# YAP ISLANDS NATURAL COASTAL SYSTEMS AND VULNERABILITY TO POTENTIAL ACCELERATED SEA-LEVEL RISE

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## *ABSTRACT*

*Yap State in the Federated States of Micronesia consists of 16 islands distributed over a distance of nearly 1,000 km across the western Pacific Ocean. Four island types are present in Yap State: The main Yap Island group consists of four large and several smaller, high volcanic islands surrounded by a fringing reef. Ten of the islands are atolls which consist of an annular reef rim enclosing a central lagoon. Low-lying islets, composed mainly of reefal debris, are scattered on the upper surface of the atoll reef rim. There are four reef islands, which are low-lying coral islands developed on a small reef platform and devoid of a significant lagoon. The remaining island (Fais) is a high limestone island partially surrounded by a narrow fringing reef with the remainder of the island consisting of a cliffed coast.*

*On the main Yap Islands, there are three critical coastal environments: mangrove forests, sand beaches, and coral reefs. Mangrove forests comprise about 10% of the total land area and have an alongshore distance of nearly 114 km. The mangrove area has been expanding throughout the Holocene, and will continue to expand in a landward direction as low-lying coastal land becomes intertidal. Shore erosion would probably be minimized due to mangrove protection. Sand beaches and associated coastal plains are limited in extent, occurring in exposed localities and comprising only about 0.25% (0.24 km$^2$) of the total land area. However, they form important settlement sites and are critical to modern and traditional Yapese culture.*

Journal of Coastal Research, Special Issue No. 24, 1997

*Sand beaches are extremely vulnerable to accelerated erosion, and a landward shift of the shoreline profile during a rising sea level can be expected. Coral reefs surround the main Yap Islands and are a source of sediment for the beaches and adjacent coastal plains. Reef response to accelerated sea-level rise is probably one of expanded vertical growth and increased carbonate production as shallow substrates are submerged.*

*The low-lying atolls and reef islands of Yap State will potentially suffer severe consequences of accelerated sea-level rise. Maximum elevation of these islands is around 7 m with an average elevation of 3-4 m above MSL. They are composed primarily of easily eroded unconsolidated reef debris.*

*Additional Index Words: shore erosion, mangrove forests, beaches, coastal plains, reefs, Bruun rule, Federated States of Micronesia, atolls, reef islands.*

## INTRODUCTION

Yap State, a remote island group in the western Pacific Ocean, is one of four states of the Federated States of Micronesia; the other states are Chuuk (Truk), Kosrae, and Pohnpei. The main islands of Yap consist of four major islands (Yap, Tamil-Gagil, Map, and Rumung) and several smaller ones. About 65% of the population of Yap State reside on the main islands which comprise about 84% of Yap State's total land mass. In addition to the main Yap Islands there are 10 atolls, 4 reef islands, and one high limestone island which extend nearly 1,000 km across the Pacific Ocean (Figure 1; Table 1).

Field studies were conducted on the Yap Main Islands, Falalop Islet on Ulithi Atoll, and a brief visit was made to the emerged high limestone island of Fais. The field work was part of an Intergovernmental Panel on Climate Change (IPCC) case study on the effects of potential accelerated sea-level rise (ASLR) on natural coastal systems (Richmond and Reiss, 1994). There is very little scientific data on the morphology of Yap coastal systems upon which to base predictions on the effects of ASLR. The purpose of this study was to examine the field relationships between the important Yap coastal systems and collect field measurements useful in interpretation of geologic coastal development and the potential effects of sea-level rise.

## METHODOLOGY AND ANALYSIS CONDITIONS

We focused our study on the present shoreline but considered areas between the 5 m contour (the lowest contour on available topographic maps) and the reef crest which is readily identifiable in the field and on maps. Sea-level rise boundary conditions, as established by the IPCC (1991), were a low value of +0.3 m above present mean sea level and a high value of +1.0 m by the year 2100. Data used in this study was derived from numerous sources, including:

- Published maps. General topographic information was derived from analysis of these maps. Primary sources were US Geological Survey 1:25,000 scale topographic maps and US Army Corps of Engineers, Army Map Service (Defense Mapping Agency) 1:25,000 scale maps.

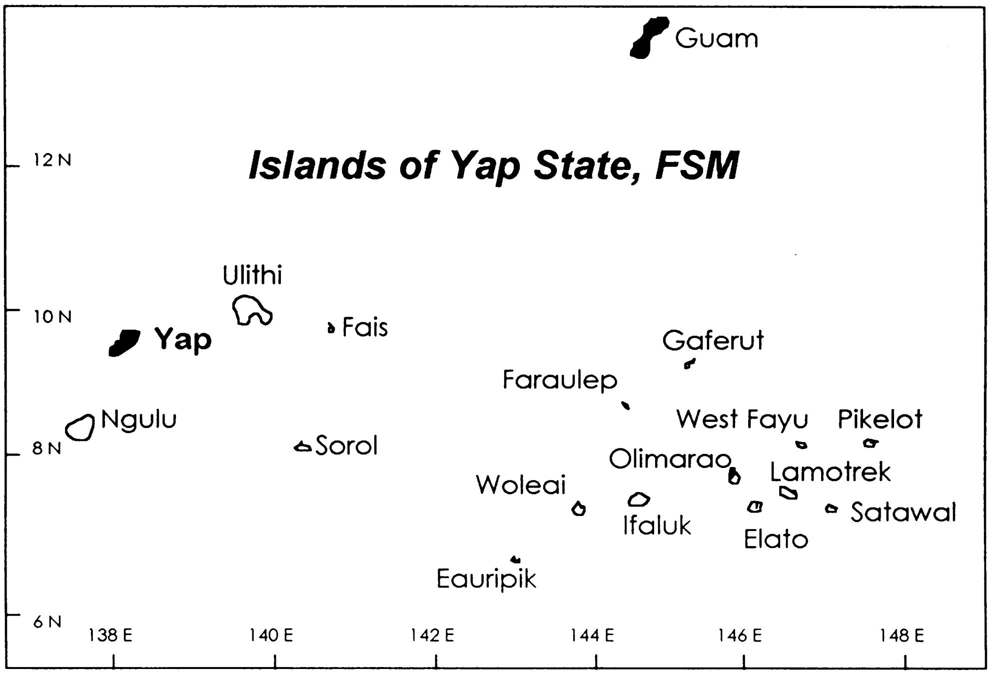


Figure 1. Location of islands within Yap State. The main Yap Islands are about 450 miles southwest of Guam.

Table 1. Summary of characteristics of the islands of Yap State, FSM. Data are from Nugent (1946), Tracey et al., (1961), Ashby (1985), Gillett (1987) and this study. Question marks indicate suitable data was not located during the course of the study.

| ISLAND | ISLAND TYPE | POPU-LATION | MAXIMUM DIMENSIONS (km) | MAXIMUM ELEVATION (m) | LAND AREA ($km^2$) |
|---|---|---|---|---|---|
| Ngulu | Atoll | <60 | 25 X 39 | low | ? |
| Yap | High Volcanic | ~7,000 | 42 X 16 | 170 | 96 |
| Ulithi | Atoll | ~ 750 | 26 X 35 | 6+ | 4.6 |
| Sorol | Atoll | <60 | 12 X 3.1 | low | 1.2 |
| Fais | High Limestone | ~250 | 1.4 X 3.2 | 19 | 2.2 |
| Eauripik | Atoll | ~150 | ? | low | ? |
| Woleai | Atoll | ~750 | 9.3 X 5.3 | low | 4.4 |
| Ifaluk | Atoll | ~400 | 4.0 X 3.1 | 5 | 1.0 |
| Faraulep | Atoll | ~150 | ? | low | ? |
| Gaferut | Reef Island | 0 | 0.5 X 0.9 | low | ? |
| Olimarao | Atoll | 0 | ? | low | ? |
| Elato | Atoll | <60 | 13 X 2.4 | low | 0.6 |
| Lamotrek | Atoll | ~250 | 6.5 X 15 | low | 1.0 |
| West Fayu | Atoll | 0 | ? | low | ? |
| Satawal | Reef Island | ~400 | 0.9 X 2.3 | 7 | 1.3 |
| Pikelot | Reef Island | 0 | ? | low | ? |

The shoreline position, mangrove areas, sandy shorelines, and topographic contours (5, 25, 50, and 75 m) were digitized from these maps.

- Coastal profiles. Specific topographic data were obtained from field collection of coastal profiles extending from the reef flat inland as far as logistically feasible. These profiles provide accurate elevation and coastal profile shape and are used to supplement elevation measurements derived from topographic maps.
- Vertical aerial photographs. These photographs were used to define features not depicted on maps.
- Site data. To characterize the natural coastal systems of Yap State, fourteen representative coastal sites, eleven on the Yap Islands (Figure 2) and three on Falalop Islet (Figures 3 and 4), as well as Ulithi Atoll were examined in detail. Data collected at each site included coastal profiles, site descriptions, and reference photographs.

## CHARACTERISTICS OF YAP NATURAL COASTAL SYSTEMS

Three distinct island types occur within Yap State: high islands of volcanic and metamorphic rocks, atolls and low-lying reef islands, and a high limestone island. Because each island type has distinct coastal environments, they can be expected to respond uniquely to changes in relative sea-level position.

### High Islands Of Volcanic And Metamorphic Rocks: The Main Yap Islands

The Yap Islands consist of four main high islands (Yap, Rumung, Gagil-Tamil, and Maap; Figure 2) and numerous smaller islands composed primarily of metamorphic rocks with smaller amounts of sedimentary (breccia) and volcanic rocks (Johnson et al., 1960). The principal coastal deposits are either mangrove swamps, beaches, or alluvium. The beaches front coastal plains in exposed locations. In contrast, the mangrove forests inhabit the more protected environments where they often front alluvial deposits. Remaining coasts are marked by seacliffs. The entire group of main islands is surrounded by a fringing reef. Areal distribution of Yap coastal zone environments are summarized in Table 2.

There are three critical natural environments of the main Yap islands that have the potential to be substantially affected by changes in relative sea-level position. These are mangrove forests, sand beaches, and reefs.

Yap mangroves generally occur in intertidal, sheltered environments and are believed to be associated with the accumulation of fine-grained sediment in areas typical of high primary productivity. Approximately 10 taxa (species and hybrids) of mangroves occur in Yap (Woodroffe, 1987) where they are distributed between deltas, embayments, and protected reef flats (Figure 3). Mangrove forests comprise about 10% of the total land area and extend along nearly 114 km of shoreline (Table 2). We believe the forests to be stable features that have slowly expanded their territory throughout the last 6,000 years. The landward extent of mangroves is the approximate spring high-tide level.

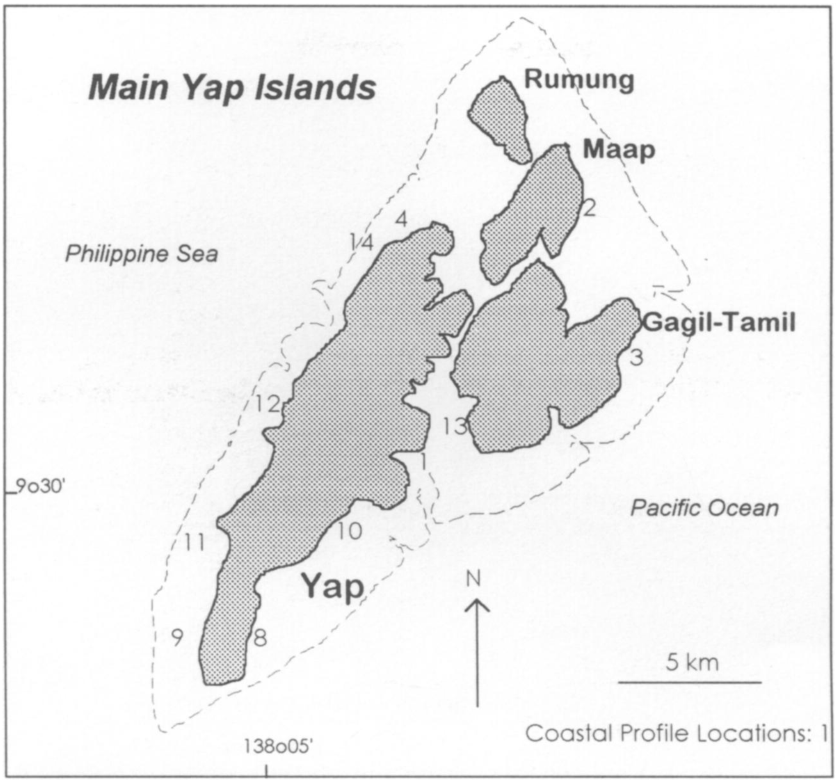


Figure 2. Main Yap Islands and location of coastal profile sites.

Figure 3. Young mangroves stabilizing the shore near Laey on the southeast of Yap Island. The reef crest is over 1 km away (towards the right in photograph).

Figure 4. One of the larger Yap beaches along the eastern shore of Gagil-Tamil. Note the eroded bases of the coconut trees in the background.

Table 2. Areal distribution of main Yap Island coastal environments as determined from the USGS 1:25,000 scale topographic map. The low-lying coastal areas are those between the shoreline and the first map contour (5 m).

| | YAP | GAGIL-TAMIL | MAAP | RUMUNG | TOTAL |
|---|---|---|---|---|---|
| Total Area ($km^2$) | 54.20 | 27.40 | 10.60 | 4.00 | 96.20 |
| Area Above 5m ($km^2$) | 41.10 | 21.90 | 8.60 | 3.40 | 74.90 |
| Low-lying Coastal Area ($km^2$) | 13.10 | 5.50 | 2.10 | 0.60 | 21.20 |
| Low-Lying Coast (%) | 24.10 | 20.10 | 19.30 | 15.40 | 22.10 |
| Mangrove Area ($km^2$) | 5.60 | 2.90 | 1.20 | 0.20 | 9.90 |
| Mangrove (%) | 10.30 | 10.80 | 10.90 | 6.00 | 10.30 |
| Sand Beach Area ($km^2$) | 0.07 | 0.02 | 0.09 | 0 05 | 0.24 |
| Sand Beach (%) | 0.13 | 0.09 | 0.80 | 1.30 | 0.25 |
| Mangrove Shoreline Distance (km) | 62.90 | 31.40 | 14.60 | 4.90 | 113.70 |
| Sand Shoreline Distance (km) | 3.60 | 1.40 | 3.80 | 2.00 | 10.80 |

Sand beaches are formed from terrigenous, carbonate, or a mixed terrigenous-carbonate sediment and typically occur on more exposed locations such as south and northwest Yap, east Gagil-Tamil (Figure 4), and east and north Maap. Nearly 11 km of sand beach, mostly composed of reef-derived carbonate sediment, occurs along the shoreline of Yap. Coastal beach deposits comprise a very small percentage of the total land area (approximately 0.25%), yet sand-rich coastal plains are the sites of most of the coastal villages. They are a very important, if not critical, component of traditional and modern settlement and culture. Because beaches are very susceptible to changes in sea-level position and are easily eroded under rising water levels, they are the most precarious natural environment on Yap in the event of accelerated sea-level rise.

Fringing coral reefs enclose the main Yap Islands covering approximately 93 $km^2$. They are continuous except for several deep reef passages which appear to be connected to on-land drainage systems. The reef flats are generally shallow allowing the passage of small boats only. Numerous blue holes, which are steep-sided enclosed basins, are scattered within the fringing reef and total about 4 $km^2$ in area. Elsewhere, the formation of blue holes has been attributed to karst processes during lower sea-level stands (Dill, 1977). The Yap reefs are described in more detail in Orcutt et al. (1989). Reefs are important for several reasons: they provide habitats for numerous fish and other food sources, they protect the coast from waves and severe storms, and the continual natural breakdown of reef skeletal material provides a major source of coastal sediment. A number of inspection dives were made during the course of this study to examine the state of the coral reefs opposite the on-land profile sites. Visual observations indicate that overall the reefs of Yap appear healthy and contain diverse coral communities.

**Atolls and Reef Islands: Ulithi Atoll**

Atolls are islands composed of an annular reef rim surrounding a central lagoon, often with small low-lying islets of reef-derived sediment occurring scattered on the upper reef rim surface (Figures 5 and 6). Ten of the outer islands of Yap State are atolls and four are single reef islands (low-lying islands composed of reef-derived sediment but without a significant lagoon). The atoll islets and reef islands are Holocene in age and include a significant amount of unconsolidated storm deposits and possibly record deposition under a slightly higher than present (<2 m) mid-Holocene sea level.

Ulithi Atoll, approximately 180 km from Yap, was visited during this study. Three sites were profiled on Falalop Islet and brief visits were made to Mogmog and Yasor Islets. Falalop is one of the larger islets (approximately 1 $km^2$) of the atoll, the center of government activities, the site of the atoll airstrip, and the most populated islet. It is triangular in plan shape with a maximum elevation of about six meters and surrounded by a fringing reef up to 150 m wide. The reef flat covers nearly 0.5 $km^2$, whereas the submerged reef, to the east and northeast of the islet, is over 2 $km^2$ in area.

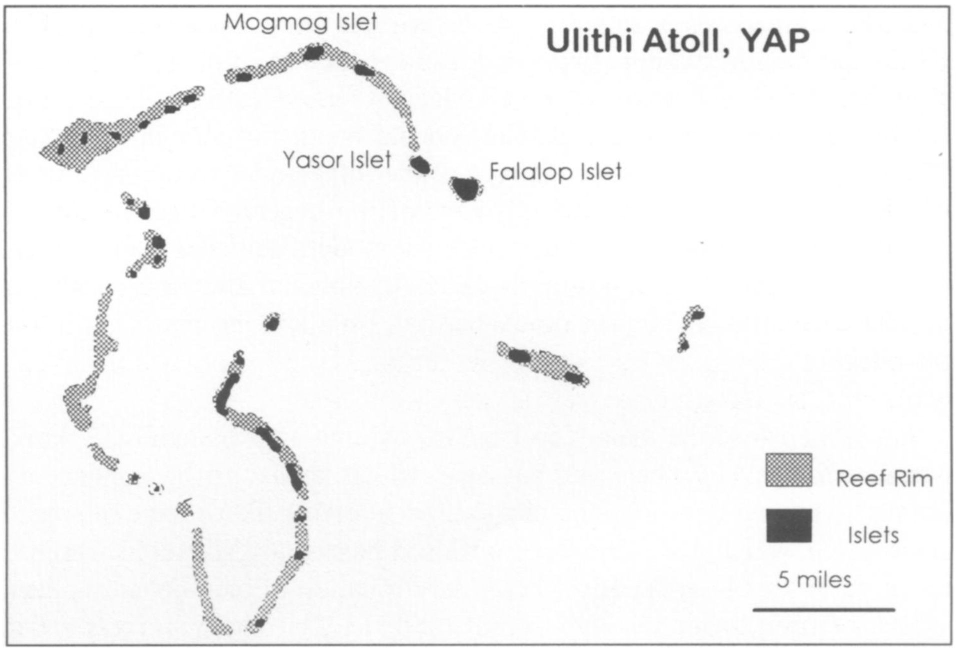


Figure 5. Sketch map of Ulithi Atoll showing the islets visited during the study.

Figure 6. Oblique aerial photograph of Falalop, an islet on the reef rim of Ulithi Atoll. The reef flats, reef crest (zone of breaking waves), and shallow submerged reef are clearly visible. View to the northwest.

Coastal profiles for three sites on Falalop are shown in Figure 7. In each profile there is an active beach face immediately adjacent to the reef flat. Landward of the active beach is an inactive higher storm ridge which reaches nearly seven meters in height in exposed locations. Average elevation of the islet landward of the outer storm ridge is between two to four meters.

The islets of Mogmog and Yasor display asymmetrical cross sections with steep, high (5+ m), gravel beach ridges along their open ocean shores and lower sand-rich beach ridges along their protected lagoon shorelines. This asymmetry is typical of atoll islets where there is a pronounced difference between exposed open-ocean coasts and protected lagoon coasts. The settlements are located along the lagoon shores, and it is estimated that they lie two meters or more above the reef flat surface (approximate MSL position).

**High Limestone Island: Fais**

The high limestone island of Fais (Figure 8) was briefly visited during this study. This small island (2.2 $km^2$ total land area) is about 75 km from Falalop, Ulithi and 250 km from Yap. The age of the limestone is unknown and presumably composed of uplifted reef deposits. The shoreline of Fais varies between limestone seacliffs and carbonate sand beaches. The beaches are the seaward margins of narrow coastal plains (total coastal plain area is about 0.5 $km^2$) which are backed by limestone cliffs. The beach sediment is mostly derived from the adjacent reefs rather than from breakdown of the limestone cliffs. The largest village, Choichoi on the south coast, is situated on the island's most extensive coastal plain which is about 150 m wide. The elevation of the coastal plain appears to be about 2-4 m above sea level, whereas maximum elevation of the island is about 19 m. Fringing reefs, up to 150 m wide and covering about 0.4 $km^2$, are adjacent to the beach shoreline whereas poorly-developed shallow reefs are opposite the cliffed shoreline.

## PHYSICAL CHANGE AND NATURAL SYSTEMS RESPONSE TO ASLR

A number of critical coastal environments were identified in Yap. Using profile data, environment maps, and assumptions regarding sea-level rise and system response, we have predicted the potential effects of accelerated sea-level rise (ASLR) within various Yap coastal systems including coastal plains, mangrove forests, coral reefs, and engineered shorelines (in Colonia).

The low-lying coastal plains, which are the sites of many of the coastal settlements, are particularly vulnerable to sea-level rise. Beaches, which act as a natural buffer, respond to storm impact through beachface erosion and transportation of sediment offshore. 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 (the Bruun rule). The landward displacement of the shoreline is a complex function of the initial profile shape, grain size, and nearshore wave characteristics. Bruun's rule theoretically applies to depositional coastlines where the bed material is movable to the maximum depth of sediment movement (Bruun, 1962; 1983), and therefore it does not strictly apply to reef environments where much of the

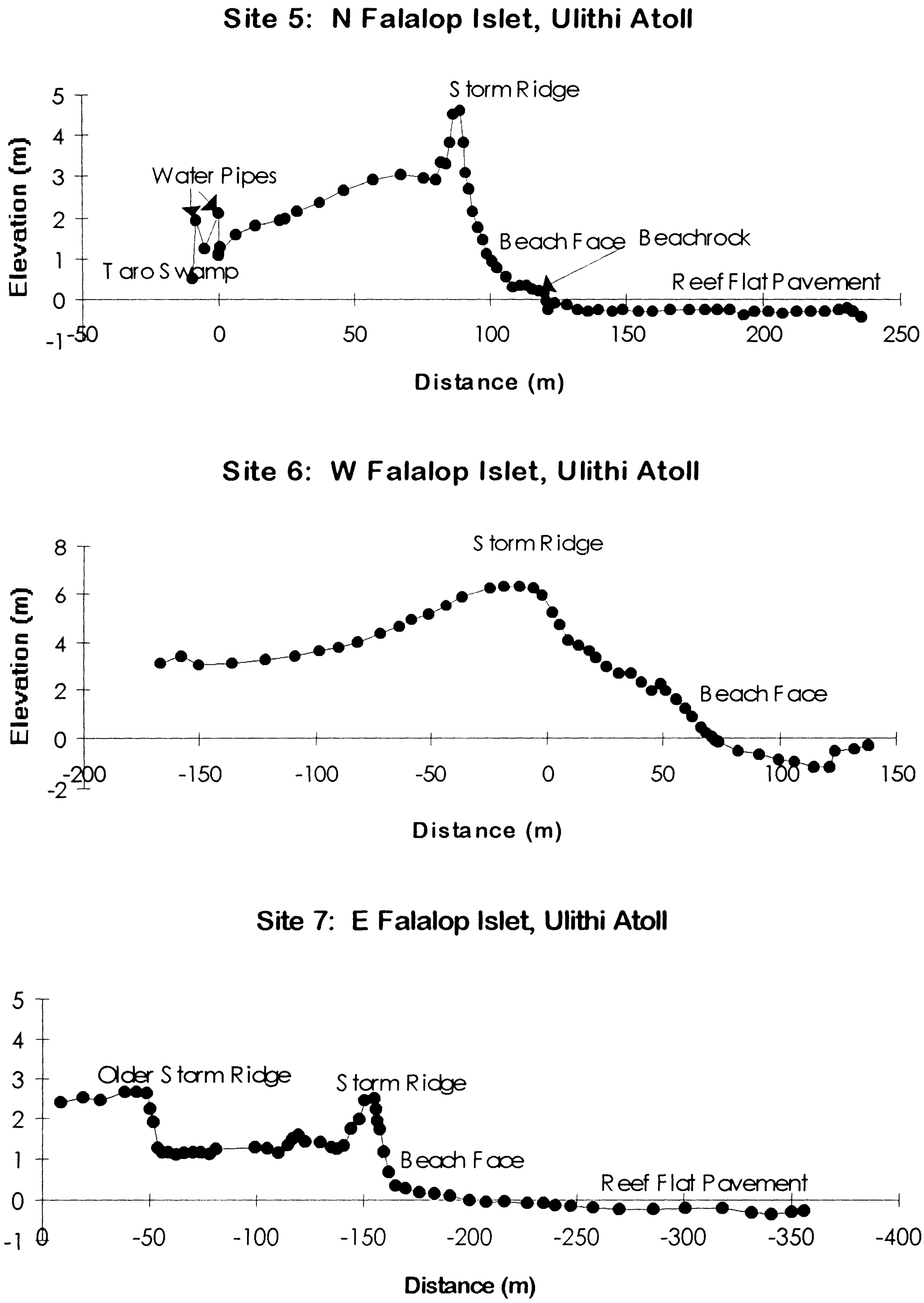


Figure 7. Coastal profiles from Falolop Islet, Ulithi Atoll. The vertical and horizontal "0" points are arbitrary.

Figure 8. Oblique aerial photograph of the high limestone island of Fais showing a shoreline alternating between carbonate sand beach and vertical limestone cliffs. View to the east.

nearshore bed is a coral/algal pavement. A simplified equation of the Bruun rule for estimating the width of beach erosion (W) is given by the relationship:

$$W = XS/Y$$

where 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. In some reef settings, the reef flats are non-erodable pavement surfaces such as those on Falalop, Ulithi and the active profile is essentially limited to the beach itself. In other areas, such as most of the reef flats of the main Yap Islands, unconsolidated sediment and seagrass beds are common. It is uncertain how these areas will respond to changing sea level.

For each of the profile sites fronted by a sand beach, the beach width and height were measured, and the amount of simplified Bruun rule shore retreat has been estimated (Table 3). For the main Yap Island beach sites, two shoreline recession values are given for each scenario rise because of the uncertainties regarding response of the reef flats to ASLR. The reef flat values extend from the beach crest seaward across the reef flat to the MSL position; the beach values cover only from the toe of the beach to the beach crest. For the reef flat series, there is an order of magnitude variation in profile width (14 to 296 m) and predicted shoreline recession rates (0.3 m rise = 3 to 37 m retreat; 1.0 m rise = 9 to 96 m retreat). The beach-only profiles show a lower range: profile width variation of 3.5 to 26 m and predicted shoreline

Table 3. Summary of shoreline parameters and simplified Bruun rule shoreline recession amounts for the profile sites fronted by a sand beach. The reef flat values (Yap Islands only) refer to sediment covered reef flats and extend from the current MSL position to the top of the first beach ridge. The beach values extend from the toe of the beach to the top of the first beach ridge. On Falalop, Ulithi (sites 5,6,7) the beach (ridge) refers to the active beach face at the time of profiling (generally the level of unvegetated sand) and extends to the toe of the beach. The storm ridge is the highest storm deposit along the profile line.

| SITE: YAP MAIN ISLANDS | PROFILE WIDTH (m) | PROFILE HEIGHT (m) | SHORELINE RECESSION: 0.3 m RISE (m) | SHORELINE RECESSION: 1.0 m RISE (m) |
|---|---|---|---|---|
| 2 reef flat | 296 | 2.8 | 37 | 106 |
| 2 beach | 26 | 2.3 | 4 | 11 |
| 3 reef flat | 14 | 1.5 | 3 | 9 |
| 3 beach | 3.5 | 1.3 | 1 | 3 |
| 4 reef flat | 178 | 3.0 | 21 | 59 |
| 4 beach | 24 | 2.3 | 4 | 10 |
| 8 reef flat | 47 | 1.4 | 12 | 35 |
| 8 beach | 4 | 0.9 | 2 | 4 |
| 14 reef flat | 61 | 1.6 | 13 | 38 |
| 14 beach | 16 | 1.4 | 4 | 12 |
| YAP reef flat range | 14 to 296 | 1.4 to 3.0 | 3 to 37 | 9 to 106 |
| Beach range | 3.5 to 26 | 0.9 to 2.3 | 1 to 4 | 3 to 12 |
| **FALALOP** | | | | |
| 5 beach | 28 | 3.0 | 3 | 9 |
| 5 storm ridge | 32 | 4.6 | 2 | 7 |
| 6 beach | 24 | 2.2 | 4 | 6 |
| 6 storm ridge | 85 | 6.3 | 5 | 18 |
| 7 beach ridge | 41 | 2.5 | 6 | 16 |
| Falolop beach (ridge) range | 28 to 41 | 2.3 to 3.0 | 3 to 6 | 6 to 16 |
| Storm ridge range | 32 to 85 | 4.6 to 6.6 | 2 to 5 | 7 to 18 |

recession rates of 1 to 4 m (0.3 m rise) and 3 to 12 m (1.0 m rise). In general, the gentler the slope the greater the amount of shoreline retreat for any given amount of sea-level rise.

At Falalop, two sets of beach profile/retreat values are given (Table 3). The beach values extend from the toe of the beach to the berm crest or upper limit of the active profile (generally limit of vegetation) and the storm ridge values extend to the top of the highest coastal ridge. The Falalop coastal deposits are higher than equivalent deposits on Yap, probably a result of greater exposure to wave and storm activity. Predicted shoreline recession values varied from 2 to 18 m.

Mangrove forests comprise about 10% of the total land area of Yap. At present, they appear to be expanding their distribution in a seaward direction as evidenced by young mangrove trees colonizing the reef flats in many areas. It is proposed here that under the scenario of a moderately rising sea level they would also expand in a landward direction as present low-lying coastal land becomes intertidal which is consistent with findings elsewhere (Woodroffe, 1988). We interpret the potential change in Yap associated with a rising sea-level to be one of initial inundation followed by landward colonization accompanied by minor or no shore erosion. Therefore, a rising sea level may actually increase the area of mangrove forest where there are suitable low-lying areas available for landward colonization. It is assumed here that mangroves protect most Yap coasts from eroding, and the amount of landward expansion would be simply related to the area of land inundated. Table 4 summarizes the inundation information derived from the shore-normal profile at each mangrove-dominated site. The maximum potential landward displacement of the shoreline through inundation was estimated at about 80 m for the sites visited. However, settlements, roads and other structures in mangrove areas which lie below the projected ASLR scenario water-level elevations would be subject to flooding.

Coral reefs are unique in their ability to "grow" vertically under conditions of rising sea level. The rates of vertical growth for coral reefs with high coral/algal coverage can average 7 mm/yr which is adequate for them to keep pace with projected rates of sea-level rise (Buddemeir and Smith, 1988; Kinsey and Hopley, 1991). In other words, healthy reefs should be able to expand vertically with a rising sea level and perhaps extend their territory as substrates are submerged (assuming the rate of submergence is not too rapid or over very long time periods). Although increased turbidity could affect erosion of such deposits, we expect the reefs of Yap to respond favorably to a rise in sea level.

Because most of the Colonia shoreline is stabilized by some type of engineering structure, shoreline retreat due to erosion is inhibited or not strictly applicable. Therefore, simple inundation is the probable response.

Table 4. Estimated change in shoreline position (negative numbers indicate a landward shift) for the two ASLR scenarios based on inundation only (i.e., no erosion). These are the coastal sites which are dominated by mangroves. The zero value at site 13 is related to a vertical seawall in which no overtopping is predicted.

| Yap Main Islands | Inundation 0.3 m Rise (m) | Inundation 1.0 M Rise (m) |
|---|---|---|
| 9 / Thabeeth | -7 | -10 |
| 10 / Qoon | -4 | -75 |
| 11 / Taafmith | -1 | -10 |
| 12 / Kanif | -13 | -79 |
| 13 / Meqruur | 0 | -57 |

Twelve detailed coastal profiles were collected from the Colonia area and were used to determine the present mean sea-level position (the average MSL during the study period), the present level of the higher high tide level (HHTL), the projected spring high water levels at the 0.3 m and 1.0 m high sea-level positions (HHTL+0.3 and HHTL+1.00m respectively), and the high water level under an arbitrarily chosen storm surge of 2.0 m (HHTL+2.00m). With the exception of one profile site (site 4: reclaimed land west of the police station), the projected ASLR scenario water levels do not overtop existing structures (Table 5). At site 4, a portion of the reclaimed land would be submerged at +1.0 m sea level at high tide. It should be stressed that these water levels are "still water levels" and do not take into account any increased water levels due to the presence of waves, the passage of storms, or low-frequency variations in water level.

The freeboard (area above the high tide level) of existing structures under the +1.0 m sea-level scenario is very low (Figure 9), generally less than 1.0 m (Table 5). Because of the low freeboard, the effects of storms on coastal flooding and wave overtopping of structures will be dramatically increased at higher sea levels. Although most of the Colonia area appears to be above the projected +1 m stillwater MSL, the effects of storms on shore erosion and coastal flooding can be expected to increase significantly.

Table 5. Summary of profile elevation data for the Colonia area. The shoreline recession values are based on landward shift of shoreline position due to simple inundation of existing profiles under calm sea conditions.

| Colonia Profile | Elevation Range (m above Sea Level) | Freeboard at +1.0m ASL | Shoreline Recession (m) |
|---|---|---|---|
| 0 | 2.05 - | 0.50 | <1.0 |
| 1 | 2.0 - 2.9 | 0.40 | <1.0 |
| 2 | 2.3 - 2.95 | 0.75 | 2.5 |
| 3 | 1.75 - 2.25 | 0.20 | 2.0 |
| 4 | 1.4 - 1.5 | -0.15 | 32.0 |
| 5 | 3.0 - 3.7 | 0.45 | 4.0 |
| 6 | 1.65 - 1.8 | 0.15 | 1.5 |
| 7 | 2.3 - 2.5 | 0.80 | 4.0 |
| 8 | 1.9 | 0.40 | 1.5 |
| 9 | 1.7 - 1.8 | 0.20 | <1.0 |
| 10 | 2.4 - 2.6 | 0.90 | 1.0 |
| 11 | 3.4+ | 1.05+ | <1.0 |
| Range | 1.4 - 3.7 | -0.15 - 1.05 | <1 - 32 |

Figure 9. Local housing and shoreline structures in the inner harbor area at Colonia.

## ASSESSMENT OF NATURAL SYSTEM RESPONSES

There are many unknowns regarding the potential effects of accelerated sea-level rise on natural systems. Table 6 presents estimated maximum shoreline changes for mangrove and sandy shorelines in the main Yap Islands. These are considered maximum values because the maximum estimated recession value for each shoreline type was used, and no landward limits of recession due to the presence of bedrock, engineering structures, or coastal plain extent are applied. Under our current state of knowledge, these can be considered worst-case scenarios. Figure 10 shows the area of low-lying land (< 5 m) for the main Yap Islands.

The mangrove forests will, in all likelihood, expand landward under a rising sea level, therefore, even though the shoreline may recede the area of mangroves will increase assuming they do not erode on their seaward margins. The 15% and 91% estimated increase in mangrove forests (Table 6; ASLR scenario I and II, respectively) may be an overestimate by 50% or more primarily because there may not be low-lying land for the forests to advance over. In addition, it is not clear if mangrove forests can maintain their present seaward extent during rapid inundation. For example, it has been shown in the Bahamas under conditions of moderately rapid sea-level rise (>2.8 mm/yr), dieback and erosion of the seaward mangrove margin has occurred (Ellison, 1993). In discussing the wider Caribbean region, Parkinson et al. (1994) determined a critical sea-level rise threshold of 1.3 mm/yr where mangrove forests

Table 6. Estimated maximum amounts of areal change under the two different ASLR scenarios. Although the shoreline is expected to recede in mangrove areas, the actual size of mangrove forests is expected to increase (hence negative numbers for shoreline recession and positive numbers for areal change in mangroves). Shoreline recession along sand beaches is expected to result in a net land loss.

| | YAP MANGROVE SHORELINE | YAP SAND SHORELINE |
|---|---|---|
| Shoreline Distance (km) | 114 | 10.8 |
| Maximum Recession with 0.3 m Rise | -13 | -4 |
| Maximum Area Change ($km^2$) | +1.48 | -0.043 |
| Percent Change | +15% | -18% |
| Maximum Recession with 1.0 m Rise | -79 | -12 |
| Maximum Area Change ($km^2$) | +9.01 | -0.13 |
| Percent Change | +91% | -54% |

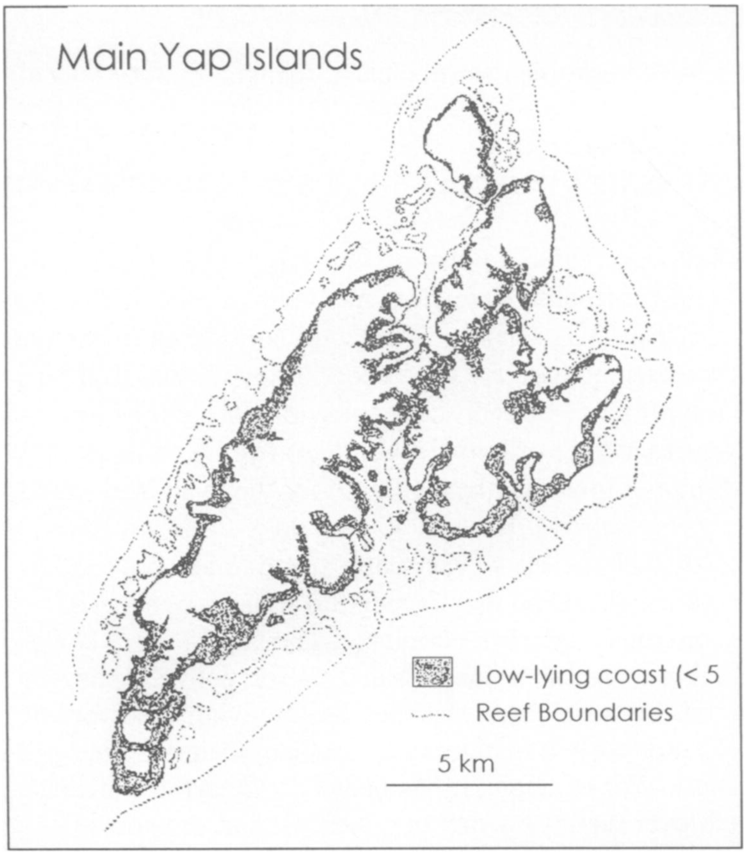


Figure 10. Map of the main Yap Islands showing the reef boundaries, shoreline, and land area less than 5 m above MSL (shaded area).

become unstable. However, field evidence of extensive mangrove retreat, such as stranded stumps, dieback, and scarp formation, was not observed in Yap during the course of this study. Until further research is conducted, it is not clear what the response of the Yap mangrove forests will be to ASLR (e.g., negligible dieback was assumed in the study).

The potential loss of sandy shoreline is a major concern because there is only a small amount present, and are the sites of many important coastal settlements. Local-based land reclamation and shoreline protection projects have been an ongoing activity within traditional Yapese settlements. Yapese houses are typically constructed on reclaimed land on the coast. Seawalls constructed of hand-fitted coral blocks collected from adjacent reefs are commonplace. The recessional values in Table 6 are the maximum beach (toe of beach to top of the beach ridge) values for the beach sites in Table 3. The beach values are used here instead of the reef flat values because it is unclear how the reef flats will respond to rising sea level, whereas the beaches are expected to erode according to the Bruun rule. The reef flats may aggrade vertically through increased carbonate production as substrates are submerged, increasing the area available for carbonate-producing organisms.

Recent tide gauge data from Colonia indicate a relative sea-level rise of 3 mm/yr from 1975 to 1995 (TOGA Sea-Level Center, University of Hawaii) which is higher than the Pacific basin average of approximately 1 mm/yr (Wyrtki, 1990). Some of this relative rise is probably due to tectonic subsidence of the main Yap Islands. Although caution should be exercised in extrapolating relatively short-term tide-gauge data to long-term tectonic trends because of potential errors caused by low-frequency sea-level variations, morphologic evidence on Yap, such as extensive shallow submerged reef flats, drowned valleys, and armored shorelines, is consistent with recent submergence.

The islets of Ulithi Atoll have the potential to be severely affected by ASLR because of their open exposure and low elevations (they are generally less than 5 m above sea level). Unlike the main Yap Islands or the high limestone island of Fais, there is no higher ground for relocation. However, because atoll islets are constructed primarily through the action of extreme events which deposit reef debris above "normal" tidal limits, an increase in storminess and/or an increase in carbonate productivity could lead to an increase in material available for islet building. If ASLR is below the rate at which reefs can sustain vertical growth, and it appears the IPCC scenarios are below this value, then it is possible that some atoll islets should be able to continue vertical accumulation. As discussed by Richmond (1992), atoll islets can be expected to show varying responses to ASLR depending upon their location within the atoll and geologic history. For example, islets formed at convex bends of the atoll reef rim are typically large with good soil development, have relatively stable shorelines, are the sites of the oldest and largest settlements, and importantly, derive their sediment from a number of directions and sources within the atoll. Islets at convex bends may be more stable under rising sea levels than other islets within the atoll system.

On Fais, the settlements are located on beach ridges which form the narrow coastal plain and are therefore subject to potential land loss under ASLR scenarios. Although there is higher land available for relocation, the uplifted limestone is a markedly different foundation than the present coastal plain sediment. It is possible, however, that reef expansion and subsequent coastal plain sedimentation and growth could continue under conditions of ASLR.

## CONCLUSIONS

There are three vulnerable areas that are considered priorities under ASLR scenarios:

1. Colonia lowlands. The largest and most important coastal infrastructure development in Yap State is in the greater Colonia area. Although much of the Colonia shoreline is bordered by engineering structures, many of those structures are barely above ASLR scenario still-water levels and are likely to incur damage through direct wave attack, undermining, and overtopping. A number of construction types of variable quality occur. If a particular section of poorly built seawall should fail, adjacent sections would be subject to considerable damage.
2. Coastal plains. The loss of low-lying coastal sand plains, which are typically fronted by sandy beaches, could have a dramatic effect on current settlement patterns on the main Yap Islands. Unprotected sand beaches are considered highly vulnerable to ASLR. Armoring of such shorelines is not recommended because it is costly and could lead to undesirable side-effects such as accelerated erosion of unprotected beaches.
3. Outer island atoll islets and reef islands. The low-lying landmasses of the outer islands are particularly susceptible to ASLR because there is no higher ground available for relocation. The potential effects on these types of islands has been described by Woodroffe and McLean (1992) and can summarized as follows: (a) Bruun rule response where sediment from the beach face is eroded and deposited offshore, in this case over the adjacent reef flat, resulting in an overall reduction in island size, (b) equilibrium response which is similar to the Bruun response except that some sediment is transported landward to the beach ridges maintaining a balance in islet size, (c) Continued growth through increased sediment production of adjacent reefs and deposition of that sediment onto the islets.

At present, it is not possible to quantify which of these responses is the most likely, but it is conceivable that each type of response can occur depending upon local conditions. It is proposed that Yap coastal mangrove forests will undergo little retreat and may actually expand their territory as low-lying land is inundated under rising sea level (assuming there will be little or no dieback along their seaward margins).

## ACKNOWLEDGMENTS

Funding for this project was provided by the USGS and NOAA. Stephen Anthony (USGS/WRD Honolulu) and Greg Ikehara (USGS/WRD Guam) provided information on the water resources and tides of Yap. John Sogalith, Chief of the Division of Planning in Colonia, was our primary contact during the survey. Numerous people assisted with data collection and provided background information, these include: John Waayan and Sebastian L. Anefal from the Office of Planning and Budget; Martin Falanug and John Kentun of the Weather Service Office; Moses Ngirmekur surveyor for Land Resources; John Iou and Barry Goldman from the Marine Resources Management Division of the Department of Resources and Development;

James Gilmar, Director of the Department of Resources and Development; James Sarmog from PUC; and Kenmed from the Pilung Council. Accommodations and support on Falalop, Ulithi Atoll were kindly provided by John Rulmal and family. The above are greatly appreciated for their support and assistance to the survey team.

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