Government of the Republic of Kiribati

Tarawa Water Master Plan:

Te Karau, Rainwater Harvesting, Storage and Use

Coordinated by the National Adaptation Steering Committee
under Office Te Beretitenti
and the National Water and Sanitation Coordination Committee
through the Ministry of Public Works and Utilities

Kiribati Adaptation Programme Phase II Water Component 3.2.1, World Bank, AusAID, NZaid

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This Water Master Plan is a response to widespread public concerns over freshwater voiced during wide spread public consultations conducted during the National Adaptation Program of Action, Kiribati Adaptation Project Phase I (KAP I). It was developed under the Kiribati Adaptation Project Phase II Water Component Project 3.2.1 and was overseen by the National Water and Sanitation Coordination Committee under the chair of the Ministry of Public Works and Utilities and by the National Adaptation Steering Committee under the chair of the Office Te Beretitenti. This plan has been drafted by Professor Ian White, Australian National University with the valuable assistance of Tony Falkland of Island Hydrology Services, a tireless and long standing friend of Kiribati and Marella Rebgetz, KAPII Water Specialist. This plan is based on the National Water Resources Policy and its accompanying National Water Resources Implementation Plan*.* This plan has involved help, critical inputs and useful comments from:

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Scope

The scope of this Technical Assistance activity is to produce a Water Master Plan for water development, management, protection and monitoring in Tarawa taking account of all available water resources (primarily groundwater and rainwater) and possible additional sources.

Terms of Reference

The original terms of reference (ToR) for this Tarawa Water Master Plan are:

1. Review relevant parts of existing documents related to water master planning including the following: Draft Water Master Plan of 1992 (Shalev, 2002) and subsequent revisions (WEU, 2000); PUB Business Plan, 2004-2006 (PUB, 2004) (and updated documents if available); Project reports from the water component of the SAPHE project including the Review of Groundwater Resources Management for Tarawa (Falkland, 2003); Draft National Water Policy (EU-SOPAC, 2007a); Revised Draft National 10-Year Water Plan (EU-SOPAC, 2007b).
2. Consult with relevant GoK agencies and individuals (refer list above) about water planning and management issues in relation to both groundwater and rainwater.
3. Consult with other organisations including local NGOs and private companies, as appropriate.
4. Estimate future demands for water based on most current population data, growth trends, per capita consumption and estimates water use for commercial, community and industrial activities. Use planning horizons of 10 and 20 years.
5. Develop a logical sequence of water resources development based on technical assessments, cost estimates, and land ownership/management issues and environmental factors.
6. Review current water management, protection and monitoring procedures and recommend, as appropriate, additional mechanisms to ensure that the groundwater resources are usable by present and future generations.
7. Prepare a draft Water Master Plan for Tarawa, ensure that it is consistent with the draft National Water Policy and 10-Year Water Plan and present to the NWSCC and key KAPII consultants.
8. After feedback from the NWSCC and KAPII personnel, assess the comments received, undertake additional analysis as required and prepare a final draft Water Master Plan for Tarawa.

On 27 February 2009 it was agreed to alter ToR point 8 and include an additional point 9:

8. After feedback from the NWSCC, NASC and KAPII personnel at initial and final Workshops, assess the comments received, undertake additional analysis as required and prepare a final draft Water Master Plan for Tarawa
9. The consultant will compile a brief final report which records activities undertaken and documents produced in fulfilment of both Parts 1 and 2 of the consultancy. The purpose of the report is to demonstrate fulfilment of TOR, provide a list of final draft documents submitted clearly indicating versions and dates, and electronic file names of documents submitted.
10.

Process

After review of all relevant documents, consultations with all relevant Ministries, private companies and NGOs were carried out in the course of this work. Draft reports were circulated to Ministries for comment in August and September 2009. Workshops on the TWMP were held with key government agencies on 9 and 14 December 2010. Presentations of material in this plan were also given to the NWSCC, chaired by Secretary MPWU, on 4 August 2008, 23 June 2009 and 13 December 2010 and to the NASC, chaired by Secretary OB, on 5 August 2008 and 15 December 2010. Plan documents were revised in light of the comments received prior to finalising them.

Acronyms and Abbreviations

A	roof catchment area (m^2)
$\overline{A}$	reduced effective roof area $\overline{A} = C \cdot A / M_t$ (mm^{-1})
ADB	Asian Development Bank
AusAID	Australian Agency for International Development
BTC	Betio Town Council
C	roof catchment runoff coefficient (dimensionless)
°C	degrees Celsius
cm	centimeter (one hundredth of a metre)
CO_2	carbon dioxide
CV	coefficient of variation
d_t	number of days in the month t
D	daily per capita demand (L/pers/day)
EC	electrical conductivity
GCM	Global Climate Model
GIS	Geographical Information System
GOK	Government of Kiribati
IHP	International Hydrological Programme (of UNESCO)
IPCC	Intergovernmentall Panel on Climate Change
IPO	Interdecadal Pacific oscillation
KAP	Kiribati Adaptation Program (Phases I, II & III)
KHC	Kiribati Housing Corporation
km	kilometre
km^2	square kilometre
kL	kilolitre (= 1 m^3)
L	litre
L/day	litres per day
L/pers/day	litres per person per day (water use)
m	metre
m^2	square meter
m^3	cubic metre (= 1 kL = 1,000 L)
M_t	total monthly water demand of the household $D \cdot N \cdot d_t = M_t$ (L)
ML	mega litre (one million litres)
ML/day	mega litre per day
mm	millimetre (one thousandth of a metre)
KMS	Kiribati Meteorological Service (within MCTTD)
MLPID	Ministry of Line and Phoenix Island Development
MPWU	Ministry of Public Works and Utilities
mth	month
N	number of people per household
NIWA	National Institute of Water & Atmospheric Research, New Zealand
NSO	National Statistics Office
NZAID	New Zealand International Aid and Development Agency
NWSCC	National Water and Sanitation Coordination Committee
pers	person
P_t	monthly rainfall (mm)
PUB	Public Utilities Board (within MPWU)
S	storage capacity of the rainwater tank (L)
$\overline{S}$	Non-dimensional relative rainwater tank capacity $\overline{S} = S / M_t$ (dimensionless)
SAPHE	Sanitation, Public Health and Environment Improvement Project
SCOPIC	Seasonal Climate Outlook for Pacific Island Countries
SOI	Southern Oscillation Index
SOPAC	Pacific Islands Applied Geoscience Commission
SRES	Special Report on Emission Scenarios
SST	sea surface temperature
STP	Sustainable towns project
ToR	terms of reference
TUC	Teinainano Urban Council
TWMP	Tarawa Water Master Plan
TWSP	Tarawa Water Supply Project
UNESCO	United Nations Educational, Scientific and Cultural Organization
V_t	volume of rainwater stored in month t (L)
$\overline{V}_t$	non-dimensional volume stored in the rainwater tank $\overline{V}_t = V_t / M_t$
V_{t-1}	volume of rainwater stored in the previous month $t-1$ (L)
$\overline{V}_{t-1}$	non-dimensional volume stored in the rainwater tank in previous month $\overline{V}_{t-1} = V_{t-1} / M_t$
WB	World Bank
WEU	Water Engineering Unit (within MPWU)

Summary

Previous work in the Tarawa Water Master Plan has identified significant shortfalls in the ability of treated reticulated groundwater to meet the water needs of future populations in Tarawa. This component of the Tarawa Water Master Plan aims to examine the potential for meeting some of the future water needs of Tarawa for the next 20 years through rainwater harvesting. A brief summary of the characteristics of rainfall in Tarawa is given which reinforces the importance and impact of the large variability of rainfall in Tarawa, mostly driven by ENSO events. Major droughts occur on average about every 7 years and can last for two years. The predictions from climate change studies Global Circulation Models (GCMs) of changes in future rainfall and drought frequency due to climate change are problematic since the GCMs do not simulate ENSO events. It is assumed here that the future variability of rainfall in Tarawa over the next 20 years will be similar to that in Betio over the period 1947 to the end of 2008.

Legal requirements for rainwater harvesting

The Council Bye-Laws for new buildings are briefly reviewed. They require all new houses and buildings with suitable roof materials to have rainwater harvesting and storage systems installed. It also specifies these systems must be maintained properly. The draft National Building Code also mandates installation of rainwater harvesting and storage. These are not enforced and many new buildings with large, suitable roof areas have been built in Tarawa without rainwater harvesting and storage systems. Since building approvals are at the Council level and since there are currently no qualified building inspectors in Tarawa, the Bye-Laws are never enforced. This needs to be addressed as a matter of urgency.

Information of rainwater harvesting

Tarawa and particularly South Tarawa leads the Nation in the use of rainwater harvesting. It is estimated that currently about 43% of households in South Tarawa and 12% in North Tarawa harvest and store rainwater. Despite the obvious importance of rainwater harvesting, there is a lack of information on the amount used and the characteristics of the systems used. This study of the potential for rainwater harvesting in Tarawa has been limited by the lack of data on the current use of rainwater and on the physical characteristics of rainwater harvesting and storage systems in Tarawa so that it is not possible to say what is the future potential for expanding the use of rainwater. It is strongly recommended that the lead water agencies conduct surveys of household rainwater use and develop a data base of the physical characteristics of rainwater storages in Tarawa.

Estimation of the risk of failure of rainwater storage

The estimations made here on the risk of failure of rainwater harvesting and storage in Tarawa rely on a number of assumptions and estimates. There are five key parameters on which the simple, monthly mass balance estimate of rainwater harvesting depends: the number of people per household; the per capita demand; the size of the roof catchment; the roof catchment runoff coefficient and the volume of the rainwater storage. Because of the lack of information, this study has assumed reasonable values of the size of rainwater tank storage capacities, roof catchment areas, roof runoff coefficients, and per capita demand and has used the average size of households in South and North Tarawa from the 2005 Census.

Using the assumed baseline parameter values and the historic monthly rainfall record for Tarawa, estimates of the risk of failure of rainwater tanks were found for an assumed constant rate household demand by varying one parameter at a time with the others constant. It was found that for the average household size in South Tarawa, and for average-sized roof catchment areas and rainwater tank storage capacities, rainwater harvesting could only supply water at a modest rate (about 5 L/pers/day, sufficient for drinking and cooking only) without risk of excessive rainwater tank failures. It was shown that for average roof areas, the storage capacity of the rainwater tank needed to supply water without failure was 6 times the average total household monthly water use for drinking and cooking. For a rainwater tank capacity of 6,000 L, it was found that a rather large roof area of about 7.7 m^2/pers was required to prevent rainwater tank failure at a per capita demand of 5 L/day.

The key parameters of rainwater harvesting

A non-dimensional form of the water balance equation was introduced with only two parameters which incorporate the other parameters, the non-dimensional relative rainwater tank capacity, $\overline{S}$, which is the total rainwater tank capacity divided by the average monthly household water demand, and the reduced effective roof catchment area, $\overline{A}$, which is the roof catchment area multiplied by the runoff coefficient and divided by the average monthly household demand. These two parameters determine the failure rate of rainwater tanks. Using the historic rainfall record in Tarawa, it was possible to produce families of pairs of these parameters for specified failure rates. This non-dimensional analysis is independent of any assumptions about parameter values but is specific for Tarawa as the analysis used the Tarawa rainfall record. The results of the simple spreadsheet developed here and supplied to the lead agencies are quite general and can be used for any roof area, rainwater tank storage capacity, household size or per capita demand.

Inability to supply total households water demand with rainwater harvesting

Worked examples of the use of the non-dimensional analysis are given and show that for the usual average sized households in Tarawa, it is not generally possible to supply all the household water requirements from rainwater as impractically large storage capacities and very extensive roof areas are required. Instead, more modest rainwater harvesting and storage systems can be constructed which can provide the needs for drinking and cooking, at about 5 L/pers/day with relatively small or zero rates of failure. The above calculations contain no conservation strategies. An example is given of a conservative management strategy which limits water use when the stored water volume reaches a specified level, such as half tank full. Such strategies need to be complemented by warnings from the government on predicted drier periods determined by the Kiribati Meteorological Service using the SCOPIC program. These would limit failure of rainwater storage but would require a major public education campaign and improved rainwater tank management.

The monthly water balance model was tested against a daily water balance model and was found to be in good general agreement. The monthly water balance predicted the capacity of rainwater tanks necessary to prevent failure for a specified demand and roof area that was up to about 10% smaller than the daily water balance. The conclusion from the monthly water balance that, due to frequent severe droughts, rainwater harvesting and storage in Tarawa can only supplement household water requirements rather than meet all household water needs was therefore confirmed by the daily model.

The costs and advantages of rainwater harvesting

A crude analysis of the cost of rainwater harvesting systems using historic rainfall data estimated that the cost to households of harvested rainwater exceeds $8/kL which is considerably greater than the current charge for PUB water but much less than bottled water. If properly managed, rainwater harvesting and storage systems, however, have several distinct advantages in Tarawa: source of good quality water for drinking and cooking; limited risk of human or domestic animal faecal contamination; constant, limited supply of water always continuously available; under the direct control of the household; a convenient household water storage for deliveries during droughts and, conservation messages are clearly signaled by the decreasing volume of water in the rainwater tank. It was estimated that rainwater harvesting contributes less than 100 kL/day to the water supply in South Tarawa but could be expanded in the future to around 160 kL/day.

Public education in rainwater harvesting

The National Water Policy recognizes that rainwater harvesting is an important and relatively safe source of the several available sources for meeting water needs. Rainwater harvesting and storage bye-laws need to be enforced and considerable community education and training in the judicious and careful use of rainwater from harvesting and storage systems and in their installation, proper maintenance and repair is required.

Information Gaps

This component of the Tarawa Water Master Plan examined the ability of rainwater harvesting and storage systems to supply part of the future water demand in Tarawa. The estimates here have been hampered by a lack of knowledge. There is no information in Tarawa on:

1. The current average amounts of household use of water from various sources including stored rainwater.
2. The range of roof catchment areas.
3. The range of rainwater tank capacities.
4. The state of maintenance of rainwater harvesting and storage systems.
5. Water losses from rainwater tanks in Tarawa.
6. Water quality of stored rainwater

This lack of information makes the development of a soundly-based Tarawa Water Master Plan difficult. It is strongly recommended that the lead water agencies conduct two surveys.

- Use of rainwater by household and community organizations
    - Surveys of selected households in South and North Tarawa to determine the type of use of rainwater and the per capita use of rainwater.
    - Surveys of selected agencies, organizations and businesses to determine uses of rainwater and the approximate per capita rainwater use.
    - Surveys of selected rainwater tank storages on the microbiological quality of stored water.
- Properties of rainwater storages. Construct a data base linked to a GIS containing:
    - Location of all rainwater tanks
    - Storage capacity of rainwater tanks
    - Area of roof catchment for rainwater collection
    - Quality of guttering and connection
    - Quality of stored rainwater.

While both surveys will be time consuming for the small number of people in the lead water agency, it must be recognized that Tarawa and particularly South Tarawa face major water shortfalls in the future. There will need to be a major improvement in water monitoring to ensure sustainable management. The information from these rainwater surveys will be invaluable in improved water resource management both now and in the future.

Assumptions

The main assumptions underpinning this component of the plan are outlined below:

The characteristics of rainfall in Tarawa over the next 20 years will be similar to those over the past 62 years.

Climate change predictions of changes in rainfall in Tarawa are based on the results of Global Circulation Models, GCMs. Current GCMs do not simulate ENSO events. Rainfall in Tarawa is strongly correlated with ENSO events. Predictions of changes in the amount of rainfall in Tarawa based on GCMs are therefore doubtful. The best assumption is that in the next 20 years rainfall temporal patterns in Tarawa will be similar to those in the past 62 years, for which a rainfall record exists.

The frequency and duration of severe droughts in Tarawa over the next 20 years will be similar to those over the past 62 years.

Climate change predictions of changes in the frequency and duration of droughts in Tarawa are also based on the results of Global Circulation Models, GCMs. Again, current GCMs do not simulate ENSO events well. Severe droughts in Tarawa are strongly correlated with ocean surface temperatures and the La Niña phase of ENSO events. Predictions of changes in the amount of rainfall in Tarawa based on GCMs are therefore largely irrelevant especially if climate change alters the characteristics of ENSO events.

Monthly rainwater tank water balance provides a reasonable estimate of the reliability of rainwater tanks.

Ideally, rainwater catchment water balance studies should use daily rainwater tank water balances. Because of the limited availability of recent daily rainfall data in Tarawa, monthly water balances have been used here. These provide a first order estimate the reliability of rainwater tanks. The reliability of this has been tested against a daily water balance model for limited ranges of rainfall data and found to be reasonable.

Baseline estimates of the characteristics of rainwater harvesting and storage systems

Because there is no information on the characteristics of rainwater harvesting and storage systems baseline values have had to be assumed. These are listed below.

Assumed baseline values of parameters in equation

People per Household, *N*	7.7
Demand per person, *D* (L/day)	5
Roof Area, *A* (m^2)	50
Runoff Coefficient, *C*	0.85
Rainwater tank capacity, *S* (L)	6,000

Variations around these baseline values were then considered.

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1. Introduction

In the demand component of the Tarawa Master Plan for Tarawa (White and Falkland, 2009a,) it was estimated that water production in Tarawa would have to rise to somewhere between 6.3 to 11.7 ML/day by 2030 to meet the expected reasonable needs of South Tarawa's growing population, commerce, business and institutions as well as the losses of water from the supply system. Since this range is between 3.1 and 5.8 times the sustainable yield of the current piped groundwater supply from Bonriki and Buota, the critical question is from what source can the additional water be obtained? This report examines the potential of rainwater (te karau) harvesting and storage to meet some of the current and future water needs.

1.1 Sources of Drinking Water in Tarawa

The 2005 Census (National Statistics Office, 2007a) shows that households in Tarawa access freshwater for drinking from a range of multiple sources: piped or reticulated treated water from groundwater reserves at Bonriki and Buota, local groundwater from household wells, rainwater collected from roofs and bottled water, both imported and local (Table 1).

Table 1 Percentage of households in Tarawa using various sources for drinking water compared with other rural areas in the Gilbert Group (2005 Census).

Location	Total House-holds	Percentage of Households (%)				
		Rain	Piped	Open Well	Closed Well	Bottled Water
South Tarawa	5245	42.8	67.0	54.1	18.1	3.8
North Tarawa	867	12.1	1.6	87.3	19.6	0.9
Other Rural Gilbert Group*	7407	11.4	2.8	81.9	27.0	0.7

*Excluding North and South Tarawa

The reticulated supply system in South Tarawa is only able to supply water intermittently to households and other users, consequently, they have to use multiple sources for drinking water[1]. The increasing population density also imposes a significant risk that local shallow groundwater, on which households rely, will be polluted by human and animal wastes, increasing the hazards of using domestic wells in urban areas.

Surveys of communities throughout the Gilberts (ADB, 2004; World Bank, 2006) have found a preference for increasing rainwater harvesting as a way of securing safer water supplies. One of the top ten priority adaptation strategies identified in wide-spread community consultations throughout the Gilbert Group, during Phase I of the Kiribati Adaptation Project (World Bank, 2006), was to increase rainwater harvesting. In South Tarawa, the 2005 Census results show that rainwater is already used by 43% of households as a source of drinking water compared to only 12% in North Tarawa, which is close to the 11% in other outer islands in the Gilbert Group.

1.2 Use of Te Karau in Kiribati

Rainwater catchments and storages have been installed in many islands in Kiribati. Banaba currently relies almost heavily on harvested rainwater and it is also an important water source in the island of Kiebu in Makin. Previous studies of rainwater harvesting in Kiritimati (Falkland, 1983) and Banaba (Overmars and Butcher, 2001) have shown that the combination of rainfall variability, small roof areas, modest rainwater tank storages, large household sizes and constant water demands lead to unacceptable rainwater tank failure rates, where storages cannot meet demand and run dry. This was also the case, even in the high rainfall island of Butaritari (Mourits, 1996) where small roof areas could only supply a modest design demand of 10 L/pers/day for about a

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[1] While the use of multiple sources for drinking and cooking for a single household is reflected in the survey conducted by ADB (2000) the recent survey by STP(2010) seems to have overlooked the possibility.

third of the time. Supplementing groundwater sources by using rainwater has long been considered a wise but relatively expensive option in Tarawa (see e.g. Falkland, 1992).

The general conclusion from these studies is that rainwater catchments are an excellent supplementary source, rather than a primary source of water in Kiribati. This is due to frequent, prolonged droughts, in which very large household and public building storage tanks and collection surfaces would be required to meet even basic demands. These would be more expensive than groundwater pumping systems. In addition, on outer islands, many houses have thatch roofs, which are unsuitable for collecting rainwater (Harrison, 1980; Falkland, 2003).

The importance of providing training for communities in rainwater harvesting and storage as well as in the design of appropriate rainwater harvesting in the Pacific has been recognised regionally (SOPAC 2004a, 2004b). The Pacific Regional Action Plan of Sustainable Water Management (SOPAC and ADB, 2002) endorsed by GoK, calls for improved use of rainwater harvesting. In Kiribati, it has been noted that "…*rainwater collection by individuals and institutions, which could substantially alleviate the shortage of drinking water, is not widespread enough, in spite of existing regulations, and many existing roof-collection installations are inoperative or under-utilised.*" (Government of Kiribati, 2002). One of the top 10 adaptation strategies identified in extensive community consultations throughout the Gilbert Group as part of the Kiribati Adaptation Program Phase I (KAPI) was "*Install rainwater tanks*". The National Water Resources Policy's first policy objective is to "*increase access to safe and reliable water supplies".* Under that objective the National Water Resources Implementation Plan lists "*increase the use of improved rainwater harvesting*" as a key activity.

This component of the Tarawa Water Master Plan aims to examine the potential for meeting some of the future water needs of Tarawa through rainwater harvesting.

1.3 Previous Tarawa Water Supply Projects and Rainwater

Some small island countries in the Pacific, such as Tuvalu, rely heavily on the collection of rainwater for water supply. There, large buildings are used to collect rainwater which is stored in cisterns and tanks for communal use. Also, in recent years, large numbers of 10,000 L polythene tanks and associated gutters and downpipes have been installed at houses. In the island of Majuro in the Marshall Islands, the paved airport runway is used as a rainwater collector and the runoff is collected in adjacent storage tanks. These locations differ from Kiribati, in both the availability of fresh groundwater and in reliability of rainfall.

In the transition period from Tarawa being part of a British Colony (AGHDC, 1975) to the early days following independence (Harrison, 1980), rainwater harvesting was an integral part of the total water supply system. Rainwater was harvested from public buildings, stored in cisterns or rainwater tanks before being pumped to main holding reservoirs in Betio where it was mixed with pumped groundwater and delivered by tanker to households (Harrison, 1980; Fig. 1). Similar schemes also operated in Bairiki and Bikenibeu.

An earlier study by Richards and Dumbleton International (1978) believed that groundwater resources at Bonriki and Buota were insufficient to supply water during droughts. Instead, they proposed the creation of an artificial rainwater catchment to collect rainwater from the Betio to Bairiki causeway. It was planned that collected rainwater would drain to both Betio and Bairiki and supply water at the rate of 3 L/pers/day. That study, however, vastly underestimated the sustainable groundwater yield of the Bonriki and Buota groundwater reserves and was never pursued. Harrison (1980) estimated the contribution of private rainwater harvesting to be about 3% of the then total water supply. Harrison's (1980) social survey found that most I-Kiribati preferred groundwater to rainwater, partly because of taste and discoloration problems with rainwater collected from pandanus thatch roofs, but mostly because palm toddy can only be made with groundwater.

In a pre-design study for the AIDAB funded Tarawa Water Supply Project, AGDHC (1982; 1986) proposed a water demand model that depended on the class of housing. Large houses with significant roof areas and rain storage tanks were assumed to be independent of the piped groundwater supply for 90% of the time. It was estimated that their storage tanks would only fail in 1 in 10 year droughts, provided that the harvesting and storage system was adequately maintained.

About 340 houses with roof areas exceeding 130 m^2 were to be supplied with two 13,500 L rainwater tanks. It was estimated this would reduce demand on groundwater pumping by about 80 kL/day (AGDHC, 1982) when 9% of the population had rainwater tank schemes.

AGDHC (1986) recognised the cost of installing rainwater harvesting and storage systems was much larger than the cost of a groundwater pumping scheme and recommended that: "*The household rainwater tank scheme should be strictly limited because it is relatively uneconomic due to higher initial and maintenance costs."* It also recommended that: "*householders who do not either adequately maintain their tank systems or use 'excess' water should be charged a higher rate for any lens water…".*

AGHDC (1986) acknowledged that Tarawa's severe droughts were a hazard for rainwater harvesting and storage and suggested a public awareness campaign, government broadcasts and official drought declarations as a way of promoting rainwater conservation.

Shalev (1992) also recognised that rainwater harvesting was limited both by the frequent long droughts in Tarawa and by the cost of rainwater harvesting and storage, and concluded that rainwater harvesting in Kiribati can only be regarded as supplementary, rather than a main source of water. None-the-less he proposed a large-scale 31 ha rainwater catchment and storage system in the fishponds at Temaiku which were to be lined with a polyethylene membrane and backfilled with progressive layers of sand, coarse aggregates with a surface of fine aggregates to prevent evaporation from the stored rainwater. He suggested this 1 m deep storage was capable of supplying 350 kL/day. A related proposal was suggested by Falkland (1992) who proposed filling in Temaiku Bight with dredged lagoon sediments to eventually form an artificial freshwater lens. Falkland recommended that small scale rainwater catchments be re-evaluated in light of the current water supply restrictions with a view to making more houses on South Tarawa self-sufficient in rainwater at least for most of the time.

Royds (1996), in a study for the Sanitation Public Health and Environment (SAPHE) project, recommended the provision of both household and institutional rainwater tanks in buildings with suitable roofs as a high priority. They recommended that rainwater only be used for drinking and cooking supplies and that the provision of rainwater tanks in new buildings be included in the South Tarawa Building Code. Royds was apparently unaware of the existence of the 1975 Council Building Bye-Laws.

In the SAPHE project Water Supply Design Report (OEC, 2000), it was estimated that rainwater harvesting could contribute 400 kL/day to the potable water supply in South Tarawa. No basis for this estimation was given apart from the estimation that it would need 1,000 buildings of roof area 200 m^2 with an assumed average runoff coefficient of about 0.38. Under the SAPHE project, a revolving fund was set up administered by the Kiribati Housing Corporation (KHC) to provide loans for public servants to purchase rainwater collection and storage devices. This scheme has proved remarkably successful at supplying rainwater tanks (Table 2).

Table 2 Outcomes of loans from the revolving fund, set up under the SAPHE project in South Tarawa, for improved rainwater use and sanitation (KHC)

Year	Water tank	Flush toilet	Compost toilet	Water pump	Guttering
2002	207	50	0	0	0
2003	242	12	0	0	0
2004	261	11	2	9	0
2005	124	10	0	41	0
2006	105	12	0	35	0
2007	87	1	0	12	1
2008(June)	49	3	0	14	0
Total	**1075**	**99**	**2**	**117**	**1**

A Kiribati case study for the Pacific Regional Consultation Meeting on Water in Small Island Countries in Sigatoka, Fiji, 29 July - 3 August 2002 (Metutera, 2002) concluded that rainwater in Kiribati is only a supplementary water source due to frequent droughts. It pointed out that to reduce the risk of failure very large rainwater tanks were required, which are beyond the means of individuals and community groups.

1.4 Future Changes in Sources of Household Water

By 2030, it may be expected that considerable changes will have occurred in the freshwater sources used by households in Tarawa. Some idea of the expected changes can be derived from examining the historic record of sources of household drinking water contained in past census results collected by the National Statistics Office.

The SAPHE household survey (ADB, 2000) fortunately has reported limited data on water sources for South Tarawa from the 1995 Census. This is compared in Table 3 with data from the 2005 Census. It can be seen that there is almost a 20% increase in the percentage of households using rainwater tanks between 1995 and 2005. This is equivalent to an extra 1,433 houses having rainwater tanks. Table 2 shows that a total of 774 rainwater tanks were purchased under the SAPHE revolving fund scheme between 2002 and mid-2008. It is tempting to conclude that a large portion of the increase in the use of rainwater tanks between 1995 and 2005 is due to the SAPHE revolving fund scheme.

The SAPHE household survey, which surveyed 1386 rural and 1759 households in South Tarawa, reported that one significant impediment to installing household rainwater tanks was their cost. This led to the introduction of the SAPHE revolving fund. The survey did not estimate actual amounts of rainwater sourced by households. It did however provide data on whether houses had iron roofs suitable for rainwater harvesting (Table 4) and rainwater tanks (Table 5).

Table 3 Change in the percentage of households in South Tarawa using different sources of drinking water from the 1995 Census to the 2005 Census

Year	Total House-holds	Percentage of South Tarawa Households (%)				
		Rain	Piped or Tanker	Open Well	Closed Well	Bottled
1995*	3520	23	55	58†		-
2005	5245	42.8	67.0	54.1	18.1	3.8

* Data from ADB (2000)
†Only one value given for wells by ADB (2000)

Table 4 Percentage of houses in South Tarawa with iron roofs (ADB, 2000)

Iron Roof	Area				
	"Rural" South Tarawa	Bikenibeu	Bairiki	Betio	Total
yes	44.7%	72.2%	64.8%	74.7%	60%
no	55.3%	27.8%	35.2%	25.3%	40%
number	1,349	654	324	755	3,082

Table 5 Percentage of houses in South Tarawa with rainwater tanks (ADB, 2000)

Rainwater tank	Area				
	"Rural" South Tarawa	Bikenibeu	Bairiki	Betio	Total
yes, working	27%	27%	39%	27%	28%
yes, not working	11%	19%	10%	9%	12%
no	62%	53%	51%	64%	59%
number	603	472	210	564	1,849

In 2000, 60% of the houses surveyed in South Tarawa had roofs suitable for rainwater harvesting, but only 40% of houses had rainwater tanks. Of the latter, only 28% were working. Bairiki had the highest percentage of working rainwater tanks due presumably to higher government salaries there and the salinity and pollution of local groundwater.

In the intervening period to 2005, it will be assumed that there was a 10% increase in the percentage of houses with iron roofs suitable for rainwater harvesting to 66%. Table 1 suggests that in 2005, about 43% of households had some form of rainwater harvesting, This suggests that there is the potential to expand household rainwater collection in South Tarawa by about 23% of the total number of houses, or about another 1,200 houses.

1.5 Geographic Differences in Sources of Household Drinking Water

The values in Table 3 show the results for South Tarawa as a whole. The SAPHE household survey (ADB, 2000) showed that water sources vary with location in Tarawa (Table 6).

Table 6 shows that households in the high-density areas of Bairiki and Betio rely heavily on treated water supplied by PUB and much less on local household wells. In Bikenibeu, reliance on PUB-supplied water is less and use of household wells is more than in Bairiki and Betio. In areas outside these population centres, use of household wells is higher and reliance on PUB water is lower. It should be noted that the SAPHE 2000 water use survey suggested that on average 70% of households in South Tarawa used PUB water, which is higher than found in both the previous 1995 Census and the following 2005 Census. This raises some doubts about the accuracy of the survey but suggests that a “one-size-fits-all” design for South Tarawa may not be appropriate.

Table 6 Geographic distribution of household use of water sources in South Tarawa (ADB, 2000, Table 15)

Source	**Area**			
	"Rural" South Tarawa	**Bikenibeu**	**Bairiki**	**Betio**
PUB piped supply	54%	76%	96%	83%
PUB tanker	1%	5%	2%	19%
Shallow well - buckets	63%	51%	25%	25%
Shallow well – hand pump	3%	2%	0%	1%
Shallow well - elec pump	4%	1%	2%	3%
Rainwater tank -own	11%	6%	15%	14%
Rainwater tank -other's	3%	2%	0%	8%
Other	1%	1%	1%	1%
No. Households	1,386	649	323	787

In the next section, the characteristics of rainfall in Tarawa are presented.

2. Te Karau in Tarawa

It has long been known that rainfalls in the Pacific are highly correlated with the El Niño – Southern Oscillation (ENSO, Pittock, 1984) or sea surface temperatures (SST) in the central western Pacific. Variations in ENSO events produce variations in rainfall in Tarawa, with La Niña phases corresponding to droughts in Tarawa.

2.1 Monthly and Annual Rainfall

Monthly rainfall in Betio, South Tarawa is characterised by extreme variability (Figure 1) with monthly rainfall ranging from 0 to 825 mm with an overall mean monthly rainfall of 171 mm. There are a few features immediately apparent from the rainfall record in Figure 1. Firstly the seasonality of rainfall is apparent; secondly the longer period ENSO-related wet periods and droughts are obvious and thirdly the apparent decrease in maximum monthly rainfall over the period.

The mean monthly rainfall (1947-2008) in Betio, South Tarawa varies between approximately 116 mm in October to 277 mm in January (Figure 2) and has, on average, a wet season from December to about April and a longer, drier season from May to November. Median monthly rainfall (Figure 2) lies below the mean indicating that the monthly rainfall distributions are skewed towards lower values. The variability of these mean monthly rainfalls, expressed as the coefficient of variability (CV)[2], is high, ranging from 0.69 in June to 1.12 in October (Figure 2). Highest variability occurs in the driest months of the year. This variability has significant implications for water resource management and especially for rainwater harvesting.

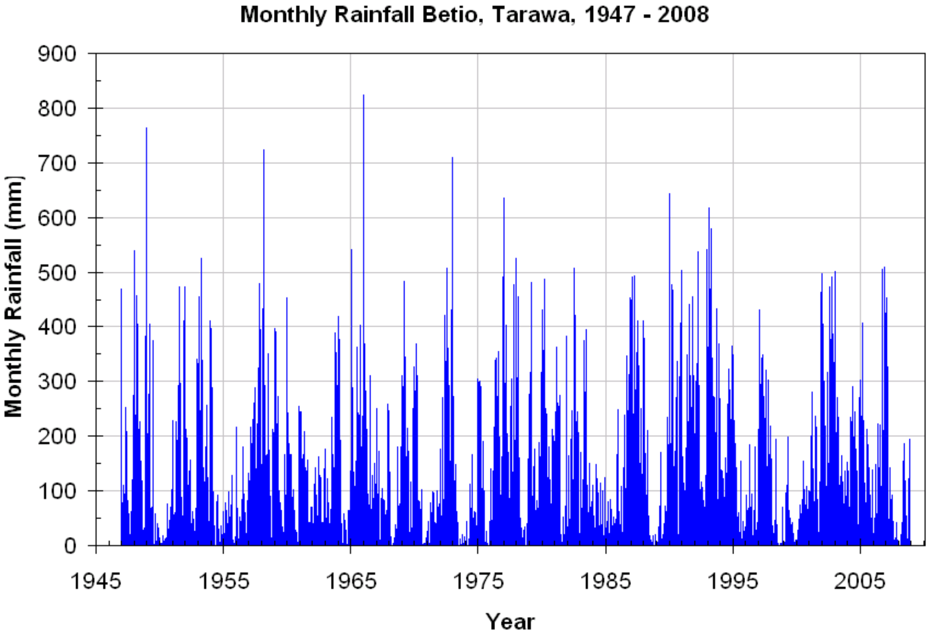

Figure 1 Historic monthly rainfalls for Betio, Tarawa for the period January 1947 to December 2008

Mean annual rainfall (1947-2008) is a substantial 2,040 mm but with significant annual variability (CV of 0.48), from a minimum of 398 mm in 1950 to a maximum of 4,356 mm in 1993 (Figure 3). Periods where there are sequences of years of below average rainfall are of particular concern for freshwater supply. Over the period of record, sequences of three or more years of below average rainfall occurred in 1954-56, 1959-62, 1973-75, 1983-86 and 1998-2000 (Figure 3) and significantly affected rainwater harvesting in Tarawa.

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[2] The coefficient of variation of monthly rainfall is the standard deviation of rainfall for a given month divided by the mean rainfall for that month.

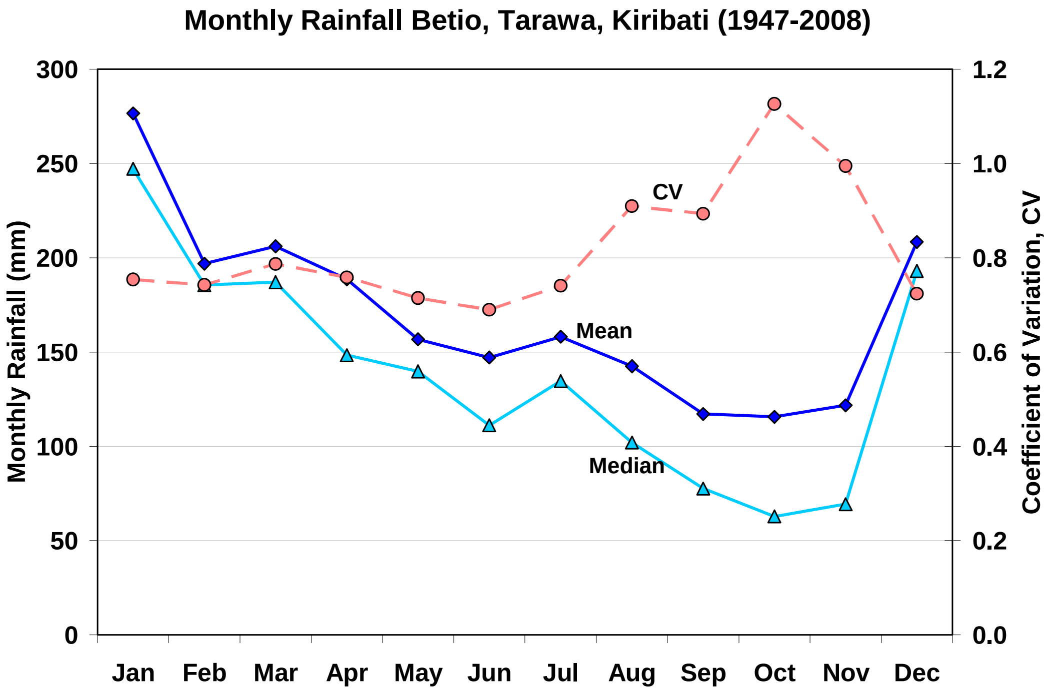

Figure 2 Mean and median monthly rainfall together with the monthly coefficient of variability of rainfall in Betio, Tarawa, Kiribati for the period 1947-2008.

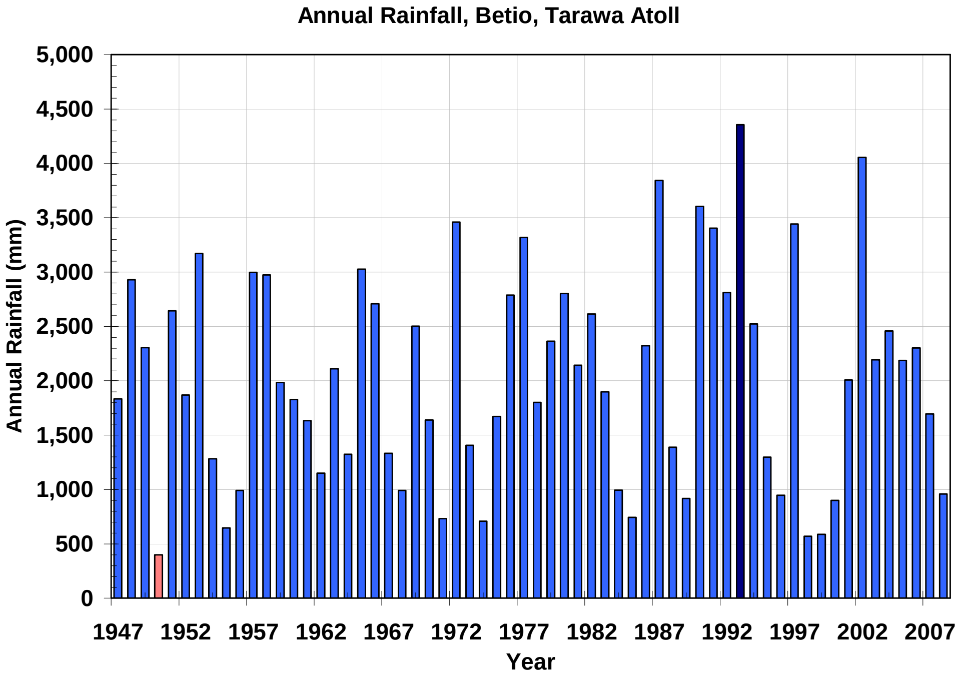

Figure 3 Annual rainfall in Betio, Tarawa, Kiribati showing the lowest (pink) and highest (dark blue) annual rainfalls for the period 1947 to 2008

Annual rainfall in Tarawa is strongly correlated with climate indices such as the Southern Oscillation Index (SOI) or sea surface temperature (SST) indices (correlation coefficient as high as 0.842) such as the central Pacific Niño region indices (Figure 4). This provides an ability to predict rainfall in Tarawa with a lead time of about 3 months as used in the Seasonal Climate Outlook for Pacific Island Countries (SCOPIC www.bom.gov.au/climate/pi-ccp/scopic.shtml) program.

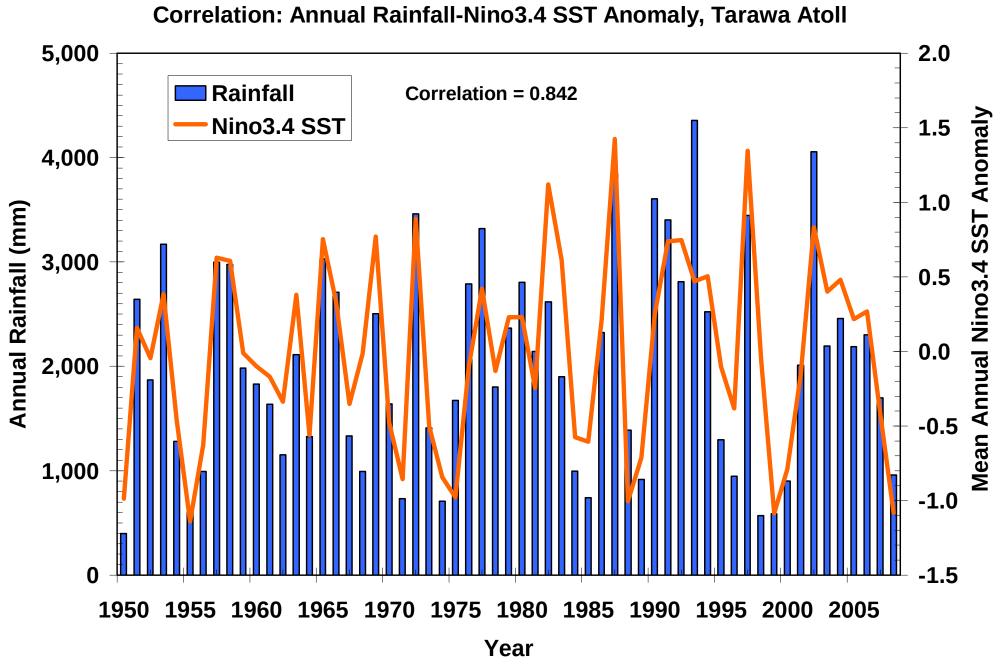

Figure 4 **The strong correlation between annual rainfall in Betio and the Niño3.4 SST anomaly.**

2.2 Spatial Distribution of Rain

Tarawa has only one official weather station in Betio near the Kiribati Meteorological Service (KMS) office at the western end of South Tarawa (Figure 5).

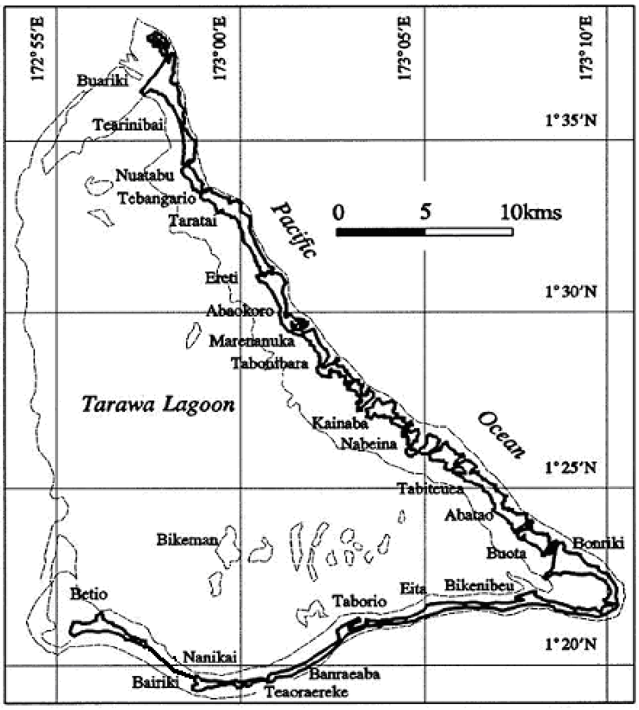

Figure 5 **The islands of Tarawa Atoll, Republic of Kiribati. South Tarawa extends from Betio to Bonriki and North Tarawa from Buota to Buariki. Rainfall is measured by the KMS in Betio.**

It has been assumed that because of the low relief of Tarawa, with its maximum elevation of about 6 m, rainfall will be relatively uniform across the atoll. The south eastern point of the atoll (Temaiku) is approximately 27 km from the Betio weather station, while the north eastern tip (Naa, above Buariki) is about 31 km across the lagoon from Betio (Figure 5). A simple manual rain gauge had been read intermittently at the PUB chlorination plant in Bonriki, about 25 km from Betio, since 1996. While the record is incomplete, it provides some information on the spatial distribution of rainfall across South Tarawa.

Figure 6 shows the comparison between the time series of monthly rainfalls at both sites between 1996 and 1998. Until mid-2004, it can be seen that, while lower rainfalls generally coincide, high rainfalls were generally larger at Bonriki than at Betio. A new rain gauge was installed at Bonriki in January 2005 after which there was a better agreement at higher rainfalls. This figure also demonstrates the importance of regular monitoring since gaps in data complicate interpretation.

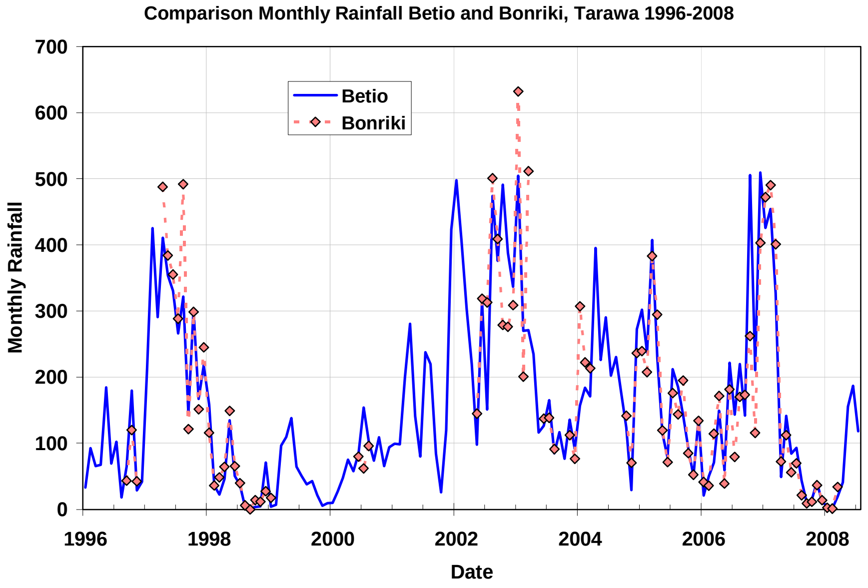

Figure 6 **Comparison of monthly rainfall at the Bonriki Chlorination Plant with that at the KMS weather site in Betio, 25 km away for the period 1996-2008**

The relationship between monthly rainfalls at the two sites is shown in **Error! Reference source not found.** for the period January 1996 - July 2008.

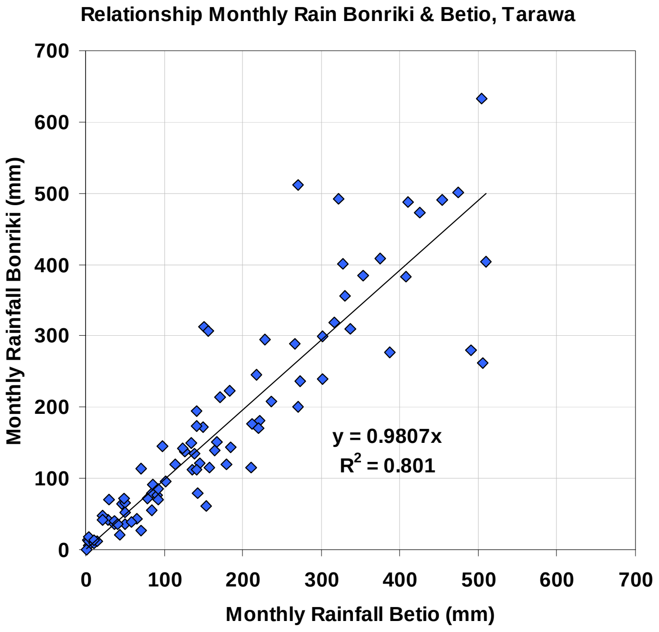

Figure 7 **Relationship between monthly rainfall at Bonriki and that 25 km away at Betio, South Tarawa for the period 1996-2008**

It can be seen that, despite considerable scatter, monthly rainfall in Bonriki is about 2% less than rainfall in Betio. Given the scatter in data, this difference may not be significant. One way of testing the agreement between different rain gauge sites is to construct a double mass plot in which the cumulative rainfall at one site over a measurement period is plotted against the cumulative rainfall at the other site for the same period. This requires having sufficiently long continuous data sets. Fortunately for the period Oct 2004 to Apr 2008 are continuous. Figure 8 shows the double mass plot for this period.

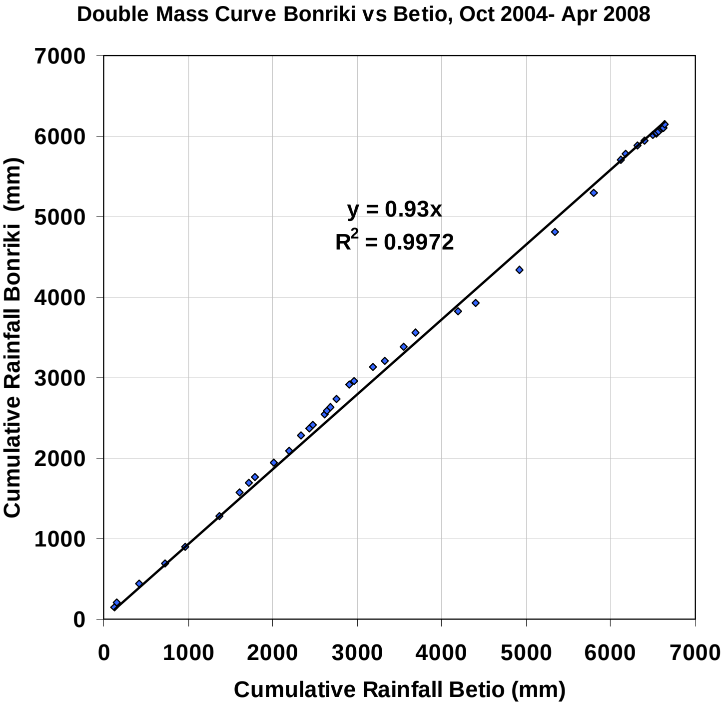

Figure 8 Double mass plot of cumulative rainfall at Bonriki versus that at Betio for Oct 2004 to Apr 2008

While there are deviations above and below the expected straight line, the double mass plot suggests the cumulative rainfall at Bonriki is 7% less than that at Betio and this appears to be significant. This comparison suggests that monitoring should continue in Bonriki and a comparison site should also be established by the KMS at Buariki in North Tarawa.

2.3 Long-term Variability of Rainfall

The annual and monthly rainfall records (Figure 3 and Figure 6) show systematic rainfall variations on a sub-decadal time scale coupled to ENSO events or SST (Figure 4). Much longer time scale variation is revealed when the cumulative residual annual rainfall[3] is plotted (Figure 9).

Figure 9 shows a general long-term drying trend from 1954 to 1975. Although this was followed by a wetter period until 1982, the overall generally drier conditions continued until 1989, giving a 45 year drier period. A very intense wet period then followed until 1997 when the very severe 1998-2001 drought set in. Since then long-term conditions have returned to near normal. These longer term variations have often been associated with the interdecadal Pacific oscillation (IPO).

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[3] The cumulative residual annual rainfall is the sum of departures of annual rainfall from the mean. Long-term, continued negative departures indicate drier than average periods, while long-term, continued positive departures show wetter than average periods.

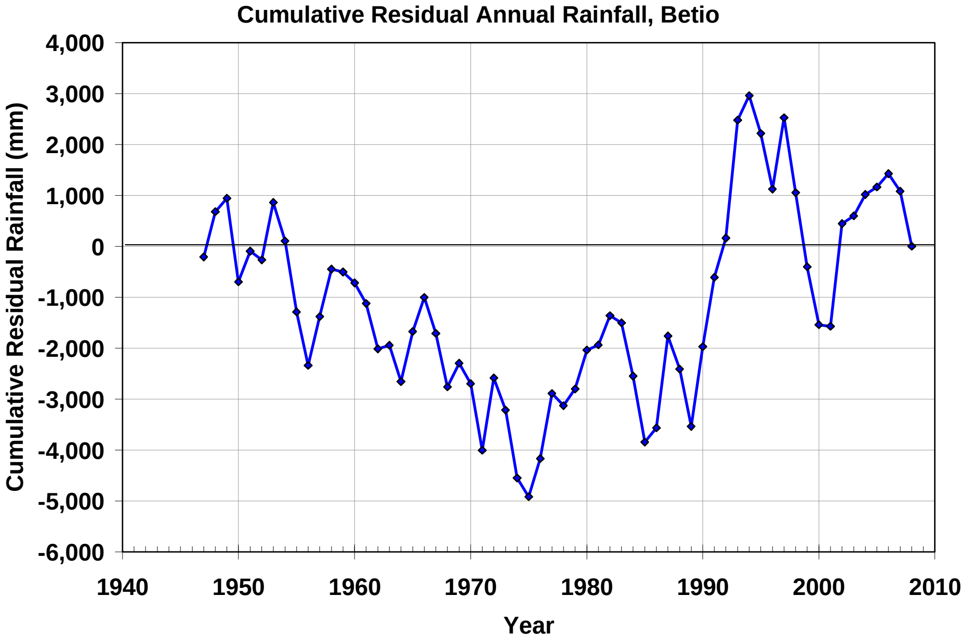

Figure 9 Cumulative residual annual rainfall, Betio, Tarawa Atoll for the period 1947 to 2008.

2.4 Impacts of Climate Change on Rainfall

The problem of predicting the impacts of climate change on future rainfall in Tarawa is complex. This is because simulations using ocean-atmosphere general circulation models (GCMs) are not presently carried out at sufficiently fine horizontal scale resolution. Their ability to generate climate change scenarios for Small Island States are therefore limited (Ali *et al.* 2001). "*GCMs (used to predict the impacts of green-house gas emission scenarios on future climates) are not good at simulating changes to the hydrological cycle and are notoriously bad on rainfall, especially in the tropics. There are two basic reasons for this: (i) they generally don't simulate tropical convection very well, and (ii) they can't reproduce some the major modes of current climate variability, including El Niño- Southern Oscillation (ENSO). Although the major American model at the US National Center for Atmospheric Research now apparently starts to simulate something that looks like ENSO.*" (Prof Will Steffen[4], private communication, 23 February 2009).)

In Pacific islands, the increase in average annual temperature has been less than 0.5℃ since 1900. Rainfall records across the Pacific for 1900 to 1995 reveal no clear general trend (Ali *et al.* 2001). The records do, however, show decadal fluctuations of mean annual rainfall linked to ENSO fluctuations or sea surface temperatures (as in Figure 4). The surrounding oceans, none-the-less, have a strong influence on the climate of Pacific islands. The Pacific Ocean is predicted, with a doubling of atmospheric carbon dioxide (CO_2) concentration, to warm in the future by 1 to 2℃ and mean rainfall intensity in small islands may increase by about 20-30% across the tropical oceans (Ali *et al.* 2001).

Unfortunately, the rainfall record in Tarawa is too short to reveal any major long-term trend and Figure 9 reveals no systematic increasing trend since 1947 but a sustained drying period followed by a wetter period. This is evident in many non-Pacific island countries so that any trend in rainfall with increasing global temperatures is difficult to discern.

Some GCMs predict increasing rainfall variability in the Pacific as a result of rising atmospheric temperatures. Since, however, ENSO is a major driver of rainfall variability in Tarawa and since current GCMs can not reproduce ENSO events; these predictions have to be treated with caution. One of the major concerns with global warming is that increasing sea surface temperatures will have significant impacts on the frequency of ENSO events with corresponding major impacts on periods of intense rainfall and droughts in the Pacific.

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[4] Professor Will Steffen is Executive Director of the Australian National University's Climate Change Institute.

2.3.1 Recent predictions of climate change impacts in Tarawa

As part of KAPII, NIWA (2008) has run 12 of the 23 GCMs[5] used by the Intergovernmental Panel on Climate Change (IPCC) for three of the IPCC (2000) Special Report on Emission Scenarios (SRES). These SRES are a range of greenhouse emission scenarios expected to cover the future range of possible emissions, from the expected highest to the lowest scenario, with intermediate scenarios representing such strategies as SRES A1FI, incorporating intensive fossil fuel use and SRES B1, a scenario involving the adoption of clean technologies. Figure 10 shows the expected range of anthropomorphic contribution to GHG emissions to the year 2100, given in gigatonnes of equivalent carbon (GtC) per year (Hadley Centre, 2003). Table 7 lists the characteristics of the SRES scenarios in the figure.

NIWA (2008) considered three SRES: low (B1); middle (A1B); and high (A1FI), in running the 12 GCMs for a region centred on Tarawa (see Figure 10 and Table 7). The models suggest that by 2025 (2015 to 2034) the mean atmospheric temperature may rise relative to mean temperature between 1980 and 1999 by between 0.1 (low), 0.7 (middle) and 1.9℃ (high). For 2050 (2040 to 2059) the mean rises are expected to be: 0.6 (low); 1.5 (middle); and 3.1℃ (high). These predicted higher temperatures mean that the atmosphere can hold larger amounts of water vapour and hence mean rainfall and rainfall intensity are expected to generally increase. It should be noted however that not all 12 GCMs used predicted an increase in rainfall in the Kiribati region, with 2 to 3 of the models predicting a decrease in mean rainfall.

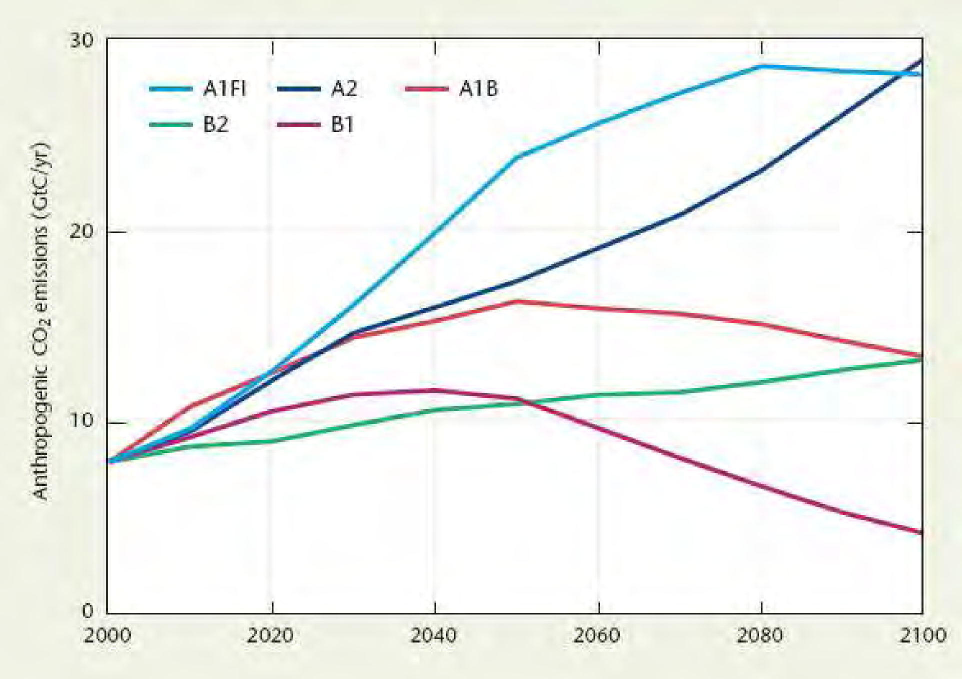

Figure 10 Projected anthropomorphic emissions of greenhouse emissions for a range of greenhouse gas emission scenarios, SRES, (Hadley Centre, 2003)

Table 7 Characteristics of the SRES scenarios in Figure 10 (Hadley Centre, 2003)

SRES	Increase in GNP 1990-2100 (Trillion $US)	Population by 2100 (billion)	Total CO_2 Emissions 1900-2100 (Gt Carbon)
A1FI	505	7.14	2190
A2	225	15.07	1860
A1B	510	7.06	1500
B2	215	10.42	1160
B1	310	7.05	980

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[5] The 12 GCMs chosen were those that are claimed to validate well for New Zealand and the South Pacific. None incorporate ENSO effects.

The agreement shown in NIWA (2008, in its Figure 10) between monthly rainfall predictions of two of the GCMs for 1950 to 2000 and the measured monthly rainfall in Betio for the period 1950 to 1996[6] is relatively poor and the predictions do not simulate well major droughts. The 12 GCMs were also tested against monthly and annual data for the period 1950 to 1996 to determine how well they predicted the mean annual rainfall, the mean CV of monthly rainfall (0.82) and the CV of annual rainfall (0.48) in Tarawa. The ratio between predicted and measured mean annual rainfall found for the 12 GCMs varied between 10% and almost 150%, while the mean CV of mean monthly rainfall varied from 0.48 to 2.00 and that for annual rainfall varied between 0.1 to about 1.3 (NIWA, 2008, Figure 11). Only one model predicted the measured rainfall behaviour in Tarawa reasonably well, with an annual rainfall ratio of about 105%, a mean monthly CV of about 0.95 and an annual rainfall CV of about 0.37. Given the generally poor agreement between the models and actual rainfall and rainfall variability, it is difficult to place much confidence in these predictions of future rainfalls and droughts.

The NIWA report has concentrated on the predicted change in rainfall intensity with increasing greenhouse gas emissions. For the period 2015-2034 (mean 2025) which is of interest to the Tarawa Water Master Plan, the predicted future rainfall intensity-average return interval results do not differ significantly from the 1980 to 1999 values. For the highest SRES, the maximum expected change in intensity is approximately 13% which is probably within the measurement error. It should also be emphasised here that the 12 GCMs used in the NIWA report do not reproduce ENSO events, which have both intense wet periods and dry periods. The lack of agreement between the GCM predictions of historic rainfall data and actual mean rainfall indicate that the predicted increases in future rainfall due to climate change are doubtful. It is assumed here that historic rainfall patterns will persist to 2030.

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[6] The NIWA study omitted the significant drought period 1998 to 2000 from the observational data.

3. Droughts in Tarawa

The unique hydrology of low coral islands means that freshwater resources are particularly sensitive to drought. The monthly and annual rainfall records (Figure 1 and Figure 3) demonstrate that droughts in Tarawa are frequent and severe.

Drought, like “bad weather” is a relative term. It is generally associated with a sustained period of significantly lower soil moisture and water supply than the normal levels to which the local environment and society have adapted. The relative nature of drought, the fact that a low rainfall period in a tropical environment can be the equivalent of a high rainfall period in a semi-arid environment, makes the definition of drought difficult as well as complicating the identification of its onset and its conclusion. Only abnormally dry conditions, which lead to a lack of sufficient water to meet normal requirements, should be recognised as drought (Gibbs, 1975). This means that normal dry seasons, evident in Tarawa’s mean monthly rainfall (Figure 2), are not classed as droughts.

3.1 Droughts and water supply systems

Emphasis on droughts has often focussed on their impacts on crop and animal production. However, there are broader issues which go beyond agriculture, such as potable water supply, which is the principal interest of this Master Plan. For water supply there are two definitions of drought which are important: meteorological and hydrologic drought. Meteorological or climatological drought is an interval of time during which the supply of moisture at a given place cumulatively falls below the climatologically appropriate moisture supply. This sort of drought has also been defined as a prolonged abnormal moisture deficiency.

Hydrologic drought is an interval of time of below-normal stream flow, or depleted reservoir or groundwater storage. Because of the residence time for water in different storages, hydrological drought can lag behind and extend beyond periods of meteorological drought. White *et al.* (1999) concluded that meteorological droughts for rainfalls over 12 months or more were equivalent to hydrological droughts for groundwater systems in atolls and are an appropriate way of identifying drought risk for groundwater supply systems. The seasonal climate outlook for Pacific island countries (SCOPIC www.bom.gov.au/climate/pi-ccp/scopic.shtml), used by KMS, provides warning of the drought risk up to about 3 months ahead.

3.2 Analysis of Droughts

There are a range of techniques for quantitatively analysing droughts. White *et al.* (1999) analysed droughts in Tarawa up to 1999 and concluded that the decile method gave an easily understood and computationally straightforward way of analysing droughts in small islands. Rainfall deciles rank the rainfall over the period of interest in terms of the relative quantity of rain that fell in that period compared with the total distribution of all recorded rainfalls over the same period. Deciles are essentially normalised departures from average conditions and are related to broad scale synoptic patterns (Smith *et al.,* 1992). The decile method is used in the Australian Drought Watch System and forms the basis for declaring drought and providing drought relief. White *et al.* (1999) concluded that deciles of rainfall summed over 12 months were relevant to the groundwater systems in smaller islands which rely on domestic water wells and large rainwater storages. The classification system used for the Australian decile method is shown in Table 8.

Rainfalls summed over a particular length of time that fall within decile 1, are in the lowest 10% of all rainfalls recorded. Using this system of classification, severe droughts are those whose rainfall percentile drops below 10%. It has been suggested that the start of a severe drought is when the rainfall percentile first drops below 40% on its way to the minimum below 10%. Similarly, the end of the drought can be identified when the rainfall percentile first returns to at least 40% from its minimum value.

Figure 11 shows the percentiles for rainfalls summed over the previous 12 months for Tarawa from 1947 to 2008. The severe droughts are easily identified as those periods where the percentile rankings drop below 10%. During these droughts it is expected that groundwater in narrower islands would become brackish and almost all rainwater harvesting systems would have failed.

Table 8 Classification system for the decile method as used in Australia

Decile	Percentile Range (%)	Climate Classification
	100	Highest of record
10	90 to <100	Very much above average
8-9	>70 to <90	Above average
4-7	>30 to <70	Average
2-3	>10 to <30	Below average
1	>0 to <10	Very much below average
	0	Lowest on record

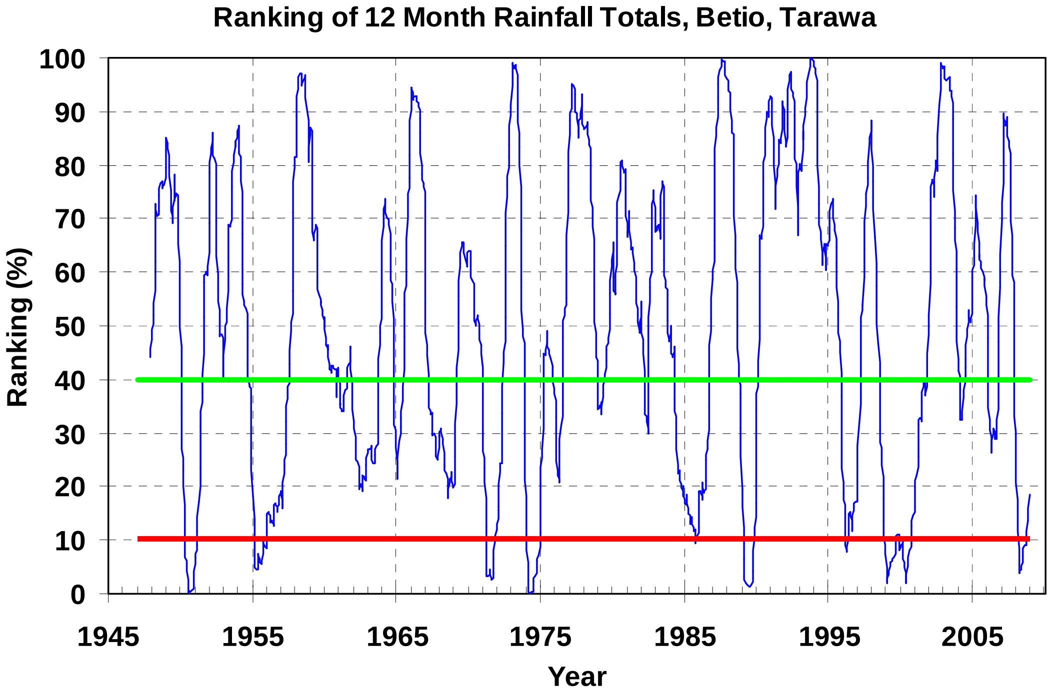

Figure 11 Percentile ranking of rainfall for Betio, Tarawa, for rainfalls summed over the previous 12 months for the period 1947 to 2008. Percentiles falling below 10% (red line) are severe droughts.

3.3 Severity, Duration and Frequency of Major Droughts

Table 9 lists all the severe droughts for rainfalls summed over 12 months (mth). The length of the drought for percentiles dropping below the 10 percentile level is gauged from the time the percentiles drops below the 40 percentile value to when it next returns to the 40 percentile level. For 12 mth rainfalls (Table 9), there were 9 severe droughts between 1947 and 2010. The most severe drought to date occurred in April 1974 when only 217.0 mm of rain had fallen in the previous 12 mths. This was closely followed by the drought in July 1950 when 217.3 mm had fallen in the previous 12 months. The average duration of droughts for 12 mth rainfalls was 23.6 months. There is, however, considerable variation in duration with the shortest length of drought being 16 months for the droughts in 1973-1975 and 1988-90 and the longest 41 months from 1998-2001. The average time between 12 month rainfall droughts is 7.2 years. The time between droughts also varies widely, with the shortest 2.8 years and the longest 16.3 years. It is expected during these droughts that almost all domestic rainfall storage systems would fail and water drawn from domestic groundwater wells in narrower islands would become noticeable more saline and probably too brackish to use for drinking.

Table 9 Dates of start, end and of the lowest percentile of severe droughts for 12 mth rainfalls in Betio, Tarawa together with lowest 12 mth rainfalls, length of drought and time between droughts for the period 1947-2010.

Start of Drought	End of Drought	Date of Lowest Percentile	Value of Lowest Percentile (%)	Lowest 12 mth Rainfall (mm)	Length of Drought (mths)	Time between Drought Maxima (yrs)
Jan, 1950	Aug, 1951	Jul, 1950	0.1	217.3	19	-
Oct, 1954	Jul, 1957	Apr, 1955	4.2	529.6	33	4.8
Sep, 1970	Jun, 1972	Aug, 1971	2.5	469.7	21	16.3
Dec, 1973	Apr, 1975	Apr, 1974	**0.0**	217.0	16	2.7
May, 1984	Oct, 1986	Oct, 1985	9.1	670.6	29	11.5
Nov, 1988	Mar, 1990	Jun, 1989	1.2	374.7	16	3.7
Nov, 1995	Apr, 1997	Apr, 1996	7.6	634.9	17	6.8
Jul, 1998	Dec, 2001	Feb, 1999	1.9	445.6	41	2.8
Dec, 2007	Sep, 2009	Apr, 2008	4.6	541.0	21	9.2
			Mean	**455.6**	**23.6**	**7.2**
			St Dev	162.7	8.9	4.8
			Median	469.7	21.0	5.8

3.4 Planning for Droughts

It is clear from the above that droughts in Tarawa are both relatively frequent and severe. It is therefore fundamentally important that risk of drought and its consequences be acknowledged and accommodated in plans for the provision of water supplies for Tarawa. In particular, sustainable yield of groundwater supply sources must take into account frequent, major droughts and groundwater pumping strategies should be conservative to allow for long dry periods. In addition, rainwater tank storages will fail in droughts so that contingency plans to accommodate this need to be in place.

3.5 Impact of Climate Change on Droughts

Some GCM studies have predicted possible changes in the frequency of drought occurrence in the central Pacific with increasing greenhouse gas emissions. Given the poor spatial resolution of GCMs with respect to small islands, poor inter-model agreement, and the failure of most current models to include ENSO events, such predictions must be considered speculative (Ali *et al.* 2001).

3.5.1 Recent predictions on the impact of climate change on droughts

NIWA (2008a) analysed past droughts in Kiribati and attempted to estimate the impacts of climate change on future droughts. The report acknowledges that the GCMs used do not reproduce ENSO events, which dominate droughts in Kiribati including Tarawa during La Niña phases and, in particular, that they do not reproduce the severe droughts in Tarawa or Kiritimati. The report predicts that "*drought characteristics will generally remain much the same over the next 100 years"* and *"there will be some periods when drought may be slightly more prevalent during this time."* It is not immediately obvious how the report reached these conclusions. These conclusions are a consequence of the GMC models used but the models do not reproduce the fundamentally important ENSO events, which are closely related to droughts. If climate change does alter the frequency of ENSO events then drought characteristics could alter radically.

The NIWA study does not define drought but it is apparent that it was concerned with meteorological drought. Despite previous work in Tarawa (White *et al.,* 1999) using deciles and its incorporation into SCOPIC, NIWA (2008a) used an open-ended drought severity index method (Phillips and McGregor, 1998) of greater complexity than the standard, non-parametric method used here. The method used by NIWA has an inbuilt assumption about the statistical distribution of rainfall (NIWA used the mode rather than mean rainfall), and so is parametric, and it does not allow for wet and dry seasons in tropical areas. This is immediately obvious when the report states that "*the drought occurrence parameter… indicates 7 - 8 droughts per decade…"* The method clearly does not differentiate between normal dry seasons, typical in tropical environments, and droughts and so totally ignores the widely accepted definition of meteorological drought (see Section 3.1).

The conclusion that can be drawn from the NIWA study is that the 12 GMCs used in the study are not capable of predicting future changes in drought frequency, severity or duration in Tarawa.

3.6 Surviving Severe Droughts

The length and severity of droughts in Tarawa (Figure 11) mean that it is vitally important to develop strategies to survive droughts. Several that can be identified include:

- Developing reliable early warning systems for the onset of droughts
- Early reporting of the risk of drought to GoK and its Ministries
- Early warning to the community of the risk of drought
- Develop a drought contingency plan
- Controlling demand and leakage during droughts
- Providing adequate water storage to meet continuing demand during droughts
- Monitoring rainfall, water use, groundwater pumping, leakage and groundwater salinity.

3.6.1 Early warning systems for the onset of droughts

The very strong relation between sea surface temperature and rainfall in Tarawa (**Figure 4**) and SOI provides a basis for predicting rainfalls in Tarawa over periods of a few months. The SCOPIC program developed by the Australian Bureau of Meteorology for Pacific Island Countries and used by KMS, is designed to provide seasonal climate forecasts in the Pacific, three months in advance. It provides forecasts in terms of the probability of below average rainfall over the next 3 months. The decrease of 12 month rainfalls below the 40 percentile as in section 3.2 also provides an early warning system for the onset of severe droughts with a mean lead time of 6 months but with an accuracy of only 50%.

The use of SCOPIC or any other early warning method, however, has to be accompanied by a plan of action which alerts appropriate authorities and agencies, as well as the community and needs to be coupled to strategies for increasing conservation of water and decreasing demand. Reducing the continuing large water losses from the domestic reticulation systems would be a major contribution to conserving water.

3.6.2 Controlling demand and leakage during droughts

Since domestic water connections in Tarawa are unmetered, there is no way of controlling demand through water pricing. The current, fixed bulk water rate does not promote conservation, even if it is levied. Under the SAPHE project in South Tarawa, an attempt was made to control demand by supplying water 24 hours/day in a trickle-feed to 500 L household water tanks from the reticulation systems, to limit supply to approximately 50 L/person/day.

This approach has proved ineffective in controlling demand, partly because only 70% of households connected to the reticulation pipes were supplied with this system. The majority of the remaining households have open-ended pipe connections. The system was also ineffective partly because there was no community education and communication program on the use of the system and partly because of deliberate by-passing or tampering with the trickle-feed systems.

Currently the PUB controls demand by supplying water in South Tarawa only on alternate days. In severe droughts it may be necessary to disconnect the leaky domestic reticulation system and supply water either from fixed location distribution centres, such as the village head tanks or by tanker delivery. This would reduce the large losses from the domestic reticulation pipes and would allow revenue collection from distribution centres, as is now done for bulk water tanker deliveries. This, of course would disadvantage the poor.

3.6.3 Drought contingency plan

The certainty of drought in Tarawa makes it essential to develop a drought contingency plan so that droughts are not considered as extraordinary, emergency situations. Such a plan should include:

- An effective early drought warning system
- An effective public drought risk communication and water conservation strategy
- A strategy to isolate excessively leaking parts of the reticulation system and to supply water from fixed distribution points or by tanker
- Ensuring that there are sufficient, well maintained water tankers to deliver water to household tanks[7]
- Increased frequency of monitoring of groundwater sources
- Ensure there is adequate legislative basis for emergency interventions

3.6.4 Providing adequate storage

In order to survive droughts, it is necessary to have adequate storage of water to meet continuing demands. In general, domestic household rainwater harvesting systems have too small rainwater tank capacities, too small roof collecting areas and too high a demand on them to last through significant droughts. Larger rainwater storages connected to bigger public buildings such as churches, maneabas, schools and government buildings have the potential to act as emergency supplies during drought. These communal supplies would have to be managed well and equitably. In Tarawa at present there is a dearth of such storages, with large, new maneabas and buildings being constructed with no or very limited rainwater collection and storage despite the potential for installation of cisterns prior to construction of the building. It is particularly disturbing to see the number of large buildings still being constructed by overseas aid programs which either have no, or inadequate rainwater harvesting and storage systems. It is fundamentally important that the building code and Bye-Laws be enforced to ensure adequate rainwater harvesting and storage in new buildings. Systems to maintain and manage communal rainwater storages need to be developed and it may be possible to involve churches in this. Possible annual prizes for the best managed and maintained community rainwater systems would help promote their importance.

The principal way of storing freshwater in coral atolls is in groundwater lenses. While groundwater lenses in narrower islands tend to become brackish or saline during droughts, those on large islands can survive long droughts well. The Bonriki and Buota groundwater lenses are prime examples. The 1998 to 2001 drought is the worst on record for Tarawa for 30 month rainfalls. During this drought, the thickness of the freshwater lenses had halved at the end of the drought and the salinity of the water pumped from the lens increased, but not to problem levels. These groundwater lenses were able to supply water to South Tarawa throughout the drought which underlines how important it is to protect both the Bonriki and Buota lenses.

3.6.5 The fundamental importance of monitoring during droughts

The fresh groundwater systems in Tarawa are delicately balanced even during wet periods between recharge, discharge to the sea, mixing with the sea, evapotranspiration losses and groundwater pumping. This means that regular monitoring of the freshwater thickness and salinity of lenses used for public water supply is always fundamentally important. It is critical during droughts, however, that more frequent and rigorous monitoring and reporting be carried out since evaporation plus over pumping can lead to salinisation of lenses making them unfit for drinking. During droughts, the Cabinet needs to be regularly updated on rainfall, water use, pumping, leakage and groundwater salinity, and conservation and demand control strategies. During the 1998 to 2001 drought, monitoring of the groundwater in South Tarawa's water reserves was almost non-existent, and a State of Disaster was declared despite there being adequate fresh groundwater available.

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[7] Tarawa currently has only one PUB water tanker. The risk of failure of bulk supply is therefore large.

4. Legal Instruments and Rainwater Collection

In this section, a brief examination is made of the adequacy of existing legal instruments, laws, regulations and codes for underpinning the installation of rainwater collection and storages in Tarawa

4.1 Local Government Bye-Laws

Government Ordinance No. 5 of 1966 established Council (Building) Bye–Laws relating to building construction. The Teinainano Urban Council (TUC) formally resolved the Council (Building) Bye-Laws (1975) on 8 July 1975. Under Water Catchment, Bye-Laws 21, 22 and 23, it states:

> 21. *Every building other than a reef latrine built in other than local materials shall have proper guttering and water storage. The amount of water storage shall be directly related to the size of the catchment area in such a proportion as the Council shall specify.*
>
> 22. *Every existing building built in other than local materials shall within two years of the coming into operation of these Bye-Laws, comply with bye-law21: Provided that in certain cases the Council may alter the conditions imposed by bye-laws 21 and 22.*
>
> 23. *The owner of any building built in other than local materials shall keep the guttering and water storage system in a reasonable state of repair.*

It has been inferred that these Council Bye-Laws, first introduced in 1966, are generally applicable in all islands of Kiribati.

4.2 Draft National Building Code of Kiribati 2004

The Draft Kiribati National Building Code 2004, developed under the Ministry of Public Works and Utilities (MPWU) specifies under section *DFP1.7 Roof drainage:*

> "*Where impermeable roofing is present in the building design, some form of rainwater collection must be provided. Any roof drainage system provided must be capable of handling the reasonably expected peak intensities of rainfall*."

This appears to require the mandatory installation of rainwater collection and storage systems on all new buildings in the country with suitable roofing materials.

Despite these very clear directions, both the local government Bye-Laws and the draft National Building Code are frequently ignored, even in South Tarawa and especially with large public buildings (Figure 12), including government buildings and buildings built through aid projects.

4.3 Bye-Laws, Building Code and Local Councils

During preparation of the TWMP, helpful consultations were held with the town clerks of Betio Town Council (BTC) and TUC concerning the use of the draft National Building Regulations in approving buildings. Both TUC and BTC were not aware that rainwater collection gutters and rainwater tanks are required under Council Bye-Laws or under the draft National Building Code. It was explained that Councils cannot enforce building codes as they have no building inspectors and cannot inspect buildings during construction or at completion. The only inspection carried out is a site inspection to ensure access and siting. Building plans are also inspected to confirm that a toilet is included in the plans.

It is clear that the existence of clear Council bye-laws and the draft National Building Code does not guarantee their application in practice. Mechanisms need to be put in place to ensure that they are carried out. In an operational sense in South Tarawa, the Council bye-laws and draft national building code are irrelevant to housing construction and the installation of rainwater tanks.

Within the National Water Resources Implementation Plan, Activity 1.6 is to: *Increase the use of improved rainwater harvesting.* The first two outputs of this activity are: 1. Review and enacting of building code and regulations requiring the installation of rainwater catchments in new buildings, and 2. Strategy developed to enforce building code for installation of rainwater tanks.

It is strongly recommended that this activity be undertaken as quickly as possible.

Figure 12 **Very large maneaba at Teaoraereke constructed in 2009 with no rainwater collection or storage.**

4.4 Communal Rainwater Management

As shown in Figure 12 many large public buildings such as government offices, churches and maneabas with suitable roofing materials are constructed without rainwater harvesting or with minimal rainwater harvesting facilities. It is particularly relevant for government organisations to set the example here. One problem that needs to be addressed is how community water harvesting and storage can be managed. In earlier times in Tarawa (Harrison, 1980), rainwater runoff collected from large government buildings was stored in large cisterns from which the water was either pumped to be mixed with groundwater in large storage tanks in Betio, Bairiki and Bikenibeu, or else it was distributed by tanker to private households.

Another proposal (ADB, 2004), has been to place all large communal rainwater storages under the control of the lead national water agency, MPWU. This, however, is problematic since MPWU does not have the staff to manage distributed rainwater sources across Tarawa. Local community management seems a better proposition but methods of operation and rules for distribution, including possible charging for water need to be developed. Already, one church group in Bairiki sells water services by charging for the use of washing machines and for showers.

4.5 Adequacy of Existing Legal Instruments

From this examination of existing legal instruments, it is concluded that, provided the Council building bye-laws are still in force in Tarawa and are applicable throughout Kiribati, that there is adequate statutory basis for mandating installation and maintenance of rainwater harvesting and storages on all new buildings constructed of appropriate materials. What is lacking at the local government level is both knowledge of the bye-laws and the mechanism for applying and enforcing the bye-laws. This appears something with which the lead construction and water Ministry could assist.

5. Estimation of the Risk of Failure of Rainwater Storages

5.1 Monthly Water Balance

In estimating the performance of rainwater catchment and storage systems, it is usual to use daily rainfall records in daily water balance models (Chapman, 1985). Because of limited availability of the full daily rainfall record for Tarawa, the historic monthly rainfall record was used as a first order estimate of the adequacy of rainwater storages. A simple, monthly mass balance approach was used to estimate the volume of rainwater V_t (L) in the rainwater storage at the end of month *t*:

$$V_t = V_{t-1} + C.A.P_t - D.N.d_t \qquad [1]$$

where V_{t-1} (L) is the volume of storage at the end of the previous month, *C* is the rainwater catchment runoff coefficient, *A* (m^2) is the area of the roof catchment, P_t (mm) is the historic monthly precipitation, *D* (L/pers/day) is the daily per capita demand, *N* is the number of people per household and d_t (day) is the number of days in the month *t*.

In this approach, it is assumed that interception water losses from the roof catchment and evaporation and other losses from the collection system and storage tank are incorporated within the rainwater catchment runoff coefficient, C. In equation [1] when $V_t \geq S$ (L), the full rainwater tank storage capacity, $V_t = S$ and when $V_t < 0$, $V_t = 0$. It is also assumed here initially that no conservation strategy is adopted when rainwater tank storages become depleted and that at the start of the sequence the tank is empty.

Parameters in this calculation are the capacity of the rainwater tank, *S*, the runoff coefficient, *C*, the area of the roof catchment, *A*, the assumed daily per capita demand, *D*, and the number of people per household, *N*. All need to be varied over a wide range. Apart from the most common size of rainwater tanks available in Tarawa (6,000 L) and 2005 census results for the average number of people per household (National Statistics Office, 2007a), there is no systematic information of the areas of roof catchments, the efficiency of collection and storage or on how much rainwater is used by households. In the absence of that information, reasonable, baseline values of these variables have been adopted here which are listed in Table 10 and will consider variations around these values. For example, for *N* we have adopted the mean value of 7.7 persons per household from the 2005 Census (Table 1A) for South Tarawa[8].

Table 10 Baseline values of parameters in equation [1]

People per Household, *N*	7.7
Demand per person, *D* (L/day)	5[9]
Roof Area, *A* (m^2)	50[10]
Runoff Coefficient, *C*	0.85
Rainwater tank capacity, *S* (L)	6,000

In order to present results, the number of months or the percentage of the total number of months over the total rainfall record of 744 months in the period 1947-2008, during which a rainwater tank of a specified volume was dry are given. The larger the percentage, the greater is the unreliability of the rainwater supply system.

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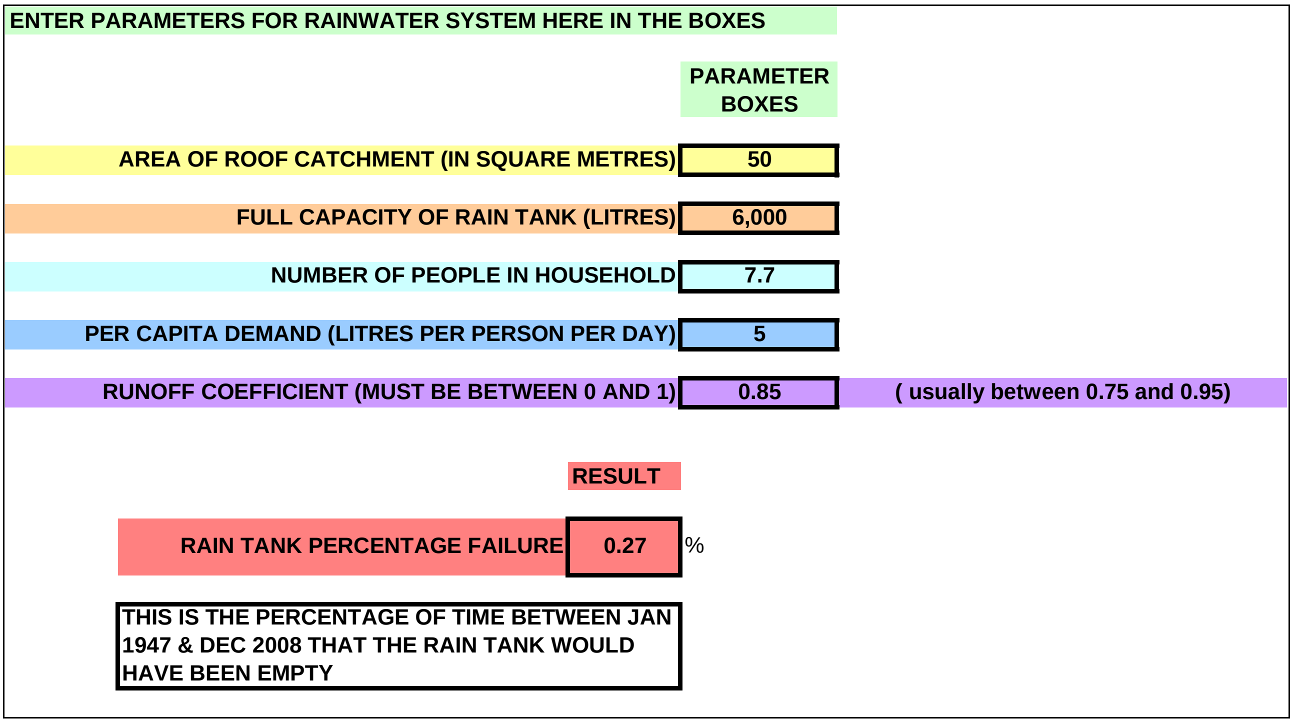
[8] In similar work in Kiritimati, a survey in 2007 found that the average household size was 9.5 people, significantly greater that the 2005 Census value of 7.3 (ADB, 2007).

[9] We have adopted a low value of per capita demand as 5 L/pers/day being sufficient for drinking and cooking requirements. Bathing, washing and other demands are expected to be met by other sources.

[10] A number of impermeable roof catchments in South Tarawa are larger than 50 m^2. However, the entire roof catchments are seldom used for rainwater collection.

A simple EXCEL spreadsheet calculator, Rainwater Tank Calculator.xls has been developed based on equation [1] and the historic monthly rainfall record, January 1947 to December 2008. This has been distributed to WEU, MPWU and the PUB (Figure 13).



ENTER PARAMETERS FOR RAINWATER SYSTEM HERE IN THE BOXES

	PARAMETER BOXES	
AREA OF ROOF CATCHMENT (IN SQUARE METRES)	50	
FULL CAPACITY OF RAIN TANK (LITRES)	6,000	
NUMBER OF PEOPLE IN HOUSEHOLD	7.7	
PER CAPITA DEMAND (LITRES PER PERSON PER DAY)	5	
RUNOFF COEFFICIENT (MUST BE BETWEEN 0 AND 1)	0.85	(usually between 0.75 and 0.95)

	RESULT	
RAIN TANK PERCENTAGE FAILURE	0.27	%

THIS IS THE PERCENTAGE OF TIME BETWEEN JAN 1947 & DEC 2008 THAT THE RAIN TANK WOULD HAVE BEEN EMPTY

Figure 13 The simple, monthly EXCEL Rainwater Tank Calculator designed to estimate the percentage of time a rainwater tank would fail for different parameter values and Tarawa's historic rainfall.

5.2 Daily Water Balance

The daily water balance model is similar to that in equation [1]. The rainwater tank storage at the end of day t , V_t is:

$$V_t = V_{t-1} + C.A.P_t - D.N - Int - E_t \qquad [2]$$

where V_{t-1} (L) is the volume of storage at the end of the previous day, C is the rainwater catchment runoff coefficient, A (m^2) is the area of the roof catchment, P_t (mm) is the daily precipitation, D (L/pers/day) is the daily per capita demand, N is the number of people per household, Int (L) is the interception losses during rainfall and E_t is the evaporation loss from the rainwater tank on day t.

In this report, a program based on equation [2] and Chapman (1985), *Rain8.exe*, is used to examine the probability of failure of rainwater harvesting-rainwater tank storage systems and to compare the results with the monthly water balance approach. Use of this daily approach has been limited by the availability of daily rainfall for data for Tarawa, which currently is only for the period 1948 to 2006[11].The program in its present form also has a significant limitation in that it can only process 20,000 days, just over 54 years of data. To overcome this, two runs of the program have been used: one from the beginning of January1948 to end December 2001 and from January 1953 to December 2006. It will be assumed here that both interception losses, Int and daily tank evaporation losses are zero and that $C = 0.8$. The program estimates the probability of rainwater tank failure by calculating the number of periods greater than one day for which the rainwater tank is dry and comparing that with the number of years of rainfall record. For example 5.4 periods of failure corresponds to a 1 in 10 year event.

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[11] Some daily rainfall data may be missing in the period 1948-49.

6. Performance of Rainwater Supply Systems

The results for the monthly water balance, outlined in section 5, are presented in terms of varying the individual parameters of equation [1], S, C, A, D, N one at a time while the others are kept constant and calculating the failure rate. Baseline values of these parameters are listed in Table 10.

6.1 Number of People per Household

Using the historic record of rainfall in Figure 1, the estimated stored volumes of rainwater in a 6,000 L rainwater tank for the parameter values in Table 10 but for 6 and 10 people per household are plotted in Figure 14 . For 6 people per household and a constant demand of 5 L/pers/day, the 6,000 L rainwater tank storage is sufficient to last through the worst droughts on record In Betio. When there are 10 people per household, the rainwater tank runs dry during the major droughts with a failure rate of 2%.

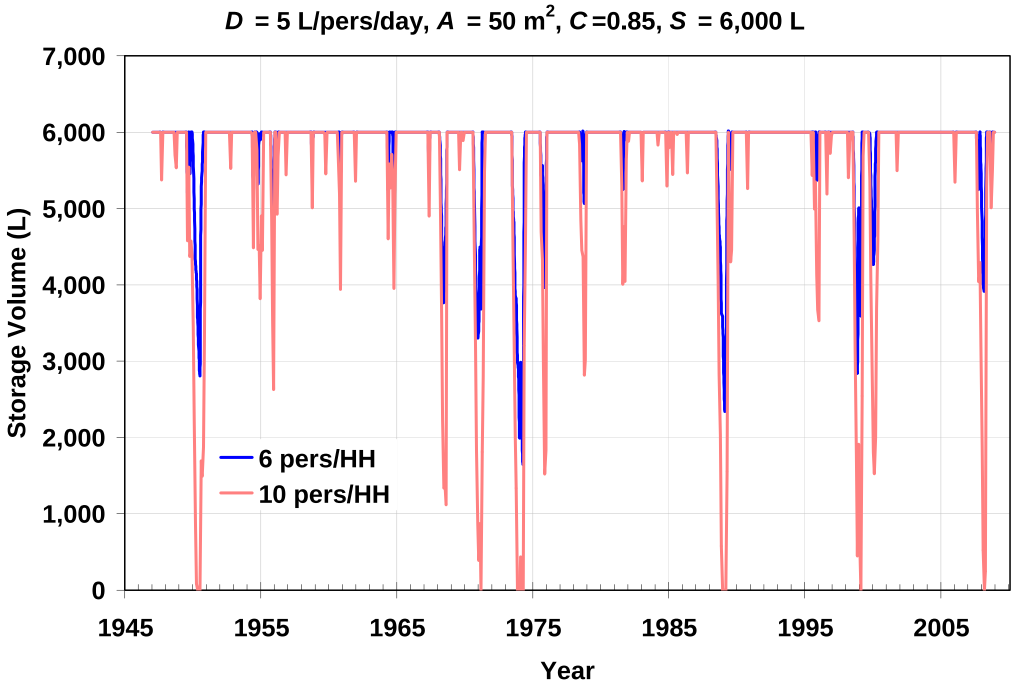

Figure 14 Monthly volume of stored rainwater in a 6,000 L rainwater tank for households of 6 and 10 people with the other parameter values listed in Table 10 for the historic monthly rainfall record.

Table 11 lists the impact of household size on the number of months of failure and the percentage of the total number of months the tank is dry for various household sizes and the results are also plotted in Figure 15. The other parameter values are as in Table 10. It can be seen that for large households, a 6,000 L rainwater tank fed from a 50m^2 roof catchment fails frequently. For the average size household in North Tarawa (6.5 persons)[12] the 6,000 L rainwater tank is sufficient to supply basic water needs without failure. For the average sized South Tarawa household (7.7 persons), the rainwater tank would fail for 2 months out of the total 744 months (0.3%). For this case, both failures were consecutive months in March and April 1974. Figure 15 shows that the increase in the rate of failure with number of people is approximately linear.

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[12] It is noted that there is a discrepancy between Volume 1 of the 2005 Census (National Statistics Office, 2007a) and Volume 2 (National Statistics Office, 2007a). Vol 2 which gives the average household sizes in North and South Tarawa as 6.2 and 7.5 respectively. Using the population and household numbers in Vol 1 the correct averages are 6.5 and 7.7 pers/household.

While the NSO provides information of the distribution of the number of people per household for all of Kiribati (National Statistics Office, 2007b, Table 23) it does not give values for individual islands. It shows that 15.3% of households have 10 or greater persons and 2.9% have 15 or greater occupants. For these larger households, rainwater tanks will fail more frequently as shown in Figure 16 for 20 people The maximum number of people per household that could continue using water at 5 L/pers/day throughout Tarawa's historic past rainfall is 7.1, and the required roof area is 7.0 m^2/pers. With this number of people consuming water at this demand rate, in the absence of any rainfall, it would take the household 5.6 months to totally exhaust an initially full 6,000 L rainwater tank.

Table 11 Influence of the number of people per household (*N* in equation [1]) on the failure of rainwater storage for the other parameters listed in Table 10.

People per Household, *N*	No. of months of failure	Percentage of total record (%)
2	0	0.0
4	0	0.0
6	0	0.0
6.5	0	0.0
7	0	0.0
7.7	2	0.3
8	4	0.5
10	15	2.0
12	27.0	3.6
15	52	7.0
20	93	12.5
30	209	28.1

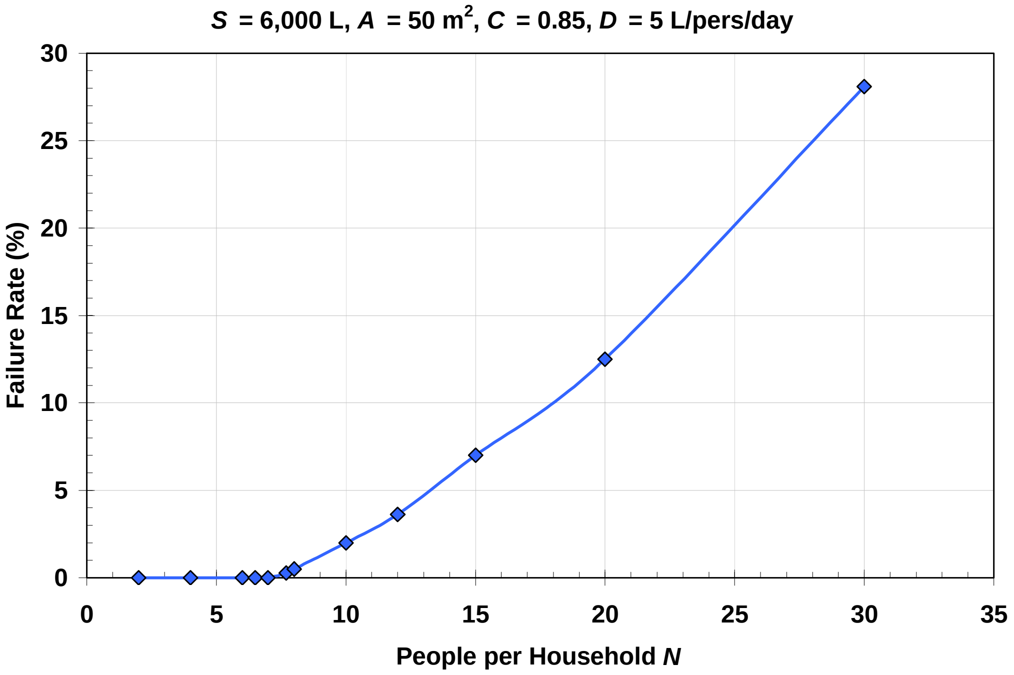


Figure 15 Dependence of the rainwater tank monthly failure rate on the number of people per household. Other parameters are listed in Table 10

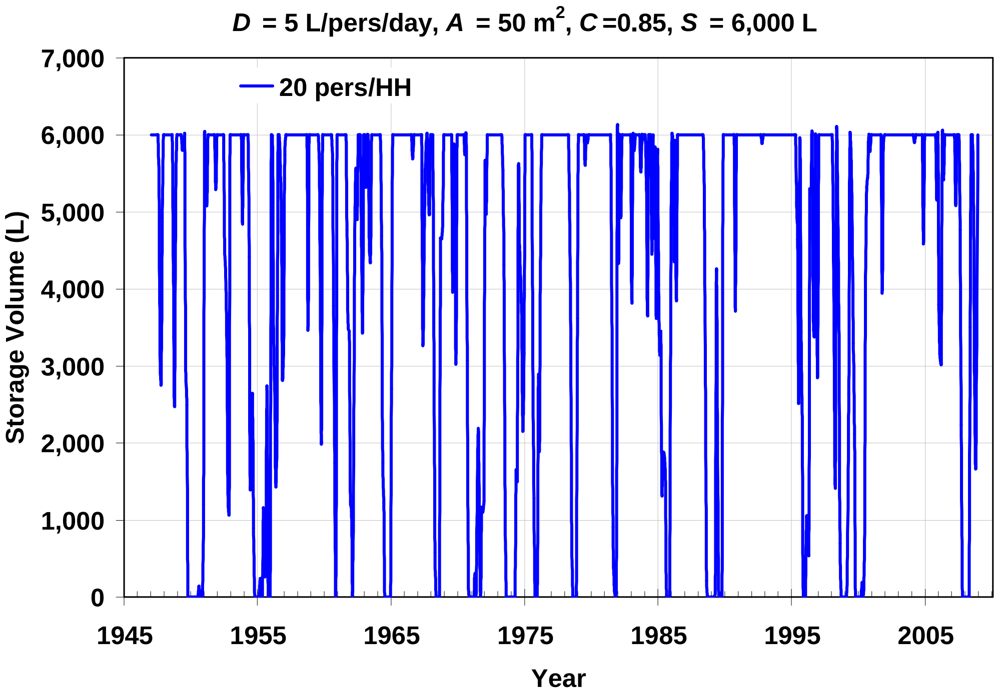


Figure 16 Monthly volume of stored rainwater in a 6,000 L rainwater tank for a household of 20 people with the other parameter values in Table 10 for the historic monthly rainfall record. The tank is empty for 12.5% of the time.

From this we conclude that, for households with 7 people, with well kept roof catchments (C = 0.85) and roof areas of 7 m^2/pers, a 6,000 L tank has a small risk of failure in Tarawa provided that rainwater is used only to supplement supplies for drinking and cooking (*D* = 5 L/pers/day). For larger households and higher demands, bigger catchment areas and larger storage tanks are required.

6.2 Per Capita Demand

Rainwater is seen as a source of supplementing freshwater supply in Tarawa. It is not usually envisaged as being able to supply the total amount of water needed for a household. In this section, we examine the rate of failure of rainwater tanks for the baseline values in Table 10. Table 12 and Figure 17 show the influence of daily per capita demand for drinking and cooking water on the failure of a 6,000 L rainwater storage for the average South Tarawa household size of 7.7 persons and the other parameters in Table 10.

If demand is kept to 4.6 L/pers/day, then a 6,000 L tank would not have failed for the average size household in South Tarawa with a roof area 6.5 m^2/pers and for the historic rainfall record. Increasing demand increases the percentage failure. Doubling the design demand to 10 L/pers/day results in an almost 27-fold increase in the number of months of failure. In order to meet a demand of 10 L/pers/day from a 6,000 L tank without failure, the number of people per household would need to be decreased to less than half i.e. 3.5 people. For North Tarawa, with fewer people per household, the average household size of 6.5 could have withdrawn 5.4 L/pers/day without the rainwater tank failing. Figure 17 shows an approximately linear increase in failure rate with demand, after the threshold of 4.6 L/pers/day is exceeded in South Tarawa.

From this we conclude that, if the average-sized household in South Tarawa with a roof area of 50 m^2 (6.5 m^2/pers) and a reasonably maintained collection system (*C* = 0.85) can control its average per capita water use to 4.6 L/pers/day, then there was little risk of failure of the 6,000 L rainwater tank throughout the past historic rainfall record. At this rate of water use, a completely full 6,000L rainwater tank would last just over 5.5 months without rain.

Table 12 Influence of the daily per capita demand (*D* in equation [1]) on the failure of rainwater storage for values of the other parameters listed in Table 10.

Daily Demand per Person, *D* (L/pers/day)	No. of months of failure	Percentage of total record (%)
2	0	0.0
3	0	0.0
4	0	0.0
5	2	0.3
6	8	1.1
8	30	4.0
10	53	7.1
12	79	10.6
15	131	17.6
20	216	29.0
25	287	38.6

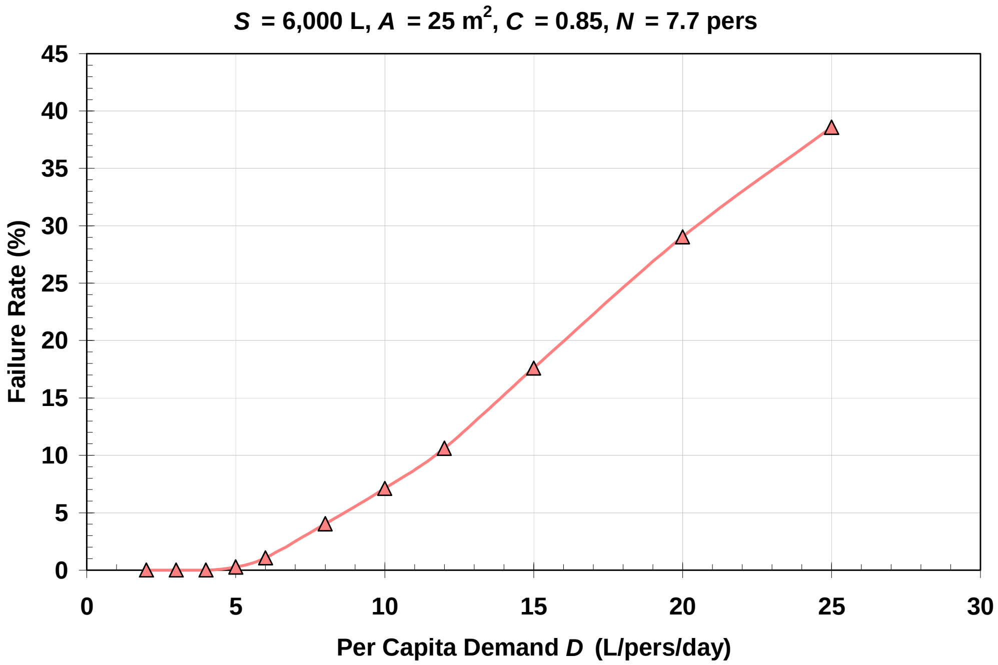


Figure 17 Dependence of the rainwater tank monthly failure rate on the per capita demand. Other parameters are listed in Table 10

6.3 Roof Catchment Area

Mourits (1996) examined the roof area per person necessary to supply a demand of 10 L/pers/day for Butaritari. To guarantee that this demand could be meet 90% of the time, she found that a roof area of at least 5 m^2/pers was required. In this section, the impact of roof area on rainwater tank failure is examined for the other baseline parameters in Table 10. Table 13 and Figure 18 shows the impact of increasing the roof catchment area in the range 5 to 60 m^2 on the failure of a 6,000 L rainwater storage for the average household size of 7.7 persons and a constant demand of 5 L/pers/day.

Table 13 Influence of the roof catchment area (*A* in equation[1]) on the failure of rainwater storage for the other parameters listed in Table 10

Roof Catchment Area, *A* (m^2)	No. of months of failure	Percentage of total record (%)
5	438	58.9
10	163	21.9
15	75	10.1
20	32	4.3
25	18	2.4
30	9	1.2
35	8	1.1
40	6	0.8
45	4	0.5
50	2	0.3
55	1	0.1
60	0	0.0

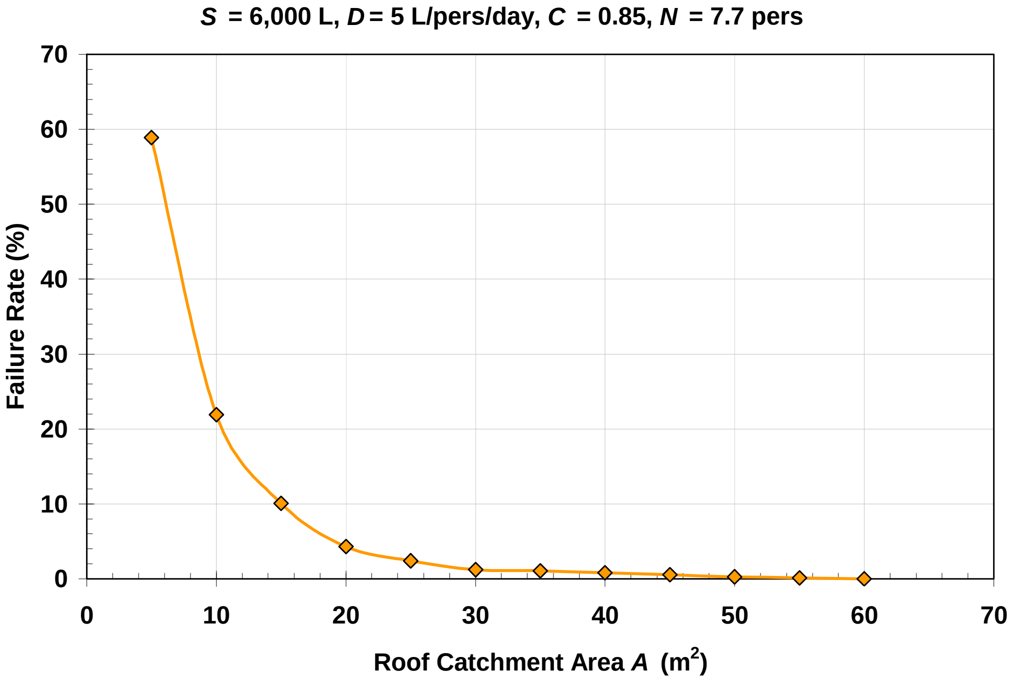


Figure 18 Dependence of the rainwater tank monthly failure rate on the area of the roof catchment. Other parameters are listed in Table 10

In order to supply the average-sized household in South Tarawa with 5 L/pers/day from a 6,000 L rainwater tank without failure over the historic rainfall record, a roof area of 59.3 m^2 is required or 7.7 m^2/pers. The highly nonlinear interaction of demand and roof area (Figure 18) can be seen by the fact that to meet a demand of 10 L/pers/day for the same household and rainwater tank size requires a roof area of nearly 310 m^2. This indicates that the roof area is a critical parameter. Roof areas below about 5 m^2 (0.65 m^2/pers) appear impractical to meet drinking and cooking water demand in Tarawa for average-sized households on a regular basis.

6.4 Roof Catchment Runoff Coefficient

In many rainwater catchment studies, roof catchment runoff coefficients (ratio of runoff to rainfall) as high as 0.95 are used. In island situations, roof harvesting systems are often inefficient and because we are using monthly rainfall data we have chosen to lump interception losses, which may be significant in Tarawa and include tank evaporation losses, losses due to spills from gutters and overflow from tanks once filled, into a roof catchment runoff coefficient of 0.85 (Table 10). In this section, the impact of altering the runoff coefficient is examined. Table 14 and Figure 19 show the impact of changing the roof catchment runoff coefficient on the failure of a 6,000 L rainwater storage for the average household size of 7.7 persons and the other parameters listed in Table 10.

Table 14 Influence of the roof runoff coefficient (*C* in equation [1]) on the failure of rainwater storage for the other parameters listed in Table 10

Runoff Coefficient, *C*	No. of months of failure	Percentage of total record
0.5	10	1.3
0.55	9	1.2
0.6	8	1.1
0.65	7	0.9
0.7	6	0.8
0.75	4	0.5
0.8	2	0.3
0.85	2	0.3
0.9	1	0.1
0.95	1	0.1
0.98	1	0.1

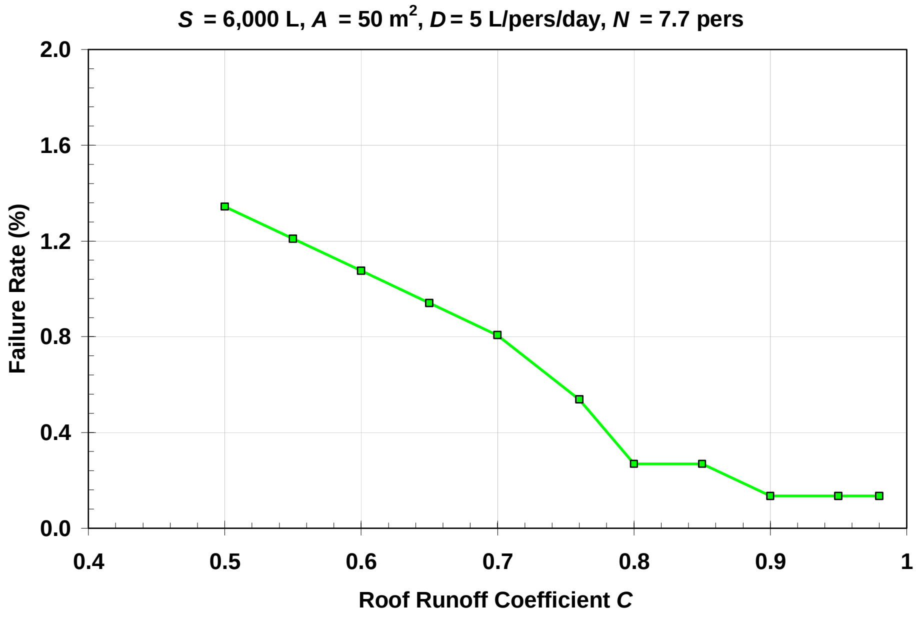


Figure 19 Dependence of the rainwater tank monthly failure rate on the runoff coefficient. Other parameters are listed in Table 10

Efficient rainwater and properly maintained harvesting systems can decrease the number of months of failure, although it is noted that the dependence of failure on runoff coefficient (Figure 19) is small and weakly non linear. Conversely, poor maintenance of rainwater roof catchments can increase greatly the percentage failure (see Figure 18). For the parameters in Table 10, increasing the roof catchment runoff coefficient to 0.95 would mean that a roof area of only 54 m^2 (7 m^2/pers) would be sufficient to have no failure of storage over the rainfall record.

6.5 Rainwater tank Storage Capacity

This work has adopted the baseline capacity of household water tanks as 6,000 L, because it is the most common capacity available in Tarawa. In this section, the impact of rainwater tank storage capacity on the likelihood of failure is examined using the other baseline parameter values in

Table 10. The range of tank capacities considered varied from 500 to 10,000 L. The percentages of failures are given in Table 15 and are plotted in Figure 20.

Table 15 Influence of the rainwater tank storage capacity (*S* in equation [1]) on the failure of rainwater storage for the other parameters listed in Table 10

Rainwater tank Capacity (L)	No. of months of failure	Percentage of total record (%)
500	75	10.1
1000	56	7.5
2000	35	4.7
3000	24	3.2
4000	11	1.5
5000	5	0.7
6000	2	0.3
7000	0	0.0
8000	0	0.0
9000	0	0.0
10000	0	0.0

In South Tarawa, if the average-sized household of 7.7 people installed a 7,000 L rainwater tank and used water a rate of 5 L/pers/day then it can be seen from Table 15 that the tank would not have failed during the period 1947 to 2008. With this capacity tank and the design demand, the tank, when full, would be sufficient to supply the demand for 8½ months. The dependence of failure rate on rainwater tank capacity is non-linear (Figure 20) but with less dramatic impact than roof area.

Figure 21 shows the change in stored volume of a 6,900 L rainwater tank for the historic rainfall record using the baseline parameter values in Table 10. In April 1974, the 6,900 L tank would have been very close to running dry with only 7 L remaining. With this rainwater tank capacity, the ratio of tank capacity to roof catchment area, *S/A* is 138 mm and the required maximum storage per person is about 900 L/pers. At a demand rate of 5 L/pers/day, without any rain, the rainwater tank would take 5.9 months to run dry.

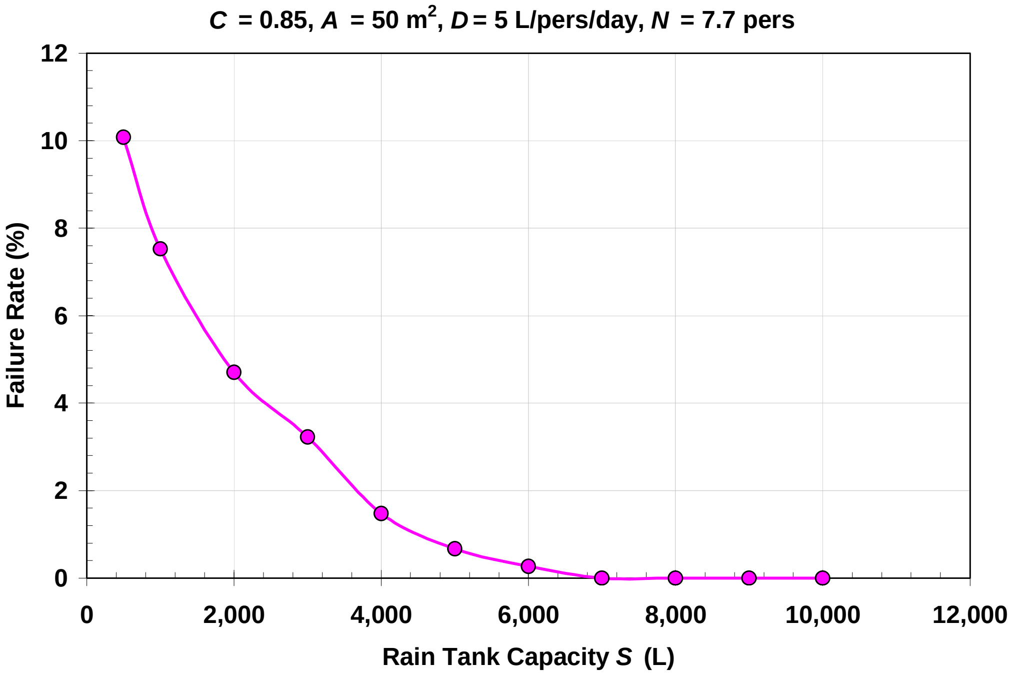


Figure 20 Dependence of the rainwater tank monthly failure rate on the rainwater tank capacity. Other parameters are listed in Table 10

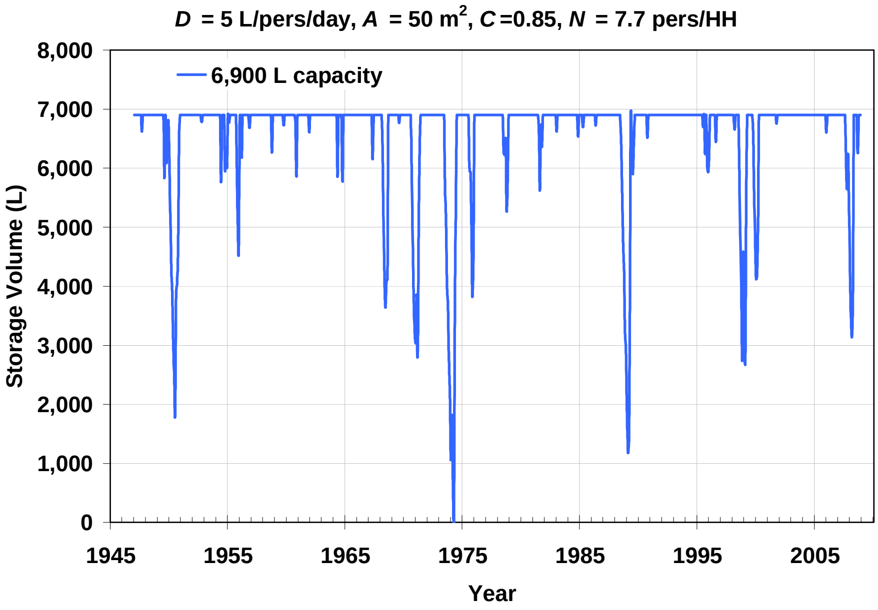


Figure 21 **Monthly volume of stored rainwater in a 6,900 L rainwater tank for a household of 7.7 people with the other parameter values in Table 10**

6.6 *Critical Parameters*

The above analysis was carried out for the baseline values in Table 10, which have been assumed to be relevant to the “average” household in Tarawa. They suggest several critical parameters. One is the ratio of rainwater tank capacity to the total monthly water demand of the household. For the baseline parameter values adopted, the above analysis suggests that a tank capacity equal to about 6 times the total household water demand is required for rainwater system that would not fail over the entire past historic rainfall record. Another critical parameter is the roof area required per person in the household to harvest sufficient water so that the storage will not fail. With the baseline values adopted here, it appears that between 7 to 8 m^2/pers is required in Tarawa. These critical parameters suggest that a non-dimensional approach to the rainwater tank mass balance equation may simplify the analysis of differing rainwater harvesting and storage systems.

6.7 *Non-Dimensional Form of the Rainwater tank Water Balance*

It is clear from the analyses above, that the parameters S, C, A, D, N defined in section 5 and used individually in section 6 all interact. These parameters can be combined into groups to incorporate that interaction. Equation [1] can be rewritten in terms of these groups to give a dimensionless equation:

$$\overline{V}_t = \overline{V}_{t-1} + \overline{A} \cdot P_t - 1 \qquad [3]$$

where the non-dimensional rainwater tank volumes are:

$$\overline{V}_t = V_t / (D \cdot N \cdot d_t), \ \overline{V}_{t-1} = V_{t-1} / (D \cdot N \cdot d_t) \qquad [4]$$

and the reduced effective roof area is:

$$\overline{A} = C \cdot A / (D \cdot N \cdot d_t) \text{ (units 1/mm if } D \text{ is in L/pers/day)} \qquad [5]$$

The non-dimensional relative rainwater tank storage capacity is:

$$\overline{S} = S / (D \cdot N \cdot d_t) \qquad [6]$$

In this dimensionless form of the rainwater tank water balance equation, there are only two parameters $\overline{A}$ and $\overline{S}$. In this parameterisation,

$$D \cdot N \cdot d_t = M_t \qquad [7]$$

where M_t (KL) is the total monthly demand of all people in the household. Subsituting eqn [7] in [5] and [6]:

$$\overline{A} = C \cdot A / M_t \qquad [8]$$

and the units of $\overline{A}$ are in m^2/KL (or m^{-1}) and

$$\overline{S} = S / M_t \qquad [9]$$

The non-dimensional rainwater tank capacity $\overline{S}$ is the ratio of the rainwater tank capacity (KL) to the total household monthly demand for rainwater (KL) and so it is the relative tank capacity. It is really the number of months a full tank could supply water for a household when there is no rain.

In order to use equations [3] to [9], the historic rainfall for Tarawa is used and the percentages of tank failures are estimated for various pairs of values of $\overline{S}$ and the reduced effective roof area, $\overline{A}$. By selecting a specified failure rate, relations can be built up between values of $\overline{S}$ and $\overline{A}$ for a specified failure rate. Table 16 lists the results for failure rates of 0%, 1%, 5% and 10%.

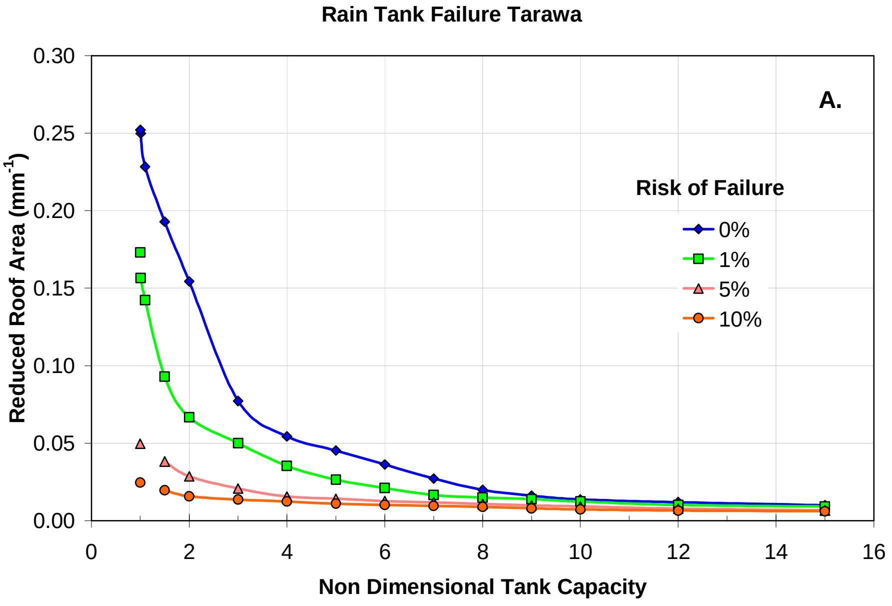
Table 16 Values of the non-dimensional relative rainwater tank capacity $\overline{S}$ and the reduced roof area $\overline{A}$ that give the specified failure rates.

Failure	**0**	**1%**	**5%**	**10%**
$\overline{S}$	**Reduced Area, $\overline{A}$ (mm^{-1})**			
15	0.00991	0.00910	0.00660	0.00606
12	0.01194	0.01020	0.00773	0.00649
10	0.01367	0.01234	0.00922	0.00725
9	0.01618	0.01384	0.00990	0.00800
8	0.01980	0.01489	0.01070	0.00891
7	0.02716	0.01651	0.01180	0.00953
6	0.03630	0.02110	0.01265	0.01016
5	0.04530	0.02641	0.01410	0.01099
4	0.05440	0.03540	0.01565	0.01240
3	0.07720	0.05010	0.02079	0.01360
2	0.15440	0.06660	0.02859	0.01572
1.5	0.19296	0.09307	0.03816	0.01960
1.1	0.22830	0.14240		
1.01	0.24990	0.15660		
1.001	0.25210			
1	-	0.17300	0.04968	0.02450

The results in Table 16 are also plotted in Figure 22, where it can be seen that as the relative tank capacity approaches 1, that is the rainwater tank capacity is just equal to the monthly total household demand, the required reduced roof area to prevent the tank from failing increases rapidly. It can be also seen that as the relative tank capacity increases, the differences in reduced roof areas for a specified failure rate decreases. In practical terms, for Tarawa's historic rainfall, relative tank capacities greater than 4 and more generally greater than 6 are needed to reduce the risk of failure.

Another critical parameter that can be identified in the non-dimensional analysis is the ratio $\overline{A} / \overline{S} = CA / S$, the ratio of the roof catchment area to the storage tank capacity. If the roof area is in units of m^2 and the storage tank capacity is in kL (m^3), then the units of CA/S are in m^{-1}. Table 17 gives values of CA/S for different non-dimensional storage capacity, $\overline{S}$, and a range of selected failure rates. These results are also plotted in Figure 23.

For small values of non-dimensional storage around 2, when the storage tank capacity is only a little larger than the monthly household demand, Figure 23 shows that, to avoid rainwater tank failure, effective roof areas have to be between 77 times the storage tank capacity in kL. For the baseline example in Table 10, this would require impossibly large roof catchment areas around 544 m^2. For larger values of the non-dimensional storage (eqn [9]) around 6, the required effective roof area is around 6 times the storage tank capacity (in kL) giving much more reasonable required roof areas around 42 m^2 for no risk of rainwater tank failure.



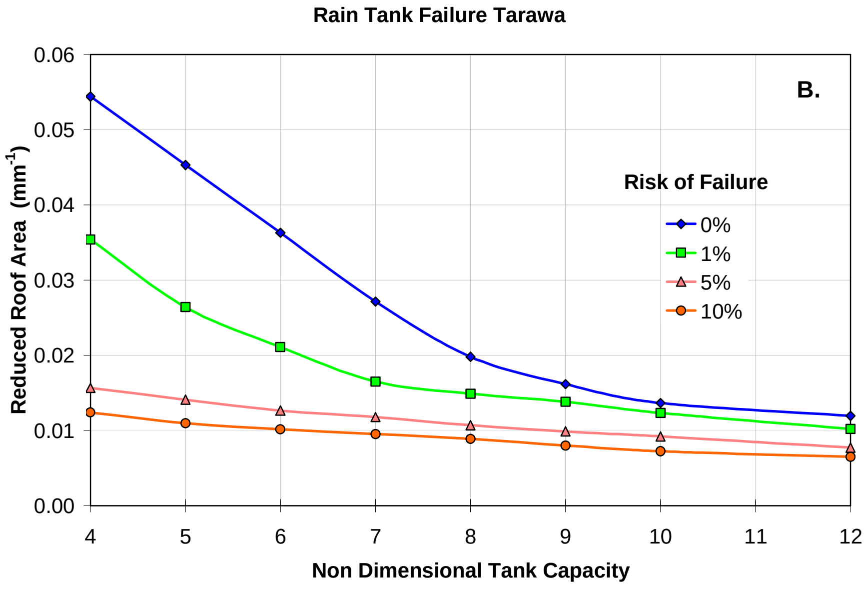


Figure 22 **Values of the non-dimensional relative rainwater tank capacity $\overline{S}$ (eqn[9]) and the reduced roof area $\overline{A}$ (eqn[8]) that give the specified failure rates. A. non-dimensional capacities in the range 1 to 15 and B. non-dimensional capacities in the range 4 to 12[13].**

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[13] It should be noted that Figure 22 is specific to the rainfall record in Betio, Tarawa. Other islands in Kiribati will have a different set of relations.

Table 17 Ratio of effective roof area (m^2) to storage tank capacity (kL), *CA/S*, as a function of the non-dimensional storage tank capacity, $\overline{S}$, for selected failure rates

Failure	0	1%	5%	10%
$\overline{S}$	Ratio *CA/S* (m^{-1})			
15	0.661	0.607	0.440	0.404
12	0.995	0.850	0.644	0.541
10	1.37	1.23	0.922	0.725
9	1.80	1.54	1.10	0.889
8	2.48	1.86	1.34	1.11
7	3.88	2.36	1.69	1.36
6	6.05	3.52	2.11	1.69
5	9.06	5.28	2.82	2.20
4	13.6	8.85	3.91	3.10
3	25.7	16.7	6.93	4.53
2	77.2	33.3	14.3	7.86
1.5	129	62.0	25.4	13.1
1.1	208	129		
1.01	247	155		
1.001	252			
1	-	173	49.7	24.5

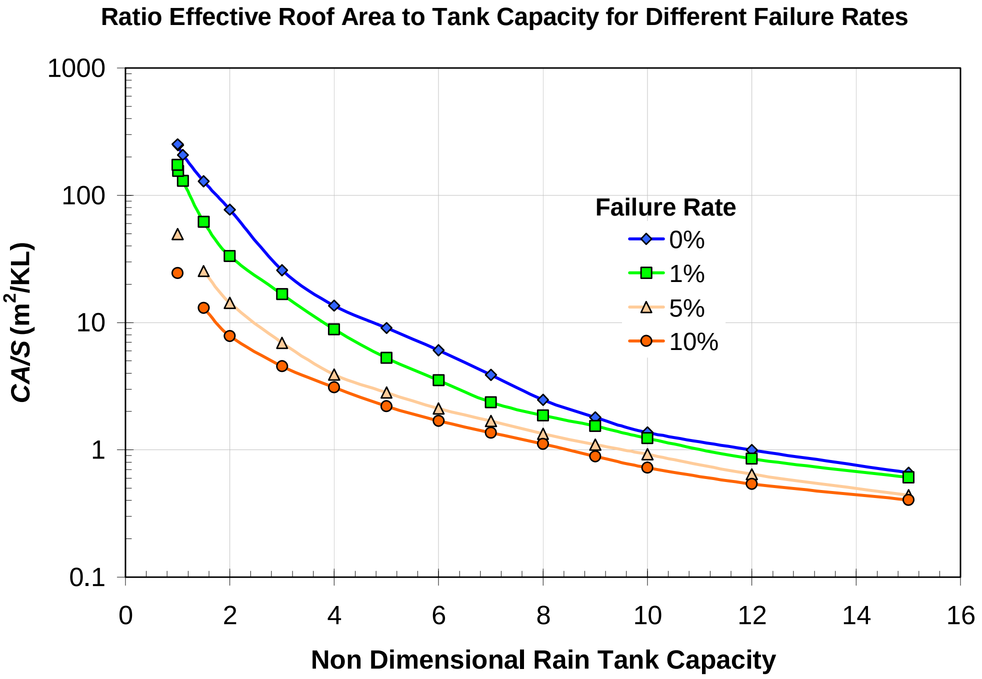

Figure 23 Dependence of the ratio of effective roof area to tank capacity (eqn [9]) as a function of non-dimensional storage for specified failure rates

6.8 Examples of the Use of the Non-dimensional Rainwater tank Water Balance

In order to illustrate the use of the results in Table 16 and Figure 22, some worked examples will be given. A simple spreadsheet has been developed for this and has been transferred to MPWU.

Example 1. What are the roof areas required for a household with 6,000 L capacity water tank and having a family of 8 people using 4.11 L/pers/day (average monthly demand, M_t, of 1,000 L) for a.) no rainwater tank storage failures, b.) 1% failure, c.) 5% failure and d.) 10% failure? (assume the roof runoff coefficient is 0.85 and the average number of days per month is 30.433 days).

The reduced rainwater tank capacity is (eqn [6]) $\overline{S} = 6{,}000/(8 \times 4.11 \times 30.433) = 6$

From Table 16, the values of the reduced roof area (eqn [5]) , $\overline{A}$, for 0, 1, 5 and 10% failures for $\overline{S} = 6$ are 0.03630, 0.02110, 0.01265 and 0.01016 mm^{-1} respectively.

Now the reduced area is $\overline{A} = C \cdot A/M_t$ (eqn [8]) so that the required roof area is $A = \overline{A} \cdot M_t / C$. The calculated required roof areas for the specified failure rates are given in Table 18.

Table 18 Required roof areas for a household demand of 1,000 L/month with a rainwater tank of 6,000 L capacity for specified failure rates

Failure	$\overline{A}$ **(mm^{-1})**	**Roof Area (m^2)**
0	0.03630	42.7
1%	0.02110	24.8
5%	0.01265	14.9
10%	0.01016	12.0

In order to ensure that the 6,000 L tank would not fail if Tarawa's historic rainfall continues into the future, the household would need a roof area of about 43 m^2. If the household were willing to expect failures for 1% of the time, a roof area of 25 m^2 would be sufficient.

Example 2. The household in example 1 decides to buy a bigger 10,000 L rainwater tank but increases its per capita water use to 5.13 L/pers/day (average monthly demand, M_t, of 1,250 L). What roof areas are required for the failure rates in example 1?

The reduced rainwater tank capacity is $\overline{S} = 10{,}000/(8 \times 5.13 \times 30.433) = 8$.

From Table 16, the values of the reduced roof area, $\overline{A}$, for 0, 1, 5 and 10% failures for $\overline{S} = 8$ (eqn [9]) are 0.01980, 0.01489, 0.01070 and 0.00891 mm^{-1} respectively. The required roof areas for the specified failure rates are given in Table 19.

Even though the household per capita water demand has increased by nearly 25% to 5.13 L/pers/day the required roof area to prevent failure relative to example 1 has decreased significantly. In order to ensure that the 10,000 L tank would not fail if Tarawa's historic rainfall continues into the future, the household would need a roof area of less than 30 m^2, which is realistic in Tarawa. For a 1% risk of failure the required roof area is only 22 m^2.

Table 19. Required roof areas for a household demand of 1,250 L/month with a rainwater tank of 10,000 L capacity for specified failure rates

Failure	$\overline{A}$ **(mm^{-1})**	**Roof Area (m^2)**
0	0.01980	29.1
1%	0.01489	21.9
5%	0.01070	15.7
10%	0.00891	13.1

Example 3. A community has built a large maneaba of area 30 m x 15 m = 450 m^2. They have very wisely decided to construct a cistern in the base of the maneaba which holds 450,000 L of rainwater. In the average rainfall year in Tarawa, about 900,000 L could be harvested from the roof. The community wants to know, how many people could be supplied continuously with drinking and cooking water from the cistern without the cistern running dry.

To answer this question a spreadsheet is needed since the calculation is an iterative one. If we assume that the daily basic drinking and cooking requirements are 5 L/pers/day then the answer is 225 people ($\overline{S}$ = 13.14 {eqn (9)} and $\overline{A}$ = 0.0112 mm^{-1} {eqn (8)}).

Example 4: A household with 6 family members in North Tarawa decides that it will only use rainwater to supply all the household water needs. What size rainwater tank and roof area does it need to have no failure of supply or 10% failure of supply? (assume roof catchment runoff coefficient of 0.85).

To answer this question, it will be assumed that the basic per capita water need is 50 L/pers/day for outer islands. The household's average monthly water demand is 9,130 L. From Figure 22, it is apparent that for realistic roof areas the storage capacity of any rainwater tanks should be at least 4 times the average monthly demand ($\overline{S} \geq 4$, eqn(9)). Table 20 lists the required tank capacities and roof areas necessary to supply all the household water needs.

Table 20 Required tank capacities and roof areas to supply a household of 6 people in North Tarawa with 50 L/pers/day without failure of the rainwater tanks.

$\overline{S}$	Rainwater tank Capacity (L)	$\overline{A}$ (mm^{-1})	Roof Area (m^2)
4	36,520	0.05440	584
5	45,650	0.04530	487
6	54,780	0.03630	390
7	63,910	0.02716	292
8	73,040	0.01980	213
9	82,170	0.01618	174
10	91,300	0.01367	147
12	109,560	0.01194	128

It is apparent from Table 20 that it is not practical to supply without failure the full household water needs of a family of 6 solely from rainwater in Tarawa, since both the required rainwater tank capacities and roof areas are impractical for almost all of Kiribati and many other places. Even if the failure criterion is relaxed to a 10% failure rate, the required storages and roof areas are still relatively large (Table 21) and a 10% failure rate means that alternate water sources are essential.

Table 21 Required tank capacities and roof areas to supply a household of 6 people in North Tarawa (as per Table 20) with 50 L/pers/day with 10% failure rate.

$\overline{S}$	Rainwater tank Capacity (L)	$\overline{A}$ (mm^{-1})	Roof Area (m^2)
4	36,520	0.01240	133
5	45,650	0.01099	118
6	54,780	0.01016	109
7	63,910	0.00953	102
8	73,040	0.00891	96
9	82,170	0.00800	86
10	91,300	0.00725	78
12	109,560	0.00649	70

Example 5: in example 4, 3 of the family members leave the household. Does that improve the ability of the household to supply all the household water needs?

As in example 4, it is assumed that the basic per capita water need is 50 L/pers/day for outer islands. The household's average monthly water demand with three people is 4,565 L. Again using Figure 22, the storage capacity of any rainwater tanks should be at least 4 times the average monthly demand ($\overline{S} \geq 4$, eqn (9)). Table 22 lists the required tank capacities and roof areas necessary to supply all the household water needs.

Table 22 **Required tank capacities and roof areas to supply a household of 3 people in Tarawa with 50 L/pers/day without failure of the rainwater tanks.**

$\bar{S}$	Rainwater tank Capacity (L)	$\bar{A}$ (mm^{-1})	Roof Area (m^2)
4	18,260	0.0544	292
5	22,825	0.0453	243
6	27,390	0.0363	195
7	31,955	0.02716	146
8	36,520	0.0198	106
9	41,085	0.01618	87
10	45,650	0.01367	73
12	54,780	0.01194	64

Even with 3 people in the household, Table 22 shows that the required rainwater tank storage capacities and roof areas are still large. When a failure rate of 10% is allowed (Table 23), roof areas become more realistic but the required rainwater tank capacities are very large. For example, for the 35 m^2 roof area, the equivalent of 9 x 6,000 L rainwater tanks is required.

6.9 Rainwater Conservation Strategies to Minimise Failures

In the above calculations, water is used at a constant rate by the household until the rainwater tank fails or rain arrives. Conservative management strategies could be devised which limit use when the stored water volume reaches a specified level such as half full and so on. This would need to be accompanied by timely warnings from the government on predicted drier periods determined by the KMS using the SCOPIC program. These would limit failure of rainwater storage but would require a major public education campaign as it requires close management at the household level to control demand.

Table 23 **Required tank capacities and roof areas to supply a household of 6 people in Tarawa with 50 L/pers/day with 10% failure rate.**

$\bar{S}$	Rainwater tank Capacity (L)	$\bar{A}$ (mm^{-1})	Roof Area (m^2)
4	18,260	0.01240	67
5	22,825	0.01099	59
6	27,390	0.01016	55
7	31,955	0.00953	51
8	36,520	0.00891	48
9	41,085	0.00800	43
10	45,650	0.00725	39
12	54,780	0.00649	35

An example is now presented of the use of a conservation strategy to lower the risk of failure. For this example, one of the original design assumptions for large houses used in the Tarawa Water Project (AGDHC, 1982) will be used.

It is assumed that the roof catchment area is 130 m^2 and the house is supplied with two 13,500 L tanks (total capacity 27,000 L). The house has the average household size in South Tarawa of 7.7 people. A roof catchment runoff coefficient of 0.85 (Table 10) is assumed. The initial per capita demand, D_0 is 50 L/pers/day. With a constant demand the failure rate is a large 22.4%.

The water use and conservation strategy used is as follows. When the tank is more than half full, the household uses water at the constant rate, D_0 of 50 L/pers/day. As soon as the tank volume drops below 50% capacity, demand is reduced by a fraction of D_0. Here fractions of 10% to 100% (constant demand) will be considered. The results are show in Table 24

Table 24 Effect of reducing demand when the rainwater tank falls to 50% capacity, N =7.7, D_0 = 50 L/pers/day, A = 130 m^2, S = 27,000 L

Conservation Strategy	Reduced Demand at 50% Capacity (L/pers/day)	No. of months of failure	Percentage Failure (%)
0.1x D_0	5	0	0.0
0.2x D_0	10	22	3.0
0.3X D_0	15	45	6.0
0.4x D_0	20	66	8.9
0.5x D_0	25	97	13.0
0.6x D_0	30	108	14.5
0.7x D_0	35	126	16.9
0.8x D_0	40	143	19.2
0.9x D_0	45	151	20.3
D_0	50	167	22.4

In this example, it can be seen that by decreasing the demand back to 5 L/pers/day when the rainwater tank falls to half full permits the rainwater tank to be used without failure through the historic rainfall record. Conservation management of rainwater tanks is therefore an effective strategy for reducing failure but it requires careful management and training.

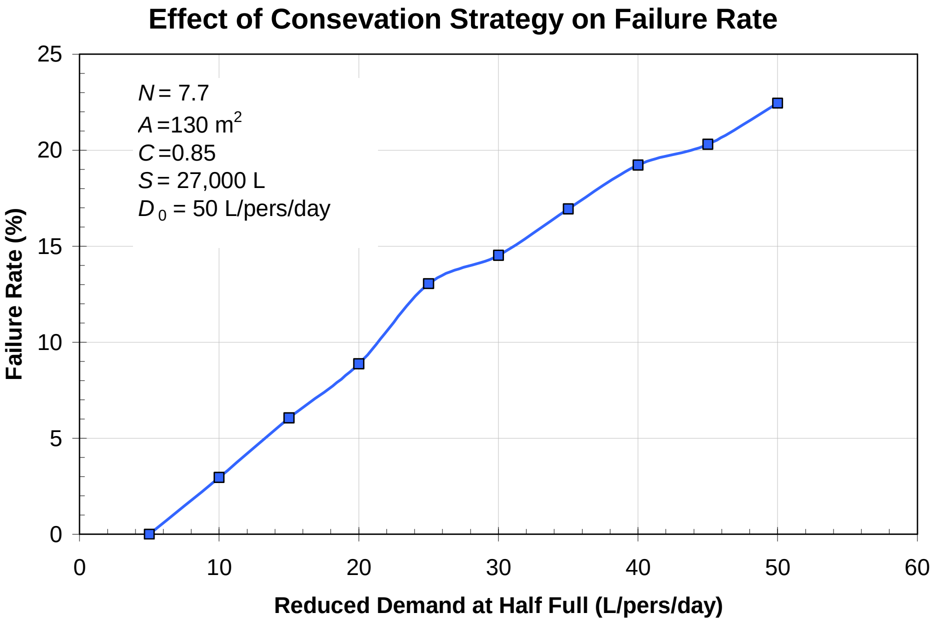

Figure 24 Effect of reducing per capita demand when the rainwater tank falls to 50% capacity

6.10 Comparison of Monthly and Daily Water Balance Models

As mentioned in section 5.1, rainwater tank performance ideally should be assessed using a daily rainwater tank water balance. The limited availability of daily data and the fact that the rainwater tank water balance program is currently limited to just over 54 years of data (less than 20,000 days), meant that a monthly water balance was used in the above assessments. A comparison between the results of the daily and monthly water balance models was undertaken.

For both the monthly (Rainwater tank Calculator.xls) and the daily water balance (RAIN8.exe) two periods of 54 years of Betio rainfall data were used:

(a) 1948 - 2001 (54 years from first year of full daily data), and

(b) 1953 - 2006 (54 years to last year of full daily data).

Comparisons were done on the basis of the required volume of storage to just allow for no failure of the rainwater tank in the period of record used. In all cases, the parameters used were the total household daily demand, $D.N$ (L/day) and roof area, A (m^2) in equations [1] and [2]. It was assumed that $C = 0.8$ in equations [1] and [2] and both $Int, E_t = 0$ in equation [2]. The results of the comparison are listed in Table 25.

It can be seen in Table 25 that the results of the daily model for the two overlapping 54 year periods differ slightly with the capacity of rainwater tanks required to prevent failure being smaller for the period 1948 to 2001 than for the period 1953 to 2006 (mean ratio 0.96±0.02). The monthly model results are much less sensitive to the selected period of the rainfall record (mean ratio 1.01±0.02), since it averages out over approximately 30 day periods.

When the two models are compared, the daily models estimates higher capacity tanks are required to prevent failure than the monthly models. The mean ratio of the required tank capacities estimated by the daily model to that of the monthly model is 1.07±0.09 for the 1948 to 2001 period and 1.12±0.09 for the period 1953 to 2006. This shows that the capacities estimated by the monthly model are on average about 10% too low, and so are good first order approximations.

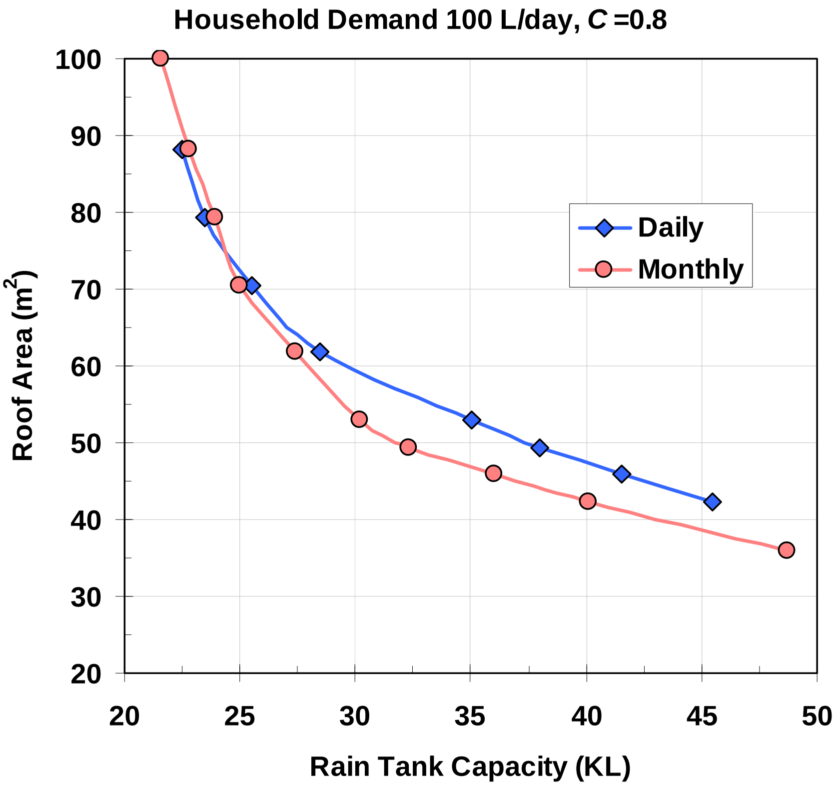

Figure 25 compares the daily and monthly model predicted rainwater tank capacities required for no failure for different roof areas for a daily household demand of 100 L/day and a runoff coefficient of 0.8. This shows that for large roof areas the monthly models is in good agreement with the daily model, while at smaller roof areas the monthly model consistently underestimates the required rainwater tank by up to 10%.

Table 25 Comparison of the predictions of the daily and monthly rainwater tank water balance models

Parameters		Required tank volume to avoid failure (kL)				Ratios			
Household Demand (L/day)	**Roof Area (m^2)**	**Daily Model**		**Monthly Model**		**Daily / monthly**		**Daily (a)/(b)**	**Monthly (a)/(b)**
		(a) 1948 - 2001	**(b) 1953 - 2006**	**(a) 1948 - 2001**	**(b) 1953-2006**	**(a) 1948 - 2001**	**(b) 1953 - 2006**		
50	25	18.5	19.0	15.8	15.8	1.17	1.20	0.97	1.00
50	40	12.0	12.5	11.9	11.9	1.01	1.05	0.96	1.00
100	80	23.5	25.0	23.8	23.8	0.99	1.05	0.94	1.00
100	120	beyond data	beyond data	19.9	19.9	-	-	-	1.00
150	80	52.0	53.5	45.0	43.0	1.16	1.24	0.97	1.05
150	120	35.0	37.0	35.7	35.7	0.98	1.04	0.95	1.00
500	400	117	124	119	119	0.98	1.04	0.94	1.00
500	250	185	190	158	158	1.17	1.20	0.97	1.00
Mean						**1.07**	**1.12**	**0.96**	**1.01**
Standard deviation						0.09	0.09	0.02	0.02

6.11 Concluding Remarks on the Rainwater Tank Water Balance

In this section, an examination has been made of the ability of rainwater tanks in Tarawa to supply household water needs. In the absence of information for Tarawa on how much stored rainwater is used by households, on what roof catchment areas are common, on the condition of roof catchments , and on size of rainwater tanks normally employed, estimates have been made of the various parameters in the rainwater tank water balance. Reasonable baseline values were assumed for the average per capita demand for rainwater, the average number of people per household, the storage capacity of available rainwater tanks, and estimates were made of the approximate roof area and the roof catchment runoff coefficient. The per capita demand was assumed constant throughout the historic rainfall record and a monthly rainwater tank water balance was used as a first order estimate.

In the first part of this section, parameters were kept constant while one was varied through a reasonable range and Tarawa's historic monthly rainfall from 1947 to 2008 was used as the rainfall input. Household demand plays a big but reasonably linear role in the rate of failure. For a single 6,000 L rainwater tank and a roof catchment area of 50 m^2, it was found that the average sized household in South and North Tarawa could be supplied with 4.6 and 5.4 L/pers/day, respectively, throughout the historic rainfall record without failure of the rainwater tank.

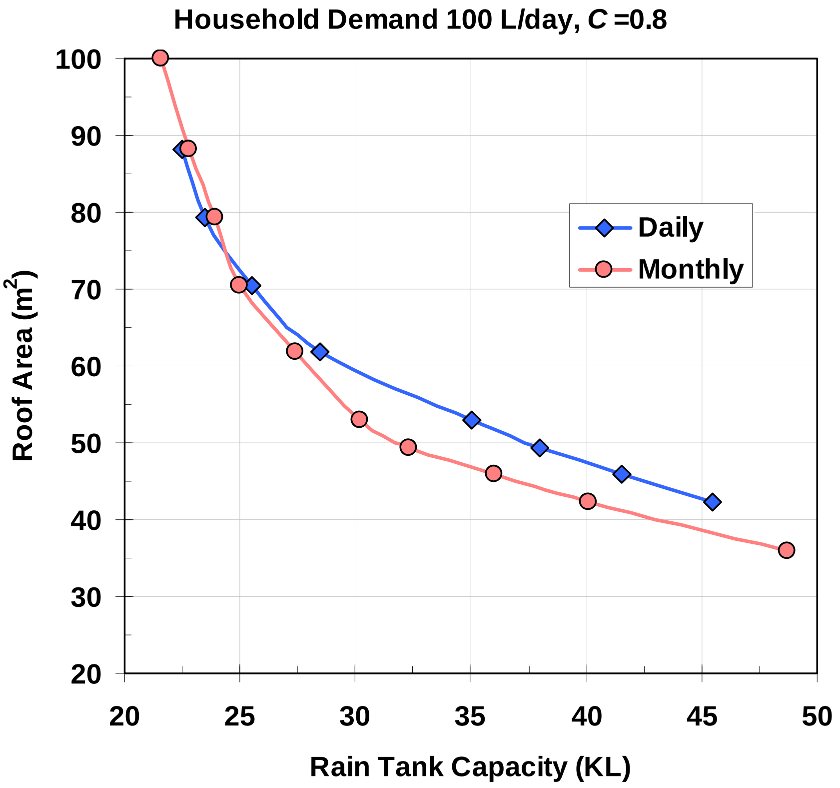

Figure 25 **Comparison of the daily and monthly model predicted rainwater tank capacities required for no failure for different roof areas for a daily household demand of 100 L/day and a runoff coefficient of 0.8**

The roof catchment area had a pronounced non-linear impact on rainwater tank storage failure. It was found that in order to supply the average size household in South Tarawa with 5 L/pers/day, without storage failure, a large roof area of about 60 m^2 or 7.7 m^2/pers was required. The roof catchment runoff coefficient had a relatively minor impact on failure of the rainwater tank compared to the other variables. If the average household in Tarawa with characteristics in Table 10 were equipped with a 6,900 L rainwater tank, it was found that at a constant demand of 5 L/pers/day the rainwater tank would not have failed throughout the historic rainfall record. For this example, it was found that the required rainwater tank storage capacity was 5.9 times the average household monthly water use.

It is clear that the separate parameters in the rainwater tank water balance equation interact. A non-dimensional form of the water balance equation was introduced with only to critical parameters which incorporate all the other parameters. There two parameters are the non-dimensional relative rainwater tank capacity, $\overline{S}$, which is the total rainwater tank capacity divided by the average monthly household demand, and the reduced effective roof catchment area, $\overline{A}$, which is the roof catchment area multiplied by the runoff coefficient and divided by the average monthly household demand. These two parameters, which incorporate average monthly household demand, determine the failure rate of rainwater tanks.

Using the historic rainfall rate in Tarawa, families of pairs of these parameters were produced for specified failure rates. This non-dimensional analysis is independent of any assumptions about parameter values but is specific for Tarawa as the analysis used the local rainfall record. The analysis shows that rainwater tank storage capacities have to be greater than 4 times the monthly household demand in order to give reasonable roof areas required for no failure of the system. The results are quite general and can be used for any roof area, rain storage capacity, household demand, and roof catchment runoff coefficient.

Worked examples of the use of the non-dimensional analysis are given. In these examples, it is shown that for the usual sized households in Tarawa it is not possible to supply all the household water requirements at a constant demand from rainwater since impractically large rainwater tank capacities and very extensive roof areas are required. Instead more modest rainwater harvesting and storage systems can be constructed which can provide the needs for drinking and cooking, at about 5 L/pers/day with relatively small rates of failure. An example of conservation strategies, which allow greater demands when tanks are near full, but use smaller demands when tanks start to empty is given. These require careful management.

Comparison with a daily rainwater tank water balance model shows that the simpler monthly water balance model underestimates the required capacity of rainwater tanks for a given roof area, necessary to prevent rainwater tank failure, by up to about 10%. The findings here reinforce earlier conclusions that, due to frequent severe droughts, rainwater harvesting and storage in Tarawa can only supplement household water requirements rather the meet all household water needs (AGDHC, 1986; Shalev, 1992).

7. Improving Rainwater Harvesting

7.1 Incentives for Purchase

The SAPHE project revolving fund for the purchase of rainwater harvesting and storage equipment by public servants provided an excellent incentive for increasing the installation of these devices in South Tarawa, as can be seen by the loans given out by the Kiribati Housing Corporation (KHC) (Table 2) and the changes in the use of rainwater tanks between 1995 and 2005 (Table 3). Originally it had been planned under KAPII to establish a similar revolving fund for outer islands and particularly North Tarawa. As can be seen in Table 1, there is a relatively small percentage of households in North Tarawa using rainwater for drinking, and this was a strategic suggestion as this fund had the potential to boost that percentage. That component, however, has been abandoned although future aid projects may revive it. As ADB (2000) recognised, one of the main impediment to the purchase of rainwater tanks was the fact that their outright purchase price is beyond the means of many households.

Opportunities for taking out loans still exist in South Tarawa, although the rate of buying of new tanks seems to have slowed in recent years (Table 2). It is not clear if that is because most houses with suitable roofs have already installed tanks. From Table 4 it appears that there is the potential to increase the number of households in South Tarawa with rainwater tanks by another 1,200 houses. As more houses with suitable roofs are constructed, this number is expected to increase further. Since there are no statistics on the percentage of houses without rainwater tanks that have suitable roofs in North Tarawa, it is not possible to determine the potential for increasing the use of rainwater harvesting there.

7.2 Condition of Rainwater Systems

Brief inspections of both household and public rainwater harvesting and storage systems show a considerable range of problems, with leaky and broken gutters, poor or non existent connections, leaky pipes and unsealed and even open tanks, and leaky tanks. Some of the systems on government buildings are very poor and some rainwater cisterns designed to store harvested rainwater from large government buildings have been demolished to make room for car parks. There is a range of information available on improving the rainwater harvesting and maintaining rainwater storage tanks (see e.g. SOPAC 2004a, 2004b) and every effort should be made to ensure that installers of rainwater systems are fully trained and that households are aware of the maintenance requirements of rainwater systems. The revolving fund project does not appear to have included an education component to properly inform householders of correct installation and maintenance of rainwater systems. A public education campaign on the proper care and maintenance of rainwater harvesting and storage systems is required.

7.3 Health Hazard of Poorly Maintained Systems

Rainwater from rainwater tanks has often been promoted as a healthier option. Poorly maintained rainwater systems, however, can also be a health hazard, particularly since open tanks or tanks with unsealed inlet and overflow pipes can provide an ideal breeding habitat for mosquitoes and can collect debris. In addition, few rainwater harvesting systems in Tarawa have ‘first flush’ devices so that debris tends to accumulate in rainwater tanks. Simple, easy to use and effective first flush devices are available and their advantages and use should be publicised. Council (Building) Bye-Law 23 states (see 4.1): *The owner of any building built in other than local materials shall keep the guttering and water storage system in a reasonable state of repair.* Since government agencies neglect these requirements in their own buildings, it is not surprising that this Bye-Law is not enforced in private households.

7.4 Rainwater Harvesting in Maneabas and Public Buildings

Many new impressive maneabas have been constructed in Tarawa over recent years (e.g. Figure 12). Very few of them have rainwater collection and storage despite the Council Bye-Laws and the draft National Building Code. This is an opportunity lost, since many maneabas have the capability of storing about 0.5 ML of harvested rainwater. Every effort should be made to ensure that no new public buildings are constructed without adequate rainwater storage and a system devised for managing and distributing water from public storages. In addition to ensuring that existing building regulations are enforced, a significant issue is how community systems can be equitably managed. Two annual competitions to select the best community designed and the best community managed rainwater harvesting system could be instituted in Tarawa. The competition could include both community organizations such as churches and maneabas as well as government departments. The government should aim to make showpieces out of well designed community rainwater harvesting and storage systems.

7.5 Installation of Rainwater Harvesting and Storage Systems

The range of poorly installed rainwater harvesting and storage systems in Tarawa (even in lead government water agency buildings) indicates there is a specific need for a training on the installation of guttering and rainwater tanks and installation of first flush devices. SOPAC reports (2004a, b) provide information on installation and maintenance of rainwater harvesting and storage systems and SOPAC could be enlisted to assist in a training program.

7.6 Public Education Campaign

In previous water supply projects in Tarawa, there has been little attention given to the training of householders to maintain and manage rainwater harvesting and storage A major public education campaign on rainwater harvesting, maintenance and management, particularly during droughts is required. This campaign should include: maintenance and cleaning of roofs, guttering and rainwater tanks; repair of leaks; minimising contamination of rainwater tanks; use and conservation of stored rainwater; minimising the risk of failure of stored rainwater; and protecting rainwater tanks from disease vectors such as mosquitoes. Again, SOPAC reports (2004a, b) provide information on rainwater harvesting and SOPAC could be enlisted to assist in a public education campaign.

8. Cost of Harvesting Rainwater

Unlike the public groundwater extraction and reticulation system, the cost of harvesting and storing groundwater is borne by the individual households and organisations. The cost per kilolitre of water harvested and stored by a household can be crudely estimated from the volume of rainwater harvested by an average South Tarawa household (7.7 people/household) with the baseline parameters given in Table 10 and the approximate cost of the rainwater collection and storage equipment. It is assumed that the average life time of the standard 6,000 L polythene rainwater tank and guttering is 20 years. The historic rainfall record was used to estimate the volume of water harvested by the average household in the full 62 years of rainfall record and the average amount that could be expected to be harvested in 20 years was estimated from this. No continuing maintenance costs have been included in this estimate. Table 26 shows the values used in this estimation and the approximate cost per kilolitre (kL).

Table 26 Estimation of the cost of rainwater harvesting for the average household with baseline characteristics in Table 10

Item	Value
Cost of rainwater tank + interest	$1,600
Cost of guttering and pipes	$400
Cost of transport[14] & installation	$300
Total Cost	$2,300
Life time of tank + guttering (years)	20
Volume Rainwater Harvested in 62 years (kL)	851
Average Volume Rainwater Harvested in 20 years (kL)	279
Cost per kL	$8.24

Table 26 shows that, without maintenance costs, the average cost per kilolitre is over $8. In South Tarawa, deliveries by tanker of bulk water are charged at a rate of $2/kL for domestic use and $5/kL for commercial use with a $10 delivery charge. The piped water supply is currently charged at a rate of $10 per household per month for domestic water users and $5/kL for industrial users. The marginal cost of producing reticulated groundwater from Bonriki and Buota water reserves is currently $3.80/kL, if the costs of leasing the water reserves from traditional landowners are taken into account. This cost, however, does not include the depreciation costs of the pumping and reticulation systems or water lost from the system. If it is assumed that the total current losses are 50%, the costs of supplied groundwater are around $7.60/kL, close to the estimated cost of rainwater harvesting and storage.

According to the 2005 Census, approximately 43% of households in Tarawa use rainwater. It is not known currently how many of the remaining houses have roofs that are suitable for rainwater harvesting. In 2000, it was found that that there were approximately 1,200 house that have suitable but no rainwater collection and storage systems. If we assume that this has now increased to about 1,750 households, fitting them with rainwater collection and rainwater tank systems would cost approximately $A4 million using the cost estimates in Table 26. Under current arrangements, this cost would be borne by the householders.

The reticulated water system is operated intermittently, so that it is generally less reliable than a household rainwater tank. Having the household water supply directly under the control of the household is an advantage. The approximate $8/kL cost for rainwater is relatively cheap compared with the approximate cost of $1,500/kL for bottled water. In addition, having a household rainwater tank provides emergency water storage for tanker delivered water during droughts.

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[14] Ddelivery of rainwater tanks is currently free is South Tarawa

9. Monitoring Rainwater Harvesting and Storage

This Master Plan has been limited by the lack of information on rainwater harvesting in Tarawa. It is a problematic area since rainwater harvesting and storage is mostly private. The lead water agencies in Tarawa concentrate primarily on public sources of groundwater. As the 2005 Census results demonstrate (Table 1), the public in Tarawa use multiple water sources and the lead water agencies need to monitor the condition and use of all water sources.

Two types of information are required in order to monitor rainwater harvesting and storage:

- Use of rainwater by household and community organizations
    - Surveys of selected households in South and North Tarawa to determine the type of use for rainwater and the per capita use of rainwater.
    - Surveys of selected agencies, organizations and businesses to determine uses of rainwater and the approximate per capita rainwater use.
    - Surveys of selected rainwater tank storages on the microbiological quality of stored water.
- Properties of rainwater storages. Construct a data base containing:
    - Location of all rainwater tanks
    - Storage capacity of rainwater tanks
    - Total and effective area of roof catchment for rainwater collection
    - Quality of guttering and down pipes
    - Quality of stored rainwater.

While both surveys will be time consuming for the small number of people in the lead water agency, it must be recognized that Tarawa, and particularly South Tarawa, face major water shortfalls in the future. There will need to be a major improvement in water monitoring to ensure sustainable management. The information from these rainwater surveys will be invaluable in improved water resource management.

10. Amount of Rainwater Harvested

It is estimated that the current shortfall in being able to meet reasonable potable water requirements in Tarawa is over 2 ML/day in South Tarawa (White and Falkland, 2009a). This supply gap will increase in the next 20 years. It is important to know how much of this demand shortfall can be met by rainwater harvesting. Unfortunately, there is almost no information on capacity of rainwater storage tanks, roof catchment areas, condition of guttering and downpipes. Practically the only information that is available is the water sources for drinking water statistics provided by NSO (Table 1). Since it is clear that multiple sources are used by households and that use of other households' facilities also occurs, it is difficult to estimate household usage from these figures.

Some previous studies have given estimates of the potential contribution of rainwater harvesting to water supply in South Tarawa. These are listed in Table 27.

Table 27 Estimates of the contribution of rainwater harvesting to the water supply in South Tarawa.

Study	Rainwater Contribution (KL/day)
Harrison (1980)	170
AGDHC (1982; 1986)	80
Shalev (1992)	350*
OEC (2000)	400†
This study-currently	56 - 93
This study-in future	96 - 160

* Estimated for a proposed 31 ha artificial catchment planned for the Temaiku fish ponds.
† No basis was provided for this estimate

In order to make a rough estimate here, it is assumed that currently 43% and 12% of households in South and North Tarawa, respectively, use rainwater and each of these households have, on average, 7.7 and 6.5 persons, respectively. These estimates result in an estimated 18,600 and 700 people, respectively, consuming rainwater in South and North Tarawa. If we assume that the consumption rate is 3 to 5 L/pers/day, then the total amount of rainwater being used in South Tarawa is between 56 and 93 kL/day and in North Tarawa 2,100 to 3,500 L/day. The range of values in South Tarawa is consistent with AGDHC (1982; 1986).

If in the future, a further 1,750 houses in South Tarawa had rainwater harvesting and storage systems installed, then the amount of rainwater water supplied could increase to between 96 kL and 160 kL/day. It is clear that rainwater harvesting will not meet the shortfall in water supply in South Tarawa, but is an important source of good quality water.

11. Advantages and Limitations of Rainwater Harvesting

It is clear from the preceding sections that for most households and organisations in Tarawa, given the large variability of rainfall and Tarawa's frequent severe droughts, rainwater harvesting will not be able to supply all the household's or organisation's water needs in the majority of cases. As has been found by other studies, rainwater harvesting in Tarawa can only provide supplementary water supply. It is important that this limitation be acknowledged and publicized so that correct use of rainwater as an important source of better quality drinking and cooking water only is fostered.

11.1 Advantages

If properly managed rainwater harvesting and storage systems have several distinct advantages in Tarawa.

- Source of good quality water for drinking and cooking
- Limited risk of human or domestic animal faecal contamination if properly maintained
- Constant, limited supply of water always continuously available
- Under the direct control of the household
- Easy and cheap to disinfect
- Conservation messages are clearly signaled by the decreasing volume of water in the rainwater tank.
- A convenient household water storage for deliveries during droughts

11.2 Limitations

There are some limitations to the use of rainwater harvesting systems in Tarawa which must be acknowledged.

- Installation expenses are very high for both urban and rural households without an incentive scheme
- Cost of water per kL is more expensive than current PUB water charges
- Cannot supply the total household water needs except in a few very limited cases with large storages and roof areas
- Almost all rainwater tank storages fail during Tarawa's frequent severe droughts
- Requires continual maintenance, particularly of gutters
- Requires monitoring of use by the household
- Takes up considerable space, especially in crowded areas such as Beitio and Bairiki.
- Maneabas are low with little room for good capacity tanks[15]
- Community systems require an equitable way of distributing water
- If not properly maintained can be breeding location for mosquitos and other disease vectors

Despite these limitations, it is clear from the advantage of freedom from faecal contamination and the dramatic recent increase in the percentage of households and institutions throughout Tarawa, that rainwater tanks are a very attractive option for supplementing household water needs, provided they are maintained and managed. There is considerable potential for the use of communal rainwater harvesting from large buildings like maneabas and churches. This will, however, require communities to develop the management and maintenance skills to run such systems.

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[15] In maneabas and other large buildings, the base can be constructed as a cistern as is done in Tuvalu

12. Conclusions on Rainwater Storage Estimations

South Tarawa leads the Nation in the use of rainwater harvesting. It is estimated that, currently, about 43% of households in South Tarawa and 12% in North Tarawa harvest and store rainwater. Despite the obvious importance of rainwater harvesting, there is a lack of information on the amount of rainwater used and the characteristics of the existing rainwater collection and storages systems in use. This study of the potential for rainwater harvesting in Tarawa has therefore been limited by the lack of information on the current use of rainwater and on the physical characteristics of rainwater harvesting and storage systems in Tarawa so that it is not possible to say what is the future potential for expanding the use of rainwater. It is not known, for example, how many of the remaining households, which do not currently harvest rainwater, have roofs that are suitable for rainwater harvesting. It is strongly recommended that surveys of household rainwater use and the physical characteristics of rainwater storages in Tarawa be conducted by the lead water agencies.

Rainfall in Tarawa is highly variable and extreme events are strongly coupled to ENSO events. Severe droughts occur about every 7 years and last on average for nearly two years. Development of a drought contingency plan in which householders, commerce, industry and institutions are given early warning of droughts and are provided with advice on the management and maintenance of rainwater harvesting and storage systems is recommended.

The failure of almost all climate change predictions using GCMs to simulate ENSO events in predicting future rainfall scenarios means that they are of little relevance to predicting future rainfalls or drought in Tarawa. Instead, it has been assumed that the variability of rainfall over the next 20 years in Tarawa will be similar to that experienced in the historic rainfall record over the past 62 years.

The estimations made here on the risk of failure of rainwater harvesting and storage in Tarawa rely on a number of assumptions and estimates. It has been assumed that a monthly rainwater tank water balance is useful for providing first order estimates of rainwater tank failure during dry periods. There are five key parameters on which the simple, monthly mass balance estimate of rainwater harvesting depends which are: the number of people per household; the per capita water demand; the area of the roof catchment; the roof catchment runoff coefficient; and the capacity (volume) of the rainwater storage. Because of the lack of information, this study has had to assume reasonable values of these parameters in South and North Tarawa from the 2005 Census as a baseline value.

Using the assumed baseline parameter values and the historic monthly rainfall record for Tarawa (Betio) from 1947 to 2008, estimates of the risk of failure of rainwater tanks were found for an assumed constant rate household demand by varying one parameter at a time with the others held constant. It was found that for the average household size in South Tarawa, using water for drinking and cooking at 5 L/pers/day that if the household had a 7,000 L rainwater tank, it would have not failed throughout all the droughts between 1947 and 2008. It was also shown that, for reasonable roof areas, the storage capacity of the rainwater tank needed to prevent failure was 6 times the average total household monthly water demand for drinking and cooking. For a rainwater tank capacity of 6,000 L, it was found that a rather large roof area of about 7.7 m^2/pers was required to prevent rainwater tank failure at a per capita demand of 5 L/day.

The separate parameters in the rainwater tank water balance equation all interact. A non-dimensional form of the water balance equation was introduced with only two parameters which incorporate the other parameters. The first is the non-dimensional relative rainwater tank capacity, $\overline{S}$, which is the total rainwater tank capacity divided by the average monthly household demand. The second is the reduced effective roof catchment area, $\overline{A}$, which is the roof catchment area multiplied by the runoff coefficient and divided by the average monthly household demand. These two parameters determine the failure rate of rainwater tanks. A simple XL spreadsheet calculator (Rainwater tank Calculator.xls) was developed and supplied to the lead water agencies. Using the historic rainfall rate in Tarawa, it was possible to produce families of pairs of these parameters for specified failure rates. This non-dimensional analysis is independent of any assumptions about parameter values but is specific for Tarawa as the analysis used the Tarawa rainfall record. The results of the simple spreadsheet developed here are quite general and can be used for any roof area, rainwater tank storage capacity, household size or per capita demand.

Worked examples of the use of the non-dimensional analysis are given. It is shown that for the usual sized households in Tarawa, it is not possible in most cases to supply all the household water requirements from rainwater without risk of failure since impractically large storage capacities and very extensive roof areas are required. Instead, more modest rainwater harvesting and storage systems can be constructed which can provide the water needs for drinking and cooking, at about 5 L/pers/day with relatively small or zero rates of failure. The above calculations contain no conservation strategies so that water is used at a constant rate. An example is given of a conservative management strategy in which the use of water is greatly decreased when the stored water volume reaches a specified level such as half full. Such schemes could also be accompanied by warnings from the government on predicted drier periods determined by the KMS using the SCOPIC program. These would limit failure of rainwater storage but would require a major public education campaign and improved management of rainwater stores.

The monthly water balance model was tested against a daily water balance model and was found to be in good general agreement. The monthly water balance predicted the capacity of rainwater tanks necessary to prevent failure for a specified demand and roof area that was up to about 10% smaller than the daily water balance. The conclusion from the monthly water balance that, due to frequent severe droughts, rainwater harvesting and storage in Tarawa can only supplement household water requirements rather the meet all household water needs was therefore confirmed by the daily model.

A crude analysis of the cost of rainwater harvesting systems using historic rainfall data estimated that the cost to households of harvested rainwater exceeds $8/kL, much greater that the current charge for PUB water but much less than bottled water. If properly managed rainwater harvesting and storage systems, however, have several distinct advantages in Tarawa: source of good quality water for drinking and cooking; limited risk of human or domestic animal faecal contamination; constant, limited supply of water always continuously available; under the direct control of the household; a convenient household water storage for deliveries during droughts and conservation messages are clearly signaled by the decreasing volume of water in the rainwater tank.

The Council Bye-Laws for new buildings are very clear in that they require new houses and buildings with suitable roof materials to have rainwater harvesting and storage systems installed. The Bye-Laws also mandate proper maintenance of rainwater collection and storage hardware. The draft National Building Code also mandates installation of rainwater harvesting and storage. Neither of these legal instruments is enforced and many new buildings with large suitable roof areas have been built without rainwater harvesting and storage systems. Since building approvals are at the Council level and since there are currently no qualified building inspectors in Tarawa, the Bye-Laws are never enforced. This needs to be addressed urgently.

Brief inspections of household and public rainwater harvesting and storage systems show a considerable range of problems. There is a range of information available on improving the rainwater harvesting and maintaining rainwater storage tanks (see e.g. SOPAC 2004a, 2004b) and every effort should be made to ensure that installers of rainwater systems are fully trained and that households are aware of the maintenance requirements of rainwater systems. A public education campaign on the proper care and maintenance of rainwater harvesting and storage systems is required.

The National Water Policy recognizes that rainwater harvesting is an important and relatively safe source of the several available sources for meeting water needs. Rainwater harvesting and storage Bye-Laws need to be enforced and considerable community training in the judicious and careful use of rainwater from harvesting and storage systems and in their installation, proper maintenance and repair is required.

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