Water Resources of Yap Outer-Island Communities - Literature Review

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INTRODUCTION

Water security for the atolls of Yap State is an important area of study at this time due to historical events and project future climate change. Freshwater resources on the atolls have shown sensitivity to perturbations in nature, especially droughts associated with El Nino years and typhoons. With projected sea-level rises due to climate change, increasing overwash of the islands threatens the viability of groundwater as a source for drinking water. To support the islander communities and protect their freshwater sources, the Secretariat of the Pacific Community-Global Climate Change Alliance Pacific Small Islands States (SPC-GCCA: PSIS) developed the Adaptation Project through which this study, Detailed Hydrologic Assessment of Selected Outer-lying Islands, Yap State, FSM, was developed.

This report summarizes a review of outer-lying atolls in Yap State of Micronesia that was conducted to develop a conceptual model of existing water resource management, island hydrogeology, and future climate change conditions. Four selected atolls, Eauripik, Ifalik, Satawal, and Ulithi, will be evaluated for existing and future climate conditions to determine the adequacy of the rainwater catchment systems and fresh groundwater lens.

GEOGRAPHIC SETTING

Yap State of the Federated States of Micronesia (FSM) is located in the Carolinian archipelago of the western Pacific Ocean. The state is formed by a group of islands in western-most FSM, from longitude 137ºE to 148ºE and from latitude 7ºN to 10ºN (**Error! Reference source not found.**). These islands include Yap Island, the main island of Yap State formed by a group of high volcanic islands, Fais, a high limestone island 250 km northeast of Yap Island, and 14 outer-lying atolls situated primarily between Yap and Chuuk Islands (Richmond, Mieremet, & Reiss, 1997). The term ‘outer-lying’ refers to the remoteness of atolls or islands relative to the main islands.

Atolls are low-lying, small, coral reef formations that frequently a composite formation of reef islets in a ring-shape around a lagoon (Davis, 1928) (Vacher, 1997). Atoll is a collective term that typically refers to this classic definition of atolls, as well as and low-lying reef islands without a significant lagoon (Richmond, Mieremet, & Reiss, 1997). Low is a term originally used in relation to low visibility during early European exploration and thus difficulty of discovery (Vacher, 1997). Researchers have also made distinguishes between low-lying and ‘elevated’ or ‘high’ atolls by identifying a maximum elevation, such as 4 or 7 meters above mean

sea level (MSL) or less (Pernetta, 1992) (Richmond, Mieremet, & Reiss, 1997). Small is a term defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO) for islands with an area of 2,000 km^2 or less, or with a width of 10 km or less (Vacher, 1997).

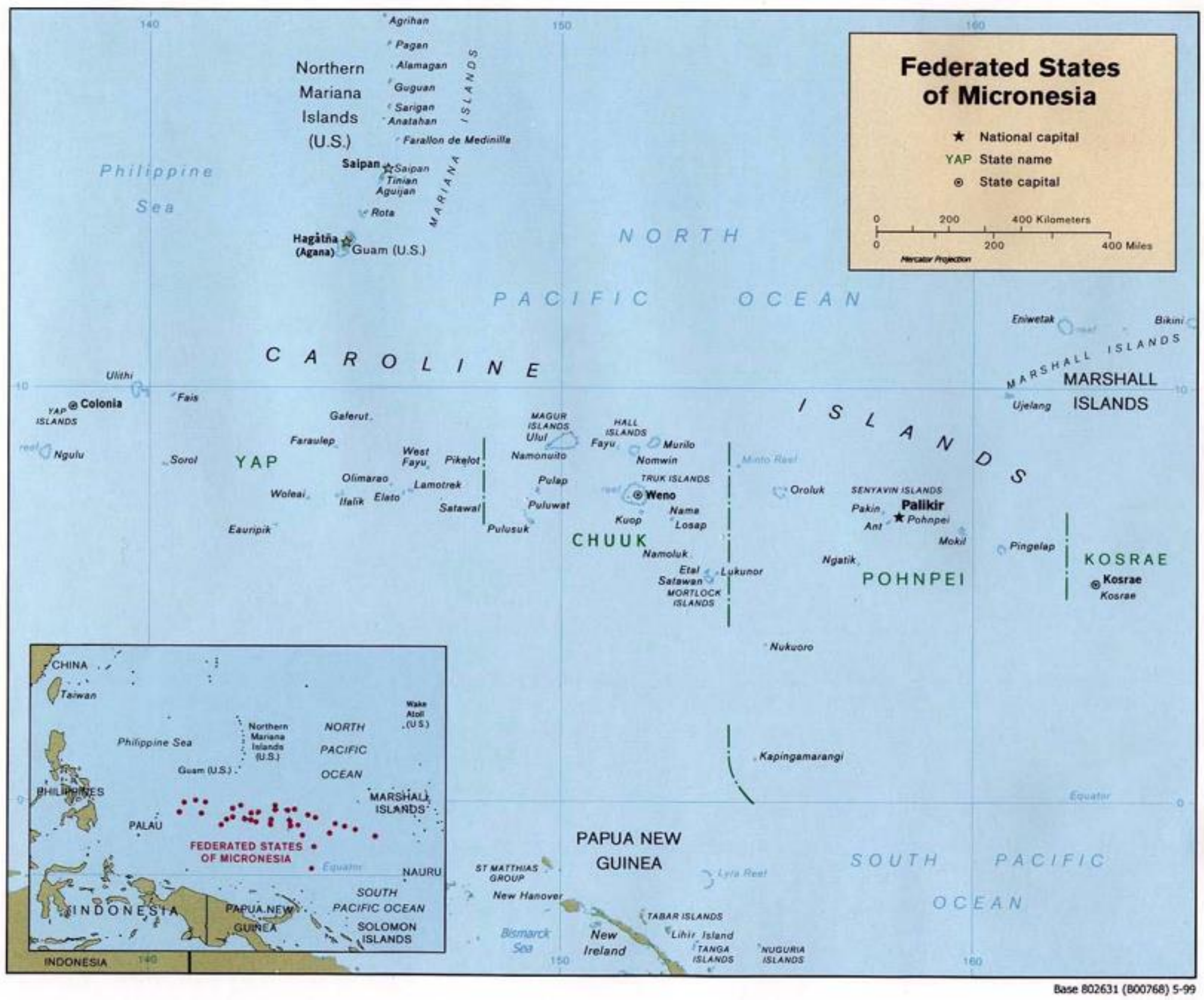

Figure 1 – Federated States of Micronesia – Regional Map (United States Central Intelligence Agency, 1999)

This study reviews literature on the following outer-lying atolls in Yap State in addition to general literature for Pacific atolls: Eauripik, Ifalik, Satawal, and Ulithi (**Error! Reference source not found.**). Literature was collected and review for information regarding climate, hydrogeology, island water consumption, climate change, and current island demographics. Island specific information is included following this section.

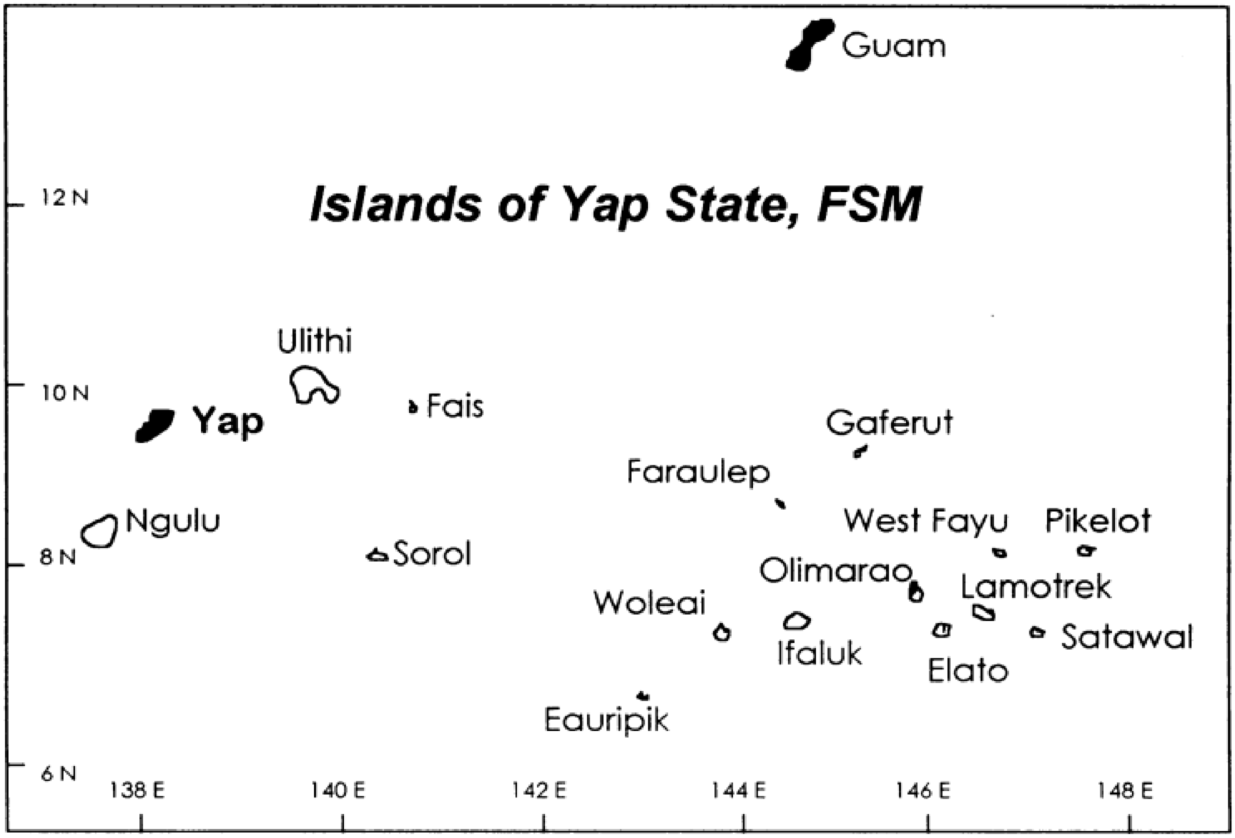

Figure 2 – Yap State Map (Richmond, Mieremet, & Reiss, 1997)

CLIMATE

Yap State lies in the tropical climate zone between the Tropic of Cancer and the equator. Weather is generally warm, humid, and rainy with regional variances occurring due to trade winds. Climatic variables, including seasonal and annual precipitation, mean sea-level, and occasional typhoon events, heavily influence the health and availability of resources on the outer-lying islands, and anticipated climate change would alter these conditions.

RAINFALL

Rainfall is the main and sole source of water for remote, outer-lying atolls, therefore accurate historical data for annual rainfall is important for future planning purposes. Historical precipitation data is available through the National Ocean and Atmospheric Administration (NOAA) for weather stations on several larger islands in Micronesia, including stations at the Yap and Chuuk Weather Service Office Airports. These two stations provide the most complete historical climatic data for Yap State dating as far back as 1951. Average climate indices for the nearest airports are shown in Table 1. Measurements have also been collected on Ulithi atoll (1989-present), Polowat atoll (1986-2005), and Woleai atoll (1968-1978, 1986-present), however the data is less complete.

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

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

[1] Data from the National Oceanic and Atmospheric Administration

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

Yap atolls experience two seasons: a dry season from November to June and a wet season from July to November. Northeasterly trade winds form conditions for the dry season and the wet season occurs when the trade winds subside creating more variable wind patterns at the

Intertropical Convergence Zone (ITCZ) (Arnow, 1955) (Anthony, 1997). Droughts commonly occur during the dry season and become increasingly severe as a result of El Nino Southern Oscillation (ENSO) events (White, Falkland, & Scott, 1999). Severe droughts typically occur in the months following an intense El Nino event (Landers & Khosrowpanah, 2004) and severity can vary to such extremes as 5% of typical monthly precipitation and 28% of normal seasonal precipitation, as was observed on Yap Island during the dry season in 1983 (Van der Brug, 1986). Historical extreme precipitation years for each airport weather station are shown in Table 2.

Table 2 – Extreme annual precipitation at regional airport weather stations

	Extreme Annual Precipitation, June to May	
STATION	Maximum [1] (m)	Minimum (m)
YAP ISLAND WEATHER SERVICE OFFICE AIRPORT FM	4.03 (2004)	2.11 (1973)
CHUUK WEATHER SERVICE OFFICE AIRPORT FM	4.59 (1956)	1.82 (1983)

[1] Data from the National Oceanic and Atmospheric Administration

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

SEA LEVEL

Sea-level is also influenced by the El Nino and La Nina episodes. El Nino commonly leads to a mean sea-level drop (Landers & Khosrowpanah, 2004), while conversely La Nina events lead to higher sea-levels. One example is the La Nina event from 2007-2008 which led to high sea-level as a result of high water temperatures and intensified easterly trade winds. Taro was lost on several outer islands due to high tides and shoreline erosion (Hezel, 2009).

TYPHOONS

Typhoons strike Yap State atolls relatively infrequently, as they typically form over eastern Micronesia near Truk as a tropical cyclone before building up and moving north to Guam (Tracey, Abbott, & Arnow, 1961) (Landers & Khosrowpanah, 2004). By definition, a tropical cyclone is a circulation of high winds that originate over tropical oceans, and it reaches typhoon status when the maximum sustained 1-minute winds reach 64 knots (74 mph). It is more common for strong winds and rain to occur as a result of passing storms or large storms at a distance (Tracey, Abbott, & Arnow, 1961), and these events are not regarded as dangerous by

the islanders (Levin, 1976). When typhoons do strike, there is typically mild to severe damage to islanders and natural resources, as well as an alteration of some kind to the island geometry. Also due to changes in technology and politics over the last several decades, response mechanisms have changed due to implementation of government aid.

Historically, typhoons striking Yap State atolls have varied in strength as did the impacts. For instance, a small typhoon that hit Eauripik Island in 1971 led to severe over-wash and salinization of the groundwater. The islanders altered their bathing habits by doing so in the lagoon instead (Levin, 1976). In a more extreme instance is the story of the Great Typhoon of 1907 that had devastating effects on Ifalik in the early 1900s. Islanders on Ifalik reported to USGS representatives in 1953 regarding a great typhoon that occurred in 1907. The typhoon ripped up and blew down most of the tree-life, including the breadfruit and coconut trees vital for everyday food, destroyed the villages, and killed 35 of the islanders (Tracey, Abbott, & Arnow, 1961). The over-wash was so significant that great sharks were left stranded on the island. Another great typhoon is chronicled in Eauripikian lore, occurring in the late 1840's or early 1850's. This typhoon that struck Eauripik Island is said to have killed perhaps most of the islanders, and required the remaining people to evacuate due to threat of starvation (Levin, 1976).

From the perspective of the atoll island, typhoons can improve or damage longevity by altering the island geometry. A large typhoon that lasts several hours can instantly alter the shape of an island by sweeping sediments in our out of the island. For example, the Great Typhoon of 1907 swept in enough gravel and sediment to fill a narrow channel between two islets of Ifalik, Maia and Falarik, which thereby merged the islets into one (Figure 3, Figure 4). The same typhoon destroyed part of Woleai and part of eastern Eauripik Island (Levin, 1976).

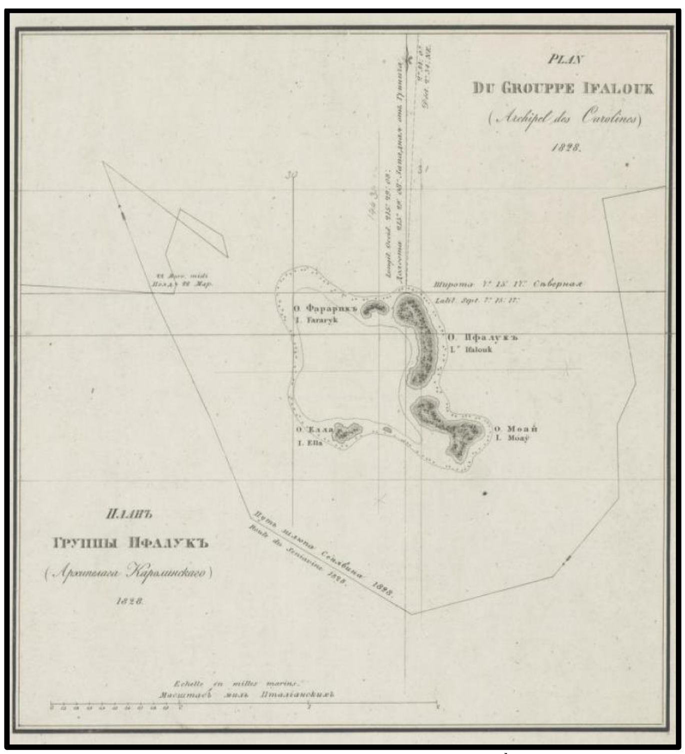

Figure 3 – Geometry of Ifalik Atoll, 19th Century

Response to typhoon impacts has evolved over time from a regime backed by neighboring-island rescue and hospitality, to strategy backed by government aid supplies. The traditional approach is evidenced by

the story of the typhoon which struck Eauripik in the late 1840's or early 1850's. The story, as told by the islanders, indicates a rescue party came from Woleai, took a few of the remaining islanders, and returned to Woleai while awaiting recovering of the island resources (Levin, 1976). Several years later, the families of native Eauripik islanders, which by then included several Woleaian islanders, returned to Eauripik and repopulated. Per the documented account, it appears that evacuation has occurred on Eauripik on more than one occasion. Alternatively, a more recent typhoon that struck Eauripik in 1975 was remediated, instead, by government surplus food. The islanders determined they could ration the supplies well enough to continue living on the island despite the damage that occurred to the vegetation and the fresh water lens.

In most recent history, super Typhoon Maysak rolled through FSM on March 31st, 2015 causing severe damage to resources on Ulithi. Up to 60% of structures were leveled due to gusts reaching 160 miles per hour (258 km per hour).

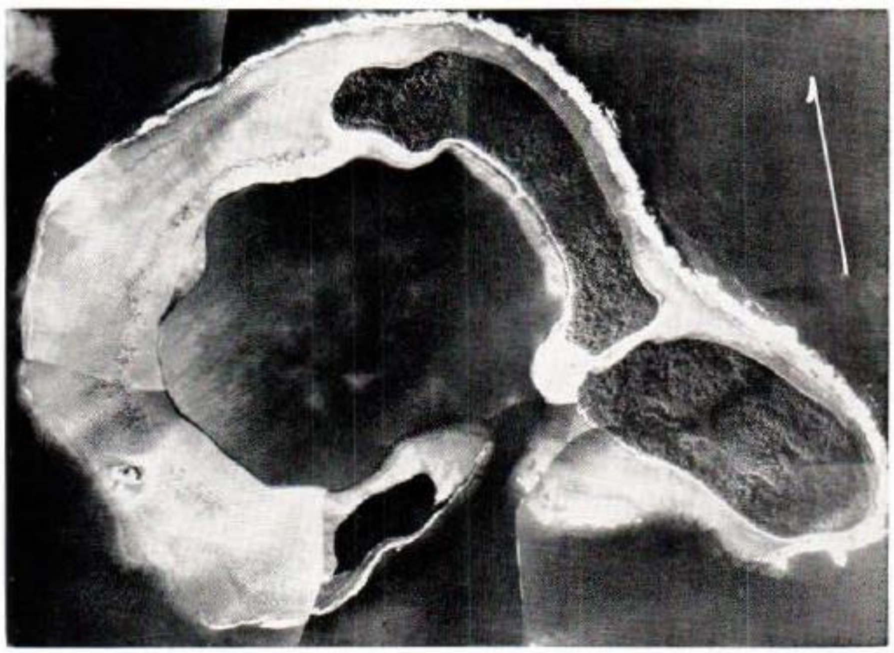

Figure 4 – Geometry of Ifalik Atoll, 1948

(Photograph by U.S. Navy) (Tracey, Abbott, & Arnow, 1961)

HYDROGEOLOGY

Sustainable groundwater use is an integral part of overall sustainability since groundwater lenses are especially susceptible to fluctuations due to hydrologic disturbances (Holding & Allen, 2015). Similarities in Pacific atoll geology has made it easier to estimate the size of the existing freshwater lenses and establish management schemes for sustainable use in future decades. Several factors influence the geology of atolls and thus the freshwater lens, including the composition and spatial distribution of soils, permeability and porosity of the coral sediments, and size of the island (particularly the width from sea to lagoon) (Falkland, 1994).

Coral atoll islands vary in sedimentary composition based on their location relative to tradewinds. The windward islands are located upwind within the atoll and are therefore exposed to the northeasterly winds and associated swells that occur during storms (Spennemann, 2006). Due to the high-exposure and incident wash-out, the islands are smaller than the leeward counterparts and contain coarser sediments with fewer fines. Therefore, due to lower permeability and larger size, greater freshwater lenses are typically observed on leeward islands than on windward islands. In addition, finer grained sediments are found on the lagoon side and coarse material is most prevalent along the ocean shore, with particle size generally decreasing from ocean to lagoon (Spennemann, 2006). For this reason, freshwater lenses are usually thickest toward the lagoon side.

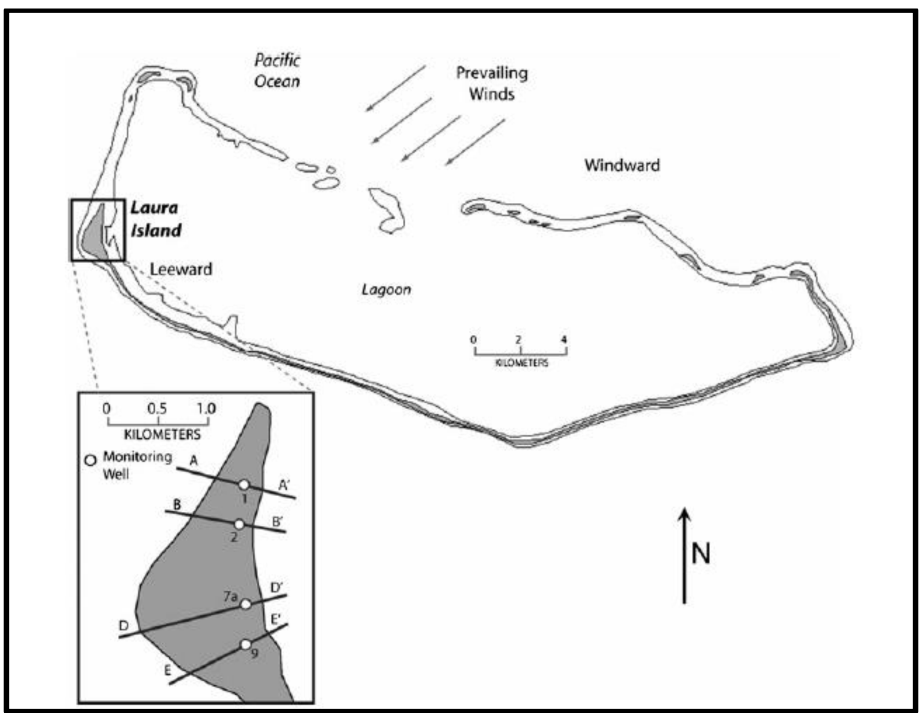

Figure 5 – Example of Windward and Leeward Islands on an Atoll (Bailey 2013)

The geology of Pacific atoll islands is generally formed by two distinct layers. The top layer that begins at the surface is a layer of Holocene sands with relatively low permeability and below this lies a Pleistocene reef deposit with relatively high permeability (Anthony, 1997). This dual-layer geology also creates a dual-layer aquifer system, with the Holocene aquifer near the surface and the Pleistocene aquifer below. The depth of contact to the Pleistocene deposits is typically 15 – 25 meters deep (Anthony, 1997) and Bailey 2013 found it varied from 15 to 20 meters for 5 selected atolls in FSM (Bailey, 2013). In addition, Pacific atolls frequently have a reef flat-plate near the surface of the atoll, layered between surficial sediments and the lower Holocene sediments. This layer is a semi-permeable reef rock that confines the upper Holocene aquifer and thickens the freshwater lens (Bailey, 2013).

As explained above, soil composition varies from island to island, from ocean to lagoon shore, and from surface to the bottom of the Pleistocene aquifer. Researchers have estimated hydraulic conductivity based on typical soil compositions that occur. For estimating hydraulic conductivity of islets based on position relative to prevailing winds on an atoll, leeward islands can be truncated to 50 m/day and 400 m/day for windward islands (Bailey, 2013). An example of windward and leeward islands on Majuro Atoll in the Republic of the Marshall Islands is shown in **Error! Reference source not found.**.

For hydraulic conductivity based on geologic layers, Falkland 1994 determined that 6 m/day was appropriate for the Holocene sediments, 30 m/day for the average of the upper part of the Pleistocene sediments, and some areas where drilling occurred below the unconformity reached 1,000 m/day. The study also estimated the porosity to be 0.3 (Falkland, 1994)

Between the fresh and saline water within the underlying aquifers is a broad, transition zone that connects the freshwater lens to the saline ocean water (Falkland, 1994). This zone is typically as large or larger than the freshwater lens. The relatively low hydraulic conductivity of the upper aquifer and existence of a reef plate, if applicable, help develop a thicker freshwater lens while the highly permeable Plesitocene sediments truncates the lens. Refer to **Error! Reference source not found.**for a typical cross-section of an atoll.

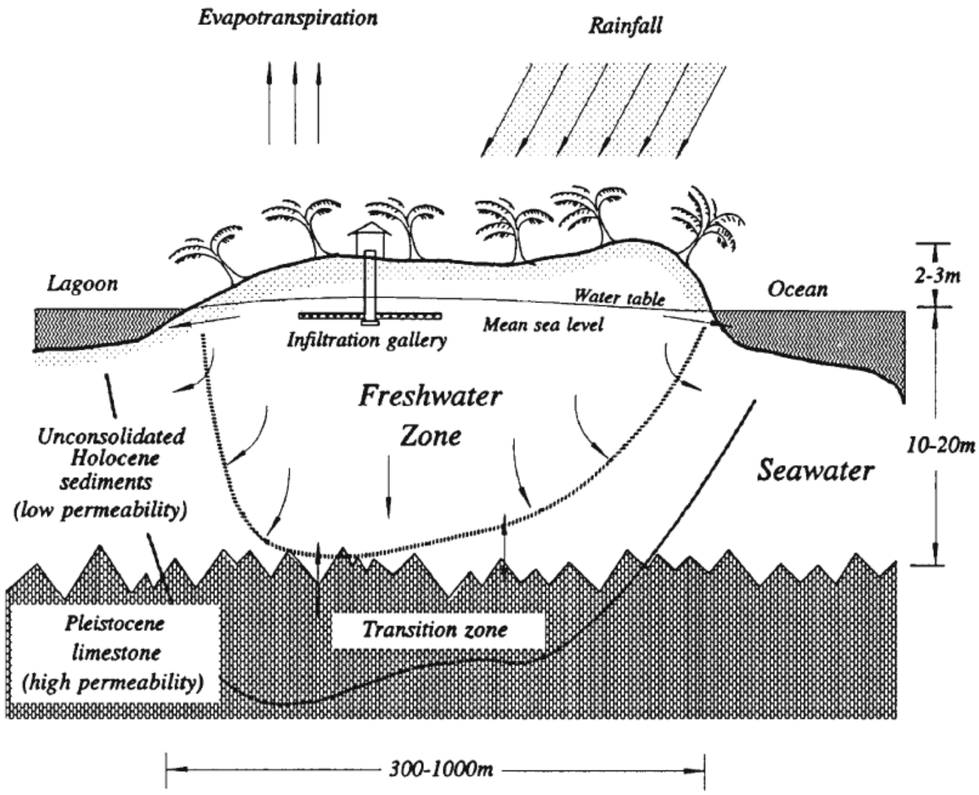

Figure 6 – Exaggerated vertical scale cross section through a small coral island (White & Falkland, 2010)

Oberdorfer and Buddemeire (1988) developed a relationship between freshwater lens thickness, annual rainfall and island width, two important factors in estimating the thickness of the freshwater lens. Since then, groundwater modeling using programs such as SUTRA and SEAWAT have been developed to estimate the existing shape and size of freshwater lenses and predict alterations under future hydrologic disturbances.

HYDROLOGY

The hydrology of coral atolls is relatively simplistic. The main and sole source of water on Pacific atolls is rainfall, which permeates readily through the permeable soils. Runoff is commonly neglected as it occurs only in paved or compacted areas or when soils are saturated during heavy rains (Arnow, 1955) (Falkland, 1994).

Atolls communities use water primarily from rain catchments for drinking water, with groundwater to supplement supplies during droughts or shortages (Anthony, 1997). Coconut water is also frequently used for drinking purposes. Islanders compete with the vegetation for water, yet need stable vegetation for self-sufficiency. This section describes the ecological and anthropogenic uses of water on coral atolls.

VEGETATIVE WATER CONSUMPTION

Ifalik and other outer-lying islands consist of three major vegetative zones: cleared coconut grove, depressed swamp, and what the Ifalukians refer to as *niwel* and other western cultures may refer to as 'boondocks' (Bates & Abbott, 1958). This third zone is perhaps best described by Marston Bates in his recount of the 1953 expedition to Ifaluk:

> "The boondocks were not exactly wild, because all sorts of useful things grew there... They were not exactly cultivated either…Coconuts grew all through these boondocks, and the principal forest tree was breadfruit. But there were a dozen other kinds of trees, and a thick undergrowth of bushes and ferns-ferns everywhere."

Trees are a vital resource to the islanders, providing much needed shade in the tropical heat and various materials for sustenance. Coconut trees are native to coral atolls in the Pacific (Dana, 1872) and they provide an important resource for island residents. Coconut trees supply water to islanders from the coconut fruit, as well as wood and leaves for various purposes. The roots of the coconut tree run deep enough to directly extract water from the groundwater lens, thereby competing directly with islanders for groundwater. Breadfruit trees also provide important resources for islanders, who use parts of the tree for various purposes. The fruit provides a fresh food source as well as a reserve food source when processed into a paste (Merlin, 2015). The wood from the tree is used for construction purposes, especially for boats, and the sap is used to adhere and seal. Other trees that grow on the outer-islands include pandanus trees, fig trees, papaya trees, and types of bonsai trees (Merlin, 2015) (Fosberg, 1969). The islanders use the wood, leaves, fruit, and roots from these trees, as well, for materials, food, and water.

Other understory vegetation includes wet taro grown in the central, swamp depressions, cultivated plants grown in and adjacent to the villages (i.e. sweet potato), and a vast array of native vines and ferns that grow uninhibited in the 'boondocks' of the islands. Plants of this size are shallow rooted and intercept water from the unsaturated zone. The prominence of certain types of vegetation is heavily dependent on annual rainfall, and islands with lower rainfall commonly have lower prevalence of breadfruit and taro (Bates & Abbott, 1958). There is also lower biodiversity and less dense vegetation.

CROPS

Quantity of the crops available for food varies from atoll to atoll, as indicated by the USGS report on the 1983 drought, which indicated Woleai generally has plentiful crops available for the inhabitants in contrast to Ulithi which generally has limited availability (Van der Brug, 1986). Observed rainfall amounts on Ulithi are generally lower than other Yap State atolls and

this may contribute to limited crop availability. For instance, crop loss in Yap due to the 1983 drought were so severe that supplements of rice and fruit juice were provided by USDA (Van der Brug, 1986).

Crops on the outer-atolls have varying levels of sensitivity to periods of drought, as well as to sea-spray and saltwater inundation. Plants in Yap state were reduced by 50-75% except for bananas which were reduced by only 20-25%. Swamp taro, a staple and "reserve" food supply, reserve meaning can be left unharvested, experienced minimal losses (10-20%) where it tapped a resilient water supply, yet losses up to 80% where the source water became dry. In contrast, dry taro (planted on dry land) consistently experienced high losses. Relatively speaking, coconut and pandanus can withstand high levels of salt, whereas taro is much more sensitive. Salinity causes a substantial reduction in taro productivity (Roy & Connell, 1991).

Just as crop loss is dependent on the vegetative species, regrowth following a period of loss is also plant-dependent. For instance, a supply of dry taro, which is particularly vulnerable to drought, recovers within 18 months after return toward normal climatic conditions. In contrast, the more robust supply of wet taro takes approximately 3-4 years.

EVAPOTRANSPIRATION

One of the least characterized yet significant components of the water balance on low-lying atolls is total evapotranspiration (White, 1996)**.** Water balances are used to determine recharge, and they commonly use daily rainfall and mean daily evaporation estimates since monthly time steps usually under-estimate recharge (Falkland, 1994). ETp, or the standard, non-vegetation and non-soil specific ET value found from using standard the Penaman Equation, is calculated on a monthly basis. Falkland 1988 calculated recharge using water balance simulations and found monthly ET rates are relatively constant from year-to-year.

Falkland 1994 formed a recharge model that considers interception storage during any rain event. This storage is filled before water is made available to the soil, and storage is dependent on vegetation (1 mm for grasses, and 3 mm for trees – particularly coconut trees). Water requirements of the plants are also met prior to draining to the water table, and maximum and minimum limits for ET are set as the "field capacity" and "wilting point". The field capacity was assumed to be 0.15 and wilting point was 0.05 based on the soil conditions.

Coconut tree roots can penetrate the water table that typically exists 1 to 2 meters below the ground surface (roughly 50% of roots from mature trees). The deep penetration to the water table allows coconut trees to transpire even when the unsaturated zone becomes dry, which makes them more robust during droughts when compared to shallow rooted plants.

The crop factor for grasses and shallow rooted vegetation is assumed to be 1.0 and the crop factor for coconut trees was taken as 0.8. Proportions of islands covered by deep rooted

vegetation were estimated from colored aerial photographs. The islet with 0.8 proportion of freshwater lens covered by deep-rooted vegetation has a recharge of 29% whereas the other islets with nearly 0 proportion have 44-49%. On a per tree basis, 400-750 mm per year can be transpired from coconut trees with 8 meter spacings and 100% cover.

ANTHROPOGENIC WATER CONSUMPTION

Two major sources of freshwater are available on coral atolls: rainwater from rainwater catchments and fresh groundwater from the underlying Holocene aquifer. In addition, islanders use certain sources for drinking water and others for washwater. For example, islanders in Eauripik prefer to use water from coconuts and rainwater catchments for drinking water and groundwater is used for washing.

The World Health Organization (WHO) recommends a minimum water supply of 15 L per capita per day. Based on a USGS study in Ulithi in 1984, water consumption appears to be significantly lower than this. The range of consumption for drinking water purposes was from ½ gallon (~2 liters) of water per capita per day on Asor and Fassarai, and 1 gallon (~4 liters) of water per capita per day on Mogmog. Freshwater is used for up to 70% of cooking water and this can be up to 6.3 gallons per household. Otherwise, saltwater is used for washing clothes and dishes and bathing.

CLIMATE CHANGE

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

ENSO EVENTS

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

ACCELERATED SEA LEVEL RISE

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

One potential side effect of sea-level rise is shoreline recession which is estimated by Bruun's Rule (Richmond, Mieremet, & Reiss, 1997). During rising sea level, material is transported offshore from the beach, and the shoreline recedes landward in an effort to maintain a profile of equilibrium and the displacement of the shoreline is a complex function of the profile shape, grain sizes, and nearshore wave characteristics. It was developed for depositional coastlines which have more rigid geology structure (Bruun, 1962; 1983), and therefore it does not exactly translate for reef environments. Bruun's rule is described by $W=SX/Y$, where W is the width of beach erosion, X is the horizontal distance from the shore to the limited depth of sediment transport, S is the sea-level rise, and Y is the vertical height of the profile.

Effects due to ASLR will be quite different from atoll islet to atoll islet depending on their

location within the atoll and the geologic history. Notably, atolls with convex bends can receive sediments from storms moving in different directions which can decrease shoreline recession or reverse it. Also, the reef can grow vertically up to 7 mm/yr and diminish negative ASLR effects that way.

Areas in atoll nations experience different levels of SLR depending on location. According to a figure provided, FSM has seen between 1 and 2 mm/yr.

Under conditions of SLR, atolls may increase, maintain or decrease in surface area depending on the impact of shoreline erosion or accretion, manifestation of storm events, and anthropogenic modifications. Accretion of island area is linked to deposition of gravel deposits from tropical cyclones, and erosion occurs more commonly in islands that are primarily sand with low sediment inputs. Thus, the author concludes that atolls with higher gravel content may be more stable and islands with primarily sand are less resilient.

INTENSIFIED TYPHOONS

In addition, the IPCC notes that it is likely that wind speeds of tropical cyclones will intensify in the future, however, frequency will likely remain stable or decrease. Typhoons with higher intensity can more dramatically alter the freshwater lens and natural resources for the atolls.

DEMOGRAPHICS

Settlement of the islands occurred during relatively recent human history, nearly 1-2 thousand years ago, by people migrating from the Philippines, Indonesia, and/or the Solomon Islands (Rainbird, 1994) (Intoh, 1997). Population fluctuations have been partially documented since Western civilization discovery, particularly since the mid-1800s, and most occurrences that happened prior to the 1950s are stories told by descendants of islanders that witnessed them. Several recounts explain atoll-specific incidences of depopulation, which has occurred in one or more of the selected Yap State atolls due to migration, warfare, disease, and natural disasters , within the past couple centuries (Lessa, 1955) (Bates & Abbott, 1958) (Levin, 1976).

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

Table 3 – Historical Population for Yap State and Selected Atolls

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

[1]Population data from FSM 2000 and 2010 Census

As shown by Table 3, population fluctuations are most significant in Ulithi which also has the greatest number of inhabitants, and populations remain most stable on Eauripik which has the lowest number of inhabitants. Ulithi also has four inhabited islands and is located closest to the mainland, therefore there is more opportunity for migration and disturbances to the atoll population.

From 2000 to 2010, Ulithi also had the highest annual growth rate at 1% for a total growth of 10% between Census cycles. Satawal was the only atoll that actually decreased in population size, with roughly 30 fewer inhabitants and an annual population growth rate of -0.6%.

The population density of Eauripik is high despite the relatively small size of the island, at roughly 950 persons per square kilometer (Roy & Connell, 1991) (Pernetta, 1992). Size of the population is very limited by the natural resources and thus the population has remained fairly stable over time. Limitations due to fish catches are expected to limit the population to no more than 150 residents (Levin, 1976). The population on Ifalik has grown sizably since 1980, most likely due to migration and increased availability of resources that resulted from merging of three islets during the past 100 years.

ATOLL LITERATURE REVIEW

EAURIPIK ATOLL (EAURIPIK ISLAND)

Eauripik Atoll (Auripik, Aurupig, Iuripik) (N 6° 41′ E 143° 3′) is a low-lying coral atoll located 108 km southwest of Woleai atoll and is the southernmost atoll in Yap State (Bryan, 1953). It is also located approximately 630 km from Yap Island and 775 km from Guam. It contains three islets with the largest, Eauripik Island, as the only inhabited (Scourse & Wilkins, 2009). Land area on Eauripik is small, 0.2 km^2, and it is approximately 11 km long east-to-west and 3 km wide north-to-south. The lagoon encompassed by the islets is approximately 7 km^2. Refer to Figure 7 for an image of present day Eauripik Atoll, and Figure 8 for a present day image of Eauripik Island.

Figure 7 – Eauripik Atoll (2015)

CLIMATE

Eauripik has a climate similar to the other outer-lying islands, described by Levin 1976 as marine-tropical. He noted at the time that temperatures rarely exceed 80 degrees Fahrenheit, however, historical averages for the three regional weather stations in Yap, Chuuk, and Guam show daily average temperatures at 81 to 83 degrees Fahrenheit.

Rainfall was estimated by Levin 1976 at 100 inches (2.54 meters) annually, which is lower than Yap Island at 3.07 meters and Chuuk Island at 3.42 meters. It is unclear in the dissertation how

the estimation was made and it was likely a rough estimate.

Eauripik has experienced a few large typhoons within the past 200 years, namely the Great Typhoon of 1907 that washed away part of eastern Eauripik Island and an especially devastating typhoon in the mid-1800's. According to stories from the islanders, the typhoon killed several or most of the existing population and threatened to kill the rest due to famine (Levin, 1976). Woleai islanders rescued several of the survivors, housed them for several months or perhaps years while island resources recovered, and helped them return to repopulate.
The size and limited resources of Eauripik makes the island especially vulnerable to typhoons and future increases in intensity may be the largest concern for this island community.

HYDROGEOLOGY

Eauripik Island is a leeward island with an average width of approximately 150 meters (~500 feet) and a maximum of roughly 200 meters (~650 feet) (Levin, 1976). It is a wide island with a low, swampy area in the middle that is used to cultivate swamp taro (Roy & Connell, 1991). The freshwater lens on Eauripik is small due to the small width (Levin, 1976). The maximum elevation on Eauripik is low, perhaps around 20 feet (6 meters) due to artificial build-up that occurred from digging out the swamp for taro (Levin, 1976) (Richmond, Mieremet, & Reiss, 1997). Levin 1976 remarked that the soils on the island are similar to other atolls.

Bailey 2013 estimated the freshwater lens size for several islands in Yap State using an algebraic model, including Eauripik Island designated 'Eauripik Atoll B' (Bailey, 2013). It found that the freshwater lens for Eauripik under steady state conditions has a maximum lens of 2.66 meters, assuming 3.5 annual meters of rainfall.

ECOLOGY

Eauripik grows coconuts, bananas, taro, and breadfruit trees for sources of food (Scourse & Wilkins, 2009), in addition to catching fish (Levin, 1976). Vegetative food sources are commonly insufficient in supply and the islanders supplement with fish.

DEMOGRAPHICS AND WATER USE

The population on Eauripik is small relative to the other atolls examined in this report. The 2010 Census indicates the population is 114 persons and the average annual growth rate is roughly 0% (FSM National Government, 2010). According to Levin 1977, Eauripik people perceive that population is limited by fish catches to roughly 150 people.

Figure 8 – Eauripik Atoll, Eauripik Island (2015)

Per the 2010 census data, Eauripik has a total of 17 housing units, 16 of which were occupied at the time of the census. The units are primarily constructed of wood walls, thatch roofs, and coral floor material with a few exceptions. Two units are constructed of concrete walls and flooring, one unit is constructed of metal/tin, three units have metal/tin roofing, and two units have wood pier/pilings for flooring.

According to the 2010 census, all 16 households get their drinking water from household tanks and 14 of the 16 households get their washwater from wells. Source water for the washwater may be subject to change as a result of hydrologic disturbances. This was evidenced in the 1970's when the islanders began bathing in seawater due to salinization of the groundwater during a typhoon (Levin, 1976).

IFALIK ATOLL (IFALIK ISLAND)

Ifalik Atoll, or Ifaluk, (N 7° 15′ E 144° 27′) is a low-lying coral atoll located 1ocated 745 kilometers southeast of Yap Islands and 690 kilometers east of Chuuk Islands. The native people pronounce the island name using an English phonetic spelling "Eefahlook" (Bates & Abbott, 1958). Ifalik is a circular atoll composed of two islets: Ifalik, the main island on which the Ifalik habitants resides, and Ella, a small, uninhabited islet west of Ifalik. Approximately 650 meters of channel separate the islets with the deepest section of atoll at the middle. Refer to **Error! Reference source not found.** for a present day image of Ifalik Atoll and Figure 11for Ifalik Island.

Figure 9 – IfalikAtoll (2015)

CLIMATE

The climate of Ifalik is tropical and rainy, consistent with the neighboring outer-lying atolls. The atoll experiences relatively small seasonal changes, as exhibited by similar temperature and pressures throughout the year (Tracey, Abbott, & Arnow, 1961), due to proximity to the equator. Ifalik receives an average rainfall of approximately 100 to 120 inches (2.5 to 3.04 meters) annually (Bates & Abbott, 1958) (Tracey, Abbott, & Arnow, 1961). During the expedition of 1953, the researchers asked local islanders if they could recall a time of drought, to which on islander replied, "Always too much rain,". Similar response led them to conclude that for Ifalik,

rainfall is not the limiting factor for their existence. Humidity is typically between 82 and 86%, and 100% humidity is seen during periods of rainfall. Cloud cover is common, usually ranging from 25 to 50% (Tracey, Abbott, & Arnow, 1961). Ifalik was also struck hard by the Great Typhoon of 1907, and storm surges from the south leveled most of the trees and killed at least 35 islanders. According to islanders, freshwater only becomes a scarce resource after typhoons when overwash and salinization occurs.

HYDROGEOLOGY

Ifalik Island is a semi-circular, elongate island with maximum dimensions 2.45 km north-to-south and 1.9 km east-to-west. Ella Island is 0.35 km north-to-south and 0.7 km east-to-west. Ifalik has a maximum elevation of approximately 5 meters, or 15 feet (Tracey, Abbott, & Arnow, 1961) (Richmond, Mieremet, & Reiss, 1997).

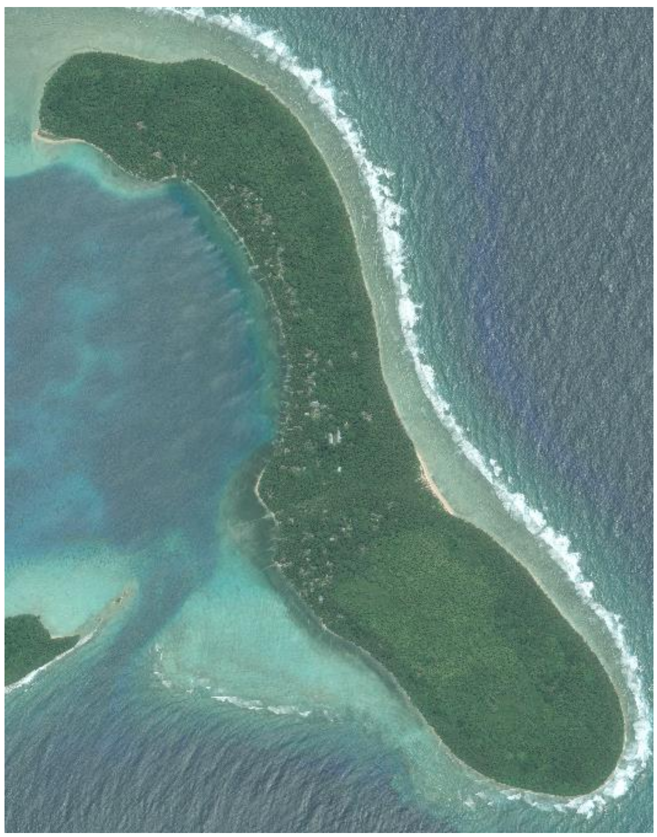

Figure 10 – Ifalik Atoll, Ifalik Island (2015)

Ifalik Island was once a chain of three separate islets: Maia, Falarik, and Falalop. According to Tracey et. al (1961), Maia, the northernmost part of what is now Ifalik island, merged with Falarik during the Great Typhoon of 1907 (Tracey, Abbott, & Arnow, 1961). The typhoon inundated the island, depositing sediment including coarse yellow gravelly sand and “young boulders and cobbles” that filled the shallow Maia channel.

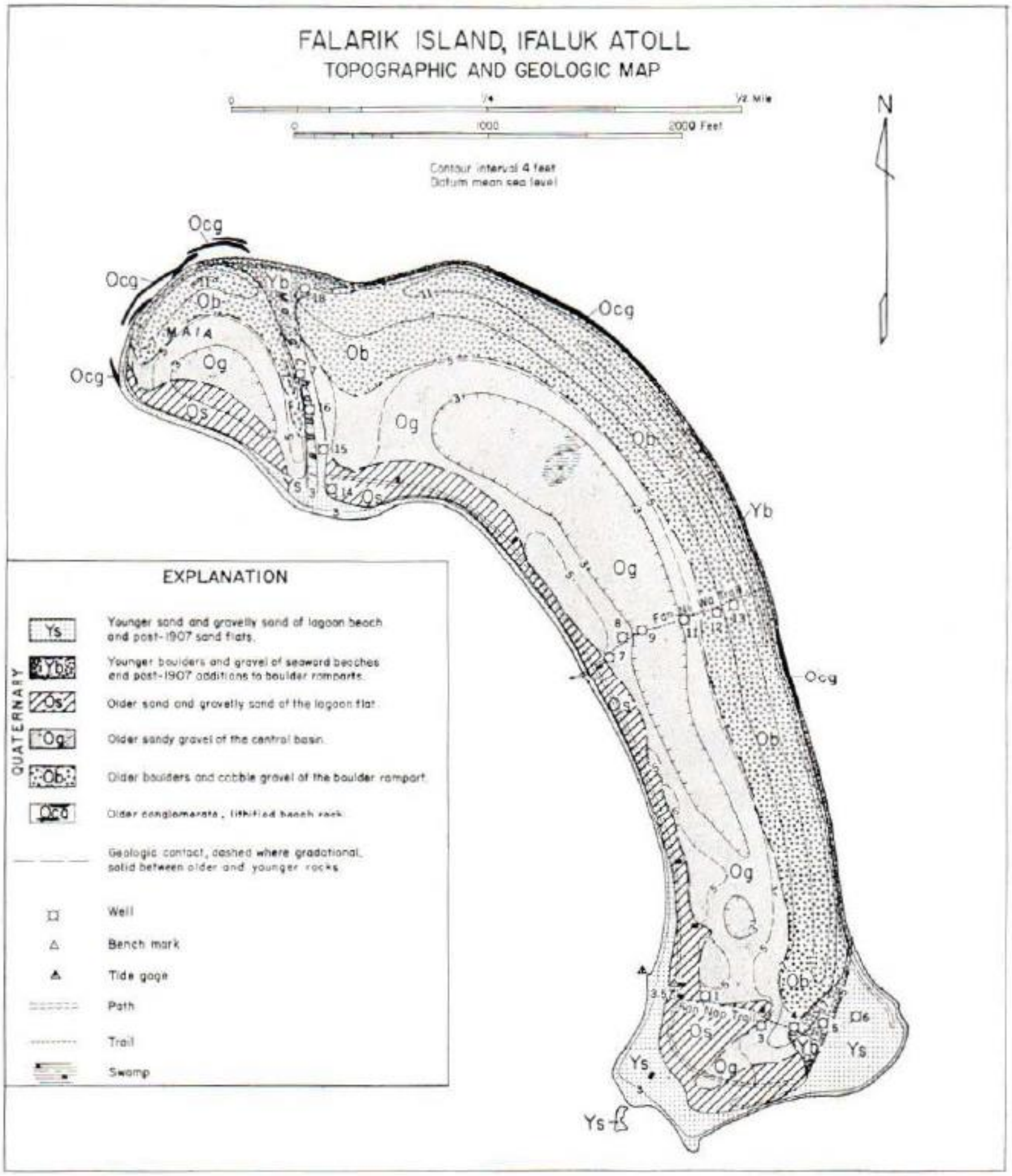

Figure 11 – Geology and Topography of Ifalik Atoll, Falarik Island (1953)

(Tracey, Abbott, & Arnow, 1961)

Figure 11 from the USGS expedition in 1953 shows the overall geology and topography of Falarik Island, which is the present day north portion of Ifalik Island. Generally, younger sediments are prominent along the ocean and lagoon shorelines, occurring through island cross-sections in areas where sediments have been deposited in depressions. The soil in the central part of the island is an older, sandy gravel, marked Og. Older sand and gravelly sands (Os) are

predominant along the lagoon shore, and older boulders and cobble gravel of the boulder rampart (Ob) are predominant along the ocean shore. Hydraulic conductivity of these soils would be, from highest to lowest, Ob > Og > Os. This geologic structure would result in a freshwater lens that is thickest toward the lagoon side, which is what is typically found for Pacific atolls.

Another interesting observation from the 1953 USGS expedition was the existence of a freshwater lens on Ella Island at a location where the width was 700 ft wide, but no existence where the island was 350 feet wide. Bailey 2013 estimated the steady-state, freshwater lens for Ifalik Island (‘Ifalik Atoll B’) has a maximum lens thickness of 4.69 meters, assuming 3.5 annual meters of rainfall (Bailey, 2013).

ECOLOGY

Vegetation is observed nearly everywhere on the island that is above the ‘high water mark’ (Tracey, Abbott, & Arnow, 1961). The three vegetative zones on Ifalik Island are: cleared coconut grove, depressed swamp, and what the Ifalukians refer to as *niwel* and other western cultures may refer to as ‘boondocks’ (Bates & Abbott, 1958). Coconut groves exist in areas around the villages, as well as along the stretchces of young soil that have been deposited in depressions (Tracey, Abbott, & Arnow, 1961). As noted by Tracey et al., the breadbruit trees, however, did not establish themselves along the Maia channel but grow readily in the boulder rampart.

DEMOGRAPHICS AND WATER USE

As of the 2010 FSM census, the population of Ifalik was 578 residents which corresponds to an additional 17 residents from the 2000 census and an average annual growth rate of 0.3%.

Per the 2010 census data, Ifalik has a total of 83 housing units, all of which were occupied at the time of the census. The units are primarily constructed of thatch or wood walls and roofs, and coral floor material with a few exceptions. Seven units are constructed with concrete walls and flooring, and one unit is constructed with concrete roofing. Two units have metal/tin walls and seven have metal/tin roofing. One unit has wood pier/pilings for flooring, and fifteen have other floor material.

At the time of the USGS expedition, the Ifalukians made almost no use of rainwater catchments for drinking water and relied almost entirely on groundwater wells. Today, it is estimated there are 3 to 7 rainwater catchments on the island that are actively used for drinking water. According to the 2010 census, all 83 households use a household tank for drinking water supply (FSM National Government, 2010). For washwater, the islanders primarily use other sources: 44 households use sea water, 27 households use well water, and 12 use household tanks.

SATAWAL ISLAND

Satawal Island (Satuwal, Satowal, Satowalairak) (N 7° 21′ E 147° 02′) is a reef island located in the easternmost part of Yap State, approximately 530 km from Chuuk Island and 1,010 km from Yap Island, east-south-east. Satawal has no significant lagoon and thus is considered a reef island or in some literature a ‘table reef’ (Fosberg, 1969). The island is a semi-circular, elongate island with maximum dimensions 1.35 km north-to-south and 1.8 km east-to-west. The maximum elevation on Satawal is also 7 meters and by some definitions would not be considered low-lying (Richmond, Mieremet, & Reiss, 1997). Refer to Figure 11 for a present day image of Satawal Island.

Figure 12 – Satawal Island (2015)

CLIMATE

The climate of Satawal is not well documented in the literature, however, due to the proximity near Chuuk Island it is probably that Satawal receives more rainfall than Yap islands further west.

HYDROGEOLOGY

The soil on Satawal consists primarily of sands and gravels. As is typical for atolls, the leeward

side, which is frequently the west side for Caroline Islands, is composed of sands and the windward side is primarily gravel (Fosberg, 1969). Peat is also present at localized areas.

Bailey 2013 estimated the steady-state, freshwater lens for Satawal Island (‘Satawal Atoll A’) has a maximum lens thickness of 9.45 meters, assuming 3.25 annual meters of rainfall (Bailey, 2013).

ECOLOGY

According to Fosberg (1969), the vegetation on Satawal is dominated by forests that consist of coconut trees with lower-lying vegetation. Breadfruit trees are also present primarily in the central part of the island. Aerial images of Satawal show two large unforested areas in the central-east part of the Island. Fosberg (1969) also identified such a region and classified it as a ‘tiny scrub-covered mangrove depression’ while also noting minimal presence of taro swamp.

DEMOGRAPHICS AND WATER USE

Satawal is the only atoll examined in this study that exhibited a decrease in population from year 2000 to 2010. The 2010 population was 501 residents, a decrease of 30 residents from the 2000 Census.

Per the 2010 census data, Satawal has a total of 65 housing units, 59 of which were occupied at the time of the census. The units are primarily constructed of wood walls, metal/tin roofs, and concrete floor material with a few exceptions. Fourteen units are constructed with concrete walls, and five with thatch walls. Eighteen units are constructed with thatch roofs, seven with concrete roofs, two with wood, and one with other material. Ten units have coral floor material, five units have wood pier/pilings for flooring, and four units have other floor material.

According to the 2010 Census, all 59 occupied housing units obtain their drinking water from household tanks (FSM National Government, 2010). Interestingly, 58 of the 59 households also obtain their washwater from household tanks, and the remaining household uses sea water. Thus, it appears groundwater as a freshwater source is not necessary for the Satawal islanders, perhaps due to the high amounts of rainfall in that area.

ULITHI ATOLL (FALALOP ISLAND)

Ulithi (Uluthi, Urushi To) Atoll (N 9° 56′ E 139° 40′) is a low-lying coral atoll located 170 km northeast of Yap Island. The atoll is roughly 26 km north-to-south, 19 km east-to-west at the north end, and 6 km east-to-west at the south end (Anthony, 1997). The lagoon is 474 km^2 and is surrounded by 49 islets, four of which are inhabited: Falalop, Asor, Mogmog, and Fassarai. According to Roy 1997, Ulithi Atoll has a maximum elevation of over 6 meters.

Falalop, or Fl'aal'ap, Island is an island in the northeast part of Ulithi Atoll, approximately 195 km from Yap Island Airport and 665 km to Guam airport. Shoreline-to-shorline, Falalop is only 1.5 km southeast of Asor and outside of the main ring of Ulithi islets. Falalop is a triangular island, the maximum width approximately equal to the length and general taper in width throughout the full length (1.2 km long, maximum 1.1 km width). Refer to Figure 13 for a present day image of Falalop Island.

Figure 13 – Ulithi Atoll, Falalop Island (2015)

Falalop is the main island of Ulithi that is the site for government activities, the air strip and the majority of the Ulithi population (Richmond, Mieremet, & Reiss, 1997). The air strip is a potential source for run-off due to the large paved area.

CLIMATE

According to Anthony (1997), Ulithi receives approximately 2.8 meters of rainfall each year, which corresponds to a recharge of 1.4 meters based on an assumed recharge rate of 50%.

HYDROGEOLOGY

Anthony (1997) calculated the freshwater lens on Falalop Island to be 5 meters at the maximum thickness and the volume to be 96,000 cubic meters. Similarly, Bailey 2013 found a the steady-state, freshwater lens for Falalop Island (‘Ulithi D Falalop’) has a maximum lens thickness of 5.91 meters, assuming 2.8 annual meters of rainfall (Bailey, 2013).

HYDROLOGY

According to Lessa 1955, Ulithi atoll islands grow coconut and breadfruit trees, taro, and root vegetables such as squash and sweet potato (Lessa, 1955).

DEMOGRAPHICS AND WATER USE

The population on Ulithi is largest of the four atolls and experienced the highest increase in population from 2000 to 2010, at a rate of 1%. The population in 2010 was 847, and increase of 74 residents from year 2000.

Per the 2010 census data, Ulithi has a total of 177 structures, 140 of which housing units, all of which were occupied at the time of the census. All units are one family detached structures with an average of 1.5 rooms. Most units were constructed from 1980 to 2005, except for 11 units constructed prior to 1980 and 5 units constructed after 2005.

The units are primarily constructed of thatch or wood walls and roofs, and coral floor material with a few exceptions. Seven units are constructed with concrete walls and flooring, and one unit is constructed with concrete roofing. Two units have metal/tin walls and seven have metal/tin roofing. One unit has wood pier/pilings for flooring, and fifteen have other floor material.

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