PACIFIC ADAPTATION TO CLIMATE CHANGE PROJECT

KINGDOM OF TONGA

WATER RESOURCE AND SUPPLY CLIMATE CHANGE GUIDELINE

Prepared and compiled by

Quddus Fielea

on behalf of PACC Project for the

Ministry of Environment Climate Change and Natural Resources

June 2014

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ABoM	Australian Bureau of Meteoroly
AC	Asbestos cement
AusAID	Australian Agency for International Development
CGPS	Continuous global-positioning system
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Cv	Coefficient of variation (= standard deviation divided by mean
EC	electrical conductivity
ENSO	El Niño Southern Oscillation
GEF	Global Environment Facility
HLT	High level tank (elevated water storage on a tankstand)
HVWC	Hihifo village water committee
JICA	Japan International Cooperation Agency
kL	kilolitres
kL/day	kilolitres per day
L	Litre(s)
L/person/day	Litres per person per day
L/s	Litres per second (a measure of flow)
m^3	cubic metre(s)
MECC	Ministry of Environment and Climate Change
MOH	Ministry of Health
MSL	Mean sea level
NGO	Non-governmental organisation (also called civil society organisation)
PACC	Pacific Adaptation to Climate Change (Project)
PMU	Project Management Unit
PS	Pump station
PASAP	Pacific Adaptation Strategy Assistance Program
PCCSP	Pacific Climate Change Science Program
PIC	Pacific Island Country

PICCAP	Pacific Islands Climate Change Assistance Programme
PI-CPP	Pacific Islands Climate Prediction Project
PVC	polyvinyl chloride
VWC	Village Water Committee
μS/cm	micro siemens per centimetre (measure of electrical conductivity or salinity)
SOI	Southern Oscillation Index
GIS	Geographical information system
RO	Reverse osmosis
HLT	High Level Tank
LLT	Low Level Tank

1. EXECUTIVE SUMMARY

This guideline has been prepared for the Ministry of Land, Environment, Climate Change and Natural Resources as part of the Pacific Adaptation to Climate Change (PACC) demonstration project initiative. The Kingdom of Tonga is one of the 14 Pacific island countries taking part in the regional Pacific Adaptation to Climate Change (PACC) Project with support from SPREP and UNDP Samoa. Tonga signed on to the initiative in 2005, with project development completed by 2008. Implementation was started in 2009 with the inception meeting for all the participating countries. The implementation started in 2009 with the inception meeting for all the participating countries. The implementation and augmentation of the Hihifo water supply project in February 2010 to March 2014. This guide will be utilized if the Ministry of Environment, Climate Change and Natural Resources, the Government of Tonga or funding agencies would like to replicate the design to other parts of Tonga.

While the guide is primarily focused on water resources for Tongatapu, the guide can also be used for outer islands of Tonga or at a smaller scale such as village water community projects. It contains information about the risks associated with climate change. It explains how existing social, technical, institutional, economic and environmental vulnerability can magnify the risks associated with climate change. It describes actions that shall be undertaken to prepare for climate change.

The goals of this guides are to facilitate the planning and sustainable management of the water resources and supply 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 water resources and supply. Evaluation of the impact of climate change on water resources are vitally necessary for the assessment of threats to water resources and their ability to supply population centre, 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.

This guide has been divided into a number of main sections, as follows:

- Overview of the water sector
- Institutional issues
- Current water resource and supply issues
- Climate change projection for Tonga
- Climate change impact on water resources and supply
- Response to potential impact
- Identification of gaps and future needs
- Basis for design, construction and monitoring

As will be explained in the section on climate change projections (section 5), all projections of climate changes are based on scenarios of future emissions that are inherently uncertain. However, future emissions may not have significant impacts on climate at shorter time scales, so consideration of different emissions scenarios may be unnecessary. In addition, climate impacts on variability and extremes (i.e., changes in flood and drought frequencies) are harder to detect than changes in averages and may be impossible to separate from the natural variability of the climate system at shorter time scales. Projects with a time horizon of less than 30 years may justify the use of detailed climate projections.

The impacts of projected climate change and associated mean sea level rise on water resources and water supply systems have been considered to the year 2030 based on interim climate projections provided by the Pacific Climate Change Science Program (PCCSP). These interim projections are based on “most likely” and ““largest change” conditions from the outputs of 18 global climate models (GCMs). The parameters of most relevance for water availability are mean rainfall, rainfall intensity, mean temperature and mean sea level change. No projections are available yet from PCCSP for other relevant parameters i.e. evaporation and tropical cyclone activity. Also, El Niño Southern Oscillation (ENSO) activity, the main driver of current climate variability in Tonga, is assumed by PCCSP to remain the same as at present due to a lack of consensus in the GCMs. This guide describes how to incorporate climate change scenarios and other anthropogenic impact into the design and monitoring of water resources and supply projects design and construction.

Summary and Conclusions

Diversity between the island group of Tonga (Tongatapu, Vava'u, Ha'apai, Niua's and 'Eua)

There is considerable diversity between and within the rural villages, urban areas and outer islands in physiographic, geological, demographic and hydrologic characteristics, all of which have impacts on water resources availability and water supply systems. The land masses vary from mountainous islands with surface water and groundwater resources to small, low-lying coral sand and limestone islands with very limited groundwater resources and no surface water resources. The populations of each island group vary from 1,282 to over 75,416. Average island-wide population densities vary from 18 to 290 people/km² with the urban areas of Nuku'alofa having the highest densities of 1035 people/km². The percentage of urban and rural populations in the rural villages, urban areas and outer islands was 77% rural to 23% urban.

Freshwater sources and use

The main sources of freshwater throughout the rural villages, urban areas and outer islands are naturally occurring groundwater, surface water and rainwater harvested from roofs and other surfaces. Surface water is only available in 'Eua but fresh groundwater is also available, even in limited quantities, in some island. Desalination is not common and it was only used in Nomuka for a short time as a primary source of water. Recently the Tonga Water Board use desalination as an emergency source after tropical cyclone Ian at Lifuka. Importation of water to some small islands occurs via barge or boat in droughts during the drought of 1997.

Water resources availability is most critical in the small coral sand and limestone islands in the Tonga group of islands, especially in densely populated areas on island like Lifuka.

The main consumptive use of freshwater in the Tonga group is water supply for urban and rural communities. The conjunctive use of rainwater, when available, for potable purposes and other sources for non-potable purposes is common in some islands. Brackish water and seawater are used in some islands as a source of supplementary water for some non-potable uses.

100% of the total population across all the rural villages, urban areas and outer islands had access to improved water supplies in 2011 which is significantly better than the world average of 86%. Freshwater is rarely used for irrigated agriculture and industry (limited in most islands).

Current water availability issues

Water availability in the rural villages, urban areas and outer islands is impacted at present to various degrees from current climate variability and human factors. The most vulnerable groups include densely populated urban and peri-urban settlements and remote communities.

Droughts associated with El Niño and La Niña episodes are a major problem for the rural villages, urban areas and outer islands, causing severe water shortages in some. For some of the smaller islands, emergency measures such as the use of desalination and importation of water via barge or boat are required. Droughts also severely impact on agriculture in most islands.

Floods caused by tropical storms and cyclones are a major problem in low lying areas within the rural villages, urban areas and outer islands, particularly for urban centres located at low coastal swampy lands (Sopu, Popua).

Human factors are already having a large impact on water availability, particularly in urban and peri-urban areas where rapidly increasing populations place increasing demands on water resources. Inadequate water supply systems, often suffering from large pipeline losses, mean that many people are going do have poor access to safe water in adequate quantities. High population densities and inadequate sanitation facilities lead to pollution of nearby groundwater and surface water resources and resultant water quality degradation. Population pressures mean that adjacent areas reserved for water resources development are also polluted due to human activity and settlement within them. As a result, the incidence of water-borne disease will be high in some islands. The incidence rate of diarrheal diseases, linked to contaminated drinking water and poor sanitation conditions, is going to be higher (about four to five times higher) than in developed countries such as Australia and New Zealand.

Other sources of pollution include oil and fuel leaks and spills and agricultural chemical on rural land. Over-pumping causing salinisation of groundwater is a problem in some islands.

Damage to water infrastructure, particularly associated with land disputes between land owners and government authorities, is another human-induced problem in some islands.

Poor water governance and management is also a major factor in decreasing current water availability. Problems include lack of water policy, plans and legislation and ineffective coordination and administration of water sector agencies. Most rural villages and isolated islands suffer from insufficient knowledge of national water resources due to limited effort and resources being applied to water resources assessment and monitoring. Ineffective or no water source protection measures will increase the vulnerability of water resources to contamination from human settlements and activities. Human and financial resource capacity limitations often prevent even essential tasks from being undertaken. Insufficient training, education and ongoing development of water sector personnel and loss of such personnel to more lucrative positions within or outside the country are ongoing problems.

Lack of, or limited community education, awareness and participation in freshwater management, conservation and protection are additional problems which impact on water availability.

Climate change projections

The impacts of projected climate change and associated mean sea level rise on water resources and water supply systems have been considered to the year 2030 based on interim climate projections provided by the Pacific Climate Change Science Program (PCCSP). These interim projections are based on "most likely" and ""largest change" conditions from the outputs of 18 global climate models (GCMs). The parameters of most relevance for water availability are mean rainfall, rainfall intensity, mean temperature and mean sea level change. No projections are available yet from PCCSP for other relevant parameters i.e. evaporation and tropical cyclone activity. Also, El Niño Southern Oscillation (ENSO) activity, the main driver of current climate variability in Tonga, is assumed by PCCSP to remain the same as at present due to a lack of consensus in the GCMs.

The PCCSP interim projections to 2030 for Tongatapu are summarised below.

<u>Mean annual rainfall</u>

For the "most likely" condition, Tonga show relatively small reductions.
For the "largest change" condition, Tonga show small to moderate reductions.

<u>Mean dry season rainfall</u>

For the "most likely" condition, Tonga show small to moderate reductions.
For the "largest change" condition, Tonga show relatively small reductions.

<u>Mean wet season rainfall</u>

For the "most likely" condition, Tonga show small to moderate increases.
For the "largest change" condition, Tonga show small reductions.

<u>Mean monthly rainfall intensity</u>

For the "most likely" condition, Tonga show increases in either all or most months. Where decreases are shown, these are relatively small.
For the "largest change" condition, Tonga again show increases in either all or most months.

<u>Mean monthly temperature</u>

For the "most likely" condition, Tonga show increases between 0.6ºC and 1.1ºC.

For the “largest change” condition, Tonga show increases between 0.6ºC and 1.2ºC.

Mean sea level

Increases are shown to be in the range from 0.03 m to 0.17 m within Tonga. Projections made in some other studies were also reviewed and the results are presented in the report.

Climate change impacts on water resources by 2030

Impacts on surface and groundwater resources availability due to projected changes to rainfall, temperature and mean sea level rise were assessed. This was done by assessing impacts on groundwater recharge, the main drivers of (or inputs to) these water resources, using water balance approaches.

Emphasis was placed on the reduction in mean rainfall under the “most likely” or “largest change” conditions for Tonga are projected to have small to large increases in mean rainfall which will have beneficial effects on water resources.

Key findings regarding projected impacts on groundwater recharge, and hence groundwater availability, are:

- Small reductions in mean annual groundwater recharge for Tongatapu (up to 2%) under the “most likely” condition.
- Moderately significant reductions in mean annual groundwater recharge for Tongatapu (up to 12%).

The estimated recharge changes due to projected mean rainfall changes are rather coarse. However, such estimates are considered reasonable given the uncertainties inherent in the interim projections of rainfall and the scale at which they are available, the lack of projections regarding evaporation and the assumption that climate variability due to ENSO activity will be the same as at present.

Impacts from projected increases in rainfall intensity in Tonga are likely to be:

- Increased flooding and consequent problems including damage to infrastructure (including water infrastructure), increased land erosion, especially in cleared, steep catchments, and sedimentation of downstream reaches of streams and rivers and the coastal environment.
- Beneficial impacts due to enhanced groundwater recharge to freshwater lenses on coral sand and limestone islands and to coastal aquifers in high islands.
- Beneficial effects on high islands from higher stream flows.

Mean sea level impacts on groundwater resources by 2030

The impact of projected mean sea level rises is not expected to have a significant impact on groundwater resources in small islands and coastal areas of larger islands except where land surface elevations are currently very low. Rising sea levels will not adversely impact on groundwater resources unless there is loss of land.

Hence, the main issue is whether or not land will be lost. An inundation study for Tongatapu, showed that a sea level rise below 2m will inundate 4.1sqkm of the land area that is 1.6% of the total land area. Areas particularly those along the coast are the most vulnerable and affected areas. Some of the coastal lands are not effective recharge zone but act as buffers zones to salt water intrusion. The actual loss of these lands through inundation will shrink the actual recharge zone with depleting recharge to ground water.

Further work is required to assess the vulnerability of shorelines to erosion due to mean sea level rise. Erosion of shorelines due to extreme events such as major waves from storms or cyclones is more likely to affect low-lying coastal areas and small islands than a gradual change in sea level. A better understanding of the processes and impacts on coastlines due to sea level rise is required, particularly on small low lying islands.

Climate change impacts on water demand by 2030

Projected air temperature increases are unlikely to have a significant impact on water demand especially when compared with the water demand increase due to population increases and losses in pipe networks. An increase in water demand of 2% due to projected temperature increase was used in a recent water master plan study for Tarawa, Kiribati.

Comparisons of risks to water availability by 2030

Key findings from an analysis and comparison of risks to water availability due to climate and non climate related factors are:

- In general, the highest risks to water availability are from increasing water demands due to population increase and other activities and pollution of water resources.
- Increasing water demands based on current annual population growth rates in some urban areas have the potential to increase water demands in 2030 by between 70% and 240%.
- The loss of freshwater resources due to pollution is hard to quantify. In most cases, water treatment systems can be installed to improve the water quality so the impact is one of additional cost rather than total loss of the resource.
- Contamination of fresh groundwater due to seawater intrusion from over-pumping is reversible if pump rates are reduced to sustainable levels. The main impact would be the cost of developing additional water sources once the pump rates were reset in order to meet the required water demand.
- The reduction in water resources availability due to mean sea level rise is hard to quantify. The assumption was made that the impact of this projected climate change is again significant but relatively small compared to the large demand on water resources due to population increase.
- Leakage from many rural and urban pipe distribution systems is 50% or higher. This loss of potential usable freshwater is greater than the effect of projected climate change impacts on stream flow, groundwater recharge and the assumed loss of 20% of groundwater resources on low islands.
- The impact of temperature rise on water demand based on the 2% increase used for Tarawa is insignificant compared with the other impacts.
- Impacts of natural hazards such as overtopping waves due to cyclones and tsunamis, while devastating in the short to medium-term, may not lead to a long-term loss in groundwater resources unless major changes in landform are experienced. Also, damaged infrastructure can be repaired or new infrastructure installed if communities have and use the opportunity to resettle to higher ground.
- Impacts from poor water governance and management are considered to be moderate to high on overall water availability. While these factors do not directly lead to a loss of water resources, they can lead to poor decisions about water resources development and protection. This can cause further water quality degradation on existing developed water resources due to lack of action regarding encroachment onto water protection areas. Poor governance can also lead to other problems including delays in implementing much needed water augmentation works for existing populations.
- Impacts from vandalism are also considered to be moderate on overall water availability. Vandalism can cause damage to infrastructure with temporary loss or reduction in water supply services. Damaged infrastructure can be repaired or replaced but this can be expensive and time consuming.
- Impacts from works that alter existing coastlines making them more vulnerable to erosion, or gravel mining that exposes shallow groundwater to direct evaporation can potentially lead to a loss of groundwater resources due to man-induced erosion of land or increased evaporation.

In summary, non-climate related factors of increasing water demand due to increasing population and leakage from pipe systems pose the greatest risks to water availability.

Water availability implications for vulnerable groups

The main vulnerable groups of people in terms of water availability from both climate and non-climate related factors are those living in:

- Crowded urban and peri-urban areas, which are at major risk because of lack of adequate water supply and the need to use polluted sources for some water uses.
- Remote islands, which are at risk during droughts if the local water resources are depleted (e.g. rainwater tanks) or become saline (groundwater) and require importation of water.
- Remote parts of larger islands, which are at risk during droughts if water resources are depleted and food crops fail, due to the difficulty of access for emergency assistance and the time taken to regrow crops once rainfall returns to normal.
- Very low level parts of islands, which are at risk of overtopping, erosion and temporary salinisation of groundwater from waves caused by cyclones or tsunamis in addition to potential inundation from projected sea level rise.

Review of experiences to improve water availability

Many recent programmes and initiatives in the water sector have been implemented without the recognition of potential climate change impacts but with a primary focus on more immediate needs such as providing improved water supplies to cater for population growth and development. There is a general lack of focused on water governance, water resources assessment, water supply development and management, capacity building and training, and community education and awareness. These improvements are required regardless of the additional stresses imposed due to climate change. The ultimate aim of these projects is the improvement of water supply for rural and urban communities for the current and future populations. Other projects have been or are being implemented to install new water supply systems or reconstruct/rehabilitate existing systems for communities devastated by natural disasters.

Water sector projects which aim to improve water availability through proper planning, design and implementation and which cater for current climate variability are also building resilience into physical and human systems which can assist in coping with future climate change. The Hihifo water resource and supply project is an example of good practices.

Practical strategies to improve water availability

A number of strategies for managing the implications of climate change in addition to existing stresses on water availability for rural, urban and remote islands are outlined in the guideline under the following categories:

- Water governance
- Assessment and monitoring of water resources
- Management and protection and of water resources
- Appropriate water supply systems
- Demand management
- Drought and flood planning
- Capacity building and training
- Community education, awareness and participation
- Other water supply strategies for specific circumstances.

Key principles for this guideline are:

- Ensuring that the water sector is resilient to current climate variability, in addition to major pressures from increasing water demand and stresses from water pollution associated with human settlements, is the most effective overall adaptation strategy to cope with future climate change.
- Strategies to reduce vulnerability of the water sector to climate change and, thus, increase water availability are essential components of good water management practice, and are required whether climate changes or not.

- There are "no simple technical fixes" or no single action that will improve water availability. Rather a range of strategies are required including improved water governance; effective assessment, development, management, protection and conservation of water resources; effective operation, maintenance and management of water supply systems and other water development schemes; enhanced community participation in the water sector and improved community education and awareness.
- Although there are some similarities between islands, each island is different and some have wide variations in water resources and water availability between different parts of the island (e.g. Hihifo and Fua'amotu). The mix of potential strategies to improve water availability must be adapted to suit local circumstances taking account of population growth and the pattern of settlement and development.
- Introduction of new technologies requires parallel investment in training, education and awareness to gain community and government acceptance.
- In specific circumstances, particularly in rural villages, urban areas and outer islands with limited land and water resources (e.g. crowded low-lying islands and remote islands), there are a number of options to assist in development and management of water resources.

Identification of gaps and future needs

Information gaps and research needs, aimed at a better understanding of the implications of climate change on water availability, shall be identified according to the following categories:

- Climate change projection deficiencies and needs
- Water resources data deficiencies and needs
- Other data deficiencies and needs
- Research into impacts on surface water and groundwater resources
- Further development of effective water supply technologies.

Basis for design and implementation

A brief back round of the study area (project site) where it describes the geographical location of the site, population and a brief history of the water supply system and its current state. It should also highlight any alternative water resources that supplement the use of underground waters with some notes on the governing body of the existing water supply system. It should address the result of the concepts of basic design study and the basis for a new system as follows:

- Status of the project
- Improvement of the water resource and supply conditions
- Conservations of water and alternative supplementary sources
- Potential climate change impacts and adaptation strategies
- Transmission and distribution pipelines and elevated tank
- Pipe replacement (asbestos, galvanized, uPVC etc)
- Leakage control and improvement
- Training and awareness programs
- Monitoring and evaluation
- Improvement and suitability of the financial status

2. OVERVIEW OF WATER SECTOR & CLIMATE CHANGE IMPACTS

2.1 Outline of the Kingdom of Tonga

Figure 1 shows the Kingdom of Tonga, of the 172 coral and volcanic islands which extends from latitude 15º and 23° South and longitude 173º and 177º West. The rural villages, urban areas and outer islands of Tonga have one of immense diversity in geography, climate, hydrology, biodiversity and demography.

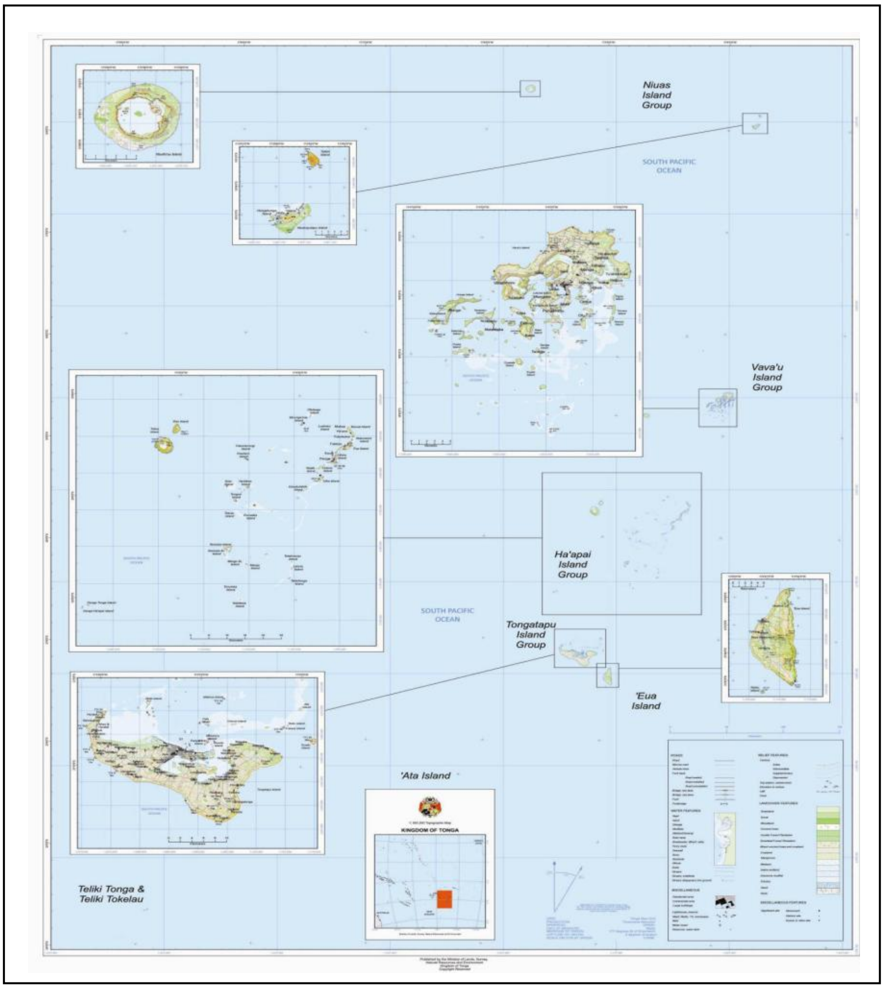


Figure 1 Map showing the locations of the Kingdom of Tonga (from TSNCCCR, 2012)

A summary of key physiographic, geological, demographic and hydrologic characteristics which are relevant to the availability and use of water resources shall be provided in this section. The information must shows the characteristics of the project site in terms of total land area, topography, number of islands, geology, rainfall, total population and the distribution and density of the population. All of these characteristics, together with climate variability, have impacts on water resources availability and water supply systems in Tonga. Climate variability under current conditions and impacts of this variability on water resources are covered in section 4.

2.2 Physiographic and geological characteristics

Table 1 presents a summary of key physiographic and geological characteristics for each of main island groups. Figure 2 show the range of land areas, population densities and elevations,

Table 1Summary of physiographic and geological characteristic of Tongatapu and 'Eua

Island	Total land area (km²)	No. of uninhibited	Island types according to geology	Highest elevation

		Island		(m)
Tongatapu	260.48	22	Limestone, reef islands	65
‘Eua	87.44	1	Volcanic, limestone, reef islands, mixed	312

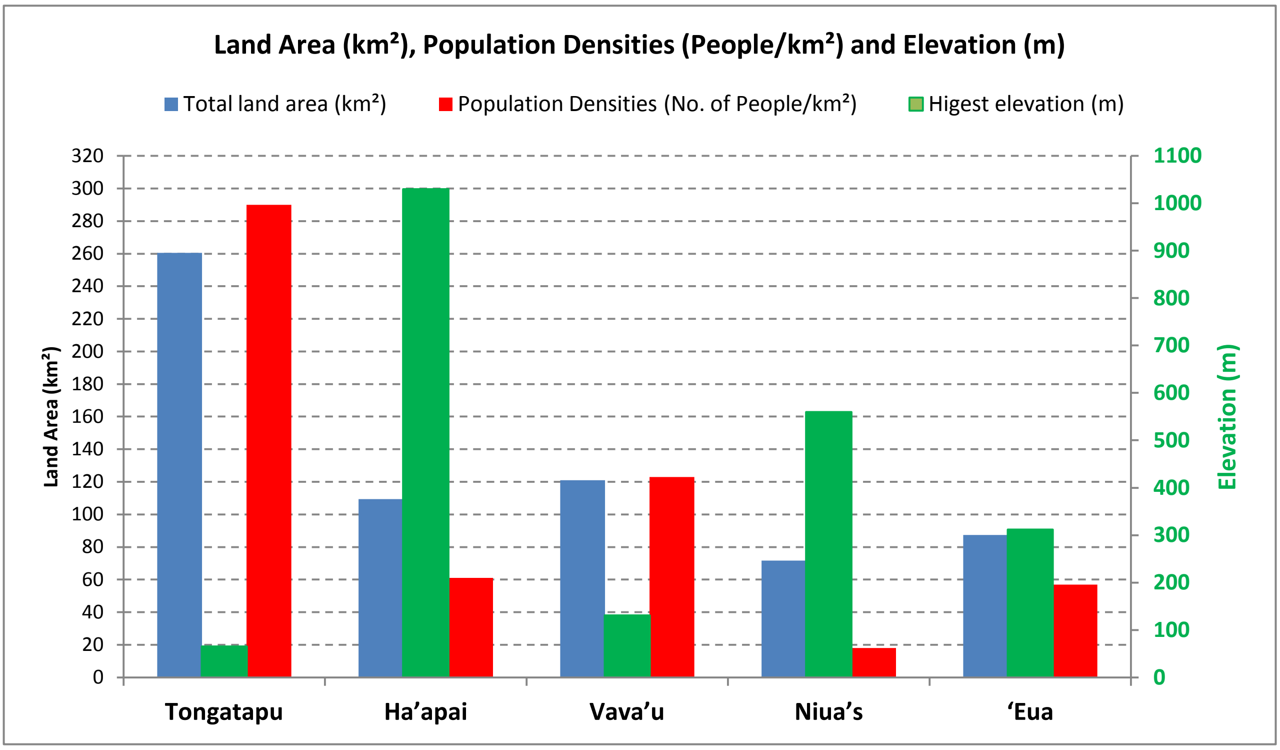


Figure 2 Land area, population densities and elevation

Observations shall be made about the diverse physiographic and geological characteristics of the selected island or project sites:

- The total land area of the project site.
- Geological features of the project site.
- Topography of the project site relative to mean sea level.

2.3 Hydrologic characteristics

This section provide a summary of key characteristics related to rainfall, the main influence on water resources, and the types of water resources in each island groups or project site. It shows the mean annual rainfall and the minimum and maximum annual rainfall and the coefficient of variation (Cv) of annual rainfall, a measure of annual rainfall variability. Other parameters of equal importance such as evapotranspiration shall be considered.

The spatial distribution of rainfall varies slightly between and within each island and project site and has an important role in determining the distribution of rainfall and availability of water resources. Evapotranspiration is also a very important component of the hydrological cycle and of significance to water resources availability. It comprises the processes of evaporation from open surfaces and transpiration from vegetation and is dependent on many factors including solar radiation, temperature, humidity, wind speed and carbon dioxide levels. Potential evapotranspiration occurs when there is an adequate supply of moisture available at all times. Actual evapotranspiration from a land mass is dependent not only on the potential evapotranspiration but also on the availability of moisture in the soil and type and density of vegetation.

Mean annual rainfall varies from 1,771 mm at southern Tonga (Tongatapu) to 2,432 mm at northern Tonga. (Niua’s) The mean annual rainfall at the 2 Niua’s are relatively high and gradually reduces to 1,771 at Nuku’alofa and 1,707 at central Tonga (Lifuka).

Table 2 Summary of hydrologic characteristics for the main island groups of Tonga

Island Group	Mean annual rainfall (mm) at the capital	Coefficient of variation (Cv) of annual rainfall at the capital	Range of mean annual rainfall in the 5 island group(mm)	Main freshwater resources
Tongatapu	1,771	0.25	1,707 – 2,432	GW, RW (limited)
Ha'apai	1,707	0.27		GW, RW (limited)
Vava'u	2,185	0.22		GW, RW (limited)
Niuafo'ou	2,432	0.18		RW,SW (limited)
Niuatoputapu	2,303	0.19		GW, RW (limited)
'Eua	None			GW,RW,SW (limited)

Rainfall also displays considerable temporal variability within and between the rural villages, urban areas and outer islands. For example, the Cv of annual rainfall (at the capitals varies from lows of 0.18 and 0.19 for the Niua's, respectively, to highs of 0.25 for Tongatapu, and 0.27 for Ha'apai. The highest Cv's are associated with island groups showing relatively low mean rainfall (e.g. Tongatapu and Lifuka) and, conversely, the lowest Cv's are associated with relatively high mean rainfall (e.g. Niua's)

High temporal variability due to major influences from El Niño and La Niña episodes (refer section 4.2**).**

2.4 Demographic characteristics

This section outlines the demographic trends of population growth and its implication on water demand and quality in the project site.

Demographic factors are commonly recognized as one of the primary drivers of human induced water resources and supply change, along with biophysical, economic, socio-political, technological, and cultural factors. Concerns about demographic effects on demand and water quality are fuelled by demographic trends such as population growth and the exponential growth of urban areas which stress out the availability and accessibility to water especially in areas of limited fresh water resources.

Table 3 presents a summary of key demographic characteristics for each of island group. Table 3 show total (national) populations and average population densities, respectively. Table 4 uses a logarithmic scale owing to the large range in populations and the diverse demographic characteristics of the island group:

Table 3 Summary of demographic characteristics of the main island group of Tonga

Country	2011 Population Census	Average population density (people/km²)	Population growth rate (%)	Urban Population (Tonga) (%)	Rural Population (Tonga) (%)
Tongatapu	75,416	290	0.9	23	77
Ha'apai	6,616	61	-2.7		
Vava'u	14,922	123	-0.8		
Niua's	1282	40	-5.9		
'Eua	5016	57	-0.7		

Using the national population growth rates from the 2011 census from Table 3, the changes in population (in numerical and percentage terms and the estimated total population by 2030 were calculated as shown in Table 4.

Table 4 Summary of estimated population changes and total populations by 2030

Island Group	2011 Population Census	Change in population to 2030	Estimated change in population to 2030 (%)	Estimated population in 2030
Tongatapu	75,416	14604	19%	90020
Ha'apai	6,616	-1083	-16%	5533
Vava'u	14,922	-2442	-16%	12480
Niua's	759	-210	-16%	1072
'Eua	5016	-821	-16%	4195

Notes: The planning horizon for this guideline is 2030). This is also the selected year for climate change projections made available to PASAP from the Pacific Climate Change Science Program (PCCSP) as presented in section 4.

From Table 4, the following observations are made:

- Tongatapu shows an estimated increase in population of 19%.
- Ha'apai, Vava'u, Niua's and 'Eua shows an estimated decrease in population by 2030 of -16%.In the past, Tongatapu and Nuku'alofa have experienced enhanced growth rates due to inward migration from outer islands to the main population centre.
- The results here assume that the current estimated population growth rates apply over the next 20 years. This assumption may not be correct.

This will have a large impact on the ability of water resources to meet urban water demands in Tongatapu especially in Nuku'alofa.

2.5 Types of water resources

This section categorized the types of water resources that are available for each island or project sites. The needs for an alternative source of water to supplement one another shall be considered with a clear and detail explanation in this section.

2.5.1 Categories

Freshwater resources in Tonga can be classified into two main categories:

- Naturally occurring water resources requiring a relatively low level of technology in order to develop them. This category includes surface water, groundwater and rainwater.
- Water resources involving a higher level of technology (sometimes referred to as "nonconventional water resources). This category includes desalination, importation and the use of seawater or treated wastewater as a substitute for some uses.

2.5.2 Surface water

Surface water can occur on 'high' volcanic islands in the form of ephemeral and perennial streams and springs, and as freshwater lagoons, lakes and swamps. Perennial streams and springs occur mainly in volcanic islands where the permeability of the rock is low. Many streams are in small, steep catchments and are not perennial. Low-lying coral islands and limestone islands rarely have fresh surface water resources except where rainfall is abundant. Many small island lakes, lagoons and swamps, particularly those at or close to sea level, are brackish.

2.5.3 Groundwater

Fresh groundwater occurs on many islands including small coral islands where there is an absence of surface water. Groundwater can be found as either 'perched' (high-level) or 'basal' (low-level) aquifers. Perched aquifers are found on many high volcanic islands above or behind relatively impermeable geological layers ('Eua). These aquifers are the source of springs which occur mainly above sea level and sometimes below sea level. Basal aquifers occur at or below sea level and are found on many low islands of adequate size and rainfall and in the coastal margins of high volcanic islands. On many small coral islands and some limestone islands, the basal aquifer takes the form of a 'freshwater lens' (or 'groundwater lens'), which underlies the whole or most of the island. An example of a cross section of a freshwater lens is shown in Figure 3.

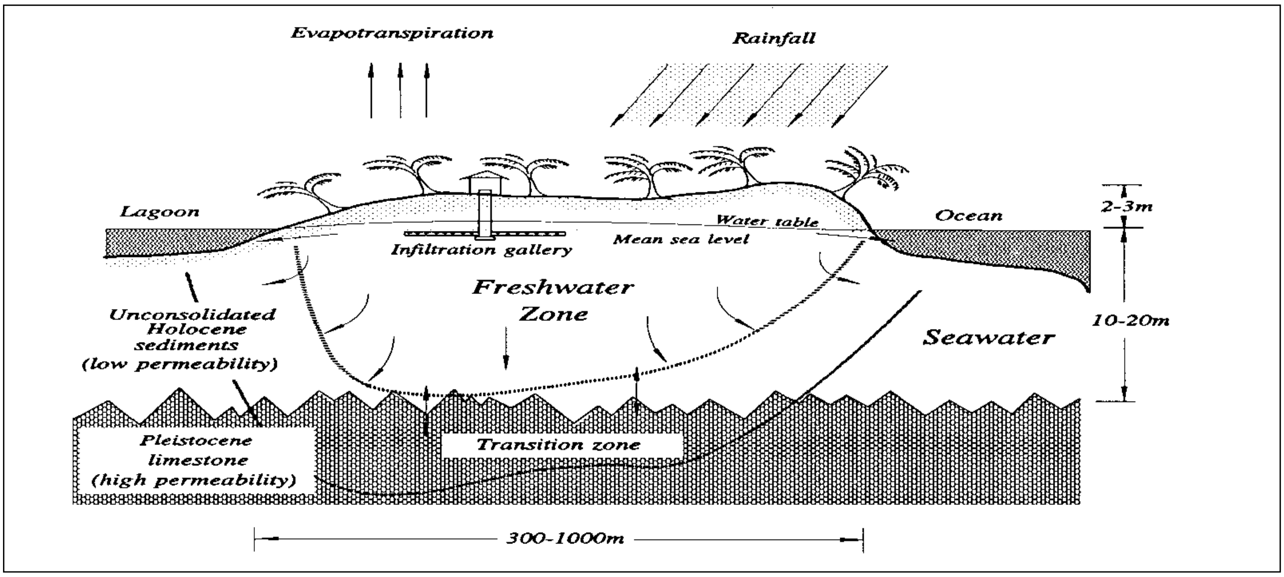


Figure 3 Cross section through a small coral island showing main features of a freshwater lens (exaggerated vertical and location of an infiltration gallery

The term 'freshwater lens' can be misleading as it implies a distinct freshwater aquifer. In reality, there is no distinct boundary between freshwater and seawater but rather a transition zone as shown in Figure 3. Also, it is noted that diagrams such as that above exaggerate the vertical scale relative to the horizontal scale. In reality, the vertical scale is very small in comparison to the horizontal scale, often by a factor of 50 to 100. Basal aquifers often tend to be more important than perched aquifers because they are more common and generally have larger storage volumes. Basal aquifers are, however, vulnerable to saline intrusion owing to the freshwater-seawater interaction, and must be carefully managed to avoid over-pumping, consequent seawater intrusion and salinisation of water supplies. The use of infiltration galleries (Figure 11) rather than conventional boreholes for groundwater pumping can avoid these problems.

2.5.4 Influences on occurrence of surface water and groundwater

The occurrence of surface water and groundwater on islands is dependent on many natural influences including the size of island or land mass, spatial and temporal distribution of rainfall, evaporation, soils, vegetation, geology and hydrogeology, topography and, for low-lying islands, sea level movements.

Human activities can also impact on the occurrence and distribution of fresh water resources primarily through the development of urban areas near or over groundwater resources, clearing of land for agriculture, forestry and mining and non-sustainable extraction of water particularly over pumping of groundwater in coastal areas or small islands. Human activities can lead to biological and chemical contamination of both surface and groundwater due to urban and industrial development, soil erosion and consequent sedimentation of surface water systems due to inappropriate land clearing and saline intrusion into otherwise fresh groundwater due to over pumping. Pollution problems associated with human settlement and activities are considered further in section 4.5.2.

2.5.5 Rainwater

Rainwater collection and storage ('rainwater harvesting') systems are common in many of the 5 island group. In islands with high rainfall (e.g. Niua's), rainwater harvesting using the roofs of individual houses and some community buildings, is the primary source of freshwater. In most islands, rainwater is used as a supplementary source to other water sources, especially groundwater. When rainfall is plentiful, rainwater is sometimes used for all household needs but limited to potable water needs (drinking, cooking and hand-washing) in dry periods. Common materials for rainwater tanks are ferro-cement, fibre-glass, steel and plastic (polyethylene). In recent years, plastic tanks have become popular for household rainwater collection in many islands.

2.5.6 Desalination

Desalination was only used in a limited number of times in the island of Nomuka as a primary or supplementary source of freshwater. Desalination is a relatively expensive and complex method of obtaining freshwater for small islands. The cost of producing desalinated water is almost invariably higher than developing groundwater or surface water due to the high energy and operating expenses. Desalination systems also require skilled operators to ensure the necessary operation and maintenance procedures are implemented. Desalination using reverse osmosis (RO) units was recently used as the primary freshwater supply source on Lifuka after tropical cyclone Ian and as a supplementary source to limited rainwater when rainwater harvesting facilities are broken and not available and polluted groundwater are the only source.

2.5.7 Importation

Water is imported between islands and in some islands, especially as an emergency measure during droughts. Water has been imported by sea transport (boats or barges) during droughts, for instance, to outer islands of Ha'apai during the droughts of 1998. During water shortages, people on some islands travel by boat or canoe to collect water from nearby islands with more plentiful water sources. The Government of Tonga spent TOP$200,000 on shipping water to the islands in the Ha'apai group during the drought periods in 1998 (Tu'i'afitu ,et al, 2005). Bottled water has become an alternative source of drinking water and has been produced from local desalination (RO) units (e.g. Tongatapu). The cost of bottled water is invariably much higher than for water supplied by local water authorities and is not used by most of the population.

2.6 Water supply and use

2.6.1 General

The main consumptive uses of freshwater especially the water supply for urban and rural communities. Freshwater (direct from rainfall or from surface and groundwater sources) is also used for subsistence agriculture and for farm and domestic animals to support these communities. Small scale irrigation of food crops starts to occur in Tongatapu (e.g. using of underground water for squash production).

Additional freshwater from private own desalination unit is used in some islands to support tourist facilities (e.g. some islands in Vava'u and Ha'apai Islands) and limited industry. Overall, there is only minor utilization of freshwater for industrial and other business purposes. Groundwater and rainwater is used for production of bottled water on Tongatapu.

Water supply systems and associated management approaches vary from household systems to community or centralized water supply systems in both rural and urban areas. At household level, freshwater is generally obtained from a rainwater collection tank or other containers, groundwater withdrawal from wells and, on high islands, collection of water from nearby springs or streams.

Typical community water supplies in rural areas have a distribution pipe network using water from surface or groundwater sources. Surface water systems normally use gravity flow pipelines from springs or streams to tanks or standpipes in the village. Groundwater systems often use petrol, diesel or solar pumps, which may be operated for a number of hours each day, to supply water to a storage tank feeding standpipes within the village. Rural water supply systems are often managed by village or island councils or community 'water committees'. In some cases a small fee is charged to households benefiting from the water supply in order to cover operational expenses.

Urban water supply systems commonly consist of source works (e.g. groundwater pumping areas and/or surface water collection and storage), transmission pipelines and networks of distribution pipes to consumers. Urban water supply systems are generally run by the Tonga Water Board, a government own board is responsible for water supply. Cost recovery by fixed fee or metered usage has been implemented in urban areas of Tonga and recently to rural areas including Hihifo.

On most small isolated island, rainwater is the primary freshwater resource and is collected in both household and community tanks. Where shortages are experienced at household tanks during extended dry periods, water is delivered by tanker from the community tanks. Per capita freshwater usage varies considerably between islands and within islands of the country depending on availability, quality, type and age of water distribution systems, cultural and socio-economic factors and administrative procedures.

Freshwater usage varies from low values of approximately 20-80 litres per person per day (L/p/d), where water is very limited, to more than 100 L/p/d on Tongatapu and Vava'u where water resources are plentiful. Water usage tends to be higher in urban than in rural areas for a number of reasons, including the use of water consuming devices (e.g. washing machines) and leakage from pipe distribution systems. The latter can be 50% or more of the water supplied from sources. Typical per capita water usage in well-managed water supply systems is in the order of 50-150 L/p/d.

2.6.2 Access to improved water supplies

Access to an improved water source refers to the percentage of the population with reasonable access to an adequate amount of water from an improved source. Reasonable access is defined as access to at least 20 litres per person a day from a source within one kilometre of the dwelling.

"Safe" drinking water means water that is safe to drink and available in sufficient quantities for hygienic purposes. National statistics do not normally have data based on this definition but rather have data associated with "access" to drinking water sources (e.g. piped water to standpipes or into houses, boreholes, protected springs or wells or rainwater catchments). Unimproved sources include unprotected wells and springs, water trucks, surface water including streams and lakes. Thus, "access" to drinking water sources is used as a proxy for "safe" drinking water sources. It is noted that many "improved" wells are not safe to drink. For instance, in low-lying sand islands, well improvements such as concrete surrounds and covers do nothing to prevent the movement of pathogens through the groundwater and into the well

The data in Table 5 shows a considerable compliance within all the islands of Tonga to portable water and access to the physical quantity adopted. For urban areas, access to improved water supplies is 100%. For rural areas, 100 % accessed is accomplished. Overall, the 100% rate is accomplished at normal conditions for Tonga. According to the 2011 Census, out of 18,033 private households in Tonga, 67.3% (12,142 households) obtained their drinking water from a cement tank, 25.2% (4546 households) from the neighbours, 3.6% (651 households used bottle water, 0.56% (102 households) from boil water, 3.1% (households) from pipe water and the remaining 0.1% (25 households) from other sources of water.

Each island division and districts obtained their water for drinking principally from water captured and stored in cement tanks. According to census 2011, 63.9 per cent (8186 households) of the total households in Tongatapu (12818 households) obtained their drinking water from cement tanks, 36.1 percent used piped water, bottled, boiled, neighbours and other source of water account for the remaining balance. In Vava'u 72.8% (2052 households) of the total households obtained their drinking water from cement tanks, Ha'apai (89.6%, 1127 households of 1258 total), 'Eua (59.8%, 516 households of 862 households), Niuafo'ou (94.7% of 114 households and (92.5% of 282 total household for Niuatoputapu) (Table 6).

Table 5 Main source of drinking waterby division, 2011 census

Island Group	Total	Cement Tank	Neighbour	Bottle water	Boil Water	Piped water supply	Other
Tonga	18,033	12,142	4546	651	102	567	25
Tongatapu	12,818	8,186	3410	636	93	473	20
Vava'u	2,818	2,052	721	11	6	20	3
Ha'apai	1,258	1,127	122	1	2	4	2
'Eua	862	516	273	3	1	69	0
Niuatoputapu	282	261	20	0	0	1	0
Niuafo'ou	114	108	6	0	0	0	0

Table 6 Access to drinking water (household by drinking water)

Name of Island Group	Total	Piped water supply	Cement or other tank	Own Well	Other
Tonga	18,033	16,014	4546	651	102
Tongatapu	12,818	11,796	829	103	90
Vava'u	2,818	2,386	399	4	24
Ha'apai	1,258	913	295	44	6
'Eua	862	779	79	0	4
Niuatoputapu	168	138	28	0	2
Niuafo'ou	114	2	112	0	0

2011 census

3. INSTITUTIONAL CONTEXT

3.1 Management, monitoring activities and responsibilities

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

- The Geology Section of MLECCNR has been designated as Tonga's lead national water resource agency. There is, however, a formal legal basis is current under consideration 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. There is also a formal requirement in the process to report on the results of these measurements to GoT and there is 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 a statutory basis for the latter functions on the process of approving. 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 MLECCNR. The last major report on the results of water resource monitoring in Tonga by MLECCNR was published in 1993.
- 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 well field 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 is carried out by the Geology Section of MLECCNR 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

each individual wells meter is functioning. Access to the important data collected by the TWB is limited.

- 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.
- 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. 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.
- The Water Resources Committee is a subcommittee of the Development Co-ordination Committee (to be designated as the National Water Authority under the Water Resources Bill which is before cabinet), and is responsible for initiating and reviewing development and other proposal related to water resources, and making recommendations to the Development Co-ordination Committee.
- The Ministry of Infrastructure (MOI) 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. The absence of a government licensed and controlled drilling rig is a major concern.
- The Waste Management Authority will be responsible for the management of solid waste, which includes the new waste management facility at Tapuhia near Vaini on Tongatapu which has an aerated wastewater treatment plant treating leacheates and dispersing the treated effluent by irrigation. Groundwater at Tapuhia is monitored to ensure leachate is not impacting on groundwater. Closure of the previous waste dump will allow for restoration of the associated coastal area.
- The Ministry of Agriculture Forestry and Fisheries (MAFF) 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 and fertilisers, or records of who is using irrigation systems.
- 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 MLECCNR 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 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.
- Village Water Committees are responsible for the operating and maintaining the technical components of village water supply systems. Generally, there has been minimal organised community monitoring of quality apart from individual observations on taste, smell, colour or

sediment. Some villages are now installing water meters at households to measure consumption and charge accordingly.

- The Environment Section in MLECCNR is responsible for assessing environmental impacts of development and extraction, Fanga'uta Lagoon water quality, biodiversity impacts and climate change impacts. MLECCNR 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 MECCNR, TWB, MAFFF, and the Tonga Visitors Bureau. The team was project-based and now appears to be defunct.
- 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.
- NGOs, such as Tonga National Council of Churches, 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.
- Householders manage their own rain harvesting systems, wells and connections to the reticulated supply. Sanitation and grey water disposal are also strictly a household concern. There are no reticulated sewerage or wastewater systems in Tonga. 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.
- The Ministry of Finance and Planning (MFOP) 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.
- GIS section MLECCNR 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. MLECCNR cannot access its own data on the GIS server on-line because of the slow speed internet connection.

3.2 Coordination at different levels

There have been many water (and sanitation) sector programmes and initiatives in Tonga with the aim of improving water security without the inclusion of climate change variability in the design and operations.

Many recent programmes and initiatives have been implemented without recognition of potential climate change impacts but with a primary focus on more immediate needs such as providing improved water supplies to cater for population growth and development. Many projects have focused on water governance, water resources assessment, water supply development and management, capacity building and training, and community education and awareness. These improvements are required regardless of the additional stresses imposed due to climate change.

The ultimate aim of these projects is the improvement of water supply for rural and urban communities. Other projects have been or are being implemented to install new water supply systems or reconstruct/rehabilitate existing systems for communities (e.g. Council of Churches water project).

Water sector projects which aim to improve water security through proper planning, design and implementation and which cater for current climate variability are also building resilience into physical and human systems which can assist in coping with future climate change.

The new water system at Hihifo have been design and built with design timeframes of typical 30 years which are similar to the timeframe adopted for this report (2030). Within this timeframe, many existing systems will need to be re-evaluated for their ability and capacity to supply the ever-increasing populations and further impact of climate change. It is possible that alternative water technologies which are not commonly used, or are yet to be developed, will be available and affordable to enable them to cope primarily with future water demands and at the same time with impacts from climate change

3.3 Technical capacities

There is a serious need for continued recruitment and training of staff in water resource and supply 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 Tonga 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 Tonga 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 and is now back to the original set up and is facing operational inadequacies and difficulties.

4. CURRENT WATER RESOURCE AND SUPPLY ISSUES

4.1 Main categories

This section provides an overview of current or "baseline" water availability issues in Tonga. These water availability issues shall be presented according to the following main categories:

- Current climate variability
- Geological hazards
- Human factors.

4.2 Current climate variability and impacts

4.2.1 Main features of current climate

The current climate, particularly rainfall, is highly variable both spatially and temporally across the Tonga group. The spatial variability of annual rainfall over the Tonga group is shown in Figure 5 using two methods giving similar results.

The major influence of ENSO events on Tongatapu rainfall is shown, for example, in Figure 4.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 were long-term wetter periods. The 1940s represented a drier period, although we are hampered in examining it because the lack of a continuous rainfall record. 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 1999. The driest period for all rainfall summation periods from 12 to 60 months occurred during this prolonged dry period in the 1980s. Superimposed on these long-term events there are also shorter term cyclic behaviour, most noticeable in figure 4 and in the period 1947 to 1971. These shorter-term cycles of wetter periods separated by brief drier periods that appear to occur every 4½ to 5 years but these cycles were interrupted by the longer wetter period in the mid 1970s and the long dry period in the 1980s. There were far fewer droughts in the period 1946 to the end of 1982 than in the period 1983 to 2007. A curious detail observed even in longer period rainfall data was the appearance of higher frequency rainfall variations with period around 10 to 13 months. These high frequency fluctuations are normally removed at longer rainfall summation periods.

On low islands and the low lying parts of high islands, droughts lead to contraction of the thickness, areal extent and hence volume of freshwater lenses and coastal aquifers. This causes normally fresh groundwater in some islands and parts of other islands to become brackish during and for some months after droughts

High rainfall associated with La Niña episodes in Tonga can result in high stream flows causing flooding and damage. It can also have the beneficial effect of increasing recharge to groundwater, resulting in replenishment of groundwater aquifers, raising of water tables and reductions in salinity for freshwater lenses and coastal aquifers.

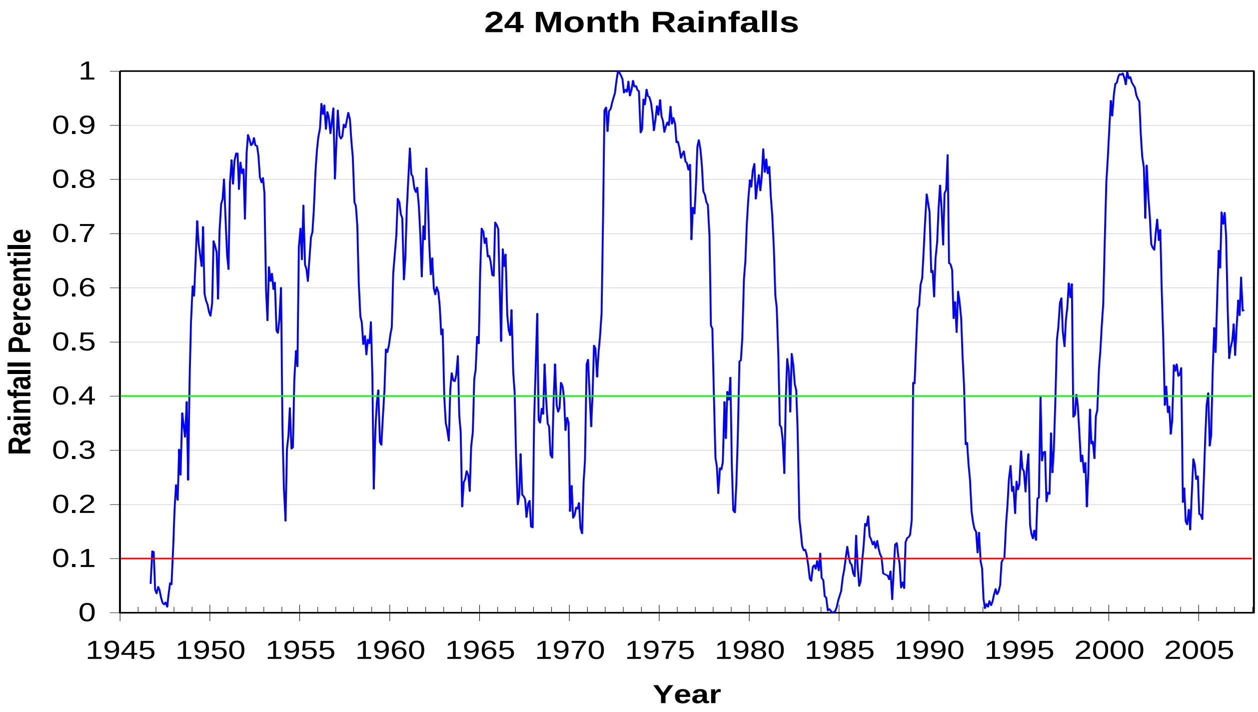


Figure 4 Decile ranking over the previous 24 months in Tongatapu

4.2.2 Tropical storms

Large tropical storms in Tonga are responsible for major floods in downstream areas. These have resulted in loss of life, destruction of houses and infrastructure, and damage to agricultural land. Tropical cyclones (also called hurricanes) are also a significant feature of the current climate of all of Tonga and are known to cause considerable damage to housing infrastructure and rain water harvesting facilities.

Figure 5 shows tropical cyclones affect Tonga 1.3 times per year. This figure increases to 1.7 during El Nino years. Historical records of cyclone occurrences in the South West Pacific have shown a decreasing trend particularly in the last decade (1999-2008), however there is not enough evidence to confidently predict that this trend is permanent and not an inter-decadal cycle. There is strong evidence however that years of increased tropical cyclone activity coincide with El Nino years. The letter "E" in Figure 5 depicts El Nino years.

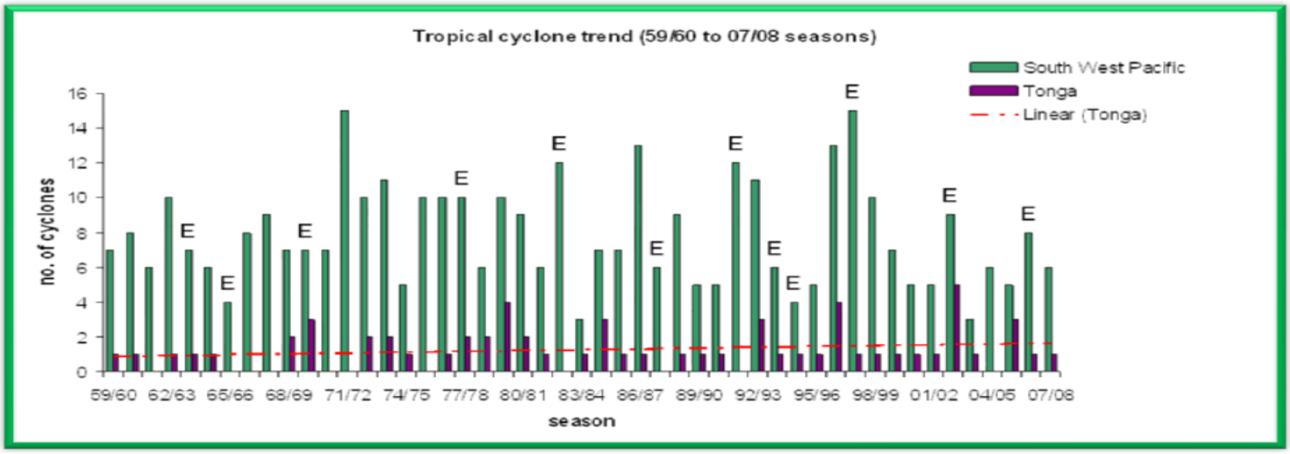


Figure 5 Tropical cyclone trend

Cyclones are a major problem for island communities, often causing severe wind damage, floods and hillside erosion with consequent downstream damage and sedimentation. The highest rainfall intensities and maximum daily rainfalls on small islands are normally associated with tropical cyclones and tropical depressions. Cyclones often cause major damage to infrastructure (including water supply infrastructure), agriculture and some cause loss of life. For instance, Cyclone Isaac

(1982) caused major flooding and damage to water storage and reticulation networks at the western part of Nuku'alofa(Sopu), and consequent disruptions to the water supply system.

Freshwater lenses on small low-lying islands can suffer due to partial inundation with seawater as a result of overtopping by waves generated by cyclonic storms. This has occurred during cyclone Isaac in 1982 at the western part of Nuku'alofa and most of the low lying costal area of Tongatapu. Many months may be required to naturally "flush" the saltwater from freshwater lenses and restore wells to a potable condition.

Severe storms generated by cyclones can also cause wind damage to houses and other buildings and severely impact on rainwater collection systems and even storage tanks. On Lifuka, the rainwater collection systems can be contaminated by sea spray and by partial overtopping by waves. Coastal erosion processes caused by severe storms can modify and even reduce the land area overlying freshwater lenses.

4.2.3 Seasonal rainfall

Table 7 shows mean annual rainfalls and percentage rainfalls during dry and wet seasons for Nuku'alofa. The mean dry and wet season percentage rainfalls were calculated using the lowest and highest six-month rainfalls, respectively.

Table 7 Mean annual and percentage seasonal rainfall for Tongatapu

Island	Location	Mean annual rainfall (mm)	Mean percentage rainfalls in dry / wet seasons
Tongatapu	Nuku'alofa	1,771	38% / 62%

Mean rainfall in Tongatapu shows a generally wet period from December to April with a dry period from May to November (see Figure 6). The data in Table 7 shows Tonga have marked wet and dry seasons, where approximately 38% of the rainfalls fall in the dry season while 62% falls in the wet season. The distinct dry and wet seasons are also a feature of most of Tonga.

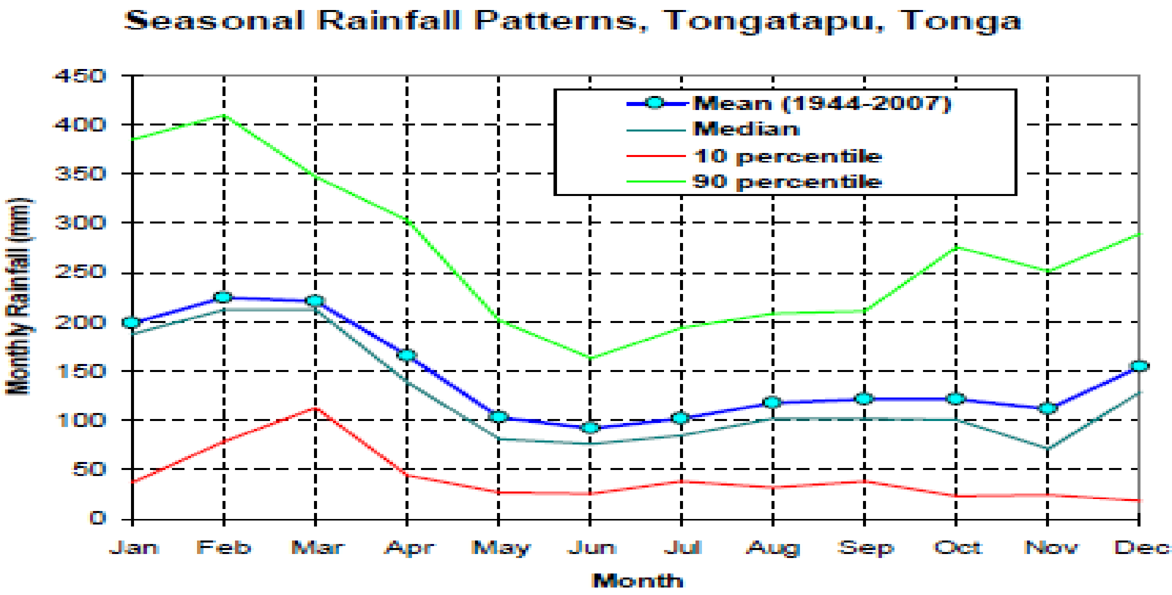


Figure 6 Mean monthly rainfall for Nuku'alofa for the period October 1944 to July 2007 shows the median (50th percentile) 10th and 90th percentile monthly rainfall

The rainfall pattern has a large impact on the seasonal availability of water resources in the island of 'Eua with water a noticeable stress and water shortages in the dry season and surplus water resources in the wet season. In El Niño years, the January – March rainfall is lower in all parts of Tonga and the wet season is generally delayed by two to three months. In the wet season, high rainfalls cause flooding with consequent damage to property and infrastructure. Flooding is exacerbated by forest clearing within many catchments (Costin and Powell, 2006).The data in Table 7 is used later in section 5.2 to assess changes in dry and wet season rainfalls based on climate change projections.

4.3 Non-climatic factors and their impacts

4.4 Geological hazards and impacts

Geological hazards include volcanic eruptions and earthquakes with the resulting hazards of tsunamis and landslides. Tonga is subject to seismic activity and has active volcanoes. Explosive volcanic activity can produce a range of problems to water supplies including contamination from ash and catastrophic damage from volcanic blast (Scott et al., 2002). This event led to the resettlement of the population requiring additional water supply development (Niua to ‘Eua). Destructive tsunamis have been generated from submarine earthquakes (e.g. Niuatoputapu in 2009). The destruction of villages including water supply facilities and the resettlement inland of 1,013. It also cause caused loss of life, destruction and damage to infrastructure including water supply infrastructure. In Niuatoputapu, 3 villages and associated water supply infrastructure were damaged or destroyed, leading to the resettlement of some coastal villages to higher areas and associated assessment and planning for the development and use of alternative water resources was undertaken and funded by the World Bank. Apart from damage to infrastructure, coastal inundation from tsunamis (and cyclone generated waves) can cause temporary salinisation and pollution of groundwater resources and the wells used to extract groundwater for many coastal villages.

4.5 Human factors and impacts

4.5.1 Increasing water demands due to high population growth

The largest water supply problems are found in relation to urban and peri-urban settlements on the fringes of the main centres, where population densities, growth rates and the increasing demands for water are highest. As shown in section 2.4, population densities exceed 250 people per km² in Tongatapu and urban growth rates was 2.4% are found (in descending order) for the other island Vava’u, Ha’apai Islands Niuas and ‘Eua.

Crowded urban and adjoining peri-urban areas with high population densities are placing large, increasing and, in some cases, non-sustainable demands on both limited land and water resources. This is particularly noticeable in the crowded urban and peri-urban areas of Nuku’alofa and Lifuka islands. In these and other urban centres, increasing populations are degrading water quality and putting increasing pressure on remaining areas designated for freshwater supply. Settlements are increasing and causing housing and population densities to rise. Urban planning is generally well behind the expansion of peri-urban and settlements within urban areas. For this reason, rainwater harvestings are likely to be required as supplementary sources in the future.

4.5.2 Pollution of water resources

Biological and chemical pollution and water quality degradation of surface water and groundwater resources has occurred through inadequate sanitation and waste disposal practices, especially in crowded urban and peri-urban areas.

Pollution of water resources and water quality degradation is one of the largest threats to water availability in Tonga especially low lying coastal aquifers such as in Lifuka. The relatively small size and steep slopes of surface water catchments on ‘Eua and Vava’u enable water and pollutants to move quickly to downstream areas and the coastal zone (including aquatic life, fish resources, inner reef lagoons, mangrove areas and coral reefs). Also, the highly permeable soils and shallow water tables on Lifuka enable pollutants to easily migrate to fresh groundwater.

There are many examples of surface water and groundwater resources, and the water supplies based on these resources, which are suffering from contamination due to human and animal excreta (e.g. White et al., 2009, 2009). Often inappropriate sanitation systems such as pit toilets and flush-toilets with septic tanks are installed in urban and rural communities on small low-lying coral islands where the soils are highly permeable and where groundwater is extracted from nearby wells. Limestone islands also offer little protection from groundwater contamination unless they are overlain by thick soil sequences. Pit toilets, which are normally dug to the water table, allow direct contamination of the underlying groundwater. Septic tanks are most often not well constructed and maintained allowing raw sewage to leak through poor joints, or overflows to occur due to blockages caused by lack of periodic de-sludging. The problem of poor sanitation is endemic in most of Tonga.

Extensive deforestation on slopes on high islands leads to erosion and loss of soil, increases water turbidity, and exacerbates flooding problems which damages infrastructure and causes sedimentation of streams and the coastal environment. The high turbidity in streams after heavy rain makes untreated water from these streams unusable for several days and leads to clogging of pipes and sedimentation in storage tanks (‘Eua).

Other inappropriate land use practices include raising of pigs and chickens, mining of gravel for sale, continued use of graveyards and growing crops on areas reserved for groundwater pumping on small coral islands. Such actions make the already vulnerable groundwater resources at greater risk from increased pollution.

Other pollution problems are:

- Pollution of groundwater from chemical sources including hydrocarbon contamination from diesel engines and fuel and oil drums and containers, many of which are not properly bunded except at major fuel installations.
- Chemical contamination of surface water and groundwater resources, caused by inappropriate and uncontrolled use of agricultural chemicals (fertilisers, and toxic insecticides and pesticides).

The major issue of water pollution, particularly faecal pollution, in Tonga and the linkages with waterborne diseases and impacts on human health is highly likely to increase with the impact of climate change. It is stated that “the pollution of drinking water and the resulting health hazard may be one of the biggest watershed issues in Tonga in the long run.”

4.5.3 Over-pumping and salinisation of groundwater resources

Over-pumping of groundwater has led to seawater intrusion and increasing salinity (salinisation) of water supplies. The most vulnerable groundwater systems to over-pumping are freshwater lenses on small coral islands.

Examples of over-pumping include major freshwater lenses on Lifuka and Hihifo, Tongatapu used for urban water supply are at risk of longer-term reduction or depletion due to pumping at higher than long-term sustainable rates. Problems have arisen due to the use of inappropriate technology and methods of groundwater extraction. For instance, in small coral islands the use of conventional boreholes for groundwater pumping can lead to greater seawater intrusion than the use of more appropriate infiltration galleries (refer Figure 11 and section 6.9.5).

4.5.4 Inadequate water supply infrastructure and high loss rates

Many water supply systems are old and dilapidated and suffer from poor maintenance over many years. Others have been partially upgraded and extended to cover new areas but leave parts of networks in urgent need of replacement. This problem is particularly prevalent in many urban water supply systems.

Symptoms of these problems include low pressure, intermittent supply, high leakage and poor water quality. As an example, over 50% of the Hihifo water supply system experiences high leakage, low or variable pressures and intermittent supply with water available between three and sixteen hours per day (Fielea, 2012). Complaints of no water and low pressure make up a significant proportion of consumer complaints. This often forces many households to obtain water from other sources including polluted wells. There are other examples of these problems throughout the rural villages, urban areas and outer islands.

Rural villages in general have relatively stable populations with generally more problems with water supplies than in urban areas. However, many villages have very basic water supply systems which are prone to pollution due to unprotected sources (streams and wells). Rural water supply and sanitation programmes in some of the more populated island (e.g. Vava’u, Ha’apai and ‘Eua, are gradually improving these systems.

Leakage from water supply pipelines and other losses including illegal connections and uncontrolled overflows at community or household tanks (“non revenue water”) in urban centres and larger rural villages are a major issue. Losses equal to or greater than 50% have been measured or estimated in a number of urban water supply systems including Hihifo, Tonga (Fielea, 2012)

Increased groundwater pumping or surface water diversions are required to cater for such losses adding to total operating costs. In many cases, water shortages during both normal climate periods and droughts could be significantly reduced if regular and systematic leakage control and other demand management measures (e.g. education and awareness) were implemented. In addition, infrastructure costs to develop new sources to supply future demands could be delayed.

Leakages in pipe networks are normally due to a combination of poor joints (e.g. PVC pipes that have been heated to form sockets, a common practice in some islands), or where joints are not properly prepared before solvent cement is used. Other problems occur with deteriorated joints (e.g. perished rubber rings) or broken, cracked or split pipes (due to earth movements or wash away after floods, or piercing due to poor backfill and insufficient cover above pipes). Corrosion of steel pipes is an additional problem. The use of pipes and other materials with different specifications is an additional source of leakages.

By-passing of water meters by consumers and non-collection of revenue by water supply authorities occurs in some water supply systems where meters are installed. Major causes of the problems above are inadequate capital investment in water supply systems and inadequate operation and maintenance budgets within water supply authorities or rural communities to properly manage water supply systems.

4.5.5 Damage to water infrastructure

Vandalism causing destruction of water supply facilities occurs in some islands due to land disputes on customary or privately owned land. This includes vandalism of water intakes and pipelines. Theft of water supply items, for example, brass water meters and stainless steel cabinets (valuable and saleable metals) is a problem in Nuku'alofa.

Failure to properly maintain infrastructure and implement remedial measures can lead to the loss of water supply due to vandalism. Subsequent delays led to vandalism of water supply infrastructure and the need for expensive rehabilitation works. This problem led to less water being available than normal in the public water supply system in Nuku'alofa and may gradually seeps through to rural villages and outer islands of Tonga.

4.5.6 Water governance and management factors

There are many factors associated with poor water governance and management that impact negatively on, and increase risks to, water availability. Many are related to "human inactivity" (Scott et al., 2003). Prime examples of these factors are:

- Constraints on effective water management due to inadequate water governance. Problems include lack of water policy and plans, water legislation and ineffective coordination and administration of water sector agencies. Water governance was considered further in section 3.1.
- Insufficient knowledge of national water resources due to inadequate effort and resources being applied to water resources assessment, monitoring, analysis and reporting to government and dissemination to the wider community. Many of the islands or rural communities have benefitted from short-term, project-based water resources assessment projects over many years. On a broad scale, water resources including surface and groundwater are reasonably well described in some islands. Few, however, have a comprehensive and detailed knowledge of their water resources and, in particular, how they respond to current climate variability. Knowledge of water resources tends to be best in areas close to large settlements, agriculture production areas and other activities but there are many rural areas and outer islands where the knowledge of water resources is limited.
- Roles and responsibilities of agencies involved in water matters are sometimes unclear, fragmented and un-coordinated. For example, in Tonga, there is, or has been until recently, a lack of a clear distinction between the agency or agencies involved in the provision of water supply and the regulation and protection of water resources.

- Ineffective or no water source protection measures implemented to ensure that important and vulnerable water resources are not contaminated from human settlements and activities.
- Inequitable distribution of available water between urban, peri-urban and nearby rural communities. This is a common problem in Tonga. In the old replaced water system at Hihifo, upstream users of water for domestic have access to a disproportionate share of water resources with detrimental impacts on downstream uses. This has been overcome by the recent augmentation of the new water supply system.
- Human and financial resource capacity limitations preventing even essential water resources assessment and monitoring from being conducted. Monitoring is often left to the vagaries of intermittent external funding for development projects. In many countries, such activities are not seen as a priority and water agencies are often very under-resourced.
- Insufficient professional and technical water resources and water supply personnel to conduct routine operations. Water improvement projects are generally beyond the financial and human resource capacity of local agencies to plan and implement and external development aid is required. Externally organised and funded projects place large additional burdens on local staff, especially where multiple projects are running concurrently. For local staff, there is often limited time available for routine tasks owing to the large amount of time and effort required to supply consultants with information as well as attendance at a large number of project-related meetings and workshops.

4.5.7 Insufficient community involvement

In most islands in the Tonga group there is a lack of, or only limited, community participation in freshwater management, conservation and protection. A case study of problems arising from limited community participation in relation to protection of groundwater reserves is provided in White et al. (1999; 2008). There are many other examples of water catchment management problems arising from lack of community participation in Tonga.

Damage to infrastructure and monitoring equipment can occur due to lack of participation of land owners in decisions about the siting of water supply infrastructure.

While there are project-related efforts at community education and awareness programmes about the need for responsible water use, conservation and protection of water sources and water supply infrastructure, there is a lack of ongoing commitment. To effectively achieve community awareness, longer-term programmes are required to allow sufficient time to build trust and achieve behavioural change.

4.6 Summary

It is fair to conclude that the problems currently experienced in the rural villages, urban areas and outer islands, particularly in urban and peri-urban areas, with regard to high and increasing populations and population densities, increasing demands for water, inadequate water supply, sanitation and solid waste disposal are of greater concern than the likely impacts of climate change in the foreseeable future. At the same time, it is recognised that the current problems will be exacerbated by any adverse climate change impacts. Storey and Hunter (2010) stress the need for approaches which concurrently strengthen the resilience of communities to future climate change impacts and the current impacts from urbanisation and pollution.

Risks posed to water availability from both non-climate and climate related factors are further considered in section 5.

5. CLIMATE CHANGE PROJECTION FOR TONGA

5.1 Outline

This section has been added to the list of requirements in the TERMS OF REFERENCE to identify the likely magnitude of changes to climate parameters of importance to water resources using available climate change projections.

Where possible, climate change projections have been based on information recently supplied to PASAP under the Pacific Climate Change Science Program (PCCSP). PCCSP is presently being conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the

Australian Bureau of Meteorology (ABoM) and funded by the Australian Government. These projections are considered in section 5.2.

It is noted that all climate change projections in this guide are based on global climate models (GCMs) which have relatively large spatial scales or grid-cell resolutions (typically 100 km to 500 km and approximately 280 km for the PCCSP climate projections). These GCMs lack definition at the scale of the small countries and individual islands in Tonga. Even proposed regional scale climate models, with typical grid-cell resolutions of 60 km, lack sufficient detail to account for local climate processes at the scale of most islands. The term “GCM” is used in this report for simplicity rather than the often-used term “AOGCM” (for atmosphere-ocean coupled general circulation model).

5.2 PCCSP Climate Change Projections

5.2.1 Summary

The PCCSP has recently provided interim projections to PASAP based on selected output from 18 global climate models (GCM’s) for a number of climatic and ocean parameters for Tonga (PCCSP; 2011a, 2011b). These interim projections, which are subject to change, are consistent with the “First Order Draft” of PCCSP (2011c). This draft report was not made available during the formulation of this guide.

The PCCSP interim projections (refer section 5.2) are for the 20-year period centred on the year 2030 (i.e. the period 2020-2039) for Tonga. Changes are relative to a baseline 20-year period centred on 1990 (i.e. 1980-1999). The spatial scale (grid-cell resolution) for the PCCSP projections is 2.5º of latitude x 2.5º of longitude (approximately 280 km x 280 km at the equator) to standardise the results from various GCMs at different spatial scales.

It is noted that the interim projections supplied by PCCSP to PASAP do not include those for two later periods centred on the years 2055 (i.e. 2045-2064) and 2090 (i.e. 2080-2099). Only the period to 2030 was selected by this guideline so as to focus on a planning horizon within the next 20 years.

For reasons of simplicity, this guideline will use “2030” to refer to the longer terms “the period 2020- 2039” or “the 20-year period centred on the year 2030”. Similarly, “2055” and “2090” are used rather than the equivalent longer terms. Interim projections to 2030 and associated comments made in PCCSP (2011a; 2011b) for a number of climatic and ocean parameters are summarised below. PCCSP (2011a) stresses the need for care in using the interim projections due to a number of uncertainties and mentions the need to consider the spread of projections from the various models and not just the average of the projections.

5.2.2 Projected mean rainfall changes

Mean rainfall conditions and annual changes

PCCSP (2011a; 2011b) presents “most likely” and “largest change” projected mean rainfall conditions for 2030 for Tonga. The projected mean rainfall conditions and changes in mean annual rainfall (in depth units, mm) are summarized in Table 7.

The following observations are made from the summary in Table 8.

- For the “most likely” future condition, Tonga shows a little change (- 22mm) reduction in 2030.
- For the “largest change” future condition, Tonga, show a drier climate (- 101mm).

Table 8 Summary of projected mean rainfall and change for 2030

Location	Rainfall projections		Change in mean annual rainfall (mm) for 2020-2039	
	Most likely	Largest change	Most likely	Largest change
Tonga (Tongatapu)	Little change	Drier	-22	-101

Adapted from: PCCP (2011a, 2011b)

If only the “most likely” projected rainfall conditions are considered, the climate by 2030 is anticipated to be similar or wetter to present conditions in Tonga. This is encouraging in terms of water resources. However, if the “largest change” projected rainfall conditions are also considered, then from a water resources perspective Tonga are projected to have drier conditions.

Table 8 shows the projected changes in mean annual rainfall expressed as percentages of present mean rainfall at Nuku’alofa.

The following observations are made about the results in Table 9:
Annual changes

- For the “most likely” future condition, Tonga shows a little change (- 1%) reduction in 2030.
- For the “largest change” future condition, Tonga, show a moderate reduction of - 6%

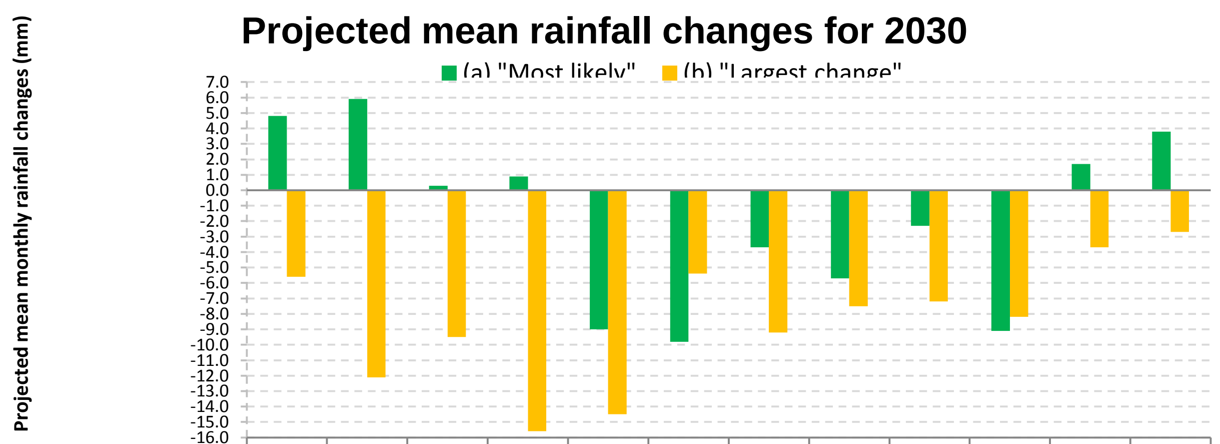
Table 9 Projected percentage changes in mean annual rainfall for 2030

Country	Location	Change in mean annual rainfall (%)	
		Most likely	Largest change
Tonga	**Tongatapu**	-1%	-6%

Adapted from: PCCP (2011a, 2011b)

Monthly changes

Projected mean monthly rainfall changes are summarised from PCCSP (2011b) for Tonga, the “most likely” and “largest change” conditions in Figure 7.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) "Most likely"	4.8	5.9	0.3	0.9	-9.0	-9.8	-3.7	-5.7	-2.3	-9.1	1.7	3.8
(b) "Largest change"	-5.6	-12.1	-9.5	-15.6	-14.5	-5.4	-9.2	-7.5	-7.2	-8.2	-3.7	-2.7

Adapted from: PCCP (2011a, 2011b)

Figure 7 Projected mean monthly rainfall changes (mm)

Following is a summary of the projected monthly rainfall changes:

- For the “most likely” projected rainfall condition, Tongatapu show six months with rainfall reductions ranging from -2.3 to -9.8mm.
- For the “largest change” projected rainfall condition, Tonga show twelve with monthly rainfall reductions ranging from -2.7 to -15.6mm.

Seasonal changes

It is also useful to examine the projected seasonal rainfall changes according to wet and dry seasons (selected as November to April and May to October, respectively, for the Southern Hemisphere countries and the opposite in the Northern Hemisphere countries). Table 10 shows the projected changes in mean dry and wet season rainfall expressed as percentages of present mean seasonal rainfalls (refer Table 6) at capitals and other locations.

Table 10 Projected percent changes in mean annual season rainfalls for 2030

Country	Location	Change in mean dry season rainfall (%)		Change in mean wet season rainfall (%)	
		Most likely	Largest change	Most likely	Largest change
Tonga	Nuku'alofa	-6%	-8%	2%	-5%

Adapted from: PCCP (2011a, 2011b)

The following observations are made from the summary in Table 10.

Dry season

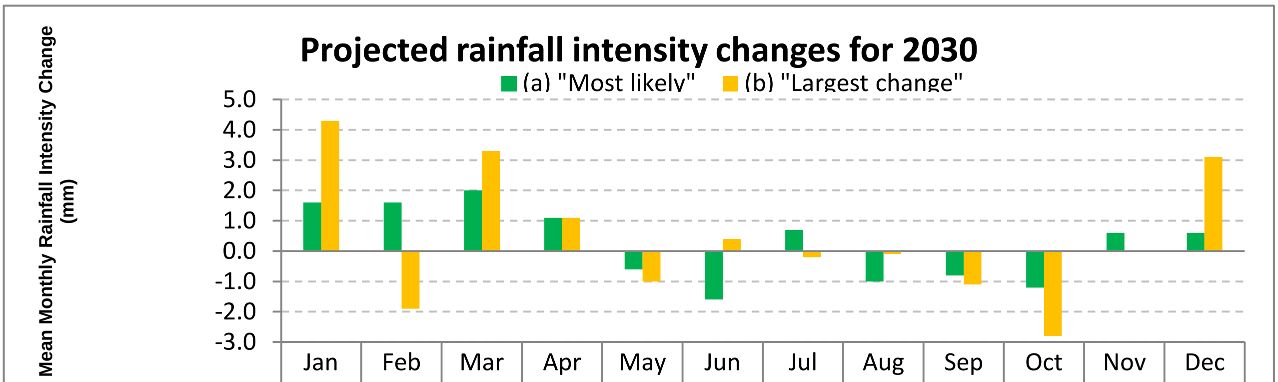
- Relatively small to moderate rainfall reductions are shown for the "most likely" condition in Tonga with the largest reduction in depth terms being for Tongatapu (40 mm). Tonga also shows a 6% reduction.
- Tonga also shows an 8% reduction for the largest change.

Wet season

- Tonga shows an increase in wet season rainfall for the "most likely" condition.
- Tonga shows the largest reduction of 49 mm which represents a percentage reduction of about 5% of wet season rainfall.

5.2.3 Projected changes in rainfall intensity

Projected changes in mean monthly rainfall intensity (or "heavy rainfall") for 2030, as defined in PCCSP (2011b), are summarised in Figure 8 for "most likely" and "largest change" conditions. Numerical values are shown in depth units (mm) rather than percentages, as advised in PCCSP (2011b)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) "Most likely"	1.6	1.6	2.0	1.1	-0.6	-1.6	0.7	-1.0	-0.8	-1.2	0.6	0.6
(b) "Largest change"	4.3	-1.9	3.3	1.1	-1.0	0.4	-0.2	-0.1	-1.1	-2.8	0.0	3.1

Adapted from: PCCP (2011a, 2011b)

Figure 8 Projected changes in monthly "heavy rainfall" for 2030

For projected mean monthly rainfall intensity changes under the "most likely" condition, the results are summarised as follows:

- Changes were either small to moderate increases or small decreases. The month of January to April, shows the largest monthly increase in rainfall intensity of 1.1 to 2mm.
- The months of May to June and August to October shows a reduction in rainfall intensity from -0.6 to -1.6mm for five months each.

For projected mean monthly rainfall intensity changes under the "largest change" condition:

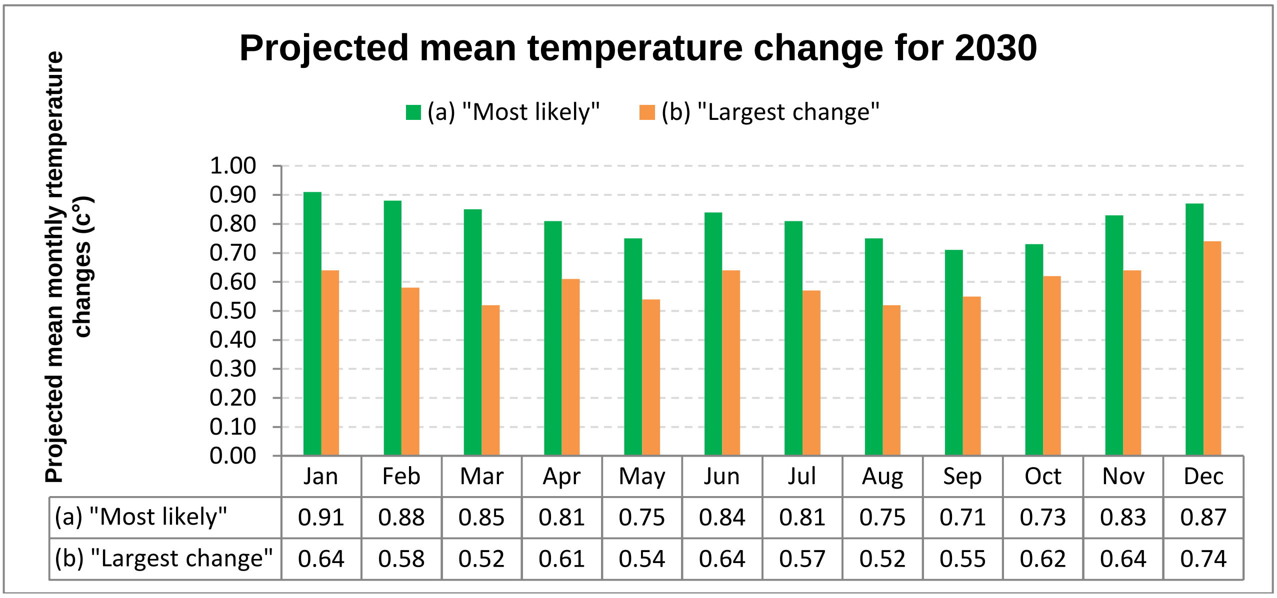
- Changes were either small to moderate increases or small decreases. The month of December, January and March, shows the largest monthly increase in rainfall intensity of 3.1 to 4.3mm.
- The months of February, May, July to October shows a reduction in rainfall intensity from -0.1 to -2.8mm for six months each.

- During the wet season (November to April), the rainfall intensity shows a relatively small increase with the highest in January (4.3 mm). In the dry season (May to October), the rainfall intensities show a relatively small decrease from -0.1 to -2.8mm.

The above results are summarised in section 5.2.4

5.2.4 Projected mean monthly air temperature changes

Projected increases in mean monthly air temperatures for 2030 (PASAP, 2011b) are summarized in Tables D1 and D2, Annex A for "most likely" and "largest change" conditions. All results show an increase in temperature, as expected.



Adapted from: PCCP (2011a, 2011b)

Figure 8 Projected mean temperature change for 2030

For the "most likely" condition, the results are summarised as follows:

- Mean monthly temperature show an increases of 0.8ºC for Tonga
- The minimum and maximum increases in projected monthly temperatures are 0.7 to 0.9ºC.

For the "largest change" condition:

- Mean monthly temperature shows an increase vary from 0.6ºC for Tonga.
- The minimum and maximum increases in projected monthly temperatures are 0.5 to 0.7ºC

5.2.5 Projected evaporation changes

As mentioned in section 6.3, PCCSP has prepared potential evaporation projections for the region but these were not available at the time of preparing this report. It would have been very useful to have projections at country scale, as evaporation is an important component of the hydrological cycle and has significant impacts on the availability of water resources.

From preliminary information provided for the whole study region by PCCSP, the projected increase in potential evaporation in 2090 is likely to be between 0.2 and 0.4 mm/day (approximately 75 to 150 mm/year). Assuming a linear increase from present to 2090, the increase in potential evaporation to the year 2030 is likely to be about one third of this range (i.e. about 25 to 50 mm/year). Given that the current range of potential evaporation within the region is in the order of 1,500 to 1,800 mm/year on average (refer section 2.3), the preliminary projected increase to 2030 is a very small increase in percentage terms (between about 1% and 3%).

5.2.6 Actual mean sea level rise

In Table 11, the relative sea level rises are shown for two periods: from start of record to December 2009 (SPSLCMP, 2010) and to April 2011 (SPSLCMP, 2011). The "relative sea level" is the sea level as measured by the tide gauge and nearby land. "Net relative sea level rises" are those which remove the effects of any land movement at the recorder, measured with a continuous global-positioning system (CGPS) relative to the International Terrestrial Reference Frame (Geoscience Australia, 2008) and barometric pressure effects. Net relative sea level changes are important when assessing the effects of global climate change. Table 11 show the net sea level changes (rises) for the period from start to December 2009 for comparison with the relative sea level rises for the same end month.

The following observations are made from the results in Table 11:

- The net relative sea level rises to December 2009 are 9.5 mm/year and 8.6 mm/year to April 2011. It is noted in SPSLCMP (2009) that Tonga is situated in the vicinity of a tectonic subduction zone with vertical motion of the whole island. The records from the CGPS station are relatively short (from February 2002) and estimates of the vertical land movements are “still too noisy to be reliable” (SPSLCMP, 2009).

Table 11 Summary of SEAFRAME sea level recorders and sea level trends

Country	Locations	Installation Date	Relative sea level rise (mm/year)		Net relative sea level rise to Dec 2009 (mm/year)
			To Dec 2009	To April 2011	
Tonga	**Nuku'alofa**	Jan 1993	9.5	8.4	8.6

Adapted from: PCCP (2011a, 2011b)

5.2.7 Projected mean sea level rise

Projected global mean sea level rises at decadal intervals to 2100 relative to 1990 for four emission scenarios (A1F1, A2, A1B and B1) are provided in PCCSP (2011a) from CSIRO (2011). These are shown as ranges of values for each emission scenario and year in Table 10. It is noted in PCCSP (2011a) that the “range represents the 5th to 95th percentile, derived by adjusting projections from the IPCC Third Assessment Report to correspond to the IPCC (2007) projections at 2095, including the potential dynamic response of the Greenland and Antarctic Ice Sheets (Hunter, 2010)”.

Table 12 Projected percentage changes in mean seasonal rainfalls for 2030

Year	A1FI	A2	A1B	B1
1990	0	0	0	0
2000	9-28	9-27	10-27	12-25
2010	19-60	20-60	21-59	26-56
2020	32-99	32-97	35-96	44-92
2030	**48-146**	**47-139**	**55-143**	**64-132**
2040	**69-204**	**67-190**	**77-200**	**84-178**
2050	**96-278**	**89-251**	**102-266**	**105-227**
2060	**130-368**	**115-320**	**126-337**	**127-279**
2070	**165-471**	**142-401**	**150-413**	**145-333**
2080	**200-584**	**173-490**	**173-493**	**161-388**
2090	**234-701**	**203-588**	**192-571**	**175-444**
2100	**266-819**	**237-692**	**208-649**	**185-496**

Adapted from: PCCP (2011a, 2011b)

The projected global MSL rises of most interest in Table 10 are for 2030, the nominated time horizon for this report. The range of MSL rises for each of the four emission scenarios are reasonably similar in 2030 and range from the lowest value of 47 mm (0.048 m) for the A2 scenario to 146 mm (0.146 mm) for the A1F1 scenario.

The projected global MSL rises of most interest in Table 12 are for 2030, the nominated time horizon for this guide. The range of MSL rises for each of the four emission scenarios are reasonably similar in 2030 and range from the lowest value of 47 mm (0.048 m) for the A2 scenario to 146 mm (0.146 mm) for the A1F1 scenario.

6. CLIMATE CHANGE IMPACTS ON WATER RESOURCES AND SUPPLY

6.1 Outline

The main climate change impacts to the year 2030 on surface water and groundwater resources in Tonga are likely to be caused by changes to rainfall patterns. Changed rainfall patterns will impact on stream flows, availability of water in streams and recharge to groundwater and groundwater in storage.

From section 5 the rainfall is likely to increase in Tonga with positive impacts on water resources through increases in stream flows and groundwater recharge. Individual analysis of rainfall in each island group of Tonga is required to see if is likely to decrease with corresponding negative impacts on stream flows and groundwater recharge.

Lesser impacts on water resources are likely to be caused within the period to 2030 from increased evaporation and mean sea level rise. Increased evaporation would act to reduce stream flows and groundwater recharge. Mean sea level rise beyond 2030 has the potential to impact on groundwater resources in low-lying parts of “high islands” (coastal aquifers) and low lying islands (freshwater lenses). If tropical cyclone severity was to increase, this could also impact on storm surge and potential erosion and inundation of at least parts of low-lying islands and coastal areas of high islands.

There are also likely to be some relatively minor impacts on water demand due to increasing temperature.

Assessment of changes to surface water resources, coastal aquifers and freshwater lenses requires an understanding of the hydrological cycle. This is particularly relevant to small island water resources, where the hydrological cycle occurs within a limited areal domain and processes occur over relatively short time frames.

In section 6.2, water balance principles are briefly introduced. These principles are used to demonstrate the effects of changed rainfall and other parameters on the key water resource components of stream flow and groundwater recharge, which impact on surface and groundwater availability. Following, an analysis is presented of the likely magnitude of impacts on water resources and water demand in Tonga based on the climate change projections in section 5.

6.2 Water balance

Simple water balance equations are often used to describe the main elements of the hydrological cycle and their inter-relationships. They can also be used to assess changes in water resources due to changes in climate, starting with very simple approaches to gain a general understanding to more complex equations where further information is required. The latter requires adequate definition of the various parameters for these to be of any real benefit. In this report, simple approaches only are considered due to the uncertainty in the likely changes of key parameters due to climate change.

A water balance (or water budget) for a single catchment or an island equates water inputs to outputs, storage terms and a possible error term (UNESCO, 1991). The following two sub-sections outline the main features of the water balance for (a) the land surface, which affect both surface water and groundwater depending on the type of island, and (b) under the land surface, which affects groundwater systems.

6.2.1 At the land surface

At the surface of a catchment or island, rainfall is the input (of the water balance). Evaporation (or evapotranspiration), surface runoff (if it occurs) and recharge to groundwater are outputs. Surface retention (interception by vegetation and surface depressions) and water held in the soil and the unsaturated zone (between the soil and the groundwater table) are the storage terms.

A general water balance equation at the surface is:

$P = Et_a + SR + R + \Delta V$ (1)

where P is precipitation (most commonly rainfall), Et_a is actual evapotranspiration (evaporation from soil and other open surfaces and transpiration from vegetation), SR is surface runoff (most commonly in the form of streamflow), R is recharge to groundwater, and ΔV is the change in moisture within the soil and the unsaturated zone.

If the water balance at the surface is considered over a sufficiently long time-scale (e.g. several months), the change in soil moisture component becomes insignificant to the water balance, and equation (1) can be simplified to:

$P = Et_a + SR + R$ (2)

Equation (2) can also be expressed in terms of the available water remaining after subtracting evaporation from rainfall (i.e. surface runoff and groundwater recharge) as follows:

$SR + R = P - Et_a$ (3)

Equations (1) to (3) relate to "high islands" where surface runoff occurs and where the relative magnitude of actual evapotranspiration, surface runoff and recharge is largely dependent on the vegetation cover, the permeability of soils and the near-surface geology, and the topography, particularly the gradient of stream channels.

On relatively flat coral sand and limestone islands with highly permeable soils and subsurface geology, infiltration occurs rapidly and surface runoff is negligible (except on paved surfaces). By deleting surface runoff, water balance equations (2) and (3) can be simplified to:

$P = Et_a + R$ (4)

or, expressed in terms of groundwater recharge, as:

$R = P – Et_a$ (5)

Figure 22 shows a water balance model used for estimating recharge on a typical low coral island with a shallow water table. In this model, Et_a has three terms, namely, interception (E_I), evaporation and transpiration from the soil zone (E_S), and transpiration of deep rooted vegetation directly from groundwater (T_L).

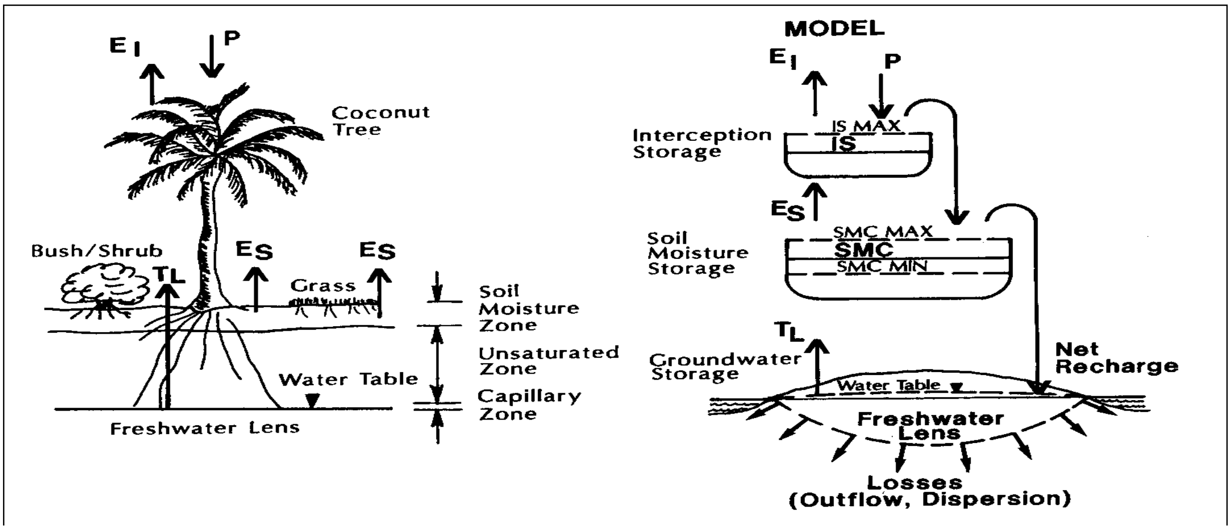


Figure 9 Water balance model to estimate recharge for a coral island (from Falkland & Woodroffe, 1997)

Actual evapotranspiration is a very important component of the water balance and can range from about 50% to more than 70% of rainfall in some small islands. White et al. (2002; 2007a) provide a detailed analysis of the water balance for Bonriki island, Tarawa atoll, Kiribati. There the actual evaporation and recharge components were estimated to be approximately 50% of rainfall based on detailed rainfall, climate, tree sap flow (in coconut trees), soil moisture and groundwater measurements over several months and longer-term calculations taking account of the variability of rainfall and estimated tree density.

The water balance is more complex for islands with raised topography including limestone islands, volcanic and bedrock islands, and islands with mixed geology. Further information and case examples can be found in UNESCO (1991) as well as many country-specific reports.

6.2.2 Under the land surface

For the water balance under the land surface and within the groundwater system, recharge (from the surface zone) is the input with the outputs being discharges from the groundwater. For a perched aquifer on a "high" island, the natural discharges are outflows at springs and possible leakage to deeper aquifers. For a basal aquifer (either coastal aquifer or freshwater lens), the natural discharges are outflows at the edge to surrounding seawater and mixing (dispersion) of fresh groundwater with underling seawater. Groundwater extraction (pumping) is a possible additional discharge for both types of aquifers.

The water balance within a basal island groundwater system can be expressed in terms of groundwater recharge as:

$R = GF + D + Q + \Delta S$ (6)

where R is groundwater recharge, GF is groundwater flow to the sea, D is dispersion at the base of the groundwater, Q is groundwater extraction and ΔS is change in fresh groundwater storage. If the groundwater balance is considered over a sufficiently long time-scale (e.g. several years), the change in fresh groundwater storage becomes insignificant to the water balance, and equation

6) can be simplified to:

$R = GF + D + Q$ (7)

Figure 23 shows a typical groundwater balance for a freshwater lens on a small coral island.

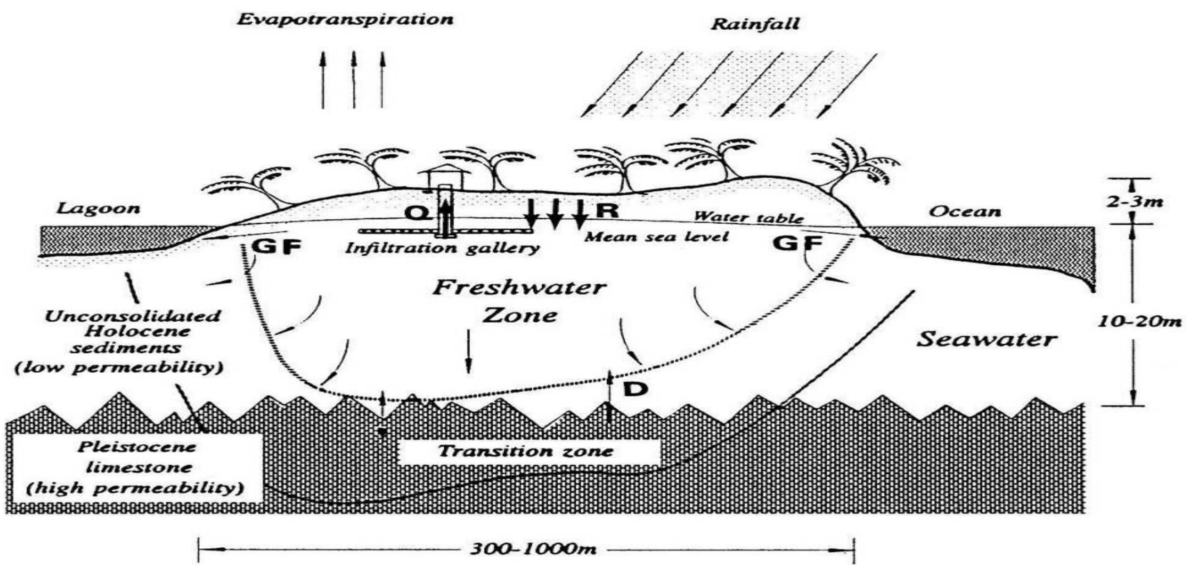


Figure 10 Groundwater balance for a typical coral island freshwater lens

6.3 Impacts from mean rainfall and evaporation changes

6.3.1 Overview

The main potential impacts from mean rainfall and evaporation changes will be on stream flows and groundwater recharge, and hence surface and groundwater availability particularly in the drier parts of the year. Impacts of projected changes on potential evaporation cannot be quantified at present as the PCCSP projections are not yet available (refer section 5). However, given the preliminary estimates of a relatively minor increase in potential evaporation in the study region (refer section 5.2.5), the impacts on stream flow and recharge compared with projected changes in rainfall are likely to be relatively small.

It is noted that larger impacts on water resources are likely from changes to the variability of rainfall, due mainly to changes in ENSO activity, than from changes in mean rainfall. Hence, future rainfall variability is potentially of much greater importance regarding impacts on water resources.

As outlined in section 5, the lack of consensus in projections from GCMs has led to the assumption that future climate variability including rainfall variability will be the same as at present (PCCSP, 2011a).

For this report, relatively simple methods based on water balance principles are used to assess impacts on groundwater recharge. Given the extent and accuracy of the interim projections, any more complex hydrological modelling is not warranted.

6.3.2 Groundwater recharge

Of most interest Tonga shows projected mean rainfall reductions, and hence will experience reduced groundwater recharge of at least 2%.

To assess recharge for an island including the impact of reduced rainfall on recharge, a number of methods can be used. One approach is to use water balance models based on equation (3) for high islands with surface runoff (stream flow) and equation (5) for coral sand or limestone islands with no surface runoff.

For some coral sand and limestone islands, detailed water balance studies to estimate recharge have been made including Tongatapu and Vava'u. These studies have used the historical daily rainfall record, estimates of monthly potential evaporation and parameters related to soil types and depths and vegetation types and densities.

Table 13 Estimated percentage changes in mean annual recharge for 2030

Island (and island type where applicable)	Estimated current mean annual rainfall range (mm)	Estimated current mean annual recharge range (mm)	Estimated changes in mean annual recharge (%)	
			Most likely	Largest Change
Tongatapu (limestone & coral sand	1771	531	-2%	-11%

The following observations are made about the estimated percentage changes in mean annual groundwater recharge in Table 13:

- For the "most likely" condition, the reductions for Tongatapu are less than 2%. These are reasonably insignificant changes given the uncertainties associated with these estimates.
- For the "largest change" condition, Tonga shows reductions of 11% which are moderately significant.

Results for both groundwater recharge and stream flow are summarised below.

6.3.3 Summary

In summary, estimated changes in groundwater recharge due to projected mean rainfall changes are:

- Small reductions in mean annual groundwater recharge for Tongatapu (up to 2%) under the "most likely" condition.
- Moderately significant reductions in mean annual groundwater recharge Tongatapu (up to 11%).Impacts of reduced recharge are outlined in **section 6.3.2** and any further reductions would obviously exacerbate existing impacts on the sustainable yields from surface water and groundwater resources.

It is recognised that the above estimates of recharge changes due to projected mean rainfall changes are rather coarse. However, such estimates are considered reasonable given the uncertainties inherent in the interim projections of rainfall and the scale at which they are available, the lack of projections regarding evaporation and the assumption that climate variability due to ENSO activity will be the same as at present.

It is not possible in this guideline to estimate impacts on recharge conditions at catchment scale given the resolution of the projected rainfall conditions. As mentioned in section 5, the spatial scale (grid-cell resolution) for the PCCSP climate projections is 2.5º of latitude x 2.5º of longitude (approximately 280 km x 280 km at the equator). This scale is larger, and in most cases much larger, than the size of the islands or the specific project site in Tonga such as Hihifo. As an example, the main island of Tongatapu has approximate east-west and north-south dimensions of 30 km and 17 km.

Even proposed regional scale climate models, with typical grid-cell resolutions of 60 km, lack sufficient detail to account for variations in stream flow at catchment scale, which have typical areas on many islands of only several square kilometres.

As mentioned above, the estimated changes recharge do not take account of potential changes to evaporation as these projections are not yet available from PCCSP. However, given the preliminary estimates of a relatively minor increase in potential evaporation in the study region (refer section 5.2.5), the impacts on stream flow and recharge compared with projected changes in rainfall are relatively small. This aspect can be further considered when the evaporation projections from PCCSP are available.

6.4 Impacts from rainfall intensity changes

Projected increases in rainfall intensity by 2030 are provided in section 5.2.3. These show that most Tongatapu will experience increases rather than decreases in rainfall intensity. Under the “most likely” condition, the monthly changes were either small increases and decreases or moderate increases. Under the “largest change” condition, most countries show similar results except for PNG which shows relatively high increases in most months and East Timor which shows small to moderate decreases in most months.

It is not possible to provide quantitative assessments of impacts from heavy rainfall increases, given the information available. However, in qualitative terms the following impacts would be expected:

- Increased flooding and consequent problems including damage to infrastructure, increased land erosion, especially in cleared, steep catchments, and sedimentation of downstream reaches of streams and rivers and the coastal environment.
- Beneficial impacts due to enhanced groundwater recharge to freshwater lenses on coral sand and limestone islands and to coastal aquifers in high islands. Groundwater recharge is enhanced during periods of heavy rainfall as rainfall percolates quickly through the highly permeable soils and thus evaporative losses are minimised.
- Some beneficial effects are also likely on high islands due to lakes and larger water storages being replenished from higher streamflows.

6.5 Impacts from mean sea level changes

The prospect of sea level rise is one of the main concerns to small island and coastal communities (e.g. Burns, 2002. Mimura et al., 2007). Low-lying coral islands are perceived to be vulnerable to sea level rise with potential impacts on shoreline erosion, inundation and saline intrusion into freshwater lenses (Woodroffe, 2008).

Increases in mean sea level (MSL) by 2030, using PCCSP projections, are presented in section 5.2.7**.** These projections show sea level increases to be in the range from 0.03 m to 0.17 m within the region (about 0.7 to 4.1 mm/year since the baseline year of 1990). Other projections and sea level recordings in recent years (refer section 4.3.4) were in broad agreement with the projections by PCCSP.

The central question is whether a MSL rise of 0.17 m will have a significant effect on the freshwater lenses of small, low-lying coral islands and coastal aquifers in low-lying areas of high islands.

A number of impact studies are needed to be done for freshwater lenses on islands using groundwater models for a range of projected mean sea level rises and rainfall changes. The studies shall use the variable density, two-dimensional model SUTRA (Voss 1984; Voss et al. 1997).

Further work is required to assess the vulnerability of shorelines to erosion due to mean sea level rise (White and Falkland, 2010). It is also noted that erosion of shorelines due to extreme events such as major waves from storms or cyclones is more likely to affect low-lying coastal areas and small islands than a gradual change in sea level (Woodroffe 2007). Webb and Kench (2010) show that many reef islands have remained largely stable or increased in size over the past 20-60 years.

These results are contrary to the widespread perceptions that all atoll/reef islands are eroding in response to recent sea level rise. Some are likely to erode, as at present, while others are likely to remain stable with the type and magnitude of changes varying (Webb and Kench, 2010). A better understanding of the processes and impacts on small islands, and coastal areas of larger islands, due to sea level rise is required.

6.6 Impact on water demand

Projected air temperature increases are important as they can impact on evaporation and also on water demand.

Increases in air temperature could increase the demand for water. Given that the maximum monthly rise in projected temperature by 2030 is 1.3ºC under the PCCSP “largest change” condition (refer section 5.2.4), the increase in water demand due to temperature rise is not expected to be significant.

In a recent study of future water demand to 2030, as part of a water master plan for Tarawa, Kiribati, White (2011a; 2011b) made a small per capita increase in potable water demand of 2 litres per person per day (L/p/day) to cater for a potential temperature increase of 1°C (very similar to the PCCSP projected mean monthly temperature rise by 2030). The allowance for an increase in per capita demand for Tarawa represents only a small increase in total water demand (approximately 3% increase in the design potable water demand of 60 L/p/day and a 2% increase in the design total water demand of 90 L/p/day). For the present Tarawa population of approximately 56,000 (preliminary estimate from national census of 2010), the water requirement to meet the increased demand of 2 L/p/d would be approximately 110 kilolitres per day (kL/day). For the lower bound population of 84,000, the increase in demand of 2 L/p/d would be approximately 170 kL/day, which again is about 2% of the total water demand.

To put this potential increase in water demand for Tarawa due to projected temperature rise in perspective, it should be noted that the following two factors have a much higher impact on water demand:

- Population increase. The population on Tarawa is expected to increase from the 2010 population to between 84,000 and 110,000 by 2030 based on upper and lower bound population growth rate estimates (White, 2011a; 2011b). Using these future population estimates, the future daily water production is estimated to be between 5,700 and 7,400 kL/day, assuming no losses from pipe distribution systems.
- Losses from pipes. Based on current pipe distribution system losses (mainly leakage) of about 50% of production, the total water supply production in 2030 would be between 11,400 and 14,900 kL/day. Even with an ongoing and effective water leakage control program, losses are unlikely to be reduced to and remain below 25% of production. Assuming the best case scenario in 2030 of the lower bound population estimate and a system loss of 25%, the total water required would be approximately 7,600 kL/day (White, 2011a; 2011b).

Overall, the projected air temperature increases to 2030 are unlikely to have a significant impact on water demand.

6.7 Comparison of risks to water availability

A number of potential impacts on, or risks to, water availability have been outlined under both current climate conditions. These risks are related to both climatic and non-climatic factors in relation to water resources, water demand and water infrastructure, particularly water supply systems.

A summary of the potential impacts according to four selected factors (water resources, water demand, water infrastructure and water governance) are listed below for current climate conditions and for projected climate change conditions.

Water resources

For current climate conditions

- Pollution of surface water and groundwater
- Salinisation of groundwater due to over-pumping
- Salinisation of groundwater in low-lying areas due to partial overtopping by waves from current storms, cyclones or earthquakes

For projected climate change conditions

- Reduced availability of surface water and groundwater due to reductions in rainfall
- Partial salinisation and reduced availability of groundwater due to sea level rise

Water demand

For current climate conditions

- Increasing demand due to increasing population and development of agriculture and industry
- Increasing demand due to increasing per capita demand, as expectations increase especially in urban areas

For projected climate change conditions

- Increased demand due to air temperature increase

Water infrastructure

For current climate conditions

- Damage and destruction from natural hazards (cyclones, landslides, earthquakes,
- volcanic eruptions, tsunamis)
- Leakage and other losses in pipe distribution systems
- Damage and destruction from vandalism

For projected climate change conditions

- Damage and destruction from higher flooding due to increased rainfall intensity
- Damage due to rising sea levels
- Higher rate of deterioration due to higher temperature

Water governance and management

For current climate conditions

- Inadequacies in management, protection and conservation of water resources due to lack of legislation, policies and plans, inefficient and/or ineffective water sector administration, lack of human and financial resources, lack of consultation with and participation by affected communities
- Inadequacies with water supply systems due to poor planning, management, operation and maintenance leading to impacts on water infrastructure and ability of systems to cope with present demand

For projected climate change conditions

- No change to above

Table 14 provides a summary of the risks to water availability by the factors and their potential impacts listed above. Risks are shown, in qualitative terms, for current climate conditions and for projected climate change conditions. The latter is shown as the increased risk compared with current climate conditions. Because Table 14 relates to all the 5 island groups, the results are necessarily broad-based. It would be more useful to prepare such a table for each country to identify the relative water availability risks in each country. However, such a task is well beyond the scope of this report.

From the risks shown in Table 14, the following comments are made:

- In general, the highest risks to water availability are from increasing water demands due to population increase and other activities and pollution of water resources.
- The loss of freshwater resources due to pollution is hard to quantify. Pollution, especially faecal pollution, has the potential to degrade water resources leaving some effectively unsafe and unusable except for limited purposes. In most cases, water treatment systems can be installed to improve the water quality so the impact is one of additional cost rather than total loss of the resource.
- Contamination of fresh groundwater due to seawater intrusion from over-pumping is also hard to quantify. The process is reversible if pump rates are reduced to sustainable levels. The main impact would be the cost of developing additional water sources once the pump rates were reset in order to meet the required water demand.

Table 14 Summary of risk to water availability

Factors and potential impacts	**Risk to water availability**	
	Under current climate conditions	**Increased risk due to climate change**
Water Resources		
Under current climate conditions		
Pollution from all sources	Very high	None
Salinisation due to over-pumping	Moderate to high on some islands	None
Salinisation of groundwater due to waves overtopping	Moderate for some islands Non	None
Due to projected climate change		
Reduced availability due to reductions in rainfall	Not applicable	None to high
Reduced availability of groundwater due to sea level	Not applicable	Moderate for low islands and coastal areas on high islands
Water Demand		
Under current climate conditions		
Increasing demand due to increasing population and associated development of agriculture and other activities	Very high	None
Increase due to increasing per capita demand	Moderate	Moderate
Due to projected climate change		
Increased demand due to temperature increase	Not applicable	Low
Water Infrastructure		
Under current climate condition		
Damage/destruction from natural hazards	Low to high	None unless cyclone

		become more frequent and/or severe
Leakage and other losses in pipe distribution systems	**High**	**None**
Damage/destruction from vandalism	**Moderate for some islands**	**None**
Due to projected climate change		
Damage/destruction from higher flooding	**Not applicable**	**None on low islands, moderate on high islands**
Damage due to rising sea levels	**Not applicable**	**Low on low islands and coastal areas on high islands**
Higher rate of deterioration due to higher temperature	**Not applicable**	**Low**
Water Governance and Management		
Under current climate conditions		
Inadequacies in management, protection and conservation of water resources	**Moderate to High**	**None**
Inadequacies with water supply systems	**Moderate to High**	**None**
Due to projected climate change		
Nil	**Not applicable**	**None to moderate**

From a comparison of the climate and non-climate related impacts and risks, the following comments are made:

- The reductions in annual groundwater availability in Tonga to the “most likely” conditions are between zero and 2% (refer Table 13). For the lower probability, “largest change” conditions, the reductions in surface water and groundwater availability are between 7% and 20%.
- If the “most likely” conditions for groundwater recharge above are used, then the impact of projected climate change on the main drivers of water resources (groundwater recharge) show reductions less than 25% for the worst case scenario. While significant, this is much less than the demand on water resources which could be as high as 200% or more.
- The reduction in water resources availability due to mean sea level rise is hard to quantify. If the assumption made for Tarawa of a 20% reduction in groundwater sustainable yield is applied to other similar small islands, the impact of this projected climate change is again significant but relatively small compared to the large demand on water resources due to population increase.
- Leakage from many urban pipe distribution systems is 50% or higher. This loss of potential usable freshwater is greater than the effect of projected climate change impacts on groundwater recharge and the assumed loss of 20% of groundwater resources on low islands.
- The impact of temperature rise on water demand based on the 2% increase used for Tonga is insignificant compared with the other impacts.
- Impacts of natural hazards such as overtopping waves due to cyclones and tsunamis, while devastating in the short to medium-term, may not lead to a long-term loss in groundwater resources unless major changes in landform are experienced. Also, damaged infrastructure can be repaired or new infrastructure installed if communities have and use the opportunity to resettle to higher ground.
- Impacts from poor water governance and management are considered to be moderate to high on overall water availability. While these factors do not directly lead to a loss of water resources, they can lead to poor decisions about water resources development and protection. This can cause further water quality degradation on existing developed water resources due to lack of action regarding encroachment onto water protection areas. Poor

governance can also lead to other problems including delays in implementing much needed water augmentation works for existing populations.

- Impacts from vandalism are also considered to be moderate on overall water availability. Vandalism can cause damage to infrastructure with temporary loss or reduction in water supply services. Damaged infrastructure can be repaired or replaced but this can be expensive and time consuming.
- Impacts from works that alter existing coastlines making them more vulnerable to erosion, or gravel mining that exposes shallow groundwater to direct evaporation can potentially lead to a loss of groundwater resources due to man-induced erosion of land or increased evaporation.

In summary, non-climate related factors of increasing water demand due to increasing population and leakage from pipe systems pose the greatest risks to water availability.

6.8 Water availability implications for vulnerable groups

The main vulnerable groups of people in terms of water availability from both climate and non-climate related factors are those living in:

- Crowded urban and peri-urban areas, which are at major risk because of lack of adequate water supply and the need to make use of polluted sources. Water availability issues associated with these groups are provided in section 3.5.1.
- Remote islands, which are at risk during droughts if the local water resources are depleted (e.g. rainwater tanks) or become saline (groundwater) and require importation of water. Examples are provided in section2.5.7.
- Remote parts of outer islands (e.g. Niuatoputapu), which are at risk during droughts if water resources are depleted and food crops fail, due to the difficulty of access for emergency assistance and the time taken to regrow crops once rainfall returns to normal.
- Very low level parts of islands, which are at risk of overtopping, erosion and temporary salinisation of groundwater from waves caused by cyclones or tsunamis in addition to potential inundation from projected sea level rise. Examples are provided in sections 3.4 and 5.6.

6.9 Example of good practices

Below are some of the projects that have made a positive impact on the water sector or have the potential to do so. It is noted that these do not necessarily specifically address climate change impacts but rather consider climate change as one of many stresses on water availability.

Section 6.6 has some examples of mal-adaptation practices.

6.9.1 Water governance

Key water governance instruments are water policy and plans, water legislation and national water and sanitation coordinating committees (or “peak bodies”) to facilitate dialogue and decision making between water agencies and other interested stakeholders including NGOs and representatives of civil society.

In Tonga, key documents related to water governance (e.g. draft water policies and legislation) have been available for a number of years but have not been formally adopted by governments. In others, recent steps have been taken to develop draft documents and in a few cases these have been approved by governments.

Peak water committees consisting of government water agencies and in some cases wider groups have been established. In many cases, these committees lie dormant and have not met for some years.

Table 19 provides a summary of progress on key water governance activities in Tonga. Green cells in the table means that the item has been formally adopted, yellow cells means that a draft or interim version exists and red cells means the item does not yet exist. While some items are shown in green, this does not mean that the item is fully functioning.

Table 15 Summary of water governance progress for Tonga

Country	PACC Water Policy	Water Legislation	National Water and Sanitation committee or similar	IWRM Plan(s) or similar
Tonga				

Notes: Legend: green: the item has been formally adopted, yellow: draft or interim version exists, red: item does not yet exist.

From Table 19, it is evident that there are many further steps to be taken to improve the water governance in most of Tonga. As stated in White et al. (2007), “there has been a general reluctance to announce national water policies, enact national water legislation, define rights and responsibilities, adopt whole-of government approaches, and involve communities in planning and managing water and related land resources”.

In recent years, however, considerable steps have been made in this area and PACC have water policies in place, plans and supported legislation under review and heading towards government acceptance. Once formally accepted, the challenge remains for these measures to be implemented for the benefit of all.

6.9.2 Rainwater harvesting projects

Some of the most successful projects implemented in Tonga are rainwater harvesting schemes for households and community buildings. Rainwater collection at household level provides a source of good quality water, except in severe droughts, which is suitable for potable purposes with the added convenience of being close at hand. Rainwater can be best used in many countries as a supplementary source to other sources used for non-potable purposes. There are many examples of this type of project, funded by bilateral aid projects and NGOs.

In Hihifo, about 30 fibre glass 10,000 litre tanks were installed under the PACC water supply project. The total capacity of the rainwater storage of 300,000 litres would be enough to reduce the load on the water supply system by approximately 25% (100 to 80 l/p/day) under normal conditions. Under drought conditions water conservation measures is required to be strictly undertaken including restriction on non domestic usage. The same strategies need to be duplicated on reducing the leakage rate from 25% to 15%.

6.9.3 Drought and flood planning

As part of climate change adaptation strategies, disaster risk reduction strategies and IWRM, the preparation of drought response plans is an essential component, as all islands are affected to a greater or lesser extent by droughts. Steps have been taken in recent years to “change the paradigm for dealing with Island Vulnerability from disaster response to hazard assessment and risk management” (section 6.7).

Drought plans can be stand-alone documents or part of wider disaster response plans. A good example is to use the “percentile method” based on monthly rainfall to determine different levels of alert and corresponding actions required (Refer Figure 4). Designer of water resources and supply project needs to take into consideration the implication of floods and drought covering flood plain management and response to floods and droughts.

6.9.4 Pumping strategies and salinity levels

Three salinity monitoring boreholes (Hihifo SMB1, Hihifo SMB2 and Hihifo SMB3) were drilled in the western and central part of the Hihifo well field in September 2011. The initial salinity monitoring test results from September 2012 (Refer Figure 11) shows that the freshwater lens thickness at these boreholes at the western boundary of the Tongatapu freshwater lens was about 6-7m. The freshwater lens thickness is defined by an EC of 2,500 μS/cm, as the upper limit.

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.

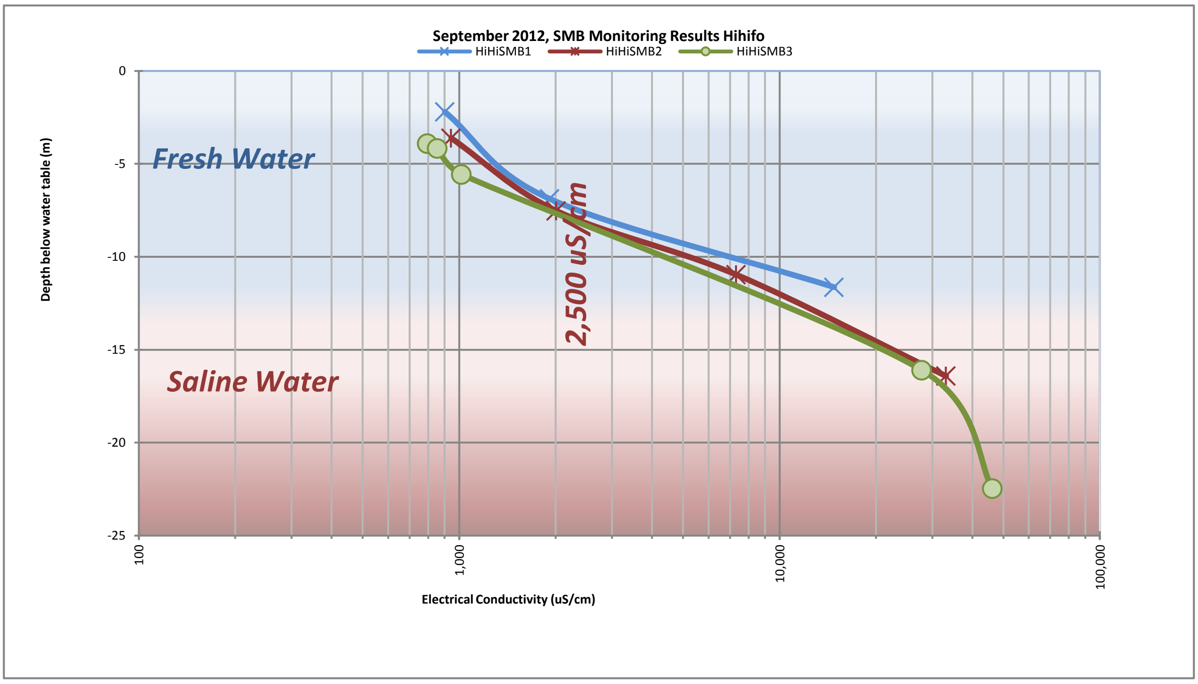
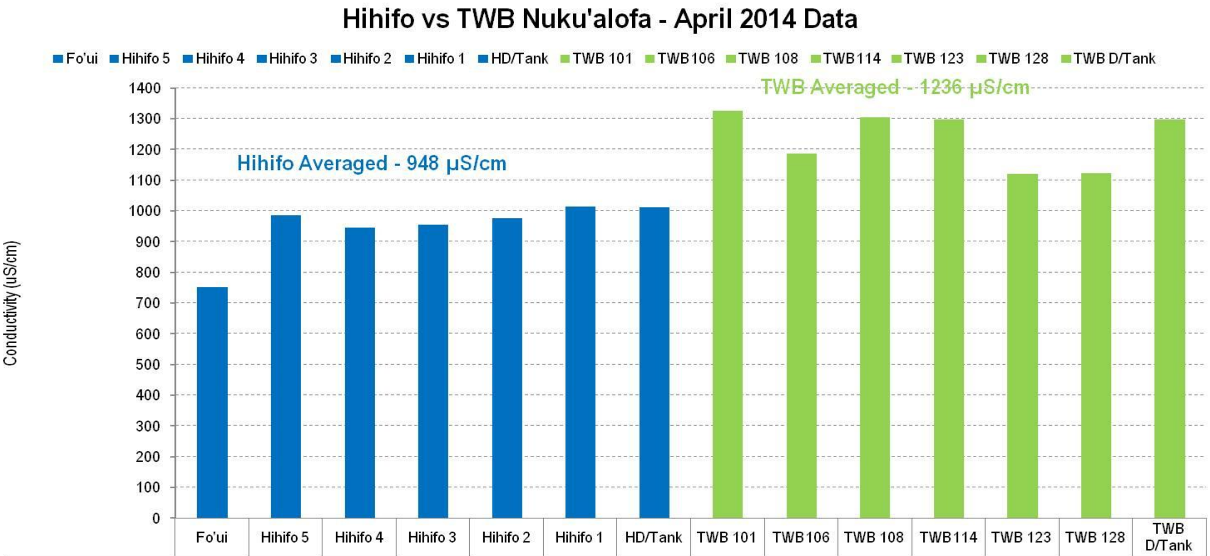


Figure 11 Salinity profiles of the Hihifo Monitoring Boreholes, September 2011

The initial measurement of salinity at the five production wells at Hihifo compared to the salinity of seven productions well at the TWB well field at Mataki'eau. The TWB production well was measured at an average of 1236 µS/cm while the five productions well at Hihifo were measured at an average of 948 µS/cm. The thickness of the water lens at Matki'eua well field was in the range of 10 to 15m while Hihifo was measured at 6 to 7m. The pumping rate a Hihifo was set at a maximum of 1.5 l/s while the TWB was at 3 l/s.



	Fo'ui	Hihifo 5	Hihifo 4	Hihifo 3	Hihifo 2	Hihifo 1	HD/Tank	TWB 101	TWB106	TWB 108	TWB114	TWB 123	TWB 128	TWB D/Tank
Hihifo vs TWB Nuku'alofa	752	985	945	955	976	1015	1011	1325	1186	1304	1297	1120	1124	1298

Figure 12 Salinity levels at the Hihifo production well compared to the TWB selected well at Mataki'eua well field

6.9.5 Adaptation option

6.9.6 Appropriate technologies

Examples of appropriate technology for use in island situations are outlined in previous summary reports including IETC (1998) and Falkland (2002b).

Other reports have identified additional technologies suitable in specific circumstances.

One example of an appropriate technology is the use of horizontal infiltration galleries on low-lying coral islands, or in some coastal areas of smaller volcanic islands, for moderate to relatively high pumping rates rather than conventional vertical boreholes. Where extraction rates are small, dug wells are appropriate and are common in many village areas. However, moderate to high pumping from wells or boreholes can lead to upconing of brackish water, causing the pumped water to become saline. The reason for this is that the impact of the pumping is localised near the point of extraction.

A much more appropriate method of groundwater pumping from freshwater lenses on small coral islands is to pump from infiltration galleries (also called “horizontal wells” or "skimming wells"). Infiltration galleries (refer Figure 11) avoid the problems of saline intrusion because they spread the impact of pumping over a wider area of the freshwater lens. Infiltration galleries generally consist of buried horizontal conduits which are permeable to water, for example PVC slotted pipes (Figure 13) which are laid in trenches dug at or close to mean sea level. Once the pipes are laid and connected to one more sealed pump wells, the area is backfilled.

Infiltration galleries are successfully operating in a number of islands in the Pacific including (Fakland and Woodroffe, 1997; White and Falkland, 2010), Kwajalein in the Marshall Islands (Hunt, 1996) and Lifuka, Tonga (TWB, 2000). On the island of Lifuka in Tonga, where groundwater pumped to the residents from a combination of wells and later shallow boreholes had traditionally been quite saline, improvements using infiltration galleries in the late 1990s significantly lowered the salinity of the water supply (TWB, 2000). The salinity of the water supply remains low to the present (from recent TWB data).

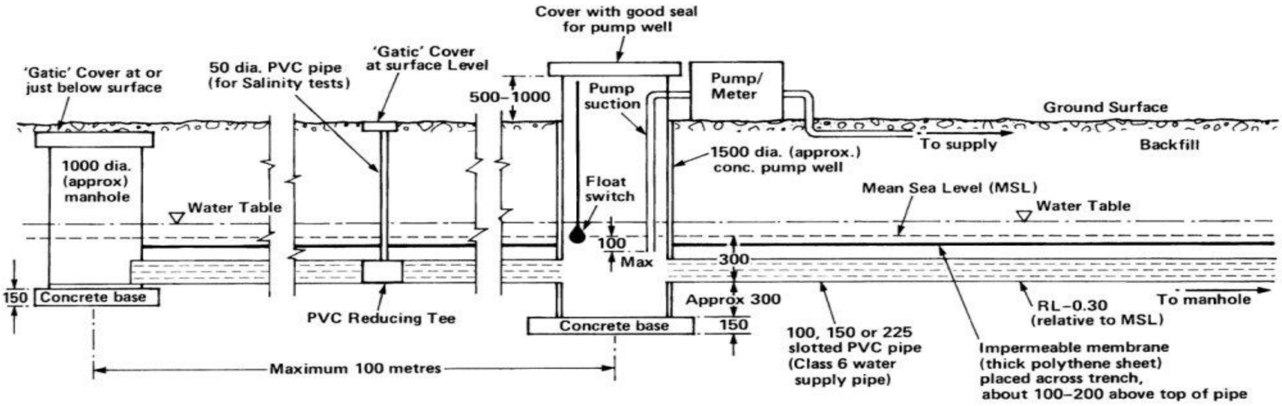


Figure 13 Cross section through a typical infiltration gallery of skimming the fresh top layer of freshwater (Falkland and Brunel (1993)

6.9.7 Relocation within islands to avoid future problems

In some island, coastal communities on high islands that have been affected by tsunamis have relocated, or are in the process of relocating, to higher ground to avoid future similar disasters. This has the additional benefit of removing the potential problem of sea level rise into the future. Examples of islands where such relocations have occurred after such events include Niuatoputapu (Refer section 3.4). New water supply sources and systems require assessment, planning and development in these situations (e.g. TWB, 2013).

Low-lying islands do not have the same option of relocation within the island often due to the small size and limited land availability.

6.10 Example of poor practices

6.10.1 Poorly implemented projects

There are a sizeable number of projects which have (a) not achieved their original objectives through poor project management or (b) left behind infrastructure, plans or outcomes which are of inferior quality. There is no need to give specific examples here.

6.10.2 Desalination units inappropriate settings

The performance of desalination (reverse osmosis, RO) units for water supply has generally been unsuccessful in most of the Pacific Island Countries Desalination is, in many cases, an inappropriate technology due to high operational costs and maintenance requirements and the need for highly skilled operators. A notable exception in recent years is on Nauru where desalination provides the primary source of freshwater in droughts due to the unavailability of both fresh groundwater and rainwater. It also provides a supplementary source in non-drought periods. On Nauru, the advantages with the installed RO units have been continual operation and regular contact between operators and the company that installed the units.

6.10.3 "Mal-administration"

On a broader scale, there are many examples of "mal-administration" in relation to water availability, whether it is adapting to climate change or addressing more immediate and fundamental needs such as provision of adequate and safe water for present populations. Some examples are:

- The timeframes for most water (and sanitation) development projects and other water sector initiatives are too short to make a significant long-term difference to water availability and improvements to human health. Most projects have timeframes of one to five years, whereas interventions in the water supply and sanitation sector require much longer timeframes to be of significance. This applies to all activities from water governance; water resources assessment, monitoring and management; water infrastructure improvements, capacity building for water agencies and community participation education and awareness programs. To make a significant difference, timeframes of at least 10 years and more like 15-20 years are required. One example is the **PACC** regional project which ran for four years and then funding ceased, bringing to an end important assistance from experienced professional and technical staff to professional and technical personnel at village levels in the monitoring and assessment of both surface water and groundwater resources. Other examples relate to implementation of water projects where new water supply systems are installed without substantial, long-term assistance to local water utilities to address leakage and other losses from pipe networks, and to water resources agencies to manage and protect valuable water resources in conjunction with local communities. The need for long-term, coordinated and multi-disciplinary programs to deal with the water, sanitation and related health problems has long been recognised (for example, (White et al., 2008).
- There is insufficient attention being given to water resources assessment and monitoring by national government and development aid agencies. Given that there is real concern about the possible impacts of climate change to water resources on top of existing stresses, the lack of commitment to ensuring adequate stream flow and groundwater monitoring networks can only be described as negligent. There is a lot of emphasis being given to discussions and workshops about the possible impacts of climate change on water resources without a commensurate emphasis being given to setting up systems, or at least maintaining existing ones, to measure the long-term trends in flow and groundwater systems.
- There is insufficient attention being given to staffing and resourcing of water agencies including those involved with water resources assessment and monitoring and operation and maintenance of water supply systems.

7. RESPONSE TO POTENTIAL IMPACTS

7.1 Overview

This section outlines strategies and guidelines for managing the implications of climate change in addition to existing stresses on water availability for all urban and peri-urban areas, rural villages and outer islands in Tonga.

Key principles for these strategies are:

- Ensuring that the water sector in each of the rural villages and outer islands is resilient to current climate variability, in addition to the major pressures from increasing water demand and stresses from water pollution associated with human settlements. This is the most effective overall strategy to cope with future climate change.
- Strategies to reduce vulnerability of the water sector to climate change and, thus, increase water availability are essential components of good water management practice, and are required whether climate changes or not.
- There are “no simple technical fixes” or no single action that will improve water availability. Rather a range of strategies are required including improved water governance; effective assessment, development, management, protection and conservation of water resources; effective operation, maintenance and management of water supply systems and other water development schemes; enhanced community participation in the water sector and improved community education and awareness.
- Although there are some regional similarities between villages and islands, each island is different and some have wide variations in water resources and water availability between different parts of Tonga (e.g. high islands and low islands). The mix of potential strategies to improve water availability must be adapted to suit local circumstances taking account of population growth and the pattern of settlement and development.
- Introduction of new technologies requires parallel investment in training, education and awareness to gain community and government acceptance.
- In specific circumstances, particularly in countries with limited land and water resources (e.g. crowded low-lying islands and remote islands), there are a number of options to assist in development and management of water resources.

The sub-sections below summarise strategies to improve water availability under key headings. The order of these headings does not reflect priorities. Together, these can be viewed as an integrated approach to water resources management.

7.2 Water governance

In all rural villages and outer islands, further work is required in the area of water governance (refer Table 15) to establish a sound institutional basis for effective management of the water and sanitation sector. In Tonga’s, there is a need to enforce existing water policy and plans and water legislation and to establish or reconvene national water and sanitation coordinating committees (or peak bodies). Coordinating committees should include representatives from the government agencies involved in the water and sanitation sector and other interested stakeholders including NGOs and representatives of civil society. In some of the larger countries, regional coordinating committees may also be appropriate.

Enhanced and ongoing commitment to the water and sanitation sector at national level is required. Improved coordination between agencies in the water and sanitation sector is essential. This can be at least partially achieved through the use of regular review and decisions about water and sanitation project proposals and other activities within the sector by a national coordinating committee.

Specific items of relevance in Tonga are the reviewing or revising of building codes and regulations requiring appropriate rainwater harvesting facilities (gutters, tanks) for all new houses and buildings and controls on the types and locations of sanitation facilities. Other items are regulations concerning activities that are not allowable on areas designated as water resources protection zones for both surface water and groundwater supplies. Enforcement of regulations is also a priority.

7.3 Assessment and monitoring of water resources

There is a real need to improve the assessment and monitoring of water resources. This applies to all rural villages and outer islands.

Such improvement can only occur through a commitment at national government level, supported by appropriate training, education and capacity building efforts at national and regional level.

National water resource assessments should aim towards a water resources database supported by a geographical information system (GIS) with relevant information about surface water and groundwater resources in all rural villages and/or outer islands of the country. This information should be updated with additional monitoring data. As such activities are beyond the capacity of water agencies, significant input from regional and bilateral organisations is required.

Monitoring of water resources should be seen as a long-term activity and not a short-term project related one. This is especially important now that there is an increased awareness of potential climate change impacts on water resources. There is a real need to move beyond the rhetoric and act to support water monitoring activities to better understand water resource behaviour at catchment scale into the future. Monitoring data should be processed, reviewed and reported to government through the national water and sanitation committees on an annual basis. This requires considerable and ongoing capacity building, training and development of existing water resource agencies in terms of both human and financial resources. Again, the assistance of regional and bilateral organisations is essential.

7.4 Management and protection of water resources

Again, this is a priority issue in all rural villages and outer islands. As mentioned earlier in this report, protection of water resources from pollution from human settlements, animals, agriculture and industry is a major requirement.

Strategies for achieving good management and protection include:

- Effective land use management and control practices including regulations concerning activities that are not allowed on water protection areas.
- Community education and awareness of the problems associated with poor land management and negative impacts on water resources through pollution.
- Community participation in catchment management and protection.

7.5 Appropriate water supply system

The following strategies are suggested:

- Water resources development should utilise naturally occurring freshwater resources before other options such as desalination and importation are considered.
- Selection of water supply and sanitation technology should take account of all factors - technical, economic, social, cultural and environmental. Materials and equipment should be robust and protected from corrosion in the largely warm, oceanic environments of the region and technologies should be simple.
- Operation and maintenance requirements are most important factors that must be matched to the capacity of water agencies (for urban systems) and the capacity of local government and/or communities (for rural and community based systems).
- The conjunctive use of water from different sources (rainwater, surface water, and groundwater) is a most appropriate approach to water resources management in rural villages and islands with scarce water resources, or where water quality has degraded. Where available, rainwater is generally the most appropriate source of water for potable purposes with other sources being used for non-potable purposes.
- Rainwater harvesting at households and community buildings should be encouraged for existing buildings and regulated for new buildings. Subsidies or, where appropriate, revolving funds to assist households to take out loans for the provision of rainwater tanks and associated materials, should be encouraged.

- Properly constructed capping is required for water supplies using springs to rural and some urban areas so as to minimise local pollution from animal and human activity. It is also important that catchments above springs are properly managed to prevent pollution.
- Appropriate methods of pumping for groundwater supply schemes should be used. Boreholes and wells are appropriate in many circumstances but infiltration galleries should be used in low-lying islands with freshwater lenses that are vulnerable to seawater intrusion (Lifuka)
- At present, desalination should be seen as a realistic option for emergency and possible long-term water supply only when all other naturally occurring and available water resources have been fully committed or where the cost of development of alternative sources exceeds that of desalination. In the future, with technological improvements, desalination is likely to be a more appropriate solution for some islands such as the crowded urban areas of Lifuka. This is especially so in cases where land ownership issues may present additional access problems to water resources on private or customary land.
- Sanitation methods that are non-polluting should be encouraged wherever possible. Dry composting toilets have this advantage as well as not requiring water. Introduction of this technology in Lifuka has, in general, not been successful to date owing to cultural perceptions.
- Use of seawater for toilet flushing water and fire fighting may be appropriate in particularly water scarce islands (as in Lifuka). However, these systems are expensive to build, operate and maintain.
- Use of recycled wastewater is not a viable option owing to the level and cost of wastewater treatment technology required and the high operation and maintenance requirements.
- Importation of water is only an economic option in special circumstances. Examples are the importation of water by pipeline to smaller, water scarce islands from larger, nearby islands with more abundant resources (e.g. Vava'u), and emergency shipment of water by boat or barge to water stressed islands in droughts.

7.6 Demand management

There is an ongoing need for demand management programmes to ensure that water supplied from existing water sources is used wisely, especially before any new sources are considered for development. The focus here is on urban water supply systems, as the largest water supply problems are experienced in these areas and hence the need for demand management is greatest.

Given that many urban and some rural water supply systems have extensive (above 50%) losses due to leakage in both main pipelines and household plumbing, effective leakage control programs are generally the most economical means of augmenting water supplies to meet demands. Reduction of loss rates to 20-25% is achievable in well managed systems. Reductions below these loss rates generally become much more expensive in systems that have been installed for many years.

Water supply flow and leakage monitoring is essential, especially for effective management of urban water supply distribution systems. Leakage control programmes need to become part of mainstream activities rather than short-term, project-oriented activities associated with infrastructure rehabilitation or expansion, or activities to be undertaken solely during droughts. Such programmes require regular monitoring and assessment of pipe network flows and losses using meters at water supply head works (surface water intakes or groundwater pumping systems), within the distribution systems and at household connections.

While training and capacity building efforts have been made in this area (e.g. through SOPAC and PACC in Tonga), many rural villages and urban areas in Tonga have not adopted leakage control as a mainstream activity. This is largely due to the lack, again, of adequate financial resources and sufficient trained personnel to conduct these efforts.

Metering of connections and appropriate water tariffs based on water usage are a means of controlling demand in well managed water supply systems. Tariffs should be structured to enable those with limited capacity to pay to obtain an allocation at no or very little cost. Tiered tariffs that charge higher rates as water consumption increases are appropriate as they encourage water conservation. Some water supply systems suffer from tampering or bypassing of meters, non payment and non-enforcement of tariffs due to ineffective surveillance and administration in water utilities. A major effort with capacity building and community education is required where these problems occur. Technical “fixes such as tamper-proof meters have been tried but they are not the long-term answer as they often encourage more ingenious methods of obtaining water.

In rural areas, where metering of connections or standpipes is not usually implemented, it is often appropriate to charge a small flat fee to cover operational costs especially where groundwater pumping is involved (e.g. Rural villages where fees are collected by village water committees).

Community education and awareness programs highlighting the need for water conservation and the wise use of water are an essential part of sustainable water resources management.

Other practical measures that assist in reduction of leakage and water demand management are:

- Designs of water supply systems should ensure adequate but not excessive pressure, as leakage rates increase with water pressure (Hihifo water system with a minimum pressure of 5m and maximum of15m)
- Use of pipe materials that allow for effective and fewer joints should be encouraged. An example is the use of polythene pipes with mechanical compression joints rather than PVC pipes with solvent-welded (glued) joints. The former is available in long coils for diameters less than 100 mm leading to fewer joints (and less leakage). Also, in many PICs the use of non-standard jointing methods to connect PVC pipes (by heating of pipe ends over open fires to form sockets) has led to serious leakages at joints.
- Measures to reduce leakage in plumbing systems in houses and other buildings (e.g. offices, schools) can have a beneficial impact on operational costs for pumped systems. In Hihifo, for instance, a saving in water usage and pumping costs of over 50% was achieved by replacing the whole water system and training in water conservations and leak prevention was undertaken.
- Water saving devices, such as spring loaded taps for standpipes and improved household plumbing fixtures (low and dual-flush toilet cisterns, low-flow taps and shower heads) can assist in water conservation. Where appropriate, introduction of dry composting toilets can reduce household consumption by 30% or more.

Some water supply systems are so dilapidated and suffering from leakage through poor joints, cracks in pipes and illegal connections that partial or whole replacement of pipe networks is required. A recent example of a full pipe network replacement occurred at Hihifo. There the existing public water supply system consisting of a variety of pipe materials which had been installed in the 1960s and later was suffering from leaks, inadequate water quality and frequent breakdowns. The pipe network was replaced with uPVC pipes. At the same time, old diesel powered groundwater pumps were replaced with solar powered pumps to lower operational costs.

7.7 Drought and flood planning

Planning and preparation for droughts and, where applicable, floods are essential components of strategies to deal with disaster risk reduction under current climate variability and potential climate change.

Planning and preparation for droughts should include:

- Preparation of response plans.
- Forecasting (e.g. using the SCOPIC seasonal climate outlook software developed and disseminated to PICs under PI-CPP).
- Dissemination of information via community meetings, radio and other means to the public including encouragement of simple measures such as conservation of rainwater in tanks.
- Appropriate response measures including possible water restrictions and reductions in groundwater pumping. In the more extreme cases, this may also include the preparation for use of stored desalination units. Reacting after a drought has commenced by declaring emergencies, as has happened in the past is not a useful measure. Droughts are a reality and measures should be taken well in advance to cope with them.

Planning for floods should involve preparation of flood plain maps and response plans, as well as education and awareness of communities at risk about the impacts of floods and necessary actions to be taken if intense rainfall occurs.

7.8 Capacity building and training

As outlined in section 3.1, limited human and financial resource capacities are major impediments to effective water management and, as such, are major risks to water availability.

There is an urgent, large and long-term need for capacity building and training within water and sanitation agencies. A combination of in-country training and development programs for technical and professional staff combined with appropriate external courses are required to build the capacity of these agencies.

Recruitment, training and on-going development of professional and technical staff in the water sector should allow for the loss of well-trained staff to more lucrative offers with consulting firms and external opportunities.

7.9 Community education, awareness and participation

As outlined in section 3.1, lack of, or limited community participation can lead to water management and water supply problems. There is an ongoing need to engage communities at all stages of water supply projects development and implementation as well as the long-term management of water resources and water supply systems.

Ongoing community education and awareness programs are required with emphasis on responsible water use, conservation and protection of water sources and water supply infrastructure. A training program was undertaken at Hihifo covering all areas of water resource and supply management to facilitate the VWC to sustainably manage the new water system.

7.10 Other water supply strategies for specific circumstances

Other currently available and possible water supply strategies to improve water availability in specific circumstances include:

- Use of commercially available, low-pressure, easily operated and maintained water treatment systems for degraded water sources. Membrane filtration systems are available which can filter out bacteria, sediment and algae from water supplies.
- Use of simple ‘solar stills’ to produce freshwater from seawater or brackish groundwater. They can supply basic potable water needs of households during droughts, particularly on small, remote islands or remote coastal communities on larger islands. Such systems are not difficult or expensive to construct and some companies manufacture and sell these systems. Daily freshwater production rates of 2 to 5 litres per square metre are achievable.

8. IDENTIFICATIONS OF GAPS AND FUTURE NEEDS

8.1 Outline

This section identifies information gaps and research needs for a better understanding of the implications of climate change on water availability into the future. These gaps and needs are presented according to the following categories:

- Climate change projection deficiencies and needs
- Water resources data deficiencies and needs
- Other data deficiencies and needs
- Research into impacts on surface water and groundwater resources
- Further development of effective water supply technologies.

8.2 Climate change projections gaps, deficiencies and needs

The following gaps, deficiencies and needs are identified:

- Projections of evaporation are not yet available from **PCCSP**.

- Current GCMs are unable to project changes in ENSO activity and hence changes to future climate variability, which is of most significance for future droughts and high rainfall periods. Also, it is “difficult to use GCMs to make robust regional projections for tropical cyclone activity under climate change” (PCCSP, 2011a). Further research and development of GCMs is required before the projections can be of significant benefit to the selected countries in terms of water resources.
- The scale of current GCMs is too coarse for the size of most of the countries within the study region. More accurate models at regional scale (approximately 50 km) and better still at a scale of approximately 10-20 km are required to be of significant benefit to water resources impact studies for small islands or significant catchments on larger islands.

8.3 Water resources deficiencies and needs

The following deficiencies and needs shall be identified:

- Available rainfall data is of good quality and long duration (generally from the late 1940s or early 1950s) at a number of key locations in and throughout the country. Other locations have shorter or discontinued records. Care shall be taken to reliance on automatic rain gauges in remote islands which are not visited often enough to prevent loss of data. There is a real need to continue, manually read (daily) rain gauges in key outer islands of Tonga.
- The absent of stream flow data from ‘Eua shall be taken care of in the future, it will take many more years for a stations to produce useful data. However, it is essential to implement these efforts.
- Existing groundwater monitoring networks are not regularly monitored except during the passage of short-term projects. These include networks in Tongatapu, Lifuka and Neiafu. Insufficient staffs, inadequate support from management, lack of transport and failure of equipment are all factors contributing to the shortage of regular monitoring data.
- Long-term funding arrangements (20 years or more) through external donors are required to support the national water resources agencies in operating and maintaining networks of stream flow gauging stations and groundwater monitoring sites. The overall costs of operating and maintaining such sites is small compared to the development costs required for surface water and groundwater schemes for urban and village water supply and agriculture.

8.4 Other data deficiencies and needs

Topographic information for many “low islands” and low-lying parts of high islands is not of sufficient resolution to accurately assess the areas which are vulnerable to inundation due to projected sea level rise (refer section 5.2.6) . There is a need for improved survey information to produce topographic maps with better vertical resolution (to 0.1 m accuracy).

8.5 Research into impacts on water resources

Further research into the effects of climate variability and change on surface water and groundwater resources is warranted. The research and analysis should include the following:

- Research into relevant stream flow multipliers applicable to catchments in ‘Eua with surface water resources, for use in estimating reductions or increases in mean stream flow based on mean rainfall data. This work should use relevant rainfall-runoff models and the longest available stream flow and rainfall data sets. As most data records are relatively short, use of longer stream flow records from nearby catchments in similar hydrological and environmental settings could be used. Streamflow and rainfall data for 22 New Caledonia catchments with data extending over periods from 15 to 52 years (Terry and Wotling, in press) and for catchments in the Hawaiian Islands (Oki, 2011) could possibly be used for developing stream flow multipliers applicable to similar catchments in Tonga.
- Further groundwater catchment research into evaporation and recharge to groundwater (perched and basal aquifers, including freshwater lenses).
- Ongoing research work into the vulnerability of the shorelines on low islands and low-lying parts of high islands to projected sea level rise and extreme events, such as cyclone driven waves (refer section 5.2.7).

8.6 Further research and development of water supply technology

Further research and development of effective water supply technologies is required. In particular, research and development leading to improved efficiency of desalination (reverse osmosis or other methods), primarily to reduce the operational costs, is warranted. There is significant potential for desalination technology to resolve water supply problems of urban areas, particularly those on crowded islands. However, current systems suffer from high operational costs and maintenance requirements.

8.7 Practical strategies to improve water availability

A number of strategies for managing the implications of climate change in addition to existing stresses on water availability for the country are outlined in the guideline under the following categories:

- Water governance
- Assessment and monitoring of water resources
- Management and protection and of water resources
- Appropriate water supply systems
- Demand management
- Drought and flood planning
- Capacity building and training
- Community education, awareness and participation
- Other water supply strategies for specific circumstances.

Key principles for these strategies are:

- Ensuring that the water sector is resilient to current climate variability, in addition to major pressures from increasing water demand and stresses from water pollution associated with human settlements, is the most effective overall adaptation strategy to cope with future climate change.
- Strategies to reduce vulnerability of the water sector to climate change and, thus, increase water availability are essential components of good water management practice, and are required whether climate changes or not.
- There are “no simple technical fixes” or no single action that will improve water availability. Rather a range of strategies are required including improved water governance; effective assessment, development, management, protection and conservation of water resources; effective operation, maintenance and management of water supply systems and other water development schemes; enhanced community participation in the water sector and improved community education and awareness.
- Although there are some similarities between each project, each site or island is different and some have wide variations in water resources and water availability between different parts of the country (e.g. high islands and low islands). The mix of potential strategies to improve water availability must be adapted to suit local circumstances taking account of population growth and the pattern of settlement and development.
- Introduction of new technologies requires parallel investment in training, education and awareness to gain community and government acceptance.
- In specific circumstances, particularly in countries with limited land and water resources (e.g. crowded low-lying islands and remote islands), there are a number of options to assist in development and management of water resources.

8.8 Identifications of gaps and future needs

Further development of effective water supply technologies. Information gaps and research needs, aimed at a better understanding of the implications of climate change on water availability, are identified according to the following categories:

- Climate change projection deficiencies and needs
- Water resources data deficiencies and needs
- Other data deficiencies and needs
- Research into impacts on surface water and groundwater resources

- Further development of effective water supply technologies.

9. BASIS FOR DESIGN, CONSTRUCTION AND MONITORING

9.1 Water resources and supply design examples

The following measures were implemented in the Hihifo Water Supply Improvement Project (PACC) to improve the water supply for the residents of Hihifo in terms of water quality, pressure and reliability.

(a) Improve access to town water by:

(i) Providing a 3.5 km long 150mm diameter PVC transmission pipeline ("rising main") and a new pipe reticulation system for the four Hihifo villages of Kolovai, 'Ahau, Kanokupolu and Ha'atafu. The existing 100 mm PVC distribution pipeline to feed the water consumers at Ha'atafu.

(ii) Increasing the water storage capacity to around 136 kL consisting of both an elevated storage ("high level tank" or HLT) and ground level storages ("low level tanks" or LLT).

(iii) Feeding all water connections in the four villages using two water supply zones to water control pressures. To do this, the higher elevation parts of Kolovai and all of Ha'atafu will be fed from the HLT and most of Kolovai and all of 'Ahau and Kanokupolu villages will be fed from the LLT.

(iv) Adopting a minimum residual water pressure of 5 m at peak hour in the highest areas of the reticulation systems in both water supply zones.

(v) Installing transfer pumps to enable water to be pumped from the LLT to the HLT, if required.

(vi) Installing hydrants for fire fighting purposes and for emergency use.

(vii) Reducing unscheduled interruptions to town water supply by installation of flow control valves and training in system operation. These valves will also enable possible step testing for leakage detection purposes.

(b) Improve the quality of town water by:

(i) Having a minimum of 5 production wells/boreholes and 3 monitoring wells to meet demand in the year 2031.

(ii) Setting out the new wells/boreholes 150 m apart, and having a maximum pumping rate of 1.5 litres per second (L/s) per well/borehole compared to the current pumping rate per well of 3 L/s. This strategy will minimise the pumping impact on the groundwater salinity.

(iii) Adopting a freshwater upper limit in terms of electrical conductivity (a measure of salinity) of 2,500 µS/cm.

(iv) Carrying out regular monthly groundwater level and salinity measurements of pumped groundwater at all 5 production wells/boreholes.

(v) Carrying out salinity monitoring of the 3 monitoring boreholes every three months.

(vi) Carrying out bacteriological, chlorine residual and nitrate tests at each well/borehole.

(c) Improve the pumping systems from the well field by:

- Installing three solar pumps and two diesel pumps at the 5 production wells/boreholes. This will also act to decrease operational costs and the risk of groundwater pollution from oil and diesel. A conservative estimate of 2/3 solar pumping and 1/3 diesel pumping is assumed.
- Provide electricity back-up to the solar pumps to enable pumping to occur on cloudy days.

(d) Implement demand management and leakage control strategies with set targets by:

- Allowing for a per capita demand of 100 L/person/day.
- Further reducing demand to 80 L/person/day where rainwater harvesting systems are available.

- Allowing for a leakage rate equivalent to 7.5 L/property/hour.
- Installing district flow meters at strategic locations in the system.
- Installing connection meters will be installed at all houses and other buildings.
- Using the meter data to monitor water usage and help identify the location and magnitude of leakages within the distribution system.
- Repair household leaks prior to the new system being commissioned.
- Implementing a leakage control program with trained staff. This is essential in order to maximise the benefits of the improved water supply infrastructure.

(**e**) Increase access to rainwater by providing 30 rainwater tanks with gutters, fittings, downpipes and concrete bases to selected houses.

(f) Increase the level of service provided by the HVWC by:

- Offering a better maintenance service for all leaks by increasing the plumbing capability of HVWC personnel, re-training meter readers as plumbers, providing more transport and improving fault reporting and responses, including car to base communications.
- Moving the office to the main town to make payments easier and provide a venue for other demand management activities.
- Conducting surveys of consumers to gauge response to the water supply improvements in terms of water quality, pressure and reliability.
- Becoming a provider of plumbing services. Consideration will be given to including gutter and downpipe maintenance and new plumbing.

(g) Contribute to the community by increasing public awareness on issues such as:

- Health aspects of water
- Water use efficiency
- Maintenance of rainwater harvesting systems (gutters, downpipes and tanks)
- Potential impacts from climate change as well as current climate variability. This aspect will be a component of the training and public awareness program.

(h) Encourage economic growth by extending water supply service to all holiday resorts in Hihifo. This aspect was covered by the project.

9.1.1 Scope of work

The scope of works included the following components:

9.1.1.1 Review available data, collect more data, and process data

Liaise with key Ministries in Tonga and any other relevant stakeholders to outline the project and request relevant data, reviewing and processing the data. In addition, collect additional field data data prior to analysis.

9.1.1.2 Estimate recharge

Using the processed data, to
perform an estimation of recharge to groundwater from rainfall data, estimates of evapotranspiratio
n and climate change mainly the projected increase/decrease of rainfall.

9.1.1.3 Estimate sustainable yield

Estimate the "sustainable yield" or "safe yield" of the freshwater lens based on the recharge estimates, known fresh groundwater thicknesses and impact of climate change. Decision shall be made on abstraction rate and pumping strategies

9.2 Water supply

A brief background of the study area (project site) where it describes the geographical location of the site, population and a brief history of the water supply system and its current state. It should also highlight any alternative water resources that supplement the use of underground waters with some notes on the governing body of the existing water supply system. It should address the result of the concepts of basic design study and the basis for a new system as follows:

1. Status of the project
2. Improvement of the water supply conditions
3. Conservations of water
4. Transmission and distribution pipelines and elevated tank
5. Pipe replacement (asbestos, galvanized, uPVC etc)
6. Leakage control and improvement
7. Improvement and suitability of the financial status

9.2.1 Objective of project

Clearly state the main objectives of the project and any other aim such as conserving environmental aspect of the water resource system in the Kingdom of Tonga. A list of execution items that highlights the overall project requirement is required:

Example

- Replacement of existing mains and distribution lines
- Enlargement of pipe's diameter etc.
- Upgrade of production facilities

9.2.2 Basic Concept of the Project

This is a more detail explanation of the result from the preliminary study of the project site and how it is define. It shall also highlight the main content of the project and the basis for basic design.

Example

- The target year for the project and time bound for completion
- Reduction in leakage
- The design target for minimum residual pressure
- The design consumption rate in litres per person per day
- Intake capacity
- Disinfection system if required

9.2.3 Basic Design

9.2.3.1 Design Concept

Natural Conditions to be considered

The basis for design from the view point of climate change impact, energy efficiency and saving on account of high energy cost in Tonga. For distribution purposes, the use of corrosion free and less joint material is preferred.

Local Contractors and Materials / Equipment

The use of local Contractors and Materials / Equipment availability and access to construction materials, local mechanical, electrical and construction materials shall be considered. Procurement from other countries such as Australia and New Zealand shall be considered from the viewpoint of readiness for spare parts and technical assistance as well as cost and time for transportation.

9.2.3.2 Basic Design

9.2.3.2.1 Water Demand

The calculation of water demand shall be base on the following:

Domestic Use

Project service area and current service area with population forecast of at least 30 years with the projected increase in water demand due to projected increase in temperature. The unit water demand in l/p/d and in total of m^3/day.

Public Use

Water demand for public use such as Schools, Hospital and Government Offices in m³/day

Commercial Use

Water demand for industrial and commercial purposes in m³/day

From the above calculation the total daily average consumption can be derived.

9.2.3.3 Design Capacity

Base on the water demand forecast, design capacities for the system can be define as in Table 2.1.

Table 16 Design capacity & parameters

(A)	Daily Averaged Demand	? m³/day	Total Volume of water that is consumed (Domestic) + (Public) + (Commercial) + 2% impact of increase temperature
(B)	Daily Averaged Production	? m³/day	Water volume delivered from tank or reservoir (A) + Leakage (Unaccounted for Water)
(C)	Daily Maximum Demand	? m³/day	Peak daily distribution volume supplied on a peak day demand throughout the year = (B) × (Daily maximum factor : 125% = (B) × 1.25 = ?l/sec (Daily maximum factor of 125% is a design standard of Tonga)
(D)	Peak Hourly Flow	? l/sec	The maximum hourly flow which will be occurred in the peak demand hour in the day of the daily maximum Demand. This parameter determines the sizing diameters of distribution pipelines. = (C) × (Peak Hourly factor: 180% = (C) × 1.80 (Peak hourly factor of 180% is estimated based on past record of Nuku'alofa. The peak demand hour is supposed to be 7:00 am)

9.2.4 Facilities design

9.2.4.1 Water Supply System

A flow chart of the propose water resource and supply system under a proposed project showing the items to be provided and constructed.

Example.

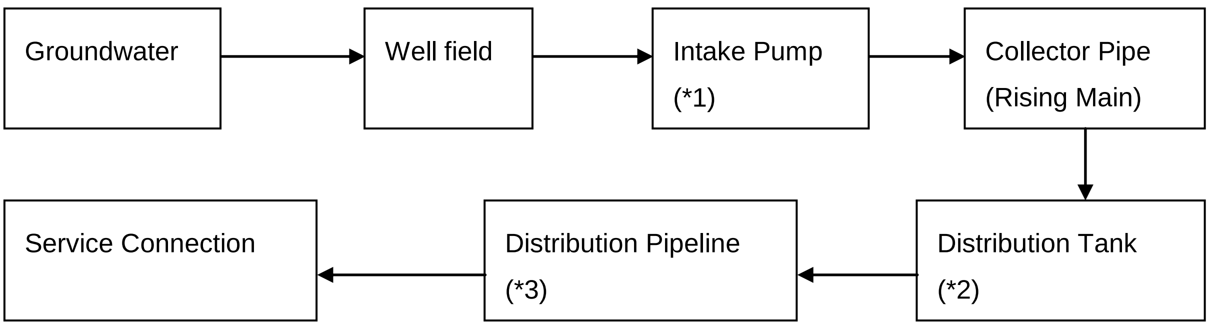


Figure 14 Flowchart of a propose of major component a propose water resource and supply project

Table 17 Items to be provided/constructed under a given project

(*1)	Intake Pump	Provision of ? Stand by Engine
(*2)	Distribution Tank	Replacement or upgrade
(*3)	Distribution pipeline	Full replacement of existing Distribution Pipeline?

Further note is required to explain the existing systems that needs to be retained

9.2.4.2 Production Facilities

Detail explanation with a tabulated format of the capacities, operation ratio of the intake facilities and the proposed benefit in leakage reduction in the following categories:

- Existing system, after the project, without project and Volume of water to be saved.

Table 18 Water volume to be saved by reducing leakages ratio by a given project

Categories		After Project	Without project	Saved water volume
(A)	Leakage ratio	?%	?%	?%
(B)	Daily Averaged Water Demand = (Water Demand of year ?)	?m³	?m³	?m³
(C)	Daily Averaged Water Demand =(B) / (1- (A))	?m³	?m³	?m³
(D)	Daily maximum water production = (C) × (Daily max. factor: 125%	?m³	?m³	?m³

Table 19 Operation ratio of intake facilities

Operation ratio	100%	95%	90%	85%	80%
No. of Pump	?	?	?	?	?
Intake capacity	?m³	?m³	?m³	?m³	?m³

9.2.5 Distribution facilities

9.2.5.1 Collection Tank

As for the distribution Tank, its capacity shall be able to supply the demand in 24 hours in times of full breakdowns. It should have an allowance for fire fighting and shall be able to supply the maximum hourly outflow without flow disruption.

9.2.5.2 Distribution Pipelines

The designer shall come up with some alternatives considering the advantage and disadvantages of several factors; among the comparison factors the cost difference between the alternatives must be considered. Each case must highlight the reliability of each system. It should have a plan of the following:

- Enlargement of the pipe diameters
- Restoration of house connections

- Selection of pipeline route
- Pipe embedding / restoration of road pavement
- Construction pipelines
- Hydraulic calculation result
- Pipeline to be constructed by the project
- Hydraulic calculation result

As a result of the hydraulic analysis, the pipeline networks which assure appropriate water supply shall be established. Firstly the targeted pressure would be satisfied in the off-peak hours. Secondly the necessary water volumes can be supplied without interruption.

9.2.5.3 Disinfection

The selection of disinfectant to be used, taking into account the following:

- easiness of mechanical handling
- safety of chemical handling
- construction and maintenance cost
- chlorine dosing system
- chlorine dosing rate

9.2.5.4 Leakage Control measures

The Consultant (TWB) shall come up with a leakage control strategy that will be incorporated in the operation of the new system with a provision of equipment to assist the villagers in leakage control. A provision of a simple mobile flow measuring unit may be necessary and affordable providing that the flow control system of the propose system is adequately provided in the Project. It shall have a representative process of leakage investigation and repair works.

9.2.6 Provision of Equipment

The component of equipment to be provided under the Project shall be summarizing with the following on a tabular format with the following heading:

- Purpose, Name of Equipment, Quantity and Necessity of Equipment

9.2.7 Basic Design Drawings

For the process of negotiation and implementation of the project the concept and basic design drawings shall be prepared as follows:

- Propose Production and Distribution Pipelines : Key Plan
- Longitudinal profile of pipelines
- Trench work Standard
- Site plan of Production area
- Tank / Reservoir (Elevated or on the ground)
- Chlorination Equipment: Process flow diagram & Piping Arrangement

9.3 Implementation plan

9.3.1 Implementation Plan and Concept

(1) Basic Condition for Implementation

Project components shall be summarize on a tabular format highlighting the Scope of Works and project components. A brief description of the scope of works is also required. The local villagers may have some contribution and it is required to be highlighted.

Example:

Table 20Scope of works and project component

Scope of Works	Items to be constructed
Intake Facility	Provision of intake pumps
Distribution Pipelines	Construction of PVC pipelines (2km)
Service Pipes	Restoration of connection
Local labour	Trenching etc

(2) Local Contractor

A brief / Detail description of the responsibilities, expertise and ability of the Local Contractor shall be established.

(3) Expatriate Engineers

Only if required

(4) Executing Organization of Tongan Side

Highlight the Executing Agency (TWB) of the project. Who is responsible for the implementation and supervision of the Project?

A conceptual structure for the Project Implementation shall be required.

Example:

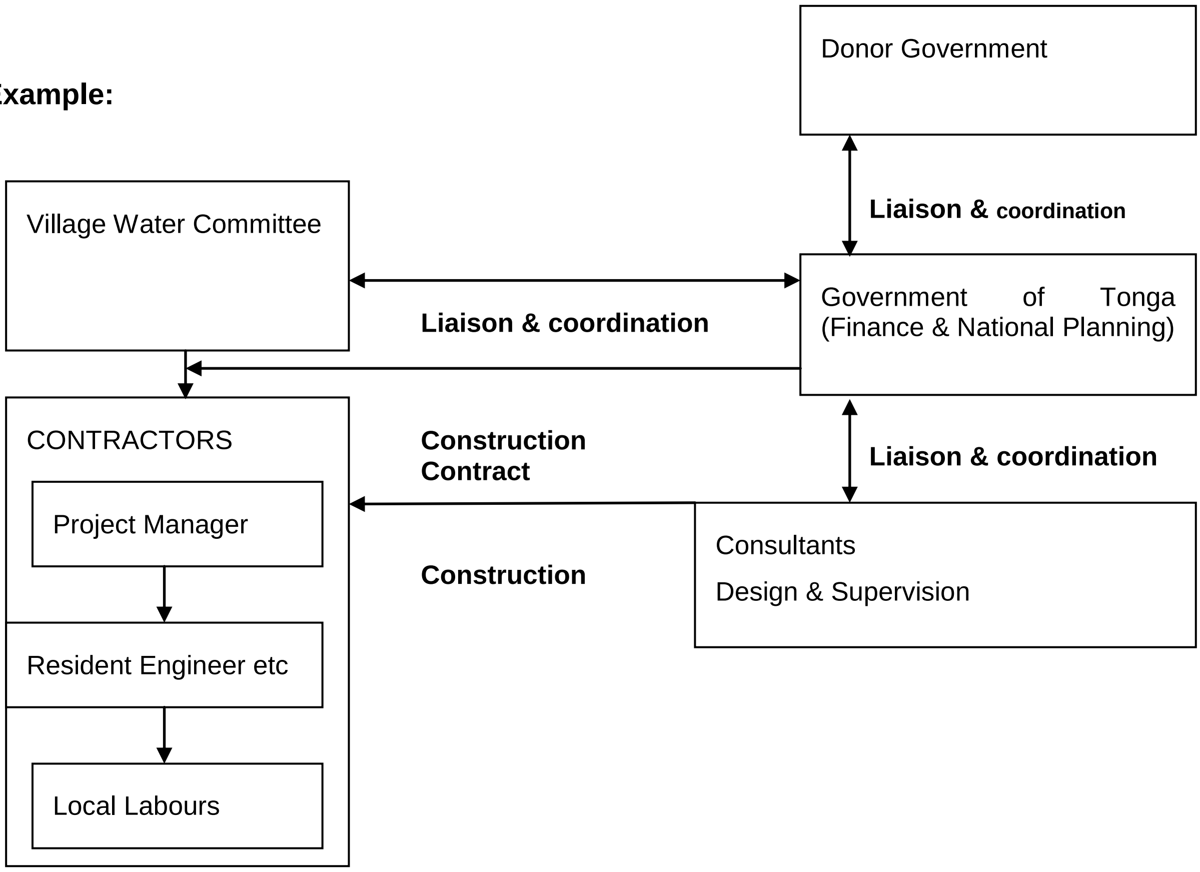


Figure 15 Conceptual structure of a project implementation schedule

9.3.2 Implementation Conditions

(1) Natural Conditions on Construction

The following natural conditions shall be explained as follows:

- Geology
- Climate Change
- Rainfall
- Earthquake
- Cyclone etc.

(2) Related Laws and Regulation

Establish drinking water standard (WHO's guideline) and standards for designing structures and other water supply facilities (Australian and New Zealand Standard, AS & NZS)

9.4 Detail Design and Construction Supervision

(1) Detail Design

In the detail design study the following works shall be carried out:

- Field study (site reconnaissance of the pipeline routes, Investigation of underground installations and other obstacle, existing pipe etc, trial pit excavation, topographic survey
- Basic design shall be reviewed on the basis of field study
- Comparison on construction method, structural planning and temporary planning to decide implementation plan
- The structural calculation
- Drawings (Location map, plans, longitudinal section drawings, detail drawings and structural drawings
- Calculation Sheets
- Cost estimate of the basic design shall be reviewed
- Tender document shall be prepared

(2) Construction Supervision

Following the detail design, the construction supervision shall be undertaken. Major items of the construction supervision services are summarized below:

- Close coordination with parties concerned for completing the construction work as schedule in the implementation program of the Project
- Precise and timely advises to the contractor and the executing agency to construct the facilities consistent to design drawing and contract document
- Proper transfer of knowledge to the staff of the Village Water Committee on construction methods to optimize the effect of the Grant Aid Project in the form of on the Job training
- Provide adequate advice and guidance on operation and maintenance of the constructed facilities to facilitate the operation of the Project
- Make sure that water supply and other utilities services disruption is minimize by cooperation with all parties involve
- Operation and Maintenance Manual (O&M) for equipment and pipelines is to be prepared by the Contractor

The above supervision works include the following duties and responsibilities:

- supervision of construction program and quality control, such as approval and inspection of construction materials and work
- Inspection and approval of dimensions, and numbers of the constructed works and facilities
- Change order of the contract as required
- Preparation of reports and papers required as specify by Donor and executing agency

The above consulting services will be required from the commencement of the construction to the completion of all construction works. Throughout the construction period an Engineer will be assigned to coordinates the construction works. Expert in several disciplines will be dispatched to the site in addition to the Engineer for smooth operation of the implementation of works.

9.5 Procurement Plan

(1) Labour

Labour and foreman are locally available and shall be provided by the Contractor and Village Water Committee.

(2) Materials and Equipment

A brief description of the availability of materials and equipment for construction purposes. It shall show the expected time of order to the first delivery and arrival.

(3) Construction Machinery

A brief description of the availability of construction machinery for construction purposes.

Example.

Table 21 List of procurement plan

Item	Specification	Country		
		Tonga	2nd Country	3rd Country
Labours		☑		
Construction Material				
PVC Pipe	100 – 50mm dia.		☑	
Sand for Backfill		☑		
Provision of Equipment				
Trencher		☑		

9.6 Implementation Schedule

To be explain on tabular format as follows:

Month	1	2	3	4	5
Detail Design	Field Survey				
		Design			
			Tendering		
Procurement/ Construction	Manufacturing				
		Distribution Pipeline			
				Miscellaneous works	

Figure 16 Implementation schedule

9.7 Undertaking of the Village Water Committee

This component of the project shall highlight the contribution of the Village Water Committee

9.8 Operation and Maintenance Plan

(1) Organizations

Explain who is in control of the facility after the Project and the operation and maintenance.

(2) Operation and Maintenance

Explain the ability of the owner to generate revenue for operation and maintenance. Revenue and expenditure forecast with a projection of Annual Revenue.

9.9 Project evaluation and recommendation

9.9.1 Project Effect

Explain the effect of the implementation of the Project on the following:

- Improvement of living conditions
- Sustainable management of waterworks
- Conservation of groundwater resources
- Technical assistance and cooperation with other donors
- Financial and Economic Impact

Recommendation

Provision of recommendation that shall execute stable water supply both in quantity and quality and to operate the facilities properly. The following points shall be considered for further references and action:

Example:

- monitoring of water sources
- Promotion of leakage control program
- Improvement of accounted for water
- Environmental issues

9.10 Technical specification

This is a separate volume of the Contract document where it spells out the specification of the following items:

- General Conditions
- Mobilization and Demobilization
- Temporary Works
- Site survey and Investigation
- Earth Work
- Concrete Work
- Pipe Laying Work and Restoration Work
- Road Work
- Architectural Work
- Mechanical Work
- Electrical Work
- Chlorination System
- Chlorination Equipment
- Electrical Equipment
- Procurement and supply of Equipment and Materials

9.11 Training

- Training needs analysis
- Training Programme Approach
- Communication strategy
- Training Budgets

9.12 Community Awareness Programme

Content of Community Awareness Program (One-Off – "Project Related" Awareness (Project Information, Community roles and responsibilities, Tariff composition and level, Water conservation (Leak prevention practices) (On-going / Recurrent Awareness) – Sanitation, Environmental Management, Water management and Conservation)

- Delivery of Community Awareness Programme
- Training of Trainers
- Training of Village Water Committees
- On the job training

10. ACKNOWLEDGEMENTS

The following people are thanked for providing information and advice:

Paula Taufa, PACC Tonga
Tony Falkland

11. REFERENCES

Burns W.C.G. (2002). Pacific Island Developing Country Water Resources and Climate Change, in The World's Water (Peter Gleick, ed., 3rd Edition, 2002), pp113-132. Website http://www.internationalwildlifelaw.org/BurnsChapterPDF.pdf.

CSIRO (2011). Sea level rise, Understanding the past – Improving projections for the future, CSIRO National Research Flagships Wealth from Oceans. Website: http://www.cmar.csiro.au/sealevel/sl_proj_21st.html.

Falkland A. (2002a). A Synopsis of Information on Freshwater and Watershed Management Issues in the Pacific Islands region. IWP Technical Report 2002/02. *In* Wright A. and Stacey N. (eds). Issues for Community based sustainable resource management and conservation: considerations for the Strategic Action Plan for the International Waters of the Pacific Small Island Developing States. International Waters Programme, South Pacific Regional Environment Programme. 132pp.

Falkland A. (2002b). Water Resources Management. Theme 1 paper. Proceedings of the Pacific Regional Consultation on Water in Small Island Countries (ed. C. Carpenter, J. Stubbs and M. Overmars), co- ordinated by SOPAC and ADB, Sigatoka, Fiji, 29 July-3 August 2002, 76pp

GHD (2008). Report on Water Security and Vulnerability to Climate Change and other Impacts in Pacific Island countries and East Timor, August 2011.

IETC (1998). Source book of alternative technologies for freshwater augmentation in Small Island Developing States. International Environmental Technology Centre, UNEP in collaboration with South Pacific Applied Geoscience Commission and the Water Branch of UNEP, Technical Publication Series No. 8, 223pp.

Scott D. (2002). Island Vulnerability. Theme 2 paper. Papers and Proceedings of the Pacific Regional Consultation on Water in Small Island Countries (ed. C. Carpenter, J. Stubbs and M. Overmars), co- ordinated by SOPAC and ADB, Sigatoka, Fiji, 29 July-3 August 2002, 25pp.

Storey D. and Hunter S. (2010). Kiribati: an environmental 'perfect storm'. Australian Geographer, 41(2): 167-181.

White I., Falkland A., Etuati B., Metai E. and Metutera T. (2002). Recharge of fresh groundwater lenses: field study, Tarawa Atoll, Kiribati. In: Hydrology and Water Resources Management in the Humid Tropics, Proc. Second International Colloquium, 22-26 March 1999, Panama, Republic of Panama, IHP-V Technical Documents in Hydrology No 52, UNESCO, Paris, 2002, 299-332.

White I., Falkland A. and Fatai T. (2009). Groundwater Evaluation and Monitoring Assessment, Vulnerability of Groundwater in Tongatapu, Kingdom of Tonga. SOPAC/EU EDF8 Reducing the Vulnerability of Pacific APC States, Australian National University, Canberra, Australia, June 2009, 351pp.

Woodroffe C.D. (2008). Reef-island topography and the vulnerability of atolls to sea-level rise. Global Planetary Change, 62:77–96.

Mimura N., Nurse L., McLean R.F., Agard J., Briguglio L., Lefale P., Payet R. and Sem G. (2007). Small Islands. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M. L. Parry,

O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.). Cambridge, UK: Cambridge University Press. 687-716.

PCCSP (2011a). Interim climate projections, 25 March 2011. CSIRO and Bureau of Meteorology, Pacific Climate Change Science Program (supplied in email from Martin Sharp, Director, International Adaptation Strategies Team, Adaptation, Land and Communications Division, Department of Climate Change and Energy Efficiency on 17th May 2011).

PCCSP (2011b). Document "PCCSP projections for PASAP v3.xls". CSIRO and Bureau of Meteorology, Pacific Climate Change Science Program (supplied in email from Martin Sharp, Director, International Adaptation Strategies Team, Adaptation, Land and Communications Division, Department of Climate Change and Energy Efficiency on 17th May 2011).

PCCSP (2011c). Climate change in the Pacific. First Order Draft. CSIRO and Bureau of Meteorology, Pacific Climate Change Science Program. Prepared for Department of Climate Change and Energy Efficiency.

Voss C.I. (1984). SUTRA, A finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically-reactive single- species solute transport. USGS Water Resources Investigations Report 84-4389, 409pp.

Voss C.I., Boldt D. and Sharpiro A.M. (1997). A Graphical-User Interface for the US Geological Survey's SUTRA Code using Argus ONE (for Simulation of Variable –Density Saturated-Unsaturated Ground- Water Flow with Solute or Energy Transport), U S Geological Survey, Open-File Report 97-421, Reston, Virginia.

UNESCO (1991). Hydrology and water resources of small islands, a practical guide. Studies and reports on hydrology No 49. prepared by A. Falkland (ed.) and E. Custodio with contributions from A. Diaz Arenas and L. Simler and case studies submitted by others. Paris, France, 435pp.

Terry J.P. and Wotling, G. (in press). Rain-shadow hydrology: Influences on river flows and flood magnitudes across the central massif divide of La Grande Terre Island, New Caledonia. Journal of Hydrology (2011), doi:10.1016/j.jhydrol.2011.04.022.

TWB (2000). An Outline of Recent Water Supply Improvements for Pangai-Hihifo, Lifuka, Kingdom of Tonga. prepared by A. Falkland and S. Helu, Tonga Water Board, August 2000.

TWB (2011). Water production and consumption data for 2010. Tonga Water Board, unpublished data.