ENOUGH WATER FOR EVERYONE?

A Modeling Study of Freshwater Resources for Selected Atolls of Yap State, FSM

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WATER AND ENVIRONMENTAL RESEARCH INSTITUTE OF THE WESTERN PACIFIC
UNIVERSITY OF GUAM

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Water and Environmental Research Institute of the Western Pacific
University of Guam, UOG Station, Mangilao, Guam 96923

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Abstract

Water security for the atolls of Yap State is an important area of study at this time due to historical events and projected future climate change. Freshwater supplies on atolls are collected by island residents using rainwater catchments and groundwater is often used to supplement wash water supplies. As a result of the direct collection methods and limited available space for storage, islands are highly sensitive to short-term changes in climate, especially droughts. To aid the island communities in managing their freshwater sources, the Secretariat of the Pacific Community-Global Climate Change Alliance Pacific Small Islands States (SPC-GCCA: PSIS) developed the Adaptation Project through which this study was developed. This report summarizes the tools available to estimate the existing collection and storage capacities of four atoll islands: Eauripik, Ifalik, Satawal, and Falalop (Ulithi). Rainwater collection and storage was modeled using an algebraic model, while the groundwater availability was modeled using a modified version of the USGS numerical model SEAWAT.

One major finding from this study suggests historical rainfall data is adequate for drought planning and preferred to global circulation models (GCMs). Simulations for rainwater catchment and groundwater models show simulations using historical rainfall data provide the most conservative results. This study also provides planning and management strategies including a stepped approach to improving the rainwater collection network, reliability charts for making effective changes to rainwater catchment systems, a range of expected groundwater lens sizes based on future climatic conditions, and general recommendations for preserving sources for future shortages.

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We wish to thank the island residents of Ifalik and Eauripik for graciously inviting our field team into their homes and for their assistance with the field surveys. For assistance with literature and census collection, we would like to thank Bruce Robert of the College of Micronesia – FSM, Stuart Dawrs and Allyson Ota from the University of Hawaii – Manoa, and Itorie Amond and Arnold Canete at the Statistics Bureau of FSM. Finally, we wish to thank Pasha Carruthers from the European Union (EU) and Gillian Cabers from the United States Geological Survey (USGS) for funding the resources for the study.

Introduction

Atolls are perhaps one of the most dynamic geologic formations on earth, subject to change on a whim as a result of surrounding forces from the Pacific environment. There are over 400 atolls in the Pacific and all are constantly building-up, eroding, rotating, or shifting as a result of the surrounding ocean currents, trade winds, and climate disturbances. It seems unlikely that 20 meter high coconut trees are able to survive in this ever changing environment, and even less likely that humans have for hundreds and perhaps thousands of years. Yet, the island communities have thrived and adapted to the dynamic ocean environment, often adapting to temporary losses of resources or migrating to a neighboring island for several months until resources replenish. With help of emergency aid from the Federated States of Micronesia, the outer-lying atolls of Yap State are better equipped to handle loss of life-sustaining resources than they were one hundred years ago. However, anticipated climate change may present intensified challenges for these communities and thus, planning and management of their freshwater resources is an even more critical need.

Area of study

Atolls are low-lying, small, coral reef formations that frequently a composite formation of reef islets in a ring-shape around a lagoon (Davis, 1928) (Vacher, 1997). Atoll is a collective term that typically refers to this classic definition of atolls as well as low-lying reef islands without a significant lagoon (Richmond, Mieremet, & Reiss, 1997). Low is a term originally used in relation to low visibility during early European exploration and thus difficulty of discovery (Vacher, 1997). Researchers have also made distinguishes between low-lying and 'elevated' or 'high' atolls by identifying a maximum elevation, such as 4 or 7 meters above mean sea level (MSL) or less (Pernetta, 1992) (Richmond, Mieremet, & Reiss, 1997). Small is a term defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO) for islands with an area of 2,000 km^2 or less, or with a width of 10 km or less (Vacher, 1997).

Yap State of the Federated States of Micronesia (FSM) is located in the Carolinian archipelago of the western North Pacific Ocean. The state is formed by a group of islands in western-most FSM, from longitude 137ºE to 148ºE and from latitude 7ºN to 10ºN. These islands include Yap Island, the main island of Yap State, formed by a group of high volcanic islands; Fais, a high limestone island 250 km northeast of Yap Island; and 14 outer-lying atolls situated primarily between Yap and Chuuk Islands (Richmond, Mieremet, & Reiss, 1997). The term 'outer-lying' refers to the remoteness of atolls or islands relative to the main islands.

Objectives

The objective of this study is to investigate the existing supply and demand structure for water resources in outer-lying atolls of Yap and identify planning and management tactics that may be

used by the island communities to ensure accessibility in the future. This study examines the water supplies based on historical climate and also lends analysis based on projected climate change scenarios. The method of analysis was divided into the following components:

- Conduct a literature review of published and unpublished materials that aid in evaluating water supplies of Yap outer-island.
- Conduct field survey on Ifalik island by documenting rainwater catchment infrastructure, groundwater wells, public and household storage capacity, and household water needs and use (Maybe note that this portion was done by field team).
- Approximate the water supply-demand structure for the four selected atolls, using data collected from Ifalik and information from the literature.
- Analyze algebraic models and USGS software to find the suitability of the supplies under historical conditions and for projected climate conditions.
- Quantify reliability and recommend improvements for the island communities.

Climate

Atoll island hydrology is heavily shaped by its immediate environment as is the availability of its water supply. In particular, annual precipitation, sea-level, and typhoons are most influential and anticipated climate change would alter these conditions.

Precipitation

Rainfall is the main and sole source of freshwater for remote, outer-lying atolls, therefore, accurate historical data for annual rainfall is important for future planning purposes. Historical precipitation data is available through the National Ocean and Atmospheric Administration (NOAA) for weather stations on several larger islands in Micronesia, including stations at the Yap and Chuuk Weather Service Office Airports. These two stations provide the most complete historical climatic data for Yap State dating as far back as 1951. Average climate indices for the nearest airports are shown in Table 1.

Table 1 – Average annual precipitation and daily temperature for regional airport weather stations.

STATION_NAME	Annual Precipitation (m)	Average daily temperature (ºC)[1]	Maximum daily temperature (ºC)	Minimum daily temperature (ºC)
YAP ISLAND WEATHER SERVICE OFFICE AIRPORT FM	3.07	27.6	30.2	24.9
CHUUK WEATHER SERVICE OFFICE AIRPORT FM	3.42	28.2	30.9	25.4

[1] Data from the National Oceanic and Atmospheric Administration

As shown in Table 1, the amount of annual rainfall varies regionally and generally decreases from south to north and east to west. Rainfall also varies locally within atolls (Falkland, 1994) (Spennemann, 2006), and according to Falkland 1994, errors in rainfall due to local spatial distribution can be up to 10%. The climate is also humid with average humidity between 83 – 87% (Alkire, 1959) (Tracey, Abbott, & Arnow, 1961).

Yap atolls experience two seasons: a dry season from November to June and a wet season from July to November. Northeasterly trade winds form conditions for the dry season and the wet season occurs when the trade winds subside creating more variable wind patterns at the Intertropical Convergence Zone (ITCZ) (Arnow, 1955) (Anthony, 1997). Droughts commonly occur during the dry season and become increasingly severe as a result of El Nino Southern Oscillation (ENSO) events (White, Falkland, & Scott, 1999). Severe droughts typically occur in the months following an intense El Nino event (Landers & Khosrowpanah, 2004) and severity

can vary to such extremes up to 5% of typical monthly precipitation and 28% of normal seasonal precipitation, as was observed on Yap Island during the dry season in 1983 (Van der Brug, 1986). Historical extreme precipitation years for each airport weather station are shown in Table 2.

Table 2 – Extreme annual precipitation (m) at regional airport weather stations (June to May)

	Precipitation (m), End year - ENSO Event			
STATION	Maximum		Minimum	
YAP ISLAND WEATHER SERVICE OFFICE AIRPORT FM	4.03	(2004)	2.11	(1973 - Strong El Niño)
CHUUK WEATHER SERVICE OFFICE AIRPORT FM	4.59	(1956 - Mild La Niña)	1.82	(1983 - Very Strong El Niño)

[1] Data from the National Oceanic and Atmospheric Administration

As Table 2 demonstrates, annual rainfall can drop to 2/3 the annual average during some El Nino years.

Sea Level

ENSO events also alter sea level elevation. El Nino episodes frequently correspond to a mean sea-level drop (Landers & Khosrowpanah, 2004), while conversely La Nina events lead to higher sea-levels due to higher water temperatures and intensified easterly trade winds. For low-lying atolls, the higher tides exhibited during La Nina events may lead to shoreline erosion and episodes of over wash which can harm important resources such as water and taro (Hezel, 2009).

Typhoons

Both rainwater and groundwater supplies are affected by over wash and salinization that occurs during typhoon events. Typhoons strike Yap atolls relatively infrequently since they typically form over eastern Micronesia near Truk and traverse north to Guam as they develop (Tracey, Abbott, & Arnow, 1961) (Landers & Khosrowpanah, 2004). Instead, strong winds and rain occur as a result of passing storms or large storms at a distance (Tracey, Abbott, & Arnow, 1961) and these events are not regarded as dangerous by the islanders (Levin, 1976). On the rare occurrence that a typhoon strikes, mild to severe damage to natural resources and often human life will occur, and frequently the atoll landform will be altered in some way. In most recent history, super Typhoon Maysak rolled through FSM on March 31st, 2015 causing severe damage to resources on Ulithi among other islands. Up to 60% of structures were leveled due to gusts reaching 160 miles per hour (258 km per hour).

Climate Change

Climate change, naturally or anthropogenically accelerated, alters the frequency, duration, and intensity of extreme weather events and low-lying atolls are especially vulnerable to the impacts. Yap State atolls are susceptible to climate change effects due to their remoteness, limited resources, low topography, and easily erodible sediments. The Intergovernmental Panel on Climate Change (IPCC) predicts the following climate change impacts will occur for small island states in the Pacific: more frequent ENSO events, increase in mean sea level rise, and intensified typhoons (Barros, Field, Dahe, & Stocker, 2012).

ENSO Events

IPCC noted they have a medium confidence that an observed increase in frequency of ENSO events has occurred since 1950 in the equatorial Pacific (Barros, Field, Dahe, & Stocker, 2012). Future increases in intensity and frequency of ENSO events will increase the occurrence and severity of droughts for the outer-lying atolls which inhibits access to freshwater.

Accelerated Sea Level Rise

Sea-level rise (SLR) is occurring on a global scale at roughly 1.7 mm/yr based on tide gauge observations, and roughly 2.8-3.6 mm/yr based on satellite altimetry data. This is referred to as the global mean sea level (GMSL) (Kensch, Ford, & McLean, 2015). Pacific island nations have observed an increase in mean sea level and it is very likely to continue in the near future (Barros, Field, Dahe, & Stocker, 2012).The impacts of SLR include saltwater inundation of the surface, saltwater intrusion into the aquifers, erosion of shoreline, and a landward shift of the saltwater interface (Barros, Field, Dahe, & Stocker, 2012) (Holding & Allen, 2015). However, atolls have shown dynamic responses and some may be more resilient to SLR than others (Kensch, Ford, & McLean, 2015). In addition, effects would vary from depending on island location within the atoll and the geologic history.

Intensified Typhoons

In addition, the IPCC notes that it is likely that wind speeds of tropical cyclones will intensify in the future, however, frequency will likely remain stable or decrease (Barros, Field, Dahe, & Stocker, 2012). Intensified typhoons may result in more devastating effects on the natural resources and loss of human life. The landform shape, location, and size would also be more dramatically altered by intensified typhoons.

Hydrology

The hydrology of coral atolls is relatively simplistic. The - sole source of freshwater on Pacific atolls is rainfall, which permeates readily through the permeable soils and becomes stored in the underlying aquifer as a freshwater lens. Runoff is commonly neglected as it occurs only in paved or compacted areas or when soils are saturated during heavy rains (Arnow, 1955) (Falkland, 1994). Storage is impacted primarily by island geology and vegetation.

Coral atoll islands vary in sedimentary composition based on their location relative to the tradewinds. The windward islets are located upwind within the atoll and are therefore exposed to the northeasterly winds and associated swells that occur during storms (Spennemann, 2006). An example of windward and leeward islands on Majuro Atoll in the Republic of the Marshall Islands is shown in Figure 1. Fine grained sediments are found on the lagoon side and sediments become coarser across the island to the ocean shore (Spennemann, 2006). This leads to an asymmetrical freshwater lenses that is thickest toward the lagoon side.

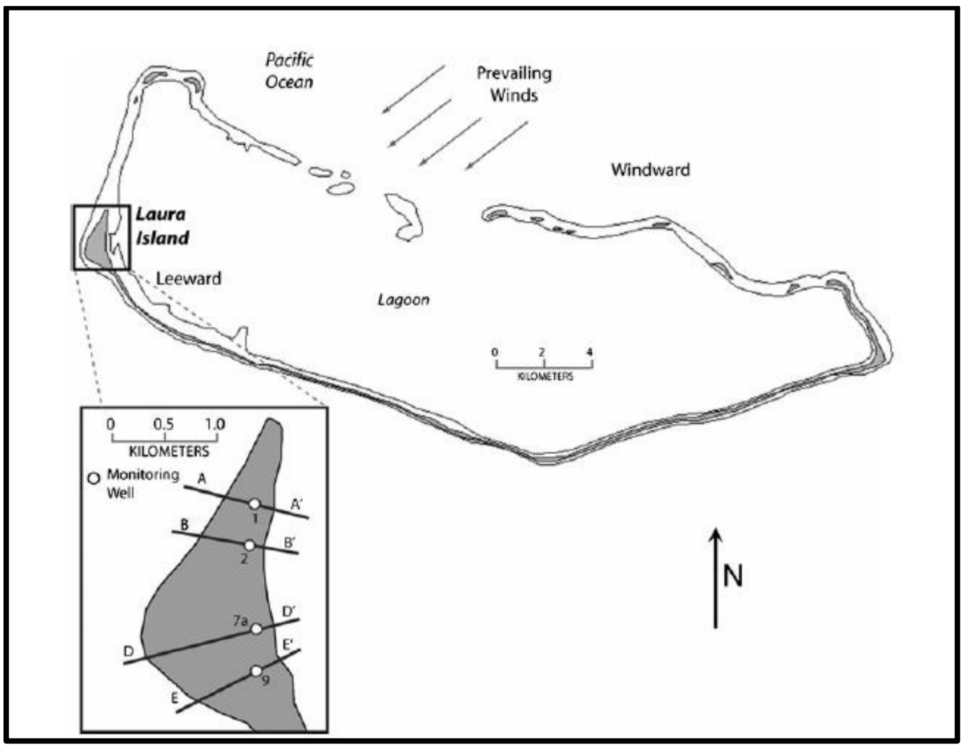

Figure 1 – Example of Windward and Leeward Islands on an Atoll (Bailey 2013)

The geology of Pacific atoll islands is formed by two distinct layers. The top layer is a layer of Holocene sands with relatively low permeability and below this lies a Pleistocene reef deposit

with relatively high permeability (Anthony, 1997). This dual-layer geology also creates a dual-layer aquifer system. The depth of contact to the Pleistocene deposits is typically 15 – 25 meters deep (Anthony, 1997) and Bailey found it varied from 15 to 20 meters for 5 selected atolls in FSM (Bailey, 2013). In addition, Pacific atolls frequently have a reef flat-plate near the surface of the atoll, layered between surficial sediments and the lower Holocene sediments. This layer is a semi-permeable reef rock that confines the upper Holocene aquifer and thickens the freshwater lens (Bailey, 2013). Finally, island width is an important parameter to consider in estimation of the lens size.

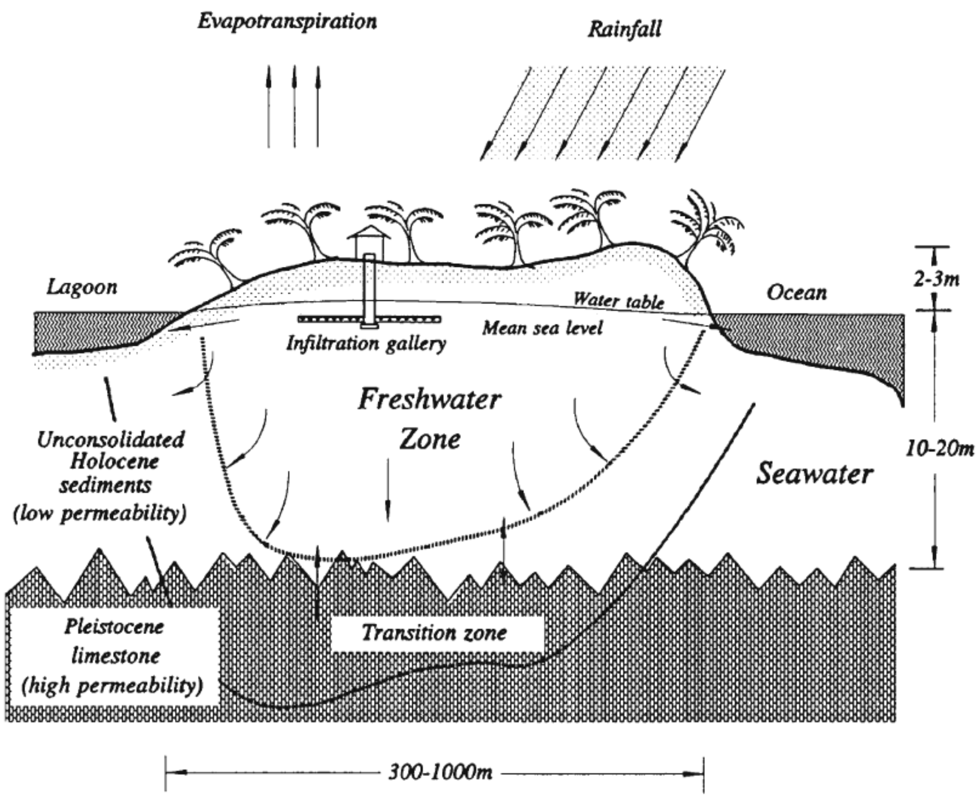

Figure 2 – Exaggerated vertical scale cross section through a small coral island (White & Falkland, 2010)

Researchers have estimated hydraulic conductivity based on typical soil compositions that occur. For estimating hydraulic conductivity of islets based on position relative to prevailing winds on an atoll, leeward islets can be truncated to 50 m/day and 400 m/day for windward islands (Bailey, 2013). Between the freshwater lens and seawater is a broad transition zone that connects the freshwater lens to the saline ocean water (Falkland, 1994). This zone is typically as large or larger than the freshwater lens.

Precipitation measured on land is much greater than the amount of water that reaches the groundwater lens, or recharge. There are several 'sinks' by which precipitation is intercepted before reaching the groundwater lens, and the largest are vegetative losses and storage in the

unsaturated zone. Vegetative losses are an important component of island hydrology, and coconut trees perhaps play the largest role. The trees are foremost a vital resource to the islanders providing water, food, and shade; however, deep-rooted trees also compete with residents for water through interception, evapotranspiration, and direct extraction from the groundwater. Besides vegetation, water is stored in pore spaces within the unsaturated zone which is another ‘sink’ that intercepts water from the lens.

To account for these sinks in the water balance, recharge to the freshwater lens is often simplified to a percentage of the measured precipitation to account for these vegetative losses and water remaining in the unsaturated zone. This recharge percentage is often estimated at 50% of precipitation.

Demographics and Water Demands

As of the 2010 census, the population in Yap State was 11,377 residents and most residents reside in Yap Proper while 4,006 residents live in the outer-islands (FSM National Government, 2010). Refer to Table 3 for population of the outer-lying atolls from 1920 to the present.

Table 3 – Historical Population for Yap State and Selected Atolls

	Population[1]					
Year	**Yap**	**Outer-Islands**	**Ulithi**	**Eauripik**	**Ifalik**	**Satawal**
1920	8,338	2,960	450	-	-	292
1925	7,366	2,711	508	103	295	250
1930	6,486	2,465	448	110	305	253
1935	6,006	2,312	408	102	252	264
1958	5,540	2,299	460	141	301	285
1973	7,870	2,731	710	127	314	354
1980	8,100	2,908	710	121	389	386
1987	10,139	3,488	852	101	477	466
1994	11,178	4,259	1,016	118	653	560
2000	11,241	3,850	773	113	561	531
2010	11,377	4,006	847	114	578	501

[1]Population data from FSM 2000 and 2010 Census

As shown by Table 3, population fluctuations are most significant in Ulithi which also has the greatest number of inhabitants, and populations remain most stable on Eauripik which has the lowest number of inhabitants. From 2000 to 2010, Ulithi had the highest annual growth rate at 10%. Satawal was the only atoll that decreased in population size, with an annual population growth rate of -0.6%.

In general, atolls communities use water primarily from rain catchments for drinking and cooking certain types of foods. Most other purposes, including washwater purposes, pose a lower risk of health concerns by water contamination and, therefore, groundwater or seawater is used for these needs. Groundwater is also occasionally used to supplement drinking water supplies during droughts or shortages and it is common for island residents to boil the water first (Anthony, 1997). Coconut water is also frequently used for drinking purposes. It should be noted that there are variations to this structure on an island to island basis.

Since island residents typically use saline groundwater or seawater for washwater needs, water demands typically are in reference to drinking water demand. Generally, residents have low demands due to limited availability of freshwater and estimates range from 8 to 16 liters per capita per day (WERI Report No. 157). Refer to Table 4 for estimated water demands for each island.

Table 4 – Estimated water demands for selected Yap outer islands

Island	2010 Population	Annual growth rate	Projected 2020 Population	8 liters/capita/day 2010 Demand (L)	8 liters/capita/day 2020 Demand (L)	16 liters/capita/day 2010 Demand (L)	16 liters/capita/day 2020 Demand (L)
Eauripik	114	0.09%	115	912	920	1,824	1,840
Falalop	475[1]	0.96%[2]	521	3,800	4,168	7,600	8,336
Ifalik	578	0.30%	596	4,624	4,768	9,248	9,536
Satawal	501	-0.56%	473	4,008	3,784	8,016	7,568

[1] Estimate based on 2010 Census and Ulithi Marine Conservation

[2] Assume same growth rate as Ulithi Atoll

Additionally, residents can ration at great lengths when necessary. For instance, a USGS study in Ulithi during the 1983-1984 drought found that water consumption dropped to 1.89 liters of water per capita per day on Asor and Fassarai islands (Van der Brug, 1986).

Rainwater collection and storage

An effective rainwater catchment system (RWCS) both collects and stores water to sufficiently meet the demand of the users. A standard household rooftop RWCS (Figure 3) consists of a guttered catchment area, a conveyance system to deliver capture rainwater from the catchment area, and a storage tank.

Time-dependent fluctuation of rainwater volume in the tank can be estimated using a simple water balance. The method accounts for depth of rainfall, water demand, guttered roof catchment area, storage tank capacity, and gutter system conveyance efficiency.

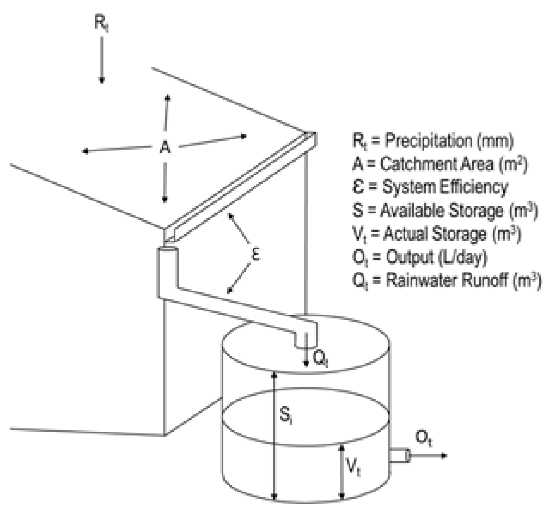

Figure 3 – Schematic of Rooftop Catchment System

Efficiency is defined as the portion of rainwater volume that is delivered from the catchment area to the storage tank after losses due to leaking or spills. The volume stored at the end of the selected time step is calculated as:

$$V_t = \max\left\{V_{t-1} + \min\left[\left(AP_t\varepsilon\right),\left(S - V_{t-1}\right)\right] - O_t, 0\right\} \quad (1)$$

where V_t is the volume of stored rainwater at the end of the day, V_{t-1} is the stored rainwater volume at the end of the previous day, A is the rooftop catchment area connected to the guttering system, P_t is the depth of precipitation for the day, ε is the efficiency, S is the storage tank volume, and O_t is the water removed from the tank during the day. The volume of captured rainwater volume for a given day is calculated by the product AP_t, which is multiplied by ε to provide the potential volume of water entering the tank.

Overview of Methods

This section provides estimates of stored rainwater volume by rainwater catchment systems (RWCS) for the island of Ifalik for both historical and future rainfall conditions. A simple water

balance model is used to estimate daily stored volumes in each RWCS for the 1997-1999 time period and for the 2015-2086 time period, with General Circulation Model (GCM) output used as rainfall data for the latter. Model simulations were run using both current roof catchment areas and potential roof catchment areas, with the latter using all of the available roof area to collect rainwater. The water balance model also was used to develop design curves; i.e., relationships between roof catchment area and water tank volume that will provide a certain rate of reliability.

Rainwater Catchment Systems of Ifalik

One hundred operational RWCS were identified through field work performed on the island during August 2015. Pictures showing examples of RWCS are contained within the field work portion of this report (cite report #157). The characteristics of each RWCS were recorded, including guttered roof area, potential guttered roof area, water tank volume, condition of gutter, and the number of residents within each compound. If multiple catchment systems are contained within a single compound, then the number of residents using each storage tank was estimated using the size of each tank. Figure 1 shows the currently used catchment area for each of the 100 systems (Figure 1A) and the potential catchment area for each system (Figure 1B), with the latter using all of the available roof area. As will be shown in the following sections, using the available roof area as a catchment area could greatly increase reliability for the island community.

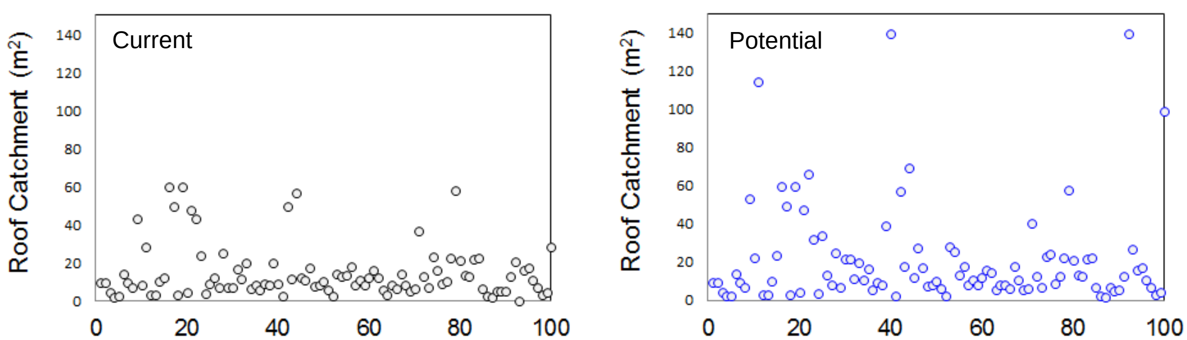

Figure 4 – Current and Potential Roof Catchment areas for the RWCS of Ifalik.

Analysis of Water Storage – Historical Rainfall Patterns

Equation (1) is used to estimate daily stored volumes of rainwater for each of the 100 RWCS during the 1997-1999 time period. This period was chosen due to the extreme drought that occurred in the western Caroline Islands during the first few months of 1998. To perform the analysis, the following characteristics are needed for each RWCS (see Equation 1 above):

- Roof catchment area A (m^2)
- Storage tank capacity S (m^3)
- System efficiency ε

- Daily output *O* (m^3)

Values of roof catchment area and storage tank capacity are obtained from the household surveys. System efficiency is estimated from the surveys, with the following values related to qualitative descriptions of the guttering system:

- "Very Good" = 0.8
- "Good" = 0.7
- "Fair" = 0.55
- "Poor" = 0.4
- "Very Poor" = 0.2

These ratings are based on a survey of the published literature, with a system efficiency value of 0.7 considered to be "average" or "good". Of the 100 RWCS, 90 received a rating of "Good".

Daily output was estimated using an estimate of the daily per capita demand (L/day) and the number of residents using each storage tank. The daily per capita demand (L/day) was estimated using results of the household interviews, particularly from Question 13: "**If it stopped raining from now on, how long would your full supply last?"** The answers ranged from 2-3 weeks to 1 month. The majority of answers indicated that approximately 2 weeks would be required to deplete a full water tank to half capacity. Using this information and the estimated number of residents for each tank, the average per capita demand rate is estimated to be approximately 12 L/day, with minimum and maximum of 7 L/day and 16 L/day.

For the first set of model simulations, the per capita demand rate was set to 12 L/day. Figure 3 shows the simulated daily volumes of 3 RWCS during 1997-1999. RWCS 1 and 2 have a tank capacity of approximately 1.8 m^3 (1,800 L), whereas RWCS 3 has a tank capacity of 3.0 m^3. Notice that steep decline in stored water during the 1998 drought months. Only RWCS 3 has water stored during the drought due to the larger tank size and the less number of residents (three compared to four residents for RWCS 1 and six residents for RWCS 2).

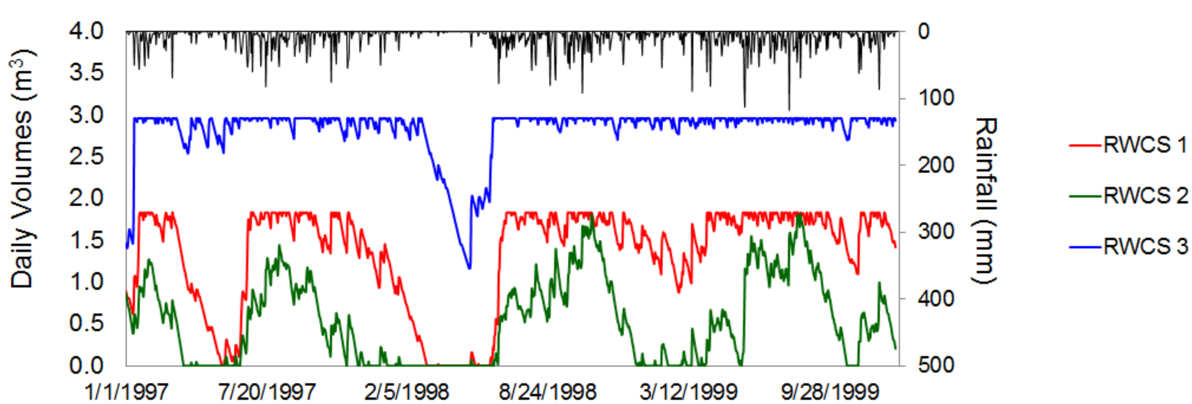

Figure 5 – Estimated daily stored volumes for 3 RWCS of Ifalik, during the 1997-1999 time period.

Figure 4 shows the daily stored water for each of the 100 RWCS of the community. Figure 5 shows the "Reliability" of each system, with reliability defined as the portion of days during the study period that have water in the storage tank. A value of "1.00" indicates that the tank has water during each day during 1997-1999, even during the drought period of 1998. As seen in Figure 5, only a small fraction of the RWCS on the island likely had sufficient water during the drought.

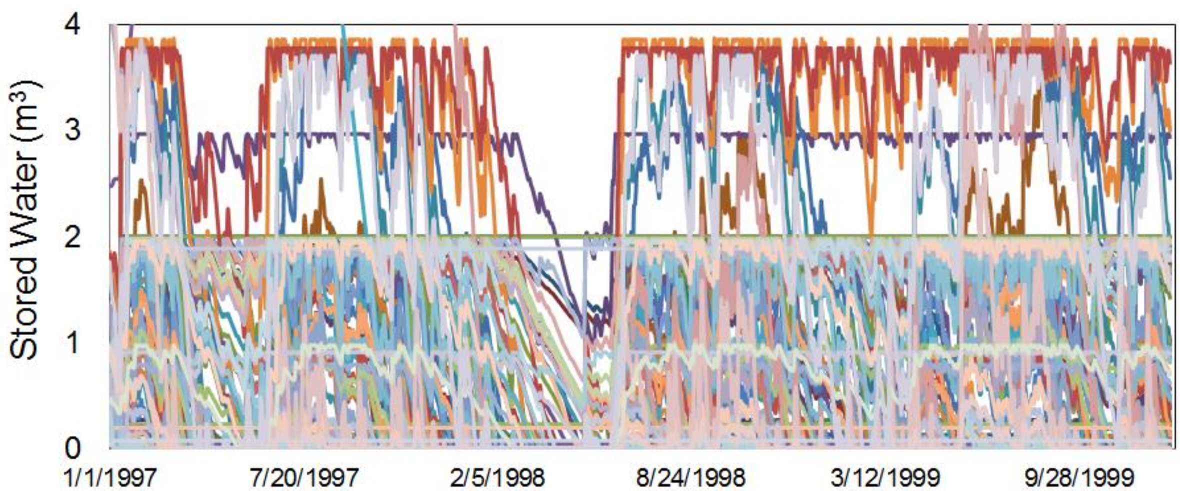

Figure 6 – Estimated daily stored volumes for each of the 100 RWCS of Ifalik, during the 1997-1999 time period.

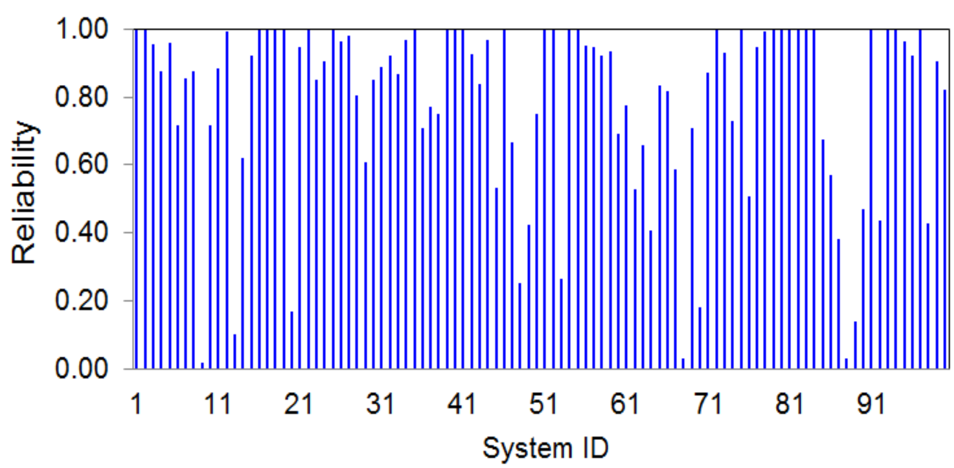

Figure 7 – Reliability of each RWCS during the 1997-1999 period.

Due to several system parameters (degree of rationing, fraction of tank that is full at the beginning of the study period, per capita daily demand), simulations were run for various values of these parameters. Seven scenarios were run, with degree of rationing (i.e. fraction of daily

demand that is implemented when the tank is less than half full) ranging between 50% and 75%, fraction of tank full at the beginning of the study period ranging between 30% and 70%, and per capita daily demand ranging between 8 L/day and 16 L/day. For each model run, the total stored water volume in the entire community (i.e. adding up volumes in the 100 RWCS) is calculated for each day. Results of the seven scenarios are shown in Figure 6, with the average of the seven scenarios shown in red. As seen in the figure, there is a significant range in estimated stored volumes, although the stored volumes do not reach zero during the drought period in any of the scenarios. This is consistent with results from the household surveys, which indicated that community water has never run out, although individual RWCS can become depleted and households need to borrow water from neighbors.

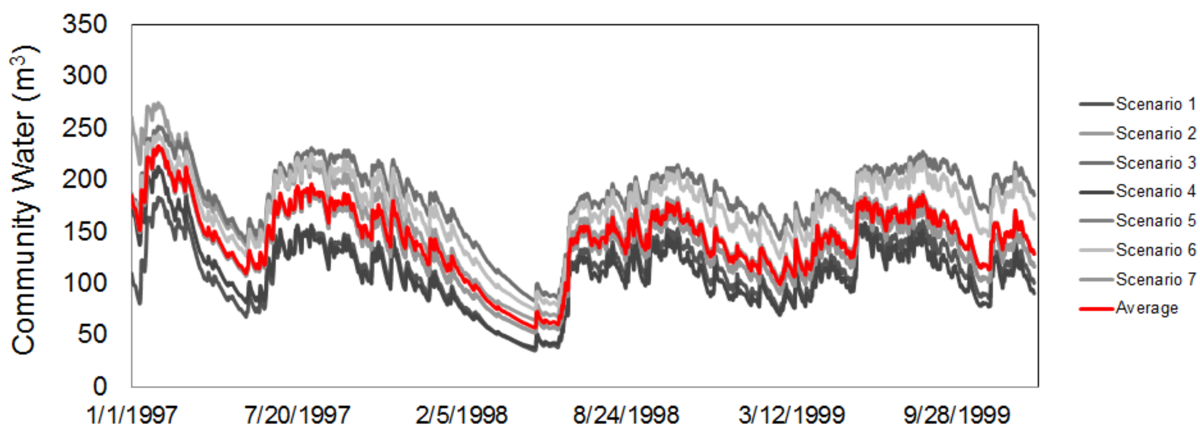

Figure 8 – Total daily stored volume in the 100 RWCS during the 1997-1999 period.

To determine which system parameters should be modified to increase future water storage, the values of 4 parameters (Tank Volume, Guttered Roof Area, Efficiency, Number of Residents) are plotted against reliability for each of the 100 RWCS (Figure 7). As seen in the figure, there is no identifiable trend between reliability and Tank Volume, Efficiency, and Number of Residents, i.e. stored rainwater volume is not influenced significantly by these parameters. On the other hand, there is a trend between Guttered Roof Area and Reliability, with increasing roof area leading to a much higher rate of reliability of the RWCS. These results indicate that Roof Area should be targeted for system improvement.

As such, the effect of increasing Roof Area on stored water volume and associated system reliability was analyzed. This was performed using the potential roof area measured during the household surveys to determine the amount of water that could be stored if the potential roof area is guttered and feeds the storage tank. Figure 8 shows the times of daily stored rainfall for the three individual RWCS (see Figure 3), with the results of using the potential roof area also shown for the three systems. As can be seen, using the potential area greatly increases the amount of water available during the 3-year period, particularly for RWCS #2. For RWCS #2,

the Reliability increased from 0.72 (72% of the days had water) to 0.92 (92% of the days had water) when the potential area is considered. The seven scenarios (see Figure 6) also were re-run using the potential roof areas, with results shown in Figure 9.

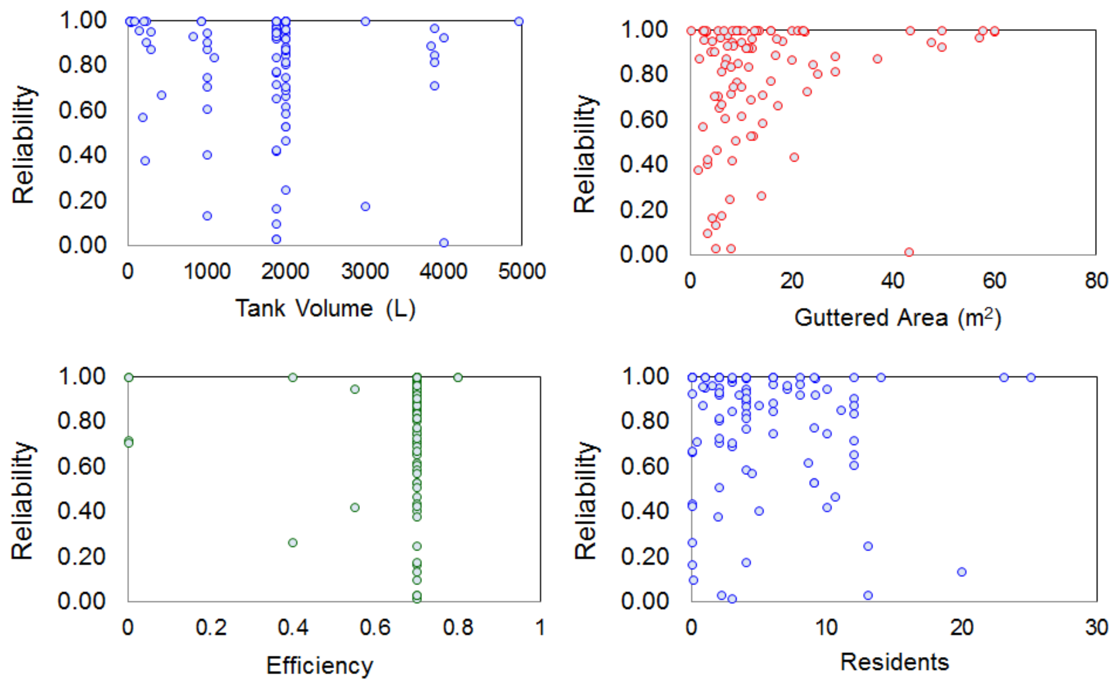

Figure 9 – Plots of parameter values vs. Reliability for Tank Volume, Guttered Roof Area, Efficiency, and number of Residents using water from the RWCS.

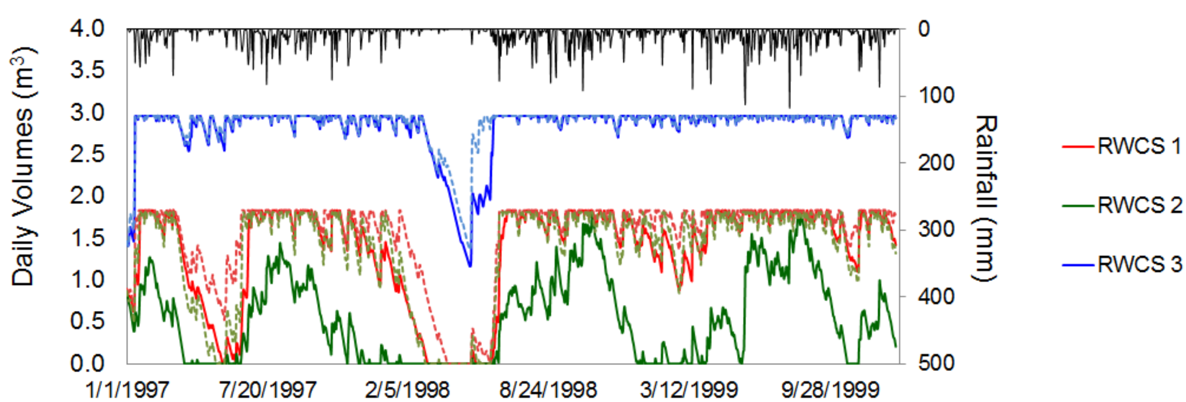

Figure 10 – Estimated daily stored volumes for 3 RWCS of Ifalik, during the 1997-1999 time period, using both Actual Roof Area (dark lines) and Potential Roof Area (dotted light lines).

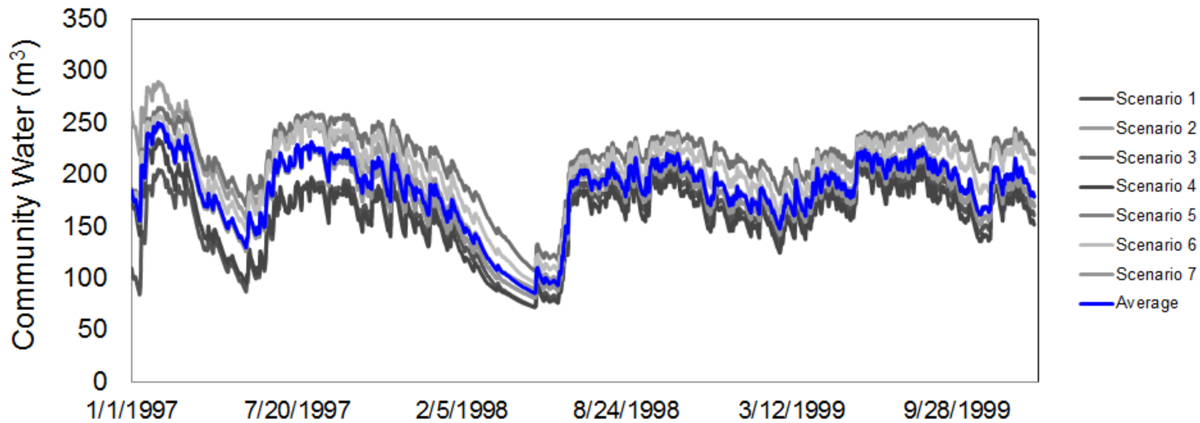

Figure 11 – Total daily stored volume in the 100 RWCS during the 1997-1999 period, using the potential areas.

Analysis of Water Storage – Future Rainfall Patterns

The water balance model also was applied to future time periods using rainfall output from General Circulation Models (GCMs). Monthly precipitation data were statistically downscaled to daily data (Wallace, Bailey, & Arabi, 2015), then the GCM data covering historical periods were compared with measured data to determine which GCMs represented accurately the rainfall patterns of the western FSM region. Details of these methods are contained in Wallace et al. (2015). Of the 26 GCMs assessed, only 5 were found to be accurate in terms of replicating historical rainfall patterns. For the analysis presented in this section, only models from the RCP2.6 model scenario were used as these data are adequate to demonstrate the overall stored volume of rainwater in the community. For the construction of design curves (see Section 1.6.3), models from the RCP8.5 also are used.

Using a rationing value of 75% and a per capita daily demand of 12 L/day, the results of running the water balance model for the time period 2015-2086 for each of the 5 accepted GCMs is shown in Figure 10 for both actual guttered rooftop areas (top figure) and potential areas (bottom figure). As seen in the figures, the total community water never reaches 0 during the 72-year period. Also, using potential areas can greatly increase the stored water volume during the future decades.

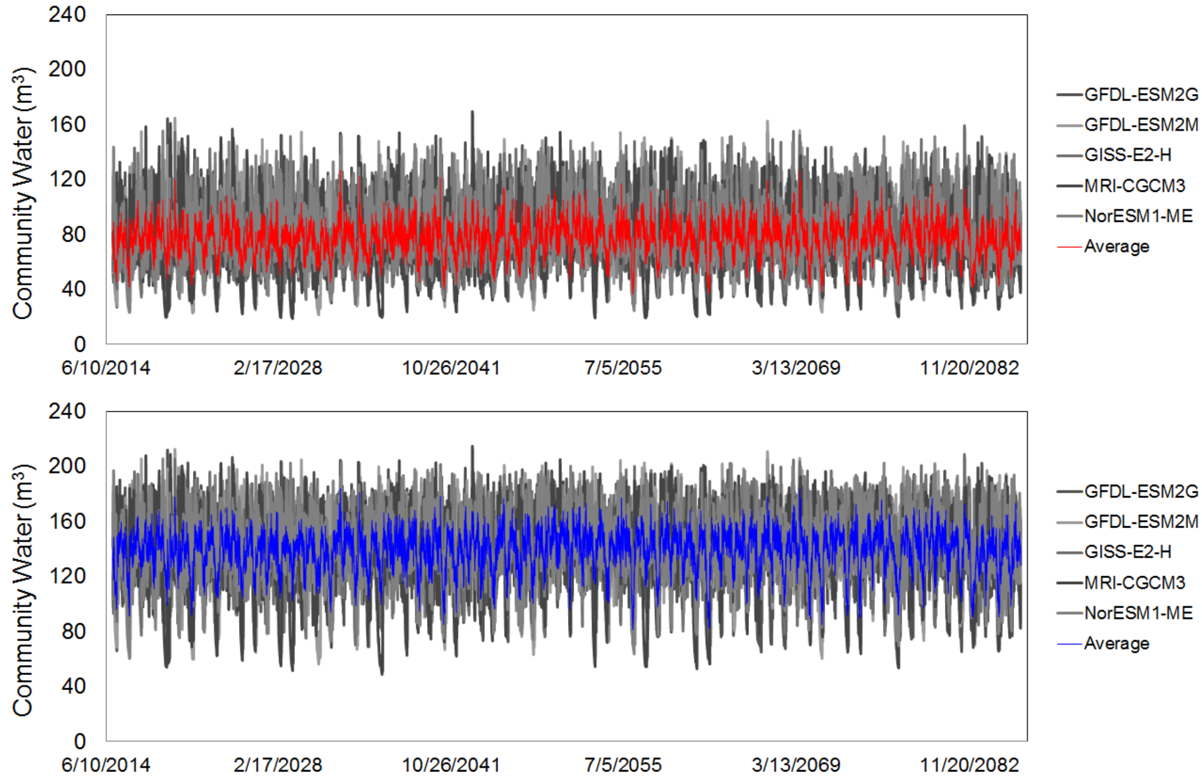

Figure 12 – Total daily stored volume in the 100 RWCS during the 1997-1999 period, using the potential areas.

Design Curves for Rainwater Catchment System Design

Overview of Design Curves

The water balance model of Equation (1) also can be used to develop combinations of roof area and tank size that meet a certain level of reliability, with reliability defined as the portion of time (e.g. 80%, 90%) that the system will meet water demand based on rainfall patterns for a given geographic location. Figure 11 shows an example of a set of design curves. The curves can be used to find the set of catchment area and storage tank size that will meet a certain level of reliability. For example, the capacity of an available storage tank is measured, and the curve can be used to determine which roof area is required to meet that degree of reliability.

The design curves are created using the following method:

1. Select a rate of reliability (for example, 95% = the tank will have water 95% of the days)
2. Select a Roof Catchment Area (for example, 15 m^2)
3. Run the water balance model over the selected study region (for example, 1997-1999). Find the storage tank size that will provide the desired rate of reliability.

4. Repeat Steps 2 and 3 until a sufficient number of area-capacity pairs are assessed that a curve can be drawn through the data points.

In this project, design curves are created using 1) the 1997-1999 rainfall data; and 2) the GCM rainfall data for the years 2015-2086.

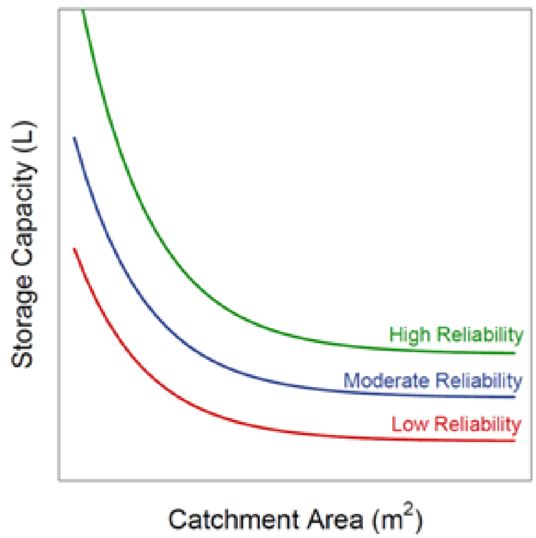

Figure 13 – Example Design Curves for Rainwater Catchment Systems.

Design Curves using 1997-1999 Rainfall Data

The design curves using the 1997-1999 rainfall data are shown in Figure 12. A different set of design curves is presented for differing number of residents (3, 6, 9, and 12) using water from the RWCS. These design curves can be used to determine required roof catchment area for a given tank volume, or the required tank volume for a given roof catchment area, to achieve a certain level of reliability. Reliability rates of 80%, 90%, 95%, and 99% are presented. Notice that larger roof areas and tank volumes are required to achieve a higher rate of reliability, and also that larger areas and volumes are required for households with a higher number of residents.

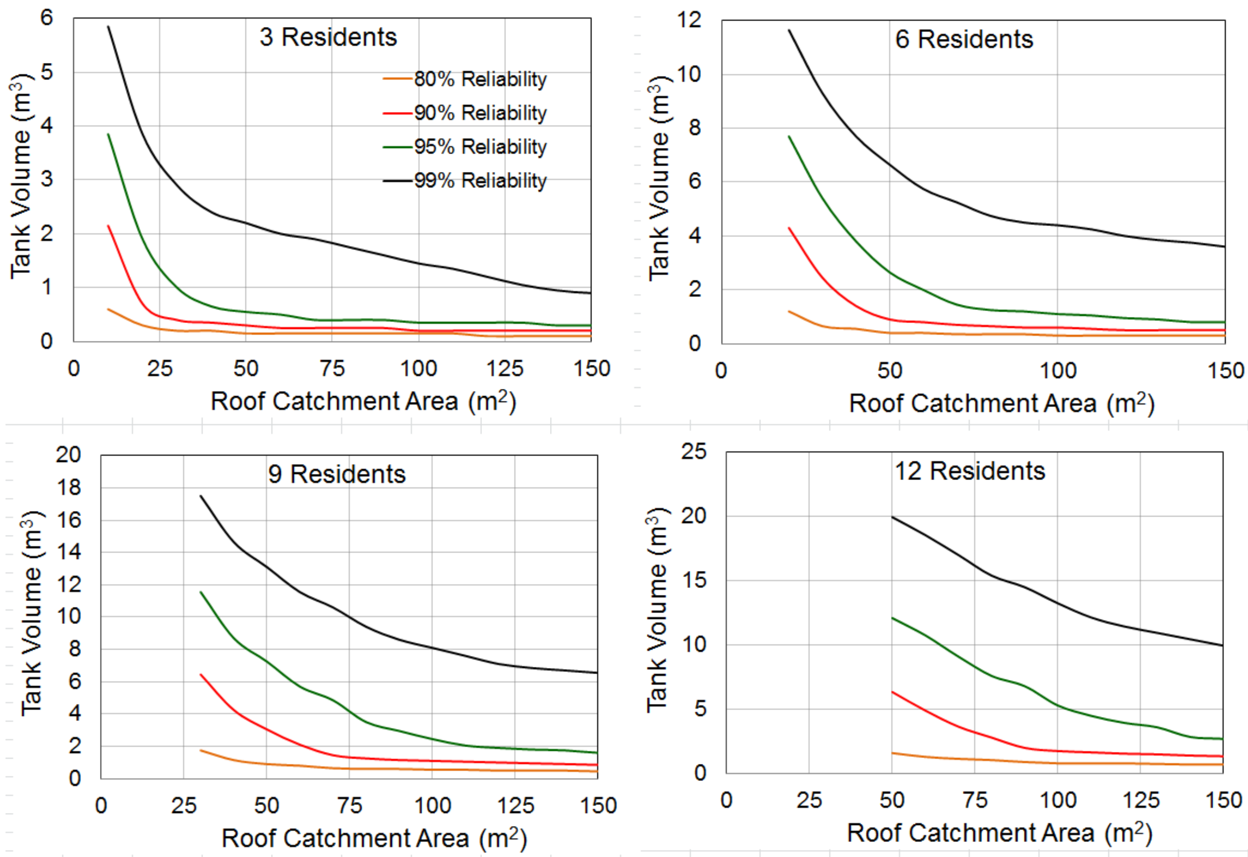

Figure 14 – Design Curves for the 1997-1999 period, for different number of residents using water from the RWCS.

Design Curves using GCM Rainfall Data

Design curves also were created using downscaled rainfall data from the GFDL-ESM2G model. Notice that these curves are much different than the curves created using the 1997-1999 data (see Figure 12). This is due to the fact that the GCMs have difficulty simulating major drought periods, and hence smaller values of roof catchment area and tank volumes will yield a higher rate of reliability. For example, the design curves for the 99% reliability rate are compared in Figure 14 for the 1997-1999 data (red), 3 of the GCMs (GFDL-ESM2G, MRI-CGCM3, and GISS-E2-H) from the RCP2.6 model scenarios, and 5 of the GCMs (MRI-CGCM3, NorESM1-M, GFDL-ESM2G, GFDL-ESM2M, and GISS-E2-H-p2) from the RCP8.5 model scenarios. The design curves using the rainfall data from MRI-CGCM3 are similar to those from using the 1997-1999 data, but the other GCMs have design curves that have much smaller required roof areas and tank volumes to achieve 99% reliability. **Thus, design curves using the 1997-1999 data should be used to design new RWCS or modify existing RWCS, rather than the design curves generated from the GCM climate data. Using the design curves created from the GCM rainfall data likely will underestimate the required roof areas and tank volumes to achieve sustainability during a major drought.**

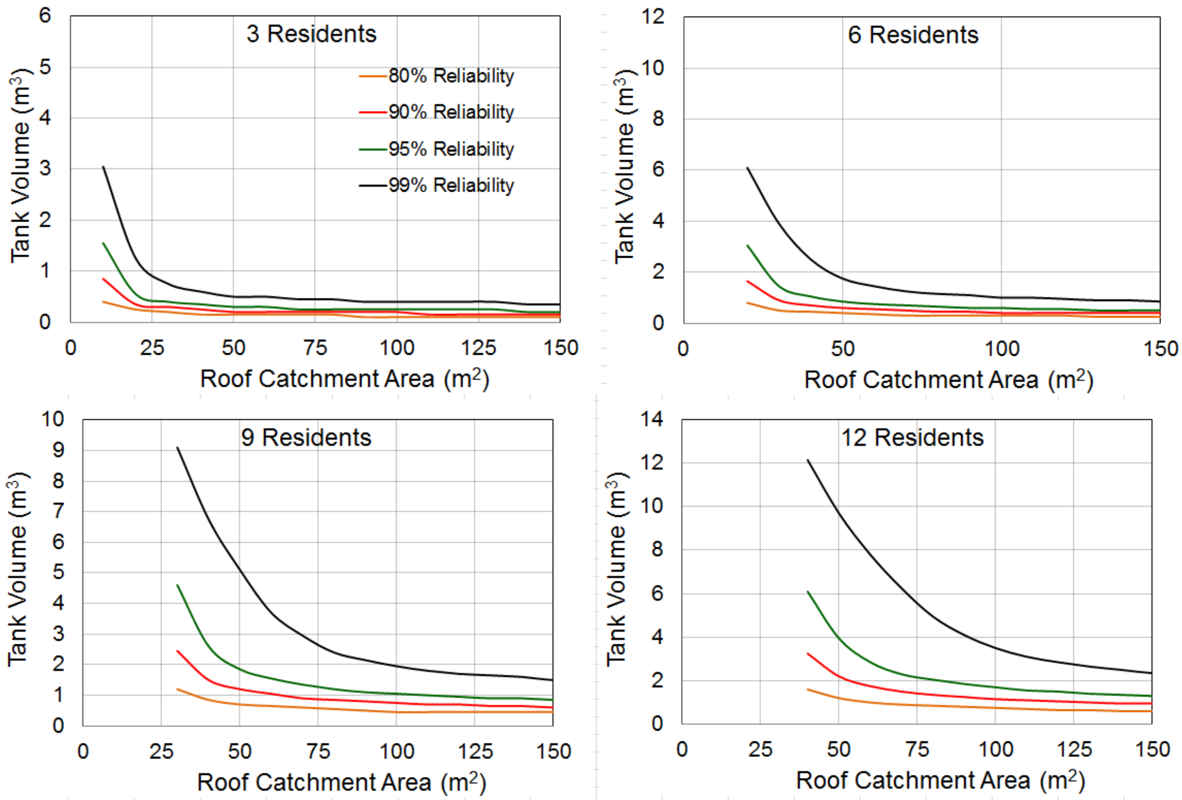

Figure 15 – Design Curves for the 2015-2086 period (using rainfall data from the GCM GFDL-ESM2G), for different number of residents using water from the RWCS.

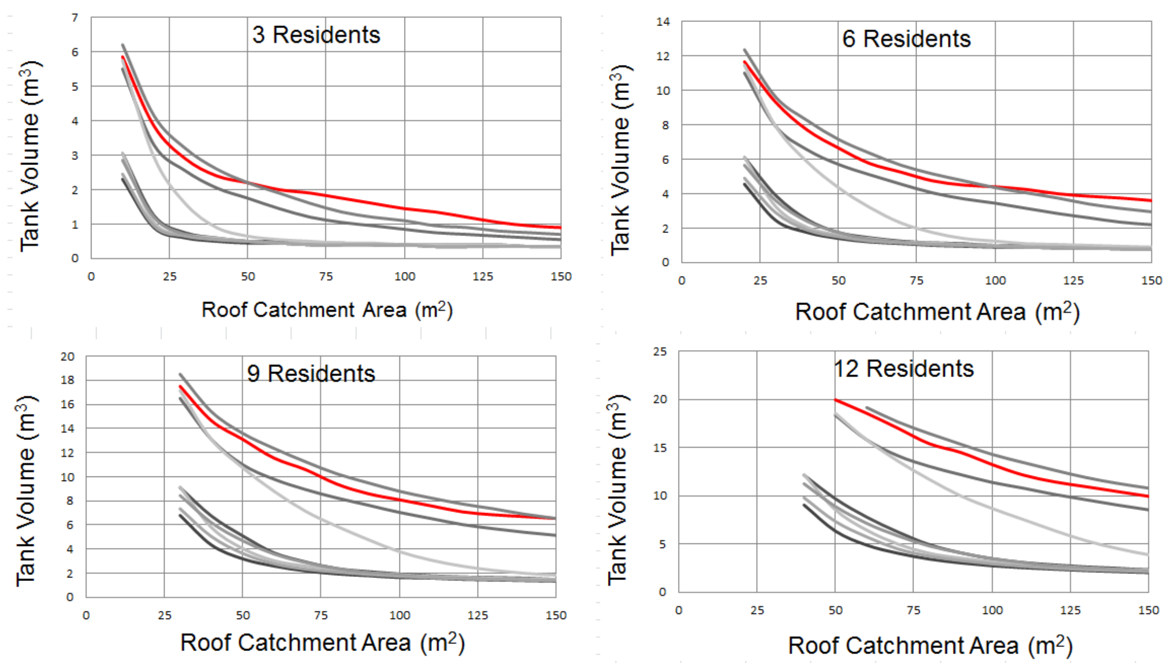

Figure 16 – Design Curves created using the 1997-1999 data and the 2015-2086 period for the GFDL-ESM2G, MRI-CGCM3, and GISS-E2-H models from the RCP2.6 scenarios, and for the MRI-CGCM3, NorESM1-M, GFDL-ESM2G, GFDL-ESM2M, and GISS-E2-H-p2 models from the RCP8.5 scenarios.

Groundwater collection and storage

This section provides preliminary results regarding future groundwater resources for four atolls in Yap State. These atolls are Eauripik, Ifalik, Satawal, and Ulithi. Results will be shown in terms of the thickness of the freshwater lens under the center of each island. The freshwater lens is the body of fresh groundwater, which floats atop the underlying seawater within the aquifer. The following diagram shows the freshwater lens for a typical atoll island.

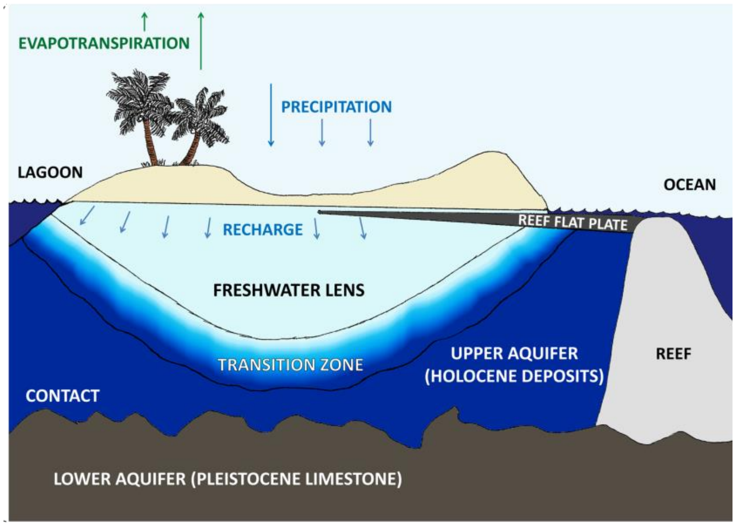

Figure 17 – After Wallace (2015), MS Thesis, Colorado State University (Wallace, 2015)

To provide a prediction of lens thickness under future climate scenarios, the following features were considered:

1. Future variable rainfall patterns
2. Sea level rise

Algebraic Model

Rainfall patterns and rates affect the amount of water that recharges (is added to) the freshwater lens, and sea level rise affects the width of the island and hence the thickness of the freshwater lens. For these preliminary results, annual average rainfall rates for the years 2030 and 2050 were taken from output of General Circulation Models (GCMs) participating in the CMIP5 climate model inter-comparison program. Outputs from the five highest-performing models, in terms of the ability of the models to accurately simulate historical rainfall patterns in Yap State, were used. For each rainfall pattern, sea level rise rates of 0 mm/yr, 3 mm/yr, and 6 mm/yr were assessed, with each rate resulting in a certain decrease in island width. Using the rainfall rates and the new island widths for each of these scenarios, the atoll island algebraic model (Bailey et al., 2010) was used to estimate the lens thickness under the center of the island for the islands on the four atolls.

The first set of figures (Fig. 18?) shows the range of possible lens thickness for each island, for the years 2030 and 2050. The red dots indicate the current lens thickness for each island. The maps indicating the specific islands (e.g. Ifalik A, Eauripik B, etc.) are shown on the following pages. The second set of figures (Fig…) shows the same data, but–as a function of island width–showing that the smaller islands (e.g. Fassarai on Ulithi) generally have thinner lenses, while larger islands (e.g. Satawal) generally have thicker lenses. These results show that there is much variability in future groundwater resources, depending on future rainfall patterns and the expected rate of sea level rise.

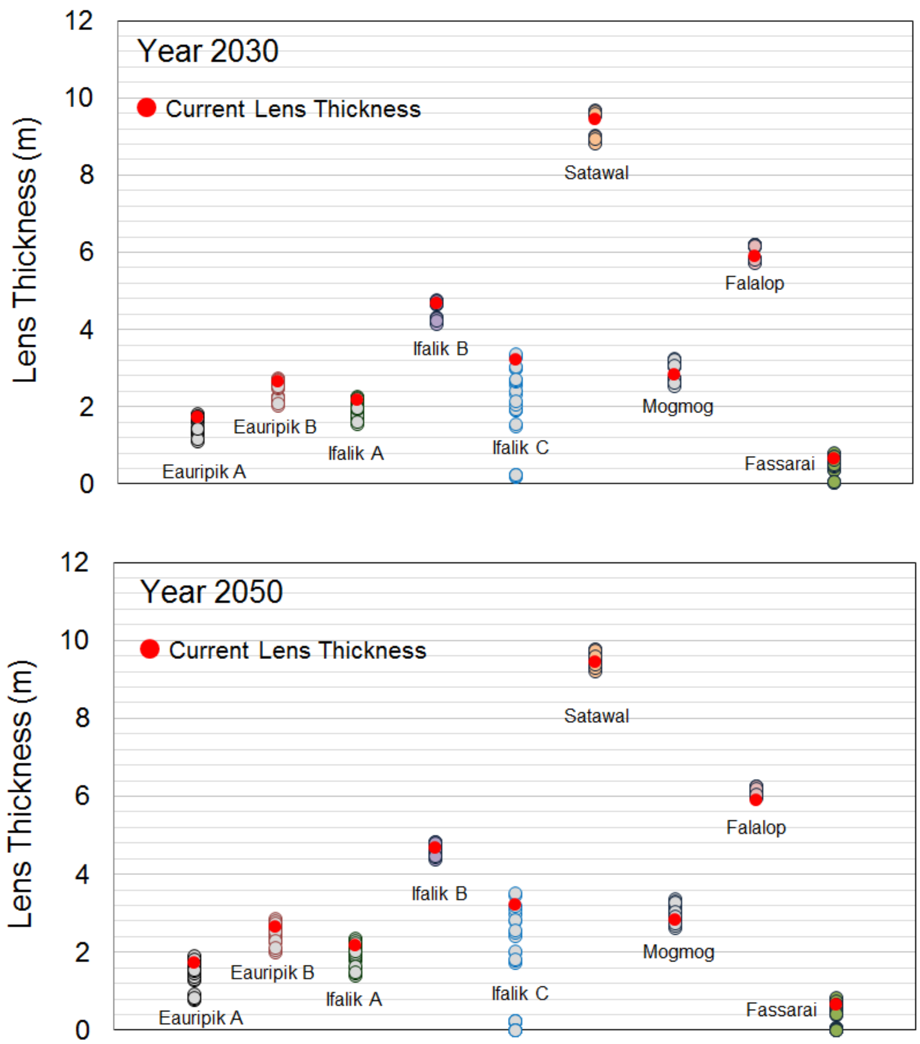

Figure 18 – Maximum groundwater lens thickness for 2030 and 2050 using five different global circulation models

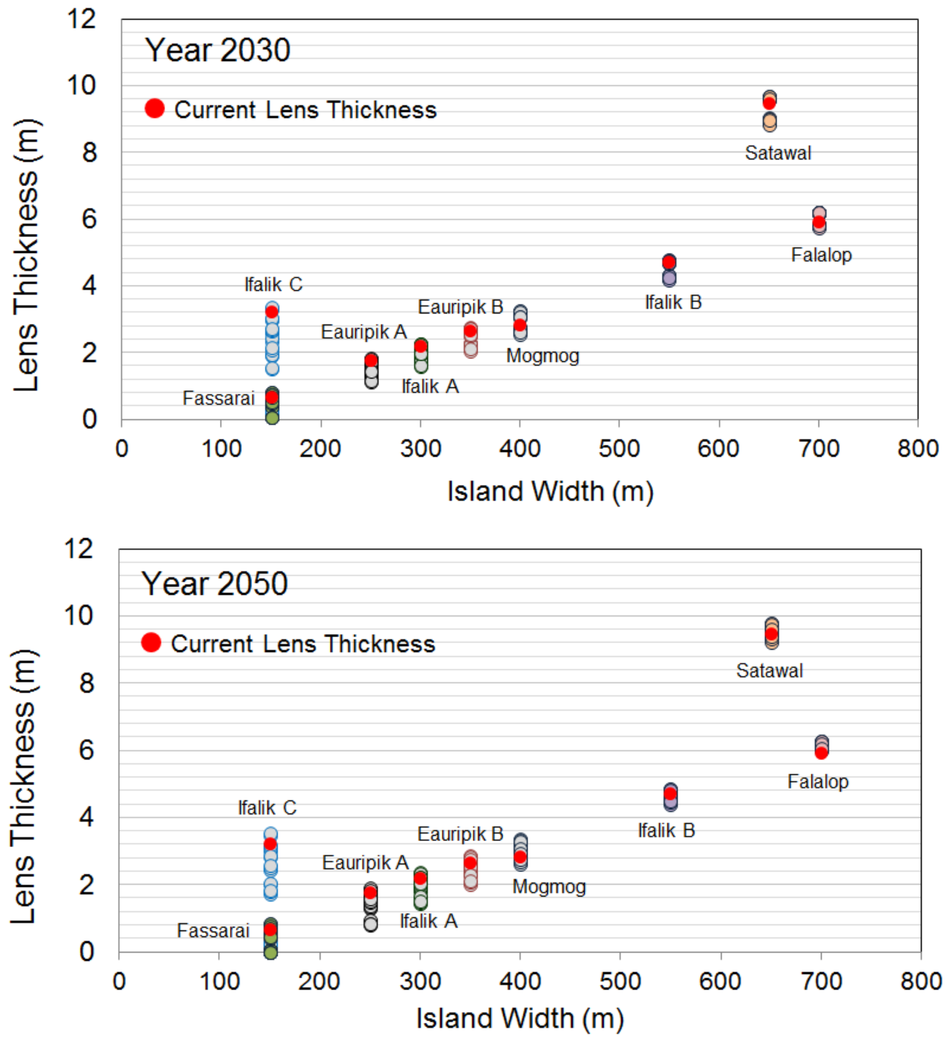

Figure 19 – Maximum groundwater lens thickness by island thickness, for 2030 and 2050 using five different global circulation models

Numerical Model (SEAWAT)

The United States Geological Survey software, SEAWAT, is a MODFLOW derivative software program that models groundwater flow through aquifers with consideration to density.

Steady-state models

For the four islands of interest, a preliminary model was created to estimate steady-state conditions under average annual rainfall. As previously indicated, this is 3.04 meters for Yap State. Recharge to the groundwater lens for this scenario and climate change scenarios was assumed to be 50%, a common simplification in groundwater modeling. In addition, parameters for the Holocene and Pleistocene aquifer were selected based on previous work done on similar islands, and these are included in Table 5.

Table 5 – Initial SEAWAT Parameters

Holocene Aquifer	
Hydraulic conductivity (m/day)	200
Vertical hydraulic conductivity (m/day)	40
Porosity	0.2
Specific storage (m^{-1})	7.50E-04
Specific yield	0.32
Longitudinal dispersivity (m)	5
Transverse dispersivity(m)	1.00E-02
Diffusion (m^2/day)	1.00E-04
Pleistocene Aquifer	
Hydraulic conductivity (m/day)	5,000
Vertical hydraulic conductivity (m/day)	1,000
Porosity	0.3
Specific storage (m^{-1})	7.50E-04
Specific yield	0.32
Longitudinal dispersivity (m)	5
Transverse dispersivity(m)	1.00E-02
Diffusion (m^2/day)	1.00E-04

To discretize the model, ArcGIS map software was implemented to create a shapefile outline of each island. Then, each shapefile was exported into Modelmuse, the USGS MODFLOW program, to aid in creating the grid space. The grid space for the larger islands was composed of 10-meter cells and 5-meter cells were used for smaller islands. Refer to Table 6 for the grid cell size selected for each island and Figure 20 for a visual representation of the Ifalik grid space. Each model used thirty layers of cells and the cell thickness becomes coarser with depth, with the first layer having a thickness of 0.25 meters and the bottom layer thickness at 8 meters. The freshwater lenses for islands of this size are limited to the top 1 – 8 meters, therefore, a finer grid space in this section provides more accurate model results.

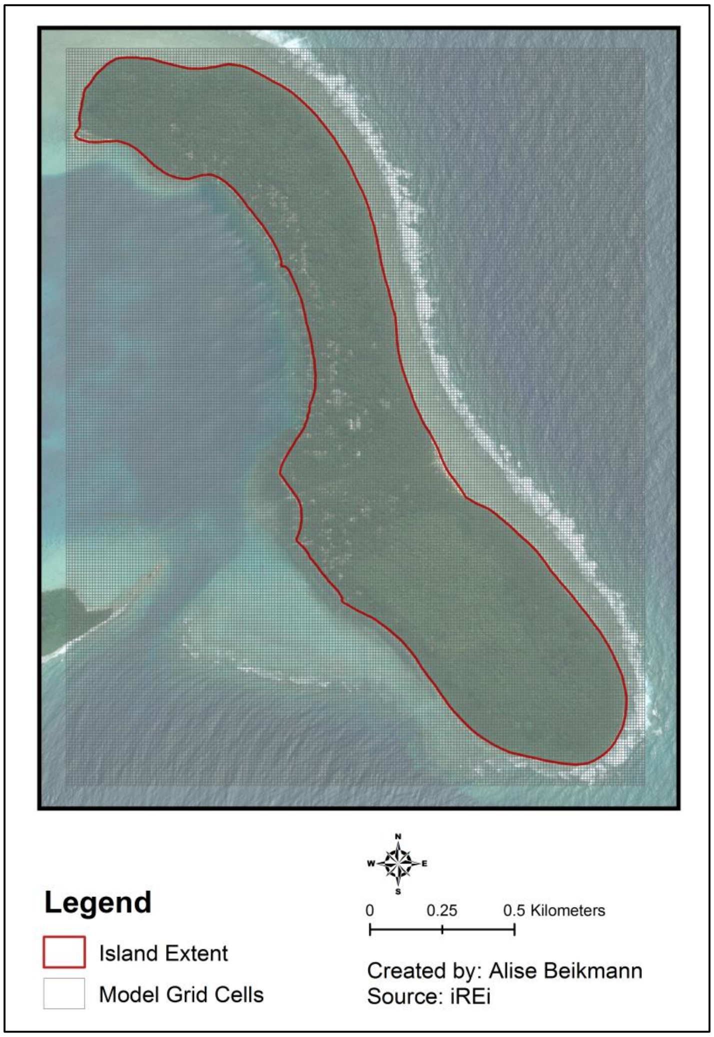

Figure 20 – Discretization for Ifalik SEAWAT Model (10 meter cell size)

Table 6 – Grid cell discretization

Island	Island Area (km^2)	Cell size (m)	Rows	Columns
Eauripik	0.10	5 x 5	62	142
Falalop	0.92	10 x 10	130	120
Ifalik	1.33	10 x 10	255	200
Satawal	1.29	10 x 10	150	190

Calibration of the models relied on data collected on Falalop by Stephen Anthony in 1987-1988, as there is no groundwater data collected on Eauripik or Satawal and data collected in 1953 on Ifalik is minimally useful as Ifalik was still separated into two islands at the time. Therefore, the calibration for the Falalop model with respect to historical rainfall data and corresponding lens

thickness was used for all four models. This was done in the model by changing the hydraulic conductivity until the groundwater thickness in the model corresponded most closely to the water levels measured in October 1987 and January 1988 of the study by Stephen Anthony. Since five wells were measured during this study, the hydraulic conductivity with the lowest average error and lowest residual mean squared error (RSME) is selected for further modeling. Figure 21 shows the locations of the calibration wells on Falalop.

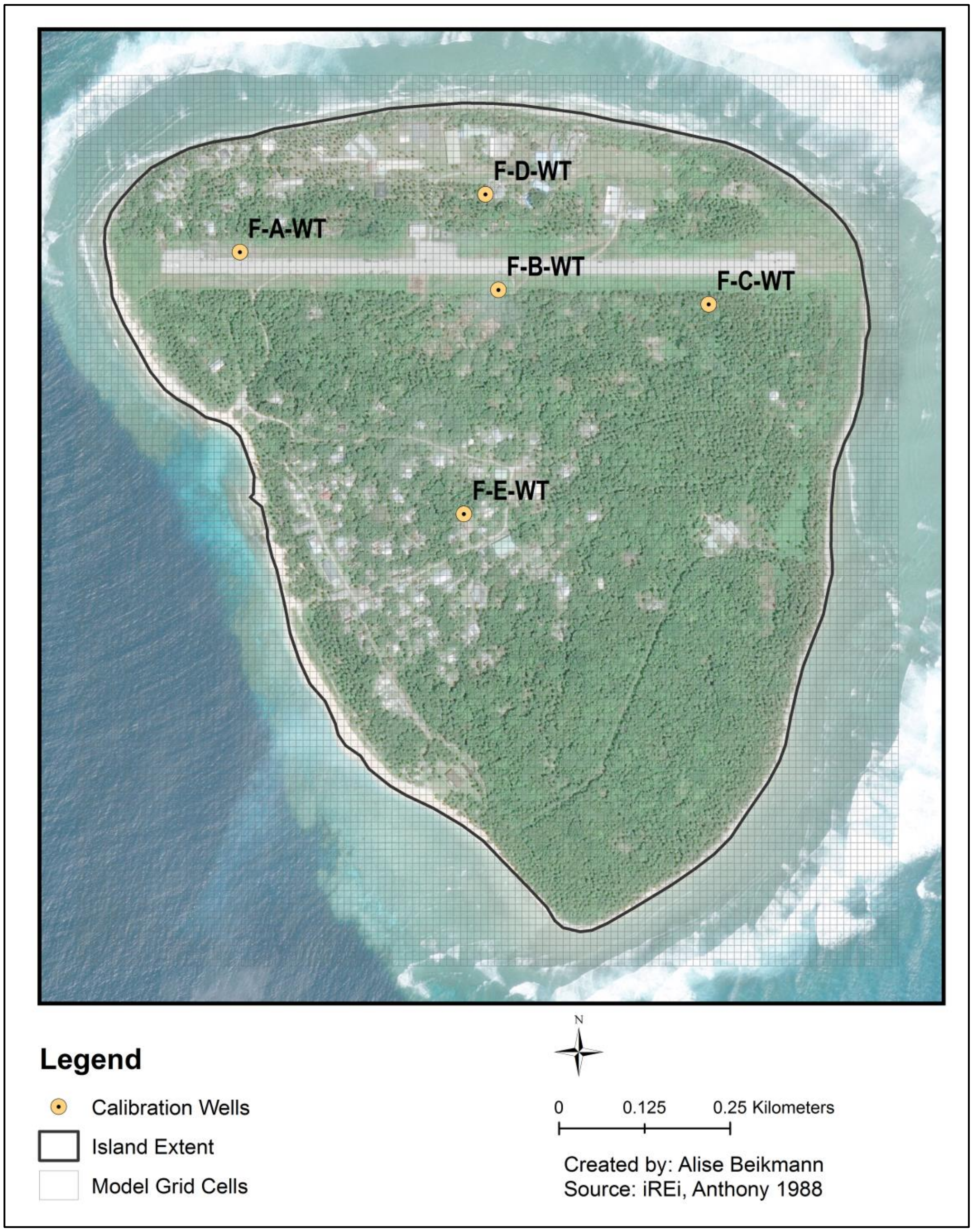

Figure 21 – Map of calibration wells on Falalop

The model hydraulic conductivity was slightly decreased to 175 m/day to develop a thicker lens that matches the observed values. Refer to Table 7 for the final model parameters and Figure 22 for a view of the SEAWAT calibrated model. Results from the calibration are shown in Appendix A.

Table 7 – Calibrated SEAWAT Parameters

Holocene Aquifer	
Hydraulic conductivity (m/day)	175
Vertical hydraulic conductivity (m/day)	35
Porosity	0.2
Specific storage (m^{-1})	7.50E-04
Specific yield	0.32
Longitudinal dispersivity (m)	5
Transverse dispersivity(m)	1.00E-02
Diffusion (m^2/day)	1.00E-04
Pleistocene Aquifer	
Hydraulic conductivity (m/day)	5,000
Vertical hydraulic conductivity (m/day)	1,000
Porosity	0.3
Specific storage (m^{-1})	7.50E-04
Specific yield	0.32
Longitudinal dispersivity (m)	5
Transverse dispersivity(m)	1.00E-02
Diffusion (m^2/day)	1.00E-04

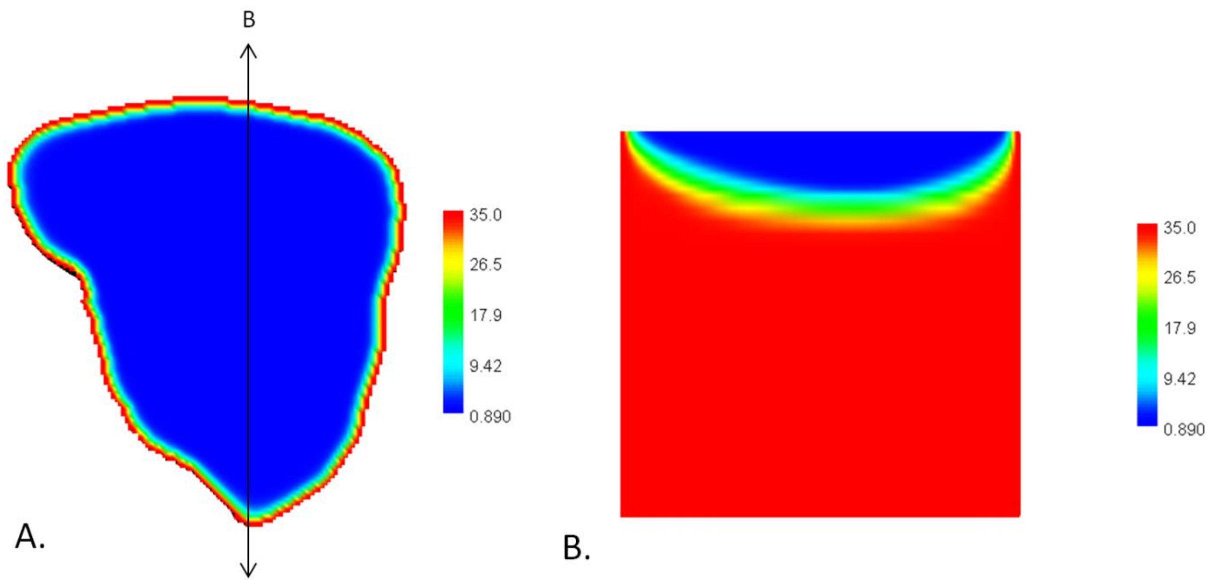

Figure 22 – Falalop Calibrated Model; A. Plan view, B. Profile view

With the calibrated hydraulic conductivity, spin-up models were ran once more for the islands to redevelop the freshwater lens size. Plan and profile views of these islands are shown in Figure 23, Figure 24, and Figure 25. The maximum freshwater lens thickness and total lens volume for each island is shown in Table 8.

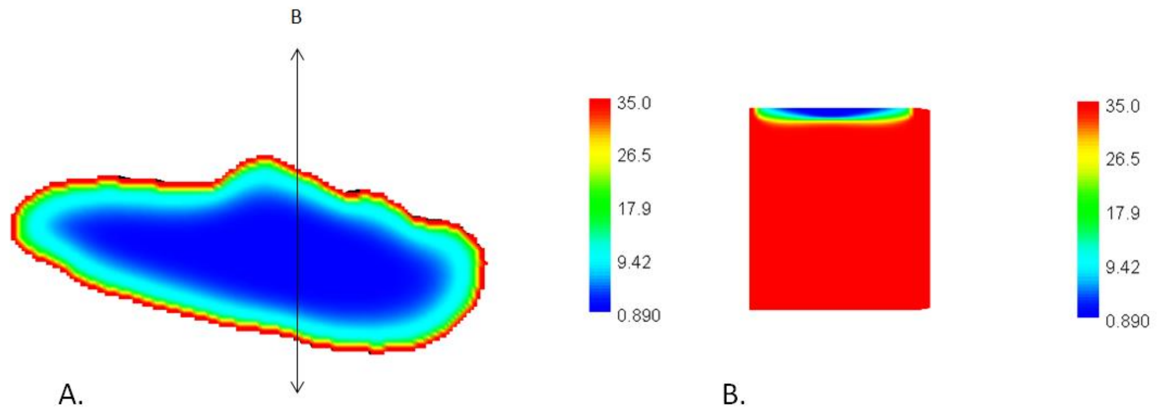

Figure 23 – Eauripik Steady-State Model; A. Plan view, B. Profile view

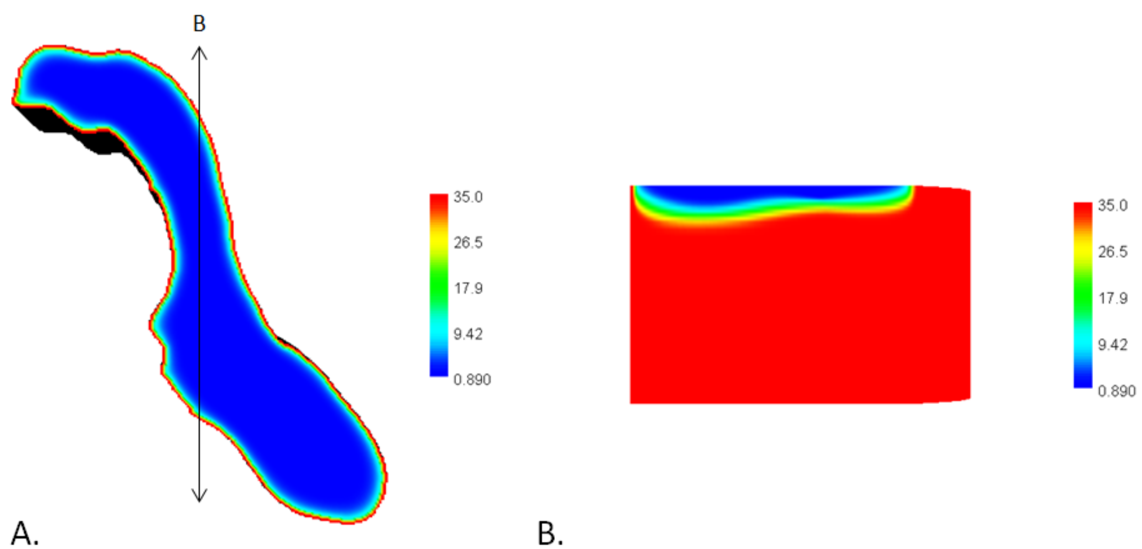

Figure 24 – Ifalik Steady-State Model; Plan view, B. Profile view

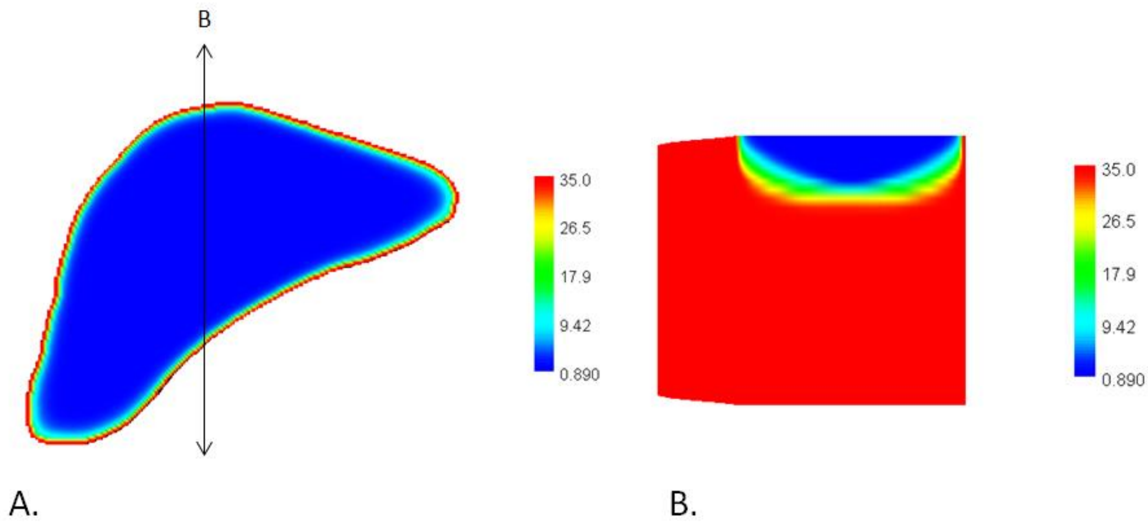

Figure 25 – Satawal Steady-State Model; A. Plan view, B. Profile view

Table 8 – Freshwater lens characteristics under steady-state conditions

Island	**Maximum Lens Thickness (m)**	**Lens Volume (m^3)**
Eauripik	0.86	8,700
Falalop	7.64	2,881,000
Ifalik	5.60	2,473,000
Satawal	7.65	4,100,000

As shown in Table 8, the freshwater lens on Eauripik is less than 1 meter at maximum thickness for average rainfall conditions due to the small island width. Actual lens thickness is most likely smaller since the island is frequently over-washed.

Future Climate Models

Global Circulation Models (GCMs) are used to examine the effects of global climate change, and subsequently precipitation, on the size of the fresh groundwater lens. Due to limitations on time and computer memory, two representative GCM climate models were selected based on the lower and upper representative concentration pathways (RCPs). RCPs are the four greenhouse gas concentration projections selected by the International Panel on Climate Change (IPCC), of which RCP 2.6 is the lower concentration projection and RCP 8.5 is the highest. Qualitatively, RCP 2.6 assumes that anthropogenic greenhouse gas (GHG) emissions peak in the 2010-2020 decade and decrease in annual emissions in years following. Conversely, RCP 8.5 assumes that emissions continue to rise for the next several decades. As found by Wallace et al. 2015, the GCMs that best correlate to historical rainfall data for Yap State are GISS-E2-H for RCP 2.6 and GISS-E2-H-p2 for RCP 8.5. These two models were selected to capture the range of groundwater lens sizes expected with respect to climate change, from 2010 to 2040.

RCP 2.6 Scenario

Results from the 30-year RCP 2.6 climate change scenario are shown graphically in Figure 26 and Figure 27, as the maximum freshwater lens depth, and in Figure 28 – Groundwater lens volume (m^3) for RCP 2.6 Scenario (Falalop, Ifalik, and Satawal)and Figure 29 – Groundwater lens volume (m^3) for RCP 2.6 Scenario (Eauripik) as the lens volume. Note: The groundwater lens thickness for Eauripik is typically zero and is thus shown separately. A statistical summary of the results is displayed in

Table 9.

Table 9 – Statistics for RCP 2.6 GCM GISS-E2-H groundwater model (2010-2040)

	Maximum Thickness (m)				Volume (m^3)			
Island	Average	Maximum	Minimum	Range	Average	Maximum	Minimum	Range
Eauripik	0.05	0.46	0.00	0.46	240	4,599	0	4,599
Falalop	5.55	6.66	4.54	2.12	2,221,676	2,881,682	1,452,704	1,428,978
Ifalik	3.35	4.22	2.46	1.76	1,442,197	2,151,803	737,526	1,414,277
Satawal	5.94	6.95	4.77	2.17	3,272,475	4,195,318	2,189,538	2,005,780

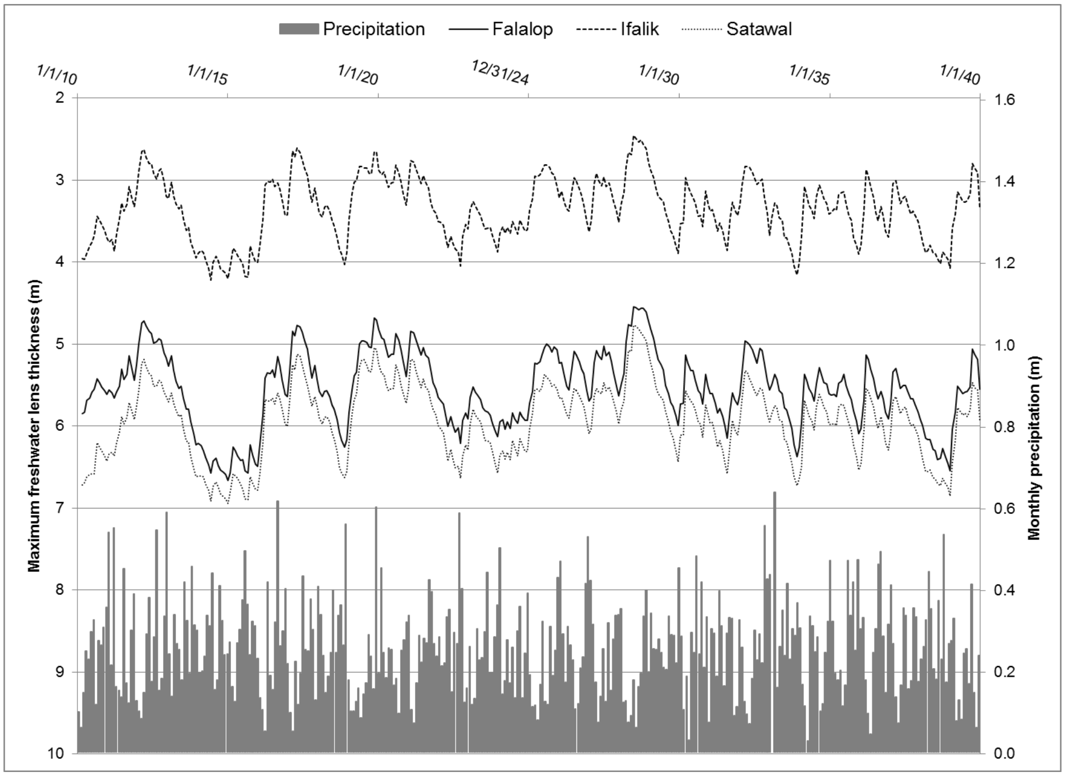

Figure 26 – Groundwater lens thickness (m) for RCP 2.6 Scenario (Falalop, Ifalik, and Satawal)

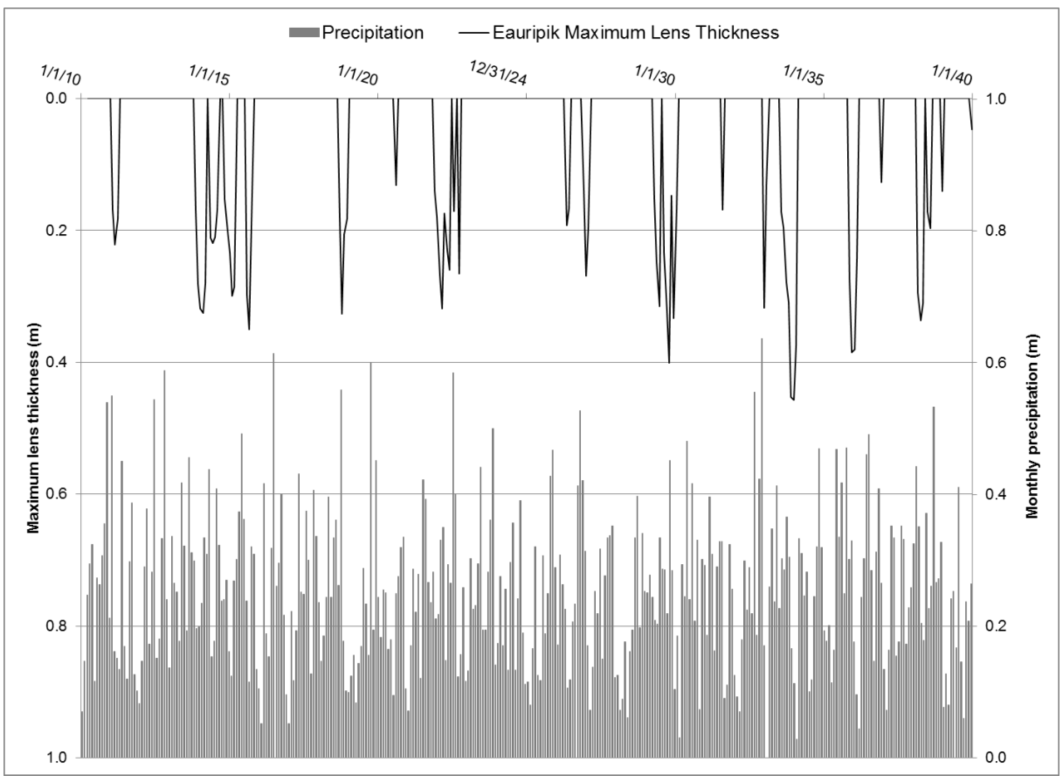

Figure 27 – Groundwater lens thickness (m) for RCP 2.6 Scenario (Eauripik)

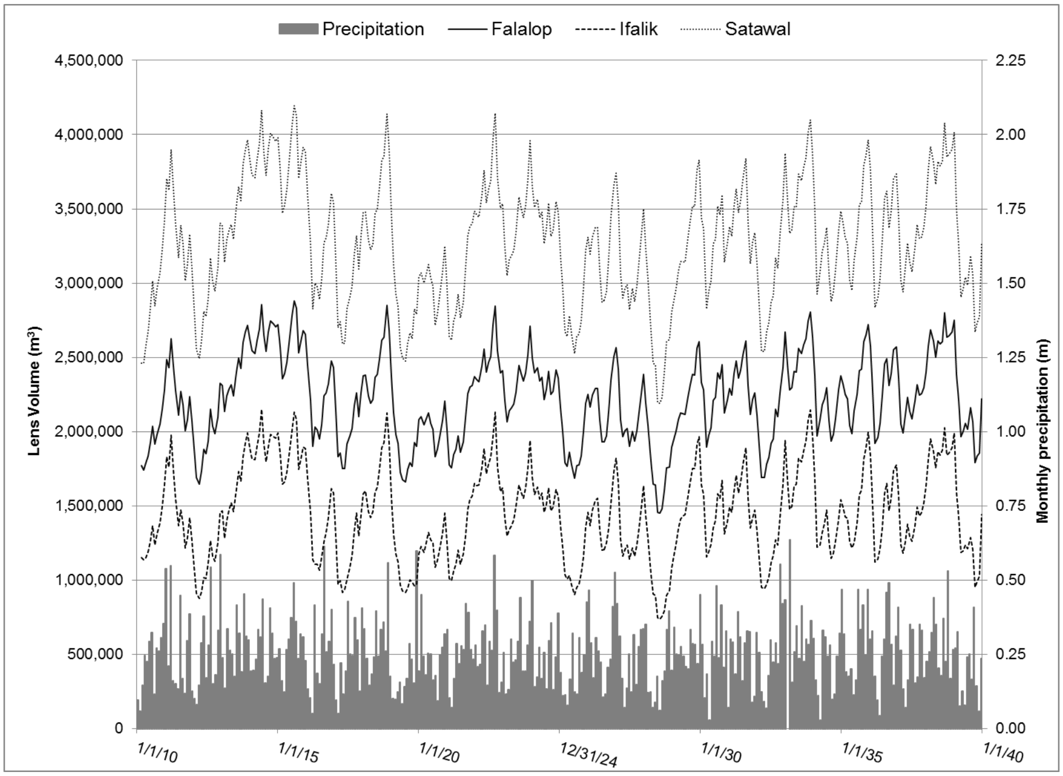

Figure 28 – Groundwater lens volume (m^3) for RCP 2.6 Scenario (Falalop, Ifalik, and Satawal)

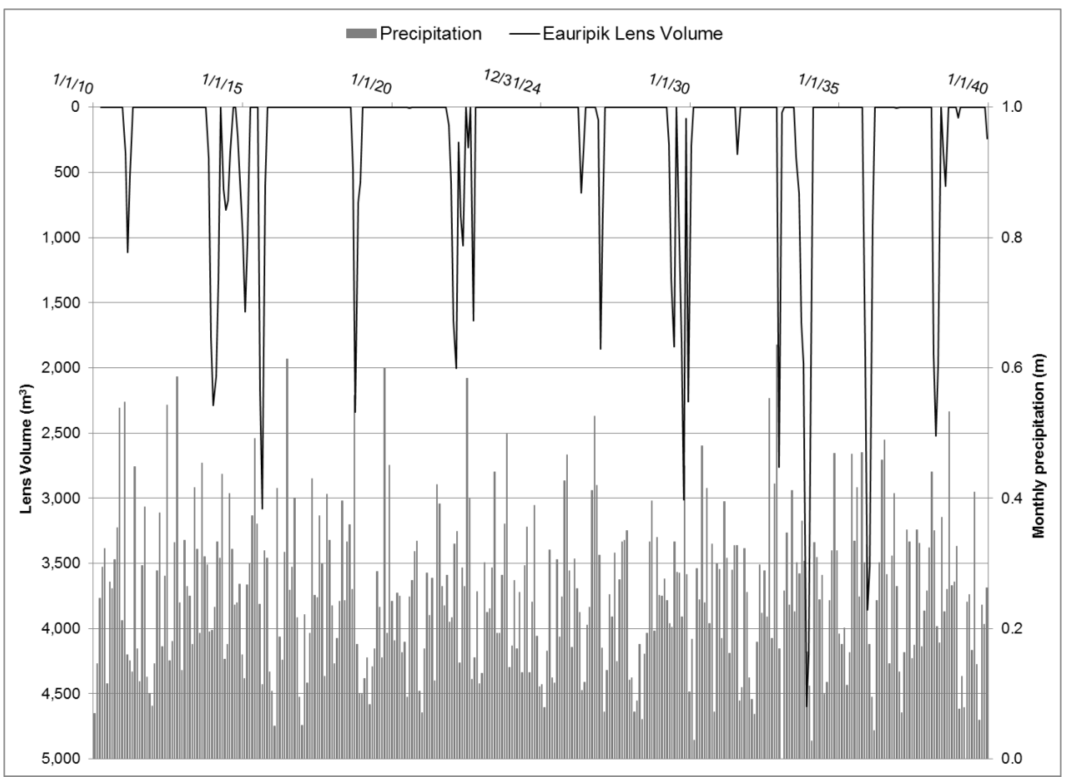

Figure 29 – Groundwater lens volume (m^3) for RCP 2.6 Scenario (Eauripik)

As shown by the figures, the freshwater lens thickness and volume varies in time for the islands in response to recharge. The response, or trend, of the freshwater lens thickness and volume is similar for the three larger islands. In contrast, the maximum freshwater lens thickness for Eauripik never exceeds 0.45 meters and does not exceed 0 meters for over 50% of the 30 year simulation.

RCP 8.5 Scenario

Results from the 30-year RCP 8.5 climate change scenario, based on the GISS-E2-H-p2 global circulation model, are shown graphically in Figure 30 and Figure 31, as the maximum freshwater lens depth, and in Figure 32 and Figure 33 as the lens volume. A statistical summary of the results is displayed in Table 10.

Table 10 – Statistics for RCP 8.5 GCM GISS-E2-H-p2 groundwater model (2010-2040)

	Maximum Thickness (m)				**Volume (m^3)**			
Island	Average	Maximum	Minimum	Range	Average	Maximum	Minimum	Range
Eauripik	0.07	0.85	0.00	0.85	683	18,503	0	18,503
Falalop	5.46	7.01	4.40	2.62	2,225,293	3,173,582	1,550,548	1,623,034
Ifalik	3.33	4.80	2.29	2.51	1,443,308	2,607,779	692,558	1,915,221
Satawal	5.84	7.88	4.73	3.15	3,274,714	4,682,408	2,320,881	2,361,527

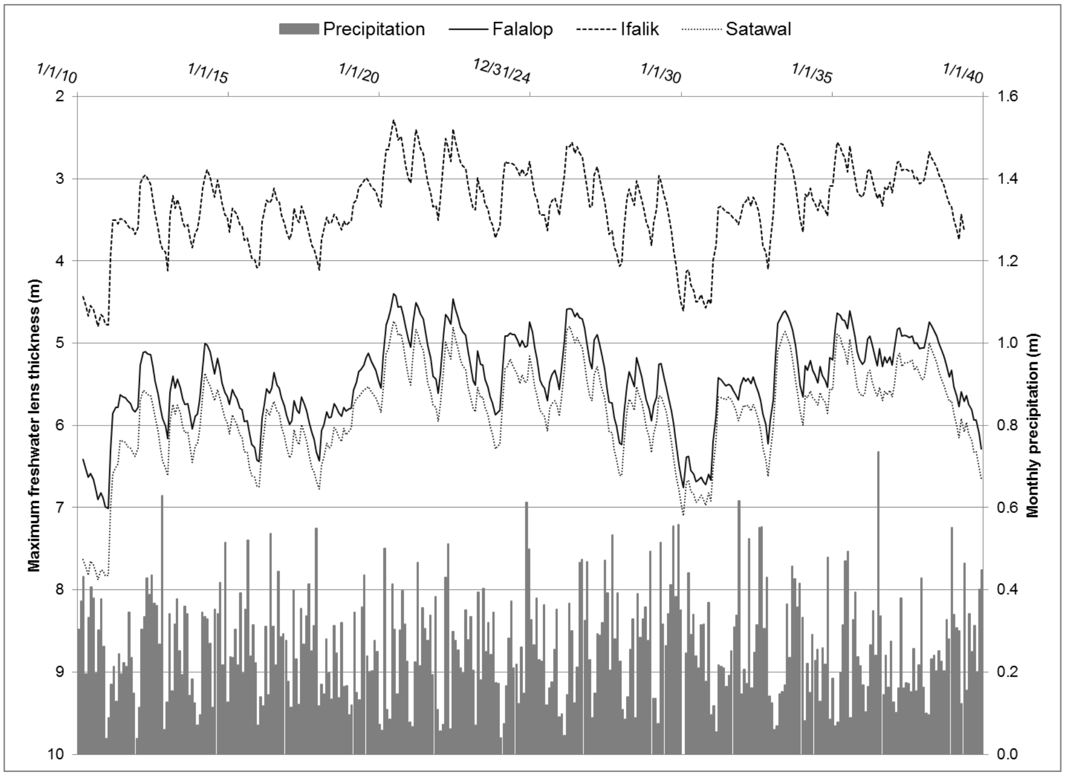

Figure 30 – Groundwater lens thickness (m) for RCP 8.5 Scenario (Falalop, Ifalik, and Satawal)

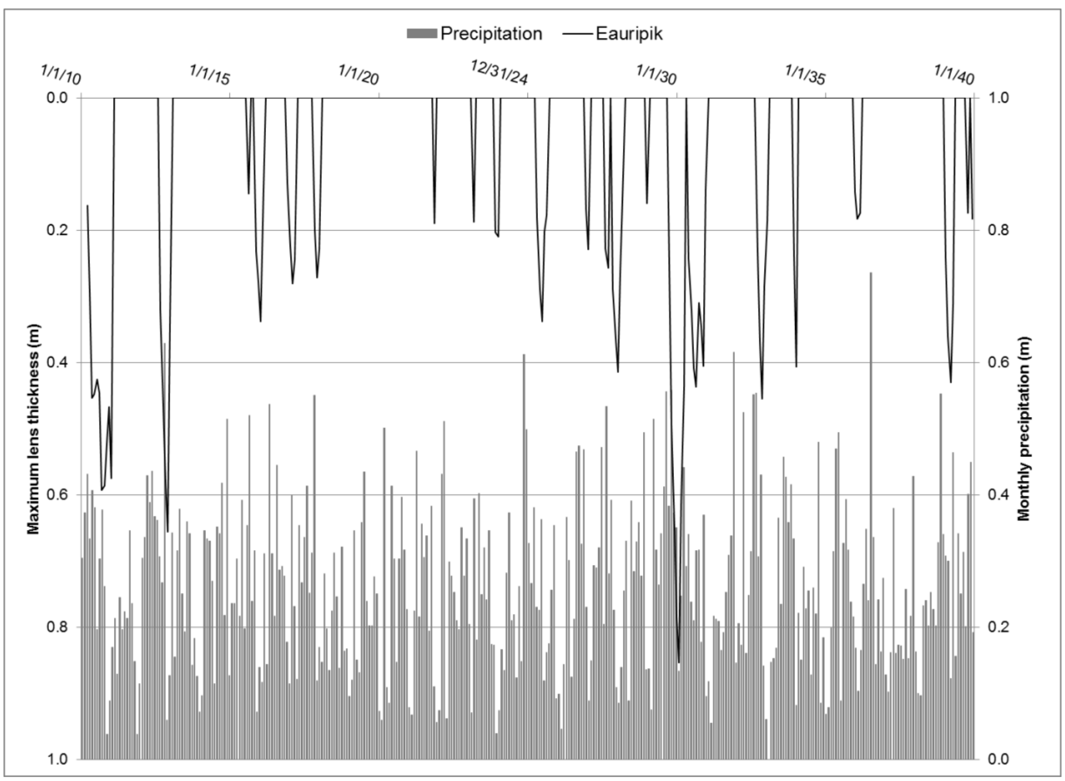

Figure 31 – Groundwater lens thickness (m) for RCP 8.5 Scenario (Eauripik)

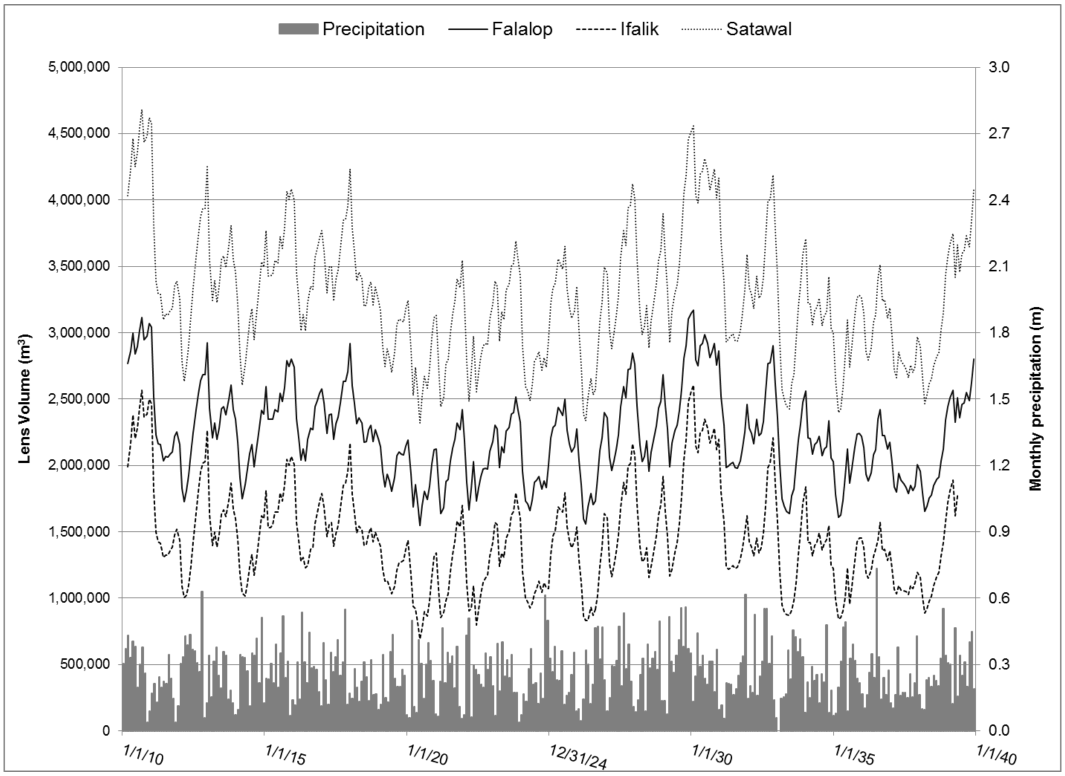

Figure 32 – Groundwater lens volume (m^3) for RCP 8.5 Scenario (Falalop, Ifalik, and Satawal)

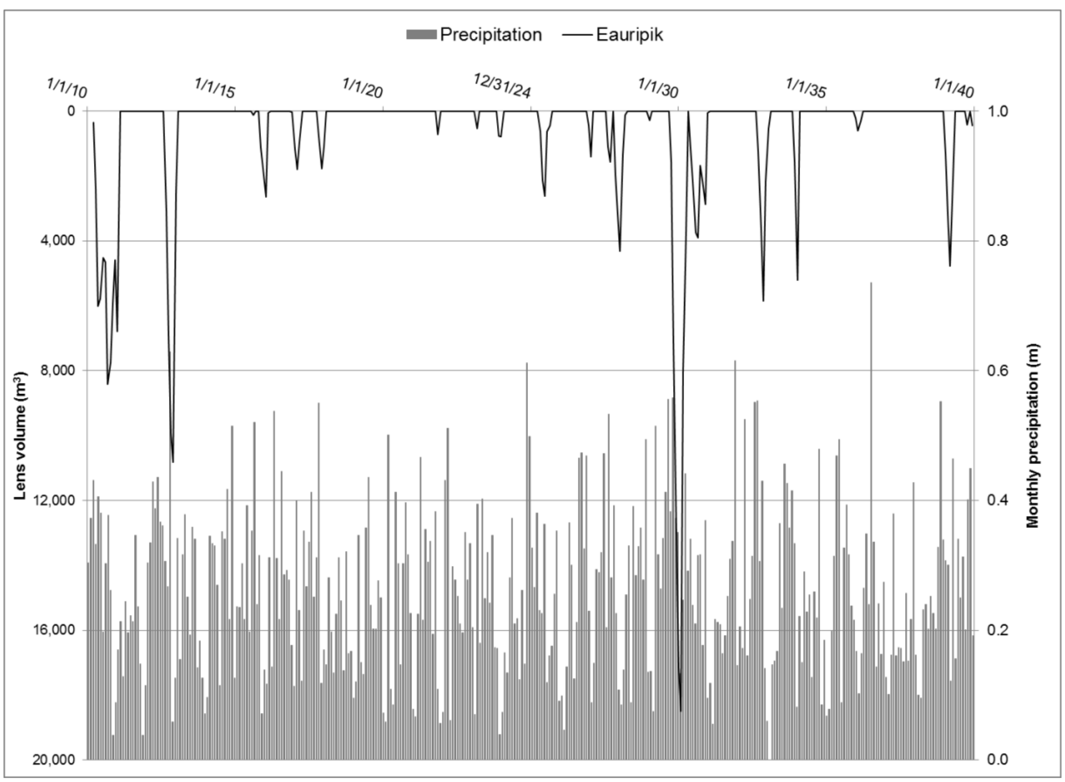

Figure 33 – Groundwater lens volume (m^3) for RCP 8.5 Scenario (Eauripik)

Discussion

Rainwater catchment systems

Since the rainwater catchment systems provide the water used for bare necessities, optimization and rationing of this resource is paramount. Our findings from the rainwater catchment models suggest the following recommended practices or alterations to improve reliability of this source.

A. Modifying catchments

In general, modifying rainwater catchments should start at the smallest scale and move to larger scales as improvements are made. The following recommendations are described in such an order.

1) Repairing existing equipment is recommended as the first step in modifying catchments due to the low-cost potential for improving. Patching and filling leaks that form in gutters, catchment panels, and storage tanks improve the catchment efficiency at a low cost. It is also recommended to keep stock of patching material, such as caulk, to promptly repair leaks as they develop.
2) Increasing the guttered area to the extent of the catchment panels is recommended next. Some catchments are only partially guttered and extending the gutter would significantly increase the capture and storage capacity of RWC systems. Since several rainwater catchment structures are abandoned over time, it is recommended to salvage gutter materials from these structures before constructing or purchasing any additional.
3) Enlarging the rainwater catchment panels is another useful way to increase storage capacity of the RWCS and is recommended before increasing storage tank volume. This is a very good option for catchments constructed for the sole purpose of collecting rainwater and are not connected to a structure that serves another purpose. Again, salvaging existing materials is recommended.

   When deciding how much larger to expand the rainwater catchment, or if the expanded size is already known, the reliability charts shown in Figures Figure 34, Figure 35, and Figure 36 are a good resource to determine the improvement in water supply volume. The reliability term is based on the percent of days in which enough water supply was provided to meet the demand, from July 1st, 1951 to April 30th, 2015. Each chart is based on water usage: Figure Figure 34 assumes 24 L/day (or 3 users at 8 L/day), Figure Figure 35 assumes 84 L/day (or 7 users at 12 L/day), and Figure Figure 36 assumes 192 L/day (or 12 users at 16 L/day). Each chart has three curves based on the mean, median, and mode average storage tank size on Ifalik.

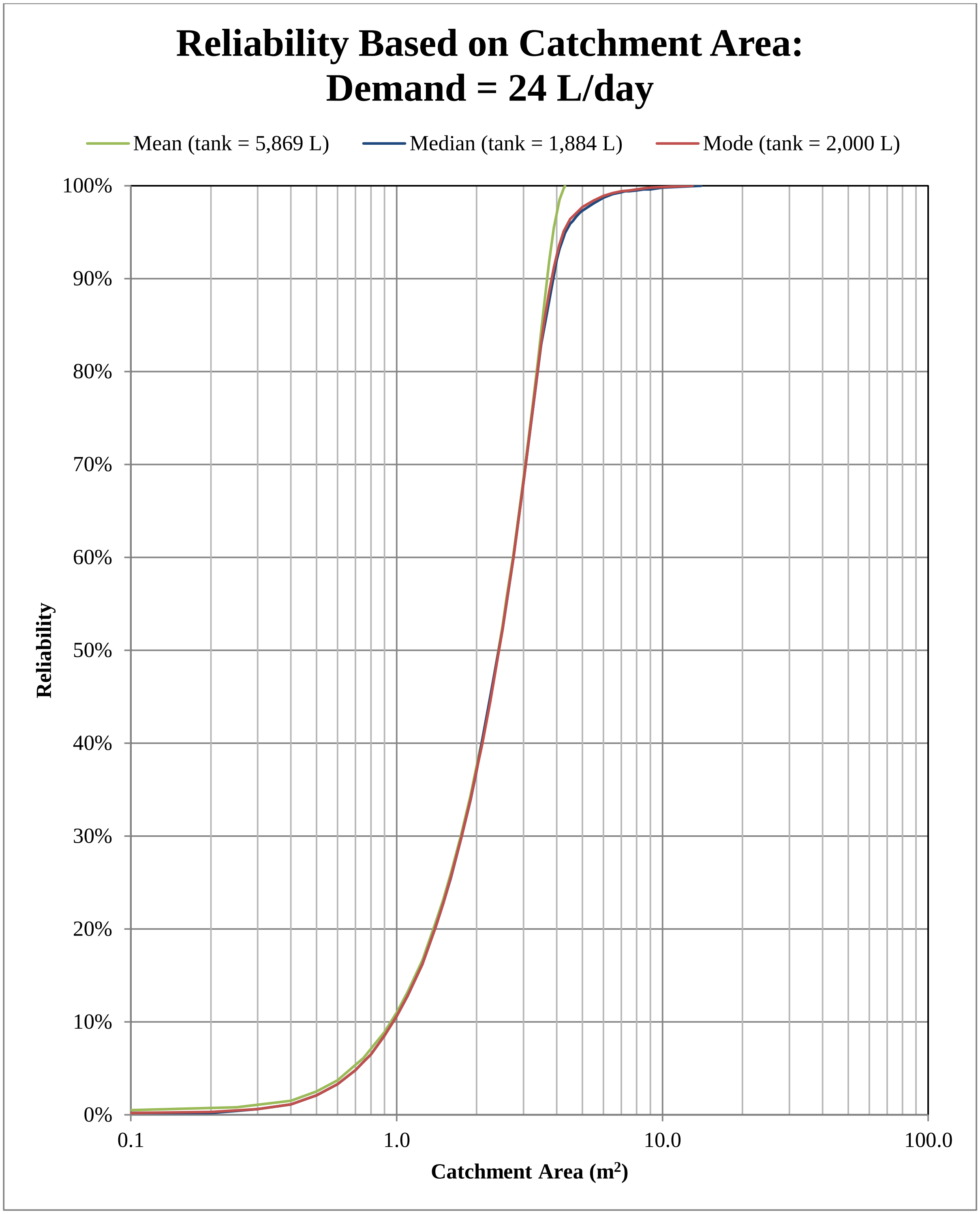

Figure 34 – Reliability Based on Catchment Area (Demand = 24 L/day)

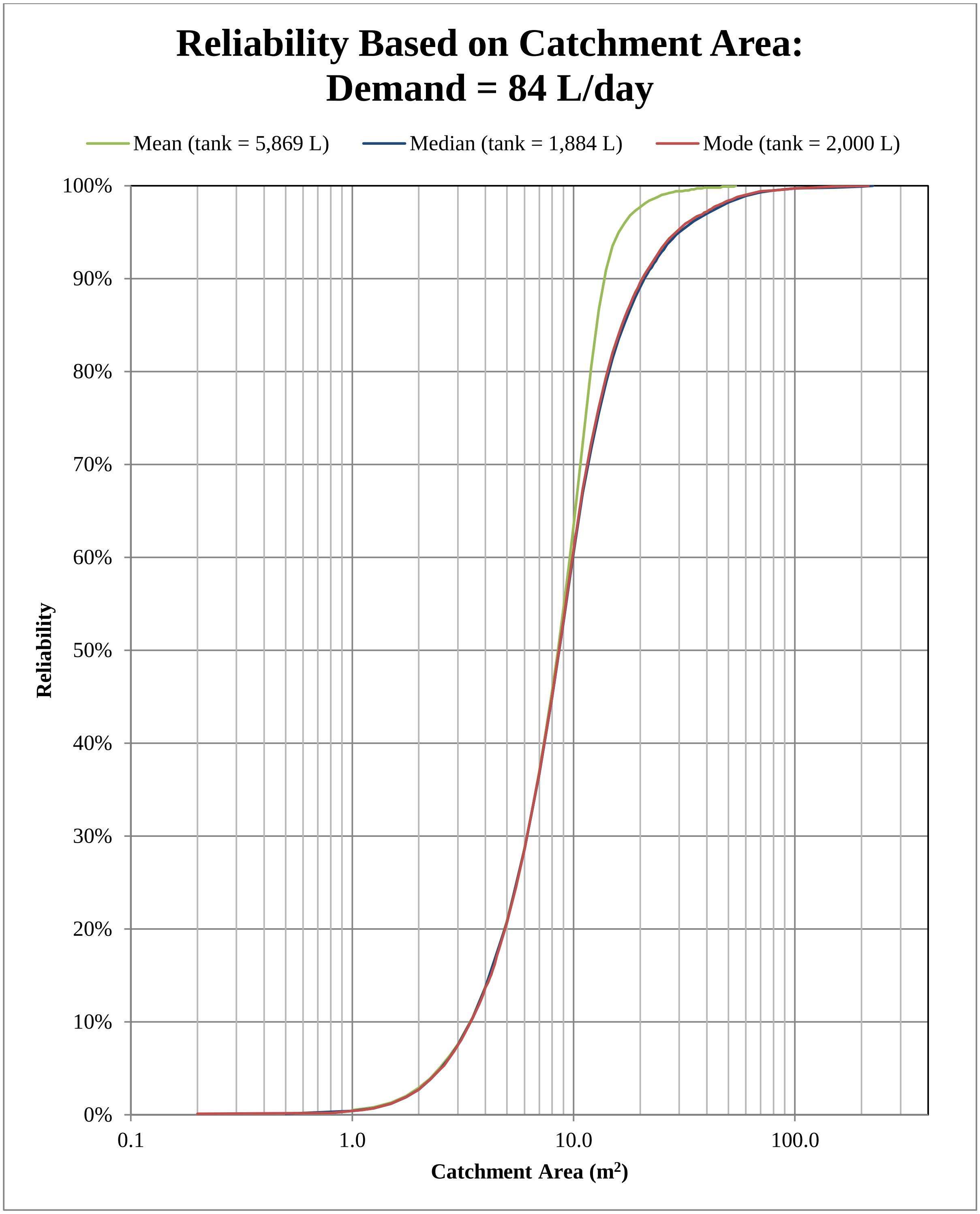

Figure 35 – Reliability Based on Catchment Area (Demand = 84 L/day)

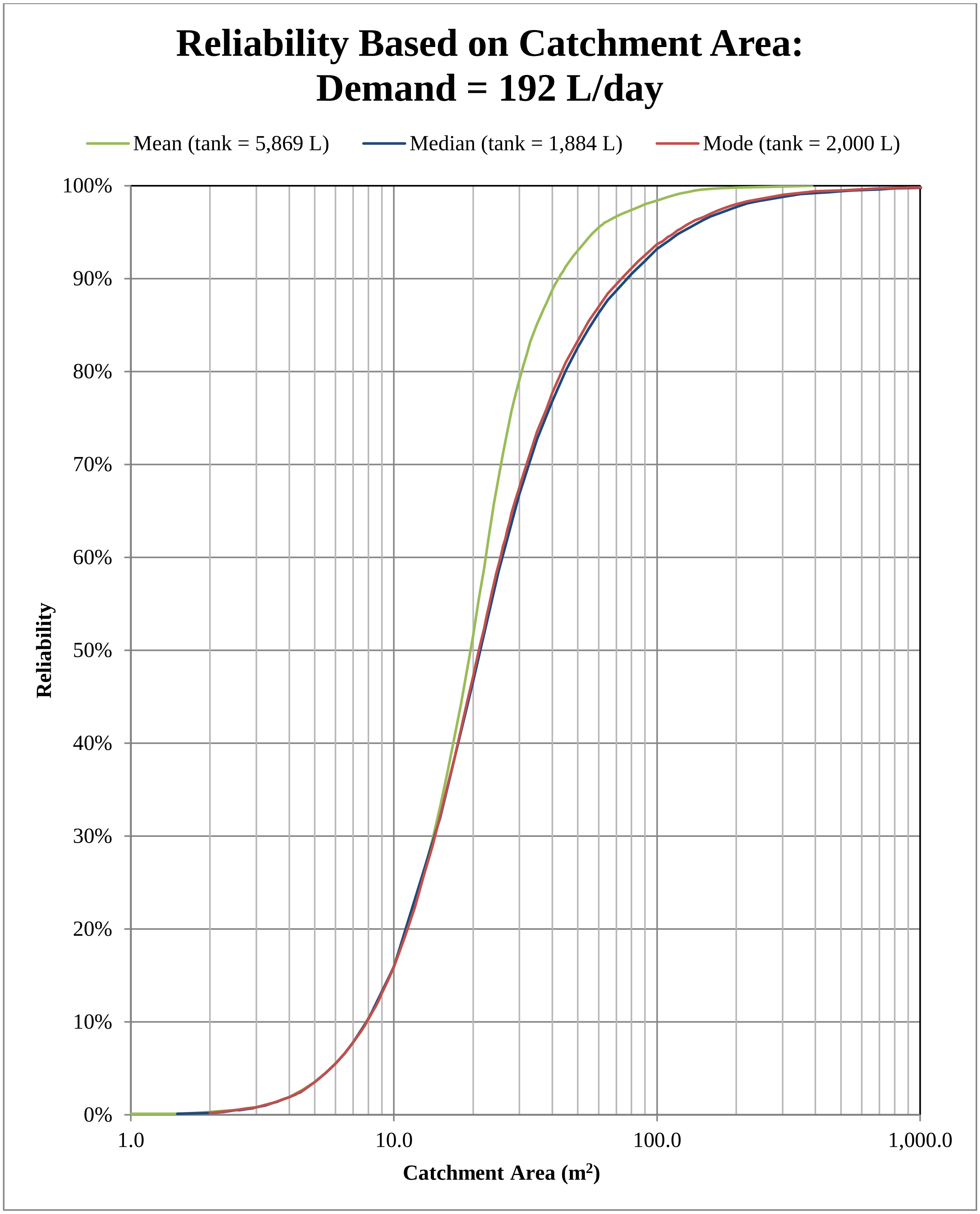

Figure 36 – Reliability Based on Catchment Area (Demand = 192 L/day)

4) Finally, increasing the storage tank volume is recommended as the last step to increase storage capacity of an existing rainwater catchment system. It is recommended that storage tanks purchased be relatively lightweight (i.e. constructed with PVC). In the event a RWCS is abandoned, it is important that tanks are moveable for relocation to another catchment system. Similar charts are provided for reference when expanding the tank size as the charts shown for increasing the catchment area in Figures Figure 37, Figure 38, and Figure 39 are a good resource to determine the improvement in water supply volume. Each chart has three curves based on the mean, median, and mode average catchment size on Ifalik.
   These reliability curves show that it is generally more effective to increase the catchment area than the storage tank volume. For example, a rainwater catchment with a 1,884 liter tank and 9.99 square meter catchment area is approximately 60% reliable for a demand of 84 L/day. To improve reliability to 84%, one could either increase the catchment area to 16.4 square meters or increase the tank size to 650,000 liters (for reference, the largest tank on Ifalik is approximately 338,000 liters).

B. Rationing

1) Rationing as a tactic for drought preparation may be the most beneficial method to improve supply during times of need, if started several weeks prior to a drought. Increasing the initial storage volume at drought onset extends the time to depletion, although in most cases will not eliminate depletion altogether. Since island residents are often informed of El **Niño** events prior to start of the dry season, preparation in this way should be a viable option. This may also be a good time to take inventory of the catchments and make repairs as needed.
2) Other than for drought preparation, no changes to existing water use practices are recommended. This is because typical water use ranges from 8 – 16 liters per person per day and only minor rations can be made without impacting daily needs for sustenance.

C. Future planning and management considerations

1) For quantifying the reliability of RWCS using the methods included in this report (algebraic models and design curves), it is recommended that users model with short-term drought scenarios on the order of months to a few years. Models at this time-scale provided the best results for capturing the reliability of rainwater catchments at the individual and community scale. Rainfall data from the 1997 – 1999 drought is the scenario used for this report.
2) Global circulation models (GCMs) are useful for quantifying community water supplies at an annual scale; however, it is not recommended to use GCM rainfall data for drought planning or overall reliability. Using historical rainfall data proved to be a more conservative approach.

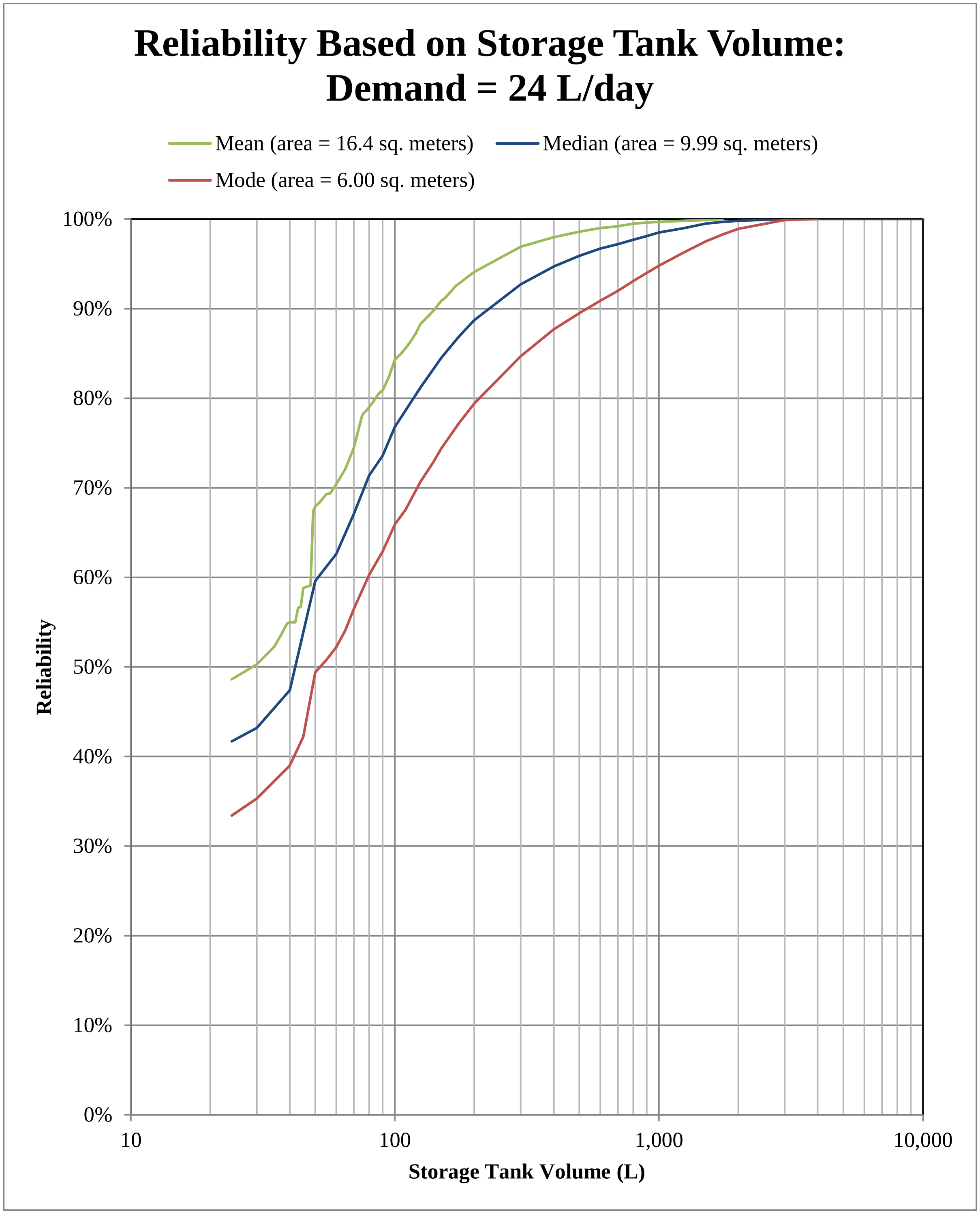

Figure 37 – Reliability Based on Storage Tank Volume (Demand = 24 L/day)

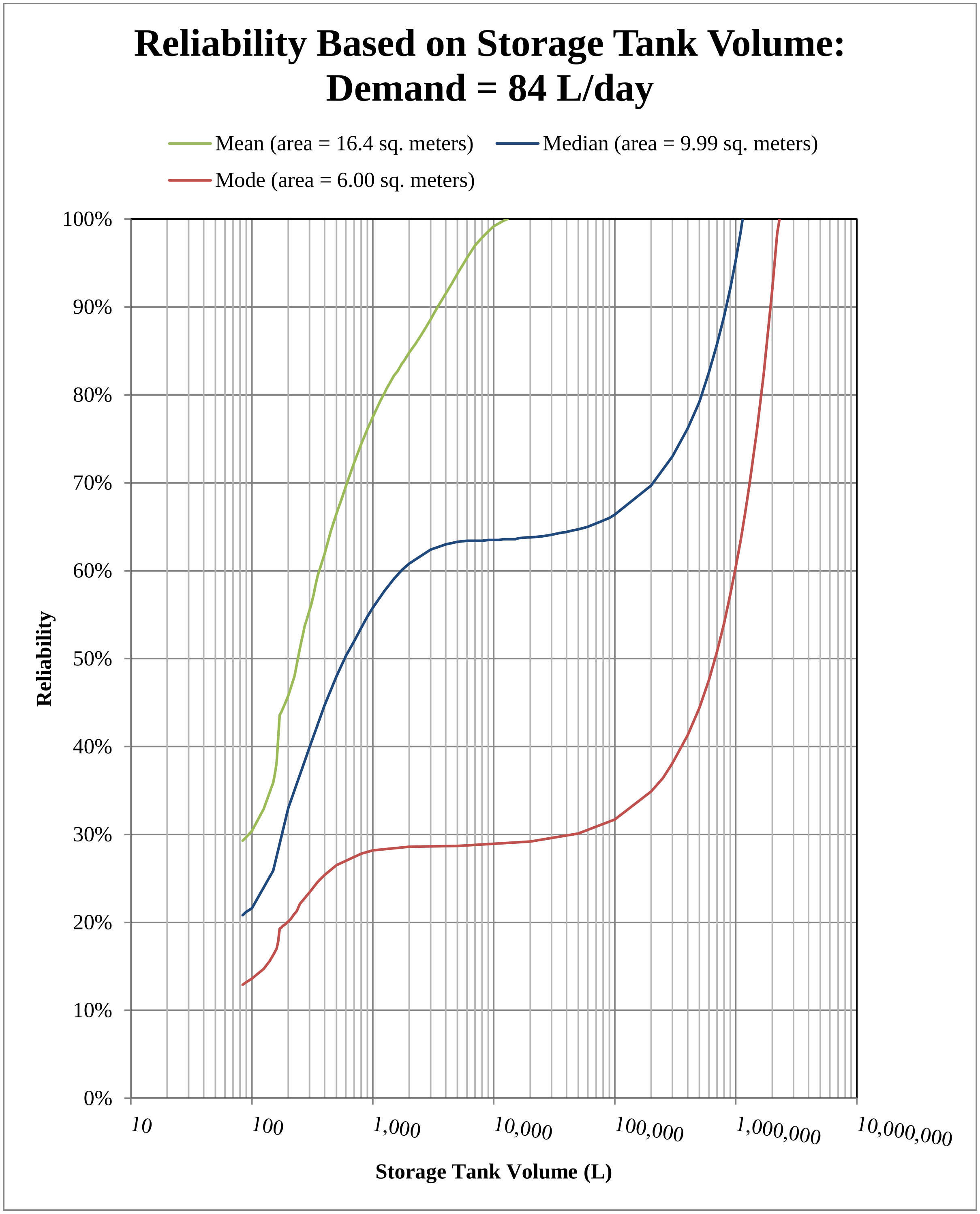

Figure 38 – Reliability Based on Storage Tank Volume (Demand = 84 L/day)

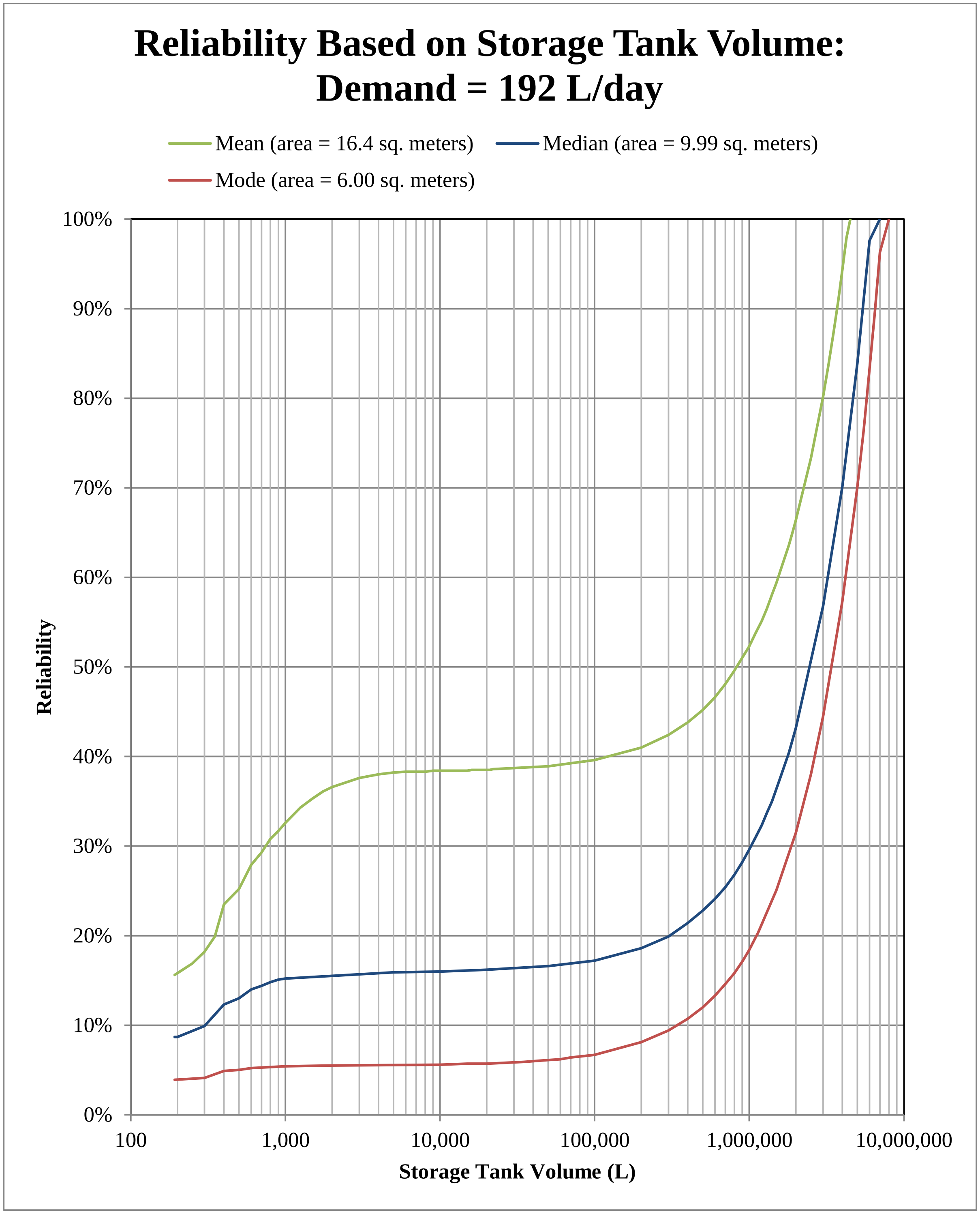

Figure 39 – Reliability Based on Storage Tank Volume (Demand = 192 L/day)

Groundwater collection and storage

Future groundwater storage values found by simulating global circulation models helped establish a general range of volumes for each island. Refer to Figure 40 for a comparison of the groundwater storage volumes for both RCP scenarios, and Table 11 for the statistical comparison.

Table 11 – Comparison of Climate Scenarios (RCP 8.5 vs. RCP 2.6)

	Maximum Thickness (m)				Volume (m^3)			
Island	Average	Maximum	Minimum	Range	Average	Maximum	Minimum	Range
Eauripik	0.02	0.39	0	0.39	443	13,904	0	13,904
Falalop	-0.09	0.35	-0.14	0.5	3,617	291,900	97,844	194,056
Ifalik	-0.02	0.58	-0.17	0.75	1,111	455,976	-44,968	500,944
Satawal	-0.1	0.93	-0.04	0.98	2,239	487,090	131,343	355,747

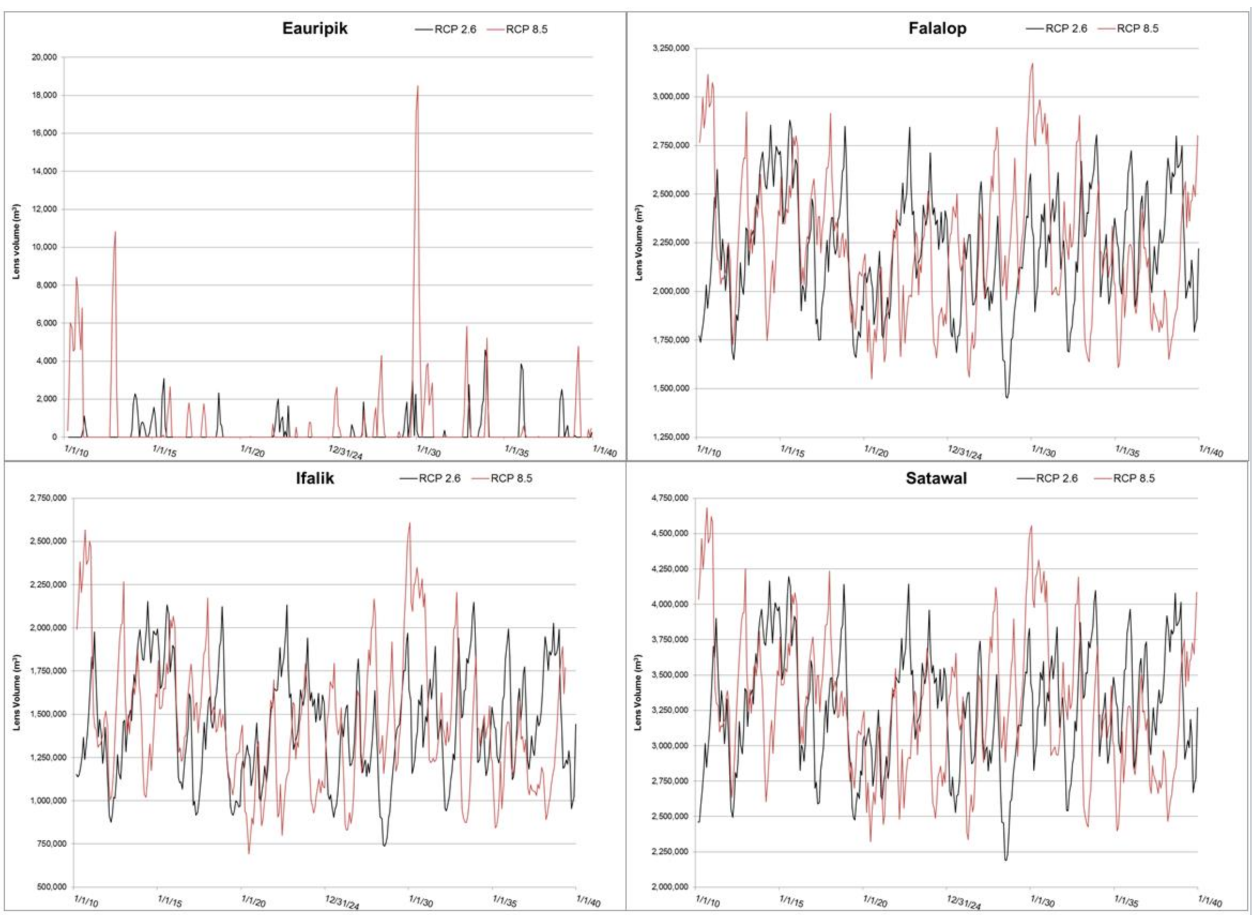

Figure 40 – Graphical comparison of climate scenarios by island

One major outcome from the climate models was that they proved Eauripik has a limited groundwater lens that should not be relied on as a freshwater source. The thickness of the lens averaged under a tenth of a meter and due to over-washing, the actual average would be less than this. Another major outcome was that models showed a higher greenhouse gas concentration (i.e. RCP 8.5) leads to higher overall precipitation and larger overall groundwater volume. Also evident was greater variability in lens volume and thickness over time (Table 11).

Issues with groundwater most frequently relate to quality as it is much less frequently used for drinking purposes. The following recommendations are proposed for successful planning and management of groundwater collection.

A. Modifying and constructing wells
    a. Cover wells with lids and ensure the top of well extends at least two feet above ground. These measures reduce contact with organic material and improve long-term quality of the groundwater.
    b. Construct new wells up gradient from potential contamination sources, such as cemeteries, and build new cemeteries down gradient from wells.
    c. New wells should be constructed in the thickest section of the freshwater lens, which is generally along the center profile of the island skewed to the lagoon side.
B. Practices in water use
    a. Continue boiling groundwater when needed for drinking water purposes.
    b. Limit contamination by animals and daily water uses.
C. Future planning and management considerations
    a. For quantifying the availability of groundwater as an emergency drinking water supply, it is recommended to use the methods included in this report (algebraic models and numerical SEAWAT models) with short-term drought scenarios on the order of several months, or with long-term scenarios using historical rainfall data on the order of several decades.

Conclusions

Atoll island water resources are dynamic systems that grow and thin in direct response to fluctuations in local sea and climate. Water security depends on the reliability of the network of rainwater catchment systems and the availability of fresh groundwater as a secondary source during periods of low rainfall. Findings from this study suggest that historical rainfall data is adequate for drought planning and preferred to global circulation models (GCMs). Simulations for short-term droughts using historical data from 1997-1999 provided the most conservative results for rainwater catchment models, and historical rainfall data yielded the smallest groundwater lens size for SEAWAT simulations. Therefore, historical rainfall data is recommended over GCMs for drought planning.

Rainwater Collection

Optimizing the capacity of the rainwater collection network is the best course of action for improving water security. Rainwater is foremost the best source in terms of quality and, unlike the groundwater, infrastructure may be modified to increase collection and storage capacity.

Improving the network of rainwater catchments may begin at any point that is best suited for current conditions. However, the following general outline of steps would be effective for most rainwater infrastructures: 1) rehab and repair existing materials to close leaks and improve efficiency, 2) extend the gutters to the full dimensions of the catchment to capture more water, 3) increase the catchment area to improve long-term water security by using reliability curves such as those shown in this report, and 4) increase the storage tank size if overflow is frequent, using reliability curves.

Groundwater Collection

Atoll islands large enough to develop a useful groundwater lens may wish to manage this source for future droughts. Findings from this study suggest the freshwater lens volume will fluctuate more significantly from year-to-year as a result of higher levels of climate change and although there is little to do about shrinking groundwater volumes, sanitation measures are an excellent way to preserve the quality for when it is needed. Practices that include covering wells and keeping pigs out will achieve a better level of quality and keep the water usable in the future.

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Appendix A - Calibration Results

October 1987 Calibration Point

Well Name	Description	DATE	Measured freshwater lens depth (m)	Modeled			Error		
				HK = 125 m/day	HK = 150 m/day	HK = 175 m/day	HK = 125 m/day	HK = 150 m/day	HK = 175 m/day
F-A-WT	West by airstrip	10/14/87	1.80	2.43	1.97	1.57	0.63	0.16	-0.23
F-B-WT	Central	10/13/87	6.71	5.70	5.08	4.54	-1.01	-1.63	-2.17
F-C-WT	East by airstrip	10/14/87	1.34	4.29	3.69	3.17	2.96	2.35	1.83
F-D-WT	North	10/23/87	4.56	3.45	2.90	2.42	-1.12	-1.67	-2.14
F-E-WT	South-central	10/12/87	1.75	5.94	5.53	4.87	4.18	3.78	3.12
						Average Error (m/day)	1.13	0.60	0.08
						RMSE (m/day)	5.38	5.03	4.74

Rank (1-Best, 3-Worst) 3 2 1
Rank (1-Best, 3-Worst) 3 2 1

January 1988 Calibration Point

Well Name	Description	DATE	Measured freshwater lens depth (m)	Modeled			Error		
				HK = 125 m/day	HK = 150 m/day	HK = 175 m/day	HK = 125 m/day	HK = 150 m/day	HK = 175 m/day
F-A-WT	West by airstrip	1/28/88	-	1.62	1.07	0.56	-	-	-
F-B-WT	Central	1/28/88	6.81	5.03	4.41	3.77	-1.78	-2.40	-3.04
F-C-WT	East by airstrip	1/28/88	-	3.49	2.85	2.30	-	-	-
F-D-WT	North	1/28/88	1.51	2.56	1.95	1.40	1.05	0.44	-0.11
F-E-WT	South-central	1/28/88	1.45	5.38	4.77	4.15	3.93	3.33	2.70
						Average Error (m/day)	1.07	0.46	-0.15
						RMSE (m/day)	4.44	4.13	4.07

Summary

	HK = 125 m/day	HK = 150 m/day	HK = 175 m/day
Overall Average Error (m/day)	1.10	0.53	-0.03
Overall RMSE (m/day)	4.91	4.58	4.40
Rank (1-Best, 3-Worst)	3	2	1