GROUNDWATER RESOURCES ANALYSIS OF ATOLL ISLANDS IN THE FEDERATED STATES OF MICRONESIA USING AN ALGEBRAIC MODEL

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UNIVERSITY OF GUAM

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ABSTRACT

The water resources of the islands composing the 32 atolls of the Federated States of Micronesia (FSM) are under continual threat due to El Niño-induced drought events and potential sea-level rise. With current government policies encouraging the sustainability of atoll island communities, accurate and efficient methods to estimate the water resources of atoll islands of the FSM are of critical need. Of prime importance is an estimation of groundwater resources, which the communities are dependent upon for sustainability during prolonged drought events.

Due to the sparseness of actual hydrologic data and the exorbitant cost of procuring data sets required for hydrologic trend analysis, we present the use of a recently-developed algebraic model, based on numerical modeling results of atoll island hydrogeology, to estimate groundwater resources of atoll islands. Specifically, the model provides estimates of the freshwater lens thickness during normal and drought-induced climatic conditions. The model is validated for use in the FSM under average climatic conditions through comparison of model results with the available data regarding the freshwater lens thickness on several atolls in the FSM, and validated for use under El Niño-induced conditions through comparison of model results with freshwater lens data gathered during the 1998 drought on Majuro Atoll, which experiences a climate similar to the FSM.

The model is then applied to each atoll island within the FSM, to determine the freshwater lens thickness to be expected during both average and drought-induced hydrologic conditions. Results indicate that of the 105 atoll islands considered only 6 would retain a fresh body of groundwater able to sustain the community during a drought similar to that experienced in 1998. In general, results can provide water resources managers and policy makers with important information regarding the sustainability of atoll island communities.

TABLE OF CONTENTS

Contents

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Atolls, defined as a ring of small, coral islands surrounding or partially surrounding a shallow lagoon, have been the subject of interest to hydrogeologists during the last half of the twentieth century and into the twenty-first century due to their extensive remoteness, the unique geology of the shallow subsurface, and the vulnerability of atoll island communities to shortages in water supply. Elevation of the ground surface on atoll islands typically does not exceed a few meters [*Wheatcraft and Buddemeier*, 1981], and island widths vary from 100 m to approximately 1500 m. With a small rain catchment spatial area, low-lying topography, isolation from other island communities, and continual threat of El Niño-induced drought events, the sustainability of island water resources is a constant concern.

Similar to the Republic of the Marshall Islands and the Republic of Kiribati, the Federated States of Micronesia (FSM), spread across more than 2 million km^2 of the western Pacific Ocean [*Anthony*, 1997], is composed in part by atolls and associated atoll island communities. Of the approximately 450 atolls worldwide [*Bryan*, 1953; *Dickinson*, 2009], 32 reside within the FSM, with many island communities threatened by the lack of freshwater resources. Groundwater resources for the FSM are of particular interest, since the small spatial area of the island land surface and the highly-porous nature of the shallow subsurface sediments prevent the development of natural surface water bodies or reservoirs [*Urish*, 1974]. Man-made storage tanks are used to collect rainwater, although these soon become depleted during drought events. During, such times, the island inhabitants turn to groundwater to fulfill all domestic water needs. However, the fresh groundwater, residing in a nucleus of freshwater floating atop the underlying seawater and termed the "freshwater lens", itself is subject to stress and threat of depletion during El Niño-induced droughts [*Meehl*, 1996; *White and Falkland*, 2009], hence bringing into question the sustainability of the atoll island communities in regards to water supply.

The current policy of the FSM government is to make each atoll island community sustainable in regards to resources, hence preventing the migration of atoll island communities to the main islands within the FSM. This sustainability is dependent on the availability of freshwater resources, which must be analyzed under normal climatic conditions as well as periods of scarce rainfall [*Bailey et al.*, 2010]. Field studies conducted during the 1980s [*Ayers and Vacher*, 1986; *Anthony*, 1997] provided a delineation of the freshwater lens and an estimate of available fresh groundwater for several atoll islands within the FSM during average climatic conditions. In general, however, hydrologic data regarding the volume of available groundwater under both average seasonal and drought conditions are sparse, and due to the high cost and difficulty of conducting hydrologic analyses in the remote and isolated atoll island communities, will likely remain so in the foreseeable future.

Several simple models have been proposed to analyze the extent of the freshwater lens on oceanic island [e.g., *Fetter*, 1972; *Chapman*, 1985; *Oberdorfer and Buddemeier*, 1988; *Vacher*, 1988]. Due to the unique geologic structure of atoll island aquifer systems, however, each model includes or precludes characteristics that prevent reliable estimates when applied to atoll islands. In general, these models over-predict the thickness of the lens [*Bailey et al.*, 2010].

In this study we make use of the limited available hydrologic data regarding groundwater in the FSM and a recently developed algebraic model [*Bailey et al.*, 2010] to provide information regarding the expected groundwater resources for atoll island communities in both average seasonal and El Niño-induced drought conditions. The model is based on numerical simulation results of groundwater flow in atoll island aquifers, and takes into account both hydrologic and the unique geologic characteristics of atoll island aquifer systems. The model can be used to quickly provide estimates of the thickness of the freshwater for both average seasonal and drought conditions, with drought conditions similar to those experienced during the 1997-1998 El Niño period in the western Pacific Ocean. The model is confirmed for average climatic conditions by testing results against the data provided by *Ayers and Vacher* [1986] for (i) Deke, Pingelap Atoll, and by *Anthony* [1996a, 1996b, 1996c] for (ii) Pingelap, Pingelap Atoll, (iii) Kalap, Mwokil Atoll, (iv) Falalop, Ulithi Atoll, and (v) Ngatik, Sapwuahfik Atoll. Falalop is located within Yap State, whereas the other four reside within Pohnpei State.

The model is further confirmed for drought conditions using the data provided by *Presley* [2005] for Laura Island, Majuro Atoll, Republic of the Marshall Islands. Although not within the FSM, Laura was selected due to (i) available data regarding the freshwater lens thickness through drought conditions, and (ii) the similarity in climate between the geographic regions of the Marshall Islands and the FSM. Following model confirmation, the model is used to provide estimates of the freshwater lens thickness for both average and drought conditions for each atoll island within the FSM. Results can provide water resources managers and policy makers with important information regarding the sustainability of atoll island communities.

WATER RESOURCES OF ATOLL ISLANDS OF THE FEDERATED STATES OF MICRONESIA

General Atoll Island Hydrogeology

The accepted conceptualization of atoll island hydrogeology [*Ayers and Vacher*, 1986], depicted using a cross section of an atoll island surface and shallow subsurface, is shown in Figure 1. The aquifer system consists of an upper aquifer lying atop a lower aquifer, composed of particulate Holocene sediments and Pleistocene paleo-karst, respectively, with a solution unconformity, termed the "Thurber Discontinuity" [*Vacher*, 1997], delineating the separation between the two. This dual-aquifer system is general to atolls across the Pacific and Indian Oceans, and as discussed by *Dickinson* [2004], is a result of glacio-eustatic sea-level positions. Limestone platforms formed atop subsiding ancient volcanoes became exposed during the most recent glacial episode, during which the mean sea level dropped approximately 300 m, and were eroded down to the current level of the Thurber Discontinuity. Upon glacial melting and re-filling of the Ocean basins, the sea-level rose to and over-topped the vertical extent of the eroded limestone platforms, allowing the formation of the upper aquifer. The erosion of the limestone platform during the glacial episode created a highly-porous structure, and investigators have estimated that the hydraulic conductivity of the lower aquifer is one to two orders of magnitude higher than that of the upper aquifer [*Woodroffe and Falkland*, 1997]. A second unique feature of the atoll island aquifer system is the presence of a reef "flat plate", a semipermeable reef rock that acts as a confining layer to the upper aquifer [*Cox*, 1951] and, according to numerical simulations, slightly thickens the freshwater lens [*Bailey et al.*, 2009].

The hydraulic conductivity of the upper aquifer is itself highly variable, and depends largely on the position of the island in relation to the direction of the prevailing winds [*Anthony*, 1997; *Spennemann*, 2006], with coarse-sediment upper aquifers developed on islands in the direct path of the prevailing winds and associated high-energy waves. In contrast, upper aquifers with fine sediments developed on islands located on the partially protected leeward side of atolls. Through a comparison of numerical simulation results and observed freshwater lens thicknesses of atoll islands, hydraulic conductivity values of 400 m day^{-1} and 50 m day^{-1} has been suggested for the upper aquifers of windward and leeward islands, respectively [*Bailey et al.*, 2009].

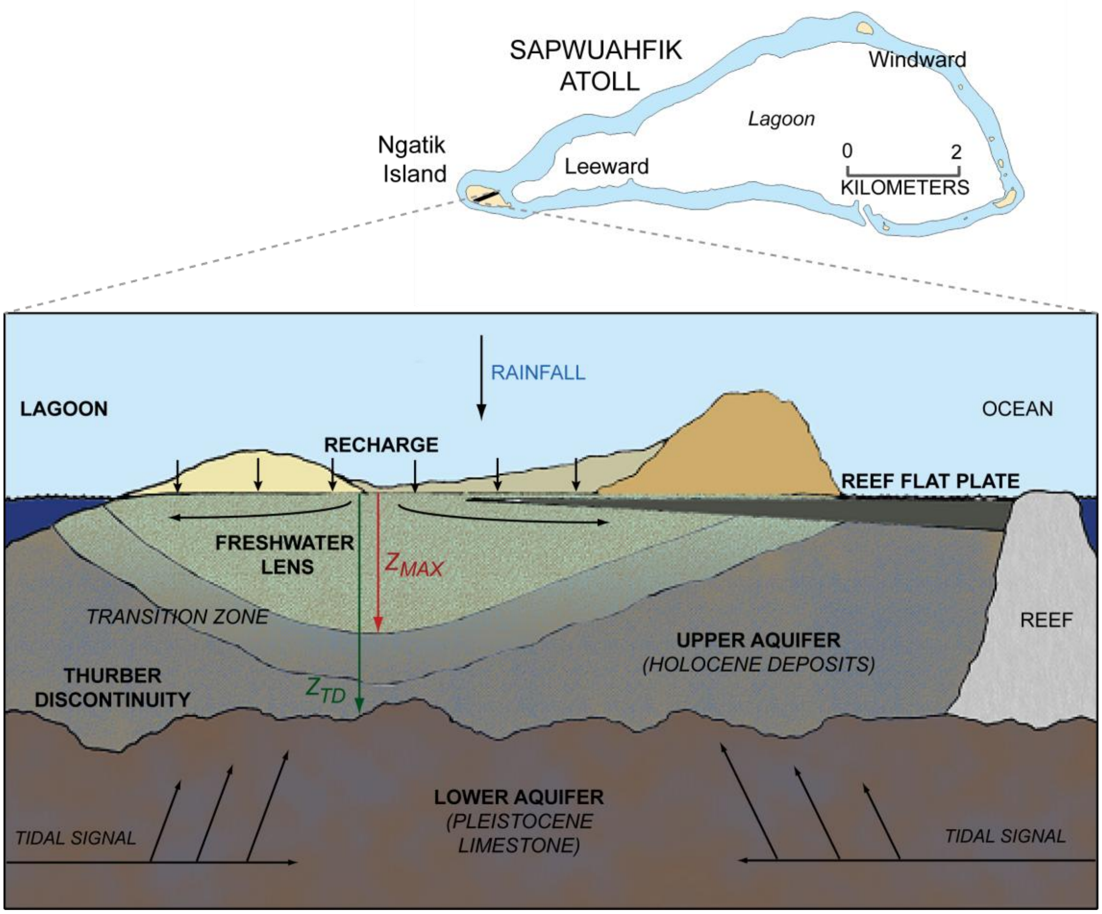


Figure 1. Cross section of atoll island from the lagoon side to the ocean side, depicting the geologic structure of the atoll subsurface and a conceptualization of atoll island hydrogeology, after *Ayers and Vacher* [1986]. The location of the cross-section is shown using Ngatik island, of Sapwuahfik Atoll (Pohnpei State, Federated States of Micronesia) as an example. Variables depicting the thickness of the freshwater lens at the center of the island (Z_{MAX}) and the depth to the Thurber Discontinuity (Z_{TD}) are also shown.

Rainfall not caught by vegetation, evaporated in the shallow soil profile, or transpired by vegetation from the shallow soil profile, percolates downward through the porous sediments and recharges the freshwater lens, which floats atop the underlying seawater. The thickness of the freshwater lens varies across the width of the island, with the maximum thickness for a given time, Z_{MAX}, typically occurring under the center of the island (Figure 1). For wide islands (> 1000 m) that receive an appreciable amount of rainfall, the base of the freshwater lens can at times reach the Thurber Discontinuity. However, any freshwater below the Thurber Discontinuity is thoroughly mixed with the seawater, hence providing a truncation of the lens at the Discontinuity [*Hamlin and Anthony*, 1987; *Hunt*, 1997]. Hence, the thickness Z [L] of the freshwater lens across the width of the island and the maximum thickness Z_{MAX} is conditional upon rainfall rate, the width of the island, the hydraulic conductivity of the upper aquifer, the depth to the Thurber Discontinuity Z_{TD}, and the presence of the reef flat plate.

Water Resources of the Federated States of Micronesia

The Federated States of Micronesia, located southeast of Guam and west of the atolls composing the Republic of the Marshall Islands and composed of 607 islands, are shown in Figure 2, with delineations between the four states of Yap, Chuuk, Pohnpei, and Kosrae. Each state is composed of a main island that bears the name of the state, and, with the exception of Kosrae, numerous outer islands that make up the 32 atolls within the FSM. Thirteen atolls reside in Yap State, 11in Chuuk State, and 8 in Pohnpei State.

Water use within atoll island communities is derived from either captured rain water (typically through a roof-gutter system that feeds a large storage tank) or groundwater. Rain catchment water is preferred for most domestic purposes such as drinking and cooking, whereas groundwater, typically accessed through hand-dug wells lined with concrete or rocks, is used for bathing and washing clothes [*Stephenson*, 1984; *MacCracken*, 2007]. Communities may also use coconut juice to supplement drinking water. Rain catchment tanks, such as those shown in Figure 3 for Falalop Island, Ulithi Atoll, vary in construction material and size. Older tanks (Figure 3A) are made from concrete, whereas newer ones (Figure 3B) are made from fiber glass. Depth to water in the hand-dug wells, as shown in Figure 4, ranges from 1 to 3 m, and fluctuates with the rise and fall of the tides. The water is extracted by either a rope and bucket or a small electric pump, and is typically shared by several households.

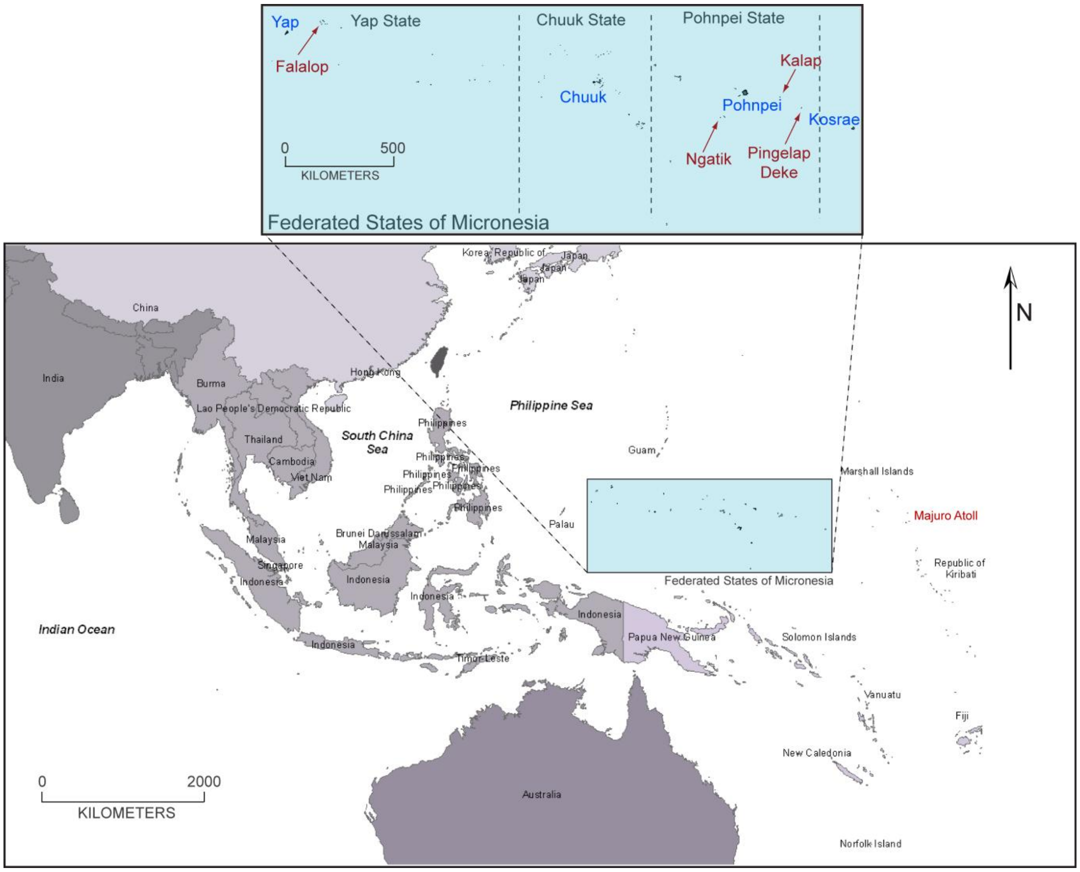


Figure 2. Map of East Indian and West Pacific oceans, showing a magnified map of the Federated States of Micronesia with boundaries separating the four states of Yap, Chuuk, Pohnpei, and Kosrae. Yap, Chuuk, and Pohnpei states include outer-island communities. Data regarding the thickness of the freshwater lens is available for the islands of Falalop, Ngatik, Kalap, Pingelap, and Deke. Limited data regarding the freshwater lens during the 1998 El Niño is available for Laura Island, Majuro Atoll, located in the Marshall Islands.

Figure 3. Roof catchments on Falalop Island, Ulithi Atoll, Yap State, FSM. Most households have their own catchment tank.

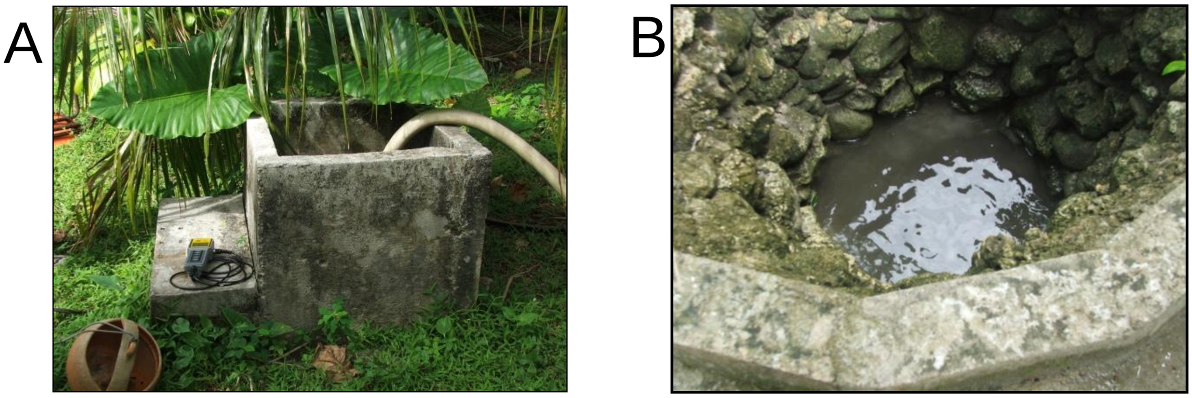


Figure 4. Hand-dug wells on (A) Falalop Island, Ulithi Atoll, Yap State, FSM and (B) Pingelap Island, Pingelap Atoll, Pohnpei State, FSM.

Freshwater Lens Data for the FSM and the RMI

Limited data regarding the thickness of the freshwater lens is available for five islands: Falalop, Ulithi Atoll, Deke and Pingelap, Pingelap Atoll, Kalap, Mwokil Atoll, and Ngatik, Sapwuahfik Atoll, the location of which are shown in Figure 2. Pingelap Atoll is shown in Figure 3, with Deke Island located on the northern, windward side of the atoll and Pingelap Island, where the Pingelap community resides, located on the southern, leeward side of the atoll. A thin freshwater lens (Z_{MAX} = 4 m) resides in the coarse, highly porous Holocene sediments of Deke Island [*Ayers and Vacher*, 1986], whereas a thick freshwater lens (Z_{MAX} = 16 m) has developed in the fine-sediment upper aquifer of the leeward Pingelap Island [*Anthony*, 1996c]. Characteristics of the five islands with observation data, including location, island width, estimated depth to the Thurber Discontinuity from either drilling or resistivity surveys, and freshwater lens thickness, is compiled from the work of *Ayers and Vacher* [1986] and *Anthony* [1996a, 1996b, 1996c, 1997] and is presented in Table 1. Z_{MAX} for the Pingelap, Kalap, and Ngatik was collected September1988, November 1989, and November 1990, respectively.

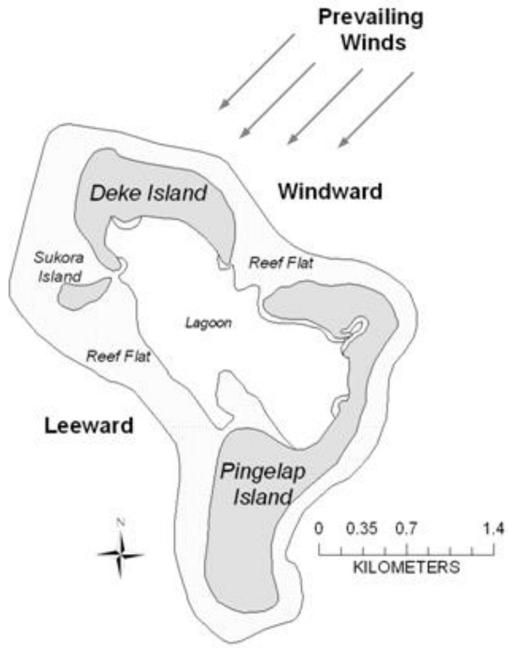


Figure 5. Pingelap Atoll, located in the Pohnpei State of the Federated States of Micronesia, showing Deke Island on the windward side of the atoll and Pingelap Island on the leeward side of the atoll.

Table 1. Observed characteristics of atoll islands in the Federated States of Micronesia

Island	**Atoll**	**FSM State**	**Island Width**[a] *m*	**Location on Atoll**	**Annual Rainfall**[b] *m yr*$^{-1}$	Z_{TD} *m*	Z_{MAX} *m*
Falalop	Ulithi	Yap	700	Windward	2.8	15	5
Deke	Pingelap	Pohnpei	350	Windward	4.0	16	4
Pingelap	Pingelap	Pohnpei	700	Leeward	4.0	16	16
Kalap	Mwokil	Pohnpei	450	Windward	4.0	16	4.6
Ngatik	Sapwuahfik	Pohnpei	1000	Leeward	4.0	20	20

[a] Measured from lagoon shoreline to ocean shoreline

[b] From *Anthony* [1997]

Climate in the geographic region of the FSM is influenced by a number of factors, including trade wind patterns and the El Niño Southern Oscillation (ENSO) [ ]. The amount of annual rainfall decreases steadily from south to north, with the northern region of the FSM experiencing a more prolonged dry season [*Landers and Khosrowpanah*, 2004]. The islands of Kosrae and Pohnpei receive annually approximately 5.24 m and 4.77 m, respectively, whereas the islands of Chuuk and Yap receive 3.41 m and 3.05 m, respectively. This difference is reflected in a chart of average monthly rainfalls over the years 1994 to 2005 shown in Figure 6.

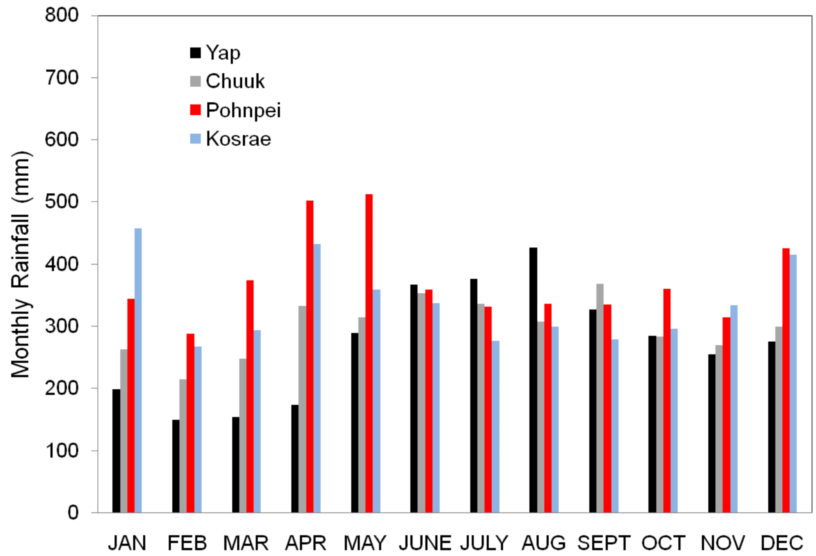


Figure 6. Average monthly rainfall for Yap, Chuuk, Pohnpei, and Kosrae over the years 1994 to 2005.

Drought events typically occur in the FSM during the winter and spring months during an El Niño event. Severe El Niño events can lengthen the drought period, with reduced rainfall conditions commencing in late autumn and extending into the summer of the following year. Figure 7 shows the daily rainfall (mm) for the island of Pohnpei during the years 1997 through 2000, during which a period of pronounced reduction in rainfall was experienced during the first half of 1998 due to an extreme El Niño event. Indeed, the annual rainfall total for Pohnpei for 1998 is the lowest on record during the period 1953 and 2001 [*Landers and Khosrowpanah*, 2004], with the 16.2 mm of rainfall for the month of January the lower month total of record. Similar reductions in rainfall during the initial months of 1998 were experienced for the other three main islands in the FSM, as shown in Figure 8, and throughout the outer islands of the FSM.

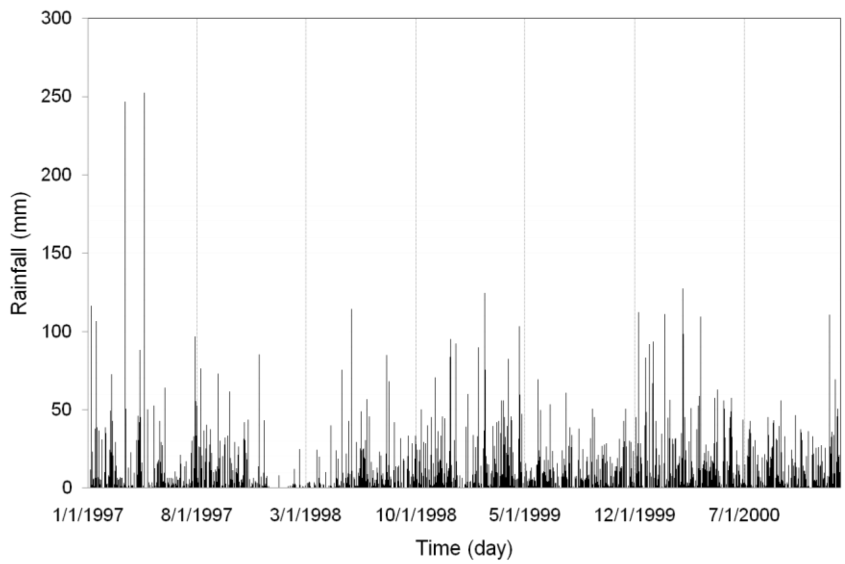


Figure 7. Daily rainfall, in mm, for the island of Pohnpei for the years 1997 to 2000, highlighting the El Niño-induced drought during the first half of 1998.

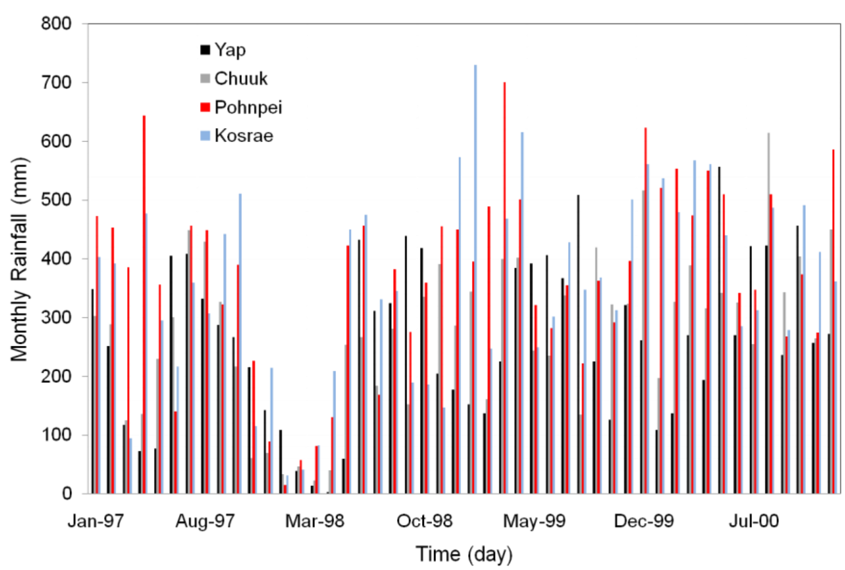


Figure 8. Monthly rainfall, in mm, for Yap, Chuuk, Pohnpei, and Kosrae islands for the years 1997 to 2000, highlighting the drought experienced during the first half of 1998.

The exact response of the freshwater lens during an El Niño-induced drought in the FSM is unknown, although through communication with residents of atoll island communities it is evident that most islands experienced a depletion of the lens during the drought period, with water in hand-dug wells becoming brackish. During the drought event of 1998, many outer islands required importation of water from the main islands to sustain living conditions.

Limited data regarding the behavior of a freshwater lens during the 1998 drought, however, was recorded for Laura Island, Majuro Atoll, located in the southeastern region of the Republic of the Marshall Islands (RMI) [*Presley*, 2005]. Majuro Atoll (Figure 9) has an approximate population of 27,000, with about 4,000 residing on Laura. The atoll receives an average annual rainfall of approximately 3.4 m, based on records from 1954 to 2000 [*Presley*, 2005] and Laura Island has a well-defined freshwater lens that has a maximum extent of approximately 14 m below the ground surface under normal climatic conditions [*Hamlin and Anthony*, 1987]. The lens is influenced by the Thurber Discontinuity, which is positioned at depths between 16.5 m and 24.0 m, with a downward slope from the ocean side to the lagoon side. The maximum thickness of the lens develops on the lagoon side of the island, where Z_{TD} is the greatest [*Hamlin and Anthony*, 1987].

Majuro Atoll experiences drought conditions similar to the region of the FSM, with rainfall during January to April 1998 only 8.2% of the average monthly rainfall for these months [*Presley*, 2005]. Recorded rainfall during the months of February, March, and April 1998 was less than one inch per month. An analysis of the freshwater lens thickness during the 1998 drought was accomplished by sampling Cl^- concentration from monitoring wells positioned along lines transecting the width of the island [*Presley*, 2005], with the limit of freshwater designated as 500 g_{Cl} m_{water}^{-3}. Location of the cross section transects, and the position of the monitoring well where the freshwater lens was at a maximum along each cross section, are shown in Figure 9. Four cross sections (A-A', B-B', D-D', and E-E') are shown in Figure 9, with the width of each cross section, and Z_{MAX} at sampling times for each monitoring well, shown in Table 2. Only the monitoring well along cross section A-A' has pre-drought freshwater lens thickness data.

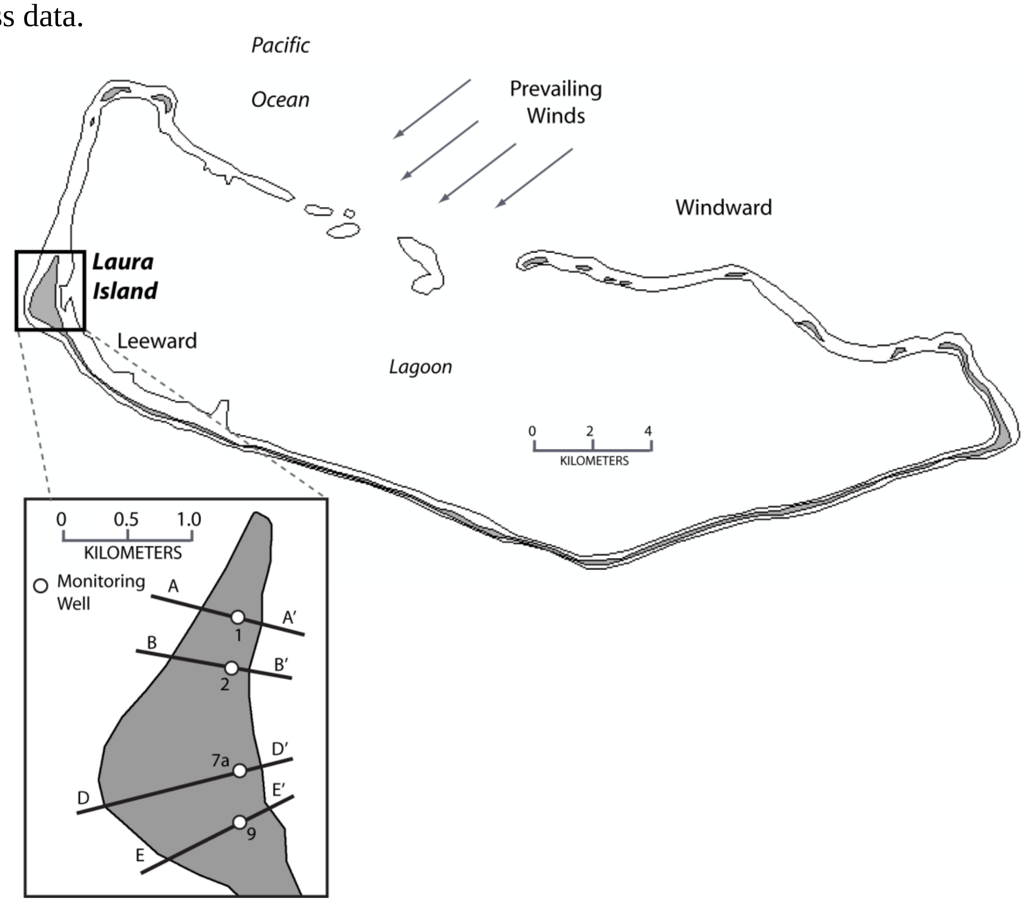


Figure 9. Map of Majuro Atoll, Republic of the Marshall Islands, with a magnification of Laura Island, located on the western platform of the atoll ring. Magnified image [after *Presley*, 2005] shows the placement of monitoring wells 1, 2, 7a, and 9 along cross-sections A-A', B-B', D-D', and E-E', respectively in the study of *Presley* [2005].

Table 2. Width of Laura Island at cross sections A-A', B-B', D-D', and E-E', with measured freshwater lens thickness Z_{MAX} at observation times during the drought and drought recovery periods during 1998 and early 1999.

	A-A'	B-B'	D-D'	E-E'
Width	450	750	1200	750
Date	Site 1	Site 2	Site 7a	Site 9
	Freshwater Lens Thickness (Z_{MAX})			
1/1/1998	15.2	-	-	-
6/8/1998	7.9	11.3	14.6	11.3
8/28/1998	8.2	11.9	15.8	13.7
1/14/1999	9.8	12.5	17.1	13.7

ESTIMATING THE GROUND WATER RESOURCES OF FSM ATOLL ISLANDS

Algebraic Model

Using the variably-density groundwater flow and solute transport finite element code SUTRA [*Voss and Provost*, 2003], a numerical model depicting the hydrologic and geologic setting of atoll islands was constructed and numerical simulations were run to investigate the influence of rainfall (2.5 to 5.5 m yr^{-1}), island width (150 m to 1100 m), hydraulic conductivity of the upper aquifer (25 to 500 m day^{-1}), depth to the Thurber Discontinuity (8 to 16.5 m), and the presence of the reef flat plate on the thickness of the freshwater lens Z_{MAX}. The model was constructed using a two-dimensional finite element mesh representing the cross section of a generic atoll island from the lagoon to the ocean side, with the reef flat plate, given a hydraulic conductivity of 0.05 m day^{-1}, located on the ocean side (Figure 4) [*Bailey et al.*, 2009]. The lower aquifer was given a hydraulic conductivity of 5000 m day^{-1} for all simulations.

Fluid pressure from seawater was simulated using specified pressure boundary conditions, with seawater entering the model domain along these boundaries assigned a salt concentration of 0.0357 kg_{salt} kg_{water}^{-1}, or 35,700 g_{salt} m_{water}^{-3}. Recharge water reaching the water table, which was assumed to equal half of the total rainfall [*Griggs and Peterson*, 1993] and was applied uniformly across the width of the island, was assigned a salt concentration of 2.0 x 10^{-5} kg_{salt} kg_{water}^{-1}, or 20 g_{salt} m_{water}^{-3}, typical of rainfall in the Pacific Basin [*Anthony*, 1987]. Freshwater in the subsurface, i.e. the water contained in the freshwater lens, was defined as any groundwater containing a salt concentration less than approximately 0.00089 kg_{salt} kg_{water}^{-1}, or 900 g_{salt} m_{water}^{-3}, which corresponds to a chloride (Cl^-) concentration of approximately 530 g_{Cl} m_{water}^{-3}. This value is a conservative approximation of the Cl^- concentration of 600 g_{Cl} m_{water}^{-3} recommended by the World Health Organization [*WHO*, 1972], and similar to the value used by *Lloyd et al.* [1980] in their study of the freshwater lens on Tarawa, Gilbert Islands in the South-Central Pacific.

For each scenario the simulation was run until steady conditions were achieved, i.e., when the delineation of the freshwater lens body did not change with time. As such, results reflected average climatic conditions for the assigned rainfall rate. Detailed results of these test runs are presented in *Bailey et al.* [2009], with the general conclusions that Z_{MAX} (i) increases with increasing rainfall rate and island width and decreasing hydraulic conductivity, (ii) increases slightly due to the presence of the confining reef flat plate layer, and (iii) is limited by the presence of the Thurber Discontinuity, with any freshwater descending below this discontinuity being thoroughly mixed with the seawater.

The influence of each hydrologic and geologic parameter on Z_{MAX} was captured in the following algebraic model, as presented in *Bailey et al.* [2010]:

$$Z_{MAX} = L(1 - e^{-bR})SC \tag{1}$$

where Z_{MAX} is the thickness of the freshwater lens at the center-point of the island [m]; R is the annual rainfall rate [m yr^{-1}]; b is a fitting parameter, and is dependent on island width; S and C are the hydraulic conductivity and reef flat plate parameters [-], respectively; and L is the maximum potential value of the freshwater lens thickness, based on the width of the island and the depth to the Thurber Discontinuity, and is given by:

$$L = y_0 + (Z_{TD} - y_0)(1 - e^{-dw}) \tag{2}$$

where y_0 and d are constants (-16.07 and 0.0075, respectively) and w is the width of the island [m] at the location of lens thickness estimation.

A detailed explanation of the derivation of Equation (1) is given in *Bailey et al.* [2010]. In general, the expression $Z_{MAX} = L(1 - e^{-bR})$ describes the increase in Z_{MAX} as the rainfall rate R is increased, but limited by the Thurber Discontinuity depth Z_{TD} and the width of the island w as contained in the expression for L in Equation (2), which was obtained through analysis of the relationship between w, Z_{TD}, and the limiting value of Z_{MAX} [*Bailey et al.*, 2010]. The inclusion of Z_{TD} in the algebraic model derivation is vital for application to atoll islands.

The S parameter is a scaling factor that increases or decreases the estimated value of Z_{MAX} according to the actual hydraulic conductivity of the upper aquifer and the width of the island. The expression $Z_{MAX} = L(1 - e^{-bR})$ is based on numerical simulations using a value of 50 m day^{-1} for the upper aquifer hydraulic conductivity, and the influence of varying degrees of hydraulic conductivity as determined through numerical simulations is captured in S [*Bailey et al.*, 2010]. A similar procedure was used to determine values of C to account for the influence of the reef flat plate on Z_{MAX}. If the atoll island structure does not contain a reef flat plate, then C is assigned a value of 1.0; otherwise, the C value is greater than 1.0 and dependent on island width. Charts for the parameters b, S, and C are provided in *Bailey et al.* [2008] and *Bailey et al.* [2010]. In situations where the hydraulic conductivity of the upper aquifer is unknown, the S parameter may be estimated using values of 50 m day^{-1} and 400 m day^{-1} for leeward and windward islands, respectively [*Bailey et al.*, 2009]. This generalization, however, is applicable only to regions with distinct trade wind patterns such as the FSM.

Additional numerical model simulations were in order to determine the influence of time-dependent rainfall and tidal fluctuations on the thickness and extent of the freshwater lens [*Bailey et al.*, 2009]. This was done using rainfall and tide data from the regions surrounding Yap (northwestern region of the FSM) and Pohnpei (southeastern region of the FSM) during the years 1997 to 1999, in order to determine the influence of drought conditions on the freshwater lens. In general, and depending on the island width used in the simulation, the lens thinned considerably during the months of the drought, and then recovered to almost pre-drought conditions during the following year and a half through the end of 1999.

Using results from these simulations and comparing them to results from the average climatic simulations, a dimensionless drought factor *D* was established for various island widths for both the northwestern and southeastern regions of the FSM. This factor is incorporated in much the same way as *S* and *C*, and is included in the algebraic model to yield:

$$Z_{MAX} = L(1 - e^{-bR})SCD \tag{3}$$

Charts are contained in *Bailey et al.* [2008] and *Bailey et al.* [2010]. Values of *D* depend on island width, and are given for each month of the 1997-1999 El Niño and post-El Niño period.

Validation of Algebraic Model for FSM

With the goal of applying the algebraic model to accurately and efficiently assess the available groundwater resources of atoll islands within the FSM, the model is tested against freshwater lens data obtained during both average and drought-induced environmental conditions.

For average climatic conditions, algebraic model results are compared against the data obtained from give atoll islands within the FSM, as presented in Table 1. The values of annual rainfall rate *R*, island width *w*, and depth to the Thurber Discontinuity Z_{TD} are provided and inserted directly into Equations (1) and (2). For the leeward islands (Pingelap, Ngatik) a hydraulic conductivity value of 50 m day^{-1} is assumed, resulting in an *S* value of 1.0 for both island; for the windward islands (Falalop, Deke, and Kalap), a hydraulic conductivity value of 400 m day^{-1} is assumed, resulting in *S* values of 0.42, 0.27, and 0.30, respectively, signifying a decrease in the freshwater lens thickness due to the high conductivity. Each island contains a reef flat plate, and values of *C* for Pingelap, Ngatik, Falalop, Deke, and Kalap are 1.03, 1.00, 1.03, 1.09, and 1.07, signifying an increased influence of the reef flat plate on the lens for smaller islands.

Figure 10 shows the observed values (black triangles) and the model-simulated values (light-grey circles), demonstrating an excellent match and the ability of the model to capture the hydrologic and geologic conditions for both leeward and windward islands. However, in general the value of Z_{TD} is not known unless drilling or resistivity surveys are accomplished for an individual island. If a Z_{TD} value of 15 m is used, which is on the lower end of observed values of Z_{TD} [*Wheatcraft and Buddemeier*, 1981] and be used to provide a conservative lens thickness estimate for islands for which there are no published values, then the model-calculated lens thickness would have underestimated the freshwater lens thickness for Pingelap and Ngatik.

Figure 10. Observed and model-calculated freshwater lens thickness for five islands in the Federated States of Micronesia: Deke, Pingelap Atoll, Pohnpei State; Kalap, Mwokil Atoll, Pohnpei State; Falalop, Ulithi Atoll, Yap State; Pingelap, Pingelap Atoll, Pohnpei State; and Ngatik, Ngatik Atoll, Pohnpei State.

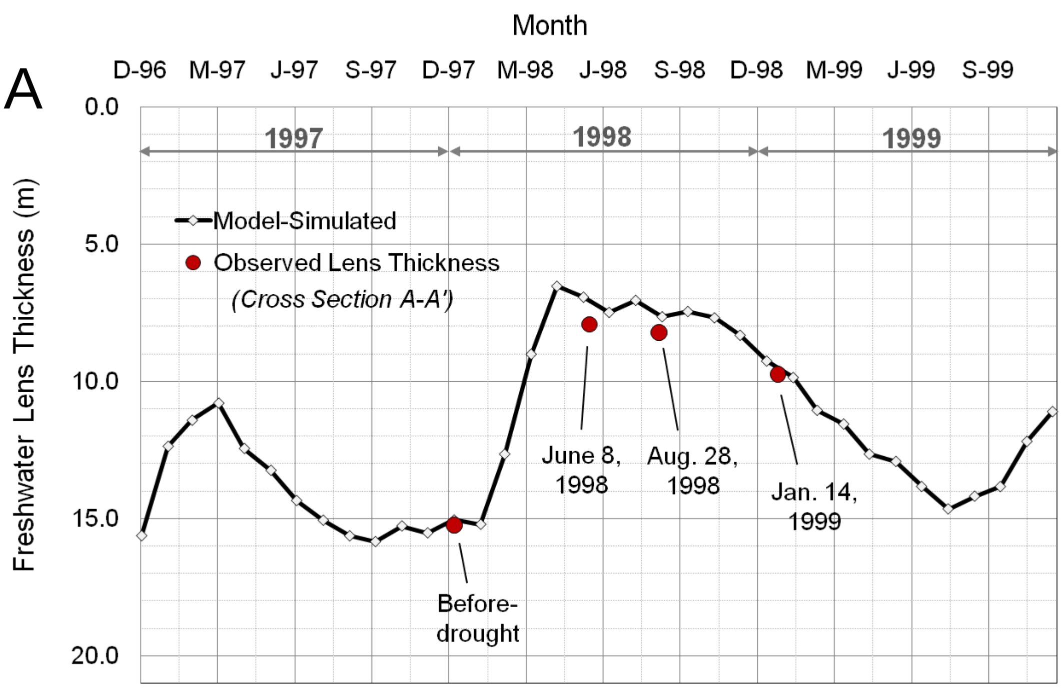
For drought conditions, algebraic model results are compared against the data obtained from the four monitoring wells on Laura Island during the 1998 drought, as presented in Table 2, corresponding to the cross-sections A-A', B-B', D-D', and E-E', as established by *Presley* [2005]. Due to the similar climatic behavior during El Niño-induced droughts between Majuro Atoll and the FSM, comparison of algebraic model results against observed freshwater lens behavior for Majuro Atoll is assumed to validate the algebraic model for use in the FSM for drought conditions.

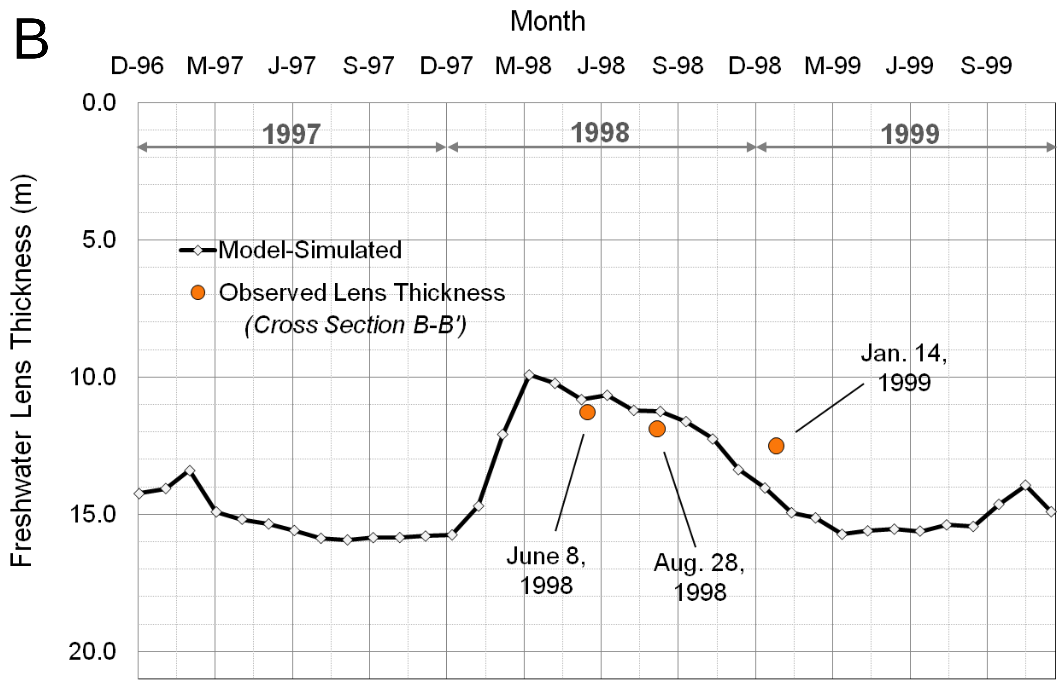
The value of annual rainfall rate R for the island of Laura is 3.38 m, and the width of the island w for the four cross sections are 450 m, 750 m, 1200 m, and 750 m. Depth to the Thurber Discontinuity Z_{TD} is set to 17.5 m for the monitoring wells along cross sections A-A', B-B', and E-E' since Z_{MAX} occurs near the center of the island cross section, whereas Z_{TD} is set to 22.0 m for the monitoring well of cross section D-D' since Z_{MAX} occurs very close to the lagoon side of the island where the Thurber Discontinuity dips downward. Since Laura is a leeward island on the Majuro Atoll, the hydraulic conductivity of the upper aquifer is assumed to equal 50 m day^{-1}, resulting in an S value of 1.0 for each cross section. The island contains a reef flat plate, and the value of C for each of the cross sections is 1.07, 1.02, 1.00, and 1.02, respectively, signifying no influence by the reef flat plate for the 1200 m-wide cross section D-D'. Since cross sections B-B' and E-E' have the same island width, all parameters placed in the algebraic model are the same.

For each of the four monitoring wells, the validation test consists of using the drought indices provided by *Bailey et al.* [2010] to calculate the freshwater lens thickness during each month of the 1997-1999 El Niño period (pre-drought year, drought year, post-drought year) and comparing the observed freshwater lens thicknesses with the calculated freshwater lens thicknesses at each observation time.

Results are shown in Figure 11, with the plot of the monthly algebraic model-calculated freshwater lens thickness and associated observed lens thicknesses shown for cross sections A-A’, B-B’, D-D’, and E-E’ in Figure 11A, 11B, 11C, and 11D, respectively. Although additional observed data is required to provide a more complete comparison, the current comparison demonstrates the ability of the model to capture the general trend of the freshwater lens behavior, i.e., the thickening of the lens during the latter half of 1998 and the first month of 1999. For cross section A-A, calculated Z_{MAX} also compares well with the observed pre-drought freshwater lens thickness. Figure 12 shows a plot of model-calculated Z_{MAX} against the observed Z_{MAX} data for the four cross sections, demonstrating the close match between the two. Since the values of Z_{MAX} are calculated for the beginning of each month, the values to compare with the observed values were calculated using linear interpolation between two monthly values.

It is important to note that no calibration was performed during this validation exercise, i.e., the model parameters that are not known with a high degree of certainty (S, C, and D) were not modified in order to determine the best fit between the model results and observed data. This is important since such an exercise cannot be performed when applying the algebraic model to other islands.




B
Month
D-96
M-97
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S-97
D-97
M-98
J-98
S-98
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M-99
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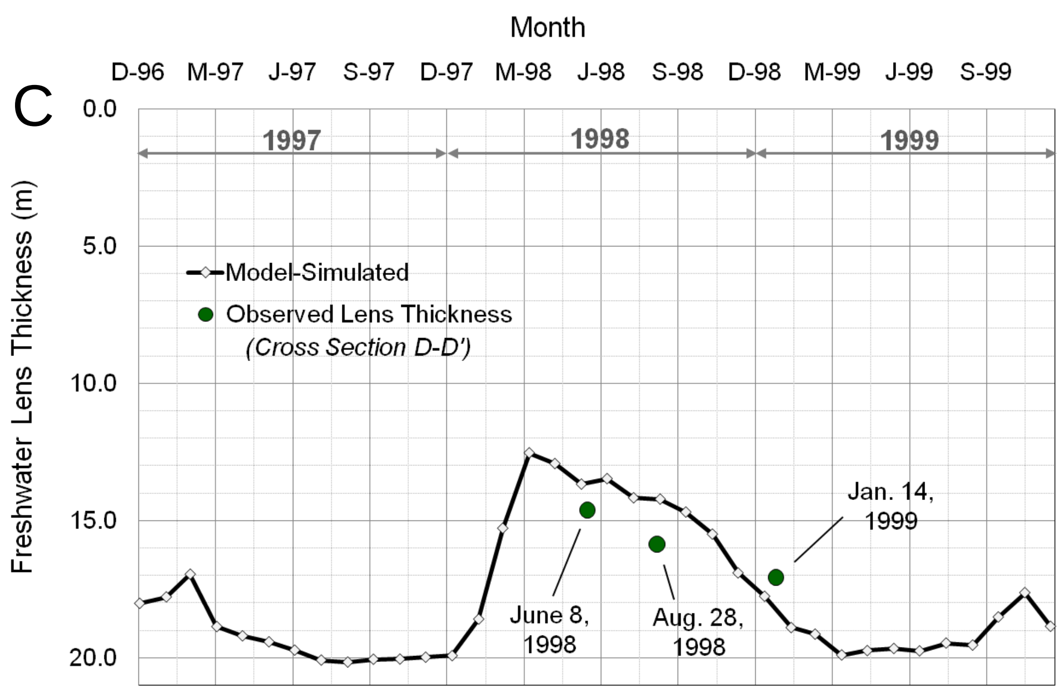
S-99
0.0
5.0
10.0
15.0
20.0
1997
1998
1999
Freshwater Lens Thickness (m)
Model-Simulated
Observed Lens Thickness
(Cross Section B-B')
June 8, 1998
Aug. 28, 1998
Jan. 14, 1999


C
Month
D-96
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J-97
S-97
D-97
M-98
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D-98
M-99
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S-99
0.0
5.0
10.0
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20.0
1997
1998
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Freshwater Lens Thickness (m)
Model-Simulated
Observed Lens Thickness
(Cross Section D-D')
June 8, 1998
Aug. 28, 1998
Jan. 14, 1999

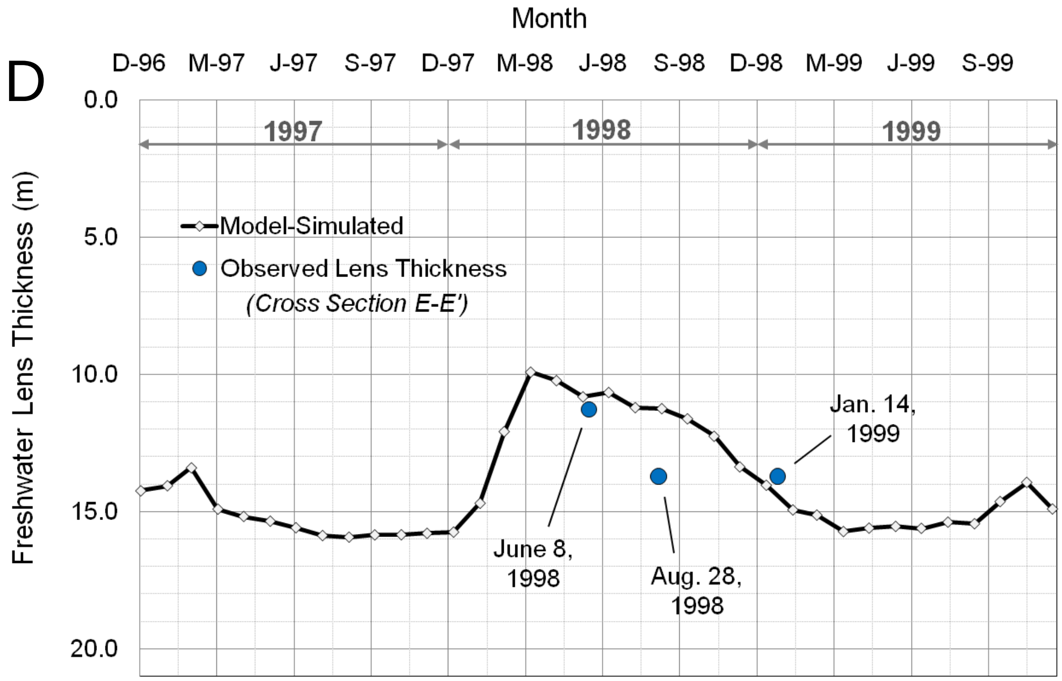

Figure 11. Comparison of observed lens thicknesses and corresponding model-simulated freshwater lens thickness during the 1997-1999 period for Laura Island, Majuro Atoll, using the algebraic model, for monitoring wells at cross sections (A) A-A', (B) B-B', (C) D-D', and (D) E-E', as shown in Figure 9.

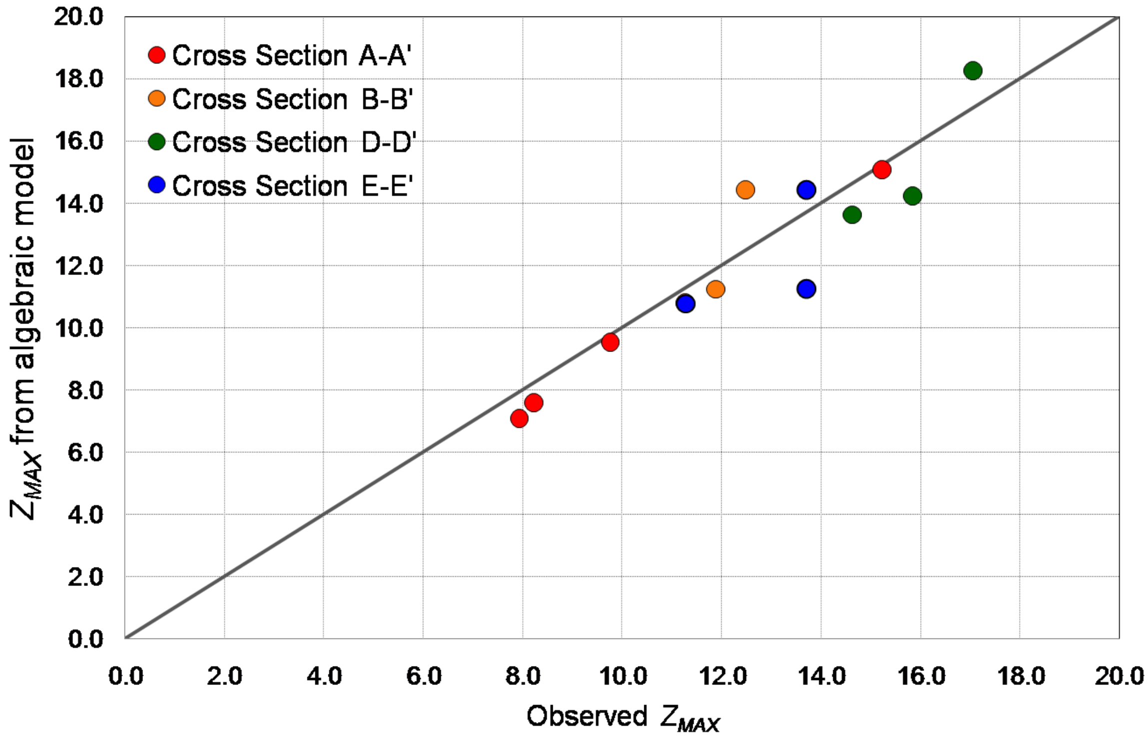

Figure 12. Comparison of observed Z_{MAX} with model-calculated Z_{MAX} for the four cross sections of Laura Island, Majuro Atoll, during the 1998 drought, demonstrating the accuracy of the algebraic model.

Assessment of Groundwater Resources of the FSM using the Algebraic Model

With the algebraic model successfully tested for the FSM, the model is used to assess the freshwater lens thickness for each of the atoll islands in the FSM for both average and drought-induced climatic conditions. A complete listing of atoll islands, including the annual rainfall rate *R*, island width *w*, and others parameters used in the algebraic model for each island, is contained in the Appendix. A total of 105 islands (45 for Yap State, 37 for Chuuk State, 23 for Pohnpei State) were included in the analysis. For leeward islands, the hydraulic conductivity was assumed to equal 50 m day^{-1}; for windward islands, 400 m day^{-1}, and for islands positioned between the leeward and windward sides, 200 m day^{-1}. The vast majority of the islands (95) are either windward or between leeward and windward. The value of Z_{TD} was set to 15.0 m for all islands in order to provide a conservative estimate of Z_{MAX}. Values of *b*, *S*, and *C* are determined by island width and the use of the charts in *Bailey et al.* [2008].

The value of Z_{MAX} for average climatic conditions as calculated by Equation (1) for each of the 105 islands is shown in Figure 13A. Values are also listed in the Appendix. The general windward position of the islands is seen through the linear trend of Z_{MAX} as a function of island width near the lower portion of Figure 13A, with thin lenses (< 5 m) existing for the majority of the windward islands. For the leeward islands the values of Z_{MAX} are larger, with the maximum value of Z_{MAX} controlled by Z_{TD} (15.0 m) for the larger islands (> 700 m in width).

The minimum value of Z_{MAX} for during a 3-year period similar to the 1997-1999 El Niño and post-El Niño period for each of the 105 islands, as calculated by Equation (3) using monthly drought indices, is shown in Figure 13B. Values are also listed in the Appendix. The minimum value of Z_{MAX} is the focus value since it is the condition against which sustainability must be measured. As can be seen from Figure 13B, only 3 islands (Pingelap, Kalap, Ngatik) are predicted to maintain a lens thickness greater than 5 m during the peak of the drought, whereas the lens on the vast majority (97 out of 105) of the islands is completely depleted. This is due to (i) the windward position of the majority of the islands, with a high hydraulic conductivity that allows the freshwater to be carried quickly to the perimeter of the island, resulting in a depletion of the lens when the lens cannot be replenished from rainfall, and (ii) the majority of the island residing within the Yap and Chuuk states, which receive less rainfall than the geographic region of Pohnpei State.

As an example of the time-dependent lens thickness, Figure 14 shows the predicted fluctuation of the lens thickness during the 1997-1999 period for one representative island from each of the three FSM states containing atolls that has a substantial atoll island community. Woleai, Lukanor, and Pingelap islands are located in Yap State, Chuuk State, and Pingelap State, respectively. Pingelap, a leeward island with an island width of 700 m, maintains a thick lens throughout the 3-period; Lukanor, a leeward island with an island width of 350 m, maintains a lens always greater than 2.5 m; and Woleai, a windward island width an island width of 900 m, experiences a complete depletion of the lens during the peak of the during the spring months of 1999. Even though Woleai has a width much larger than Lukanor, the lens is depleted due to its position on the windward side of the atoll and the resulting high hydraulic conductivity of the upper aquifer.

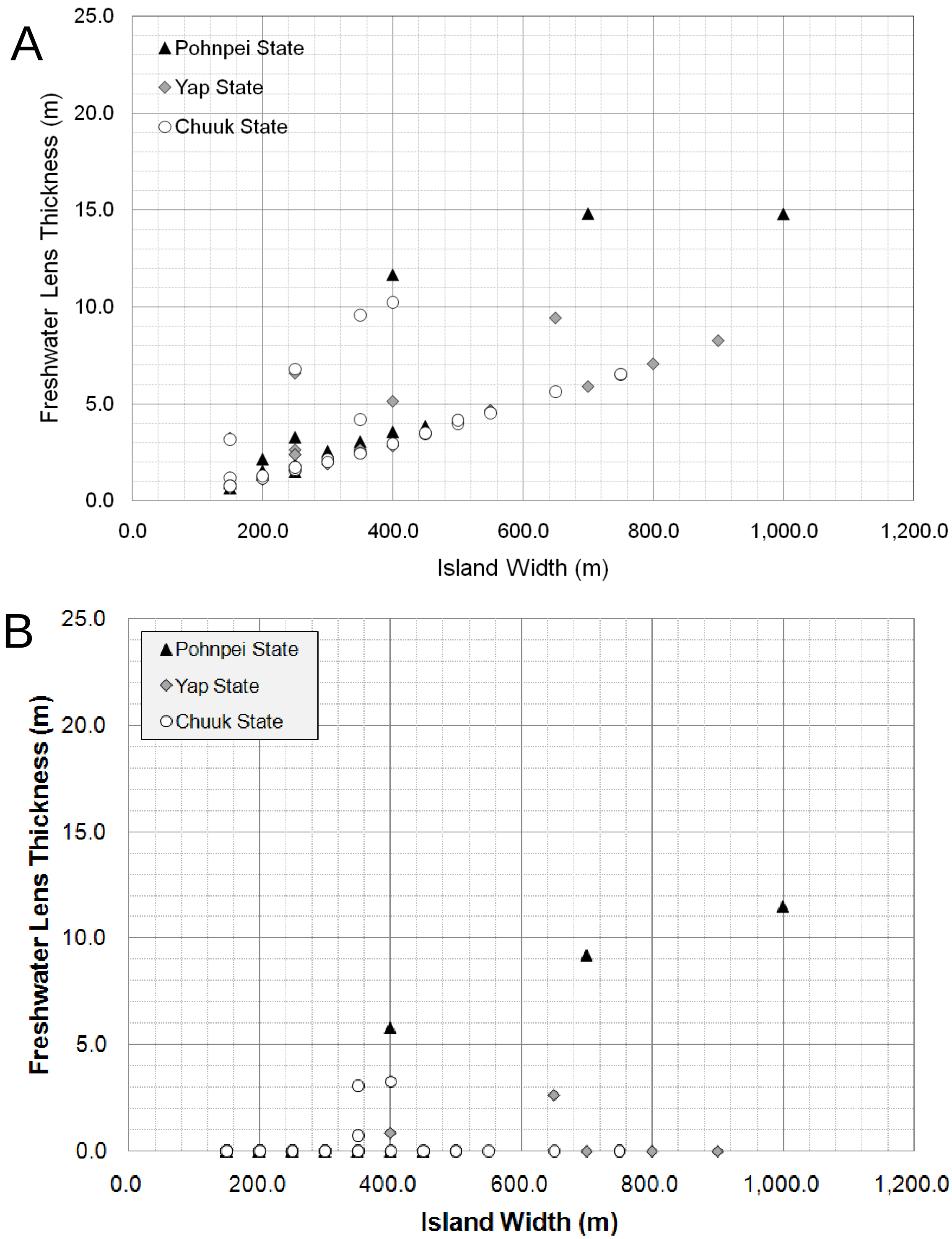

Figure 13. Estimated freshwater lens thickness Z_{MAX} of atoll islands in Yap State, Chuuk State, and Pohnpei State in the Federated States of Micronesia for (A) Average rainfall rates, and (B) Drought conditions similar to the 1998 drought.

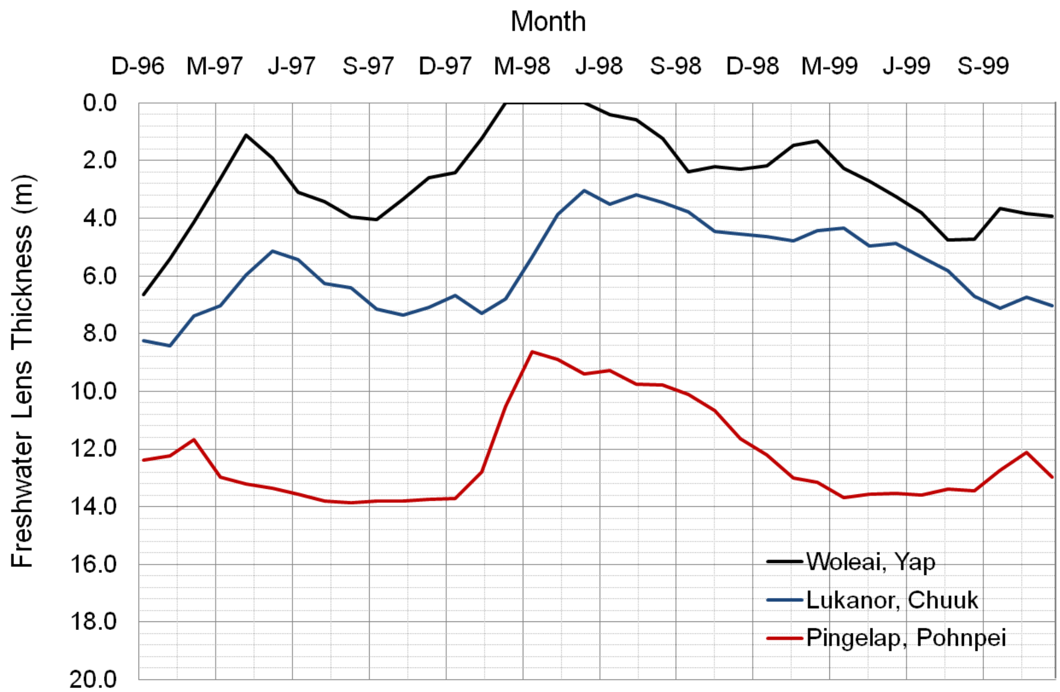

Figure 14. Model-calculated fluctuation of Z_{MAX} during the 1997-1999 period for one island from each state that has a substantial island community. Woleai, Lukanor, and Pingelap are located within the Yap, Chuuk, and Pohnpei states of the FSM.

SUMMARY

The algebraic model developed for atoll islands [*Bailey et al.*, 2010] to predict the freshwater lens thickness during both average and drought-influenced climatic conditions was validated for use in the FSM through comparison of model results with observed lens thickness data. The validation exercise yielded close matches between observed and model-calculated values. The model was then used to assess the freshwater lens thickness of 105 atoll islands within the FSM for both average and drought-influenced climatic conditions. Rules of thumb include setting the value of the Thurber Discontinuity depth Z_{TD} to 15.0 m in order to provide conservative estimates of the freshwater lens thickness, as well as using hydraulic conductivity values of 50 m day^{-1} and 400 m day^{-1} for leeward and windward islands, respectively. For islands situated between the leeward and windward regions of the atoll, a value in between (e.g., 200 m day^{-1}) can be used. The vast majority of atoll islands are positioned on the windward side of their respective atolls.

In general, only large leeward islands are able to maintain a substantial freshwater lens during both average and climatic conditions, with the majority of islands being windward and hence containing a thin lens no matter the rate of rainfall. These results provide water resources managers of atoll island communities with important information regarding the sustainability of island resources, and can be used for future planning within these communities.

It should also be noted that these analyses do not include the effects of pumping, which may increase during drought conditions. However, only a few islands have resources for pumping and hence does not figure into the analysis for most of the islands. Furthermore, the effects of rain catchment storage volumes, in corporation with the length of drought period that can be withstood through the use of rain catchment water and hence prevent use of the groundwater, have not been included. In general, and as discussed by *White and Falkland* [2009], future assessments of water resources on atoll islands must include a coupled rainwater-groundwater assessment, with a focus on optimizing the storage of water for use during drought conditions.

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APPENDIX

Z_{MAX} for atoll islands in the Federated States of Micronesia

Tables 1, 2, and 3 contain parameter values for the algebraic model and the resulting Z_{MAX} for both average and drought conditions, for atoll islands within Yap State, Chuuk State, and Pohnpei State of the Federated States of Micronesia, respectively. The values for drought conditions correspond to the peak of the drought, i.e., the worst-case scenario. The simulated drought corresponds to a severe drought similar to the one experienced in Micronesia during 1998.

Table 1. Z_{MAX} calculations for atoll islands within Yap State, FSM

Island	**Location on Atoll**	**Width** *w* *m*	**Annual Rainfall** *R* $m\ yr^{-1}$	**Limiting Value** *L*	**Fitting Parameter** *b*	**Hydraul. Cond. factor** *S* [-]	**Reef Flat plate factor** *C* [-]	Z_{MAX} Average *m*	Z_{MAX} Drought *m*
Eauripik Atoll A	Windward	250	3.50	10.24	0.26	0.25	1.12	**1.75**	**0.00**
B	Windward	350	3.50	12.75	0.34	0.27	1.09	**2.66**	**0.00**
Elato Islands A	Windward	450	3.25	13.94	0.49	0.30	1.07	**3.58**	**0.00**
B	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
C	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
D	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
Faraulep Atoll A	Windward	300	3.10	11.73	0.29	0.26	1.11	**2.04**	**0.00**
B	Windward	500	3.10	14.27	0.57	0.32	1.06	**4.03**	**0.00**
C	Windward	200	3.10	8.07	0.24	0.25	1.14	**1.20**	**0.00**
Ifalik Atoll A	Windward	300	3.50	11.73	0.29	0.26	1.11	**2.19**	**0.00**
B	Windward	550	3.50	14.50	0.66	0.34	1.05	**4.69**	**0.00**
C	Leeward	150	3.50	4.91	0.24	1.00	1.17	**3.23**	**0.00**
Lamotrek Atoll A	Windward	250	3.25	10.24	0.26	0.25	1.12	**1.67**	**0.00**
B	Windward	550	3.25	14.50	0.66	0.34	1.05	**4.60**	**0.00**
C	Leeward	250	3.25	10.24	0.26	1.00	1.12	**6.60**	**0.00**
Ngulu Atoll A	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
B	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
C	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
D	Mixed	250	3.25	10.24	0.26	0.40	1.12	**2.65**	**0.00**
Olimarao Atoll	Windward	250	3.25	10.24	0.26	0.25	1.12	**1.67**	**0.00**
Pulueuk	Windward	800	3.10	14.92	1.00	0.49	1.02	**7.08**	**0.00**
Satawall Atoll	Mixed	650	3.25	14.76	0.83	0.66	1.03	**9.45**	**2.64**
Sorol Atoll A	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
B	Windward	150	3.25	4.91	0.24	0.24	1.17	**0.74**	**0.00**
C	Windward	350	3.25	12.75	0.34	0.27	1.09	**2.56**	**0.00**
Ulithi Atoll A Mogmog	Windward	400	2.80	13.45	0.41	0.29	1.08	**2.84**	**0.00**
B	Windward	200	2.80	8.07	0.24	0.25	1.14	**1.12**	**0.00**
C	Windward	300	2.80	11.73	0.29	0.26	1.11	**1.91**	**0.00**
D Falalop	Windward	700	2.80	14.84	0.89	0.42	1.03	**5.91**	**0.00**
E	Windward	300	2.80	11.73	0.29	0.26	1.11	**1.91**	**0.00**
F Fasserai	Windward	150	2.80	4.91	0.24	0.24	1.17	**0.66**	**0.00**
G	Windward	150	2.80	4.91	0.24	0.24	1.17	**0.66**	**0.00**
H	Windward	200	2.80	8.07	0.24	0.25	1.14	**1.12**	**0.00**
I	Mixed	250	2.80	10.24	0.26	0.40	1.12	**2.40**	**0.00**
J	Mixed	250	2.80	10.24	0.26	0.40	1.12	**2.40**	**0.00**

West Fayo Atoll	Windward	150	3.53	4.91	0.24	0.24	1.17	**0.78**	**0.00**
Woleai Atoll A	Windward	900	3.53	14.96	1.06	0.56	1.00	**8.28**	**0.00**
B	Windward	250	3.53	10.24	0.26	0.25	1.12	**1.76**	**0.00**
C	Windward	150	3.53	4.91	0.24	0.24	1.17	**0.78**	**0.00**
D	Windward	350	3.53	12.75	0.34	0.27	1.09	**2.67**	**0.00**
E	Leeward	150	3.53	4.91	0.24	1.00	1.17	**3.25**	**0.00**
F	Mixed	400	3.53	13.45	0.41	0.47	1.08	**5.15**	**0.86**
G	Windward	250	3.53	10.24	0.26	0.25	1.12	**1.76**	**0.00**
H	Mixed	150	3.53	4.91	0.24	0.38	1.17	**1.23**	**0.00**
I	Windward	200	3.53	8.07	0.24	0.25	1.14	**1.31**	**0.00**

Table 2. Z_{MAX} calculations for atoll islands within Chuuk State, FSM

Island	Location on Atoll	Width w m	Annual Rainfall R $m\ yr^{-1}$	Limiting Value L	Fitting Parameter b	Hydraul. Cond. factor S [-]	Reef Flat plate factor C [-]	Z_{MAX} Average m	Z_{MAX} Drought m
Etal Atoll A	Windward	250	3.40	10.24	0.26	0.25	1.12	**1.72**	**0.00**
B	Windward	150	3.40	4.91	0.24	0.24	1.17	**0.76**	**0.00**
C	Windward	200	3.40	8.07	0.24	0.25	1.14	**1.28**	**0.00**
D	Leeward	150	3.40	4.91	0.24	1.00	1.17	**3.17**	**0.00**
Murilo A	Windward	400	3.00	13.45	0.41	0.29	1.08	**2.94**	**0.00**
B	Windward	200	3.00	8.07	0.24	0.25	1.14	**1.18**	**0.00**
C	Leeward	400	3.00	13.45	0.41	1.00	1.08	**10.24**	**3.24**
Losap Atoll A	Windward	650	3.40	14.76	0.83	0.39	1.03	**5.64**	**0.00**
B	Windward	250	3.40	10.24	0.26	0.25	1.12	**1.72**	**0.00**
C	Mixed	150	3.40	4.91	0.24	0.38	1.17	**1.20**	**0.00**
Lukanor Atoll A	Windward	150	3.41	4.91	0.24	0.24	1.17	**0.76**	**0.00**
B	Windward	250	3.41	10.24	0.26	0.25	1.12	**1.72**	**0.00**
C	Windward	500	3.41	14.27	0.57	0.32	1.06	**4.16**	**0.00**
D	Leeward	350	3.41	12.75	0.34	1.00	1.09	**9.59**	**3.04**
Namoluk Atoll A	Windward	250	3.40	10.24	0.26	0.25	1.12	**1.72**	**0.00**
B	Windward	300	3.40	11.73	0.29	0.26	1.11	**2.16**	**0.00**
C	Mixed	350	3.40	12.75	0.34	0.44	1.09	**4.20**	**0.70**
Namonuito Atoll A	Windward	500	3.00	14.27	0.57	0.32	1.06	**3.98**	**0.00**
B	Windward	350	3.00	12.75	0.34	0.27	1.09	**2.45**	**0.00**
C	Windward	250	3.00	10.24	0.26	0.25	1.12	**1.59**	**0.00**
D	Windward	450	3.00	13.94	0.49	0.30	1.07	**3.46**	**0.00**
E1	Windward	400	3.00	13.45	0.41	0.29	1.08	**2.94**	**0.00**
E2	Windward	750	3.00	14.89	0.95	0.45	1.02	**6.52**	**0.00**
Neoch A	Windward	300	3.40	11.73	0.29	0.26	1.11	**2.16**	**0.00**
B	Windward	150	3.40	4.91	0.24	0.24	1.17	**0.76**	**0.00**
Nomwin A	Windward	300	3.00	11.73	0.29	0.26	1.11	**2.00**	**0.00**
B	Windward	200	3.00	8.07	0.24	0.25	1.14	**1.18**	**0.00**
C	Windward	350	3.00	12.75	0.34	0.27	1.09	**2.45**	**0.00**
Pulap Atoll A	Windward	450	3.07	13.94	0.49	0.30	1.07	**3.49**	**0.00**
B	Windward	250	3.07	10.24	0.26	0.25	1.12	**1.61**	**0.00**
Puluwat Atoll A	Windward	750	3.07	14.89	0.95	0.45	1.02	**6.54**	**0.00**
B	Windward	550	3.07	14.50	0.66	0.34	1.05	**4.53**	**0.00**
Satawan Atoll A	Windward	200	3.40	8.07	0.24	0.25	1.14	**1.28**	**0.00**
B	Windward	250	3.40	10.24	0.26	0.25	1.12	**1.72**	**0.00**
C	Windward	500	3.40	14.27	0.57	0.32	1.06	**4.16**	**0.00**
D	Windward	150	3.40	4.91	0.24	0.24	1.17	**0.76**	**0.00**
E	Leeward	250	3.40	10.24	0.26	1.00	1.12	**6.79**	**0.00**

Table 3. Z_{MAX} calculations for atoll islands within Pohnpei State, FSM

Island	Location on Atoll	Width w m	Annual Rainfall R $m\ yr^{-1}$	Limiting Value L	Fitting Parameter b	Hydraul. Cond. factor S [-]	Reef Flat plate factor C [-]	Z_{MAX} Average m	Z_{MAX} Drought m
Ant Atoll A	Windward	150	4.77	4.91	0.24	0.24	1.17	**0.93**	**0.00**
B	Windward	300	4.77	11.73	0.29	0.26	1.11	**2.57**	**0.00**
C	Mixed	250	4.77	10.24	0.26	0.40	1.12	**3.29**	**0.00**
Kapingamarangi Atoll A	Windward	150	2.79	4.91	0.24	0.24	1.17	**0.66**	**0.00**
B	Windward	150	2.79	4.91	0.24	0.24	1.17	**0.66**	**0.00**
C	Windward	250	2.79	10.24	0.26	0.25	1.12	**1.51**	**0.00**
D	Windward	150	2.79	4.91	0.24	0.24	1.17	**0.66**	**0.00**
Mwokil Atoll A Kalap	Windward	450	4.00	13.94	0.49	0.30	1.07	**4.13**	**0.00**
B	Leeward	400	4.00	13.45	0.41	1.00	1.08	**12.50**	**5.79**
C	Windward	200	4.00	8.07	0.24	0.25	1.14	**1.55**	**0.00**
Ngatik Atoll A	Windward	300	4.00	11.73	0.29	0.26	1.11	**3.26**	**0.00**
B	Windward	250	4.00	10.24	0.26	0.25	1.12	**2.68**	**0.00**
C	Leeward	1000	4.00	14.98	1.11	1.00	1.00	**19.74**	**11.48**
Nukuoro Atoll A	Windward	200	3.79	8.07	0.24	0.25	1.14	**1.37**	**0.00**
B	Windward	300	3.79	11.73	0.29	0.26	1.11	**2.29**	**0.00**
C	Mixed	200	3.79	8.07	0.24	0.39	1.14	**2.16**	**0.00**
Oroluk Atoll	Windward	350	4.10	12.75	0.34	0.27	1.09	**2.88**	**0.00**
Pakin Atoll A	Windward	200	4.77	8.07	0.24	0.25	1.14	**1.56**	**0.00**
B	Windward	150	4.77	4.91	0.24	0.24	1.17	**0.93**	**0.00**
C	Windward	350	4.77	12.75	0.34	0.27	1.09	**3.07**	**0.00**
D	Windward	400	4.77	13.45	0.41	0.29	1.08	**3.57**	**0.00**
Pingelap Atoll A Deke	Windward	350	4.00	12.75	0.34	0.27	1.09	**3.05**	**0.00**
B Pingelap	Leeward	700	4.00	14.84	0.89	1.00	1.03	**15.82**	**9.20**