SEA LEVEL RISE IMPACTS AND ADAPTATION IN YAP PROPER, FEDERATED STATES OF MICRONESIA

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By
Nadia Einfalt

Thesis Advisor

Dr. Charles Fletcher

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISOR

C. Fletcher

Dr. Charles Fletcher
Department of Earth Sciences

For my mother, Mary Alice Einfalt, my father, Peter Einfalt, and my sister, Erika Einfalt for the endless support and encouragement. Without you I would not have been able to get where I am today.

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ABSTRACT

Sea level rise (SLR) poses a significant threat to coastal communities, resulting in various impacts such as flooding, aquifer salinization, and coastal erosion. Small island nations, like Yap in the Federated States of Micronesia, are particularly vulnerable due to their low elevation, isolated geographic location, and above-average rates of sea-level rise. Yap, being one of the four member states in free association with the United States, faces heightened risks, yet lacks localized SLR data, making it a critical area for study. This research aims to address this gap by employing ArcGIS to model areas in Yap that will be inundated under one meter of SLR, providing valuable insights and potential place-based solutions. The choice of one meter as the benchmark aligns with the IPCC AR6 projection of a sea-level rise of 0.6 to 1.1 meters by 2100 under the high emissions scenario (Fox-Kemper et al., 2023). The results of this project reveal the exposure of Yap's infrastructure: four pieces of critical infrastructure, nine government or non-governmental organization facilities, 16 businesses, 29 cultural sites, and 248 buildings or other structures are projected to be inundated under one meter of SLR. Notably, the mapping results highlight Colonia as the most vulnerable area in Yap. Colonia serves as the primary center for governance and commerce for the entire state, emphasizing the urgency of understanding and addressing the potential impacts of SLR in this critical location. This research not only sheds light on the exposure of Yap but also underscores the importance of localized data for effective climate resilience planning and policy development in vulnerable coastal regions.

Keywords: Sea level rise, coastal flooding, erosion, saltwater intrusion, adaptation, Yap, FSM.

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LIST OF ABBREVIATIONS

Digital Elevation Model	DEM
Federated States of Micronesia	FSM
Geographic Information System	GIS
Greenhouse Gas	GHG
Intergovernmental Panel on Climate Change Sixth Assessment Report	IPCC AR6
Non-governmental Organization	NGO
Sea Level Rise	SLR
Saltwater Intrusion	SWI

1.0 INTRODUCTION

1.1 Sea level rise budget

Rising global temperatures, as a result of increased atmospheric greenhouse gas (GHG) concentrations, have led to rising sea levels (Fox-Kemper et al., 2023; Sweet, 2022). Global sea level rise (SLR) is primarily a product of three mechanisms (table 1). The first mechanism is thermal expansion, which is caused by the ocean absorbing atmospheric heat. The increased heat of the ocean causes the water column to expand, resulting in increased sea level heights (Sweet, 2022). From 1993-2018 thermal expansion was responsible for approximately 32.7 mm ± 8.9 mm of global mean SLR, which is 45.9% of the global mean sea level budget, making it one of the largest contributors to SLR (Fox-Kemper et al., 2023).

The second major mechanism contributing to SLR is the addition of water mass from melting continental ice sheets and glaciers. Ice sheet and glacial melt are caused by warmer ocean and atmospheric temperatures (Sweet, 2022). From 1993 to 2019 glaciers lost an average mass of 6200 Gt ± 1600 Gt contributing 17.1 mm ± 4.4 mm to global mean SLR, which is approximately 19.4% of the global mean SLR budget (Fox-Kemper et al., 2023). During the period from 2010-2019, glacier mass was the smallest it has been since the beginning of the 20th century (Fox-Kemper et al., 2023). The Greenland ice sheet is another major contributor of water mass to the ocean and its rate of melting has quadrupled since 2010 (King et al., 2020). Based on the NASA GRACE missions, we know that the Greenland Ice Sheet lost 4890 Gt of mass from 1992-2020 and contributed 13.5 mm ± 2.1 mm to global mean SLR, which is approximately 15.2% of the global mean SLR budget (Fox-Kemper et al., 2023). Extreme ice melt has driven the Greenland ice sheet into a state of constant loss where ice discharge is exceeding snow accumulation. Ice sheet melt will continue to occur even if climate change slows due to their lagged response to warming (Fox-Kemper et al., 2023). The Antarctic ice sheet also contributes significantly to SLR. Excess heat in the Southern Ocean has caused Antarctic melting to triple since 2010 (IMBIE team, 2018). Based on the same satellite data, we know the Antarctic Ice Sheet lost 2670 Gt of mass from 1992-2020 contributing 7.4 mm ± 2.4 mm to global mean SLR, approximately 8.6% of the global SLR budget (Fox-Kemper et al., 2023). From 1993-2018, ice sheet and glacial melt were responsible for contributing 1.23 mm yr^{-1} ± 0.19 mm to global sea levels, which could result in multimeter SLR this century (Fox-Kemper et al., 2023). The Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) projects that a global average temperature increase of 2ºC - 3ºC above preindustrial levels (years 1880-1900) will result in the almost complete loss of the Greenland and West Antarctic ice sheets over the span of millennia, contributing significantly to ongoing sea level rise (Calvin, 2023).

The third major factor contributing to SLR is anthropogenic mining and extraction of groundwater. This process, known as groundwater depletion, occurs mainly as a result of irrigation for agriculture and urban use. A large portion of mined groundwater ultimately ends up in the ocean, as a result, large and persistent groundwater depletion is a major source of water transfer from land to sea (Konikow, 2011; Pokhrel et al., 2012). Studies over the past decade indicate that the rate of groundwater depletion has more than doubled in the past 50 years (Konikow, 2011; Wada et al., 2012). This shows a dramatic increase in water demand. Groundwater depletion in the twentieth century has contributed to global SLR at a rate of 0.57 mm yr^{-1} ± 0.09 mm yr^{-1} (Caretta et al., 2023). With the increasing rate of groundwater depletion, it is estimated that in 2050 the contribution of groundwater to SLR will be 0.82 ± 0.13 mm yr^{-1}, which is about 0.78 mm yr^{-1} more than in 1900 (Caretta et al., 2023; Wada et al., 2012).

Table 1. Primary contributing mechanisms to global mean SLR from 1993-2018. Adapted from table 9.5 in Fox-Kemper et al., 2023.

Drivers of Global Mean SLR	Mass loss rate per year (mm)	Total change (mm)	Contribution to Global mean SLR
Thermal Expansion	1.31 ± 0.35	32.7 ± 8.9	45.90%
Glaciers	0.55 ± 0.15	13.8 ± 3.8	19.40%
Greenland Ice Sheet	0.43 ± 0.08	10.8 ± 1.9	15.20%
Land-water storage	0.31 ± 0.18	7.8 ± 4.4	10.90%
Antarctic Ice Sheet	0.25 ± 0.09	6.1 ± 2.3	8.60%
Total observed contributions	2.85 ± 0.44	71.2 ± 11.1	100.00%

1.2 Sea Level Rise Impacts

The IPCC AR6 states with high confidence that sea levels will continue to rise for centuries due to continuing deep-ocean thermal expansion and ice sheet melt and they will continue to remain elevated for thousands of years (Fox-Kemper et al., 2023). The NOAA 2022 Sea Level Rise Technical Report has outlined a set of global mean SLR rise scenarios spanning a range from a low scenario, consistent with no additional global mean SLR acceleration, to a worst-case, or high scenario, which represents the physically plausible limits of SLR based on the scientific literature (Sweet, 2022). Under the intermediate-high to high scenarios (Sweet, 2022), global sea level could rise 2.7 to 3.7 m by 2150. Even scenarios that include strategies for reducing GHG emissions, such as the intermediate scenario, lead to multimeter SLR by 2150 (Sweet, 2022). Furthermore, by 2100, extreme sea level events that would ordinarily occur once every hundred years will occur annually in some parts of the world. Increased sea levels lead to more frequent and severe instances of saltwater intrusion (SWI), coastal erosion, and coastal flooding. This results in damage to coastal ecosystems, people, and infrastructure.

A common impact of SLR is SWI. Due to higher sea levels, saltwater is able to rise vertically through coastal aquifers leading to salinization (Habel et al., In-Press). SWI can impact coastal communities through aquifer salinization. This occurs when coastal aquifers are contaminated with saltwater. This process leads to aquifers being abandoned because they are no longer viable for consumption or agricultural uses. SWI will continue to increase with increasing SLR (Storlazzi, 2018). SWI is only one of the many impacts that communities will face as a result of increasing SLR.

Another common impact of SLR is increased coastal erosion. The IPCC AR6 states with high confidence that relative SLR leads to increases in the frequency and severity of coastal erosion (Fox-Kemper et al., 2023). This is especially true for sandy coasts. Coastal erosion affects coastal communities through the loss of agricultural lands, damage to the coastal built environment, damage to critical infrastructure, economic losses, and loss of recreational lands. Additionally, coastal flooding is a significant concern associated with SLR, exposing communities to challenges such as increased salinity in freshwater resources, disruptions to transportation and utilities, threats to public health, and heightened risks for storm surge impacts.

Coastal flooding is the inundation of coastal land by seawater. There are several types of coastal flooding. Storm surges and high tides are two of the primary causes of coastal flooding (Doornkamp, 1998). Storm surge is one of the most dangerous types of coastal flooding and occurs when strong winds and waves from a storm push seawater inland, causing a rapid rise in sea level (Von Storch & Woth, 2008). The low atmospheric pressure associated with these storms can further exacerbate the surge. Storm surge and the associated storm set-up can lead to significant and widespread coastal flooding, posing a severe threat to coastal lives and infrastructure in communities (Von Storch & Woth, 2008). High tides, also known as tidal flooding or king tides, occur when the gravitational forces of the moon and the sun cause the ocean's water levels to rise higher than usual (Thompson et al., 2021). During certain periods of the month or year, these higher-than-normal tides can coincide with other weather events, exacerbating the flooding (Thompson et al., 2021).

The impacts on communities resulting from SWI, coastal erosion, and coastal flooding will vary in severity and timing across different locations. However, it is evident that smaller island nations, like those in the South Pacific, will experience swifter and more severe consequences, highlighting the urgency of understanding adaptation pathways that are relevant to these regions. Therefore it is critical to characterize how these impacts will affect those communities, allowing for a comprehensive identification of locally relevant adaptation needs.

1.3 Sea Level Rise Projections

One part of charcterizing how SLR will effect a community is identifying what height sea levels might reach. There are several different ways at predicting future sea level, one of which is through the

1.3 Yap

The Federated States of Micronesia (FSM) is made up of four member states, Yap, Chuuk, Pohnpei, and Kosrae, which are composed of 607 islands spanning 2,900 km across the Pacific Ocean (Figure 1). Although the islands in the FSM are linked politically, they all possess unique landscapes, livelihoods, cultures, and traditions. After a turbulent history of Spanish, German, Japanese, and American colonization, the FSM adopted its own constitution becoming an independent country on May 10th, 1979. In 1986 the FSM entered a Compact of Free Association with the United States. The Compact of Free Association specifies that the United States will provide the FSM with financial support, military defense, special immigration status, and other services. In return the United States has exclusive rights in the region, including access to land and waterways for strategic purposes (GFSM, 2016).

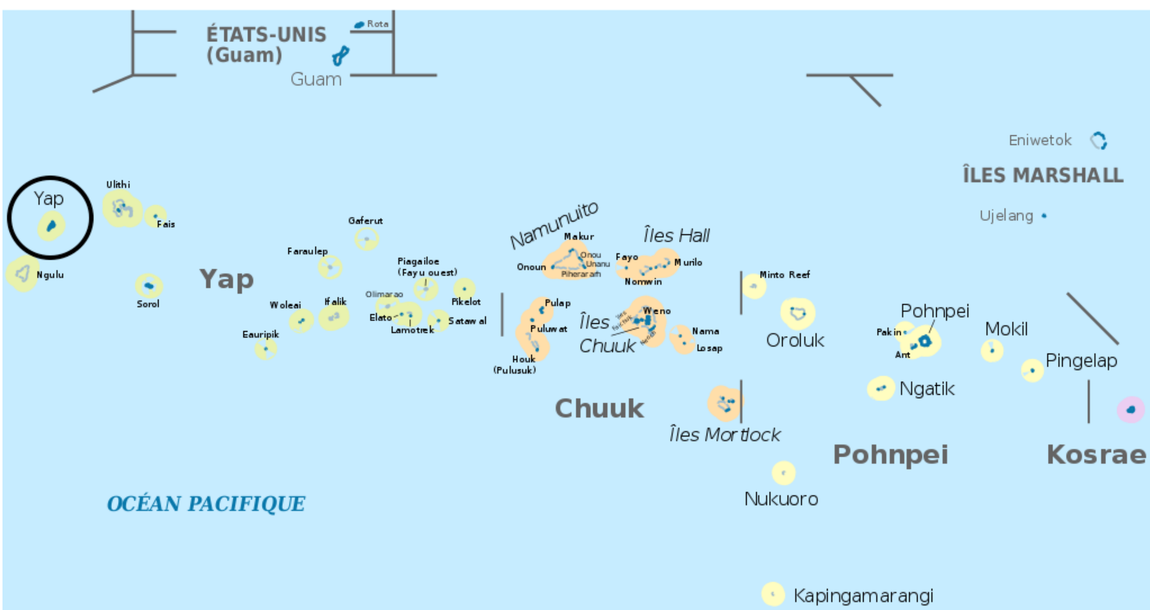

Figure 1. Map of the Federated States of Micronesia with Yap proper circled (Adapted from Skimel, n.d).

Yap is the Northwesternmost State in the FSM (Figure 2). Yap is composed of 135 islands, of which 22 are inhabited. Of the inhabited islands, the four conjoined high islands, Yap (Marabaaq), Gagil-Tomil, Maap, and Rumung, are known as the Main Island, Yap proper, or Wa‘ab. The other 18 inhabited atolls are known as the Outer Islands (GFSM, 2016). Yap's islands are spread throughout the North Western Pacific over an area of about 1000 km. The state's total land area is 128.7 km^2, which is characterized by gentle slopes, swampy lowlands, mangrove forests, and sandy beaches. (Richmond et al., 1997). Yap proper, excluding the reef area, is approximately 98.4 km^2 and has a maximum elevation of 175 m (GFSM, 2016). The population of the entire state is 11,377 people with over half of the population living in Yap proper (Perkins & Krause, 2018).

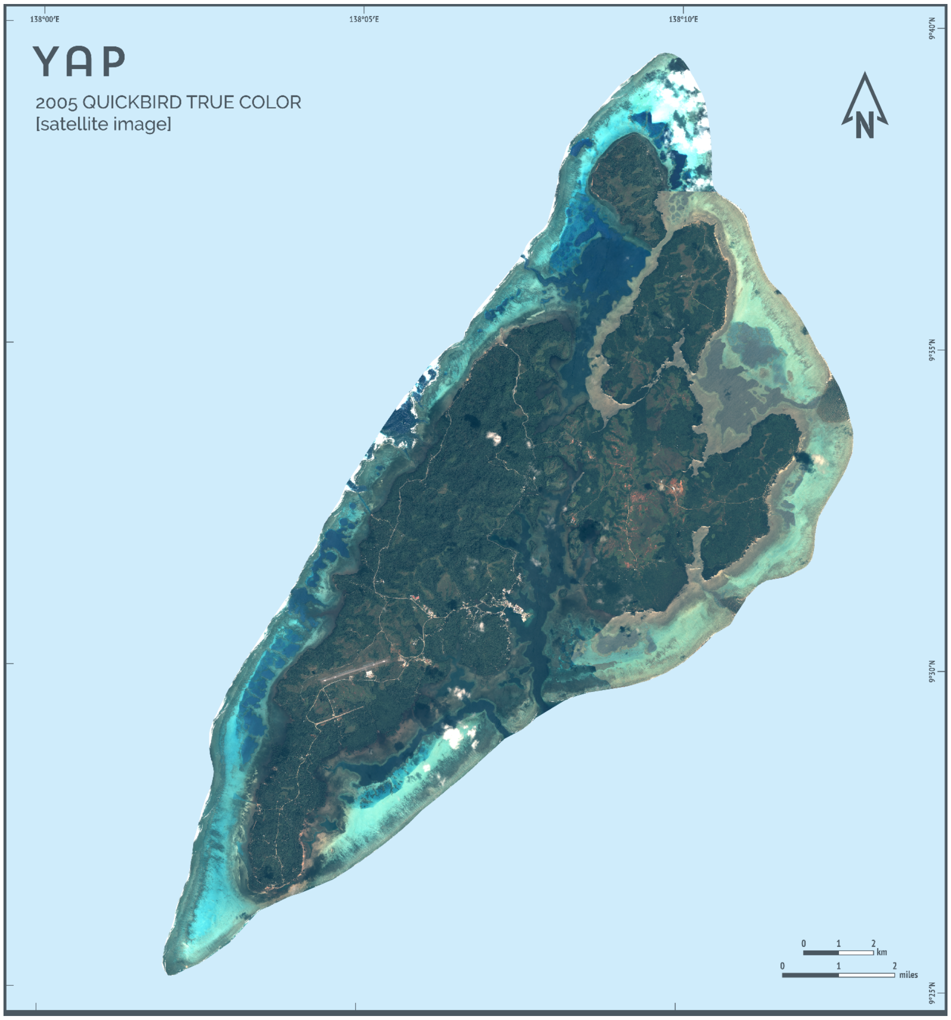

Figure 2. Map of Yap proper

Settlement in Yap is thought to have occurred more than 2,000 years ago. Unlike the rest of the FSM, Yap is said to have been settled by people from varied areas, possibly from the west and south (Throop, 2010). The population of Yap now mainly consists of two distinct indigenous groups. The majority of people in Yap proper are culturally 'Yapese', and the majority of people on the Outer Islands are culturally 'Carolinian' having come mostly from the Caroline Islands (Perkins & Krause, 2018). Languages spoken in the state include Yapese, English, Ulithian, Woleaian, and Chuukese. Yapese is the most spoken language in the state with more than 95% of the population reporting it as their first language (Throop, 2010).

Life in Yap is dominated by subsistence activities where the community provides all or most of their goods with little surplus. These activities include subsistence farming, home production, hunting, and fishing (GFSM, 2016). Female residents contribute heavily to subsistence agricultural responsibilities. 62% of crop workers and 55% of livestock workers in Yap are female (Federated States of Micronesia Integrated Agriculture Census, 2016). Subsistence hunting and fishing are responsible for the majority of the protein in Yapese diets. Approximately 61% of households in Yap fish, (1,378 households), and 40% of households hunt (912 households) (Federated States of Micronesia Integrated Agriculture Census, 2016). Government positions, private sector and service industry jobs, and agriculture activities are the main sources of income in Yap. Unlike other islands in the FSM, remittances make up less than one percent of the average household income (GFSM, 2016). Subsistence agriculture accounts for 30% of average household income, due to Yap's successful agroforestry system (GFSM, 2016).

As a community dependent on agriculture, the weather is very important to life in Yap. The weather in Yap is influenced heavily by the El Niño Southern Oscillation cycle. El Niño years in Yap can consist of severe localized droughts and La Niña years are typically characterized by chronic flooding, frequent and strong tropical cyclones, and increased sea-level height (Filho, 2017). The average annual rainfall in Yap is three meters, most of which occurs during the rainy season from July- October. During the dry season, February to April, Yap receives an average of 17 cm. The temperature does not fluctuate greatly throughout the year. Spring and summer months have an average temperature of 27ºC and fall and winter months have an average temperature of 80ºF.

1.4 Challenges to Yap

Small island communities, such as those in Yap, are disproportionately affected by climate change. Small island nations emit only about 0.2% of global emissions yet experience some of the worst effects associated with climate change (United Nations President of the General Assembly's High-Level Panel, 2023). This exposes small island communities in profound ways, such as through the deterioration of basic human rights. Basic human rights encompass a range of necessities, from food and economic security to the preservation of cultural practices. These rights are outlined in the United Nations Universal Declaration of Human Rights and the United Nations Declaration on the Rights of Indigenous Peoples (UN General Assembly, 1948; UN General Assembly, 2007). The effects of SLR threaten these basic human rights. SLR in Yap threatens fundamental human rights, including food security, economic security, and cultural preservation. These risks arise from various factors, such as coastal erosion, flooding, and SWI. Despite these inevitabilities, SLR has not been comprehensively measured in Yap, leaving the island's essential assets and its way of life potentially exposed to the impacts of SLR.

1.4.1 Food Security

SLR is already affecting life in Yap in many ways, one of which is decreased food security. Food security is the ability of an individual, household, or community to have physical and economic access to sufficient, safe, and nutritious food to a degree that meets dietary needs and preferences to maintain a healthy life (FAO, 2001). The right to food security is outlined in Article 25 of the United Nations Declaration of Rights when it states "Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food" (UN General Assembly, 1948). Maintaining food security in Yap is accomplished through a combination of subsistence agriculture and imports. The FSM imports about 10 times as many goods as it exports and food makes up a significant portion of these imports (GFSM, 2016). Agricultural lands account for about 47% of the state's total land area (Figure 3) (Federated States of Micronesia Integrated Agriculture Census, 2016). One of the primary means of subsistence agriculture in Yap is agroforestry. Yap's extensive agroforestry systems are the most developed food production systems throughout the high islands in the FSM. The people of Yap have created these systems through the combination of traditional knowledge and modern science that uses a watershed-based approach (Falanruw, et al., 1987). This approach maintains high biodiversity through a three-level system. The first level consists of food trees, such as coconut and breadfruit, and non-food trees. The second level consists of taro patches that are found in low-elevation areas connected to water sources. The third level of the agroforest is made up of yams and other crops. The agroforest systems are intentionally created to be self-sustaining and extremely resilient. The first level of the system acts as a canopy and nutrient source for the lower layers, which limits erosion during heavy rains and maintains soil health. Ditches are dug in the ground layer of the system to promote water flow and drainage (Falanruw, et al., 1987). In addition to the agroforestry systems, people in Yap also grow bananas, citrus, peppers, and papaya (Federated States of Micronesia Integrated Agriculture Census, 2016). Although Yap's agricultural sector is robust and resilient, it is not immune to the impacts of SLR.

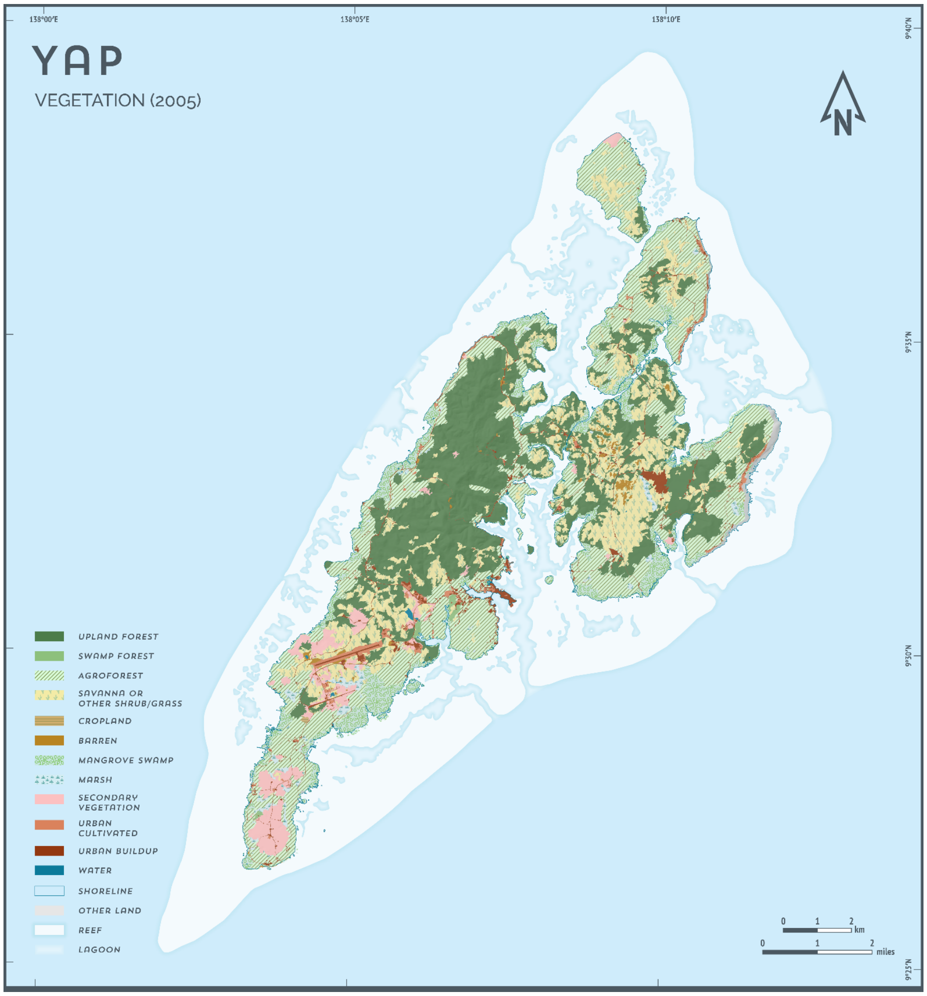

Figure 3. Map depicting vegetation in Yap, including agricultural lands such as cropland and agroforests.

SLR can affect a communities' food security in many ways. One way in which SLR will affect food security in Yap will be through coastal erosion. Coastal erosion is a naturally occurring process where ocean waves hitting the coast break down and carry away coastal sediment. The process is exacerbated by accelerated SLR, causing increased erosion rates on shorelines (Fox-Kemper et al., 2023). Coastal erosion affects food security through decreased land area for agricultural activities and damage to coastal assets on which food security relies. Most of Yap proper's agroforests are situated half a kilometer away from the coastline, which makes them particularly vulnerable to the impacts of coastal erosion. These agroforests are at risk of losing land and being damaged due to increased erosion rates. Additionally, coastal erosion can damage the coastal built environment that supports food security. There are ports and markets in Yap proper that are located on or near the coastline. These assets support food security on the island by providing access to import, buy, and sell food supplies. If these assets are damaged through coastal erosion, then the ability of residents to have access to food will be impacted leading to decreased food security. The threat of SLR becomes a concern for food security as it leads to increased coastal erosion rates, affecting both agricultural land and coastal assets crucial for accessing food.

Another effect of SLR that decreases food security is SWI. SWI occurs when ocean waters rise vertically and infiltrate freshwater aquifers or wells (Habel et al., 2024). This effect has already been documented in Yap. According to a 2016 study led by the FSM Department of Resource and Development, 20% of the households in Yap that have agricultural land have experienced damages resulting from SWI. This is the highest percentage in the FSM (Agricultural census, 2016). One crop in Yap that is specifically affected by this is taro. Taro in Yap is grown on coastal plains where the water needed to farm it has become increasingly saline. This has led to a decrease in taro corm yields, which are a staple of the Yapese diet (Nunn et al., 2017). SWI has also affected Yap's supply of fresh water. When saltwater infiltrates a freshwater aqquifer it can lead to the contamination of water used for consumption and agriculture. This has already been experienced in Yap proper in the Tamil community where saltwater has infiltrated freshwater resources (Mcleod et al., 2019). This impact is particularly threatening during El Niño years, when freshwater supplies are fragile. During the 2015-2016 El Niño, a state of emergency was declared in the FSM due to extreme water shortages. Because of the severity of the 2015-2016 droughts, the implementation of water conservation measures were required (January 2016 Drought Report, 2016). SWI puts additional pressure on Yap's already fragile water supply. Due to SWI's effects on arable land and freshwater resources, food security in Yap is negatively impacted.

Coastal flooding is another effect of SLR that will impact food security in Yap. Yap is prone to flooding during typhoon season and during La Niña years. As the sea-level rises around the Yap, coastal flooding will become more frequent and severe. This will have several consequences for food security. One effect that flooding has on food security is the damage or loss of arable land. If coastal agricultural lands are frequently flooded due to higher sea levels, crops will be damaged and the land will no longer be able to support agriculture. This has already been experienced in Yap. In 2016, 116 households reported flood damage on land used for agriculture (Agricultural census, 2016). This damage leads to decreased crop yields and therefore decreased food security. Flooding will also cause decreased food security through the damage of ports and docks on the island. Yap heavily relies on the importation of food. The docks and ports in Yap are located in low-lying coastal areas, which make them highly susceptible to flooding. As the frequency and intensity of flooding increases, the ports and docks on the island will be continually impacted by flood damage. When coastal flooding becomes so severe that the ports and docks are permanently inundated by seawater, then they will be inoperable. Cutting off the ability to import food to Yap will affect food security. This combined with crop losses, as a result of coastal flooding, will have dramatic effects to food security in Yap.

1.4.2 Economic Security

The loss of economic opportunities caused by SLR will pose a threat to Yap's economic security. Economic security is the ability of an individual, household, or community to access basic needs pertaining to health, education, housing, livelihoods, and social protection sustainably and with dignity (Economic Security Strategy, 2020) . Economic security is a human right outlined in the United Nations Declaration on the Rights of Indigenous Peoples in which it states “Indigenous peoples have the right to maintain and develop their economic systems or institutions, to be secure in the enjoyment of their own means of subsistence and development, and to engage freely in all their traditional and other economic activities” (UN General Assembly, 2007). SLR will impact economic security through coastal erosion, saltwater inundation, and coastal flooding.

Increasing rates of coastal erosion will degrade coastal land. This will lead to damage to businesses and supporting infrastructure that are located on the coast. This is relevant to Yap because Yap’s main center of commerce, known as the Colonia lowlands, is located in a low-lying coastal area. Businesses in Colonia are located directly on or near to the coastline. This makes them highly exposed to coastal erosion. As coastal erosion rates increase, coastal businesses will be damaged, which will impact the economic security of Yap.

Economic security will also be impacted by SWI. As previously mentioned, SWI will damage agricultural lands and salinize the soil, affecting crop yields. This impacts food security and will have significant implications for economic security as well. In Yap, there are a handful of crops that contribute to the islands' economy. These crops include copra, betel nut, bananas, coconuts, and taro (Yap Islands, 2015). Damage to these crops as a result of SWI directly affects the economy. SWI will also affect the coastal built environment. SWI can lead to the contamination of freshwater supplies that support coastal businesses and communities, and the degradation of built structures and buried infrastructure that are exposed to regular inundation. These impacts further compromise economic security by hindering the operability of coastal businesses. SWI adversely affects economic security by reducing crop yields, and compromising coastal businesses, ultimately contributing to a decline in overall economic security.

Coastal flooding will also impact the economic security of Yap. Similar to SWI, coastal flooding will damage coastal agricultural lands and the built coastal environment. This will lead to decreases in crop yields and the inability to maintain functioning businesses, which will negatively affect economic sustainability and growth. These damages can already be seen during typhoon events. Destructive typhoons hit Yap In 2002, 2003, 2004, and 2013, resulting in severe flooding that caused the destruction of nearly all croplands in low-lying areas, and flood damage to public utilities, commercial properties, and almost all homes located in low-lying coastal areas (GFSM, 2016). Because of this, many businesses were not able to operate and farmers had no goods to sell. This is a significant example of how coastal flooding can impact economic security. Additionally, coastal flooding will impact the communities' ability to export goods. When sea levels rise to a point where the ports and docks on the island become permanently flooded or flood at a rate that is too frequent to maintain repairs, then the ability to export goods will be disrupted. Yap currently exports fish, handcrafts, copra, betel nut, bananas, coconuts, and taro (Yap Islands, 2015). If the ports and docks are inoperable, these goods cannot be exported. This would constrain economic activity in Yap thus impacting economic security. The combined effects of decreased crop yields, impaired business functionality, and damages to the built environment, as a result of coastal flooding, significantly impact economic security in Yap.

1.4.3 Right to practice culture

Like many other indigenous peoples, the people of Yap have strong ties to their culture. The lifestyle of Yap is built largely on traditions and culture, but their ability to practice and maintain this is being impacted by SLR. The ability to maintain culture and tradition is a right outlined in the United Nations Declaration on the Rights of Indigenous Peoples, which states "Indigenous peoples have the right to manifest, practice, develop and teach their spiritual and religious traditions, customs and ceremonies; the right to maintain, protect, and have access in privacy to their religious and cultural sites; the right to the use and control of their ceremonial objects; and the right to the repatriation of their human remains" (UN General Assembly, 2007). However, this basic human right is at risk due to increasing rates of coastal erosion and flooding as a result of higher sea levels.

Around the coast of Yap close to the shoreline are stone platforms, known as chabog, that are the base for traditional men's houses, known as faluw (Figure 4). Faluw are located in each village and are used as a meeting place for the men of the community, and to greet visitors (Nunn et al., 2017). A key characteristic of faluw is that they are able to be easily spotted so they are visible to approaching visitors and so the men in the faluw can easily spot boats approaching their community. Because of this, they are located in unprotected coastal areas that are susceptible to erosion (Nunn et al., 2017). These structures have been affected by SLR impacts.

Faluw in the communities of Bechyal, Man'gil', Leang, and Riy faluw have been rebuilt several times after being continuously damaged by coastal erosion (Nunn et al., 2017). Faluw have also experienced coastal flooding. There is a faluw located on Rumung whose access path is submerged during every high tide, making it exceedingly difficult to reach (Nunn et al., 2017). Additionally, members of the community have stated that many faluw located on the eastern coasts of Yap are being regularly impacted by coastal flooding. Community members have also stated that they have noticed the issues surrounding coastal erosion and coastal flooding have become more frequent and severe in recent years, which exemplifies the connection between these problems and increasing rates of SLR (Nunn et al., 2017). Even chabogs that have been recently rebuilt higher to withstand coastal flooding have started to become inundated during high spring tides, which shows the difficulty in keeping up with rising water levels (Nunn et al., 2017). In response to this, some faluw have been rebuilt in locations further back from the coast, which is atypical of the culture's tradition. These houses are seen as less significant culturally. The functionality of faluw is being threatened by SLR, thus impacting the Yapese ability to practice and maintain their culture.

Figure 4. Traditional men's house (faluw) with stone platform (chabog) (from Joyce McClure/Flickr).

Another piece of Yapese culture that is being threatened by SLR is the Yapese traditional stone money or rai (Figure 5). Rai are stone disks that vary in size and can measure anywhere from 20 centimeters to over a meter in diameter, with the larger ones occasionally weighing over a ton (Gillilland, 1975). Historically rai were one of the most valuable forms of currency in Yap. Before European contact, limestone was mined and shaped with hand tools from caves in Palau to create rai. The rai were then transported 400 kilometers to Yap via canoe (Fitzpatrick, 2004). The rai were used as a form of payment, typically for tools, canoes, pigs, feasts, dances, or other important goods and services. The value of rai is unlike Western currency systems because the value of each rai is very nuanced (Fitzpatrick, 2004). For example, the value of the rai could depend on the difficulty of its journey to Yap or the social position of the buyer and the receiver.

Rai are still held as significant to the communities, even after other forms of currency have been introduced. During World War I and World War II, many rai were destroyed when they were smashed to be used as anchors, defense walls, airstrips, seawalls, or piers. Now less than half of the original amount of rai remains in Yap. Rai have also been damaged or lost due to natural causes.

Figure 5. Traditional rai stone money (from John Stevenson)

Rai, specifically those that are bigger or hold significant value, are found outside of faluw. Because of this they are located near the coastline and are exposed to the elements. It has been recorded that rai have been lost to typhoons and floods (Gillilland, 1975). With increasing rates of SLR these instances could occur more frequently and with more severity. Furthermore, as sea levels rise to the point where coastal lands become permanently flooded, it will become increasingly challenging to access rai located along the coast. Additionally, rai, which are made out of limestone, will face a constant threat of exposure to saltwater, which may lead to corrosion and disolution.

Beyond the threat to cultural artifacts like rai, the Yapese connection to the land is under threat from SLR. Yapese culture relies heavily on the relationship between the people and the land. Many Yapese have strong place-based identities, which are impacted when land is lost or damaged because of SLR. One example of the Yapese culture being tied to the land is the socio-political system of Yap. The status of a village, estate, or specific member of a family is tied to ancestral landed estates (Perkins & Krause, 2018). These estates are called tabinaw and they define many cultural, social, and political protocols, including resource management and others (Perkins & Krause, 2018). If a family's lands are damaged or destroyed as a result of coastal erosion, SWI, or coastal flooding, then they may be forced to relocate. However, because social, political, and cultural statuses are determined by a person's ancestral lands, relocating will not be simple. This could create conflict, tension, or displaced groups of people. Additionally, SLR poses a threat to culturally significant land on Yap due to the presence of gravesites and burial grounds where family members and culturally significant individuals have been interred. Several of these sites are located close to the coast and are therefore vulnerable to coastal erosion and coastal flooding. Coastal erosion and flooding affecting gravesites and burial sites may result in the loss of these resting places.

1.5 Lack of Localized Data

One of the barriers that many Pacific Islands, including Yap, face is the lack of localized climate change and SLR data. Localized data that includes the natural processes occurring in the region are integral to formulating an accurate understanding of current climate and sea level conditions. One major data gap is the lack of local climate modeling. The most widely recognized and used climate models are produced in the developed world and show global-scale climate projections (Barnett & Campbell, 2010). Because of this, there is a shortage of local scale models showing rain, storm, wind, evapotranspiration, surface temperature, and ENSO patterns for the Pacific Islands. Although global-scale models can be downscaled to a local level, these downscaled versions do not have the same accuracy or reliability as models developed at a smaller scale. Because of this it is crucial to have climate change and SLR data that is developed at a granular view to ensure an accurate understanding of local conditions.

Another data gap is in elevation data. This form of data is created by mapping topographic and bathymetric features, which are then processed to create digital elevation models (DEMs). A DEM shows the bare earth topography excluding any surface objects. DEMs can be used to create inundation models, which identify areas vulnerable to coastal flooding due to their lower elevation and exposure to the coastline. LiDAR is one technology used to obtain accurate and precise topographic and bathymetric data. Unfortunately, these technologies are not widely available in the Pacific Islands and therefore it is not common for Pacific Islands to have access to accurate and precise elevation data. For example, there is only one publicly available DEM for Yap proper. This DEM was created by the U.S. Geological Survey based on topography compiled in 1969 and is a coarse resolution with significant errors, specifically in areas of dense vegetation. The main drawback of using coarse elevation data is its potential to reduce the accuracy of any model in which it is used.

In the Pacific Islands, another significant data gap pertains to coastal erosion information. Given the increasing coastal erosion rates due to rising sea level, it is crucial to gain insights into which areas on each island are most affected by erosion, especially areas containing critical assets and infrastructure. Shoreline change and erosion rates can be obtained by using models informed by high-resolution GPS surveying, drone imagery, and satellite shoreline detection using Artificial Intelligence. This type of data is already being used in some areas of the Pacific to create more relevant coastal construction regulations and land use policies. Some examples of this are the Kaua'i County SLR constraint district, Maui County coastal setback, City and County of Honolulu's new coastal construction setbacks, Honolulu 2018 Mayoral Decree (18-2) to avoid the 3.2 SLR-XA in capital improvement projects and other public investments, a statewide law requiring disclosure of any property sale located within the 3.2 SLR-XA, a statewide requirement that environmental review must evaluate SLR impacts, and a statewide ban on shoreline structures or development that interferes with natural sandy beach processes. If other Pacific Islands, like Yap, also had access to coastal erosion data they could use it to inform coastal development projects and ensure new assets are not being built in areas vulnerable to coastal erosion. Coastal erosion data would also help communities understand what existing assets are threatened, leading to more informed adaptation plans.

Without comprehensive localized climate change and SLR data publicly accessible, it will be challenging for Pacific Island communities to fully evaluate the unique problems that their communities are facing and will face in the future. This makes it difficult to proactively address impacts and formulate strategic solutions to have the most economically and environmentally sound results. Because of this, many Pacific Islands, like Yap, are forced to create climate adaptation plans that are not informed by the level of data needed for them to be thorough.

2.0 METHODS

2.1 Research Approach

The goal of this project is to better understand how SLR will impact Yap proper through the use of geospatial modeling. This goal was achieved using ArcGIS, a geographic information system (GIS) software developed by ESRI. ArcGIS is a powerful tool used for mapping, spatial analysis, and decision-making that allows users to manage, manipulate, and display geographical information, making it the ideal tool for this project. Within the ArcGIS platform, I developed a hydrostatic flood model, also known as a bathtub flood model, of Yap proper using one meter of flooding to represent future SLR. A hydrostatic flood model represents all areas below a user-specified elevation as being flooded (Williams & Lück-Vogel, 2020). This is a very common GIS method used to explore coastal inundation processes because the only required input is an accurate DEM. In order to visualize what assets may be affected by SLR, GIS layers that included critical infrastructure, government and non-government organization facilities, businesses, cultural sites, and other buildings and structures in Yap proper were added to the map. This allows users to see what assets are located within the flooded zones and therefore could be impacted by SLR. Due to its high accessibility and minimal data requirements, this methodology was the most suitable choice for this project.

2.2 Data Sources

Given that the only input for a hydrostatic flood model is an accurate DEM, the acquisition and utilization of the best available elevation data for the region was crucial. This DEM was acquired from VRICON and was created using commercial satellite data from 2015-2018. The horizontal datum used for the DEM was WGS84 G1674 and the vertical data was EGM2008. It has a 0.5 m resolution and a absolute accuracy of three m and a relative accuracy of 1 m. The GIS layers that were added to the model were collected from the Digital Atlas of Micronesia. The Digital Atlas of Micronesia is a web-based platform and the leading source of geospatial data for the Federated States of Micronesia. From this platform, I was able to download shapefiles of roads, critical infrastructure, government and non-government organization facilities, businesses, cultural sites, and other buildings and structures in Yap proper. The road data, critical infrastructure data, houses and other buildings data, and major businesses data were created by the Island Research & Education Initiative in 2019 based on 2016 WorldView-3 satellite imagery by Digital Globe provided by U.S. Department of Agriculture - Natural Resources Conservation Service (Mohammed, n.d.).   The cultural sites data was created by the Island Research & Education Initiative in 2019 by combining data layers created by the Queen's University of Charlotte, Yap Historic Preservation Office, and Yap Traditional Owners based on fieldwork conducted in 2002 and 2003 in addition to on-screen digitizing of 1983 USGS topographic maps (Mohammed, n.d.). These layers are recognized as the best available data for the study area at this time.

2.3 Data Processing and Analysis

For the data analysis, the central focus was interpreting the outcomes generated by the hydrostatic flood model. The primary objective of this was to gain insight into the potential impacts of SLR in the study area, Yap proper. To achieve this, I examined the model’s inundation zone output, which represented areas susceptible to inundation under varying SLR scenarios. The first step in this process was addressing redundancy within the asset layers. When analyzing the data I found that there was overlap between the 'building and other structures' layer and other layers. To rectify this redundancy, I manually deleted any duplicate points from the ‘buildings and other structures’' layer to ensure they existed only in a single layer. After the data processing was complete, an analysis to quantify and classify the assets within the inundation zone took place. To achieve this, the inundation raster was converted into a polygon feature, followed by a spatial query operation that selected assets exclusively located within the confines of the inundation zone polygon. The selected assets were then saved as a new shapefile. Then, by examining the attribute table of the new shapefile, I was able to get a comprehensive view of the assets that were located within the inundation zone. With these results, I created graphical representations of the data.

3.0 RESULTS

The results in this section provide a comprehensive assessment of the impacts of one meter of SLR on Yap proper. The results are broken down into sections by type of inundated asset, including roads, critical infrastructure, cultural sites, businesses, government or non-governmental organization buildings, and buildings and other structures (Figure 6) (Figure 7). Together, these findings bring attention to challenges faced by the Yap's communities as they navigate the impacts of SLR.

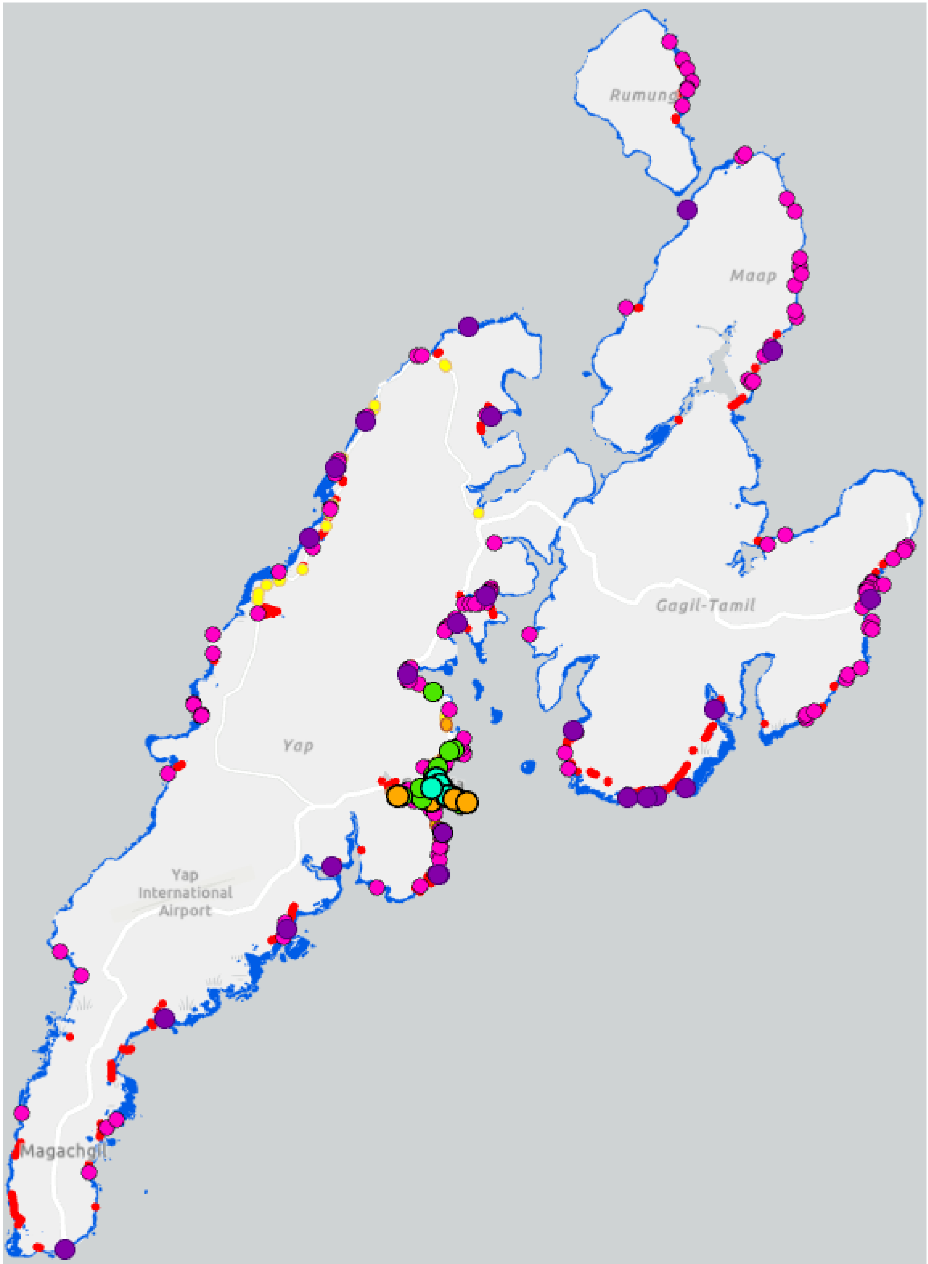

Figure 6. The left image displays Colonia, the center of commerce and most affected area in Yap Proper, before flooding. The right image depicts the same area after flooding, indicating the locations of inundated assets grouped by type: critical infrastructure (orange), cultural sites (purple), businesses (green), government or non-governmental organization buildings (light blue), and buildings and other structures (pink).

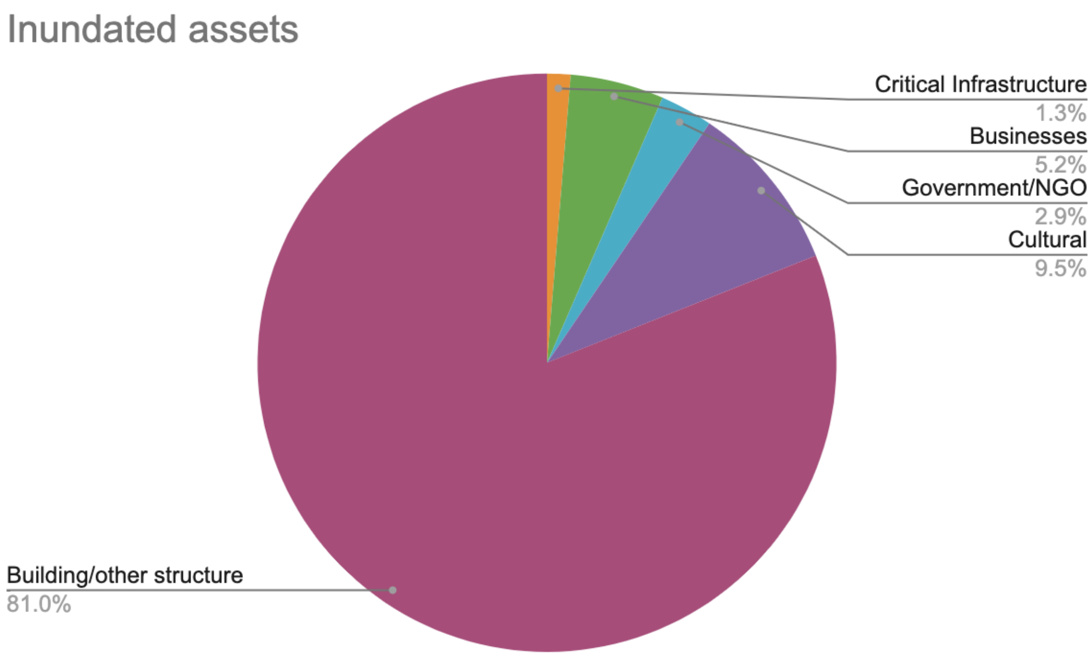

Figure 7. Inundated assets by percent of total inundated assets.

3.1 Impacts to Critical Infrastructure

In addition to impacting businesses, one meter of SLR will also affect four pieces of critical infrastructure of the 11 located on Yap (Figure 8) (Figure 9). Facilities that support the waste water system on Yap will be impacted under one meter of SLR. A wastewater pump station located in Colonia on the south side of the Chamorro bay, and a wastewater tank and discharge facility located on the tip of the Colonia peninsula will both be inundated under 1 meter of SLR. Additionally, 0.89 km of the toal 12.29 km of sewerline will be located on flooded land under 1 meter of SLR (Figure 10) (Figure 11). The inundation of wastewater facilities on Yap has already been documented and can be a cause of serious health and environmental problems due to the leaching of untreated wastewater entering sources of drinking water or coastal waters (Rouse, 2015). In addition to wastewater facilities being impacted, critical sources of energy will also be affected. The FSM Petroleum Corporation facility in Colonia will face inundation under one meter of SLR. FSM Petroleum is the largest supplier of essential energy products and services in Micronesia, including gasoline, diesel, jet fuel, kerosene. The potential inundation of this site carries significant implications for energy supply, with the potential to trigger cascading effects across all aspects of life on Yap proper. Another vital asset that will be inundated under one meter of SLR is the port located in the Tamil Harbor. This is an extremely important asset to Yap as they import many essential goods and food items. The inundation of this port would lead to significant repercussions across the community. Furthermore, under 1 meter of SLR 1.27 km of the total 26.16 km of waterline on will be located on flooded lands, which could lead to the salinization of drinking water impacting water security (Firgure 11) (Figure 12). One meter of SLR will also affect the communities' ability to move around the island. Approximately 26.16 km, out of the total 207.85 km length of roads, will be submerged under one meter of SLR (Figure 13). This inundation is distributed evenly across the island, significantly hindering island-wide transportation (Figure 14).

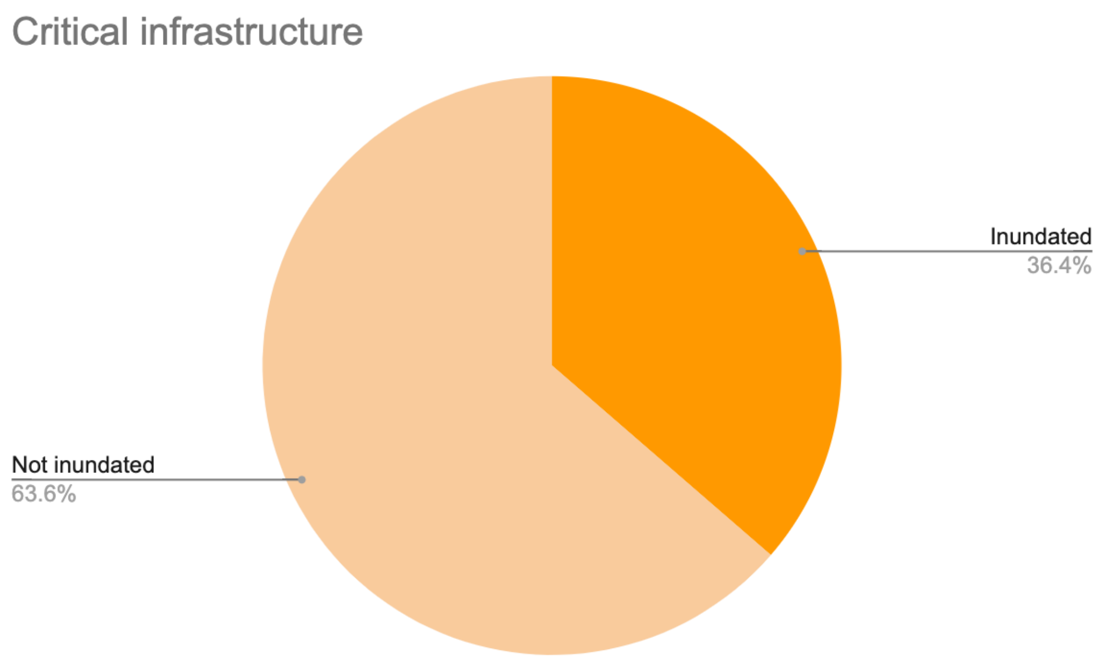

Figure 8. The ratio of inundated critical infrastructure assets to not inundated infrastructure assets on Yap proper.

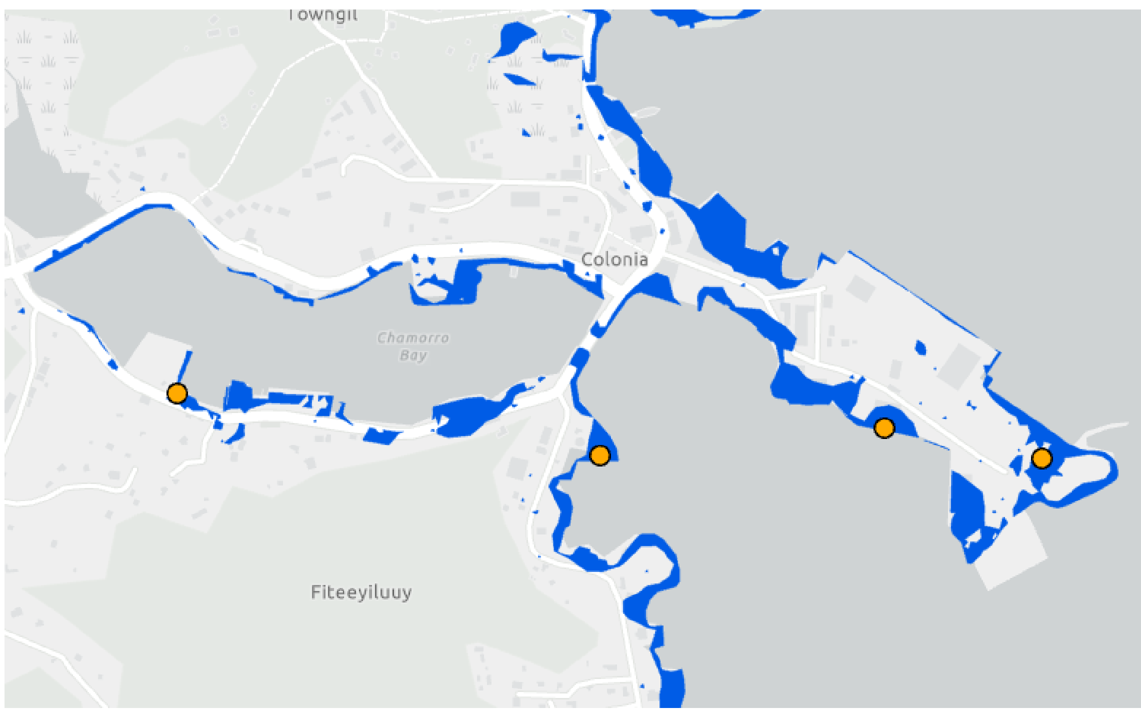

Figure 9. The location of inundated critical assets, all located within Colonia.

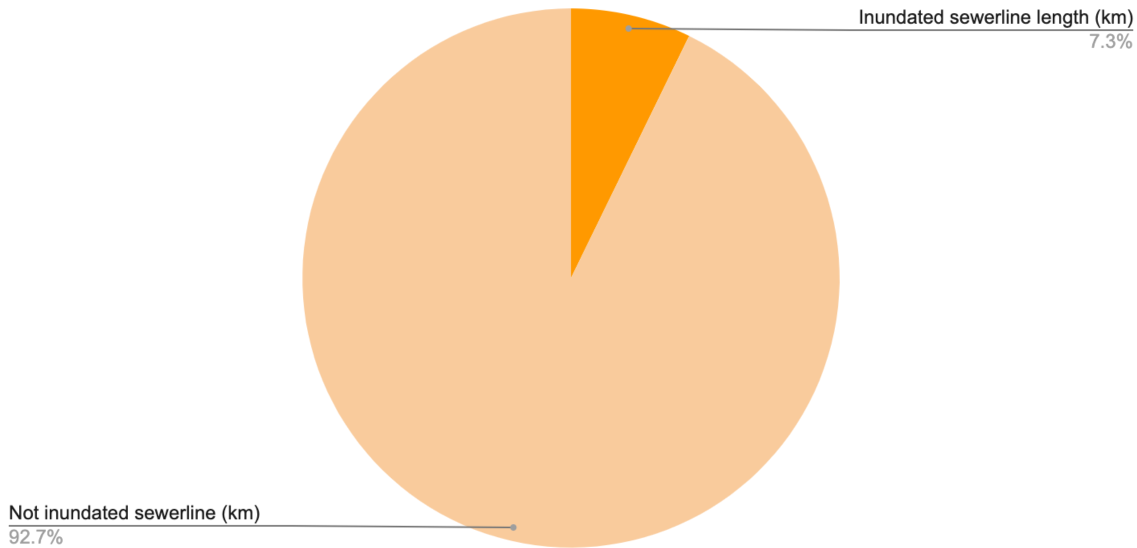

Figure 10. Percentage of inundated sewerline compared to non-inundated sewerline.

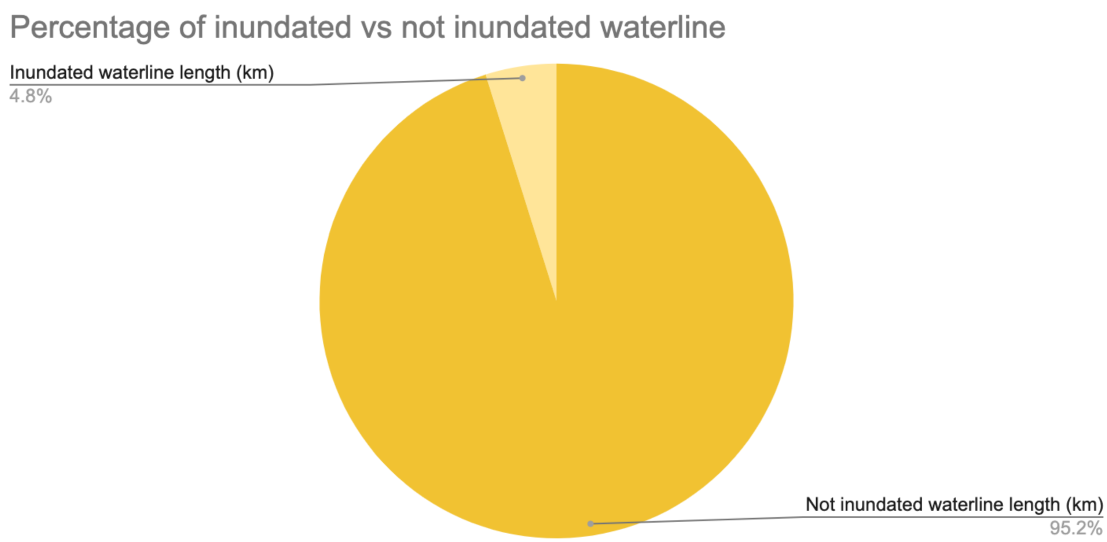

Figure 11. Percentage of inundated waterline compared to non-inundated waterline.2

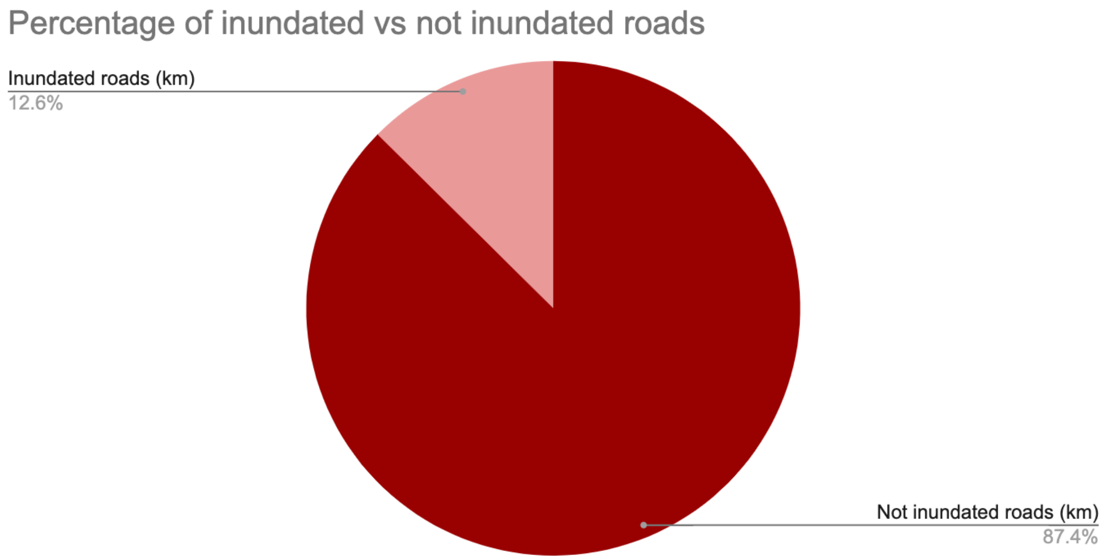

Figure 12. Percentage of inundated roadways compared to non-inundated roadways.

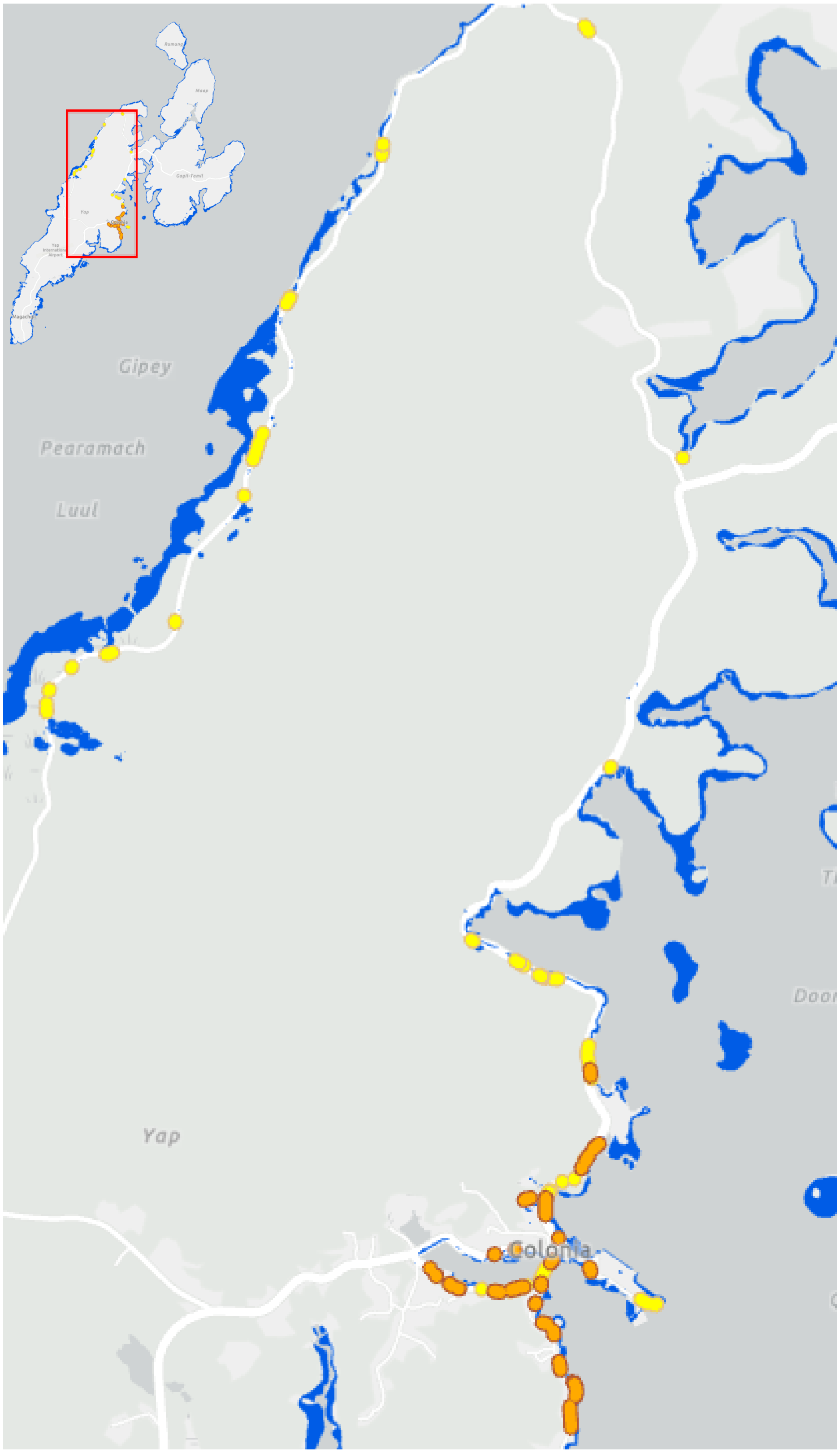

Figure 13. Location of Inundated waterline (yellow) and sewerline (orange).

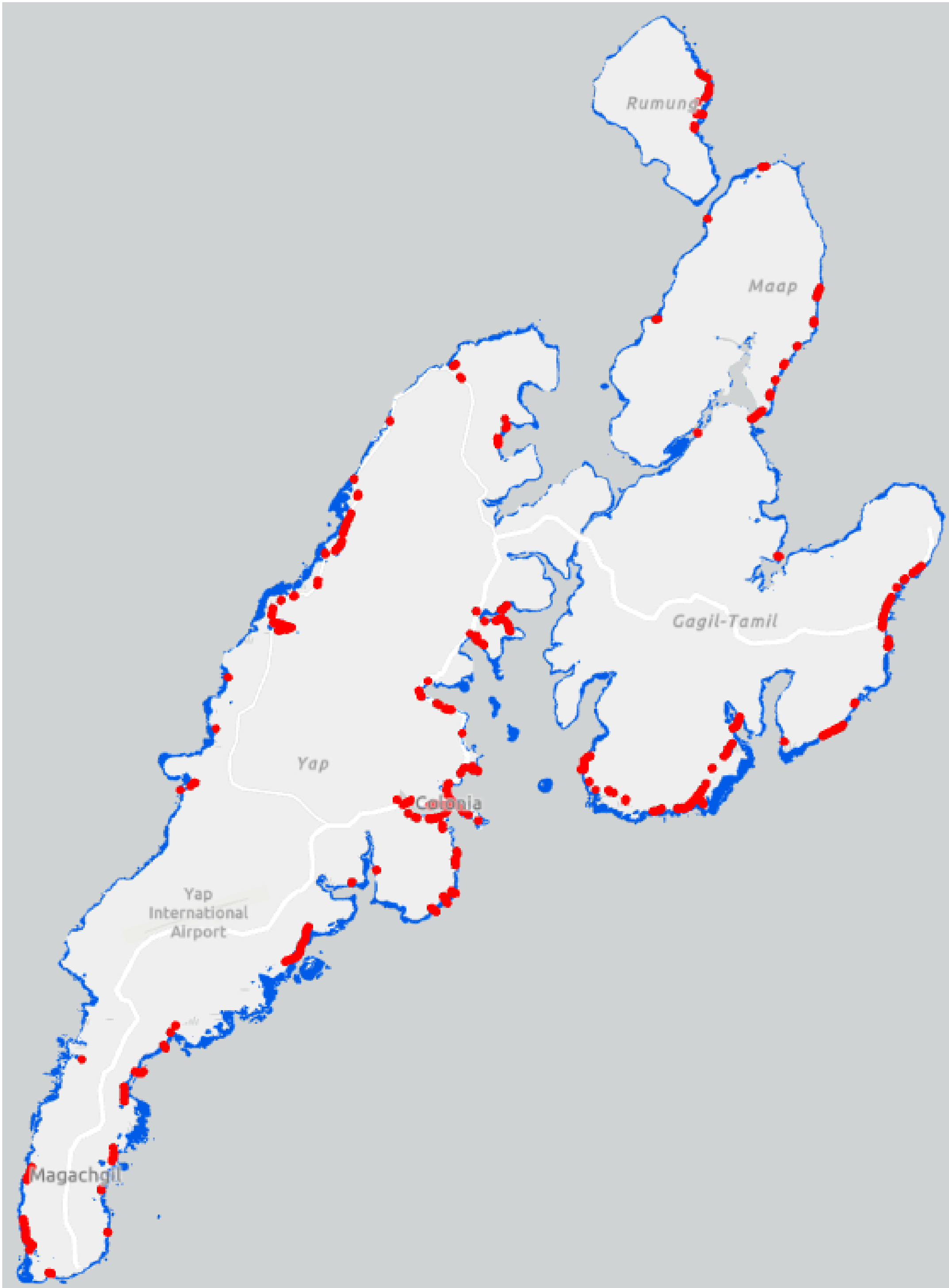

Figure 14. Location of inundated roadways.

3.2 Impacts to Cultural Sites

Some of the most devastating impacts of SLR will involve the loss of priceless cultural sites. These sites face challenges in relocation due to their profound connection to the land. Under one meter of SLR 29 of the 61 cultural sites on Yap proper will be inundated (Figure 15). This includes 23 faluw, four chabog, one dancing ground, and one church. Unlike many of the other sectors, the cultural assets that are inundated under one meter of SLR are located across Yap proper and are not concentrated in Colonia (Figure 16). This means that these assets will not benefit from adaptation plans that focus solely on the center of commerce of the island and will require specific adaptation measures.

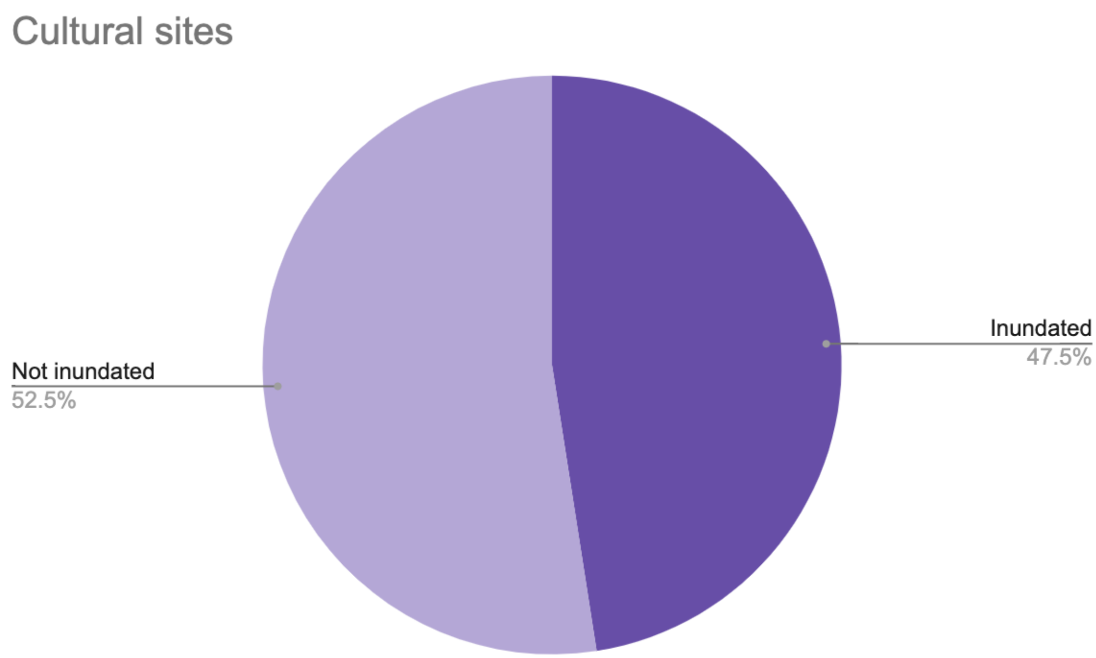

Figure 15. The ratio of inundated cultural sites to not inundated cultural sites on Yap proper.

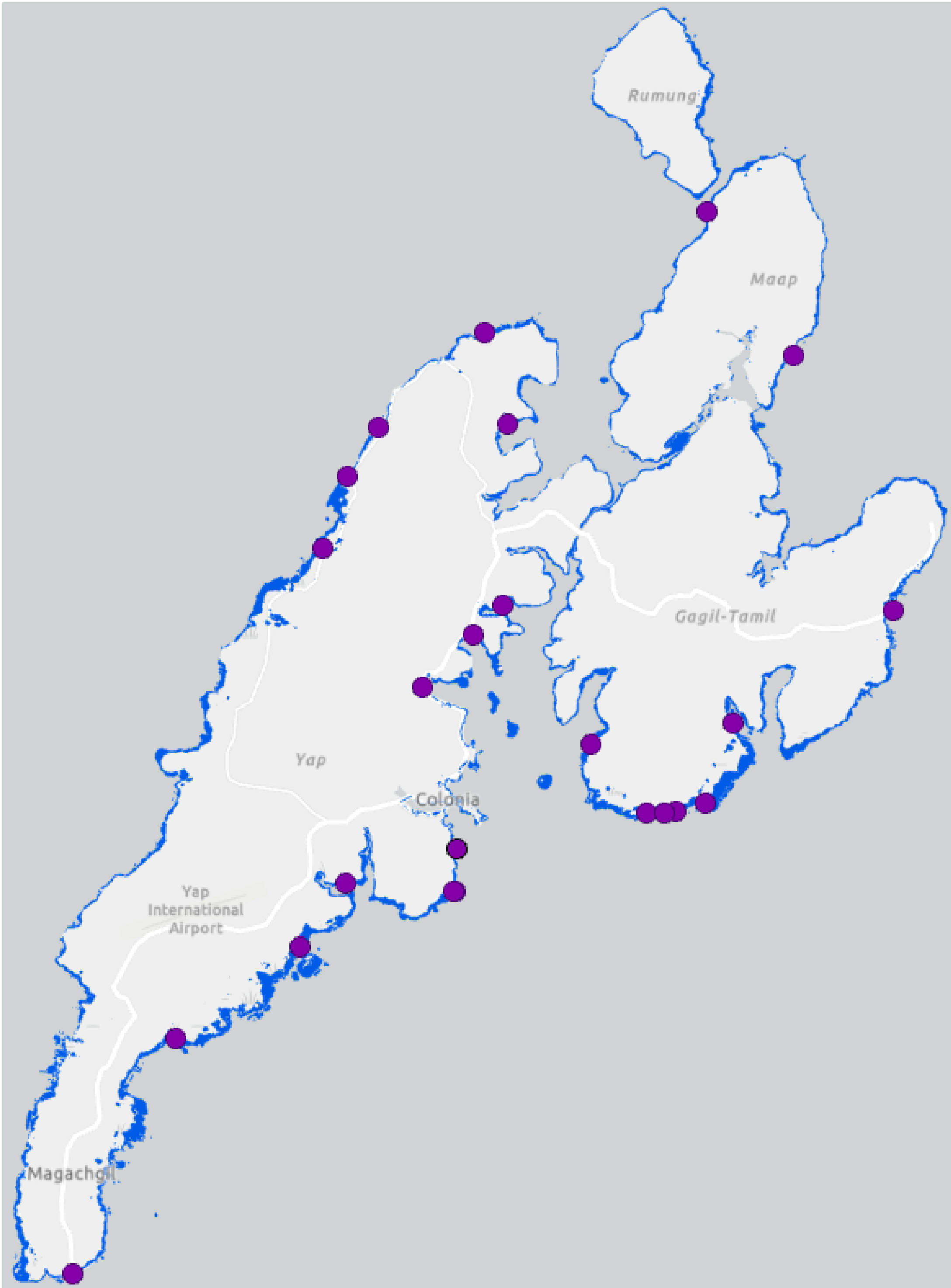

Figure 16. Location of inundated cultural sites.

3.3 Impacts to Businesses

Under one meter of SLR, 34% (16 out of 47 businesses) of businesses on Yap proper will be affected, 15 of which are located in Colonia, leading to losses related to food security and economic security (Figure 17) (Figure 18). Local markets vital to the community, such as Pik-N-Sev Enterprises, EMI Enterprises, and Quality Catch, which not only offer spaces for local vendors to sell their products but also provide imported goods for sale, will be inundated under one meter of SLR. The inundation of these businesses has two affects: it will negatively affect food security through the loss of local food suppliers and undermine economic activity by disrupting the sale of goods. Furthermore, the impacts of one meter of sea-level rise extend to businesses providing essential services to Yap proper, such as PBC Garage and YCA Rufan Gas Station. PBC Garage provides the community with car repair services and is one of only three auto repair shops on Yap proper and YCA Rufan Gas Station is one of only five gas station on Yap proper. Additionally, one-meter of SLR will also have repercussions on several businesses vital to Yap's tourism sector. Three of the four lodging facilities on Yap proper, the ESA Bay View Hotel, O'keefe's Water Front Inn, and the Manta Ray Bay Hotel, and several restaurants will be inundated under one meter of SLR. This will impact economic security by limiting the island's capacity to accommodate tourists.

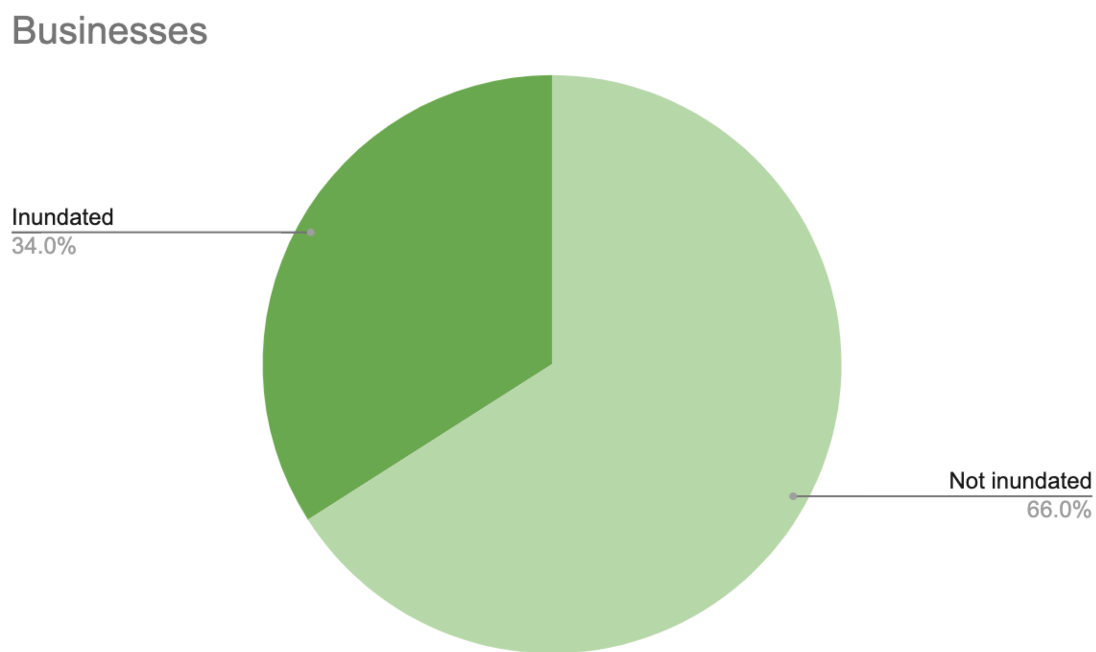

Figure 17. The ratio of inundated businesses to non-inundated businesses on Yap proper.

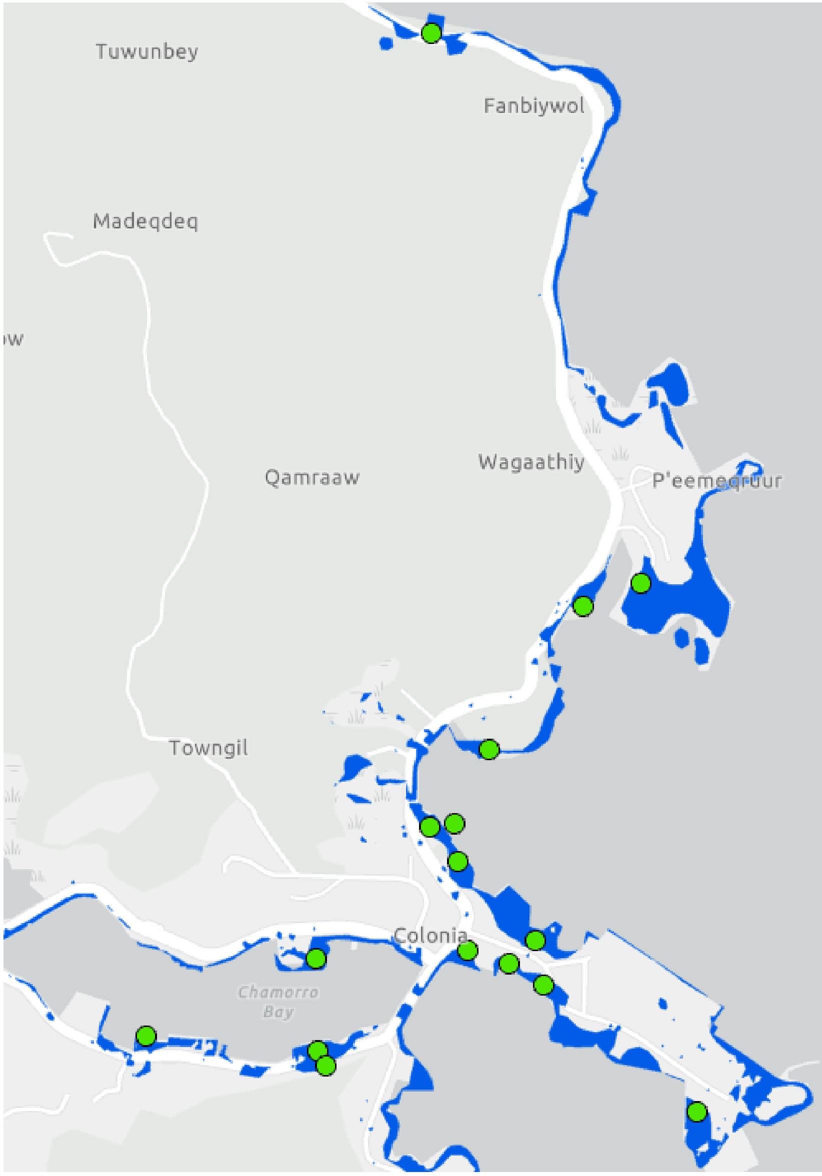

Figure 18. Location of inundated businesses, all located within Colonia.

3.4 Impacts to Government or Non-governmental Organization (NGO) buildings

A one-meter rise in sea levels on Yap Island poses a serious threat to the island's facilities, specifically government and NGO buildings that are vital to the community (Figure 19) (Figure 20). Among these facilities are five state government buildings, including the sole public library on Yap proper, the Yap Fishing Authority office, two

Marine Resources offices, and the Yap Fishing Authority shop. Additionally, one federal government building, the National Police office, will be inundated. NGO facilities exposed to inundation under one meter of SLR include the Yap Cooperative Association, a longstanding market space for locals to buy and sell goods; the Yap Living History Museum, which offers live demonstrations of traditional skills with the goal of increasing the public's knowledge of the significance of traditional culture as well as the history of Yap; and Yap's Gender Support and Youth Service office, which provides support and educational activities for women and youth. Furthermore all of the impacted government and NGO buildings are located in Colonia. These buildings provide essential services to Yap proper’s communities and the loss of them would mean the loss of access to knowledge, local commerce opportunities, cultural heritage, and critical support systems for women and youth.

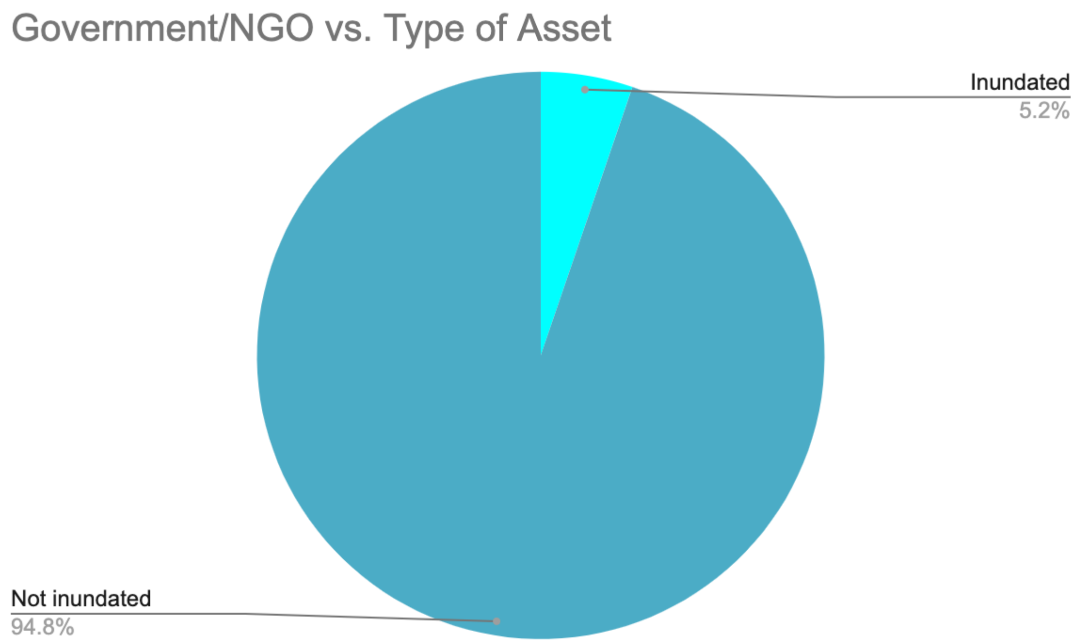

Figure 19. The ratio of inundated government/NGO buildings to not inundated government/NGO buildings on Yap proper.

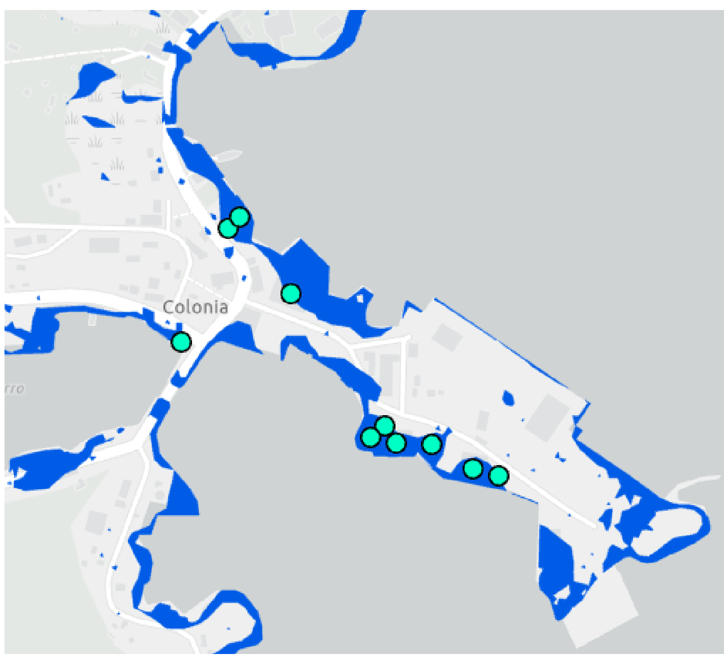

Figure 20. The location of inundated government/NGO buildings, all located within Colonia.

3.5 Impacts to Buildings and Other Structures

The buildings and other structures grouping includes all houses, buildings, and other human-made structures that are not included in the businesses or government/NGO groupings. Under the one meter SLR scenario 106 buildings and other structures of the 4390 on Yap proper were inundated (Figure 21) (Figure 22). This represents the largest portion of impacted structures and is vitally important as it includes housing. Similarly to the cultural sites the assets that are inundated under one meter of SLR are located across Yap proper and are not concentrated in Colonia.

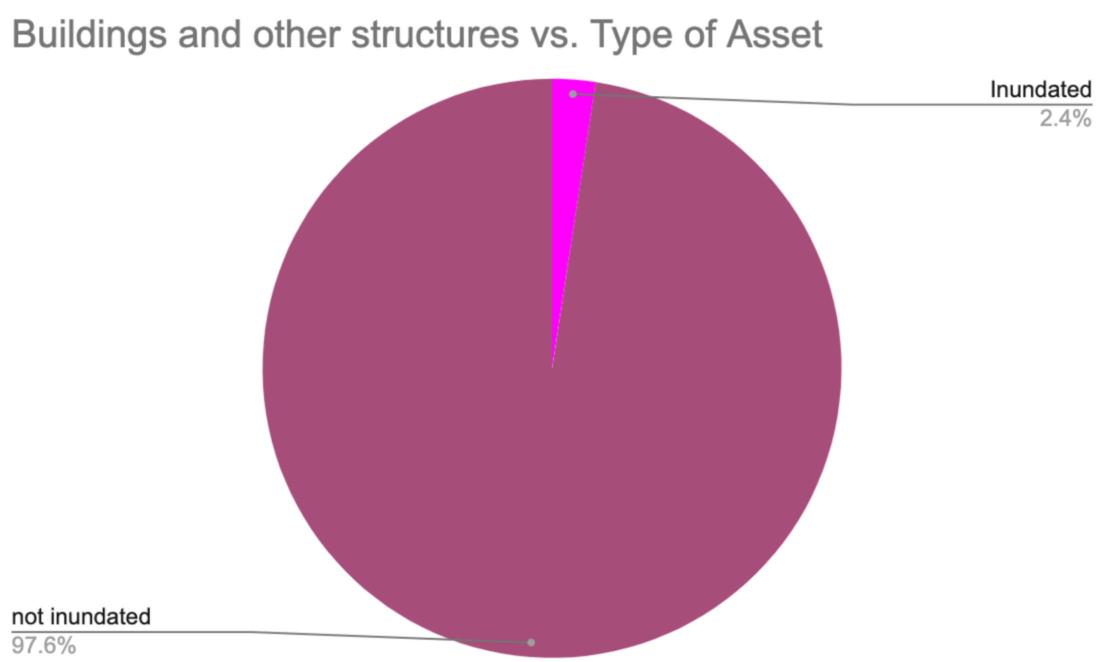

Figure 21. The ratio of inundated buildings and other structures to not inundated buildings and other structures on Yap proper.

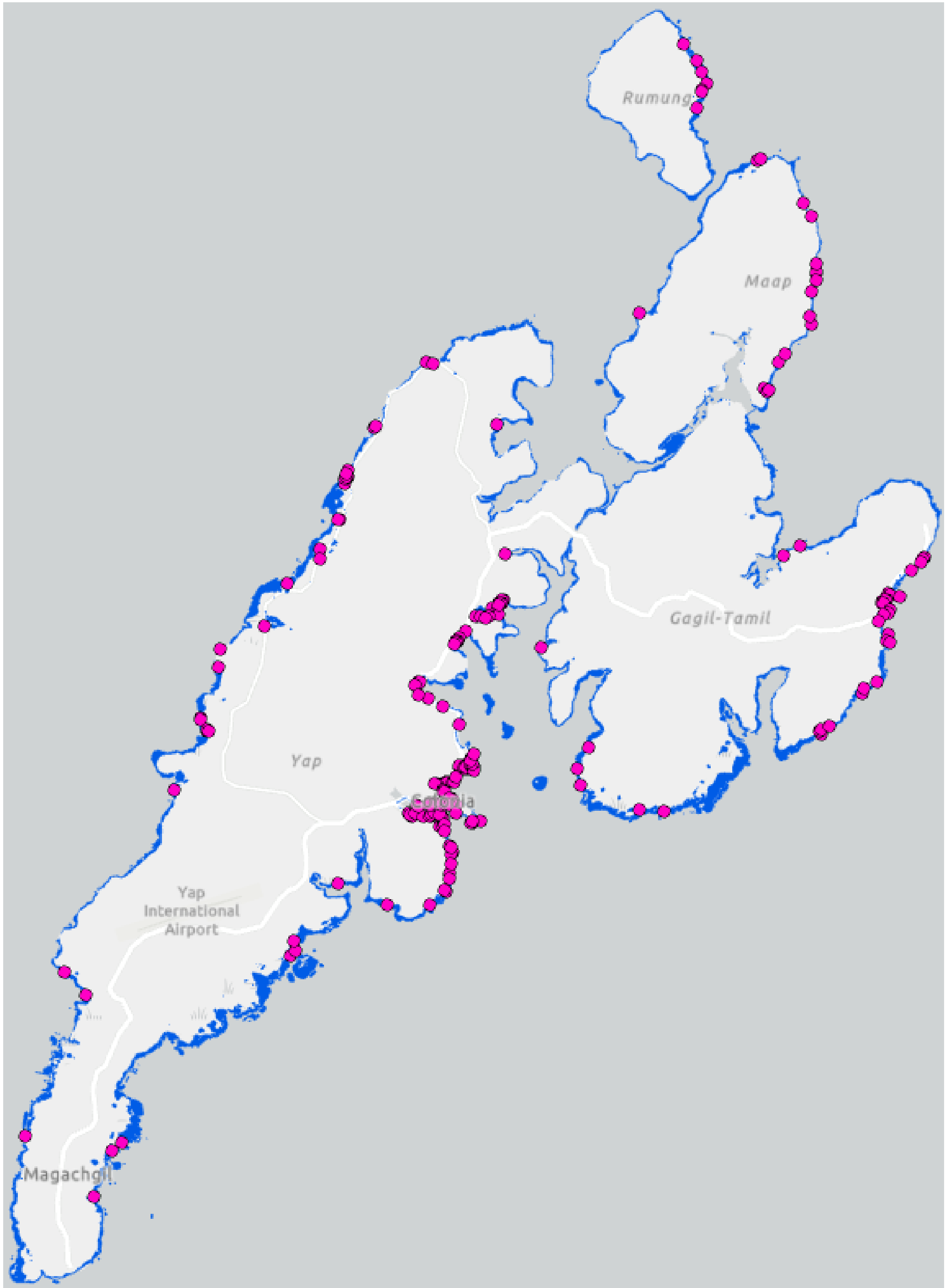

Figure 22. Location of inundated buildings and other structures.

3.6 Colonia as the Most Impacted Area

The results from the model show that Colonia, the capital and center of commerce for the Yap State, experiences severe flooding under one meter of SLR and a high concentration of inundated assets (Figure 23). While the precise boundaries of Colonia have been somewhat unclear in publicly available documents, for the purpose of this study, borders have been chosen based on Google Maps' definition (Figure 23). The high concentration of inundated assets in Colonia emphasizes the exposure of this area to SLR (Figure 23). All critical assets and government or non-governmental organization facilities at risk from inundation are situated in Colonia. Furthermore, the majority of businesses exposed to inundation, 15 out of 16, are also based in Colonia. Close to half of the inundated buildings and other structures were located in Colonia (Figure 24). The high concentration of inundated assets in Colonia is particularly alarming when considering it only represents a fraction of Yap proper's land area, only about 2% of the total land area. Given the significant exposure of Colonia to SLR and its central importance within Yap State, it emerges as a crucial area for the implementation of SLR adaptation projects.

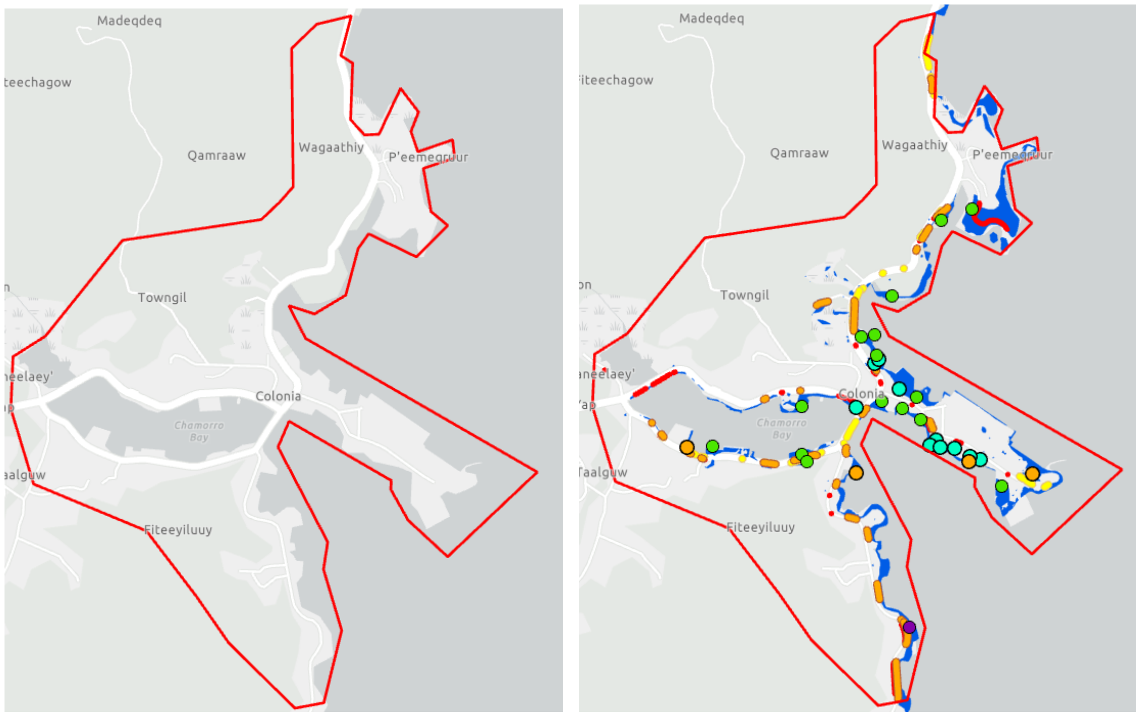

Figure 23. Colonia outlined in red before flooding (left) and with one meter of SLR with inundated assets (right).

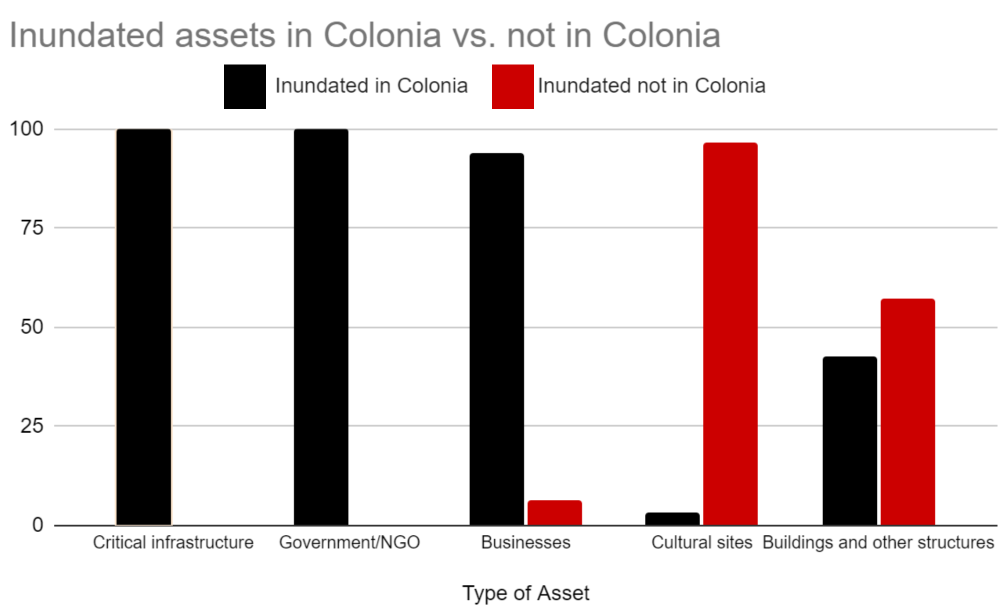

Figure 24. Graph showing inundated assets located in Colonia compared to inundated assets located outside of Colonia by percentage of asset type.

3.7 Limitations in results

Studying the impacts of SLR on Yap proper using a bath-tub flood model presents several inherent limitations. Firstly, the reliance on a bath-tub model instead of a more accurate hydrodynamic flood model stands as a significant limitation. While bath-tub models offer a basic framework for estimating inundation, they oversimplify the dynamic elements that contribute to coastal flooding. Bath-tub models statically elevate the water line excluding dynamic factors, such as high tide events, currents, and storm surges, which are crucial for achieving the most accurate and comprehensive flood predictions. Omitting these factors may result in an underestimation of the extent and severity of flooding, minimizing the actual risks posed by SLR. In a region like Yap proper, where resources are limited these issues are particularly relevant.

Additionally, the bath-tub flood model does not incorporate coastal erosion data. Erosion is a simultaneous impact of SLR and has the potential to exacerbate coastal exposure. Neglecting to consider erosion in the study may result in an incomplete understanding of the overall impacts of SLR on Yap proper's coastlines, again minimizing the actual risks posed by SLR.

Finally, one significant constraint arises from the lack of firsthand experience with the area, which inhibits the ability to "ground truth" the data. Without on-site observations and measurements, it is impossible to validate the model's inputs, the DEM and asset layers. This limitation can lead to inaccuracies in the study's findings and may result in a lack of specificity in addressing the unique challenges faced by Yap proper in the face of sea-level rise.

4.0 DISCUSSION

In regions most exposed to the imminent impacts of SLR, it is crucial to develop comprehensive solutions that reduce community risk and support community resilience. These solutions are referred to as adaptation strategies and are pivotal in addressing the complex challenges that SLR presents. It is essential to acknowledge that adapting to a changing environment is not a new phenomenon; indigenous communities have successfully practiced adaptation for thousands of years. Bridging the wealth of traditional knowledge with modern climate science is essential to effectively adapting communities to SLR. This section will examine various adaptation strategies, many rooted in traditional knowledge, categorizing them into protection, accommodation, and retreat strategies (Figure 25). Additionally, this section will also explore the advantages and potential challenges associated with these strategies, assess their past implementation in Yap and other Pacific Islands, and recommend further steps for their utilization where applicable.

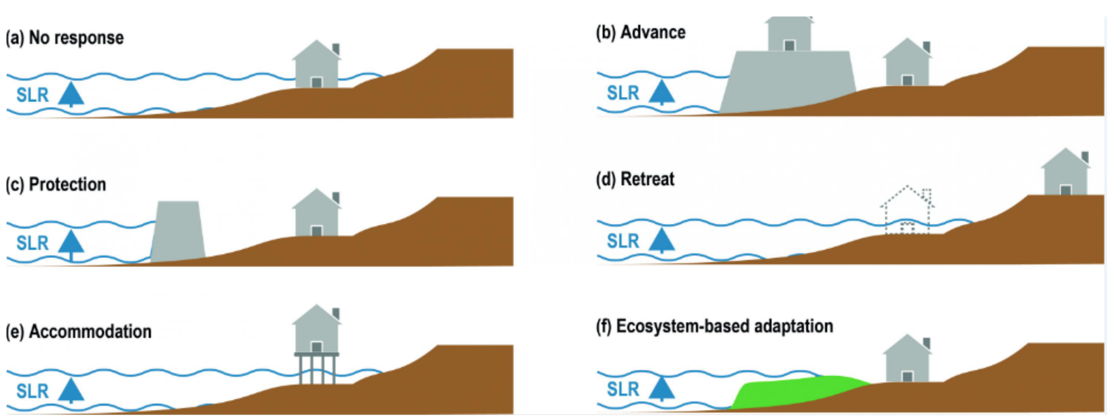

Figure 25. Image showing different types of adaptation strategies.

4.1 Protection

Protection in this context is defined as using defensive strategies, including hard and ecosystem-based protection measures, to preserve an area against the impacts of SLR (Coelho et al., 2023; Dronkers et al., 1990; Rangel-Buitrago et al., 2018). This technique is most often used in critical regions such as economic centers, and densely populated areas. Examples of hard protection measures are dykes, groins, breakwaters, revetments, and seawalls. Examples of ecosystem-based protection measures, sometimes referred to as soft protection measures, include dunes, vegetation, beach nourishment, wetlands, and mangrove forests.

4.1.1 Hard Protection Measures

Dikes are onshore structures that have a gentle seaward slope that is meant to reduce wave runup, erosion and inundation. They are typically made from a mound of materials such as sand, clay, or rocks (Figure 26). Benefits associated with dikes include a decreased risk of flooding due to storm run-up and a relatively simple design to build and maintain (Mohamed Rashidi et al., 2021). However, there can also be consequences to building a dike. If a dike is not built high enough, waves may overtop the structure thus defeating its purpose of flood protection (Mohamed Rashidi et al., 2021). Water that overtops the structure along with rainfall runoff tends to get trapped on the landward side of the dike, which creates a flood risk (USACE, 2015). Additionally, dikes can lead to scouring sand and sediment resulting in erosion of coastal lands (Mohamed Rashidi et al., 2021).

Figure 26. Armored sea dike (from K. Hanegan, 2010).

Groins are structures, typically made out of concrete, wood, geotextile bags, or stone, that are built perpendicular to the shoreline (Figure 27). These structures are typically built in series and their main purpose is to protect a beach from longshore beach erosion (Rangel-Buitrago et al., 2018). The main advantage of groins is that they are able to build up the beach on the updrift side of the structure naturally, however, this can lead to considerable erosion on the downdrift side of the groin on alongshore-dominated beaches, which can lead to complete beach loss (Rangel-Buitrago et al., 2018). This can severely impact communities and ecosystems on the downdrift side of the groin.

Figure 27. Costal groin in Honolulu Hawaiʻi (from Daniel Dennison, State of Hawaii DLNR).

Breakwaters are coastal structures that are built parallel or oblique to the shoreline (Figure 28) (Rangel-Buitrago et al., 2018). Both offshore and onshore breakwaters are constructed to reduce wave energy to the shoreline by reflecting and dissipating wave energy because they force waves to break upon their crests and transform the wave approach toward shore (Mohamed Rashidi et al., 2021; Saengsupavanich et al., 2022). These are built to protect the shoreline from flooding during high-wave events, such as storms or king tides (Mohamed Rashidi et al., 2021). Unfortunately, like the other hard protection measures, they can have unintended consequences. One consequence of breakwaters is they can disrupt the longshore transport of sand and sediment. This can lead to erosion and beach loss on the downdrift side of the breakwater (Mohamed Rashidi et al., 2021). Breakwaters can also form rip currents in the gaps between breakwaters, which create an unsafe recreational area. Additionally, it had been seen that emerging breakwaters can have a negative impact on fish, coral, algae, and seagrass ecosystems

(Saengsupavanich et al., 2022). Another reason why breakwaters may not be the best choice for coastal adaptation is that they are very expensive to build and maintain and can cost more than $1.5 million dollars per km of coastline meaning they are impractical for many communities (Saengsupavanich et al., 2022).

Figure 28. Breakwaters (from Living Shorelines).

Revetments are protective materials placed on sloped banks or bluffs parallel to the shoreline that reflect and dissipate energy from incoming waves (Figure 29). These structures are commonly built to decrease erosion and scour in the landward direction of the revetment in order to protect roads, buildings, or other coastal infrastructure (Dronkers et al., 1990). The energy that is reflected is reflected both landward and seaward (Mulvihill, 1980). The energy reflected in the seaward will result in increased erosion and scour on the seaward side of the revetment. This can lead to major beach loss in the area seaward of the revetment (Mulvihill, 1980). The loss of a beach can result in many negative impacts to a community such as the loss of economic activity, ecosystems, and recreational space.

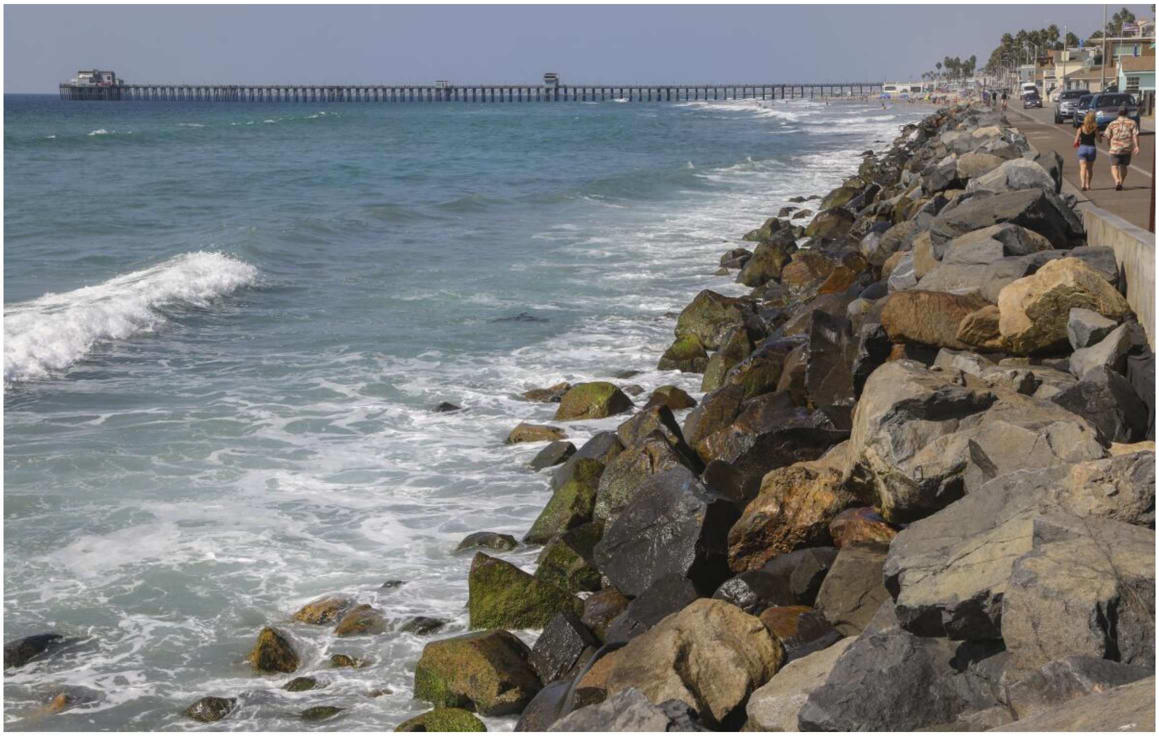

Figure 29. Revetment (from Eduardo Contreras, The San Diego Union Tribune).

Seawalls and bulkheads are some of the more common options that coastal communities implement when facing coastal erosion and flooding (Nunn et al., 2021). Seawalls are vertical structures that are constructed to protect landward assets from erosion, wave action, and flooding (Figure 30) (USACE, 2015). Like many of the other hard protection methods, seawalls increase erosion in the area seaward of the seawall due to the reflection of wave energy (Nunn et al., 2021). Additionally, if they are not built high enough and waves are able to overtop them they can trap water on the landward side of the wall, creating an additional flooding risk (Nunn et al., 2021). Also, if seawalls are built without consideration of how they will be maintained, they often become dilapidated due to a lack of community resources.

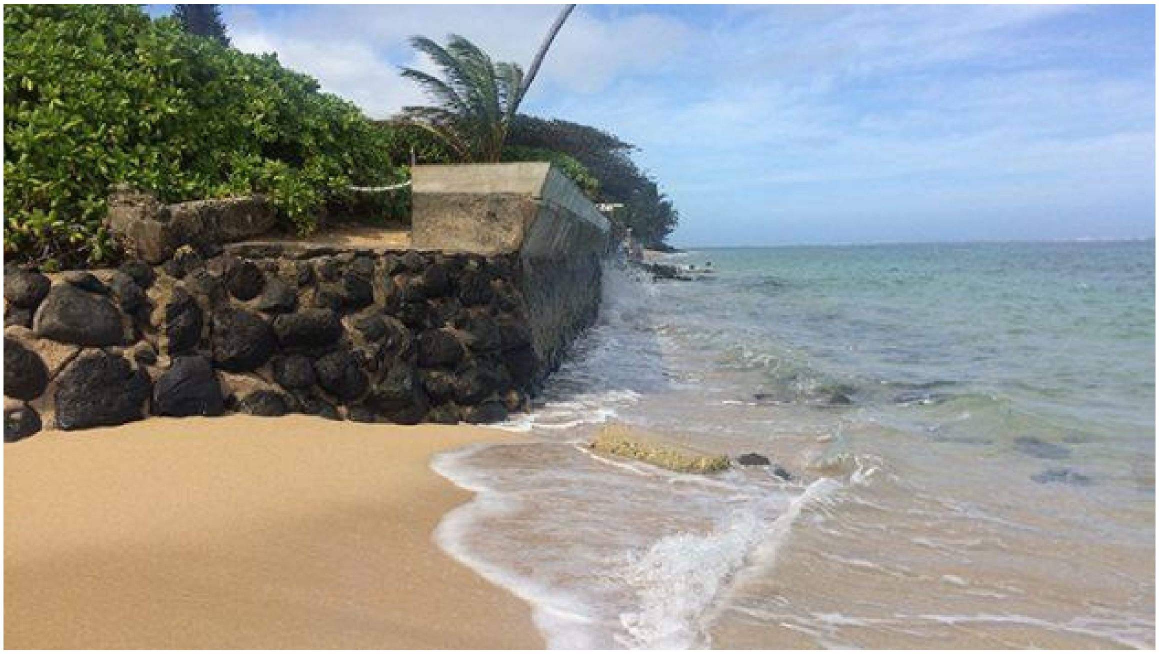

Figure 30. Seawall in Hawai‘i (from Alisha Summers University of Hawai‘i).

Implementing protection strategies is a vital part of reducing the exposure of coastal communities. What type of protection strategy will be most beneficial is dependent on the natural processes of the area and the specific circumstances of the coastal community that is considering adaptation. Although hard protection measures have known disadvantages, such as cost and maladaptive consequences, they can still serve as a reasonable adaptation solution in some contexts. Hard-protection strategies can be seen in Yap in the central port district Colonia primarily in the form of seawalls. Most of the protection structures in this area have been built barely above the accelerated SLR scenario still-water levels, which is defined as greater than one meter above the 1994 mean sea level (Richmond & Reiss, 1994a; Richmond & Reiss, 1994b). This means that the structures will be highly susceptible to direct wave action leading to overtopping, and undermining, which can increase the vulnerability of the surrounding community rather than decrease it. Additionally, a stone rip rap revetment wall is located on the inner banks of the bay to stabilize the shoreline and protect the adjacent road.

In Yap, there is a need for hard protection measures in certain areas. In coastal areas where critical infrastructure or other vital assets reside and can not be relocated, hard protection continues to be an appropriate solution, however, hard protection measures are strongly advised against in areas where they are not protecting critical infrastructure or other vital assets as they lead to increased vulnerability. Some recommendations for hard protection structures in Yap include, upgrading hard-protection measures in the central port district, raising the seawalls along the harbor shore, and building large revetments to protect vital coastal infrastructure that is not currently protected (Fletcher & Richmond, 2010). These recommendations stem from the understanding that critical infrastructure, unless relocated to a less exposed location, will require ongoing protection due to its low tolerance for risk.

4.1.2 Ecosystem-based Measures

Ecosystem-based protection methods are another option for adapting to SLR. Unlike hard protection methods, ecosystem-based protection methods do not use human-engineered hard structures. Instead they focus on using natural features such as vegetation, sediment and/or mud to protect the shoreline against the effects of SLR (Piggott-McKellar et al., 2020). Soft protection measures, including protecting and restoring natural coastlines, are a promising alternative to hard structures for areas with a higher tolerance for risk because they improve the resilience of coastal communities with less frequent instances of maladaptation (Grecni et al., 2023). Additionally, ecosystem-based-protection projects are more likely to have space to incorporate the community within the project, which can lead to increased stakeholder engagement and community support.

Revegetation, or ecosystem restoration, is a type of ecosystem-based-protection strategy that involves planting specific types of plants along the shoreline to dissipate wave energy and decrease coastal erosion. Revegetation can be done with a variety of different plants depending on where the project is taking place, but some examples are salt marsh plants, seagrasses, and mangroves (Figure 31). Mangroves are a group of trees that are found in tropical and subtropical coastal regions. Mangroves have historically provided coasts with protection during tsunamis and major storm events. Because of this, it has been suggested that mangrove restoration projects be implemented as a way to protect the coasts from SLR and its associated impacts. Mangroves have a high salt tolerance and the capacity to withstand storm events, which allows them to thrive in intertidal zones (Tomiczek et al., 2021). Due to the dense nature of mangrove forests and their aerial roots, mangroves are able to dissipate wave action. Studies on mangroves have suggested that a 500-meter plot of mangroves can reduce wind and swell waves by 50-100% over 500 meters and a 100-meter plot of mangroves can reduce wind and swell waves by 13-66% (Beck & Lange, 2016). By reducing wave height, mangroves effectively protect the coast from many impacts of SLR such as storm surges, and wave-driven flooding. It has been found that a one-kilometer-wide mangrove forest can reduce storm surge peak level by 5-50 centimeters (Beck & Lange, 2016). However, it is currently uncertain how they will react to extreme SLR. Models suggest that mangrove forests will be able to withstand SLR until the year 2060 (Buffington et al., 2021). After

2060, it is uncertain if mangroves will be able to continue to be resilient to SLR (Buffington et al., 2021). Mangroves can also play a positive role in erosion control. Due to their aerial root structures, they contribute to shoreline stabilization and the accretion of sediment (Tomiczek et al., 2021). One study found that mangroves can retain up to 80% of the sediment that is transported into their root systems (Furukawa et al., 1997). In addition to coastal protection, mangroves provide the surrounding community with other co-benefits such as timber, watershed protection, nutrient cycling, air pollution reduction, carbon storage, habitat for fish nurseries, habitat for bird nesting, and other ecosystem and community services (Tomiczek et al., 2021). Because of mangroves' capacity to reduce wave and storm-surge height, ability to accrete sediment, and capability to support ecosystem and community services they are a promising choice for coastal protection in areas when they are native.

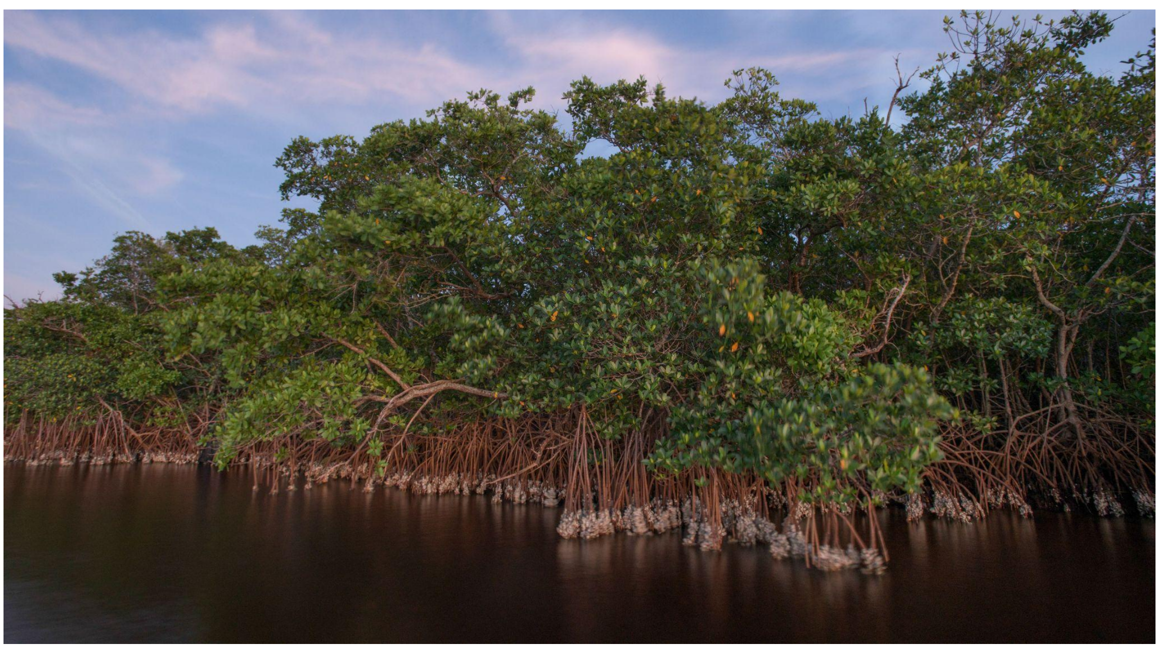

Figure 31. Mangrove forest shoreline (from Carlton Ward Jr., Nature Conservancy).

Coastal dune restoration and beach nourishment can also be used as ecosystem-based protection measures. Sand dune restoration is a process in which dunes are re-established through planting native dune vegetation, sand fencing, and occasionally sand nourishment (Johnston et al., 2023). Dune restoration is used as a ecosystem-based protection strategy because it strengthens dune systems that protect the coast from storm surge, wave-driven flooding, and erosion (Feagin et al., 2019; Johnston et al., 2023). Restoring dunes by revegetating them with native plants increases the sediment retention, elevation, and resilience of the dune, which increases the dune's capacity to not become eroded and attenuate wave energy. Dune restoration also provides co-benefits such as habitat reestablishment of dune-dwelling plants and animals and new recreational areas (Van Der Meulen et al., 2023).

Beach nourishment is another ecosystem-based technique that can be used to protect the coastline. Beach nourishment is a management technique that uses off-site sand to increase the size of the nearshore (Figure 32) (De Schipper et al., 2020). The sand that is used in the nourishment process can be taken from existing projects, such as harbor channeling deepening or coastal construction, or can be dredged from a borrow site specifically for nourishment purposes (De Schipper et al., 2020). This technique is mainly used to increase the size of eroding beaches, which protects coastal communities from flooding and erosion. There are many things that need to be considered when implementing beach nourishment. One thing that is necessary to consider is the type of sand used for nourishment. Coarser-grained sand typically creates a steeper and wider beach and is not transported as easily it can maintain nourishment for longer whereas finer-grained sand creates a less steep and narrower beach and is easier to transport leading to possible dune growth but decreased longevity of the nourishment project (De Schipper et al., 2020). Additionally, the type of sand used can also impact surrounding ecosystems if they cannot adapt to a different type of sand (De Schipper et al., 2020). It is also important to consider how frequently renourishment projects will have to take place. Sand moves cross-shore and long-shore due to wind, waves, and currents (De Schipper et al., 2020). Because of this, the sand placed during a beach nourishment project will eventually move away from the original placement site, creating the need for renourishment. This process can happen as fast as weeks, if a large storm occurs, or take as long as decades (De Schipper et al., 2020). This can be a costly process if renourishment has to take place frequently.

Figure 32. Beach nourishment on Waikiki Beach, Oahu (from Jamm Aquino, Star Advertiser).

There are some communities in the Pacific that are utilizing ecosystem-based-protection measures to reduce their exposure to SLR impacts. On Tamil, in Yap proper, the community has created a plant nursery that focuses on traditional composting techniques and cultivating plants that are to be used to revegetate coastal areas that are impacted by erosion, such as the Nipa Palm (Mcleod et al., 2019). Additionally, in Erub Island in the Torres Strait, community members are using native plant species to re-vegetate coastal areas to increase their resilience against coastal erosion (McNamara & Westoby, 2011). Beach nourishment is also being utilized on Pacific Islands. On Fongafale Island, in Tuvalu, a beach nourishment project was completed using sand and gravel to combat impacts caused by coastal erosion, wave overtopping, and flooding (Figure 33). The project was finished in 2015, and for two years following its completion, the beach underwent monitoring to assess its success. The findings revealed that after this two-year period, the beach successfully retained the sand and gravel, becoming a recreational area for the community (Trung Viet et al., 2020). Soft-protection measures have successfully decreased the exposure of Pacific communities to the impacts of SLR.

Figure 33. A comparison of the Fongafale Island beach before (left) and after (right) the beach nourishment project.

Because of this further implementation of ecosystem-based-protection methods in Yap proper are suggested as current and future adaptation solutions. Revegetation of mangrove forests is suggested to decrease exposure to marine inundation (Fletcher & Richmond, 2010). Specifically, conservation efforts should be focused on mangrove forests with the greatest distance between the forest floor and the highest tide, and mangrove forests with the ability to migrate inland. This is because these have the greatest likelihood of responding well to climate stressors, including increased SLR (Grecni et al., 2023). Beach nourishment is also suggested as an adaptation solution for Yap proper (Fletcher & Richmond, 2010). Sand nourishment, from carefully selected borrow sites, could be beneficial in areas experiencing beach loss. This would help protect coastal infrastructure and increase opportunities for recreation.

4.2 Accommodation

Accommodation is a type of adaptation option that allows development to remain in place with some adjustments. Accommodation is defined as continuing to use exposed land by modifying existing and future development to reduce the exposure of coastal residents, human activities, ecosystems, and infrastructure (Dronkers et al., 1990; Oppenheimer et al., 2019). Accommodation is a favorable approach to implement because it is typically low-cost and highly cost-effective, making it an attainable approach for many communities (Oppenheimer et al., 2019). Examples of accommodation include flood-proofing buildings, planting salt-tolerant and drought-tolerant crops, and raising the elevation of roads, infrastructure, and food production.

There are two ways that flood-proofing accommodation techniques are used in order to make buildings more resilient. One way to flood-proof a building is to elevate it on stilts to provide an open area between the bottom of the building and the ground (Figure 34). This allows water to pass underneath the building during a storm or high tide event, keeping the structure protected from water damage. This method ensures that the building can maintain its location and functions while also decreasing its exposure. One key aspect of this method is that the buildings are raised high enough to ensure that even during the highest water events of the year the buildings stay dry. In coastal areas, such as Yap, it is best practice to elevate the lowest horizontal structural component of a building one meter above the maximum overwash elevation (Fletcher & Richmond, 2010). This elevation is a base flood elevation that can be used when renovating existing buildings or during new construction in order to make them more resilient and lower their risk of exposure to flooding (Fletcher & Richmond, 2010). Elevation is a widely used accommodation technique because it is quick to implement, eliminates the need to relocate the building, reduces flood risk to the building and its contents, and does not require additional land that may be needed for other floodproofing protection methods like floodwalls or levees (FEMA, 2014). There are some disadvantages associated with elevation such as it can be cost-prohibitive, it can decrease accessibility to the structure, it is difficult to do with existing structures, and it cannot be used in areas with high rates of erosion unless special measures are taken (FEMA, 2014).

Figure 34. Elevated house to accommodate for flooding.

In addition to elevating houses in order to accommodate them to SLR, another accommodation method is elevating roadways. Flooding and inundation of roadways can be detrimental to emergency services, evacuation routes, and communication networks. In order to prevent the breakdown of these networks during extreme high tide and storm events roads can be elevated to lessen their exposure to inundation. This is best implemented on roads that are adjacent to areas such as wetlands, mangrove ecosystems, and shorelines. Similarly to buildings, it is recommended that the roads be elevated one meter above the maximum overwash elevation (Fletcher & Richmond, 2010).

Elevating buildings and roads to mitigate the impacts of sea-level rise has been widely employed as an adaptation strategy across the Pacific. A study conducted in Sāmoa found that repairing and preparing houses to withstand the effects of typhoons, heavy rains, and flooding was a prominent adaptation strategy at the household level. One of their methods to achieve this was increasing the house's elevation (Beyerl et al., 2018). Moreover, traditional Sāmoan houses (fales) and Yapese houses (faluw) were built on raised surfaces making them less exposed to flooding and inundation (Beyerl et al., 2018; Nunn et al., 2017) More recently communities in Yap proper have raised roads as a response to flood damages caused by typhoons (Nunn et al., 2017). However, these roads, while raised, are still susceptible to flooding during high tides. Future efforts could be achieved more successfully if roads are raised more aggressively.

In future adaptation planning projects, it is recommended that roads continue to be elevated in order to decrease their exposure to inundation and flooding. The roads should be raised at least one foot (0.3 meters) and roads in areas that are more prone to frequent flooding and inundation should be raised two feet (0.6 meters) (Fletcher & Richmond, 2010). If it is not economically feasible to adapt all exposed roadways within current or upcoming projects, it would also be beneficial to create a plan for incremental elevation projects that occur when resurfacing is needed (Fletcher & Richmond, 2010). Additionally, structures that are located within exposed zones and are not able to be relocated should consider opportunities to increase the elevation of their lowest horizontal structural component to one meter above the maximum overwash elevation (Fletcher & Richmond, 2010).

Another promising option for accommodation is climate-smart agriculture. Climate-smart agriculture (CSA) is an approach using traditional and modern sustainable agricultural practices to manage cropland, livestock, fisheries, and forests, fisheries with the goal of increasing food security in the face of challenges posed by climate change (Mcleod et al., 2019). CSA strives to achieve increased productivity of food systems, enhanced resilience of food systems and the communities in which they support, and reduced GHG emissions of the food sector (World Bank, 2021). It is important to note that many of these climate-smart agricultural techniques are rooted in traditional indigenous land management practices that were suppressed by colonialism and European expansion and are not newly discovered concepts. Smaller island cultures specifically have faced changing environments for thousands of years and as a result of this have developed sustainable and resilient management practices (Perkins & Krause, 2018).

CSA agriculture can be implemented through various approaches, such as cultivating resilient crops, adapting farming techniques, and incorporating agroforestry. Salt-tolerant crops, like taro, serve as an example of resilient crops, especially against the impacts of SLR. Some varieties of taro are tolerant of saline growing conditions and can thrive in brackish waters containing 20-25 percent seawater (FAO, 2010). Giant Swap taro is one variety of taro that is salt-tolerant. There are also CSA techniques that modify growing methods to help accommodate the crops to SLR. Examples are restoring degraded lands through soil revitalization, raised bed farming, and concrete taro patches.

Soil revitalization can done in a variety of ways, such as using seaweed as compost and other organic fertilizers (Mcleod et al., 2019). Raised bed farming can be done by increasing solid thickness through compost or building raised platforms into which plant beds can be incorporated (Fletcher & Richmond, 2010). Raised bed farming specifically helps eliminate the loss of crops from SWI because raised beds are less exposed to flooding and inundation (Perkins & Krause, 2018). Utilizing concrete taro patches is another accommodation method used to decrease exposure to flooding and inundation. Concrete taro patches consist of concrete containers where soil is cultivated and taro is grown (Fletcher & Richmond, 2010). This decreases the likelihood of SWI because the concrete is impermeable and therefore protects the taro plants from salinization, at least in the shorter 10-30 year timeframe. Agroforestry is another tool used in CSA. As discussed in the earlier section, agroforestry is sustainable land management approach that focuses on a tiered system that enhances land productivity while maintaining soil health (Leal Filho, 2017). Agroforestry has many benefits such as decreasing the risk of crop failure, generating additional income sources, maintaining healthy ecosystems, increasing biodiversity, improving soil health, carbon sequestration, and air and water purification - all of which contribute to community resilience (Dissanayaka et al., 2023).

As previously mentioned, indigenous communities have a historical legacy of implementing CSA techniques, and these practices continue to be employed by these communities today. In Palau, women are leading efforts in planting salt-tolerant varieties of taro to enhance the resilience of their food crops against coastal flooding and SWI (Mcleod et al., 2018). Additionally, soil revitalization initiatives are currently underway, particularly within Yap. On the Gargey-Tomil plateau of Yap proper, depleted topsoil is being restored through composting, mulching, and the addition of crushed coral. These methods facilitate improved nutrient retention in the soil, thereby supporting crop productivity (Leal Filho, 2017). Raised bed farming practices have also gained prominence in various Pacific regions, including Papua New Guinea and Yap proper. Communities in these areas have adopted this approach to protect their crops against the impacts of SLR and improve their food security (Krishnapillai, 2018; Leal Filho, 2017; Mcleod et al., 2019). Furthermore, concrete taro patches, another CSA technique, have found application in Yap, specifically the outer island of Fedraey. Because Fedraey is an atoll island it does not have the necessary swampy ecosystems for swamp taro cultivation, however, the use of concrete taro patches has enabled them to plant several swamp taro patches (Yap: Ulithi -The Land: Planting, n.d.). It is apparent that the diverse CSA techniques discussed above are being successfully implemented throughout the Pacific by indigenous communities, including those in Yap, to address the impacts of SLR and strengthen their food security.

4.3 Retreat

Retreat is another type of adaptation strategy that is often used by communities when facing climate change related impacts. In this context, retreat refers to the action of relocating people, assets, and human activities further inland from the coastline in order to mitigate and avoid the impacts of coastal hazards (Coelho et al., 2023; Oppenheimer et al., 2019). There are two types of retreat- managed and unmanaged. The IPCC 6th Assessment Report states that managed retreat is the intentional, coordinated, relocation of individuals and assets to less exposed areas whereas unmanaged retreat is the voluntary movement of people from an exposed area in an unplanned and uncoordinated manner (Oppenheimer et al., 2019). Retreat is especially relevant for regions such as Yap because of the high percentage of built infrastructure located near to or on the coastline. Due to Yap proper's high volume of coastal infrastructure, managed retreat can be used as powerful tool in its adaptation planning for communities facing SLR related coastal hazards. Retreat can be utilitzed as part of a long-term adaptation plans and can be developed to be a phased implementation of different options where there are specific trigger points for each option. Similarly to various other adaptation strategies, retreat has historically been employed by Pacific Indigenous communities as a traditional approach to address environmental challenges.

Yap's communities have a history of relocation as an adaptive strategy. The traditional sawei system encouraged Outer Islanders to journey to Yap proper with gifts and offerings in exchange for disaster relief when the Outer Islands experienced times of environmental vulnerability (Perkins & Krause, 2018). Although this system has evolved since colonization, there are still indicators that relocation is used to increase a community's resilience today (Perkins & Krause, 2018). Yap proper is experiencing an increased number of domestic migrants from the outer atoll islands. These migrants have settled in four communities located on degraded volcanic soils (Grecni et al., 2023). Relocation from outer islands to Yap proper in one way retreat has been used in traditional practices and today to increase the resilience of Yapese communities.

Another way to utilize retreat as an adaptation strategy is to relocate people and assets to higher elevations within the same island. Yap proper has a considerable amount of inland area that may serve as a safer and less exposed alternative compared to the existing coastal communities. An evaluation of these inland areas could determine their suitability, aiding in the identification of the best locations for the successful relocation of currently exposed coastal communities. Retreat is the most effective adaptive strategy in protecting people and assets from SLR impacts for the long-term, however, it can be difficult to implement because of the social, political, and economic complexities involved (Coelho et al., 2023). Consequently, it is vital to have supportive government policies encouraging and facilitating the retreat process, along with community buy-in (Fletcher & Richmond, 2010). Based on the areas and assets that are most exposed, recommendations for implementing retreat strategies include assessing the inland hills behind Colonia as a potential site for a new residential district, particularly for the residents of the low-lying Colonia Community (Fletcher & Richmond, 2010). Additionally, relocating of agricultural activities to areas situated one meter above the maximum overwash elevation (Fletcher & Richmond, 2010). Lastly, identifying areas experiencing higher-than-average erosion rates can guide the prioritization of managed retreat plans, ensuring that the most exposed areas are considered first (Fletcher & Richmond, 2010).

4.4 Policy

Policies play a pivotal role in all facets of adaptation planning, and across the Pacific region, various areas have embraced policy initiatives to aid in their adaptation planning. in adaptation planning. For example, In Palau the state residential lease/housing program promotes the use of sustainable designs in building development to enhance their resilience and sustainability. This initiative supports resilient development by requiring the revegetation of bare soils in order to increase soil health and reduce run-off, the installation of water catchment systems to decrease exposure to drought, and the inclusion of renewable energy sources, with financing facilitated through national loan programs (Mcleod et al., 2019). Additionally, in Palau, land use permits, residential development plans, and commercial development plans are mandated to incorporate measures that enhance water security and erosion control (Mcleod et al., 2019). Hawaiʻi is another region in the Pacific that has employed policy as a tool for adaptation. The City and County of Honolulu, the County of Maui and the County of Kauaʻi have increased their shoreline setbacks and integrated coastal erosion projections into their ordinances 21, 20. These setbacks are designed with careful consideration of historical erosion rates, the expected lifespan of structures, and a buffer zone to account for uncertainties in sea-level rise projections. Furthermore, the Hawaiʻi legislature, in 2021, recognized the importance of requiring sellers of real property to disclose whether the property they are selling would be impacted by 3.2 feet of SLR (H.I. Legis. Assemb, 2021). Additionally, Kauaʻi has incorporated flood depth regulations into its building code, mandating that new residential structures' lowest level be elevated above projected flood depths to mitigate flood-related impacts 22. Yap is also taking steps to enhance resilience through policy changes. In 2017, Yap declared their first Watershed Protected Area, spanning 320 acres of watershed land that is managed and protected by traditional council members and the state government, with the primary goal of increasing water security (Mcleod et al., 2019). In addition to incorporating protected lands into state policy, Yap should also consider other ways to leverage policy to support adaptation.

One way in which Yap could use policy to aid adaptation is through promoting self-sustaining food production in highland areas. Recognizing that SLR will affect coastal agricultural land, it is essential to consider alternatives for food sources. Supporting highlands self-sustaining food production not only safeguards crops from the impacts of SLR but also reduces reliance on imports, which enhances the communities' resilience during extreme climate events. The government can support this through incentives, the development of market infrastructure, and the implementation of economic policies (Fletcher & Richmond, 2010). (Fletcher & Richmond, 2010). Yap could also implement policies similar to those used in Hawaiʻi, such as establishing building codes that require new residential houses to be built with the lowest level elevated above a base flood depth, and establishing a coastal zone management program with coastal setbacks (Fletcher & Richmond, 2010). However, it is vital to acknowledge that successful policy changes require strong community support, which starts with education and community outreach. Therefore, a bottom-up, community-based approach rooted in local traditions and culture is crucial for effective policy creation and implementation.

5.0 CONCLUSION

The results of this project have illuminated that the reality of one meter of SLR on Yap proper could be the inundation of four critical pieces of infrastructure, nine government or non-governmental organization facilities, 16 businesses, 29 cultural sites, and 248 buildings or other structures. These results show a picture of SLR exposure and challenges that lie ahead. Beyond the physical impacts, it is imperative to recognize that SLR has the potential to inhibit basic human rights, such as food security, economic security, and the preservation of culture.

In regions most exposed to the imminent impacts of SLR, it is crucial to develop comprehensive solutions that reduce community exposure and support community resilience. These adaptation options, are vital in addressing the complex challenges posed by SLR. It is important to acknowledge that adaptation is not a new concept; indigenous communities have practiced adaptation for millennia, drawing from a wealth of traditional knowledge. The integration of this indigenous wisdom with modern climate science is essential for effectively adapting communities to SLR.

Furthermore, it is crucial that we continue to advance the development of SLR science and mapping, particularly in under-studied areas like Yap. This ongoing research is essential for supporting further adaptation and planning. By expanding our knowledge of the unique challenges and exposure faced by these communities, we can more accurately recommend adaptation strategies to their specific needs. The collaborative approach, combining traditional knowledge with modern science, will empower communities to confront the challenges of SLR.

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