG emission scenarios, means that these projections of future changes in rainfall and recharge must be treated with extreme caution.

“GCMs (used to here predict the impacts of green-house gas emission scenarios on future climates) are not good at simulating changes to the hydrological cycle and are notoriously bad on rainfall, especially in the tropics. There are two basic reasons for this: (i) they generally do not simulate tropical convection very well, and (ii) they can not reproduce some the major modes of current climate variability, including El Niño- Southern Oscillation (ENSO). Although the major American model at the US National Center for Atmospheric Research (NCAR) now apparently starts to simulate something that looks like ENSO.” (Steffen[30], private communication, 23 February 2009). Since it has been clearly demonstrated here (Section 12) that ENSO is a key driver of wet season rainfall in Tongatapu, the rainfall predictions here must be viewed as highly uncertain.

17.11 Impacts of quarries

The examination of quarries in this work was necessarily brief and did not involve an exhaustive examination of all quarries in Tongatapu. Apart from the detailed measurements at the abandoned Tapuhia quarry now in use as the TWMF (see section 7) no detailed measurements were made on either the hydraulic gradients around or the water quality resulting from quarries, mainly due to the absence of a groundwater monitoring borehole network. Because of this, we are unable to give recommendations on the safe distance between a quarry and a water supply well or borehole or a water supply wellfields. Nonetheless our observations and discussions with relevant agencies permit some general conclusions:

- Quarrying is largely unregulated.
- Current quarrying practice is to excavate material down to below the groundwater level. This exposes groundwater to direct evaporation losses and greatly increases the risk of groundwater contamination.
- Apart from the TWMF, there is no monitoring borehole network that can be used to determine the impacts of quarrying on groundwater hydraulic gradients or on the groundwater quality.
- Practices within quarries where the water table is exposed, such as disposal of industrial wastes and keeping of livestock, greatly increase the risk of groundwater contamination.
- Pre-existing lead and post-completion nitrate concentrations within monitoring boreholes around the TWMF warrant close attention and continued monitoring and reporting.

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[30] Professor Will Steffen is Executive Director of the Australian National University’s Climate Change Institute.

17.12 Water resource GIS

It was found that the MLSNRE has a sophisticated GIS capability and that staff are fully aware of the potential uses for a Water Resources GIS and are capable of training other agencies in the use of GIS. Some of existing MLSNRE well monitoring data base has already been entered into the GIS. Two factors delaying further development of a groundwater resources GIS are the limited resources available for this task and the lack of a high-speed electronic data link to the Geology section building.

The existing data bases in various Ministries that could be usefully incorporated into a national water resources GIS had been identified in section 15.2 above. There is a considerable amount of important information suitable for the water resources GIS, that is either in hard copy or is not available for sharing. This is a significant barrier to the creation of a comprehensive and practically useful data base. The setting up of a high speed data transfer link between the Geology section site and the main MLSNRE site would greatly increase the efficiency of the further development of a water resources data base.

17.13 Training, Workshop and Cabinet Briefing Note

The training sessions undertaken throughout this work with a range of agencies were highly successful, due to the good level of background training of the Ministry staff involved and their enthusiasm. Participation in the monitoring at the TWMF with the WA multi-agency monitoring team demonstrated to us the strengths of a collegiate approach to water monitoring and training and is one that could be emulated throughout Tonga.

The project workshop was equally successful with a very good number of participants drawn from a wide range of ministries and organisations. Discussion was lively and constructive. One issue raised in the workshop was the absence of any new government appointments in water resources over the past 11 years. The workshop was an excellent vehicle for bringing together different organisations within the water sector to exchange ideas in a collegial way.

The joint production by Workshop participants of the Cabinet Briefing Note on the results of the study was a very useful way of producing a practical output from the Workshop and one which summarised the study. The Note’s 11 recommendations are focused and if implemented should decrease the vulnerability of groundwater in Tongatapu.

A number of issues were raised during this work and they remain unresolved. These are listed at the end of each section. A number of recommendations flow on from this work. They are also given for each section and are summarised starting on page 6.

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Annex A

Terms of Reference

for

"Tongatapu Groundwater Evaluation and Monitoring Assessment, Kingdom of Tonga"

Activity 1 – Baseline Water Resource Monitoring Data

The Consultant shall liaise with Departments and Agencies and other key stakeholder organisations as appropriate to obtain all available previous rainfall, groundwater levels, bore locations, logs and construction details, groundwater abstraction rates and location, groundwater yields and aquifer properties, groundwater quality, including salinity profiling, vegetation and land-use, and any spring locations, flow rates and water quality. On behalf of and via liaison through the Government of Tonga, the Consultant shall:

(a) Identify all Departments and Agencies with responsibilities for monitoring, analysis and reporting on water resources;

(b) Review and summarise all associated water resources monitoring undertaken by Agencies and Departments over the years;

(c) Where possible, collect, collate and technically audit existing, available hydrological and hydrogeological data for Tongatapu;

(d) Advise on the QA procedures for these data sets;

(e) Review current monitoring, data collection, capture, storage, analysis and reporting procedures and existing data quality;

(f) Identify, recommend and provide training on procedures which will strengthen quality assurance, capture and security of data;

(g) Advise and coordinate with relevant Departments and Agencies for a programmed approach to allow hard copy water resource assessment data to be progressively coded for inclusion in an electronic national database;

(h) In conjunction with relevant Departments and Agencies, undertake baseline groundwater sampling and analysis from a selected number of production and monitoring bores, to be analysed for major ions, hydrocarbons, EC, N, Pesticides, PO4-, H2S, pH, Temp, faecal and total coliform. The sites are to be selected by the Consultant in conjunction with MLSNRE, TWB and SOPAC's designated representative;

(i) Assess the sustainable yield of the aquifer and primary wellfields;

(j) Discuss and transfer knowledge to local counterparts in above activities (a) to (h).

Activity 2 – Assessment of Institutional Capacity for Groundwater Monitoring

The Consultant shall examine the existing institutional capacity for groundwater monitoring on Tongatapu and:

(a) Review the adequacy of existing groundwater monitoring capacity across all relevant agencies;

(b) Determine the monitoring requirements for effective and efficient water resource management and make appropriate recommendations;

(c) Recommend improved institutional arrangements to maximise the effectiveness and efficiency of groundwater monitoring and reporting;

(d) Develop guidelines identifying appropriate groundwater monitoring methods;

(e) Where appropriate, provide training in groundwater monitoring techniques, scheduling, planning and reporting.

(f) Identify the capacity building needs for local counterparts and staff involved in water resource monitoring, analysis, assessment and reporting.

Activity 3 - Vulnerability Assessment for Groundwater Resources

The Consultant shall assess the vulnerability of the groundwater resources of Tongatapu and:

(a) Identify primary water supply resources on Tongatapu;

(b) Review current groundwater abstraction techniques and recommend improvements;

(c) Identify groundwater areas at risk of suffering from over-abstraction, saline intrusion or upcoming;

(d) Identify primary natural and anthropogenic threats to the aquifer and main water supply wellfields and assess their risks

(e) Recommend risk mitigation techniques for groundwater supply sources;

(f) Where appropriate, provide training and transfer knowledge to local counterparts in above activities (a) to (e).

Activity 4 - Review Quarrying Activities and Potential Impacts on Water Resources

The Consultant shall assess the potential impact to water resources stemming from aggregate extraction and quarrying activities and:

(a) Identify the location of all sites of aggregate extraction and quarrying activities;

(b) Review aggregate extraction licensing and enforcement processes;

(c) Review mineral land planning process and land zoning plans;

(d) Review aggregate extraction practices including excavation, blasting, waste stockpiling, site water control, fuel storage;

(e) Review dewatering practices (where occurring) including monitoring and reporting;

(f) Determine the impact on water resources for selected sites as determined with SOPAC, MLSNRE & TWB;

(g) Recommend best practice groundwater control, protection and impact mitigation of quarrying activities;

(h) Identify quarry after-use restoration practices to minimise residual risk to groundwater; advise on post-closure monitoring requirements and pollution liabilities;

(i) Develop water sources protection strategies to support land and mineral planning process;

(j) Where appropriate, provide training on groundwater environmental risk assessments for quarrying activities.

Activity 5 - Development of GIS Data Sets Suitable for Water Resources

The Consultant shall:

(a) Identify all existing data sets in Agencies and Departments that are suitable for inclusion in development of a GIS for water resource management and assessment;

(b) Where appropriate, transfer knowledge to local counterparts in applications of GIS for water resource management.

Activity 6 - Final Deliverables

The consultant shall:

(a) Provide a Final Report which includes a comprehensive summary of all the major outcomes of the Activities 1-5 as outlined above. The Final Report shall be fully supported by comprehensive photographic records, a Manual on monitoring practice, a Manual on Quality Assurance for water resource data collection and archiving, and a Manual on best practice guidelines for protection of water resources from quarrying activities.

(b) Organise and conduct a workshop (not exceeding 2-days total duration) in Nuku'alofa to present to all key stakeholders the primary elements identified during the groundwater evaluation & monitoring assessment. The workshop should include a single fieldtrip to demonstrate pertinent site operational observations and emphasise conclusions and recommendations. The workshop should also seek to maximise the community awareness raising and media opportunities, as well as completing a formal hand-over ceremony of the Final Report and associated Guidance Manuals to the Government of Tonga.

(c) Collate a draft Cabinet Briefing Paper based upon Tongan Draft National Water Policy and assimilation of the results of the groundwater evaluation & monitoring assessment within the Final Report and key stakeholder feedback received during the workshop. The Cabinet Briefing Paper should not only emphasise the key conclusions and recommendations, but most importantly also make recommendations of the most efficient and effective institutional arrangements for national water resource monitoring. Indicative annual staffing, equipment budget and training requirements should also be presented.

Annex B

Visit diary, 19 July-22 August 2007

Date	Activity
Thu 19th Jul	• Flights from home bases in Australia to Suva via Sydney and Nadi. • Accommodation in Suva
Fri 20th Jul	• Meetings at SOPAC with relevant personnel. • Meetings with AusAID, Australian High Commission, Suva • Accommodation in Suva
Sat 21st Jul	• Flights from Suva to Tonga via Nadi. • Accommodation Nuku'alofa
Sun 22nd Jul	• Site visits Western Tongatapu – Kahoua Quarry
Mon 23rd Jul	• Interviews Geology Section MLSNRE
Tue 24th Jul	• Interviews Tonga Water Board
Wed 25th Jul	• Interviews Geology Section, Land Survey & GIS Unit, Environment Section, MLSNRE; TWB
Thu 26th Jul	• Interviews TWB;
Fri 27th Jul	• Interview Solid Waste Management Project
Sat 28th Jul	• Field work Mataki'eua/Tongamai Wellfield –Kahoua Quarry
Sun 29th Jul	• Site visits Eastern Tongatapu
Mon 30th Jul	• Interviews Public Health, Ministry of Health • Interview, Agricultural Research, Ministry of Agriculture, Food, Forestry , and Fisheries
Tue 31st Jul	• Field work Tapuhia Waste Facility-Tapuhia Quarry • Visit Vaini Agricultural Research Station, MAFF • Interview Tonga Trust • Interview GIO Scrap Steel recycling • Rotary Meeting
Wed 1st Aug	• Training MLSNRE
Thu 2nd Aug	• Interviews Budget Division Ministry of Finance and Economic Planning • Field work/Training Mataki'eua/Tongamai Wellfield
Fri 3rd Aug	• Interview Meteorology Service • Comparison bacteriological tests • Visit sites for intensive water sampling
Sat 4th Aug	• Interview TWB • Flight from Tonga to Nadi for Tony Falkland
Sun 5th Aug	• Flight from Nadi to Australia for Tony Falkland • Inspection Malapo Quarry • Field work eastern Tongatapu • Intensive sampling site selection
Mon 6th Aug	• Site selection intensive sampling Tongatapu
Tue 7th Aug	• Intensive sampling 10 wells • Send off water samples
Wed 8th Aug	• Field work and training – salinity monitoring boreholes
Thu 9th Aug	• Calibration of instruments. Interviews Public Health Ministry of Health • Interview SOPAC Country Rep, MLSNRE

Fri 10th Aug	• Field work Loto'hapai , Liahona & Mataki'eua • Interview TWB • Interview Solid Waste Management Project
Sat 11th Aug	• Interview TWB • Flight from Tonga to Nadi for Ian White
Sun 12th Aug	• Flight from Nadi to Australia for Ian White
Mon 13th Aug	• Brief Trip Report to SOPAC • Calibration instruments
Tue 14th Aug	• Field work –salinity survey village wells Tongatapu
Wed 15th Aug	• Field work –salinity survey village wells Tongatapu
Thu 16th Aug	• Enter data
Fri 17th Aug	• Field work Mataki'eua
Sat 18th Aug	• Field work Mataki'eua
Sun 19th Aug	• Rest day
Mon 20th Aug	• Discussions MLSRE
Tue 21st Aug	• Flight from Tonga to Nadi for Tevita Fatai
Wed 22nd Aug	• Flight from Nadi to Australia for Tevita Fatai

Annex C

Persons interviewed

Time & Date	Person & Position	Section	Ministry/Organisation
8:30, 23 Jul 2007	Rennie Vaiomounga, Deputy Government Geologist	Geology Section	MLSNRE
14:00, 23 Jul 2007	Asipeli Palaki, Deputy CEO/Secretary		MLSNRE
11:00, 24 Jul 2007	Saimone Helu, General Manager, and Ofa Mafua, Acting Chief Engineer		Tonga Water Board
9:00, 25 Jul 2007	Kelepi Mafi, Principal Government Geologist	Geology Section	MLSNRE
12:30, 25 Jul 2007	Timote Fakatava, Laboratory Manager		Tonga Water Board
14:00, 25 Jul 2007	Richard Kautoke, Head	Land Information and GIS Unit	MLSNRE
15:00, 25 Jul 2007	Lupe Matoto, Director	Environment	MLSNRE
9:00, 26 Jul 2007	Ofa Mafua, Acting Chief Engineer		Tonga Water Board
11:00, 26 Jul 2007	Timote Fakatava, Laboratory Manager		Tonga Water Board
19:30, 26 Jul 2007	Quddus Fielea, Chief Engineer		Tonga Water Board
10:00, 27 Jul 2007	John Gildea, Australian Team Leader		Solid Waste Management Project
14:00, 30 Jul 2007	Te'efoto Mausia, Acting Supervising Public Health Inspector	Public Health	Ministry of Health
16:30, 30 Jul 2007	Dr Viliami T. Manu, Director	Agricultural Research	MAFFF
15:00, 31 Jul 2007	Sione Faka'osi, Executive Director		Tonga Trust
19:00, 31 Jul 2007	Ofa Tu'ikolovalu, Chief Executive		GIO Scrap Steel Recycling
10:00, 02 Aug 2007	Henry Cocker & Winston Halapua	Budget Division	Ministry of Finance and Economic Planning
10:00, 03 Aug 2007	Ofa Fa'anunu, Director	Tonga Meteorological Service	
9:00, 04 Aug 2007	Quddus Fielea, Chief Engineer		Tonga Water Board
10:00, 09 Aug 2007	Dr Malachi 'Ake, Director	Environmental Health Division	Ministry of Health

10:30, 09 Aug 2007	Te'efoto Mausia, Acting Supervising Public Health Inspector	Public Health Section	Ministry of Health
11:00, 09 Aug 2007	Mele Falahau, Laboratory technician		Ministry of Health
15:00, 09 Aug 2007	Dr Sione N. Halatuituia, CEO and Secretary, SOPAC Country Representative		MLSNRE
15:00, 10 Aug 2007	Ofa Mafua, Acting Chief Engineer		Tonga Water Board
15:40, 10 Aug 2007	John Gildea, Australian Team Leader		Solid Waste Management Project
9:30, 11 Aug 2007	Saimone Helu, General Manager (by phone)		Tonga Water Board

Annex D

Summary of completed tasks

1. Held discussions in Suva with SOPAC on project and related matters.
2. Held discussions and Interviews with key people and organisations in the Tongatapu Water Sector
3. Assessed the aims and capacity of organisations involved in water supply monitoring.
4. At the request of the Principal Geologist, MLSNRE, reviewed and suggested changes to the Draft Water Resources Act.
5. Identified equipment and other needs of relevant agencies for groundwater monitoring in Tongatapu.
6. Conducted a vulnerability assessment of groundwater resources.
7. Assessed the GIS capability of MLSNRE.
8. Examined 3 out of 10 limestone quarries on Tongatapu.
9. Examined the condition of all 39 Tonga Water Board well and bore pumping stations for the water supply of Nuku’alofa (the main town of Tongatapu).
10. Monitored the salinity and pH in 31 of the total of 39 Tonga Water Board well and bore pumping stations for the water supply of Nuku’alofa plus domestic TWB tap water towards the end of the piped supply plus tank rainwater [wells or bores not sampled either had no pumps or no sample valves].
11. Tested the presence or absence of faecal indicator bacteria in 6 Tonga Water Board Well and Bore Pumping Stations plus domestic TWB tap water towards the end of the piped supply plus tank rainwater and boiled tank rainwater.
12. Monitored the field salinity and pH in 10 selected village water supplies. [These were chosen to give a good geographic spread, a good spread of land use and a spread of water supply systems].
13. Tested the presence or absence (to date) of faecal indicator bacteria in 10 village water supply pumping station bores and wells and in 2 college water supply pumping station bores.
14. Monitored the salinity and pH and tested the presence or absence of faecal indicator bacteria in 7 monitoring boreholes surrounding a waste disposal site in a limestone mining quarry.
15. Compared tests for the presence or absence of faecal indicator bacteria using the Colisure and H_2S test in 23 water samples.
16. Measured the thickness of the freshwater lens in 7 salinity monitoring boreholes to a depth of up to 29 m below the water table.
17. Related the change in thickness of the freshwater lens to distance from Fanga’uta Lagoon.
18. Related the salinity at Mataki’eua to previous rainfall
19. Collected and shipped 10 water samples for intensive testing of major cations and anions, heavy metals, pesticides and hydrocarbons from 5 village water supply pumping station bores and wells. 3 and in 2 college water supply pumping station bores Tonga Water Board well and bore pumping stations for the water supply of Nuku’alofa. [These were chosen to give a good geographic spread, a good spread of land use and a spread of water supply systems].
20. Installed automatic water level, salinity and temperature sensor in Tonga Water Board pumping station well.
21. Measured the drawdown of the water table due to pumping in one well.
22. Geo-referenced all measurement and sampling sites

23. Provided laboratory and field training on the calibration and use of salinity, pH, temperature and depth monitoring equipment.
24. Provided training laboratory and field training on the techniques for the identification of the presence or absence of faecal indicator organisms.
25. Provided field training on the taking of water samples for intensive chemical analysis.
26. Provided training in the entering of field data into databases.
27. Provided training in the identification of outliers and spurious data values.
28. Examined 3 out of 10 limestone quarries on Tongatapu.
29. Transferred all collected and analysed data to Geology, MLSNRE, Tonga Water Board, and National Waste Management Authority.
30. Transferred data on faecal indicator bacteria in village water supply systems to Ministry of Health/MLSNRE.
31. Held discussions with Dr Sione N. Halatuituia, CEO and Secretary MLSNRE, SOPAC Country Representative.
32. Submitted summary report of activities to SOPAC
33. Submitted report on salinity and rainfall in Mataki'eua wells to SOPAC, MLSNRE, TWB.
34. Submitted summary report on intensive water sampling in 10 water supply wells to SOPAC, MLSNRE, TWB, MoH, WA, TT.
35. Submitted report on meteorological hydrological droughts in Tongatapu to SOPAC, MLSNRE, TWB, MS, MAFFF.
36. Held discussions with Tonga Water Board concerning the Hihifo water supply project.
37. Held discussions with HRH Princess Nanasipau'u Tuku'aho and Rev Dr ‘Ahio concerning the Hihifo water supply project.
38. Conducted Workshop to present results of project to invited staff from SOPAC, MLSNRE, TWB, MoH, TMS, MAFFF, TT and developed draft Cabinet Briefing Note.
39. Submitted summary report on Workshop to SOPAC.
40. Submitted draft Cabinet Briefing Note to MLSNRE and SOPAC
41. Submitted final report to SOPAC, MLSNRE, TWB, MoH,

Annex E

List of Tongatapu village water supply wells sampled

Location	Well No.	Date Sampled	Location	
			Longitude (West) Decimal degree	Latitude (South) Decimal degree
Niutoua	45	14-Aug-07	175.04771	21.14959
Afa	57	14-Aug-07	175.05763	21.13831
Kolonga	49	14-Aug-07	175.07413	21.14093
Manuka	62	14-Aug-07	175.09261	21.13282
Navutoka	56	14-Aug-07	175.10393	21.13702
Talafo'ou	61	14-Aug-07	175.11262	21.13865
Makaunga	59	14-Aug-07	175.11709	21.14778
Nukuleka	254	14-Aug-07	175.11540	21.14315
Hoi	47	14-Aug-07	175.10976	21.16348
Lapaha	37	14-Aug-07	175.11025	21.18396
Tatakamatonga	18	14-Aug-07	175.11773	21.18787
Alakifonua	53	14-Aug-07	175.13536	21.20376
Holonga	190	14-Aug-07	175.14223	21.19705
Malapo	55	14-Aug-07	175.15440	21.20426
Pelehake		14-Aug-07	175.13535	21.22100
Airport township	9	14-Aug-07	175.13432	21.23820
Fua’amotu	268	14-Aug-07	175.13659	21.25102
Fua'amotu	182	14-Aug-07	175.13958	21.25574
Nakolo	40	14-Aug-07	175.12527	21.26459
Hamula	256	14-Aug-07	175.11378	21.25199
Haasini	42	14-Aug-07	175.11030	21.24877
Lavengatonga	236	14-Aug-07	175.11080	21.23244
Fatumu	14	14-Aug-07	175.11044	21.21322
Haveluliku	50	14-Aug-07	175.10613	21.20012
Vaini	5	14-Aug-07	175.16603	21.20075
Vaini	29	14-Aug-07	175.18120	21.18987
Longoteme	76	14-Aug-07	175.17125	21.17635
Nukuhetulu	81	14-Aug-07	175.19389	21.16560
Folaha	78	14-Aug-07	175.18537	21.17410
LDS Nualei	252	14-Aug-07	175.19520	21.18828
Veitongo	201	14-Aug-07	175.20997	21.18997
Haateiho	83	14-Aug-07	175.23091	21.18238
Pea	88	15-Aug-07	175.24233	21.17034
Utulau	250	15-Aug-07	175.27122	21.18832
Ha'alalo	162	15-Aug-07	175.27990	21.18343
Ha'akame	163	15-Aug-07	175.28454	21.17972
Houma	166	15-Aug-07	175.30006	21.16552
Vaotu'u	66	15-Aug-07	175.31260	21.15689

Location	Well No.	Date Sampled	Location	
			Longitude (West) Decimal degree	Latitude (South) Decimal degree
Ha'utu	157	15-Aug-07	175.33048	21.14040
Kala'au	156	15-Aug-07	175.33765	21.13795
Ha'avakatolo	155	15-Aug-07	175.34175	21.10675
Fo’ui (Hihifo Water Supply)	152	15-Aug-07	175.33322	21.12564
Masilamea	68	15-Aug-07	175.32620	21.12728
Matahau	147	15-Aug-07	175.31751	21.14422
Te'ekiu	65	15-Aug-07	175.31974	21.13101
Nukunuku	144	15-Aug-07	175.30182	21.13645
Fatai	133	15-Aug-07	175.27797	21.13902
Lakepa	134	15-Aug-07	175.27784	21.14300
Matangiake	139	15-Aug-07	175.27337	21.16446
Kahoua	170	15-Aug-07	175.26937	21.16071
Lomaiviti	192	15-Aug-07	175.25821	21.16886
Tokomololo	86	15-Aug-07	175.24992	21.17407
Hofoa	89	15-Aug-07	175.22995	21.13419
Vaini	3	15-Aug-07	175.17424	21.19972
Puke	217	15-Aug-07	175.24162	21.13308
Sia'atoutai Bible College	93	15-Aug-07	175.25827	21.13804

Annex F

List of Tonga Water Board wells sampled at the Mataki'eua/Tongamai wellfield

TWB Well No.	Location Longitude (West) Decimal degree	 Latitude (South) Decimal degree	RL Top of Concrete (m)
102	175.2397	21.1568	20.320
124	175.2412	21.1578	9.920
211	175.2423	21.1576	??
218	175.2438	21.1570	??
217	175.2447	21.1561	??
122	175.2455	21.1549	17.860
110	175.2443	21.1543	18.120
108	175.2437	21.1557	21.580
106	175.2427	21.1565	21.870
104	175.2413	21.1565	16.590
105	175.2421	21.1541	15.020
103	175.2408	21.1533	12.890
101	175.2399	21.1539	12.500
107	175.2417	21.1526	13.590
109	175.2426	21.1519	11.440
111	175.2435	21.1513	10.060
115	175.2449	21.1507	12.290
117	175.2461	21.1500	12.740
114	175.2474	21.1494	11.960
116	175.2482	21.1511	13.160
118	175.2489	21.1524	13.490
120	175.2474	21.1532	13.810
112	175.2452	21.1532	16.530
113	175.2441	21.1528	16.920
212	175.2434	21.1533	??
119	175.2458	21.1520	12.540
121	175.2518	21.1512	12.550
123	175.2529	21.1505	12.090
125	175.2541	21.1498	9.870
126	175.2552	21.1492	9.210
127	175.2565	21.1485	8.370
128	175.2575	21.1478	8.590
130	175.2586	21.1469	8.110
214	175.2469	21.1541	??
131	175.2526	21.1536	??
132	175.2532	21.1550	??
133	175.2540	21.1540	??
216	175.2472	21.1555	??
215	175.2455	21.1569	??

Annex G

List of compounds and dissolved species tested in water samples from 10 water supply wells

Organochlorine (OC) Pesticides			Organophosphate (OP) Pesticides		
Compound	**Detection Limit (µg/L)**	**Analysis Method**	**Compound**	**Detection Limit (µg/L)**	**Analysis Method**
HCB	<0.01	NR_19	Demeton-S-Methyl	<0.1	NR_19
Heptachlor	<0.01	NR_19	Dichlorvos	<0.1	NR_19
Heptachlor epoxide	<0.01	NR_19	Diazinon	<0.1	NR_19
Aldrin	<0.01	NR_19	Dimethoate	<0.1	NR_19
gamma-BHC (Lindane)	<0.01	NR_19	Chlorpyrifos	<0.1	NR_19
alpha-BHC	<0.01	NR_19	Chlorpyrifos Methyl	<0.1	NR_19
beta-BHC	<0.01	NR_19	Malathion	<0.1	NR_19
delta-BHC	<0.01	NR_19	Fenthion	<0.1	NR_19
trans-Chlordane	<0.01	NR_19	Azinphos Ethyl	<0.1	NR_19
cis-Chlordane	<0.01	NR_19	Azinphos Methyl	<0.1	NR_19
Oxychlordane	<0.01	NR_19	Chlorfenvinphos (E)	<0.1	NR_19
Dieldrin	<0.01	NR_19	Chlorfenvinphos (Z)	<0.1	NR_19
p,p-DDE	<0.01	NR_19	Ethion	<0.1	NR_19
p,p-DDD	<0.01	NR_19	Fenitrothion	<0.1	NR_19
p,p-DDT	<0.01	NR_19	Parathion (Ethyl)	<0.1	NR_19
Endrin	<0.01	NR_19	Parathion	<0.1	NR_19
Endrin Aldehyde	<0.01	NR_19	Pirimiphos Ethyl	<0.1	NR_19
Endrin Ketone	<0.01	NR_19	Pirimiphos Methyl	<0.1	NR_19
alpha-Endosulfan	<0.01	NR_19			
beta-Endosulfan	<0.01	NR_19			
Endosulfan Sulfate	<0.01	NR_19			
Methoxychlor	<0.01	NR_19			

Trace Elements			Cations and Anions, TDS, Hardness, pH, EC		
Compound	**Detection Limit (µg/L)**	**Analysis Method**	**Compound**	**Detection Limit (µg/L)**	**Analysis Method**
Aluminium-Total	<5	NT2_47	Sodium total		NT2_47
Arsenic-Total	<1	NT247_251	Potassium		NT2_47
Beryllium-Total	<1	NT2_47	Calcium-Total		NT2_47
Cadmium-Total	<1	NT2_47	Magnesium-Total		NT2_47
Chromium-Total	<1	NT2_47	Chloride		NWD3_NWB14
Copper-Total	<1	NT2_47	Sulphate		NWD10NWB14
Iron-Total	<5	NT2_47	Fluoride		NW_B3
Lead-Total	<1	NT2_47	Bicarb. as (HCO_3)		NW_B1
Manganese-Total	<1	NT2_47	Carbonate		NW_B1
Mercury-Total	<0.1	NT2_47_244	Total Dissolved Solids		NW_B10A
Nickel-Total	<1	NT2_47	Hardness total		NWD5
Selenium-Total	<1	NT2_47_244	pH		NW_S11
Zinc-Total	<1	NT2_47	EC		NW_B9

BTEX and Total Petroleum Hydrocarbons			**Nutrients**		
Compound	**Detection Limit (μg/L)**	**Analysis Method**	**Compound**	**Detection Limit (μg/L)**	**Analysis Method**
Benzene	<1	NGCMS_1121	Phosphorus total	<20	NT2_47
Toluene	<1	NGCMS_1121	Nitrate as NO3		NW_B19
Ethyl Benzene	<1	NGCMS_1121	Nitrite as NO2	<20	NW_B19
m, p - Xylene	<2	NGCMS_1121			
o - Xylene	<1	NGCMS_1121			
TPH C6 - C9	<25	NGCMS_1121			
TPH C10 - C14	<25	NGCMS_1121			
TPH C15 - C28	<100	NGCMS_1121			
TPH C29 - C36	<100	NGCMS_1121			

Annex H

Mean values of EC for Tongatapu village wells, 1965-2007

Date or Average Date	EC (μs/cm)				No. of wells measured
	Mean	Std Dev	Log Mean	Median	
08-Mar-65	907	611	779	660	14
10-Sep-65	642	113	633	620	10
01-Feb-71	994	649	872	770	32
01-Jul-79	1,052	406	994	900	25
01-Mar-80	968	325	924	900	40
01-May-81	1,093	409	1,028	1,000	40
01-Apr-83	1,083	352	1,037	1,000	41
24-May-90	1,456	984	1,247	1,080	87
01-Aug-90	1,391	1,010	1,198	1,097	79
02-Nov-90	1,446	1,171	1,188	1,163	63
22-Jan-91	1,225	513	1,148	1,103	56
08-May-91	1,273	497	1,204	1,212	49
11-Sep-91	1,080	579	971	894	70
09-Dec-91	1,228	1,056	1,059	963	50
04-Mar-92	1,215	590	1,106	1,055	52
10-Nov-92	1,151	577	1,050	1,026	55
01-Apr-93	1,322	941	1,121	1,064	55
01-Sep-93	1,059	572	956	943	44
14-Dec-93	1,535	932	1,355	1,249	41
15-Mar-95	1,749	1,113	1,481	1,389	45
19-Oct-95	1,657	686	1,532	1,471	48
01-Jul-96	1,892	1,187	1,636	1,420	44
12-Nov-96	1,758	1,030	1,572	1,507	48
03-Apr-97	1,433	589	1,339	1,316	43
27-Jun-97	1,439	644	1,341	1,337	48
18-Nov-97	1,689	784	1,550	1,411	47
24-Mar-98	1,745	844	1,591	1,443	42
10-Jul-98	1,564	806	1,418	1,337	47
23-Jul-99	1,367	732	1,238	1,209	42
02-Feb-00	873	275	833	817	42
27-Jul-00	832	199	811	788	42
10-Apr-03	1,070	468	988	895	53
08-Aug-03	1,119	493	1,030	1,052	44
22-Jan-04	1,199	517	1,109	1,063	65
06-Apr-04	1,205	513	1,114	1,047	57
02-Jun-04	1,282	554	1,186	1,158	57
10-Nov-04	1,164	432	1,093	1,054	57
22-Jun-05	1,090	390	1,029	1,003	57
06-Oct-05	1,033	419	961	939	57
07-Feb-06	1,055	427	983	963	61
14-Aug-07	1,015	314	972	975	55

Annex I

Salinity profiles in and near the Mataki'eua/Tongamai wellfield measured, 8th August 2007

Salinity Monitoring Borehole	Location		Distance from Seawater (m)	Depth below WT (m)	EC (μS/cm)
	Longitude West (dec deg)	Latitude South (dec deg)			
SMB1	175.23464	21.15883	830	-1.515	637
				-6.85	5,407
				-11.92	22,282
				-14.295	39,172
SMB2	175.24172	21.15389	1,886	-1.985	790
				-4.895	1,369
				-5.18	1,352
				-11.605	11,815
				-12.44	16,097
				-24.905	53,445
SMB3	175.24494	21.15061	2,479	-0.845	931
				-2.515	883
				-4.775	981
				-11.18	5,888
				-14.445	20,300
				-22.375	49,798
SMB4	175.24830	21.15098	2,824	-3.37	837
				-6.276	971
				-10.545	2,993
				-15.275	26,009
				-18.145	44,564
				-21.705	54,476
SMB5	175.25738	21.14767	2,650	-2.595	796
				-5.189	1,377
				-10.125	2,275
				-14.965	12,053
				-20.095	41,868
				-23.705	54,080
SMB6	175.26665	21.16012	4,208	-2.745	759
				-5.26	773
				-9.745	791
				-14.235	3,628
				-19.995	44,644
				-27.32	53,128
SMB7	175.25485	21.13738	2,076	-7.41	1,055
				-8.95	1,146
				-14.595	5,242
				-19.495	3,7507
				-24.26	50,274
				-29.18	50,274

Annex J

Groundwater recharge – sample results from WATBAL

This Annex presents a sample of monthly and annual groundwater recharge estimates based on the analysis for Case 1 outlined in Section 9.

WATBAL: Water Balance Program to compute Recharge to Groundwater using Monthly Rainfall and Average Monthly Evaporation Data

```
------------------------------------------------------------------------
RAINFALL & EVAPORATION DATA USED IN WATER BALANCE
-------------------------------------------------
 Name of Monthly Rainfall File :  Nukurain.txt
 Title of Rainfall Data      :  Monthly rain data: Nuku'alofa: Tongatapu: 1945-
2006

 Name of Monthly Evap File   :  Tongevap.txt
 Title of Evaporation        :  Monthly evap (Penman):Tongatapu: (from Thompson,
1986)

 No.of Years of Rain Record  :  62
 First Year of Rain Record   :  1945
 Last Year of Rain Record    :  2006
------------------------------------------------------------------------
INPUT SOIL AND VEGETATION PARAMETERS
------------------------------------

Interception Store Capacity (ISMAX) in mm =                90
Initial Interception Store (IIS) in mm =                   90
Soil Moisture Zone Thickness(SMZ) in mm =                  1000
Field Capacity(FC)=                                        0.55
Wilting Point(WP)=                                         0.4
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)=      0.3
Ratio of these roots reaching water table(DRWT)=           0
Crop Factor for Deep Rooted Vegetation(CROPFD)=            0.8
Crop Factor for Shallow Rooted Vegetation(CROPFS)=         1
Linear Relation of Ea/Et(actual/potential evap) ratio to SMC
------------------------------------------------------------------------
```

Explanations for the column headings in the listings below:

RAIN	monthly rainfall (addition of daily values)
ET	monthly potential evaporation
EI	monthly interception loss
SMC1	soil moisture content at start of month
ES	monthly evaporation from soil moisture store
XCESS	rainfall minus evaporation losses above (EI + ES)
AVSMDEF	average soil moisture deficit for the month
SMC2	soil moisture content at end of month
GWR	gross 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)

```
YEAR 1945
---------
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
------------------------------------------------------------------------
 142  164  90  500   46   96    50  550    46    0  136   46    +0.32
 182  137  90  550   44   48     0  550    48    0  134   48    +0.26
 138  139  90  550   46    2     0  550     2    0  136    2    +0.01
 152  108  90  550   17   45     0  550    45    0  107   45    +0.30
 182   89  89  550    0   92     0  550    92    0   89   92    +0.51
  99   77  77  550    0   10     0  550    10    0   77   10    +0.10
 113   85  85  550    0   36     0  550    36    0   85   36    +0.32
 132   96  90  550    6   41     0  550    41    0   96   41    +0.31
  73  116  73  550   40  -40     0  510     0    0  113    0    +0.00
  21  144  21  510   84  -84    40  425     0    0  105    0    +0.00
  37  152  37  425   18  -18   125  407     0    0   55    0    +0.00
  12  154  12  407    6   -6   143  401     0    0   18    0    +0.00
------------------------------------------------------------------------
1283 1461 844       308                   320    0 1152  320    +0.25
------------------------------------------------------------------------
YEAR 1946
---------
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
------------------------------------------------------------------------
  10  164  10  401    1   -1   149  400     0    0   11    0    +0.00
 101  137  90  400    0   11   150  411     0    0   90    0    +0.00
 175  139  90  411    3   82   139  493     0    0   93    0    +0.00
  33  108  33  493   44  -44    57  449     0    0   77    0    +0.00
 139   89  89  449    0   49   101  498     0    0   89    0    +0.00
  30   77  31  498   28  -28    52  470     0    0   59    0    +0.00
  49   85  49  470   16  -16    80  454     0    0   65    0    +0.00
  89   96  89  454    2   -2    96  452     0    0   91    0    +0.00
  11  116  11  452   34  -34    98  418     0    0   45    0    +0.00
 276  144  90  418    6  180   132  550    48    0   96   48    +0.17
  40  152  40  550  105 -105     0  445     0    0  145    0    +0.00
  36  154  36  445   33  -33   105  412     0    0   69    0    +0.00
------------------------------------------------------------------------
 989 1461 658       272                    48    0  930   48    +0.05
------------------------------------------------------------------------
YEAR 1947
---------
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
------------------------------------------------------------------------
 118  164  90  412    5   23   138  434     0    0   95    0    +0.00
 248  137  90  434   10  148   116  550    32    0  100   32    +0.13
  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       283                   225    0 1245  225    +0.14
------------------------------------------------------------------------
```

```
YEAR 1948
---------
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
------------------------------------------------------------------------
 255  164  90  550   70   95     0  550    95    0  160   95    +0.37
 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
  44   96  44  509   35  -35    41  473     0    0   79    0    +0.00
 120  116  90  473   12   18    77  491     0    0  102    0    +0.00
  22  144  22  491   70  -70    59  421     0    0   92    0    +0.00
 351  152  90  421    8  253   129  550   124    0   98  124    +0.35
 256  154  90  550   60  106     0  550   106    0  150  106    +0.41
------------------------------------------------------------------------
1900 1461 863       439                   598    0 1302  598    +0.31
------------------------------------------------------------------------
YEAR 1949
---------
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
------------------------------------------------------------------------
 244  164  90  550   70   84     0  550    84    0  160   84    +0.35
 218  137  90  550   44   84     0  550    84    0  134   84    +0.38
 201  139  90  550   46   65     0  550    65    0  136   65    +0.32
 211  108  90  550   17  104     0  550   104    0  107  104    +0.49
  23   89  23  550   62  -62     0  488     0    0   85    0    +0.00
  25   77  25  488   29  -29    62  459     0    0   54    0    +0.00
 104   85  85  459    0   14    91  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
  84  144  84  503   39  -39    47  464     0    0  123    0    +0.00
   8  152   8  464   58  -58    86  406     0    0   66    0    +0.00
 251  154  90  406    3  158   144  550    15    0   93   15    +0.06
------------------------------------------------------------------------
1638 1461 831       416                   391    0 1247  391    +0.24
------------------------------------------------------------------------
YEAR 1950
---------
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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
 203  164  90  527   59   54    23  550    31    0  149   31    +0.15
 564  137  90  550   44  430     0  550   430    0  134  430    +0.76
 305  139  90  550   46  169     0  550   169    0  136  169    +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
  74   77  75  550    2   -2     0  548     0    0   77    0    +0.00
 104   85  85  548    0   14     2  550    12    0   85   12    +0.12
  25   96  30  550   62  -62     0  488     0    0   92    0    +0.00
 188  116  90  488   14   84    62  550    22    0  104   22    +0.12
  43  144  43  550   95  -95     0  455     0    0  138    0    +0.00
  20  152  20  455   46  -46    95  410     0    0   66    0    +0.00
   3  154   3  410    9   -9   140  401     0    0   12    0    +0.00
------------------------------------------------------------------------
1760 1461 795        394                 698    0 1189  698    +0.40
------------------------------------------------------------------------
YEAR 1952
---------
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
------------------------------------------------------------------------
 582  164  90  401    0  492   149  550   342    0   90  342    +0.59
 442  137  90  550   44  308     0  550   308    0  134  308    +0.70
 290  139  90  550   46  154     0  550   154    0  136  154    +0.53
 127  108  90  550   17   20     0  550    20    0  107   20    +0.16
  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
 165   85  85  550    0   88     0  550    88    0   85   88    +0.53
 130   96  90  550    6   39     0  550    39    0   96   39    +0.30
  99  116  90  550   24  -15     0  535     0    0  114    0    +0.00
  20  144  20  535  105 -105    15  430     0    0  125    0    +0.00
 119  152  90  430   12   17   120  447     0    0  102    0    +0.00
 155  154  90  447   19   46   103  493     0    0  109    0    +0.00
------------------------------------------------------------------------
2307 1461 927        333                 954    0 1260  954    +0.41
------------------------------------------------------------------------
YEAR 1953
---------
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
------------------------------------------------------------------------
 127  164  90  493   43   -6    57  487     0    0  133    0    +0.00
 198  137  90  487   26   82    63  550    19    0  116   19    +0.10
 193  139  90  550   46   57     0  550    57    0  136   57    +0.30
 290  108  90  550   17  183     0  550   183    0  107  183    +0.63
  69   89  69  550   19  -19     0  531     0    0   88    0    +0.00
 117   77  77  531    0   27    19  550     8    0   77    8    +0.07
  48   85  61  550   23  -23     0  527     0    0   84    0    +0.00
  37   96  37  527   47  -47    23  480     0    0   84    0    +0.00
  23  116  23  480   47  -47    70  434     0    0   70    0    +0.00
  38  144  38  434   22  -22   116  411     0    0   60    0    +0.00
  71  152  71  411    6   -6   139  406     0    0   77    0    +0.00
 114  154  90  406    2   22   144  427     0    0   92    0    +0.00
------------------------------------------------------------------------
1325 1461 826        297                 268    0 1123  268    +0.20
------------------------------------------------------------------------
```

```
YEAR 1954
---------
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
------------------------------------------------------------------------
 109  164  90  427   13    6   123  434     0    0  103    0    +0.00
 218  137  90  434   10  118   116  550     2    0  100    2    +0.01
 114  139  90  550   46  -22     0  528     0    0  136    0    +0.00
 452  108  90  528   14  348    22  550   326    0  104  326    +0.72
  64   89  64  550   24  -24     0  527     0    0   88    0    +0.00
 241   77  77  527    0  151    24  550   128    0   77  128    +0.53
  38   85  51  550   32  -32     0  518     0    0   83    0    +0.00
 135   96  90  518    4   41    32  550     9    0   94    9    +0.06
 302  116  90  550   24  188     0  550   188    0  114  188    +0.62
 132  144  90  550   51   -9     0  541     0    0  141    0    +0.00
  48  152  48  541   92  -92     9  449     0    0  140    0    +0.00
 582  154  90  449   20  472   101  550   371    0  110  371    +0.64
------------------------------------------------------------------------
2435 1461 960       330                  1022    0 1290 1022    +0.42
------------------------------------------------------------------------
YEAR 1955
---------
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
------------------------------------------------------------------------
 198  164  90  550   70   38     0  550    38    0  160   38    +0.19
  84  137  84  550   50  -50     0  500     0    0  134    0    +0.00
 389  139  90  500   31  268    50  550   218    0  121  218    +0.56
  79  108  79  550   27  -27     0  523     0    0  106    0    +0.00
  61   89  61  523   22  -22    27  501     0    0   83    0    +0.00
  64   77  64  501    8   -8    49  493     0    0   72    0    +0.00
 122   85  85  493    0   32    57  525     0    0   85    0    +0.00
 122   96  90  525    5   32    25  550     7    0   95    7    +0.06
  38  116  38  550   73  -73     0  477     0    0  111    0    +0.00
 102  144  90  477   26  -14    73  463     0    0  116    0    +0.00
 290  152  90  463   24  176    87  550    88    0  114   88    +0.30
 221  154  90  550   60   71     0  550    71    0  150   71    +0.32
------------------------------------------------------------------------
1770 1461 951       396                   423    0 1347  423    +0.24
------------------------------------------------------------------------
YEAR 1956
---------
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
------------------------------------------------------------------------
 259  164  90  550   70   99     0  550    99    0  160   99    +0.38
 343  137  90  550   44  209     0  550   209    0  134  209    +0.61
 340  139  90  550   46  204     0  550   204    0  136  204    +0.60
 335  108  90  550   17  228     0  550   228    0  107  228    +0.68
 152   89  89  550    0   62     0  550    62    0   89   62    +0.41
  28   77  29  550   45  -45     0  505     0    0   74    0    +0.00
 191   85  85  505    0  101    45  550    56    0   85   56    +0.29
  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
   5  154   5  550  140 -140     0  410     0    0  145    0    +0.00
------------------------------------------------------------------------
2296 1461 928       500                  1008    0 1428 1008    +0.44
------------------------------------------------------------------------
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YEAR 1957
---------
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
------------------------------------------------------------------------
 401  164  90  410    5  306   140  550   166    0   95  166    +0.41
 447  137  90  550   44  313     0  550   313    0  134  313    +0.70
 132  139  90  550   46   -4     0  546     0    0  136    0    +0.00
  48  108  48  546   55  -55     4  491     0    0  103    0    +0.00
  74   89  74  491    9   -9    59  483     0    0   83    0    +0.00
 241   77  77  483    0  151    67  550    84    0   77   84    +0.35
  69   85  82  550    3   -3     0  547     0    0   85    0    +0.00
 193   96  90  547    6   97     3  550    95    0   96   95    +0.49
  94  116  90  550   24  -20     0  530     0    0  114    0    +0.00
  48  144  48  530   78  -78    20  452     0    0  126    0    +0.00
  61  152  61  452   29  -29    98  422     0    0   90    0    +0.00
  69  154  69  422   12  -12   128  410     0    0   81    0    +0.00
------------------------------------------------------------------------
1877 1461 909       310                   657    0 1219  657    +0.35
------------------------------------------------------------------------
YEAR 1958
---------
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
------------------------------------------------------------------------
  31  164  31  410    9   -9   140  402     0    0   40    0    +0.00
 307  137  90  402    1  216   148  550    68    0   91   68    +0.22
 269  139  90  550   46  133     0  550   133    0  136  133    +0.49
 137  108  90  550   17   30     0  550    30    0  107   30    +0.22
  38   89  38  550   48  -48     0  502     0    0   86    0    +0.00
   8   77   8  502   44  -44    48  458     0    0   52    0    +0.00
 117   85  85  458    0   27    92  485     0    0   85    0    +0.00
 117   96  90  485    3   29    65  514     0    0   93    0    +0.00
  56  116  56  514   43  -43    36  471     0    0   99    0    +0.00
 338  144  90  471   24  224    79  550   145    0  114  145    +0.43
 137  152  90  550   58  -11     0  539     0    0  148    0    +0.00
  76  154  76  539   68  -68    11  471     0    0  144    0    +0.00
------------------------------------------------------------------------
1631 1461 834       360                   376    0 1194  376    +0.23
------------------------------------------------------------------------
YEAR 1959
---------
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
------------------------------------------------------------------------
 203  164  90  471   33   80    79  550     1    0  123    1    +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
 117  108  90  550   17   10     0  550    10    0  107   10    +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
 272   96  90  530    5  177    20  550   157    0   95  157    +0.58
 185  116  90  550   24   71     0  550    71    0  114   71    +0.38
 193  144  90  550   51   52     0  550    52    0  141   52    +0.27
  41  152  41  550  104 -104     0  446     0    0  145    0    +0.00
 107  154  90  446   18   -1   104  444     0    0  108    0    +0.00
------------------------------------------------------------------------
1799 1461 962       368                   496    0 1330  496    +0.28
------------------------------------------------------------------------
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YEAR 1960
---------
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
------------------------------------------------------------------------
  69  164  69  444   26  -26   106  418     0    0   95    0    +0.00
 323  137  90  418    5  228   132  550    96    0   95   96    +0.30
 470  139  90  550   46  334     0  550   334    0  136  334    +0.71
 193  108  90  550   17   86     0  550    86    0  107   86    +0.45
 102   89  89  550    0   12     0  550    12    0   89   12    +0.12
 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
  33   96  38  550   55  -55     0  495     0    0   93    0    +0.00
  53  116  53  495   38  -38    55  458     0    0   91    0    +0.00
 135  144  90  458   20   25    92  483     0    0  110    0    +0.00
 206  152  90  483   32   84    67  550    17    0  122   17    +0.08
 231  154  90  550   60   81     0  550    81    0  150   81    +0.35
------------------------------------------------------------------------
2080 1461 951       299                   724    0 1250  724    +0.35
------------------------------------------------------------------------
YEAR 1961
---------
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
------------------------------------------------------------------------
 371  164  90  550   70  211     0  550   211    0  160  211    +0.57
 229  137  90  550   44   95     0  550    95    0  134   95    +0.41
 241  139  90  550   46  105     0  550   105    0  136  105    +0.44
 112  108  90  550   17    5     0  550     5    0  107    5    +0.05
  48   89  48  550   39  -39     0  511     0    0   87    0    +0.00
  58   77  58  511   13  -13    39  498     0    0   71    0    +0.00
  84   85  84  498    1   -1    52  498     0    0   85    0    +0.00
 152   96  90  498    4   58    52  550     6    0   94    6    +0.04
  89  116  89  550   25  -25     0  525     0    0  114    0    +0.00
  64  144  64  525   62  -62    25  462     0    0  126    0    +0.00
 201  152  90  462   24   87    88  549     0    0  114    0    +0.00
  66  154  66  549   82  -82     1  467     0    0  148    0    +0.00
------------------------------------------------------------------------
1715 1461 949       427                   422    0 1376  422    +0.25
------------------------------------------------------------------------
YEAR 1962
---------
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
------------------------------------------------------------------------
 381  164  90  467   31  260    83  550   177    0  121  177    +0.46
 188  137  90  550   44   54     0  550    54    0  134   54    +0.29
 262  139  90  550   46  126     0  550   126    0  136  126    +0.48
 112  108  90  550   17    5     0  550     5    0  107    5    +0.05
 139   89  89  550    0   49     0  550    49    0   89   49    +0.35
  74   77  75  550    2   -2     0  548     0    0   77    0    +0.00
  84   85  84  548    1   -1     2  547     0    0   85    0    +0.00
  53   96  53  547   40  -40     3  508     0    0   93    0    +0.00
  41  116  41  508   51  -51    42  457     0    0   92    0    +0.00
  71  144  71  457   26  -26    93  431     0    0   97    0    +0.00
 117  152  90  431   12   15   119  446     0    0  102    0    +0.00
 241  154  90  446   18  133   104  550    28    0  108   28    +0.12
------------------------------------------------------------------------
1763 1461 953       288                   439    0 1241  439    +0.25
------------------------------------------------------------------------
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YEAR 1963
---------
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
------------------------------------------------------------------------
 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
 226  139  90  550   46   90     0  550    90    0  136   90    +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
  61   85  74  550   10  -10     0  540     0    0   84    0    +0.00
 150   96  90  540    5   55    10  550    44    0   95   44    +0.30
 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
  10  152  10  539  124 -124    11  415     0    0  134    0    +0.00
  23  154  23  415   13  -13   135  403     0    0   36    0    +0.00
------------------------------------------------------------------------
1378 1461 882       417                   226    0 1299  226    +0.16
------------------------------------------------------------------------
YEAR 1964
---------
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
------------------------------------------------------------------------
  99  164  90  403    1    8   147  410     0    0   91    0    +0.00
 290  137  90  410    3  197   140  550    57    0   93   57    +0.20
 279  139  90  550   46  143     0  550   143    0  136  143    +0.51
 142  108  90  550   17   35     0  550    35    0  107   35    +0.25
 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
 257   85  85  486    0  167    64  550   103    0   85  103    +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
 104  144  90  550   51  -37     0  513     0    0  141    0    +0.00
 254  152  90  513   44  120    37  550    83    0  134   83    +0.33
 216  154  90  550   60   66     0  550    66    0  150   66    +0.30
------------------------------------------------------------------------
2059 1461 993       316                   602    0 1309  602    +0.29
------------------------------------------------------------------------
YEAR 1965
---------
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
------------------------------------------------------------------------
 396  164  90  550   70  236     0  550   236    0  160  236    +0.60
 290  137  90  550   44  156     0  550   156    0  134  156    +0.54
 211  139  90  550   46   75     0  550    75    0  136   75    +0.36
  41  108  41  550   63  -63     0  487     0    0  104    0    +0.00
 211   89  89  487    0  121    63  550    58    0   89   58    +0.27
  31   77  32  550   42  -42     0  508     0    0   74    0    +0.00
  69   85  69  508   11  -11    42  497     0    0   80    0    +0.00
 130   96  90  497    4   36    53  533     0    0   94    0    +0.00
  76  116  76  533   33  -33    17  500     0    0  109    0    +0.00
 130  144  90  500   34    6    50  506     0    0  124    0    +0.00
 178  152  90  506   41   47    44  550     3    0  131    3    +0.02
  18  154  18  550  128 -128     0  422     0    0  146    0    +0.00
------------------------------------------------------------------------
1781 1461 865       516                   528    0 1381  528    +0.30
------------------------------------------------------------------------
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YEAR 1966
---------
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
------------------------------------------------------------------------
  86  164  86  422   11  -11   128  411     0    0   97    0    +0.00
  97  137  90  411    3    4   139  415     0    0   93    0    +0.00
  84  139  84  415    5   -5   135  410     0    0   89    0    +0.00
 457  108  90  410    1  366   140  550   226    0   91  226    +0.49
  64   89  64  550   24  -24     0  527     0    0   88    0    +0.00
  46   77  46  527   25  -25    24  502     0    0   71    0    +0.00
  51   85  51  502   22  -22    48  480     0    0   73    0    +0.00
  46   96  46  480   25  -25    70  455     0    0   71    0    +0.00
 180  116  90  455    9   81    95  536     0    0   99    0    +0.00
 180  144  90  536   46   44    14  550    30    0  136   30    +0.17
  28  152  28  550  117 -117     0  433     0    0  145    0    +0.00
 160  154  90  433   13   57   117  490     0    0  103    0    +0.00
------------------------------------------------------------------------
1479 1461 855       300                 256    0 1155  256    +0.17
------------------------------------------------------------------------
YEAR 1967
---------
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
------------------------------------------------------------------------
 188  164  90  490   42   56    60  546     0    0  132    0    +0.00
 104  137  90  546   43  -29     4  517     0    0  133    0    +0.00
 244  139  90  517   36  118    33  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
  64   85  64  480   10  -10    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  497     0    0   97    0    +0.00
 147  144  90  497   33   24    53  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   22  -22   125  403     0    0   37    0    +0.00
------------------------------------------------------------------------
1254 1461 756       404                 181    0 1160  181    +0.14
------------------------------------------------------------------------
YEAR 1968
---------
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
------------------------------------------------------------------------
 528  164  90  403    1  437   147  550   290    0   91  290    +0.55
 244  137  90  550   44  110     0  550   110    0  134  110    +0.45
 297  139  90  550   46  161     0  550   161    0  136  161    +0.54
  97  108  90  550   17  -10     0  540     0    0  107    0    +0.00
  59   89  59  540   26  -26    10  514     0    0   85    0    +0.00
  86   77  77  514    0    0    36  514     0    0   77    0    +0.00
  28   85  37  514   34  -34    36  480     0    0   71    0    +0.00
 203   96  90  480    3  110    70  550    40    0   93   40    +0.19
  91  116  90  550   24  -23     0  527     0    0  114    0    +0.00
  94  144  90  527   43  -39    23  488     0    0  133    0    +0.00
  25  152  25  488   70  -70    62  418     0    0   95    0    +0.00
  51  154  51  418   12  -12   132  406     0    0   63    0    +0.00
------------------------------------------------------------------------
1803 1461 879       321                 600    0 1200  600    +0.33
------------------------------------------------------------------------
```

```
YEAR 1969
---------
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
------------------------------------------------------------------------
 178  164  90  406    3   85   144  491     0    0   93    0    +0.00
 297  137  90  491   27  180    59  550   121    0  117  121    +0.41
 348  139  90  550   46  212     0  550   212    0  136  212    +0.61
  84  108  84  550   23  -23     0  527     0    0  107    0    +0.00
  23   89  23  527   53  -53    23  475     0    0   76    0    +0.00
  43   77  43  475   16  -16    75  459     0    0   59    0    +0.00
 137   85  85  459    0   47    91  506     0    0   85    0    +0.00
  18   96  23  506   48  -48    44  457     0    0   71    0    +0.00
 132  116  90  457    9   33    93  490     0    0   99    0    +0.00
  51  144  51  490   52  -52    60  438     0    0  103    0    +0.00
  51  152  51  438   24  -24   112  414     0    0   75    0    +0.00
   5  154   5  414   13  -13   136  401     0    0   18    0    +0.00
------------------------------------------------------------------------
1367 1461 725       314                 333    0 1039  333    +0.24
------------------------------------------------------------------------
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
------------------------------------------------------------------------
 180  164  90  401    0   90   149  490     0    0   90    0    +0.00
 373  137  90  490   27  256    60  550   197    0  117  197    +0.53
 137  139  90  550   46    1     0  550     1    0  136    1    +0.01
 112  108  90  550   17    5     0  550     5    0  107    5    +0.05
  97   89  89  550    0    7     0  550     7    0   89    7    +0.07
  84   77  77  550    0    0     0  550     0    0   77    0    +0.00
  64   85  72  550   12  -12     0  538     0    0   84    0    +0.00
  56   96  56  538   35  -35    12  503     0    0   91    0    +0.00
  41  116  41  503   49  -49    47  455     0    0   90    0    +0.00
 373  144  90  455   19  264    95  550   169    0  109  169    +0.45
 107  152  90  550   58  -41     0  509     0    0  148    0    +0.00
 353  154  90  509   44  219    41  550   178    0  134  178    +0.50
------------------------------------------------------------------------
1977 1461 965       306                 557    0 1271  557    +0.28
------------------------------------------------------------------------
YEAR 1971
---------
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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
  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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
 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
------------------------------------------------------------------------
```

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YEAR 1978
---------
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
------------------------------------------------------------------------
  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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
 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
------------------------------------------------------------------------
```

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YEAR 1981
---------
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
------------------------------------------------------------------------
  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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
  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  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
------------------------------------------------------------------------
 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  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
------------------------------------------------------------------------
  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
   2  152   2  415   14  -14   135  401     0    0   16    0    +0.00
 429  154  90  401    0  339   149  550   190    0   90  190    +0.44
------------------------------------------------------------------------
1362 1461 759       300                   254    0 1059  254    +0.19
------------------------------------------------------------------------
YEAR 1986
---------
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
------------------------------------------------------------------------
  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  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
------------------------------------------------------------------------
  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
  23  116  23  419   11  -11   131  408     0    0   34    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  467     0    0   90    0     +0.00
------------------------------------------------------------------------
 899 1461 639       278                     26    0  917   26     +0.03
------------------------------------------------------------------------
YEAR 1988
---------
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
------------------------------------------------------------------------
 280  164  90  467   31  159    83  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
  45   96  50  505   30  -30    45  475     0    0   80    0     +0.00
 333  116  90  475   12  231    75  550   156    0  102  156     +0.47
 113  144  90  550   51  -28     0  522     0    0  141    0     +0.00
  27  152  27  522   96  -96    28  426     0    0  123    0     +0.00
 206  154  90  426   11  105   124  532     0    0  101    0     +0.00
------------------------------------------------------------------------
1777 1461 893       391                    428    0 1284  428     +0.24
------------------------------------------------------------------------
YEAR 1989
---------
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
------------------------------------------------------------------------
 143  164  90  532   61   -8    18  524     0    0  151    0     +0.00
 726  137  90  524   36  600    26  550   573    0  126  573     +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
 212   89  89  550    0  122     0  550   122    0   89  122     +0.58
  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
------------------------------------------------------------------------
2154 1461 %1002       381                     792    0 1383  792     +0.37
------------------------------------------------------------------------
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YEAR 1990
---------
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
------------------------------------------------------------------------
 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
------------------------------------------------------------------------
YEAR 1991
---------
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
------------------------------------------------------------------------
 325  164  90  550   70  165     0  550   165    0  160  165    +0.51
 251  137  90  550   44  117     0  550   117    0  134  117    +0.47
 164  139  90  550   46   28     0  550    28    0  136   28    +0.17
 139  108  90  550   17   32     0  550    32    0  107   32    +0.23
  42   89  42  550   44  -44     0  506     0    0   86    0    +0.00
  98   77  77  506    0    8    44  514     0    0   77    0    +0.00
  29   85  42  514   31  -31    36  483     0    0   73    0    +0.00
 208   96  90  483    3  115    67  550    48    0   93   48    +0.23
  53  116  53  550   59  -59     0  491     0    0  112    0    +0.00
  80  144  80  491   36  -36    59  454     0    0  116    0    +0.00
  24  152  24  454   44  -44    96  411     0    0   68    0    +0.00
  15  154  15  411    9   -9   139  401     0    0   24    0    +0.00
------------------------------------------------------------------------
1428 1461 783       403                    390    0 1186  390    +0.27
------------------------------------------------------------------------
YEAR 1992
---------
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
------------------------------------------------------------------------
  42  164  42  401    1   -1   149  400     0    0   43    0    +0.00
  68  137  68  400    0   -0   150  400     0    0   68    0    +0.00
  39  139  39  400    0   -0   150  400     0    0   39    0    +0.00
  68  108  68  400    0   -0   150  400     0    0   68    0    +0.00
  33   89  33  400    0   -0   150  400     0    0   33    0    +0.00
  40   77  40  400    0   -0   150  400     0    0   40    0    +0.00
 160   85  85  400    0   70   150  470     0    0   85    0    +0.00
 160   96  90  470    3   72    80  542     0    0   93    0    +0.00
  58  116  58  542   52  -52     8  491     0    0  110    0    +0.00
 135  144  90  491   31   14    59  505     0    0  121    0    +0.00
  44  152  44  505   71  -71    45  434     0    0  115    0    +0.00
 186  154  90  434   14   82   116  516     0    0  104    0    +0.00
------------------------------------------------------------------------
1033 1461 747       171                      0    0  918    0    +0.00
------------------------------------------------------------------------
```

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YEAR 1993
---------
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
------------------------------------------------------------------------
  37  164  37  516   93  -93    34  424     0    0  130    0    +0.00
  97  137  90  424    7    0   126  424     0    0   97    0    +0.00
 233  139  90  424    7  136   126  550     9    0   97    9    +0.04
  85  108  85  550   22  -22     0  528     0    0  107    0    +0.00
 138   89  89  528    0   48    22  550    26    0   89   26    +0.19
  29   77  30  550   44  -44     0  506     0    0   74    0    +0.00
  68   85  68  506   11  -11    44  495     0    0   79    0    +0.00
 342   96  90  495    4  248    55  550   193    0   94  193    +0.56
 103  116  90  550   24  -11     0  539     0    0  114    0    +0.00
  37  144  37  539   93  -93    11  446     0    0  130    0    +0.00
  46  152  46  446   30  -30   104  415     0    0   76    0    +0.00
  69  154  69  415    8   -8   135  407     0    0   77    0    +0.00
------------------------------------------------------------------------
1284 1461 821       343                   229    0 1164  229    +0.18
------------------------------------------------------------------------
YEAR 1994
---------
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
------------------------------------------------------------------------
 227  164  90  407    3  134   143  541     0    0   93    0    +0.00
  85  137  85  541   46  -46     9  495     0    0  131    0    +0.00
  51  139  51  495   52  -52    55  443     0    0  103    0    +0.00
 285  108  90  443    5  190   107  550    83    0   95   83    +0.29
 145   89  89  550    0   55     0  550    55    0   89   55    +0.38
 158   77  77  550    0   69     0  550    69    0   77   69    +0.44
 213   85  85  550    0  136     0  550   136    0   85  136    +0.64
  49   96  54  550   39  -39     0  511     0    0   93    0    +0.00
  75  116  75  511   28  -28    39  482     0    0  103    0    +0.00
   8  144   8  482   70  -70    68  412     0    0   78    0    +0.00
 197  152  90  412    5  102   138  514     0    0   95    0    +0.00
 145  154  90  514   46    9    36  524     0    0  136    0    +0.00
------------------------------------------------------------------------
1638 1461 884       295                   343    0 1179  343    +0.21
------------------------------------------------------------------------
YEAR 1995
---------
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
------------------------------------------------------------------------
  69  164  69  524   74  -74    26  450     0    0  143    0    +0.00
 212  137  90  450   15  107   100  550     7    0  105    7    +0.03
 184  139  90  550   46   48     0  550    48    0  136   48    +0.26
  73  108  73  550   33  -33     0  517     0    0  106    0    +0.00
  48   89  48  517   30  -30    33  487     0    0   78    0    +0.00
 139   77  77  487    0   49    63  536     0    0   77    0    +0.00
 101   85  85  536    0   24    14  550    10    0   85   10    +0.10
  25   96  30  550   62  -62     0  488     0    0   92    0    +0.00
  38  116  38  488   43  -43    62  445     0    0   81    0    +0.00
  23  144  23  445   34  -34   105  411     0    0   57    0    +0.00
  81  152  81  411    5   -5   139  406     0    0   86    0    +0.00
  22  154  22  406    5   -5   144  401     0    0   27    0    +0.00
------------------------------------------------------------------------
1015 1461 726       346                    65    0 1072   65    +0.06
------------------------------------------------------------------------
```

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YEAR 1996
---------
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
------------------------------------------------------------------------
 469  164  90  401    0  379   149  550   230    0   90  230    +0.49
  87  137  87  550   47  -47     0  503     0    0  134    0    +0.00
 411  139  90  503   32  289    47  550   242    0  122  242    +0.59
  70  108  70  550   36  -36     0  514     0    0  106    0    +0.00
 166   89  89  514    0   76    36  550    40    0   89   40    +0.24
 163   77  77  550    0   74     0  550    74    0   77   74    +0.45
  29   85  42  550   40  -40     0  510     0    0   82    0    +0.00
  80   96  80  510   11  -11    40  499     0    0   91    0    +0.00
  69  116  69  499   29  -29    51  470     0    0   98    0    +0.00
 233  144  90  470   24  119    80  550    39    0  114   39    +0.17
  68  152  68  550   79  -79     0  471     0    0  147    0    +0.00
 210  154  90  471   28   92    79  550    13    0  118   13    +0.06
------------------------------------------------------------------------
2055 1461 942       326                   638    0 1268  638    +0.31
------------------------------------------------------------------------
YEAR 1997
---------
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
------------------------------------------------------------------------
 256  164  90  550   70   96     0  550    96    0  160   96    +0.38
 405  137  90  550   44  271     0  550   271    0  134  271    +0.67
 218  139  90  550   46   82     0  550    82    0  136   82    +0.38
 161  108  90  550   17   54     0  550    54    0  107   54    +0.34
  68   89  68  550   20  -20     0  530     0    0   88    0    +0.00
  18   77  18  530   48  -48    20  482     0    0   66    0    +0.00
  50   85  50  482   18  -18    68  464     0    0   68    0    +0.00
 126   96  90  464    2   34    86  498     0    0   92    0    +0.00
  74  116  74  498   26  -26    52  472     0    0  100    0    +0.00
 103  144  90  472   24  -11    78  461     0    0  114    0    +0.00
  37  152  37  461   44  -44    89  417     0    0   81    0    +0.00
  65  154  65  417    9   -9   133  407     0    0   74    0    +0.00
------------------------------------------------------------------------
1581 1461 852       368                   503    0 1220  503    +0.32
------------------------------------------------------------------------
YEAR 1998
---------
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
------------------------------------------------------------------------
  16  164  16  407    7   -7   143  401     0    0   23    0    +0.00
  90  137  90  401    0   -0   149  400     0    0   90    0    +0.00
 483  139  90  400    0  393   150  550   243    0   90  243    +0.50
  34  108  34  550   70  -70     0  480     0    0  104    0    +0.00
  72   89  72  480    9   -9    70  472     0    0   81    0    +0.00
  76   77  76  472    0   -0    78  471     0    0   76    0    +0.00
  41   85  41  471   20  -20    79  452     0    0   61    0    +0.00
  32   96  32  452   21  -21    98  431     0    0   53    0    +0.00
 103  116  90  431    5    8   119  439     0    0   95    0    +0.00
  53  144  53  439   22  -22   111  417     0    0   75    0    +0.00
 207  152  90  417    7  110   133  527     0    0   97    0    +0.00
 421  154  90  527   51  280    23  550   257    0  141  257    +0.61
------------------------------------------------------------------------
1628 1461 774       211                   500    0  985  500    +0.31
------------------------------------------------------------------------
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YEAR 1999
---------
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
------------------------------------------------------------------------
 153  164  90   550  70   -7     0   543    0    0  160    0    +0.00
 410  137  90   543  42  278     7   550  271    0  132  271    +0.66
 152  139  90   550  46   16     0   550   16    0  136   16    +0.10
 300  108  90   550  17  193     0   550  193    0  107  193    +0.64
  80   89  80   550   8   -8     0   542    0    0   88    0    +0.00
 148   77  77   542   0   58     8   550   50    0   77   50    +0.33
 134   85  85   550   0   57     0   550   57    0   85   57    +0.43
 205   96  90   550   6  114     0   550  114    0   96  114    +0.56
 148  116  90   550  24   34     0   550   34    0  114   34    +0.23
 345  144  90   550  51  204     0   550  204    0  141  204    +0.59
 276  152  90   550  58  128     0   550  128    0  148  128    +0.46
 189  154  90   550  60   39     0   550   39    0  150   39    +0.21
------------------------------------------------------------------------
2540 1461 %1052       383                 1105    0 1435 1105    +0.44
------------------------------------------------------------------------
YEAR 2000
---------
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
------------------------------------------------------------------------
 336  164  90   550  70  176     0   550  176    0  160  176    +0.53
 314  137  90   550  44  180     0   550  180    0  134  180    +0.57
 348  139  90   550  46  212     0   550  212    0  136  212    +0.61
 324  108  90   550  17  217     0   550  217    0  107  217    +0.67
 154   89  89   550   0   64     0   550   64    0   89   64    +0.42
  92   77  77   550   0    3     0   550    3    0   77    3    +0.03
 236   85  85   550   0  159     0   550  159    0   85  159    +0.67
  97   96  90   550   6    6     0   550    6    0   96    6    +0.07
  97  116  90   550  24  -17     0   533    0    0  114    0    +0.00
  99  144  90   533  45  -36    17   497    0    0  135    0    +0.00
  67  152  67   497  52  -52    53   445    0    0  119    0    +0.00
 244  154  90   445  18  136   105   550   31    0  108   31    +0.13
------------------------------------------------------------------------
2408 1461 %1038       321                 1049    0 1359 1049    +0.44
------------------------------------------------------------------------
YEAR 2001
---------
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
------------------------------------------------------------------------
 508  164  90   550  70  348     0   550  348    0  160  348    +0.69
 229  137  90   550  44   95     0   550   95    0  134   95    +0.41
 162  139  90   550  46   26     0   550   26    0  136   26    +0.16
 170  108  90   550  17   63     0   550   63    0  107   63    +0.37
  25   89  25   550  60  -60     0   490    0    0   85    0    +0.00
 127   77  77   490   0   37    60   527    0    0   77    0    +0.00
  69   85  82   527   2   -2    23   524    0    0   84    0    +0.00
  98   96  90   524   5    3    26   528    0    0   95    0    +0.00
 103  116  90   528  21   -8    22   520    0    0  111    0    +0.00
  20  144  20   520  93  -93    30   427    0    0  113    0    +0.00
  68  152  68   427  14  -14   123   413    0    0   82    0    +0.00
 123  154  90   413   5   28   137   441    0    0   95    0    +0.00
------------------------------------------------------------------------
1702 1461 902       377                 532    0 1279  532    +0.31
------------------------------------------------------------------------
```

```
YEAR 2002
---------
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
------------------------------------------------------------------------
  84  164  84  441   20  -20   109  420     0    0  104    0    +0.00
 572  137  90  420    6  476   130  550   346    0   96  346    +0.61
 197  139  90  550   46   61     0  550    61    0  136   61    +0.31
 218  108  90  550   17  111     0  550   111    0  107  111    +0.51
  81   89  81  550    8   -8     0  542     0    0   89    0    +0.00
  63   77  63  542   13  -13     8  530     0    0   76    0    +0.00
 231   85  85  530    0  141    20  550   121    0   85  121    +0.52
 154   96  90  550    6   63     0  550    63    0   96   63    +0.41
 143  116  90  550   24   29     0  550    29    0  114   29    +0.20
  37  144  37  550  101 -101     0  449     0    0  138    0    +0.00
  95  152  90  449   19  -14   101  435     0    0  109    0    +0.00
  49  154  49  435   23  -23   115  412     0    0   72    0    +0.00
------------------------------------------------------------------------
1924 1461 939       282                   731    0 1221  731    +0.38
------------------------------------------------------------------------
YEAR 2003
---------
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
------------------------------------------------------------------------
 319  164  90  412    6  223   138  550    85    0   96   85    +0.27
  17  137  17  550  113 -113     0  437     0    0  130    0    +0.00
 207  139  90  437   11  106   113  543     0    0  101    0    +0.00
  92  108  90  543   16  -14     7  529     0    0  106    0    +0.00
  49   89  49  529   32  -32    21  496     0    0   81    0    +0.00
  44   77  44  496   20  -20    54  476     0    0   64    0    +0.00
 109   85  85  476    0   19    74  495     0    0   85    0    +0.00
 265   96  90  495    4  176    55  550   122    0   94  122    +0.46
  87  116  87  550   27  -27     0  523     0    0  114    0    +0.00
  40  144  40  523   80  -80    27  443     0    0  120    0    +0.00
  27  152  27  443   33  -33   107  409     0    0   60    0    +0.00
 129  154  90  409    4   35   141  445     0    0   94    0    +0.00
------------------------------------------------------------------------
1385 1461 799       346                   207    0 1145  207    +0.15
------------------------------------------------------------------------
YEAR 2004
---------
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
------------------------------------------------------------------------
 103  164  90  445   21   -8   105  437     0    0  111    0    +0.00
 124  137  90  437   11   23   113  460     0    0  101    0    +0.00
 252  139  90  460   18  144    90  550    54    0  108   54    +0.21
  41  108  41  550   63  -63     0  487     0    0  104    0    +0.00
  69   89  69  487   11  -11    63  476     0    0   80    0    +0.00
 146   77  77  476    0   56    74  532     0    0   77    0    +0.00
 118   85  85  532    0   41    18  550    23    0   85   23    +0.20
 336   96  90  550    6  245     0  550   245    0   96  245    +0.73
 288  116  90  550   24  174     0  550   174    0  114  174    +0.60
  26  144  26  550  111 -111     0  439     0    0  137    0    +0.00
  41  152  41  439   27  -27   111  412     0    0   68    0    +0.00
  53  154  53  412    8   -8   138  404     0    0   61    0    +0.00
------------------------------------------------------------------------
1597 1461 842       300                   496    0 1142  496    +0.31
------------------------------------------------------------------------
```

```
YEAR 2005
---------
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
------------------------------------------------------------------------
 146  164  90  404    2   54   146  458     0    0   92    0    +0.00
  15  137  15  458   45  -45    92  414     0    0   60    0    +0.00
 172  139  90  414    4   78   136  492     0    0   94    0    +0.00
 293  108  90  492   10  193    58  550   134    0  100  134    +0.46
 195   89  89  550    0  105     0  550   105    0   89  105    +0.54
 150   77  77  550    0   61     0  550    61    0   77   61    +0.41
 143   85  85  550    0   66     0  550    66    0   85   66    +0.46
 102   96  90  550    6   11     0  550    11    0   96   11    +0.11
 118  116  90  550   24    4     0  550     4    0  114    4    +0.03
 244  144  90  550   51  103     0  550   103    0  141  103    +0.42
 179  152  90  550   58   31     0  550    31    0  148   31    +0.17
  38  154  38  550  109 -109     0  441     0    0  147    0    +0.00
------------------------------------------------------------------------
1795 1461 934       309                   515    0 1243  515    +0.29
------------------------------------------------------------------------
YEAR 2006
---------
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
------------------------------------------------------------------------
 325  164  90  441   19  216   109  550   107    0  109  107    +0.33
 260  137  90  550   44  126     0  550   126    0  134  126    +0.48
 199  139  90  550   46   63     0  550    63    0  136   63    +0.32
 215  108  90  550   17  108     0  550   108    0  107  108    +0.50
  39   89  39  550   47  -47     0  503     0    0   86    0    +0.00
 170   77  77  503    0   80    47  550    33    0   77   33    +0.19
  54   85  67  550   17  -17     0  533     0    0   84    0    +0.00
  73   96  73  533   19  -19    17  514     0    0   92    0    +0.00
 119  116  90  514   19   10    36  524     0    0  109    0    +0.00
  75  144  75  524   54  -54    26  471     0    0  129    0    +0.00
  72  152  72  471   35  -35    79  435     0    0  107    0    +0.00
  98  154  90  435   14   -6   115  429     0    0  104    0    +0.00
------------------------------------------------------------------------
1699 1461 943       331                   437    0 1274  437    +0.26
------------------------------------------------------------------------


62 YEAR AVERAGES
----------------

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
------------------------------------------------------------------------
1727 1461 884       338                   508    0 1222  508    +0.29
```

Annex K

Predicted percentage change in monthly rainfall (over the mean for 1975-2004) estimated by 23 GCMs for:

(a) SRES Low - 2020

	Rainfall Change (%) for 2020											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	1	1	3	-1	1	-3	1	-1	-2	-3	1
CCCMA_T47	6	6	3	4	4	1	0	0	1	-1	3	6
CCCMA_T63	2	-2	0	-1	1	-1	-3	-4	-2	-3	1	0
CNRM	2	0	1	3	0	2	2	1	-1	-1	-1	3
CSIRO-MK3.0	3	1	1	0	4	-3	0	0	3	5	7	3
CSIRO-MK3.5	2	0	-1	3	-2	-3	0	-1	3	3	2	0
GFDL_2.0	3	-2	3	0	-3	-1	-3	0	1	-1	2	6
GFDL_2.1	1	-2	1	5	4	-1	-5	0	-1	0	3	0
GISS-AOM	5	-2	-1	-1	0	-1	-3	-1	0	4	1	3
GISS-E-H	-1	0	0	-1	-6	-2	-3	-4	-2	-2	-3	-4
GISS-E-R	7	5	1	2	0	2	2	1	-2	-1	2	3
IAP	-1	-3	-1	3	2	4	1	1	-1	-2	1	1
INMCM	3	1	0	5	2	2	-1	-2	-1	0	2	3
IPSL	-1	1	1	2	-2	2	3	-2	-1	-1	-1	6
MIROC-H	-3	-4	-3	-1	1	1	-1	-2	-3	-3	-4	-2
MIROC-M	-5	-4	-2	-1	0	-1	-3	-3	-3	-4	-5	-3
MIUB	3	4	0	1	2	-1	-2	-1	0	1	1	4
MPI-ECHAM5	0	0	0	1	-2	-4	-3	-1	-2	-3	-1	-1
MRI	2	2	1	-1	-3	-4	-1	-3	-3	-2	1	4
NCAR-CCSM	3	3	4	4	4	1	0	0	-2	0	3	5
NCAR-PCM1	2	0	1	0	0	-3	-1	-3	0	-1	1	-1
HADCM3	4	6	2	4	6	1	-3	-1	1	0	5	6
HADGEM1	0	0	0	0	0	-1	-1	-3	-2	-2	-1	0
Mean	**1.6**	**0.5**	**0.5**	**1.5**	**0.5**	**-0.4**	**-1.2**	**-1.2**	**-0.8**	**-0.7**	**0.7**	**1.9**
StDev	2.8	2.9	1.6	2.1	2.8	2.2	2.0	1.6	1.7	2.2	2.8	3.0
CV %	**173**	**601**	**305**	**144**	**591**	**-554**	**-166**	**-137**	**-218**	**-320**	**405**	**161**
Median	2.0	0.0	1.0	1.0	0.0	-1.0	-1.0	-1.0	-1.0	-1.0	1.0	3.0
Max	7	6	4	5	6	4	3	1	3	5	7	6
Min	-5	-4	-3	-1	-6	-4	-5	-4	-3	-4	-5	-4

(b) SRES Low - 2050

	Rainfall Change (%) for 2050											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	2	2	6	-3	2	-6	1	-1	-4	-7	3
CCCMA_T47	13	12	5	9	8	1	1	0	2	-2	6	13
CCCMA_T63	5	-4	0	-3	3	-3	-7	-9	-3	-7	2	-1
CNRM	4	1	1	5	-1	5	5	2	-1	-2	-1	7
CSIRO-MK3.0	5	2	3	1	8	-6	1	0	6	11	14	6
CSIRO-MK3.5	3	1	-1	7	-4	-7	-1	-2	5	7	4	-1
GFDL_2.0	5	-5	6	1	-6	-2	-7	-1	1	-3	4	12
GFDL_2.1	3	-4	2	10	9	-2	-11	1	-1	1	7	0
GISS-AOM	10	-4	-2	-1	-1	-1	-5	-3	0	9	2	6
GISS-E-H	-1	0	1	-3	-12	-4	-5	-8	-5	-5	-7	-8
GISS-E-R	14	10	1	4	1	5	5	2	-4	-3	5	7
IAP	-1	-7	-3	7	4	8	2	3	-2	-3	3	3
INMCM	5	2	1	10	4	5	-3	-4	-2	0	4	6
IPSL	-1	2	2	4	-3	3	5	-5	-2	-2	-2	11
MIROC-H	-5	-9	-6	-3	3	2	-2	-4	-7	-6	-8	-4
MIROC-M	-10	-9	-5	-2	0	-3	-6	-5	-7	-7	-10	-6
MIUB	6	8	-1	2	4	-2	-5	-3	-1	2	2	8
MPI-ECHAM5	1	-1	0	1	-4	-9	-6	-2	-3	-5	-3	-2
MRI	5	5	3	-3	-6	-8	-3	-5	-5	-4	3	8
NCAR-CCSM	7	6	8	9	7	1	-1	0	-5	0	7	11
NCAR-PCM1	4	0	1	0	-1	-6	-2	-6	0	-2	3	-2
HADCM3	9	13	5	9	12	2	-7	-1	2	-1	10	12
HADGEM1	1	0	0	-1	-1	-1	-1	-5	-4	-5	-2	-1
Mean	**3.6**	**0.9**	**1.0**	**3.0**	**0.9**	**-0.9**	**-2.6**	**-2.3**	**-1.6**	**-1.3**	**1.6**	**3.8**
StDev	5.4	6.1	3.3	4.7	5.7	4.6	4.3	3.3	3.4	4.8	5.9	6.2
CV %	**152**	**669**	**329**	**155**	**626**	**-525**	**-168**	**-139**	**-209**	**-353**	**377**	**162**
Median	4.0	1.0	1.0	2.0	0.0	-1.0	-3.0	-2.0	-2.0	-2.0	3.0	6.0
Max	14	13	8	10	12	8	5	3	6	11	14	13
Min	-10	-9	-6	-3	-12	-9	-11	-9	-7	-7	-10	-8

(c) SRES Low - 2095

	Rainfall Change (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	3	3	10	-5	4	-10	2	-2	-7	-11	5
CCCMA_T47	22	21	9	15	13	2	1	-1	3	-4	10	22
CCCMA_T63	8	-7	0	-5	5	-4	-11	-15	-6	-12	3	-2
CNRM	6	2	2	9	-1	8	8	3	-2	-3	-2	12
CSIRO-MK3.0	9	3	4	2	13	-11	2	1	10	19	23	11
CSIRO-MK3.5	6	2	-2	11	-7	-12	-1	-3	9	12	7	-1
GFDL_2.0	9	-8	11	1	-10	-4	-12	-1	2	-4	6	21
GFDL_2.1	5	-7	3	16	15	-3	-19	1	-2	1	12	0
GISS-AOM	16	-6	-3	-2	-2	-2	-9	-5	0	15	4	10
GISS-E-H	-2	0	2	-5	-20	-6	-9	-14	-8	-8	-12	-13
GISS-E-R	23	17	2	6	1	8	8	3	-7	-5	8	11
IAP	-2	-11	-5	11	7	13	3	5	-3	-5	5	4
INMCM	9	3	2	16	6	9	-5	-7	-4	-1	7	11
IPSL	-2	4	4	6	-6	5	9	-8	-3	-3	-4	19
MIROC-H	-9	-14	-10	-5	5	4	-3	-7	-12	-11	-13	-6
MIROC-M	-17	-15	-9	-3	0	-5	-9	-9	-12	-12	-16	-9
MIUB	10	14	-1	4	7	-4	-8	-4	-2	3	3	14
MPI-ECHAM5	2	-1	1	2	-7	-14	-10	-3	-6	-9	-5	-3
MRI	8	8	5	-5	-10	-13	-5	-9	-9	-7	4	13
NCAR-CCSM	12	10	13	15	12	2	-1	0	-8	0	11	18
NCAR-PCM1	7	0	2	0	-1	-10	-3	-10	0	-4	4	-3
HADCM3	15	21	8	15	20	4	-12	-2	4	-2	17	20
HADGEM1	1	0	-1	-1	-1	-2	-2	-9	-7	-8	-4	-2
Mean	**5.9**	**1.7**	**1.7**	**4.9**	**1.5**	**-1.3**	**-4.3**	**-4.0**	**-2.8**	**-2.4**	**2.5**	**6.6**
StDev	9.1	10.1	5.6	7.6	9.6	7.6	7.3	5.5	5.8	8.1	9.7	10.3
CV %	**155**	**597**	**320**	**154**	**646**	**-564**	**-170**	**-138**	**-206**	**-339**	**393**	**156**
Median	7.0	2.0	2.0	4.0	0.0	-2.0	-5.0	-3.0	-3.0	-4.0	4.0	10.0
Max	23	21	13	16	20	13	9	5	10	19	23	22
Min	-17	-15	-10	-5	-20	-14	-19	-15	-12	-12	-16	-13

(d) SRES B1 - 2020

	Rainfall Change (%) for 2020											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	2	2	5	-3	2	-5	1	-1	-3	-6	3
CCCMA_T47	11	11	5	8	6	1	1	0	2	-2	5	12
CCCMA_T63	4	-4	0	-3	2	-2	-6	-8	-3	-6	2	-1
CNRM	3	1	1	5	-1	4	4	2	-1	-2	-1	6
CSIRO-MK3.0	5	1	2	1	7	-6	1	0	5	10	12	6
CSIRO-MK3.5	3	1	-1	6	-4	-6	-1	-2	5	6	4	-1
GFDL_2.0	5	-4	5	1	-5	-2	-6	-1	1	-2	3	11
GFDL_2.1	3	-4	2	8	8	-1	-10	1	-1	1	6	0
GISS-AOM	8	-3	-2	-1	-1	-1	-4	-3	0	8	2	5
GISS-E-H	-1	0	1	-2	-10	-3	-5	-7	-4	-4	-6	-7
GISS-E-R	12	9	1	3	1	4	4	1	-3	-2	4	6
IAP	-1	-6	-2	6	4	7	1	3	-1	-3	2	2
INMCM	5	2	1	8	3	4	-2	-3	-2	0	4	6
IPSL	-1	2	2	3	-3	3	5	-4	-1	-2	-2	10
MIROC-H	-5	-7	-5	-2	2	2	-2	-3	-6	-6	-7	-3
MIROC-M	-9	-8	-4	-1	0	-2	-5	-5	-6	-6	-8	-5
MIUB	5	7	-1	2	3	-2	-4	-2	-1	2	2	7
MPI-ECHAM5	1	-1	0	1	-4	-7	-5	-2	-3	-5	-3	-1
MRI	4	4	3	-3	-5	-7	-2	-4	-5	-4	2	7
NCAR-CCSM	6	5	7	8	6	1	-1	0	-4	0	6	9
NCAR-PCM1	4	0	1	0	0	-5	-2	-5	0	-2	2	-2
HADCM3	8	11	4	8	11	2	-6	-1	2	-1	9	10
HADGEM1	1	0	0	-1	-1	-1	-1	-5	-4	-4	-2	-1
Mean	**3.1**	**0.8**	**1.0**	**2.6**	**0.7**	**-0.7**	**-2.2**	**-2.0**	**-1.3**	**-1.2**	**1.3**	**3.4**
StDev	4.7	5.3	2.8	3.9	5.0	3.9	3.7	2.9	3.0	4.2	5.1	5.4
CV %	**154**	**642**	**295**	**151**	**713**	**-597**	**-168**	**-140**	**-223**	**-362**	**389**	**158**
Median	4.0	1.0	1.0	2.0	0.0	-1.0	-2.0	-2.0	-1.0	-2.0	2.0	5.0
Max	12	11	7	8	11	7	5	3	5	10	12	12
Min	-9	-8	-5	-3	-10	-7	-10	-8	-6	-6	-8	-7

(e) SRES B1 - 2050

Model	**Rainfall Change (%) for 2050**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	3	3	10	-5	4	-10	2	-2	-7	-11	5
CCCMA_T47	22	21	9	15	13	2	1	-1	3	-4	10	22
CCCMA_T63	8	-7	0	-5	5	-4	-11	-15	-6	-12	3	-2
CNRM	6	2	2	9	-1	8	8	3	-2	-3	-2	12
CSIRO-MK3.0	9	3	4	2	13	-11	2	1	10	19	23	11
CSIRO-MK3.5	6	2	-2	11	-7	-12	-1	-3	9	12	7	-1
GFDL_2.0	9	-8	11	1	-10	-4	-12	-1	2	-4	6	21
GFDL_2.1	5	-7	3	16	15	-3	-19	1	-2	1	12	0
GISS-AOM	16	-6	-3	-2	-2	-2	-9	-5	0	15	4	10
GISS-E-H	-2	0	2	-5	-20	-6	-9	-14	-8	-8	-12	-13
GISS-E-R	23	17	2	6	1	8	8	3	-7	-5	8	11
IAP	-2	-11	-5	11	7	13	3	5	-3	-5	5	4
INMCM	9	3	2	16	6	9	-5	-7	-4	-1	7	11
IPSL	-2	4	4	6	-6	5	9	-8	-3	-3	-4	19
MIROC-H	-9	-14	-10	-5	5	4	-3	-7	-12	-11	-13	-6
MIROC-M	-17	-15	-9	-3	0	-5	-9	-9	-12	-12	-16	-9
MIUB	10	14	-1	4	7	-4	-8	-4	-2	3	3	14
MPI-ECHAM5	2	-1	1	2	-7	-14	-10	-3	-6	-9	-5	-3
MRI	8	8	5	-5	-10	-13	-5	-9	-9	-7	4	13
NCAR-CCSM	12	10	13	15	12	2	-1	0	-8	0	11	18
NCAR-PCM1	7	0	2	0	-1	-10	-3	-10	0	-4	4	-3
HADCM3	15	21	8	15	20	4	-12	-2	4	-2	17	20
HADGEM1	1	0	-1	-1	-1	-2	-2	-9	-7	-8	-4	-2
Mean	**5.9**	**1.7**	**1.7**	**4.9**	**1.5**	**-1.3**	**-4.3**	**-4.0**	**-2.8**	**-2.4**	**2.5**	**6.6**
StDev	9.1	10.1	5.6	7.6	9.6	7.6	7.3	5.5	5.8	8.1	9.7	10.3
CV %	**155**	**597**	**320**	**154**	**646**	**-564**	**-170**	**-138**	**-206**	**-339**	**393**	**156**
Median	7.0	2.0	2.0	4.0	0.0	-2.0	-5.0	-3.0	-3.0	-4.0	4.0	10.0
Max	23	21	13	16	20	13	9	5	10	19	23	22
Min	-17	-15	-10	-5	-20	-14	-19	-15	-12	-12	-16	-13

(f) SRES B1 - 2095

	Rainfall Change (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	5	5	16	-8	6	-17	3	-3	-11	-18	8
CCCMA_T47	36	34	15	25	21	4	2	-1	5	-7	17	36
CCCMA_T63	13	-11	0	-8	8	-7	-18	-24	-9	-19	5	-3
CNRM	10	3	4	14	-2	13	14	5	-3	-5	-3	19
CSIRO-MK3.0	14	5	7	3	21	-17	2	1	17	30	37	18
CSIRO-MK3.5	9	3	-3	19	-12	-19	-2	-5	15	19	12	-2
GFDL_2.0	15	-12	17	2	-17	-6	-19	-2	4	-7	10	34
GFDL_2.1	8	-12	5	27	24	-4	-31	2	-3	2	19	0
GISS-AOM	27	-10	-5	-3	-3	-4	-14	-8	0	24	6	16
GISS-E-H	-3	0	2	-7	-32	-10	-14	-22	-14	-13	-20	-22
GISS-E-R	38	28	3	10	2	13	14	4	-11	-8	13	18
IAP	-3	-18	-8	18	12	21	4	8	-5	-9	7	7
INMCM	15	5	3	26	10	14	-8	-11	-7	-1	12	18
IPSL	-3	6	6	10	-9	9	14	-13	-4	-5	-6	31
MIROC-H	-14	-23	-16	-8	7	6	-5	-11	-19	-18	-21	-10
MIROC-M	-27	-25	-14	-4	0	-8	-15	-15	-20	-20	-26	-15
MIUB	16	23	-2	7	11	-6	-14	-7	-3	5	5	23
MPI-ECHAM5	3	-2	1	3	-12	-23	-16	-5	-9	-14	-8	-5
MRI	13	14	8	-8	-16	-22	-7	-14	-15	-11	7	21
NCAR-CCSM	19	17	21	24	20	3	-2	0	-13	0	19	29
NCAR-PCM1	12	0	3	0	-2	-16	-5	-16	-1	-6	7	-5
HADCM3	24	34	13	24	34	7	-19	-3	6	-3	28	32
HADGEM1	2	0	-1	-2	-2	-3	-3	-15	-11	-13	-6	-3
Mean	**9.7**	**2.8**	**2.8**	**8.2**	**2.4**	**-2.1**	**-6.9**	**-6.5**	**-4.5**	**-3.9**	**4.2**	**10.7**
StDev	14.8	16.6	8.9	12.3	15.6	12.3	11.8	8.8	9.6	13.0	15.9	16.8
CV %	**152**	**596**	**320**	**150**	**654**	**-579**	**-171**	**-136**	**-214**	**-332**	**380**	**158**
Median	12.0	3.0	3.0	7.0	0.0	-4.0	-7.0	-5.0	-4.0	-7.0	7.0	16.0
Max	38	34	21	27	34	21	14	8	17	30	37	36
Min	-27	-25	-16	-8	-32	-23	-31	-24	-20	-20	-26	-22

(g) SRES A1FI - 2020

	Rainfall Change (%) for 2020											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	1	1	5	-2	2	-5	1	-1	-3	-5	2
CCCMA_T47	11	10	4	7	6	1	1	0	1	-2	5	11
CCCMA_T63	4	-3	0	-2	2	-2	-5	-7	-3	-6	2	-1
CNRM	3	1	1	4	-1	4	4	2	-1	-1	-1	6
CSIRO-MK3.0	4	1	2	1	6	-5	1	0	5	9	11	5
CSIRO-MK3.5	3	1	-1	6	-3	-6	-1	-1	4	6	3	-1
GFDL_2.0	4	-4	5	1	-5	-2	-6	-1	1	-2	3	10
GFDL_2.1	2	-3	2	8	7	-1	-9	1	-1	1	6	0
GISS-AOM	8	-3	-2	-1	-1	-1	-4	-2	0	7	2	5
GISS-E-H	-1	0	1	-2	-9	-3	-4	-7	-4	-4	-6	-6
GISS-E-R	11	8	1	3	1	4	4	1	-3	-2	4	5
IAP	-1	-5	-2	5	3	6	1	2	-1	-3	2	2
INMCM	4	1	1	8	3	4	-2	-3	-2	0	3	5
IPSL	-1	2	2	3	-3	3	4	-4	-1	-1	-2	9
MIROC-H	-4	-7	-5	-2	2	2	-1	-3	-6	-5	-6	-3
MIROC-M	-8	-7	-4	-1	0	-2	-5	-4	-6	-6	-8	-5
MIUB	5	7	0	2	3	-2	-4	-2	-1	2	1	7
MPI-ECHAM5	1	-1	0	1	-4	-7	-5	-2	-3	-4	-2	-1
MRI	4	4	2	-2	-5	-6	-2	-4	-4	-3	2	6
NCAR-CCSM	6	5	6	7	6	1	-1	0	-4	0	5	9
NCAR-PCM1	3	0	1	0	0	-5	-2	-5	0	-2	2	-1
HADCM3	7	10	4	7	10	2	-6	-1	2	-1	8	9
HADGEM1	1	0	0	-1	-1	-1	-1	-4	-3	-4	-2	-1
Mean	**2.9**	**0.8**	**0.8**	**2.5**	**0.7**	**-0.6**	**-2.1**	**-1.9**	**-1.3**	**-1.0**	**1.2**	**3.1**
StDev	4.4	4.8	2.6	3.6	4.5	3.7	3.5	2.6	2.8	3.9	4.7	5.0
CV %	**153**	**619**	**315**	**144**	**697**	**-604**	**-167**	**-140**	**-207**	**-375**	**397**	**159**
Median	3.0	1.0	1.0	2.0	0.0	-1.0	-2.0	-2.0	-1.0	-2.0	2.0	5.0
Max	11	10	6	8	10	6	4	2	5	9	11	11
Min	-8	-7	-5	-2	-9	-7	-9	-7	-6	-6	-8	-6

(h) SRES A1FI - 2050

	Rainfall Change (%) for 2050											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	5	5	16	-8	6	-17	3	-3	-11	-18	8
CCCMA_T47	36	34	15	25	21	4	2	-1	5	-7	17	36
CCCMA_T63	13	-11	0	-8	8	-7	-18	-24	-9	-19	5	-3
CNRM	10	3	4	14	-2	13	14	5	-3	-5	-3	19
CSIRO-MK3.0	14	5	7	3	21	-17	2	1	17	30	37	18
CSIRO-MK3.5	9	3	-3	19	-12	-19	-2	-5	15	19	12	-2
GFDL_2.0	15	-12	17	2	-17	-6	-19	-2	4	-7	10	34
GFDL_2.1	8	-12	5	27	24	-4	-31	2	-3	2	19	0
GISS-AOM	27	-10	-5	-3	-3	-4	-14	-8	0	24	6	16
GISS-E-H	-3	0	2	-7	-32	-10	-14	-22	-14	-13	-20	-22
GISS-E-R	38	28	3	10	2	13	14	4	-11	-8	13	18
IAP	-3	-18	-8	18	12	21	4	8	-5	-9	7	7
INMCM	15	5	3	26	10	14	-8	-11	-7	-1	12	18
IPSL	-3	6	6	10	-9	9	14	-13	-4	-5	-6	31
MIROC-H	-14	-23	-16	-8	7	6	-5	-11	-19	-18	-21	-10
MIROC-M	-27	-25	-14	-4	0	-8	-15	-15	-20	-20	-26	-15
MIUB	16	23	-2	7	11	-6	-14	-7	-3	5	5	23
MPI-ECHAM5	3	-2	1	3	-12	-23	-16	-5	-9	-14	-8	-5
MRI	13	14	8	-8	-16	-22	-7	-14	-15	-11	7	21
NCAR-CCSM	19	17	21	24	20	3	-2	0	-13	0	19	29
NCAR-PCM1	12	0	3	0	-2	-16	-5	-16	-1	-6	7	-5
HADCM3	24	34	13	24	34	7	-19	-3	6	-3	28	32
HADGEM1	2	0	-1	-2	-2	-3	-3	-15	-11	-13	-6	-3
Mean	**9.7**	**2.8**	**2.8**	**8.2**	**2.4**	**-2.1**	**-6.9**	**-6.5**	**-4.5**	**-3.9**	**4.2**	**10.7**
StDev	14.8	16.6	8.9	12.3	15.6	12.3	11.8	8.8	9.6	13.0	15.9	16.8
CV %	**152**	**596**	**320**	**150**	**654**	**-579**	**-171**	**-136**	**-214**	**-332**	**380**	**158**
Median	12.0	3.0	3.0	7.0	0.0	-4.0	-7.0	-5.0	-4.0	-7.0	7.0	16.0
Max	38	34	21	27	34	21	14	8	17	30	37	36
Min	-27	-25	-16	-8	-32	-23	-31	-24	-20	-20	-26	-22

(i) SRES A1FI - 2095

	Rainfall Change (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	1	11	11	36	-18	13	-37	7	-7	-24	-40	18
CCCMA_T47	79	75	33	55	46	9	4	-2	11	-15	37	81
CCCMA_T63	30	-25	-1	-18	17	-16	-40	-54	-21	-42	12	-6
CNRM	23	6	8	32	-4	29	30	12	-7	-11	-7	43
CSIRO-MK3.0	32	10	16	6	47	-39	6	2	37	68	82	39
CSIRO-MK3.5	21	6	-6	42	-26	-42	-5	-11	33	43	26	-5
GFDL_2.0	33	-27	38	5	-38	-14	-43	-4	8	-16	22	75
GFDL_2.1	19	-26	12	59	53	-9	-68	4	-8	5	43	0
GISS-AOM	59	-22	-12	-6	-6	-8	-31	-19	0	53	13	36
GISS-E-H	-6	1	5	-17	-71	-22	-32	-49	-30	-29	-44	-49
GISS-E-R	85	62	7	23	5	29	30	9	-24	-17	29	40
IAP	-7	-41	-17	40	26	47	9	18	-10	-19	17	16
INMCM	33	11	6	58	21	31	-17	-24	-15	-2	26	39
IPSL	-7	13	14	22	-20	19	32	-29	-10	-11	-13	70
MIROC-H	-32	-52	-36	-17	17	13	-11	-24	-42	-39	-47	-23
MIROC-M	-60	-55	-31	-9	-1	-17	-34	-33	-44	-44	-59	-34
MIUB	36	51	-4	14	24	-14	-31	-16	-6	12	11	50
MPI-ECHAM5	6	-4	3	6	-27	-52	-36	-12	-20	-32	-18	-10
MRI	30	30	18	-18	-36	-48	-16	-31	-33	-25	16	47
NCAR-CCSM	42	38	47	53	44	7	-5	0	-28	1	41	64
NCAR-PCM1	26	0	7	-1	-3	-35	-11	-36	-1	-13	16	-11
HADCM3	54	77	30	53	75	15	-43	-7	13	-6	63	71
HADGEM1	5	0	-3	-5	-5	-8	-6	-32	-25	-29	-13	-6
Mean	**21.8**	**6.0**	**6.3**	**18.0**	**5.2**	**-4.9**	**-15.4**	**-14.4**	**-10.0**	**-8.3**	**9.3**	**23.7**
StDev	32.9	36.9	19.9	27.3	34.6	27.4	26.1	19.6	21.0	29.0	35.3	37.4
CV %	**151**	**611**	**316**	**152**	**663**	**-563**	**-169**	**-136**	**-211**	**-348**	**382**	**158**
Median	26.0	6.0	7.0	14.0	-1.0	-8.0	-16.0	-12.0	-10.0	-15.0	16.0	36.0
Max	85	77	47	59	75	47	32	18	37	68	82	81
Min	-60	-55	-36	-18	-71	-52	-68	-54	-44	-44	-59	-49

(j) SRES High - 2020

	Rainfall Change (%) for 2020											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	0	3	3	10	-5	4	-10	2	-2	-7	-11	5
CCCMA_T47	22	21	9	15	13	3	1	-1	3	-4	10	23
CCCMA_T63	8	-7	0	-5	5	-4	-11	-15	-6	-12	3	-2
CNRM	6	2	2	9	-1	8	8	3	-2	-3	-2	12
CSIRO-MK3.0	9	3	4	2	13	-11	2	1	10	19	23	11
CSIRO-MK3.5	6	2	-2	12	-7	-12	-2	-3	9	12	7	-1
GFDL_2.0	9	-8	11	1	-11	-4	-12	-1	2	-5	6	21
GFDL_2.1	5	-7	3	17	15	-3	-19	1	-2	2	12	0
GISS-AOM	17	-6	-3	-2	-2	-2	-9	-5	0	15	4	10
GISS-E-H	-2	0	2	-5	-20	-6	-9	-14	-9	-8	-12	-14
GISS-E-R	24	17	2	6	1	8	9	3	-7	-5	8	11
IAP	-2	-11	-5	11	7	13	3	5	-3	-5	5	4
INMCM	9	3	2	16	6	9	-5	-7	-4	-1	7	11
IPSL	-2	4	4	6	-6	5	9	-8	-3	-3	-4	20
MIROC-H	-9	-14	-10	-5	5	4	-3	-7	-12	-11	-13	-6
MIROC-M	-17	-15	-9	-3	0	-5	-10	-9	-12	-12	-16	-10
MIUB	10	14	-1	4	7	-4	-9	-5	-2	3	3	14
MPI-ECHAM5	2	-1	1	2	-7	-14	-10	-3	-6	-9	-5	-3
MRI	8	8	5	-5	-10	-13	-5	-9	-9	-7	4	13
NCAR-CCSM	12	11	13	15	12	2	-1	0	-8	0	12	18
NCAR-PCM1	7	0	2	0	-1	-10	-3	-10	0	-4	4	-3
HADCM3	15	21	8	15	21	4	-12	-2	4	-2	18	20
HADGEM1	1	0	-1	-1	-1	-2	-2	-9	-7	-8	-4	-2
Mean	**6.0**	**1.7**	**1.7**	**5.0**	**1.5**	**-1.3**	**-4.3**	**-4.0**	**-2.9**	**-2.4**	**2.6**	**6.6**
StDev	9.3	10.2	5.6	7.7	9.7	7.6	7.4	5.5	5.9	8.1	9.8	10.6
CV %	**155**	**585**	**320**	**154**	**656**	**-585**	**-170**	**-137**	**-204**	**-340**	**384**	**160**
Median	7.0	2.0	2.0	4.0	0.0	-2.0	-5.0	-3.0	-3.0	-4.0	4.0	10.0
Max	24	21	13	17	21	13	9	5	10	19	23	23
Min	-17	-15	-10	-5	-20	-14	-19	-15	-12	-12	-16	-14

(k) SRES High - 2050

	Rainfall Change (%) for 2050											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	1	8	8	26	-13	10	-27	5	-5	-17	-29	13
CCCMA_T47	57	54	24	39	33	6	3	-1	8	-11	27	58
CCCMA_T63	21	-18	-1	-13	12	-11	-29	-39	-15	-30	9	-4
CNRM	16	4	6	23	-3	21	22	8	-5	-8	-5	31
CSIRO-MK3.0	23	8	11	4	34	-28	4	2	27	49	59	28
CSIRO-MK3.5	15	4	-5	30	-19	-31	-4	-8	24	31	19	-4
GFDL_2.0	24	-20	28	4	-27	-10	-31	-3	6	-12	16	54
GFDL_2.1	13	-19	8	42	38	-7	-49	3	-5	4	31	0
GISS-AOM	43	-16	-9	-5	-4	-6	-23	-13	0	39	9	26
GISS-E-H	-5	1	4	-12	-51	-16	-23	-35	-22	-21	-31	-35
GISS-E-R	61	45	5	17	3	21	22	7	-18	-12	21	29
IAP	-5	-30	-12	29	19	34	7	13	-7	-14	12	11
INMCM	24	8	4	42	15	22	-12	-17	-11	-2	19	28
IPSL	-5	10	10	16	-14	14	23	-21	-7	-8	-10	50
MIROC-H	-23	-37	-26	-12	12	9	-8	-18	-30	-28	-34	-16
MIROC-M	-43	-40	-22	-7	-1	-12	-25	-24	-31	-32	-42	-25
MIUB	26	37	-3	10	17	-10	-22	-12	-4	8	8	36
MPI-ECHAM5	4	-3	2	5	-19	-37	-26	-9	-15	-23	-13	-7
MRI	21	22	13	-13	-26	-34	-12	-23	-24	-18	11	34
NCAR-CCSM	30	27	34	38	32	5	-3	0	-20	0	30	46
NCAR-PCM1	19	0	5	-1	-2	-25	-8	-26	-1	-9	11	-8
HADCM3	39	55	21	38	54	10	-31	-5	9	-4	45	51
HADGEM1	4	0	-2	-3	-4	-6	-5	-23	-18	-21	-9	-4
Mean	**15.7**	**4.3**	**4.5**	**12.9**	**3.7**	**-3.5**	**-11.2**	**-10.4**	**-7.1**	**-6.0**	**6.7**	**17.0**
StDev	23.7	26.7	14.4	19.6	24.9	19.7	19.0	14.2	15.1	21.0	25.4	26.9
CV %	**151**	**614**	**321**	**152**	**665**	**-559**	**-170**	**-137**	**-212**	**-347**	**379**	**158**
Median	19.0	4.0	5.0	10.0	-1.0	-6.0	-12.0	-9.0	-7.0	-11.0	11.0	26.0
Max	61	55	34	42	54	34	23	13	27	49	59	58
Min	-43	-40	-26	-13	-51	-37	-49	-39	-31	-32	-42	-35

(l) SRES High - 2095

	Rainfall Change (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	2	17	17	58	-28	22	-60	12	-10	-38	-64	28
CCCMA_T47	127	121	53	88	73	14	7	-3	17	-24	60	130
CCCMA_T63	48	-41	-2	-29	27	-25	-65	-86	-33	-67	19	-9
CNRM	36	9	13	51	-7	47	48	19	-11	-17	-11	69
CSIRO-MK3.0	51	17	25	10	76	-62	9	4	59	108	131	62
CSIRO-MK3.5	33	9	-10	67	-41	-68	-9	-17	53	68	41	-8
GFDL_2.0	53	-44	61	8	-61	-22	-69	-7	13	-26	35	120
GFDL_2.1	30	-42	19	94	85	-15	-108	7	-12	9	69	0
GISS-AOM	95	-36	-19	-10	-10	-13	-50	-30	-1	86	21	57
GISS-E-H	-10	1	9	-26	-113	-35	-52	-79	-49	-47	-70	-78
GISS-E-R	137	100	11	37	8	46	49	15	-39	-27	47	64
IAP	-11	-66	-27	65	42	75	15	29	-17	-30	26	25
INMCM	53	17	10	93	34	50	-27	-38	-24	-3	42	62
IPSL	-11	21	22	35	-32	31	51	-47	-15	-17	-21	111
MIROC-H	-51	-82	-58	-27	27	21	-17	-39	-67	-63	-75	-36
MIROC-M	-96	-88	-50	-15	-2	-28	-54	-53	-70	-70	-94	-55
MIUB	57	82	-6	23	38	-22	-49	-26	-10	19	18	80
MPI-ECHAM5	10	-7	4	10	-43	-83	-58	-19	-32	-51	-29	-16
MRI	47	48	29	-28	-58	-76	-26	-50	-53	-39	25	76
NCAR-CCSM	68	61	75	84	71	12	-8	0	-45	1	66	103
NCAR-PCM1	42	1	11	-1	-5	-56	-18	-58	-2	-21	26	-17
HADCM3	86	122	48	85	119	23	-69	-11	21	-10	101	114
HADGEM1	8	1	-4	-7	-9	-12	-10	-52	-40	-47	-21	-10
Mean	**35.0**	**9.6**	**10.0**	**28.9**	**8.3**	**-7.7**	**-24.8**	**-23.0**	**-16.0**	**-13.3**	**14.9**	**37.9**
StDev	52.7	59.2	31.9	43.6	55.3	43.8	41.9	31.7	33.5	46.4	56.5	59.8
CV %	**151**	**616**	**318**	**151**	**666**	**-573**	**-169**	**-138**	**-210**	**-349**	**380**	**158**
Median	42.0	9.0	11.0	23.0	-2.0	-13.0	-26.0	-19.0	-15.0	-24.0	25.0	57.0
Max	137	122	75	94	119	75	51	29	59	108	131	130
Min	-96	-88	-58	-29	-113	-83	-108	-86	-70	-70	-94	-78

Annex L

Predicted percentage change in monthly potential evaporation (over the mean for 1975-2004) estimated by 14 GCMs for:

(a) SRES Low - 2020

	Potential ET Change (%) for 2020											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	0.3	-0.2	0.4	0.8	1.1	1.7	1.5	1.2	0.3	0.9	0.6	0.5
CCCMA_T63	0.6	0.8	0.9	1.5	1.5	1.6	1.3	1	0.6	0.6	0.8	0.5
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	0.9	0.8	1.2	1.3	1.4	1.3	1	0.7	0.6	0.6	0.7	0.8
CSIRO-MK3.5	1.2	0.7	0.7	0.7	1.4	1.8	1.5	1.2	0.8	1.1	1.1	1.2
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	0.6	1.2	1.2	1.3	2	2.1	2	1.9	1.5	0.8	1.1	0.6
GISS-E-H	1.1	1	1.1	1.4	1.7	1.3	1.6	1.6	1.3	1.3	1.4	1.3
GISS-E-R	0.1	0.3	1.1	1.4	1.8	2.1	2	2	1.8	1.6	0.9	0.8
IAP	0.1	0.9	0.9	0.4	0.7	0.8	1	0.5	0.6	0.6	0	0
INMCM	0.1	0.1	0.7	0.4	1.1	1.4	1.3	1.1	0.6	0.4	0.5	0.5
IPSL	0.6	0.9	0.9	1.2	1.4	1.5	1.4	1.2	1.2	1.3	1.4	1
MIROC-H	1.3	1.4	1.5	1.6	1.8	1.3	1.4	1.3	1.2	1.3	1.3	1
MIROC-M	1.2	1.3	1.3	1.6	1.9	1.8	1.6	1	0.9	0.9	1	0.8
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	0.5	0.6	1.1	1.6	1.9	1.7	1.3	1.3	1.3	1.6	1	0.6
NCAR-CCSM	0.6	0.7	0.9	1.2	1.5	1.5	1.1	0.8	0.9	0.9	0.6	0.6
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**0.7**	**0.8**	**1.0**	**1.2**	**1.5**	**1.6**	**1.4**	**1.2**	**1.0**	**1.0**	**0.9**	**0.7**
StDev	0.4	0.4	0.3	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.3
CV %	**65**	**60**	**28**	**36**	**24**	**22**	**22**	**35**	**44**	**39**	**44**	**46**
Median	0.6	0.8	1.0	1.3	1.5	1.6	1.4	1.2	0.9	0.9	1.0	0.7
Max	1.3	1.4	1.5	1.6	2	2.1	2	2	1.8	1.6	1.4	1.3
Min	0.1	-0.2	0.4	0.4	0.7	0.8	1	0.5	0.3	0.4	0	0

(b) SRES Low - 2050

	Potential ET Change (%) for 2050											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	0.6	-0.5	0.8	1.7	2.2	3.5	3.2	2.6	0.5	1.9	1.2	1
CCCMA_T63	1.3	1.6	1.9	3	3	3.3	2.6	2	1.3	1.2	1.6	1.1
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	1.9	1.7	2.4	2.7	2.8	2.8	2.1	1.4	1.2	1.3	1.3	1.7
CSIRO-MK3.5	2.4	1.5	1.5	1.4	2.9	3.7	3	2.5	1.8	2.3	2.2	2.6
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	1.1	2.5	2.5	2.7	4.1	4.4	4.1	4	3	1.6	2.3	1.2
GISS-E-H	2.3	2.1	2.3	2.9	3.5	2.7	3.2	3.2	2.6	2.7	2.8	2.6
GISS-E-R	0.2	0.6	2.4	2.9	3.7	4.4	4.1	4.2	3.6	3.4	1.9	1.6
IAP	0.2	1.9	1.9	0.8	1.5	1.6	2.1	0.9	1.3	1.2	-0.1	0
INMCM	0.2	0.2	1.5	0.9	2.2	2.9	2.6	2.2	1.3	0.9	0.9	1
IPSL	1.3	1.8	1.9	2.4	3	3.2	2.8	2.5	2.6	2.6	3	2
MIROC-H	2.8	2.9	3	3.2	3.8	2.8	2.8	2.6	2.4	2.6	2.6	2.1
MIROC-M	2.5	2.7	2.6	3.4	3.8	3.6	3.2	2	1.8	1.9	2.1	1.7
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	1	1.3	2.3	3.3	3.9	3.5	2.7	2.7	2.6	3.3	2.1	1.2
NCAR-CCSM	1.3	1.5	2	2.4	3	3.1	2.2	1.7	1.8	1.8	1.2	1.2
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**1.4**	**1.6**	**2.1**	**2.4**	**3.1**	**3.3**	**2.9**	**2.5**	**2.0**	**2.1**	**1.8**	**1.5**
StDev	0.9	0.9	0.6	0.9	0.8	0.7	0.6	0.9	0.8	0.8	0.8	0.7
CV %	**66**	**61**	**27**	**36**	**24**	**22**	**22**	**37**	**43**	**39**	**47**	**46**
Median	1.3	1.7	2.2	2.7	3.0	3.3	2.8	2.5	1.8	1.9	2.0	1.4
Max	2.8	2.9	3	3.4	4.1	4.4	4.1	4.2	3.6	3.4	3	2.6
Min	0.2	-0.5	0.8	0.8	1.5	1.6	2.1	0.9	0.5	0.9	-0.1	0

(c) SRES Low - 2095

	Potential ET Change (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	1	-0.8	1.3	2.9	3.6	5.8	5.3	4.3	0.9	3.1	2.1	1.7
CCCMA_T63	2.2	2.7	3.2	5.1	5	5.4	4.3	3.4	2.1	2.1	2.7	1.8
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	3.2	2.8	4	4.5	4.7	4.6	3.5	2.3	2	2.1	2.2	2.9
CSIRO-MK3.5	4	2.5	2.5	2.3	4.8	6.2	5	4.2	2.9	3.9	3.7	4.3
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	1.9	4.2	4.2	4.5	6.9	7.3	6.8	6.6	5	2.7	3.8	2
GISS-E-H	3.8	3.5	3.8	4.8	5.8	4.4	5.4	5.4	4.4	4.6	4.7	4.3
GISS-E-R	0.3	0.9	4	4.9	6.1	7.4	6.9	7	6	5.6	3.2	2.7
IAP	0.3	3.2	3.2	1.4	2.5	2.7	3.5	1.6	2.1	2	-0.1	0
INMCM	0.3	0.4	2.4	1.4	3.7	4.9	4.4	3.6	2.1	1.5	1.6	1.7
IPSL	2.1	3	3.1	4	5	5.3	4.7	4.2	4.3	4.4	4.9	3.4
MIROC-H	4.6	4.8	5	5.3	6.4	4.6	4.7	4.4	4	4.4	4.3	3.5
MIROC-M	4.2	4.5	4.4	5.6	6.4	6.1	5.4	3.4	3.1	3.1	3.5	2.9
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	1.7	2.1	3.8	5.5	6.4	5.9	4.5	4.6	4.4	5.5	3.4	2
NCAR-CCSM	2.1	2.6	3.3	4	5.1	5.1	3.6	2.8	3	2.9	2	2
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**2.3**	**2.6**	**3.4**	**4.0**	**5.2**	**5.4**	**4.9**	**4.1**	**3.3**	**3.4**	**3.0**	**2.5**
StDev	1.5	1.6	0.9	1.4	1.3	1.2	1.1	1.5	1.4	1.3	1.4	1.2
CV %	**66**	**60**	**27**	**36**	**25**	**22**	**22**	**36**	**43**	**39**	**45**	**46**
Median	2.1	2.8	3.6	4.5	5.1	5.4	4.7	4.2	3.1	3.1	3.3	2.4
Max	4.6	4.8	5	5.6	6.9	7.4	6.9	7	6	5.6	4.9	4.3
Min	0.3	-0.8	1.3	1.4	2.5	2.7	3.5	1.6	0.9	1.5	-0.1	0

(d) SRES B1 - 2020

	Potential ET (%) for 2020											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	0.5	-0.4	0.7	1.5	1.9	3	2.7	2.2	0.5	1.6	1.1	0.9
CCCMA_T63	1.2	1.4	1.7	2.6	2.6	2.8	2.2	1.8	1.1	1.1	1.4	1
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	1.7	1.4	2	2.4	2.5	2.4	1.8	1.2	1	1.1	1.2	1.5
CSIRO-MK3.5	2.1	1.3	1.3	1.2	2.5	3.2	2.6	2.2	1.5	2	1.9	2.2
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	1	2.2	2.2	2.4	3.6	3.8	3.5	3.4	2.6	1.4	2	1
GISS-E-H	2	1.8	2	2.5	3	2.3	2.8	2.8	2.3	2.4	2.4	2.2
GISS-E-R	0.2	0.5	2	2.5	3.2	3.8	3.6	3.6	3.1	2.9	1.7	1.4
IAP	0.2	1.7	1.6	0.7	1.3	1.4	1.8	0.8	1.1	1	-0.1	0
INMCM	0.2	0.2	1.3	0.7	1.9	2.5	2.3	1.9	1.1	0.8	0.8	0.9
IPSL	1.1	1.5	1.6	2.1	2.6	2.7	2.4	2.2	2.2	2.3	2.6	1.7
MIROC-H	2.4	2.5	2.6	2.8	3.3	2.4	2.4	2.3	2.1	2.3	2.2	1.8
MIROC-M	2.2	2.3	2.3	2.9	3.3	3.1	2.8	1.8	1.6	1.6	1.8	1.5
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	0.9	1.1	1.9	2.8	3.3	3.1	2.3	2.4	2.3	2.8	1.8	1
NCAR-CCSM	1.1	1.3	1.7	2.1	2.6	2.6	1.9	1.5	1.6	1.5	1	1.1
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**1.2**	**1.3**	**1.8**	**2.1**	**2.7**	**2.8**	**2.5**	**2.2**	**1.7**	**1.8**	**1.6**	**1.3**
StDev	0.8	0.8	0.5	0.8	0.7	0.6	0.6	0.8	0.7	0.7	0.7	0.6
CV %	**64**	**60**	**27**	**36**	**24**	**22**	**22**	**36**	**43**	**39**	**46**	**45**
Median	1.1	1.4	1.8	2.4	2.6	2.8	2.4	2.2	1.6	1.6	1.8	1.3
Max	2.4	2.5	2.6	2.9	3.6	3.8	3.6	3.6	3.1	2.9	2.6	2.2
Min	0.2	-0.4	0.7	0.7	1.3	1.4	1.8	0.8	0.5	0.8	-0.1	0

(e) SRES B1 - 2050

	Potential ET (%) for 2050											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	1	-0.8	1.3	2.9	3.6	5.8	5.3	4.3	0.9	3.1	2.1	1.7
CCCMA_T63	2.2	2.7	3.2	5.1	5	5.4	4.3	3.4	2.1	2.1	2.7	1.8
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	3.2	2.8	4	4.5	4.7	4.6	3.5	2.3	2	2.1	2.2	2.9
CSIRO-MK3.5	4	2.5	2.5	2.3	4.8	6.2	5	4.2	2.9	3.9	3.7	4.3
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	1.9	4.2	4.2	4.5	6.9	7.3	6.8	6.6	5	2.7	3.8	2
GISS-E-H	3.8	3.5	3.8	4.8	5.8	4.4	5.4	5.4	4.4	4.6	4.7	4.3
GISS-E-R	0.3	0.9	4	4.9	6.1	7.4	6.9	7	6	5.6	3.2	2.7
IAP	0.3	3.2	3.2	1.4	2.5	2.7	3.5	1.6	2.1	2	-0.1	0
INMCM	0.3	0.4	2.4	1.4	3.7	4.9	4.4	3.6	2.1	1.5	1.6	1.7
IPSL	2.1	3	3.1	4	5	5.3	4.7	4.2	4.3	4.4	4.9	3.4
MIROC-H	4.6	4.8	5	5.3	6.4	4.6	4.7	4.4	4	4.4	4.3	3.5
MIROC-M	4.2	4.5	4.4	5.6	6.4	6.1	5.4	3.4	3.1	3.1	3.5	2.9
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	1.7	2.1	3.8	5.5	6.4	5.9	4.5	4.6	4.4	5.5	3.4	2
NCAR-CCSM	2.1	2.6	3.3	4	5.1	5.1	3.6	2.8	3	2.9	2	2
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**2.3**	**2.6**	**3.4**	**4.0**	**5.2**	**5.4**	**4.9**	**4.1**	**3.3**	**3.4**	**3.0**	**2.5**
StDev	1.5	1.6	0.9	1.4	1.3	1.2	1.1	1.5	1.4	1.3	1.4	1.2
CV %	**66**	**60**	**27**	**36**	**25**	**22**	**22**	**36**	**43**	**39**	**45**	**46**
Median	2.1	2.8	3.6	4.5	5.1	5.4	4.7	4.2	3.1	3.1	3.3	2.4
Max	4.6	4.8	5	5.6	6.9	7.4	6.9	7	6	5.6	4.9	4.3
Min	0.3	-0.8	1.3	1.4	2.5	2.7	3.5	1.6	0.9	1.5	-0.1	0

(f) SRES B1 - 2095

	Potential ET (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	1.7	-1.3	2.1	4.7	5.9	9.5	8.7	7	1.5	5.1	3.4	2.8
CCCMA_T63	3.6	4.5	5.3	8.3	8.2	8.9	7.1	5.6	3.4	3.4	4.4	3
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	5.2	4.6	6.5	7.4	7.7	7.5	5.8	3.8	3.2	3.5	3.7	4.8
CSIRO-MK3.5	6.5	4.1	4.1	3.7	7.8	10.2	8.2	6.8	4.8	6.3	6	7
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	3.1	6.8	6.8	7.4	11.2	11.9	11.2	10.8	8.2	4.4	6.3	3.2
GISS-E-H	6.2	5.8	6.2	7.8	9.5	7.2	8.8	8.8	7.1	7.5	7.7	7.1
GISS-E-R	0.5	1.5	6.5	8	10	12.1	11.2	11.4	9.9	9.2	5.2	4.4
IAP	0.5	5.3	5.2	2.3	4.1	4.5	5.7	2.6	3.4	3.3	-0.2	0.1
INMCM	0.5	0.7	4	2.3	6	8	7.2	5.9	3.5	2.5	2.6	2.9
IPSL	3.4	4.9	5.1	6.6	8.2	8.6	7.7	6.8	7	7.1	8.1	5.5
MIROC-H	7.5	7.8	8.2	8.7	10.4	7.6	7.6	7.2	6.5	7.2	7	5.8
MIROC-M	6.9	7.3	7.2	9.1	10.4	9.9	8.8	5.6	5	5	5.7	4.7
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	2.8	3.4	6.1	8.9	10.5	9.7	7.4	7.5	7.2	8.9	5.6	3.2
NCAR-CCSM	3.5	4.2	5.3	6.6	8.3	8.3	6	4.7	4.9	4.8	3.3	3.3
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**3.7**	**4.3**	**5.6**	**6.6**	**8.4**	**8.9**	**8.0**	**6.8**	**5.4**	**5.6**	**4.9**	**4.1**
StDev	2.4	2.5	1.5	2.4	2.1	2.0	1.7	2.4	2.3	2.1	2.2	1.9
CV %	**66**	**60**	**27**	**36**	**24**	**22**	**22**	**36**	**43**	**38**	**45**	**45**
Median	3.5	4.6	5.7	7.4	8.3	8.8	7.7	6.8	5.0	5.1	5.4	3.9
Max	7.5	7.8	8.2	9.1	11.2	12.1	11.2	11.4	9.9	9.2	8.1	7.1
Min	0.5	-1.3	2.1	2.3	4.1	4.5	5.7	2.6	1.5	2.5	-0.2	0.1

(g) SRES A1FI - 2020

Model	**Potential ET (%) for 2020**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	0.5	-0.4	0.6	1.4	1.7	2.8	2.5	2.1	0.4	1.5	1	0.8
CCCMA_T63	1.1	1.3	1.6	2.4	2.4	2.6	2.1	1.6	1	1	1.3	0.9
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	1.5	1.3	1.9	2.2	2.3	2.2	1.7	1.1	0.9	1	1.1	1.4
CSIRO-MK3.5	1.9	1.2	1.2	1.1	2.3	3	2.4	2	1.4	1.9	1.8	2
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	0.9	2	2	2.2	3.3	3.5	3.3	3.2	2.4	1.3	1.9	0.9
GISS-E-H	1.8	1.7	1.8	2.3	2.8	2.1	2.6	2.6	2.1	2.2	2.3	2.1
GISS-E-R	0.2	0.5	1.9	2.4	3	3.6	3.3	3.4	2.9	2.7	1.5	1.3
IAP	0.2	1.5	1.5	0.7	1.2	1.3	1.7	0.8	1	1	-0.1	0
INMCM	0.2	0.2	1.2	0.7	1.8	2.3	2.1	1.7	1	0.7	0.8	0.8
IPSL	1	1.4	1.5	1.9	2.4	2.5	2.3	2	2.1	2.1	2.4	1.6
MIROC-H	2.2	2.3	2.4	2.6	3.1	2.2	2.2	2.1	1.9	2.1	2.1	1.7
MIROC-M	2	2.2	2.1	2.7	3.1	2.9	2.6	1.6	1.5	1.5	1.7	1.4
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	0.8	1	1.8	2.6	3.1	2.8	2.2	2.2	2.1	2.6	1.7	1
NCAR-CCSM	1	1.2	1.6	1.9	2.4	2.5	1.8	1.4	1.4	1.4	1	1
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**1.1**	**1.2**	**1.7**	**1.9**	**2.5**	**2.6**	**2.3**	**2.0**	**1.6**	**1.6**	**1.5**	**1.2**
StDev	0.7	0.8	0.4	0.7	0.6	0.6	0.5	0.7	0.7	0.6	0.7	0.6
CV %	**63**	**60**	**27**	**36**	**25**	**23**	**21**	**37**	**44**	**38**	**46**	**46**
Median	1.0	1.3	1.7	2.2	2.4	2.6	2.3	2.0	1.5	1.5	1.6	1.2
Max	2.2	2.3	2.4	2.7	3.3	3.6	3.3	3.4	2.9	2.7	2.4	2.1
Min	0.2	-0.4	0.6	0.7	1.2	1.3	1.7	0.8	0.4	0.7	-0.1	0

(h) SRES A1FI - 2050

	Potential ET (%) for 2050											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	1.7	-1.3	2.1	4.7	5.9	9.5	8.7	7	1.5	5.1	3.4	2.8
CCCMA_T63	3.6	4.5	5.3	8.3	8.2	8.9	7.1	5.6	3.4	3.4	4.4	3
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	5.2	4.6	6.5	7.4	7.7	7.5	5.8	3.8	3.2	3.5	3.7	4.8
CSIRO-MK3.5	6.5	4.1	4.1	3.7	7.8	10.2	8.2	6.8	4.8	6.3	6	7
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	3.1	6.8	6.8	7.4	11.2	11.9	11.2	10.8	8.2	4.4	6.3	3.2
GISS-E-H	6.2	5.8	6.2	7.8	9.5	7.2	8.8	8.8	7.1	7.5	7.7	7.1
GISS-E-R	0.5	1.5	6.5	8	10	12.1	11.2	11.4	9.9	9.2	5.2	4.4
IAP	0.5	5.3	5.2	2.3	4.1	4.5	5.7	2.6	3.4	3.3	-0.2	0.1
INMCM	0.5	0.7	4	2.3	6	8	7.2	5.9	3.5	2.5	2.6	2.9
IPSL	3.4	4.9	5.1	6.6	8.2	8.6	7.7	6.8	7	7.1	8.1	5.5
MIROC-H	7.5	7.8	8.2	8.7	10.4	7.6	7.6	7.2	6.5	7.2	7	5.8
MIROC-M	6.9	7.3	7.2	9.1	10.4	9.9	8.8	5.6	5	5	5.7	4.7
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	2.8	3.4	6.1	8.9	10.5	9.7	7.4	7.5	7.2	8.9	5.6	3.2
NCAR-CCSM	3.5	4.2	5.3	6.6	8.3	8.3	6	4.7	4.9	4.8	3.3	3.3
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**3.7**	**4.3**	**5.6**	**6.6**	**8.4**	**8.9**	**8.0**	**6.8**	**5.4**	**5.6**	**4.9**	**4.1**
StDev	2.4	2.5	1.5	2.4	2.1	2.0	1.7	2.4	2.3	2.1	2.2	1.9
CV %	**66**	**60**	**27**	**36**	**24**	**22**	**22**	**36**	**43**	**38**	**45**	**45**
Median	3.5	4.6	5.7	7.4	8.3	8.8	7.7	6.8	5.0	5.1	5.4	3.9
Max	7.5	7.8	8.2	9.1	11.2	12.1	11.2	11.4	9.9	9.2	8.1	7.1
Min	0.5	-1.3	2.1	2.3	4.1	4.5	5.7	2.6	1.5	2.5	-0.2	0.1

(i) SRES A1FI - 2095

	Potential ET (%) for 2095											
Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	3.7	-2.8	4.8	10.4	13.2	21.1	19.2	15.5	3.2	11.4	7.5	6.2
CCCMA_T63	8.1	10	11.8	18.5	18.2	19.7	15.8	12.4	7.7	7.5	9.7	6.7
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	11.7	10.1	14.4	16.5	17.2	16.7	12.8	8.5	7.1	7.7	8.2	10.6
CSIRO-MK3.5	14.6	9.1	9.1	8.3	17.3	22.6	18.1	15.2	10.6	14.1	13.4	15.5
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	6.9	15.2	15.1	16.5	24.9	26.5	24.8	24	18.3	9.9	14	7.1
GISS-E-H	13.7	12.8	13.8	17.4	21.1	16.1	19.5	19.6	15.8	16.7	17.2	15.7
GISS-E-R	1.2	3.4	14.4	17.8	22.3	26.9	24.9	25.3	21.9	20.4	11.6	9.8
IAP	1.2	11.7	11.5	5	9	9.9	12.7	5.7	7.6	7.2	-0.4	0.1
INMCM	1.2	1.5	8.9	5.2	13.4	17.7	16	13.2	7.7	5.5	5.8	6.3
IPSL	7.6	10.9	11.2	14.6	18.1	19.1	17.1	15.2	15.5	15.9	17.9	12.2
MIROC-H	16.8	17.4	18.2	19.4	23.1	16.8	16.9	16	14.6	16.1	15.7	12.8
MIROC-M	15.3	16.3	15.9	20.3	23.2	22	19.5	12.3	11.2	11.2	12.8	10.4
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	6.3	7.6	13.6	19.8	23.4	21.5	16.5	16.6	16	19.9	12.5	7.2
NCAR-CCSM	7.7	9.3	11.9	14.6	18.4	18.5	13.2	10.3	10.9	10.7	7.2	7.4
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**8.3**	**9.5**	**12.5**	**14.6**	**18.8**	**19.7**	**17.6**	**15.0**	**12.0**	**12.4**	**10.9**	**9.1**
StDev	5.4	5.7	3.4	5.3	4.6	4.4	3.8	5.4	5.2	4.8	5.0	4.2
CV %	**65**	**60**	**27**	**36**	**25**	**22**	**22**	**36**	**43**	**39**	**46**	**46**
Median	7.7	10.1	12.8	16.5	18.3	19.4	17.0	15.2	11.1	11.3	12.1	8.6
Max	16.8	17.4	18.2	20.3	24.9	26.9	24.9	25.3	21.9	20.4	17.9	15.7
Min	1.2	-2.8	4.8	5	9	9.9	12.7	5.7	3.2	5.5	-0.4	0.1

(j) SRES High - 2020

Model	Potential ET (%) for 2020											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	1	-0.8	1.3	2.9	3.7	5.9	5.4	4.3	0.9	3.2	2.1	1.7
CCCMA_T63	2.3	2.8	3.3	5.2	5.1	5.5	4.4	3.5	2.1	2.1	2.7	1.9
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	3.3	2.8	4	4.6	4.8	4.7	3.6	2.4	2	2.2	2.3	3
CSIRO-MK3.5	4.1	2.6	2.5	2.3	4.9	6.3	5.1	4.3	3	3.9	3.8	4.3
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	1.9	4.3	4.2	4.6	7	7.4	6.9	6.7	5.1	2.8	3.9	2
GISS-E-H	3.8	3.6	3.9	4.9	5.9	4.5	5.5	5.5	4.4	4.7	4.8	4.4
GISS-E-R	0.3	1	4	5	6.2	7.5	7	7.1	6.1	5.7	3.3	2.7
IAP	0.3	3.3	3.2	1.4	2.5	2.8	3.6	1.6	2.1	2	-0.1	0
INMCM	0.3	0.4	2.5	1.5	3.8	5	4.5	3.7	2.2	1.5	1.6	1.8
IPSL	2.1	3	3.1	4.1	5.1	5.4	4.8	4.2	4.3	4.4	5	3.4
MIROC-H	4.7	4.9	5.1	5.4	6.5	4.7	4.7	4.5	4.1	4.5	4.4	3.6
MIROC-M	4.3	4.6	4.5	5.7	6.5	6.2	5.5	3.5	3.1	3.1	3.6	2.9
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	1.8	2.1	3.8	5.6	6.5	6	4.6	4.7	4.5	5.6	3.5	2
NCAR-CCSM	2.2	2.6	3.3	4.1	5.2	5.2	3.7	2.9	3.1	3	2	2.1
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**2.3**	**2.7**	**3.5**	**4.1**	**5.3**	**5.5**	**5.0**	**4.2**	**3.4**	**3.5**	**3.1**	**2.6**
StDev	1.5	1.6	1.0	1.5	1.3	1.2	1.1	1.5	1.4	1.3	1.4	1.2
CV %	**66**	**60**	**28**	**36**	**24**	**22**	**22**	**36**	**43**	**39**	**45**	**46**
Median	2.2	2.8	3.6	4.6	5.2	5.5	4.8	4.3	3.1	3.2	3.4	2.4
Max	4.7	4.9	5.1	5.7	7	7.5	7	7.1	6.1	5.7	5	4.4
Min	0.3	-0.8	1.3	1.4	2.5	2.8	3.6	1.6	0.9	1.5	-0.1	0

(k) SRES High - 2050

Model	**Potential ET (%) for 2050**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	2.7	-2	3.4	7.5	9.5	15.2	13.9	11.2	2.3	8.2	5.4	4.5
CCCMA_T63	5.8	7.2	8.5	13.3	13.1	14.2	11.3	8.9	5.5	5.4	7	4.8
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	8.4	7.3	10.4	11.9	12.4	12	9.2	6.1	5.1	5.6	5.9	7.6
CSIRO-MK3.5	10.5	6.6	6.5	6	12.5	16.3	13.1	10.9	7.6	10.1	9.6	11.1
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	5	11	10.9	11.9	18	19.1	17.9	17.3	13.2	7.1	10.1	5.1
GISS-E-H	9.9	9.2	10	12.5	15.2	11.6	14	14.1	11.4	12	12.4	11.3
GISS-E-R	0.8	2.5	10.3	12.8	16.1	19.3	18	18.2	15.8	14.7	8.4	7
IAP	0.9	8.4	8.3	3.6	6.5	7.1	9.2	4.1	5.5	5.2	-0.3	0.1
INMCM	0.9	1.1	6.4	3.7	9.7	12.8	11.5	9.5	5.6	4	4.1	4.6
IPSL	5.5	7.8	8.1	10.5	13	13.8	12.3	10.9	11.2	11.4	12.9	8.8
MIROC-H	12.1	12.6	13.1	14	16.6	12.1	12.2	11.5	10.5	11.6	11.3	9.2
MIROC-M	11	11.7	11.5	14.6	16.7	15.8	14	8.9	8	8.1	9.2	7.5
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	4.5	5.5	9.8	14.3	16.8	15.5	11.8	12	11.5	14.3	9	5.2
NCAR-CCSM	5.5	6.7	8.5	10.5	13.2	13.3	9.5	7.4	7.9	7.7	5.2	5.3
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**6.0**	**6.8**	**9.0**	**10.5**	**13.5**	**14.2**	**12.7**	**10.8**	**8.7**	**9.0**	**7.9**	**6.6**
StDev	3.9	4.1	2.5	3.8	3.3	3.2	2.8	3.9	3.7	3.4	3.6	3.0
CV %	**65**	**60**	**27**	**36**	**25**	**22**	**22**	**36**	**43**	**38**	**46**	**45**
Median	5.5	7.3	9.2	11.9	13.2	14.0	12.3	10.9	8.0	8.2	8.7	6.2
Max	12.1	12.6	13.1	14.6	18	19.3	18	18.2	15.8	14.7	12.9	11.3
Min	0.8	-2	3.4	3.6	6.5	7.1	9.2	4.1	2.3	4	-0.3	0.1

(l) SRES High - 2095

Model	Potential ET (%) for 2095											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BCCR	-	-	-	-	-	-	-	-	-	-	-	-
CCCMA_T47	5.9	-4.5	7.6	16.6	21.1	33.8	30.8	24.8	5.2	18.2	12	9.9
CCCMA_T63	12.9	15.9	18.8	29.6	29.1	31.6	25.2	19.9	12.3	12	15.5	10.7
CNRM	-	-	-	-	-	-	-	-	-	-	-	-
CSIRO-MK3.0	18.6	16.2	23	26.4	27.6	26.7	20.5	13.5	11.4	12.3	13	17
CSIRO-MK3.5	23.3	14.6	14.5	13.3	27.7	36.1	29	24.3	17	22.5	21.4	24.8
GFDL_2.0	-	-	-	-	-	-	-	-	-	-	-	-
GFDL_2.1	-	-	-	-	-	-	-	-	-	-	-	-
GISS-AOM	11.1	24.4	24.2	26.4	39.9	42.4	39.7	38.4	29.3	15.8	22.4	11.4
GISS-E-H	22	20.5	22.2	27.9	33.8	25.8	31.2	31.3	25.3	26.7	27.4	25.1
GISS-E-R	1.8	5.5	23	28.5	35.7	43	39.9	40.5	35.1	32.7	18.6	15.6
IAP	1.9	18.7	18.4	8	14.5	15.9	20.4	9.1	12.2	11.6	-0.7	0.2
INMCM	1.9	2.3	14.2	8.3	21.5	28.3	25.6	21.1	12.3	8.8	9.2	10.2
IPSL	12.1	17.4	18	23.3	29	30.6	27.3	24.3	24.8	25.4	28.7	19.5
MIROC-H	26.8	27.9	29.2	31.1	37	26.9	27.1	25.5	23.3	25.7	25	20.5
MIROC-M	24.5	26.1	25.5	32.5	37.1	35.2	31.2	19.8	17.9	17.9	20.4	16.6
MIUB	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ECHAM5	-	-	-	-	-	-	-	-	-	-	-	-
MRI	10.1	12.2	21.8	31.7	37.4	34.4	26.3	26.6	25.7	31.8	20	11.5
NCAR-CCSM	12.3	14.9	19	23.4	29.4	29.6	21.2	16.5	17.5	17.1	11.6	11.8
NCAR-PCM1	-	-	-	-	-	-	-	-	-	-	-	-
HADCM3	-	-	-	-	-	-	-	-	-	-	-	-
HADGEM1	-	-	-	-	-	-	-	-	-	-	-	-
Mean	**13.2**	**15.2**	**20.0**	**23.4**	**30.1**	**31.5**	**28.2**	**24.0**	**19.2**	**19.9**	**17.5**	**14.6**
StDev	8.7	9.1	5.4	8.4	7.4	7.0	6.1	8.7	8.3	7.7	8.0	6.7
CV %	**66**	**60**	**27**	**36**	**24**	**22**	**22**	**36**	**43**	**39**	**46**	**45**
Median	12.2	16.1	20.4	26.4	29.3	31.1	27.2	24.3	17.7	18.1	19.3	13.7
Max	26.8	27.9	29.2	32.5	39.9	43	39.9	40.5	35.1	32.7	28.7	25.1
Min	1.8	-4.5	7.6	8	14.5	15.9	20.4	9.1	5.2	8.8	-0.7	0.2