AN ATOLL FRESHWATER LENS ALGEBRAIC MODEL FOR GROUNDWATER MANAGEMENT IN THE CAROLINE ISLANDS

By

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WERI

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ABSTRACT

This report contains the presentation and explanation of the Atoll Freshwater Lens Algebraic Model. This model was prepared for water resources managers of atoll islands within the Federated States of Micronesia, and is capable of estimating the thickness of the freshwater lens for a variety of geological and weather conditions. The freshwater lens thickness can be estimated by manual calculations, the use of a spreadsheet user interface, or a set of curves. Of principal interest is its use in predicting the fluctuation of the freshwater lens thickness throughout an El Niño event. Users, however, should keep in mind that because the model is based on generalizations of atoll properties, which can vary significantly from one island to another, the model will be applied with greatest success when supplemented or tested against actual data from the island of interest.

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INTRODUCTION

Maintaining water supplies on atoll islands is challenging due to their low elevation and relative isolation from nearby communities. Under normal conditions the island communities rely on rain catchment water for domestic purposes such as drinking, cooking, and washing dishes. During times of water stress, however, which occurs during periods of drought associated with an El Niño event, people turn to groundwater to meet the water demand. Determining the depth and size of the freshwater lens is difficult due to the shallowness of the lens, the dual nature of the aquifer system, and tidal forcing on both the lagoon and ocean sides. Adding to this difficulty is the impracticality of performing water resources studies on every atoll due to their remote locations. Figure 1 displays several atolls from the Federated States of Micronesia.
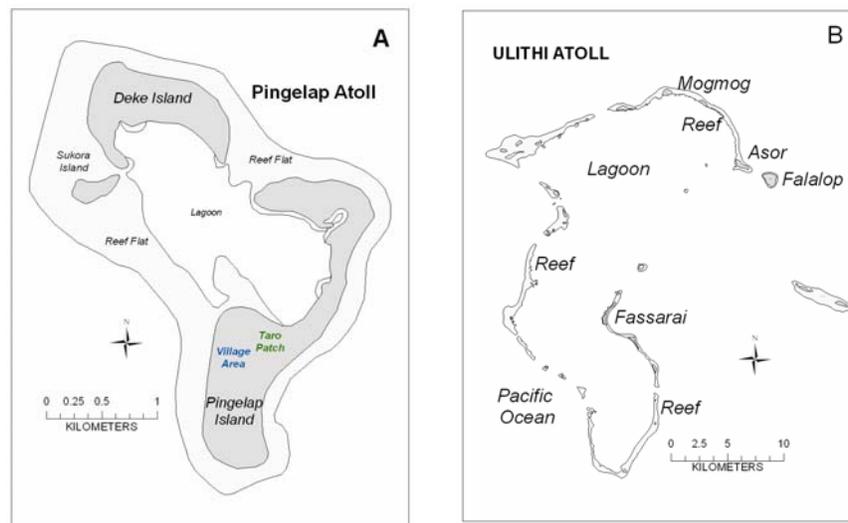
Figure 1. Maps of (**A**) Pingelap Atoll, Pohnpei State, Federated States of Micronesia, and (**B**) Ulithi Atoll, Yap State, Federated States of Micronesia

OBJECTIVES

The purpose of this report is to explain the use of the Atoll Freshwater Lens Algebraic Model, which relates climatic and geologic features of atoll islands to the thickness of the freshwater lens. The model is based on past water resource studies of atoll islands, observations performed during the course of this study, and results of groundwater modeling simulations (Bailey et al., 2008).

GROUNDWATER HYDROLOGY OF OCEANIC ISLANDS

Freshwater Lens

The source of the freshwater in the shallow island subsurface is the precipitation which falls on the ground surface of the island. A large portion of the rainwater is lost to the atmosphere through evapotranspiration. A significant portion of the precipitation is intercepted by the vegetation and subsequently evaporated, while the remainder reaches the ground, infiltrates down through the top layers of soil. A portion of this infiltrated water is taken up by the plant roots as transpiration, while the remainder, under the influence of gravity, percolates down through the soil layers, eventually reaching the part of the soil and rocks which is saturated with freshwater. This body of freshwater floats atop the denser seawater below, and is termed the *freshwater lens*. This process is summarized by the following equation:

$$R = P - ET \qquad (1)$$

where R = Recharge to the freshwater lens (meters)
P = Precipitation (meters)
ET = Evapotranspiration, which includes the precipitation intercepted by the vegetatation, and the water in the soil taken up by plant and tree roots (meters)

Hydraulic Head

As seen in Figure 2, a depiction of the groundwater system on oceanic islands, the fresh groundwater piles up at sea level. The depth of water between sea level and the water table is termed the *hydraulic head* (H in Figure 2), and, due to density differences between seawater and freshwater, directly influences the thickness of the freshwater lens below sea level. A thick freshwater lens results from a large value of hydraulic head.
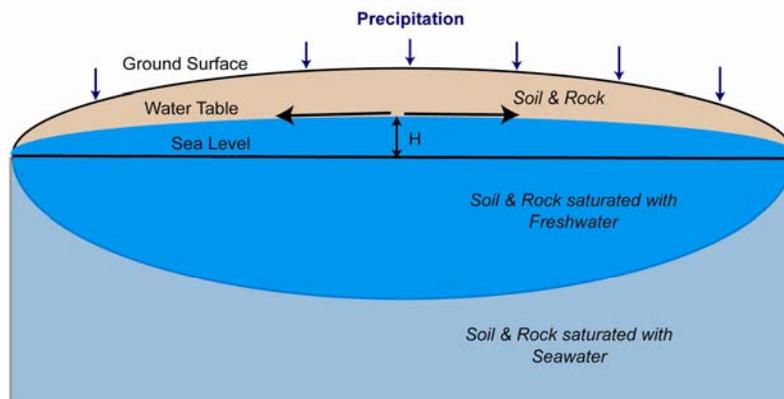
Figure 2 Island Hydrology, showing precipitation, the soil zone, the freshwater zone, and the seawater zone

Factors Influencing the Hydraulic Head

       The hydraulic head is directly influenced by the amount of recharge. With large amounts of recharge, the hydraulic head increases, and a thick freshwater lens is maintained. If, however, recharge is minimal due to low amounts of precipitation, then the hydraulic head decreases, and a thin lens results.

       The hydraulic conductivity, a property of soil, sediments and rock that describes the ease with which the water can move through the pore spaces, also has a strong influence on the hydraulic head. As shown by the arrows at the water table (see Figure 2), the groundwater that reaches the freshwater lens is continually being conducted through the soil and rocks to the coast. If the hydraulic conductivity of the subsurface sediments is low (fine-grained sediments), then the groundwater will move slowly, allowing the water to pile up and increasing the hydraulic head. This will in turn allow a thick freshwater lens to be sustained. If, on the other hand, the hydraulic conductivity of the subsurface sediments is high (coarse-grained sediments), the water will move quickly through the soil, preventing mounding of the water and creating a small hydraulic head and a thin lens.

GROUNDWATER HYDROLOGY OF ATOLL ISLANDS

       This section presents and discusses the features of the atoll island climatic and geologic system which influence the thickness of the freshwater lens. These features are included in the atoll freshwater lens algebraic model, which is presented in the next section. A conceptual model of atoll island hydrogeology is presented in Figure 3. Similar to the island subsurface depicted in Figure 2, atoll island groundwater hydrology consists of a freshwater lens floating atop the denser seawater. A unique aspect of atoll island geology, however, is the dual-aquifer system, which consists of 15-25 m of fine-grained sediments (Upper Aquifer) resting upon a thick layer of highly permeable limestone (Lower Aquifer) (Wheatcraft and Buddemeier, 1981). The freshwater lens is usually confined to the fine-grained sediments of the Upper Aquifer.

       Table 1 on the next page shows the observed freshwater lens thicknesses on atoll islands across the Pacific and Indian Oceans, for which data are available. The following items are climatic and geologic factors that have a role in determining the maximum thickness of the freshwater lens.

Recharge to the Aquifer

       As described in the previous section, the recharge is the portion of total precipitation which infiltrates the soil and recharges the freshwater lens. Several field investigators have estimated that the annual recharge rate, in meters per year, is approximately half of the annual rainfall rate (Hamlin and Anthony, 1987). The body of freshwater is in the shape of a lens (see Figure 2). As discussed previously, the rate of recharge directly influences the hydraulic head, which in turn determines the thickness of the freshwater lens.
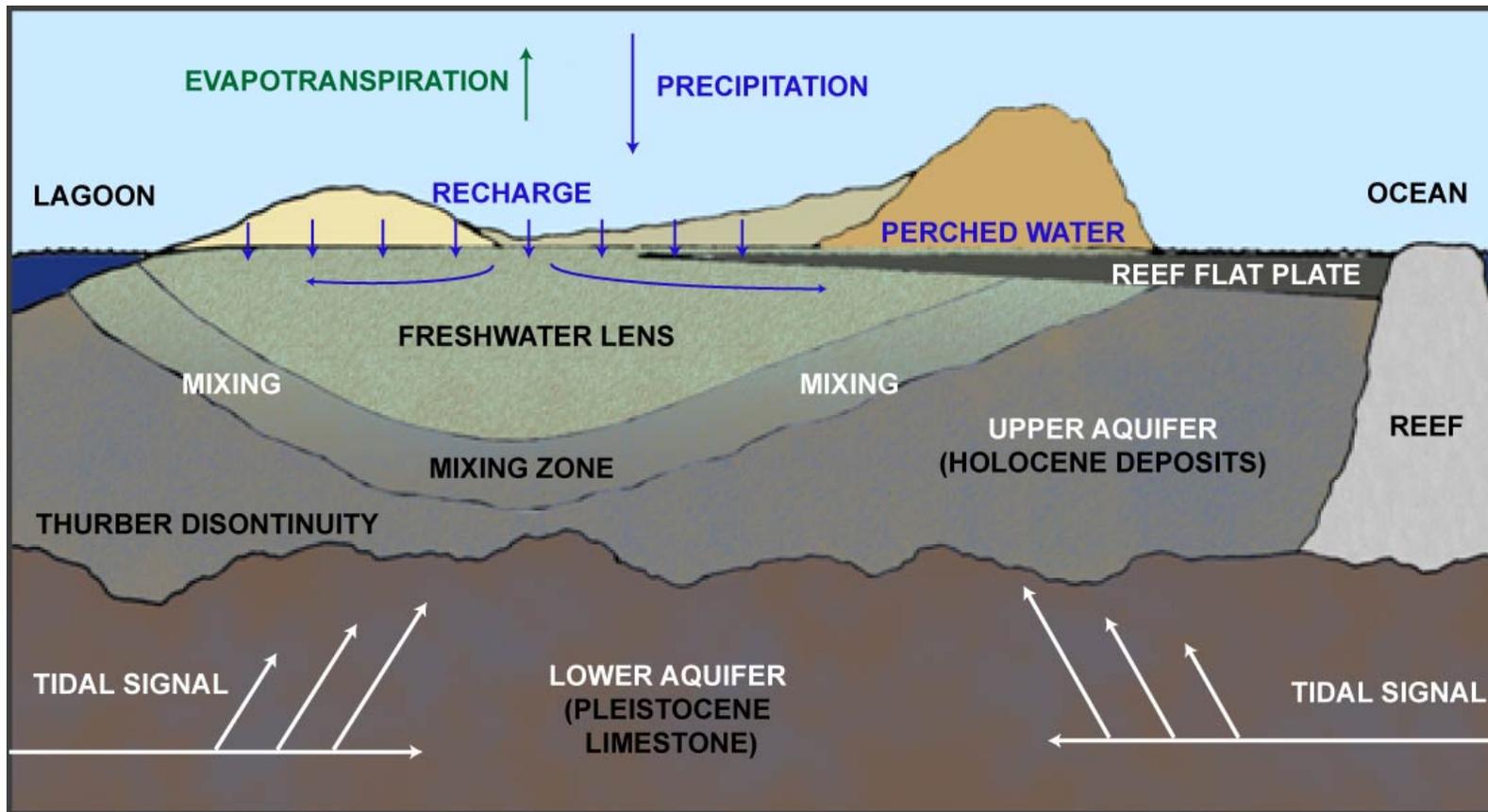
Figure 3. Conceptual Model of atoll island hydrogeology, after Ayers and Vacher (1986). The principal controlling features on the freshwater lens are (1) the width of the islands, (2) the recharge to the freshwater lens, (3) the hydraulic conductivity of the Holocene sediments, (4) the contact between the upper and lower aquifers, and (5) the reef flat plate.

Table 1 Freshwater Lens Depths

Island / Location	Atoll	Region	Source	Location on Atoll	Width m	Thickness m
Cantonment	Diego Garcia	Central Indian	PRC Toups, 1983	Leeward	2200	**20**
AO NW	Diego Garcia	Central Indian	PRC Toups, 1983	Leeward	1150	**15**
AO SE	Diego Garcia	Central Indian	PRC Toups, 1983	Leeward	1300	**20**
Home Island	Cocos	East Indian	Falkland, 1994	Offset	775	**8**
WI Northern	Cocos	East Indian	Falkland, 1994	Leeward	800	**14**
WI 1	Cocos	East Indian	Falkland, 1994	Leeward	800	**15**
WI 6	Cocos	East Indian	Falkland, 1994	Leeward	500	**15**
WI 8	Cocos	East Indian	Falkland, 1994	Leeward	400	**12**
WI 22	Cocos	East Indian	Falkland, 1994	Leeward	270	**7**
South Island	Cocos	East Indian	Falkland, 1994	Windward	1000	**11**
Falalop	Ulithi	FSM	Anthony, 1997	Offset	950	**5**
Khalap	Mwoakilloa	FSM	Anthony, 1996a	Windward	425	**6**
Ngatik	Sapwuahfik	FSM	Anthony, 1996b	Leeward	900	**20**
Deke	Pingelap	FSM	Ayes and Vacher, 1986	Windward	400	**4**
Pingelap	Pingelap	FSM	Anthony, 1996c	Leeward	750	**16**
Laura	Majuro	Marshall Islands	Hamlin and Anthony, 1987	Leeward	1200	**14 to 22**
Kwajelein	Kwajelein	Marshall Islands	Hunt and Peterson, 1980	Offset	600	**10 to 18**
Roi-Namur	Kwajelein	Marshall Islands	Gingerich, 1992	Windward	750	**5 to 7**
Eneu	Bikini	Marshall Islands	Peterson, 1997	Offset	400	**5 to 10**
Bikini	Bikini	Marshall Islands	Peterson, 1997	Windward	600	**< 2**
Enjebi	Enewetak	Marshall Islands	Buddemeier and Holladay, 1977	Windward	1000	**< 2**
Matabou	Nonouti	Gilbert Island	Falkland, 2003	Offset	375	**5**
Buariki	Tarawa	Gilbert Island	Jacobson and Taylor, 1981	Offset	1200	**29**
Buota	Tarawa	Gilbert Island	Lloyd et al, 1980	Offset	650	**23**
Bonriki	Tarawa	Gilbert Island	Falkland, 1992	Windward	1200	**23**
NZ 4	Christmas	Kiribati	Falkland, 1983	Leeward	1500	**14**
NZ 2	Christmas	Kiribati	Falkland, 1983	Leeward	1500	**17**

Rainfall Patterns

The rate of precipitation, and thus the rate of recharge, is constantly changing in day-to-day fluctuations (Lloyd et al., 1980). There are also long-term trends, such as the annual trend of wet-season and dry-season, and also periods of extreme weather patterns such as El Niño periods, which can bring long periods of drought. For small islands these periods of drought can sometimes exhaust all of the fresh groundwater.

Island Width

Larger islands are better able to sustain a thicker freshwater lens than smaller ones. Islands less than 200 meters wide seldom have a usable lens (Falkland, 1994).

Thurber Discontinuity

The upper and lower aquifers are divided by a solution discontinuity (Thurber et al., 1965), often referred to as the "Thurber Discontinuity" by island hydrogeologists (Peterson, 1997; Woodroffe and Falkland, 1997; Vacher, 1997). Usually located 15 to 25 meters below sea level (Wheatcraft and Buddemeier, 1981; Hamlin and Anthony, 1987; Anthony, 1997), it imposes a limiting depth on the growth of the freshwater lens. The lower aquifer is very porous and highly permeable, so freshwater which is pushed below the Thurber Discontinuity is rapidly mixed with the seawater. As seen in Table 1, not all islands have a freshwater lens which extends to the Thurber Discontinuity. The influence of the Thurber Discontinuity only becomes important for islands which can sustain a freshwater lens thick enough to reach it.

Hydraulic Conductivity of the Upper Aquifer

As discussed previously, the hydraulic conductivity of the subsurface sediments directly influences the hydraulic head, which in turn determines the thickness of the lens. In this way the coarseness of the sediments in the upper aquifer plays a large role in the ability of the island to maintain a freshwater lens. Fine sediments have an increased ability to retain the freshwater, whereas coarse sediments do not retain water very well. Islands with fine sediments typically have a much thicker lens than similar islands with coarse sediments. Field work has shown that islands on the windward side of an atoll, which receives the brunt of the high-energy waves driven by the trade winds, possess much coarser sediments than those on the leeward side (Anthony, 1997; Spennemann, 2006) (Figure 3). As a result, islands located on leeward portions of atolls tend to have much thicker freshwater lenses than those located on the windward portion (see Table 1).
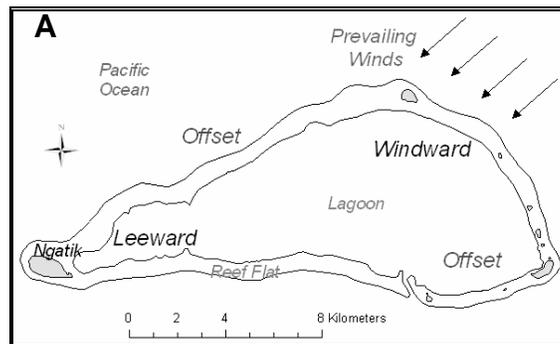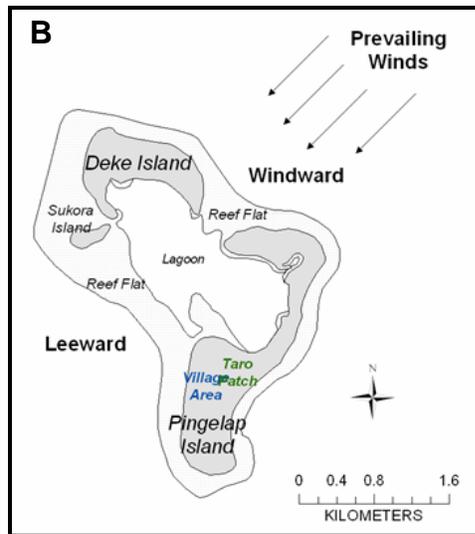
Figure 4. The layout of islands on (A) Sapwuahfik Atoll and (B) Pingelap Atoll. Both are located in the state of Pohnpei, Federated States of Micronesia. In both atolls, the leeward island (Pingelap Island; Ngatik Island) have larger surface areas and contain much thicker freshwater lens than the windward islands. Islands exposed to the prevailing winds contain subsurface sediments which have much higher hydraulic conductivity than those found on leeward islands.

Reef Flat Plate

The reef flat plate extends from the ocean-side reef to the interior of the island (see Figure 2), and has been observed on numerous atolls (Cox, 1951; Buddemeier and Holladay, 1977; Ayers and Vacher, 1986). This feature was observed on Ulithi and Pingelap Atolls during this study. The reef plate acts as a confining layer to the freshwater, forcing the water to flow under the plate to be discharged at the reef, as well as along fractures in the plate. As shown in Figure 4, residents of atoll islands sometimes punch through the plate to access the water.

Figure 5. Reef Flat Plate on Mogmog Island, Ulithi Atoll. The residents must punch through the plate to reach the fresh groundwater.

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THE ATOLL FRESHWATER LENS ALGEBRAIC MODEL

An algebraic equation, which relates the thickness of the lens to the climatic and geologic factors discussed in section 3 (Figure 5), was developed using the results of groundwater modeling simulations (Bailey et al., 2008):

$$Z_{MAX} = \left[Y + \frac{(Z_{TD} - Y)R}{B + R} \right] (K)(C)\left(T_{(r,s,w,y,m)}\right)$$

where

Z_{MAX}	=	Maximum depth of the freshwater lens for the island, in meters
R	=	Annual recharge rate, in meters per year
Y and B	=	Parameters dependent on the width of the island
Z_{TD}	=	Depth to the Thurber Discontinuity, in meters
K	=	Upper Aquifer Hydraulic Conductivity parameter
C	=	Confining (reef flat plate) parameter
T	=	Time parameter, to depict long-term rainfall patterns. The subscripts for the time parameter are *r* (region), *s* (side), *w* (weather pattern), *y* (year), and *m* (month)
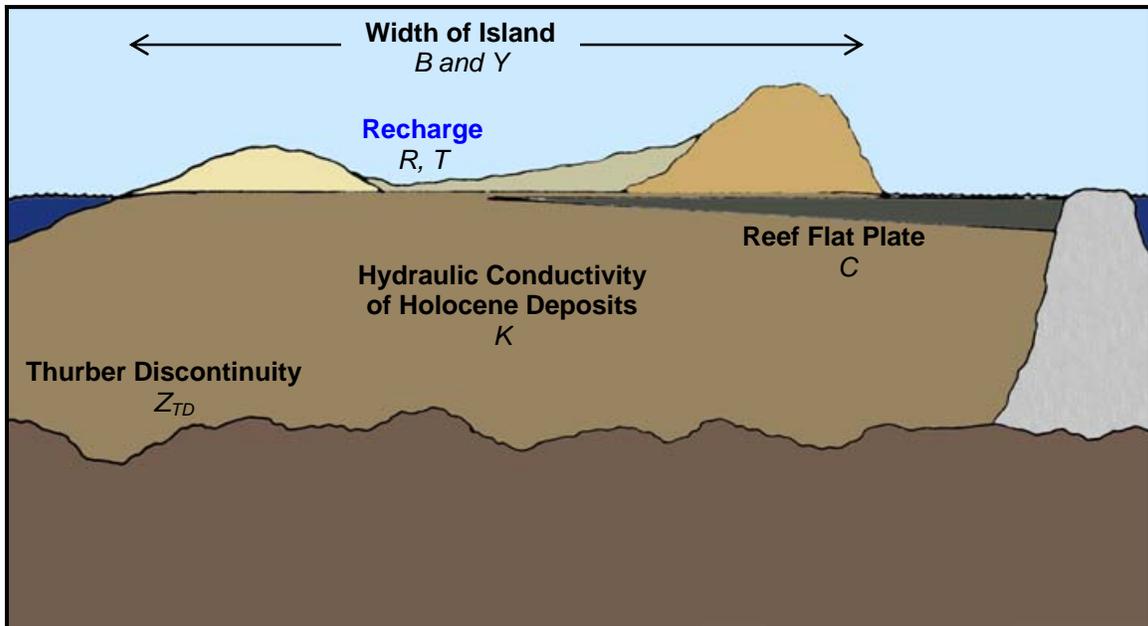
Figure 6. Climatic and geologic factors included in the Algebraic Model

There are three methods by which the algebraic model can be used to determine the maximum thickness of the freshwater lens: Manual calculations, a spreadsheet user interface, and a family of curves.

Manual Calculations

R Parameter (Recharge)

      The *R* value, the average annual recharge in meters per year, is determined from rainfall data for the atoll. If rainfall data are not available for a given island, then data from nearby islands may be used, with the understanding that it might differ. Table 2 contains average annual rainfall values for islands across Micronesia. The *R* value is normally calculated as half of the average annual rainfall value.

Table 2. Average annual rainfall rates across Micronesia

Island	State	Average Annual Rainfall m yr-1
Chuuk	Chuuk	**3.41**
Lukunoch	Chuuk	**3.41**
Polowat	Chuuk	**3.07**
Pohnpei	Pohnpei	**4.77**
Kapingamarangi	Pohnpei	**2.80**
Metalanim	Pohnpei	**4.80**
Nukuoro	Pohnpei	**3.79**
Paies-Kitti	Pohnpei	**4.80**
Palikir	Pohnpei	**4.80**
Pingelap	Pohnpei	**4.51**
Pohnpei WSO	Pohnpei	**4.80**
Yap	Yap	**3.05**
Ulithi	Yap	**2.59**
Woleai Atoll	Yap	**3.53**
Kwajelein	Marshalls	**2.59**
Majuro	Marshalls	**3.34**
Ailinglapalap	Marshalls	**2.97**
Utirik	Marshalls	**2.20**
Wotje	Marshalls	**2.46**

Source: Chip Guard, National Weather Service, Guam

B and Y Parameters (Island Width)

The *B* and *Y* parameters are dependent on the width of the island across the point on the island where the lens thickness is to be approximated. Figure 6 contains the curves used to estimate values for these parameters. To use the curves:

1. Determine the width of the atoll island in question. Locate this width on the x axis.
2. From this point, draw a vertical line to the *Y* factor curve (dotted curve).
3. From this point, draw a horizontal line to the y-axis to determine the *Y* factor value. Use this value in the equation.
4. Repeat steps 1-3 for the *B* factor.
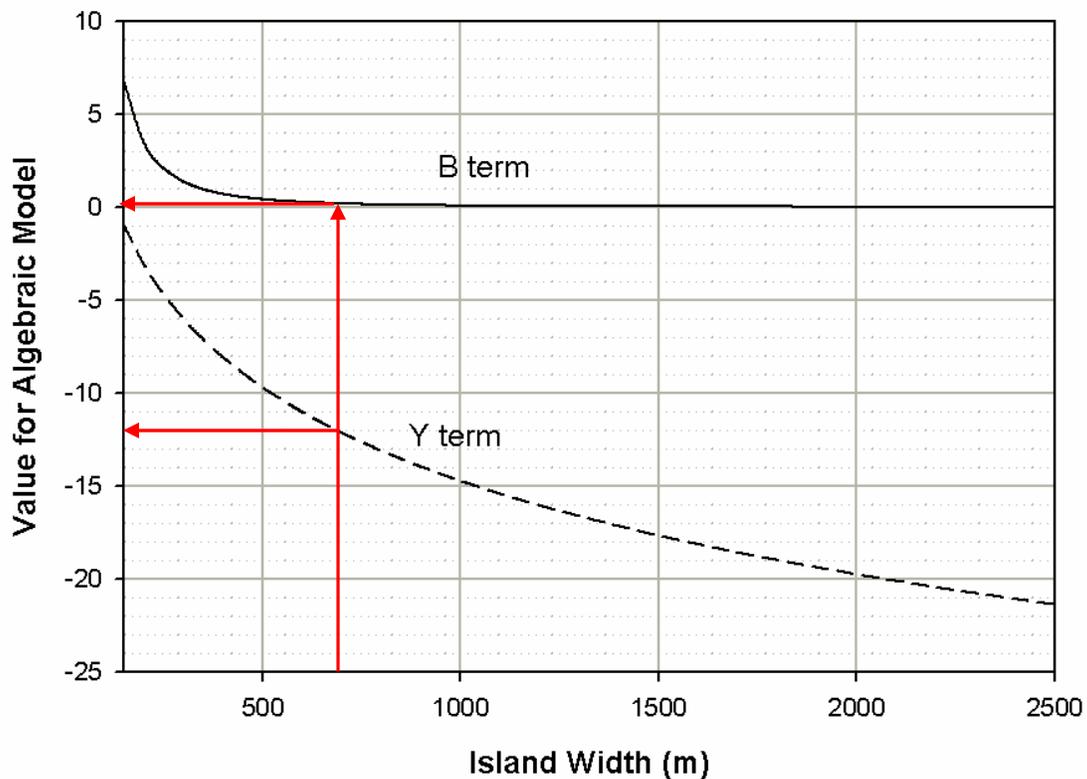
Figure 7. Curves to determine the value of the B and Y parameters. The parameters are dependent upon the width of the island.

Z_TD Parameter (Depth to the Thurber Discontinuity)

The value of the Z_{TD} parameter is the actual depth, in meters, to the Thurber Discontinuity. The average depth found from field investigations is approximately 15 to 17.5 meters. It is recommended that this value is used in the calculations, with 15 meters providing the most conservative estimate of freshwater lens thickness.

K Parameter (Hydraulic conductivity of the Upper Aquifer)

The *K* factor is determined by using the curves in Figure 7. If the island is located on the leeward portion of the atoll, use a hydraulic conductivity value of 50 m / day in the chart. If it is located within the windward portion, use 400 m / day. To use the curves:

1. Determine the width of the atoll island in question. Locate this width on the *x* axis.
2. Starting at this value, Draw a vertical line to the curve corresponding to the hydraulic conductivity of the Holocene sediments for the atoll in question.
3. From this point, draw a horizontal line to the *y*-axis to determine the hydraulic conductivity factor, *K*. Use this factor value in the equation.

If the island is located between the windward and leeward portions, use a value between 50 and 400 m / day. If the island is closer to the leeward portion of the atoll, use a value closer to 50 m / day. If it is closer to the windward portion, use a value close to 400 m / day.
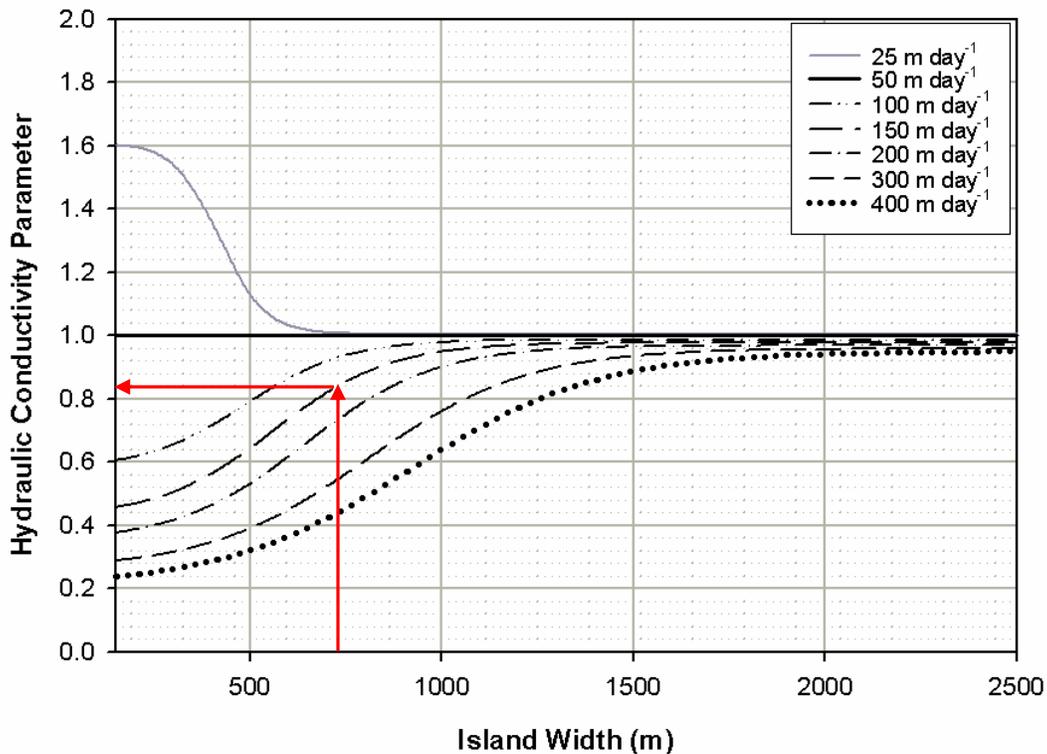
Figure 8. Curves for determining the value of the *K* factor

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C Parameter (Reef Flat Plate)

The *C* factor is the least significant term in the equation. Under most conditions, the value is 1, and the curve does not need to be used. However, if the lens thickness is being determined for a portion of the island where the reef flat plate is not present, the *C* factor will have a value slightly less than 1, thus decreasing the lens thickness by a small amount. To use the *C* curve, seen in Figure 8:

1. Determine the width of the atoll island in question. Locate this width on the *x* axis.
2. From this point, draw a vertical line to the *C* factor curve
3. From this point, draw a horizontal line to the *y*-axis to determine the *C* factor value. Use this value in the equation.
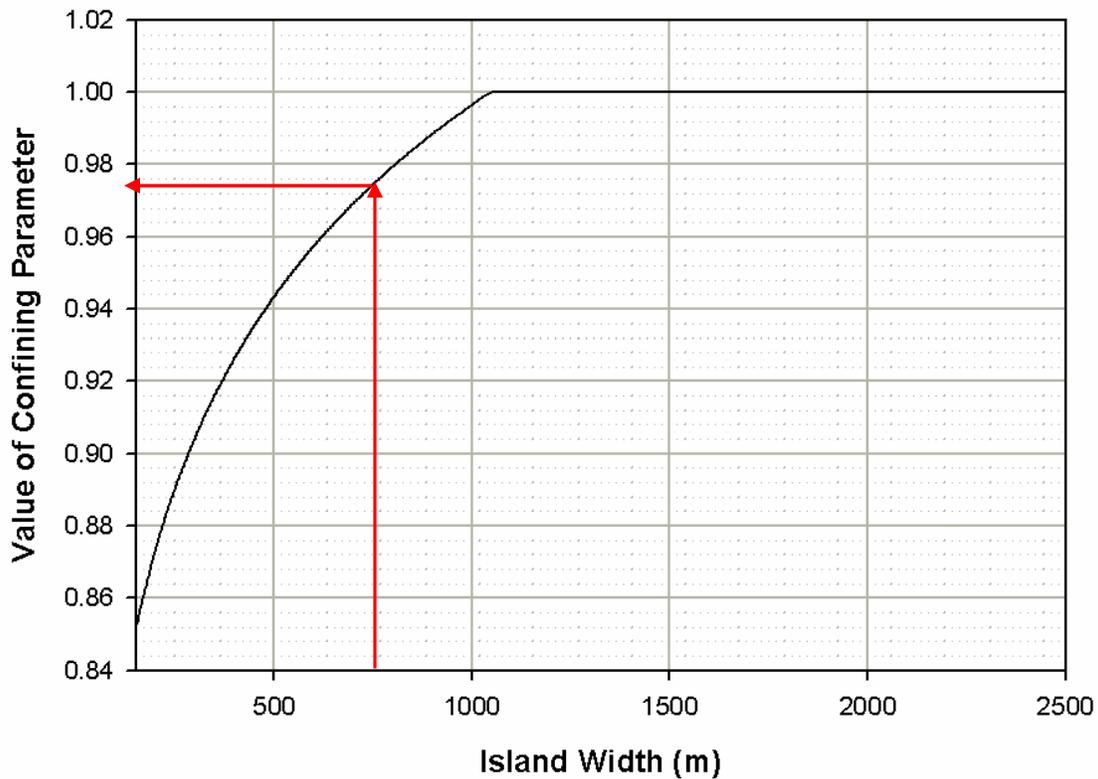
Figure 9. Curve for determining the value for the RFP factor

T Parameter (Time)

Tables 3-10 contain the values of the time parameter, for both average seasonal conditions and El Niño events. The determination of the value of the time parameter is dependent on five characteristics:

r (region). Either *W* for Western Caroline region (Yap data) or *E* for Eastern Caroline region (Pohnpei data)

s (side). Either *L* for Leeward or *W* for Windward.

w (weather Pattern). Either *S* for Seasonal Variation or *E* for El Niño.

y (year). For seasonal variation this term is always *1*. For an El Niño event it is *1*, *2*, or *3*; *1* being the year of the El Niño(El Niño), *2* being the year following the El Niño(Post-El Niño), during which Micronesia normally experiences a severe drought, and *3* being the year of recovery following the drought (Recover).

m (month). There is a time factor value for every month of the year. This allows the fluctuation of the lens thickness to be observed throughout the year.

To determine a time parameter value for a given month, each of the five terms must be assigned a value. Tables 3-6 contain the time parameter values for seasonal variation rainfall patterns, and tables 7-10 contain the time parameters values for El Niño periods. The values for the El Niño were determined using rainfall data from the regions of Yap and Pohnpei for the years 1997-1999. Each table has a label consisting of three letters. The first letter represents the region (Western Caroline or Eastern Caroline), the second represents the side (leeward or windward), and the third represents the type of rainfall pattern (seasonal or El Niño). Each table has rows for the month and year and columns for the width of the island. The time parameter value is actually a percentage of the expected steady-state thickness. For example, if the value for a certain month is 0.75, than the thickness of the lens during that month is 75% of the steady-state thickness value. The process of determining the parameter values will now be demonstrated.

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Table 3. *WLS:* Western Caroline region, Leeward island, Normal seasonal fluctuations

	ISLAND WIDTH		
MONTH	200	400	600
Jan	0.8857	0.7699	0.9020
Feb	0.8246	0.7738	0.9174
Mar	0.6841	0.7188	0.9039
Apr	0.6402	0.7064	0.9063
May	0.5893	0.7139	0.9256
Jun	0.6178	0.7339	0.9447
Jul	0.6564	0.6959	0.8942
Aug	0.7164	0.6912	0.8616
Sep	0.8596	0.7459	0.8871
Oct	0.9173	0.7495	0.8887
Nov	0.9148	0.7603	0.9003
Dec	0.9135	0.7699	0.9327

Table 5. *WWS:* West. Caroline region, Windward island, Normal seasonal fluctuations

	ISLAND WIDTH		
MONTH	200	400	600
JAN	0.7331	1.0261	0.7552
FEB	0.4470	0.8602	0.7419
MAR	0.2964	0.6396	0.6478
APR	0.0998	0.5707	0.6194
MAY	0.0000	0.5413	0.6048
JUN	0.0000	0.5895	0.6261
JUL	0.0000	0.6934	0.6922
AUG	0.1949	0.7987	0.7620
SEP	0.2867	0.7502	0.7874
OCT	0.7128	0.9192	0.8138
NOV	0.8289	1.0217	0.8200
DEC	0.6429	1.0458	0.8053

Table 4. *ELS:* East Caroline region, Leeward island, Normal seasonal fluctuations

	ISLAND WIDTH		
MONTH	200	400	600
Jan	1.0534	1.1152	0.9312
Feb	1.0384	1.0996	0.9263
Mar	0.9351	1.0397	0.9239
Apr	0.9289	0.9689	0.9238
May	0.9682	0.9842	0.9249
Jun	1.0377	1.0460	0.9257
Jul	1.0383	1.0678	0.9240
Aug	1.0439	1.1012	0.9250
Sep	1.0588	1.1088	0.9284
Oct	1.0488	1.0944	0.9331
Nov	1.0386	1.0869	0.9346
Dec	1.0294	1.0810	0.9358

Table 6. *EWS:* East Caroline region, Windward island, Normal seasonal fluctuations

	ISLAND WIDTH		
MONTH	200	400	600
Jan	0.6978	1.2256	1.1936
Feb	0.9247	1.2002	1.1960
Mar	0.9539	1.1082	1.1039
Apr	0.9236	1.0504	1.0938
May	0.5186	1.1172	1.0928
Jun	0.7927	1.2270	1.1499
Jul	1.1914	1.2537	1.1717
Aug	1.2363	1.2788	1.1883
Sep	1.2357	1.2877	1.2288
Oct	1.1936	1.2350	1.2282
Nov	1.1338	1.2134	1.2160
Dec	1.0383	1.1650	1.1863

Table 7. *WLE*: West Caroline region, Leeward island, El Niño event

| Year | MONTH | ISLAND WIDTH | | |
		200	400	600
1				
El Niño	JAN	0.9219	0.8596	0.9543
El Niño	FEB	0.9144	0.8779	0.9606
El Niño	MAR	0.7414	0.7696	0.8582
El Niño	APR	0.5834	0.7344	0.8446
El Niño	MAY	0.3351	0.6236	0.7801
El Niño	JUN	0.0687	0.5371	0.7189
El Niño	JUL	0.2991	0.5659	0.7381
El Niño	AUG	0.4974	0.6546	0.7997
El Niño	SEP	0.5923	0.6702	0.819
El Niño	OCT	0.6697	0.7451	0.8796
El Niño	NOV	0.6653	0.7671	0.9175
El Niño	DEC	0.5694	0.7402	0.9064
2				
Post-El Niño	JAN	0.4508	0.6978	0.8986
Post-El Niño	FEB	0.3489	0.7602	0.9562
Post-El Niño	MAR	0.1083	0.708	0.9537
Post-El Niño	APR	0	0.5561	0.8272
Post-El Niño	MAY	0	0.4029	0.6959
Post-El Niño	JUN	0	0.3168	0.6207
Post-El Niño	JUL	0	0.3678	0.6283
Post-El Niño	AUG	0	0.3332	0.5582
Post-El Niño	SEP	0.0745	0.361	0.5646
Post-El Niño	OCT	0.2589	0.3944	0.5598
Post-El Niño	NOV	0.4485	0.4664	0.6
Post-El Niño	DEC	0.4209	0.4747	0.6077
3				
Recovery	JAN	0.4276	0.4846	0.6177
Recovery	FEB	0.3522	0.4992	0.6535
Recovery	MAR	0.2379	0.4633	0.6526
Recovery	APR	0.2297	0.4539	0.6542
Recovery	MAY	0.4196	0.5189	0.6976
Recovery	JUN	0.4884	0.5069	0.6791
Recovery	JUL	0.6101	0.5576	0.7158
Recovery	AUG	0.7295	0.6065	0.7508
Recovery	SEP	0.886	0.6995	0.8319
Recovery	OCT	0.8606	0.7427	0.8765
Recovery	NOV	0.6834	0.7032	0.884
Recovery	DEC	0.7111	0.7328	0.9093

Table 8. *ELE:* East Caroline region, Leeward island, El Niño event

Year		MONTH	ISLAND WIDTH		
			200	400	600
1	El Niño	JAN	1.0529	1.109	0.8361
	El Niño	FEB	0.8252	0.8777	0.8252
	El Niño	MAR	0.7719	0.8103	0.7868
	El Niño	APR	0.7049	0.7661	0.8753
	El Niño	MAY	0.8799	0.8833	0.891
	El Niño	JUN	0.8781	0.9399	0.9011
	El Niño	JUL	0.8368	1.018	0.9151
	El Niño	AUG	0.8927	1.0689	0.9319
	El Niño	SEP	0.9592	1.1094	0.9353
	El Niño	OCT	0.9772	1.1242	0.9305
	El Niño	NOV	0.9139	1.0837	0.9302
	El Niño	DEC	0.8634	1.1017	0.9271
2	Post-El Niño	JAN	0.7354	1.0681	0.9245
	Post-El Niño	FEB	0.5759	1.0795	0.8627
	Post-El Niño	MAR	0.3131	0.8979	0.7092
	Post-El Niño	APR	0.0701	0.6395	0.5818
	Post-El Niño	MAY	0	0.4637	0.5999
	Post-El Niño	JUN	0.1189	0.4919	0.6347
	Post-El Niño	JUL	0.2747	0.5313	0.6254
	Post-El Niño	AUG	0.2295	0.5001	0.6578
	Post-El Niño	SEP	0.3165	0.5426	0.66
	Post-El Niño	OCT	0.3175	0.529	0.6818
	Post-El Niño	NOV	0.3822	0.5454	0.7191
	Post-El Niño	DEC	0.4863	0.5904	0.7847
3	Recovery	JAN	0.6239	0.6572	0.8241
	Recovery	FEB	0.6798	0.6998	0.877
	Recovery	MAR	0.8004	0.7846	0.8881
	Recovery	APR	0.9095	0.8202	0.9233
	Recovery	MAY	1.0107	0.8979	0.9159
	Recovery	JUN	0.9534	0.9168	0.9123
	Recovery	JUL	0.9428	0.9816	0.9164
	Recovery	AUG	0.9326	1.0397	0.9031
	Recovery	SEP	0.8143	1.0067	0.9066
	Recovery	OCT	0.8024	0.9819	0.8591
	Recovery	NOV	0.6834	0.865	0.818
	Recovery	DEC	0.6427	0.7879	0.8749

Table 9. *WWE:* West Caroline region, Windward island, El Niño event

			ISLAND WIDTH	
Year	MONTH	200	400	600
El Niño	JAN	0.3454	0.9215	0.802
El Niño	FEB	0	0.7508	0.6522
El Niño	MAR	0	0.6126	0.5004
El Niño	APR	0	0.3187	0.3177
El Niño	MAY	0	0.0168	0.1348
El Niño	JUN	0	0	0.2299
El Niño	JUL	0	0	0.374
El Niño	AUG	0	0.2177	0.4149
El Niño	SEP	0	0.315	0.4786
El Niño	OCT	0	0.4297	0.4876
El Niño	NOV	0	0.398	0.4012
El Niño	DEC	0	0.2598	0.3147
Post-El Niño	JAN	0	0.1222	0.2934
Post-El Niño	FEB	0	0	0.148
Post-El Niño	MAR	0	0	0
Post-El Niño	APR	0	0	0
Post-El Niño	MAY	0	0	0
Post-El Niño	JUN	0	0	0
Post-El Niño	JUL	0	0	0.0493
Post-El Niño	AUG	0	0	0.0716
Post-El Niño	SEP	0	0	0.1492
Post-El Niño	OCT	0	0.1009	0.2879
Post-El Niño	NOV	0	0.3168	0.2681
Post-El Niño	DEC	0	0.2616	0.278
Recovery	JAN	0	0.2522	0.2646
Recovery	FEB	0	0.1871	0.1765
Recovery	MAR	0	0.072	0.1583
Recovery	APR	0	0.0336	0.2722
Recovery	MAY	0	0.2027	0.3281
Recovery	JUN	0	0.2689	0.3924
Recovery	JUL	0	0.3966	0.4604
Recovery	AUG	0.278	0.4959	0.5733
Recovery	SEP	0.1903	0.6816	0.5686
Recovery	OCT	0	0.6378	0.4405
Recovery	NOV	0	0.384	0.4618
Recovery	DEC	0	0.3419	0.4755

The row group labels are: **1** for El Niño, **2** for Post-El Niño, **3** for Recovery.

Table 10. *EWE:* Eastern Caroline region, Windward island, El Niño event

Year		MONTH	ISLAND WIDTH		
			200	400	600
1	El Niño	JAN	0.700	1.167	1.191
	El Niño	FEB	0.075	0.796	0.943
	El Niño	MAR	0.162	0.724	0.851
	El Niño	APR	0.000	0.590	0.745
	El Niño	MAY	0.319	0.806	0.922
	El Niño	JUN	0.266	0.776	0.937
	El Niño	JUL	0.089	0.685	0.908
	El Niño	AUG	0.000	0.705	0.963
	El Niño	SEP	0.210	0.816	1.013
	El Niño	OCT	0.177	0.817	1.008
	El Niño	NOV	0.211	0.748	0.961
	El Niño	DEC	0.000	0.609	0.923
2	Post-El Niño	JAN	0.000	0.420	0.802
	Post-El Niño	FEB	0.000	0.208	0.679
	Post-El Niño	MAR	0.000	0.000	0.442
	Post-El Niño	APR	0.000	0.000	0.250
	Post-El Niño	MAY	0.000	0.000	0.149
	Post-El Niño	JUN	0.000	0.000	0.223
	Post-El Niño	JUL	0.000	0.122	0.314
	Post-El Niño	AUG	0.000	0.094	0.284
	Post-El Niño	SEP	0.000	0.169	0.363
	Post-El Niño	OCT	0.000	0.156	0.359
	Post-El Niño	NOV	0.000	0.229	0.412
	Post-El Niño	DEC	0.064	0.359	0.511
3	Recovery	JAN	0.286	0.556	0.649
	Recovery	FEB	0.142	0.624	0.718
	Recovery	MAR	0.380	0.753	0.830
	Recovery	APR	0.799	0.955	0.951
	Recovery	MAY	0.782	1.030	1.000
	Recovery	JUN	0.289	0.875	0.957
	Recovery	JUL	0.377	0.873	0.957
	Recovery	AUG	0.144	0.830	0.956
	Recovery	SEP	0.031	0.701	0.852
	Recovery	OCT	0.062	0.708	0.847
	Recovery	NOV	0.000	0.611	0.739
	Recovery	DEC	0.000	0.551	0.690

Examples
Example 1: Seasonal Variation
The manager wants to know the lens thickness for a windward atoll island located near Yap during the month of September for a regular year of rainfall. The width of the island is 400 m. Table 11 shows the process of determining which time parameter table to use.

Table 11. Term Values for Example 1

Term Value	Term Value	Indices	Table
Region	Western Caroline	W	
Side	Windward	W	*WWS*
Weather Pattern	Seasonal	S	
Year	1		
Month	September		

Thus, the appropriate table is the one labeled *WWS* (Table 5). Go to the column labeled *400 m*. Go down the column to the row for September, and read off the value. This is the value to use for the *T* term in the algebraic equation. If the fluctuation of the lens throughout the year is desired, perform the above procedure for all twelve months in the table. Figure 9 presents the fluctuation of the freshwater lens thickness during a typical year of rainfall.

Figure 10. Freshwater lens fluctuation during average seasonal rainfall pattern

<u>Example 2: El Niño Period</u>
A water resource manager wants to predict the thickness of the lens for a leeward atoll island located in Pohnpei state for the month of April during the year of drought following an El Niño. The width of the island is 600 m. Table 12 shows the process of determining which time parameter table to use.

Table 12. Term Values for Example 2

Term Value	*Term Value*	*Indices*	*Table*
Region	Eastern Caroline	E	
Side	Leeward	L	***ELE***
Weather Pattern	El Niño	E	
Year	2		
Month	April		

Thus, the appropriate table is the one labeled *ELE* (Table 8). Go to the column labeled *600 m*. Go down the column to the year *2* (*Post-El Niño*), and read off the value for April. This is the value to use for the *T* term in the algebraic equation. If the fluctuation of the lens throughout all three years of the El Niño event is desired, perform the above procedure for all thirty-six months in the table. Figure 10 presents the fluctuation of the freshwater lens thickness during an El Niño event.
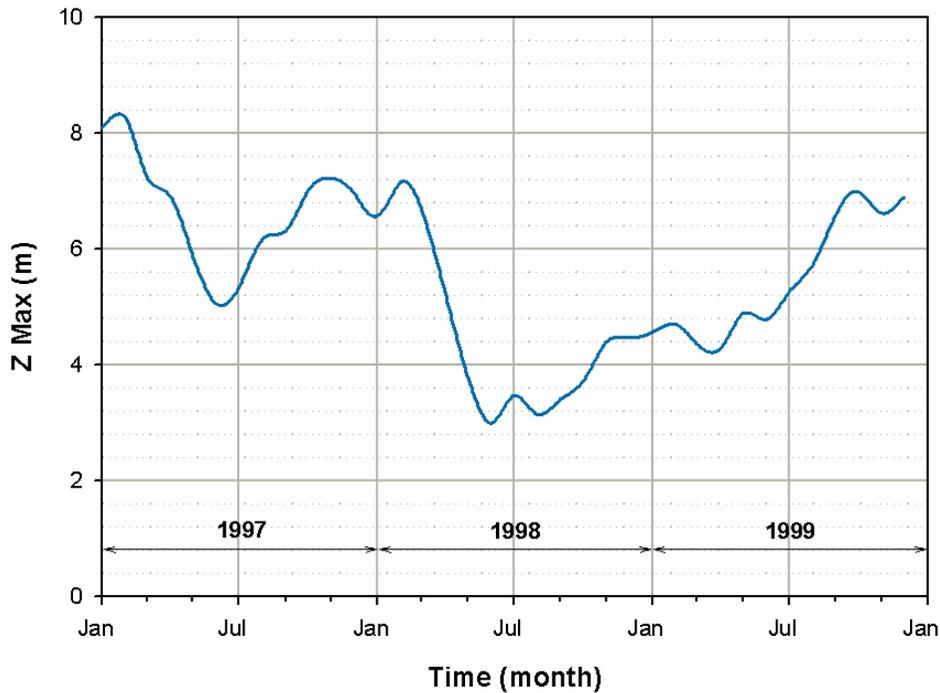

Figure 11. Freshwater lens fluctuation during El Niño period

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Further Considerations

The conditions of the atoll island in question may not be addressed with the tables for fluctuating rainfall patterns. The following rules may be applied in such cases:

1. If the width of the island is greater than 600 m, then use the parameter value in the 600 m column of the tables.
2. If the width of the island is less than 600 m and is not exactly 200 m, 400 m, or 600 m in width, choose the width closest to the island under consideration.
3. For islands within the Chuuk region, an appropriate time parameter value can be found by averaging the values from the Western Caroline and Eastern Caroline regions.
4. If the island is located in between the positions on the atoll accounted for in the tables (leeward and windward), average the given values or interpolate between them.
5. The values in Tables 7-10 are for an extreme El Niño event, since the El Niño experienced in 1997 was particularly strong and the drought in 1998 particularly intense. Using Tables 7-10 will therefore produce lens thicknesses which occur during a strong El Niño event. When using these tables for future El Niño events, the values may need to be scaled in order to reflect the current situation. For example, if the current El Niño is weak compared to the once experienced during 1997-1998, the values in Table 7-10 may need to be increased a few tenths of a point, for example from 0.25 to 0.45. The amount of increase for each value will be determined based on the judgment of the user and knowledge of the intensity of the El Niño event.

Spreadsheet User Interface

The process described in section 5.1 has been automated by use of an Excel spreadsheet program. This spreadsheet file is contained on the CD which accompanies this technical report, and is titled *Atoll Freshwater Lens Spreadsheet Tool*.

Overview of Spreadsheet

The spreadsheet consists of 4 sheets:

Sheet 1:   ***Enter Data***. This is the sheet that you will be working with.
Sheet 2:   ***Parameters***. This sheet contains the tables for the B, Y, K, and C parameters.
Sheet 3:   ***Seasonal***. This sheet contains the 4 tables for the seasonal rainfall pattern, as presented in section 5.1 (Tables 3-6).
Sheet 4:   ***El Niño***. This sheet contains the 4 tables for the El Niño rainfall pattern, as presented in section 5.1 (Tables 7-10).

The user interface, on the Enter Data sheet, is presented in Figure 11. There are 5 main parts to the interface:

A   Controls which allow the user to specify the attributes of the island hydrology, geology, and geography

B   The *Compute Thickness* button, which takes the values specified in the controls and starts a Visual Basics for Applications program.   This program uses the attributes entered to pull the necessary values from the tables contained in the *Parameters*, *Seasonal*, and *El Niño* sheets.   The program then computes the thickness of the freshwater lens using the algebraic model.

C   Output of the parameter values used in the algebraic model and the resulting steady-state lens thickness.

D   Output of the thickness of the lens through the months of a seasonal or El Niño period.

E   Display of the fluctuation of the lens through time for either a seasonal period or an El Niño Period.

The user interface was designed to fit on the typical computer monitor screen, in order to eliminate scrolling up and down to view the controls or the display. Detailed use of these parts of the user interface will be explained in the next section.
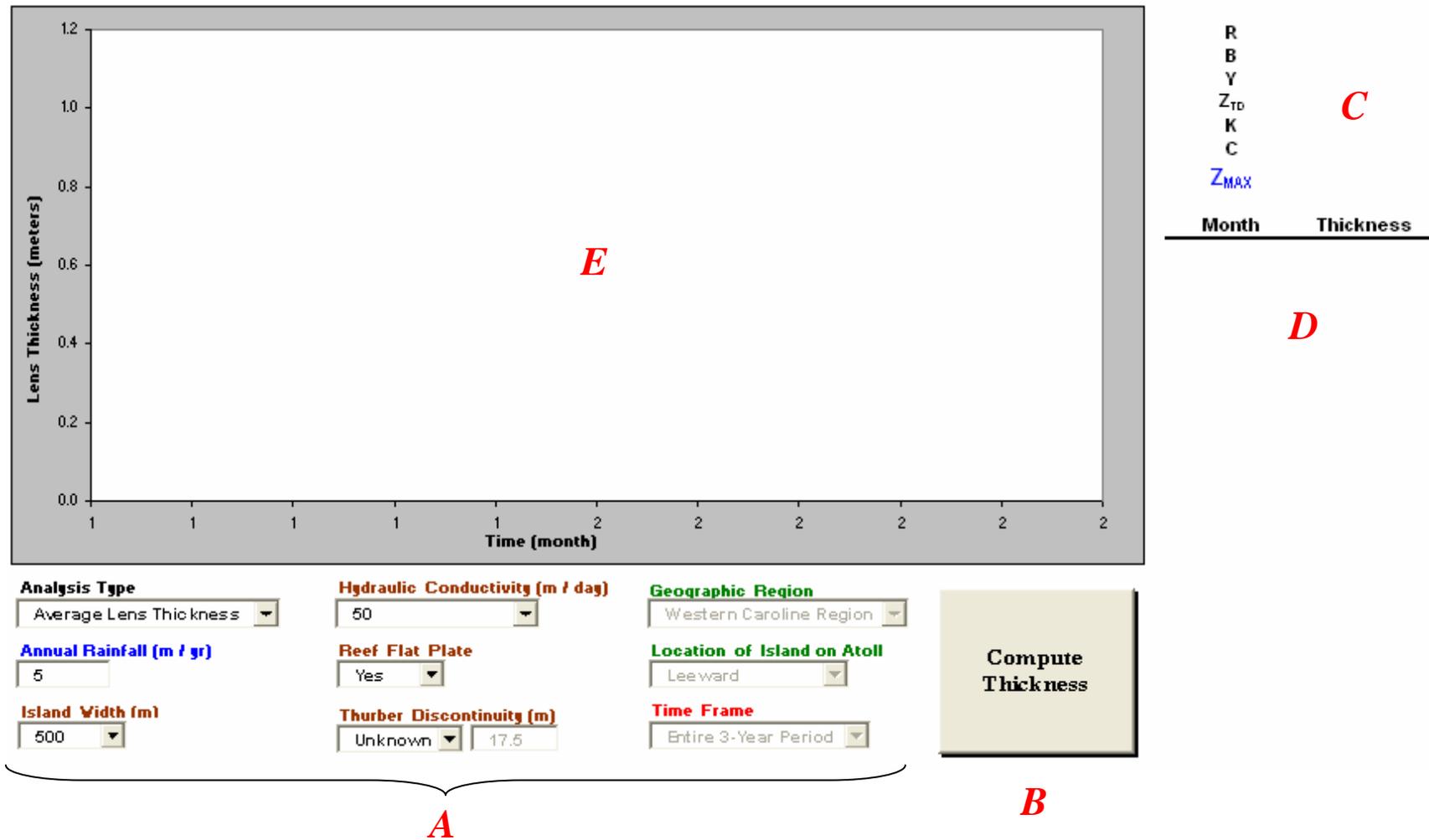
Figure 12. User Interface for the atoll freshwater lens tool spreadsheet.   Section A allows the user to enter island attributes, B runs the program which computes the lens thickness, C outputs the algebraic model parameter values calculated from the island attributes, D outputs the thickness of the lens through time, and E displays the resulting curve.

Enter Parameter Values

      Figure 12 presents the controls used to enter the hydrological, geological, and geographical attributes of the atoll island, along with the default values for each control. These attributes correspond to the parameters in the algebraic model.

Figure 13. Entering attributes of island hydrology, geology, and geography

The use of the controls is as follows:

1. **Analysis Type**
   There are three types of analyses possible: *Average Lens Thickness*, where only the steady-state thickness of the lens will be computed; *Seasonal Variation*, where the thickness of the lens will be computed for each month of an average year of rainfall; and *El Niño Period*, where the thickness of the lens will be computed for each month during the 3-year El Niño period. If the *Average Lens Thickness* option is selected, as in Figure 12, the Geographic Region, Location of Island, and Time Frame controls will be grayed out.

2. **Annual Rainfall**
   The annual rainfall, in meters per year, for the geographic region in which the atoll resides. If the rainfall rate is not known for the year in question, use the average annual rainfall values (see Table 2). The value entered in the edit field will be divided in half to produce the recharge value *R* used in the algebraic model.

3. **Island Width**
   The width of the island, in meters. Atoll islands rarely have a uniform width; thus, use the width of the island at the point of the island in question; or, if simply a maximum lens thickness value is desired for the entire island, enter the maximum width of the island. Width values range from 150 to 1200 meters. The width of the island is used to determine the values of the *B* and *Y* parameters in the algebraic model, using the table on the *Parameters* sheet.

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4. **Hydraulic Conductivity**
   The hydraulic conductivity, in meters per day, of the Holocene sediments. Values range from 25 to 400. If the hydraulic conductivity is not known, use the following rules of thumb:
   - Islands located on the leeward portion of the atoll normally have a hydraulic conductivity of 50 meters per day.
   - Islands located on the windward portion of the atoll normally have a hydraulic conductivity of 400 m per day.
   - Islands located between the leeward and windward portions of the atoll will have hydraulic conductivities varying between 50 and 400 m. The exact value will depend on its proximity to either the leeward section or the windward section.

   The hydraulic conductivity value is used to determine the value of the K parameter in the algebraic model, using the table on the *Parameters* sheet.

5. **Reef Flat Plate**
   If the reef flat plate is present in the area of concern on the island, select *Yes*. If not, select *No*. This selection is used to determine the value of the value of the C parameter in the algebraic model, using the table on the *Parameters* sheet. The plate serves to confine the groundwater and slightly thicken the lens, especially for smaller islands.

6. **Thurber Discontinuity**
   The depth, in meters, to the contact between the upper (Holocene) and lower (Pleistocene) aquifers. If the depth is known, select *Known*, which will activate the edit field to the right of it and allow you to enter the depth. Otherwise, select *Unknown*, which will place the value of 17.5 in the edit field, which is the average depth from field investigations. The value is the Z_{TD} used in the algebraic model.

7. **Geographic Region**, **Location of Island**, and **Time Frame**
   These controls only become active when either the *Seasonal Variation* or *El Niño Period* options are selected in the **Analysis Type** control. For the Geographic Region control, select either *Western Caroline Region* or *Eastern Caroline Region*. For the Location of Island control the options are *Leeward*, and *Windward*, depending where the island is located on the atoll. The Time Frame control only becomes active when the *El Niño Period* option is selected in the **Analysis Type** control. The options are to display the first year of the El Niño period, the second year, the third year, or the entire 3-year period. If the *Seasonal Variation* option is selected in the **Analysis Type** control, the lens thickness fluctuation over an entire year will be displayed, and there is no need for the Time Frame control.

Compute the Lens Thickness

Once all the attributes are entered in the control, the Compute Thickness button is pushed. This button runs the program which:

1. Retrieves the attributes placed in the controls
2. Uses the values placed in the Annual Rainfall, Island Width, Hydraulic Conductivity, Reef Flat Plate, and Thurber Discontinuity controls to pull the appropriate parameter values from the tables on the *Parameters* sheet and calculate the steady-state thickness of the lens using the algebraic model.
3. Uses the values placed in the Geographic Location, Location of Island, and Time Frame controls to pull values from the tables on the *Seasonal* and *El Niño* sheets to modify the steady-state thickness during the months of analysis.
4. Outputs the results onto the user interface and displays a curve which represents the fluctuation of the lens through time.

Results

The results of the program are output to the user interface. The algebraic model parameter values, calculated from the attribute values placed in the controls, are output in section *C* in Figure 11. The maximum steady-state thickness of the lens, Z_{MAX}, is also output. If either the *Seasonal Variation* or *El Niño Period* analysis options were selected, the calculated lens thickness for each month will be output in the columns under the **Month** and **Thickness** headings on the user interface. These results are display graphically in the chart area on the user interface. If the *Average Lens Thickness* analysis option is selected, only the Z_{MAX} value will be displayed.

Examples

The following examples show the calculation results for the *Average Lens Thickness*, *Seasonal Variation*, and *El Niño Period* analysis options. Table 13 lists the island attributes used in the three examples.

Table 13. Attribute Values used in Examples

Annual Rainfall	**5** m / yr
Island Width	**500** m
Hydraulic Conductivity	**50** m / day
Reef Flat Plate	Yes
Thurber Discontinuity	Unknown (**17.5 m**)
Geographic Region	Western Caroline Region
Location of Island	Leeward Island

Average Lens Thickness

Figure 14 shows the results from an *Average Lens Thickness* analysis. Since the *Average Lens Thickness* analysis option was selected, only the parameter values and the maximum lens thickness is displayed (circled in blue). Notice also that the Geographic Region, Location of Island, and Time Frame controls are inactive.
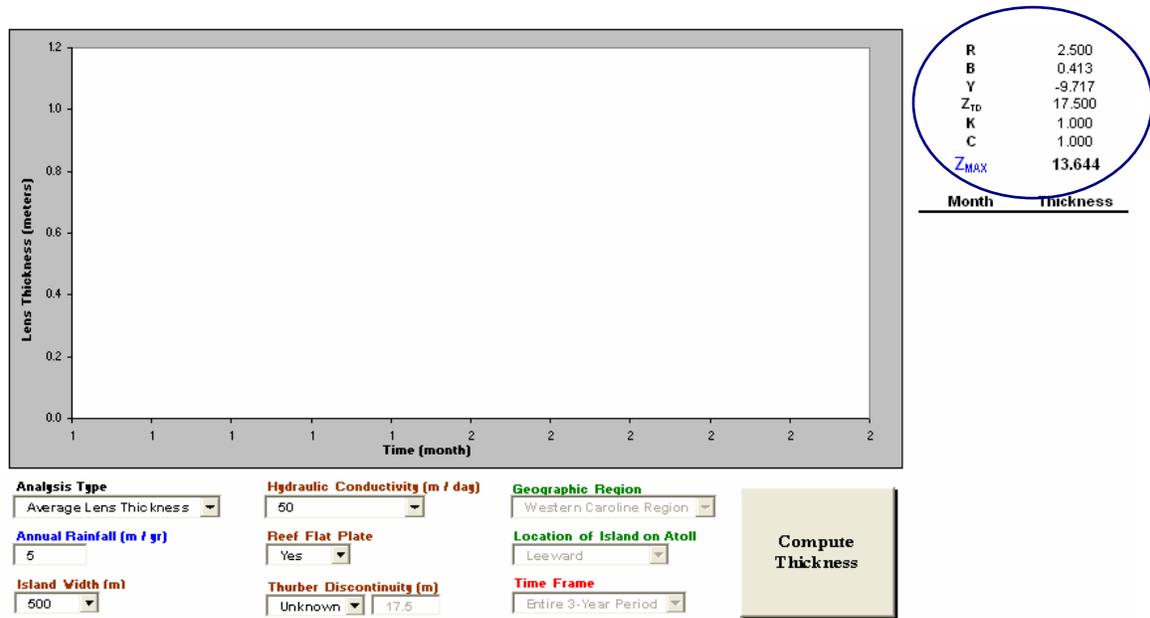

Figure 14. User interface and results for an Average Lens Thickness analysis. The calculated parameter values for the atoll freshwater lens algebraic model are circled in blue.

Seasonal Variation

Figure 15 shows the results from a seasonal variation analysis. The parameter values and maximum lens thickness are the same as in the *Average Lens Thickness* example. The maximum lens thickness is then used to calculate the lens thickness for each month of the year. The monthly values are then displayed on the chart.
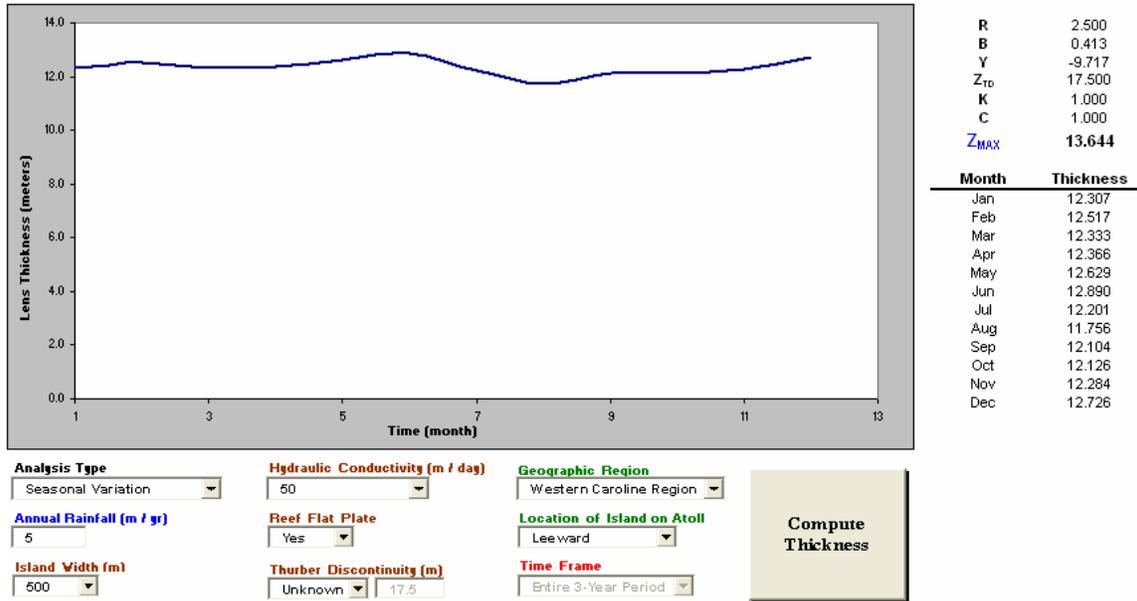

Figure 15. User interface and results for a Seasonal Variation analysis

El Niño Period

Figure 16 shows the results from an *El Niño Period* analysis. The parameter values and maximum lens thickness are the same as in the *Average Lens Thickness* example. The maximum lens thickness is then used to calculate the lens thickness for each month of the 3-year period. The monthly values are then displayed on the chart. These values are for an extreme case, since the 1997-1998 El Niño was particularly strong.
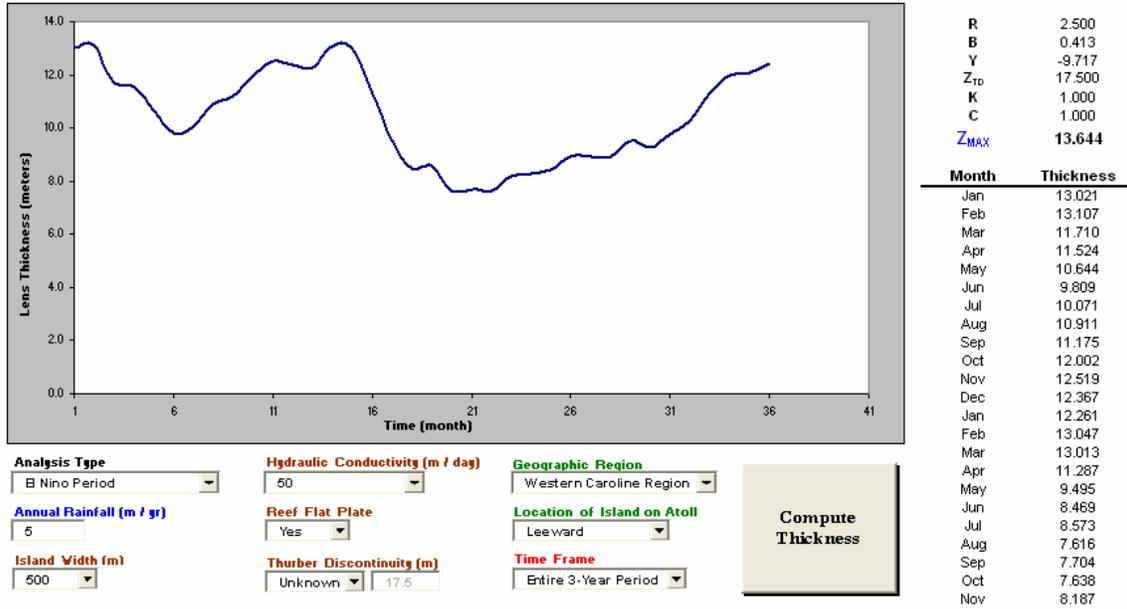

Figure 16. User interface and results for an El Niño Period analysis

Curves

        A third option in calculating the thickness of the lens is to use curves (Figure 17) which were calculated using the algebraic model. A set of curves represents leeward islands (with a set hydraulic conductivity value of 50 meters per day), and another set of curves which represents the windward islands (with a set hydraulic conductivity value of 400 meters per day). Each set of curves consists of four curves, each curve representing a different annual rainfall rate. The depth to the Thurber Discontinuity, Z_{TD} in the algebraic model, was set at 17.5 meters, the average found from field investigations.
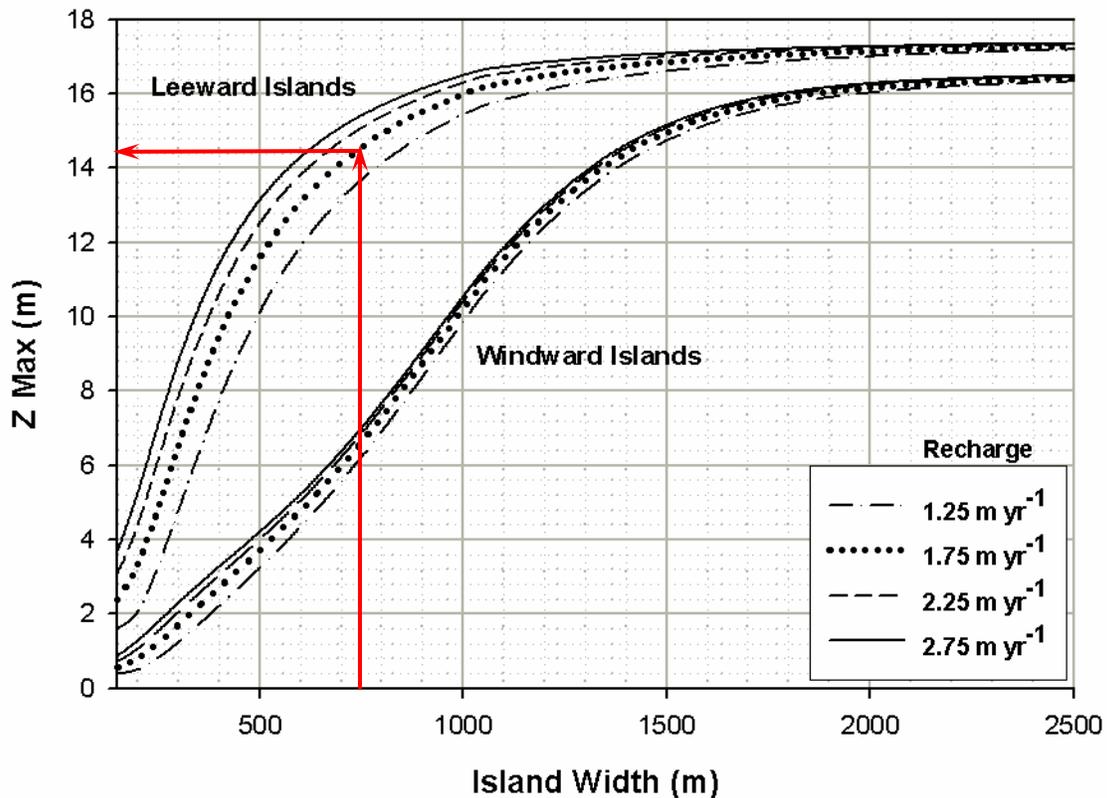

Figure 17. Curves to calculate the thickness of the freshwater lens

To use the graph:
1. Determine the width of the atoll island in question. Locate this width on the *Island Width* axis.
2. Draw a vertical line from the point on the Island Width axis to the appropriate curve (the correct rainfall rate curve) within the appropriate set of curves (Leeward Islands or Windward Islands)
3. From this point, draw a horizontal line to the y-axis to determine the thickness of the lens.

This process is described by the red arrows in Figure 16 above, for an island with of width of 750 m and an average annual rainfall of 1.75 m yr^{-1}.

If transient values are desired, follow the steps outlined in section 5.1.6 to determine the lens thickness during seasonal or El Niño rainfall period. Also, follow the items under *Further Considerations* in section 5.1.6.

PUMPING

Many atoll island communities have installed electric pumps to extract a portion of the freshwater lens (Bailey 2008). Pumping especially becomes important during times of drought. Pumping, however, must be performed with caution, especially for islands with thin lenses. Too much pumping can cause the depletion of the lens, as well as cause seawater to be introduced into the pumping system. In an attempt to deal with this issue, this section demonstrates how to include a pumping rate into the algebraic model. The water balance described by equation (1) can be modified to include a pumping rate Q:

$$R = P - ET - Q \qquad \text{(2)}$$

Pumping rates (Q) are often described as a volume of water per unit time, such as gallons per day (GPD), cubic feet per second (CFS), or cubic meters per second. The values of Recharge (*R*), Precipitation (*P*), and Evapotranspiration (*ET*), however, in equation (2), are all in meters per year. Furthermore, the *R* term in the algebraic model is in meters per year. It is thus necessary to modify the pumping rate so that it is also in meters. The key in this process is demonstrated in Figure 18. The time frame for the example will be one year. A volume (in cubic meters) of precipitation can be found by taking the depth of precipitation over the year (meters per year), and multiplying by the island surface area (in square meters), over which the precipitation falls.
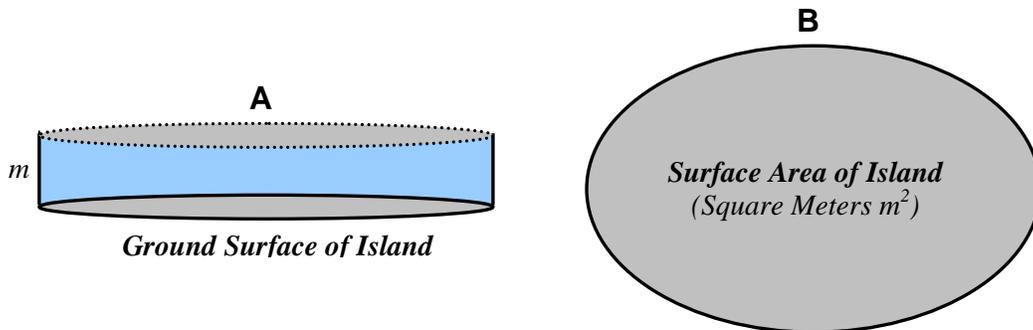

Figure 18. (**A**) Side view of island, showing depth of precipitation during one year (m), and (**B**) Top view of island, showing the surface area (m^2) upon which the precipitation is falling.

In similar fashion, a volume can be dissolved into a surface area and a depth. For example, if one starts with the volume of precipitation that the island received over the year (cubic meters per year), and the surface area (in square meters) of the island is known, then the depth of precipitation (meters per year) can be calculated. These two processes are summarized by the following equations:

$$Volume(m^3) = SurfaceArea(m^2) \times Depth(m) \quad \text{(3)}$$

$$Depth(m) = \frac{Volume(m^3)}{SurfaceArea(m^2)} \quad \text{(4)}$$

In regards to pumping, the depth of pumping Q (the amount, in meters, of water extracted from the freshwater lens per year) can be computed by dividing the volume of pumped water per year by the surface area of the island. The value Q can then be used in equation (2) to determine the value of recharge (meters per year), which is placed in the algebraic model. This value of recharge can be termed the *effective recharge*, since it is not the actual amount of water recharging the lens. Instead, it is the amount of water recharge the lens, minus the amount taken out by pumping.

Example
An atoll island receives an average rainfall of 4 meters per year. The average rate of evapotranspiration is approximately 2 meters per year. The island has a surface area of 125 000 m^2. Over the course of the year, the island community pumped 60 000 cubic meters (m^3) from the freshwater lens. To determine the R term (the effective recharge) (m) to include in the algebraic model:

1. Calculate the depth of pumped water, using equation (4):

$$Depth(m) = \frac{Volume(m^3)}{SurfaceArea(m^2)} = \frac{60000m^3}{125000m^2} = 0.48m$$

2. Calculate the effective recharge, using equation (2):

$$R = P - ET - Q = 4m - 2m - 0.48m = 1.52m$$

Thus, 1.52 (meters per year) is the R term in the algebraic model. Without pumping, the R term would be 2 meters per year (4 meters of precipitation minus 2 meters of evapotranspiration).

LIMITATIONS OF THE ALGEBRAIC MODEL

The algebraic model encompasses the effects of the principal climatic and geologic factors on the thickness of the freshwater lens. Patterns have also been demonstrated for the hydraulic conductivity on leeward and windward islands. These effects and patterns hold for the majority of observed cases for atoll islands. However, due to the unique geology and rainfall patterns of each atoll, the algebraic model can only be used as a first estimate. This estimate should not be taken as fact, but rather used as a rough estimate, best applied when accompanied by other knowledge of the island and the current weather patterns. High levels of confidence in water quantity estimates can only come through actual field work.

SUMMARY

This technical report has presented the geology and hydrology of atoll islands, the principle climatic and geologic factors which govern the thickness of the freshwater lens, and an algebraic model which relates the maximum thickness of the lens to these factors. Three methods have been presented to use the algebraic model to calculate the thickness of the lens in both steady-state and transient conditions: manual calculations, a spreadsheet user interface and program, and a set of curves. The use of these tools will enable water resources managers to assess the natural condition of a freshwater lens on a specific atoll island within Micronesia.

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