Engineering Analysis
Appendix C

Guam
Draft
Watershed Plan

US Army Corps of Engineers
Honolulu District

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Table of Contents

1 Study Information

1.1 Purpose and Scope

The purpose of this appendix is to describe the hydraulic analysis conducted in support of Watershed Assessments for Guam an organized, unincorporated territory of the United States. This final report is an addendum to the main Planning Level study report. This report incorporates comments received during District Quality Control (DQC), and Public Review. This report communicates the Coastal and hydrologic technical analysis used to support conclusions reached for this Watershed Assessment. The study will assess the watershed characteristics; identify problems and data gaps; develop, evaluate, and prioritize an array of strategies that include structural and non-structural measures; and identify funding opportunities for Federal and Territorial agencies to support the selected strategy. This watershed assessment incorporates available information from existing data, reports and, on-going efforts from local and federal agencies to provide a suite of recommendations to enhance community resiliency, improve watershed management, and assess the drivers of economic impacts through engagement with the public and other Federal and Territorial agencies.

1.2 Location

Guam is in the western Pacific Ocean and is the largest and southern-most island of the Mariana Archipelago and is located at Latitude 13° 26' 39.4944" and Longitude 144° 47' 37.4352" E (see Figure 1 and Figure 2). The island is approximately 30 miles long with a landmass of 212 square miles and is divided into 19 separate watersheds (Figure 3-6). Approximately 160,000 people inhabit the island with the main population centers located on the central western shore, in the city of Hagatna, and on the entire northern portion of the island.

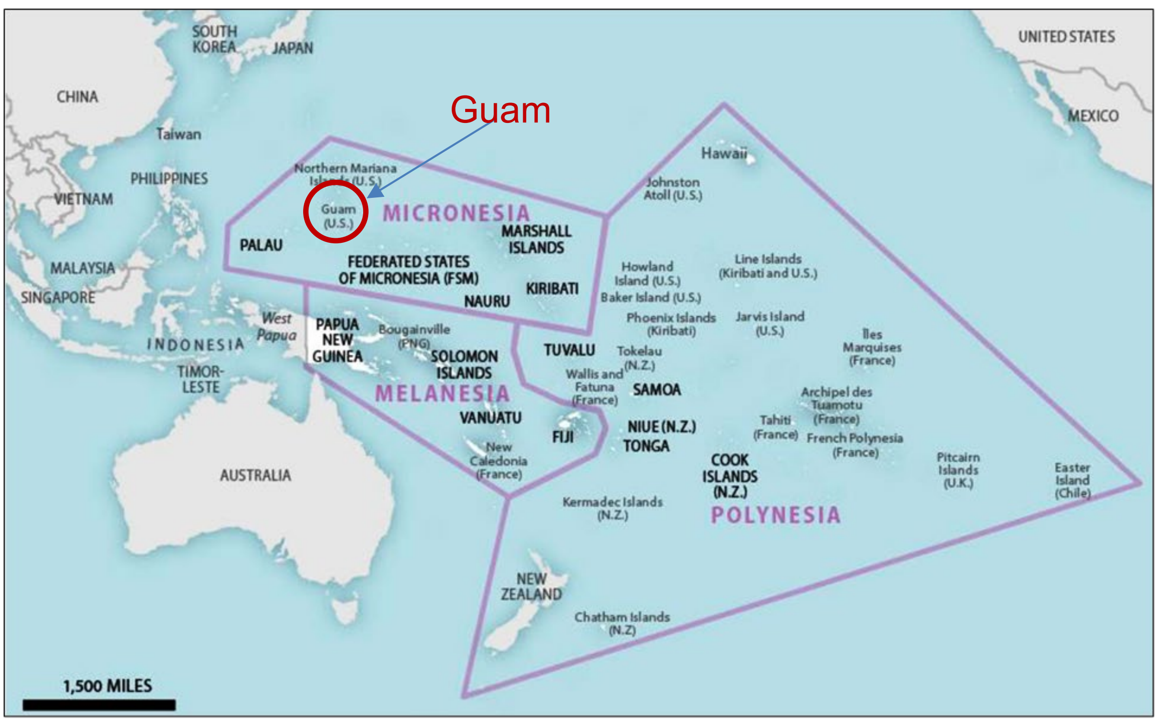

Figure 1-1 General Map of Pacific Islands Region

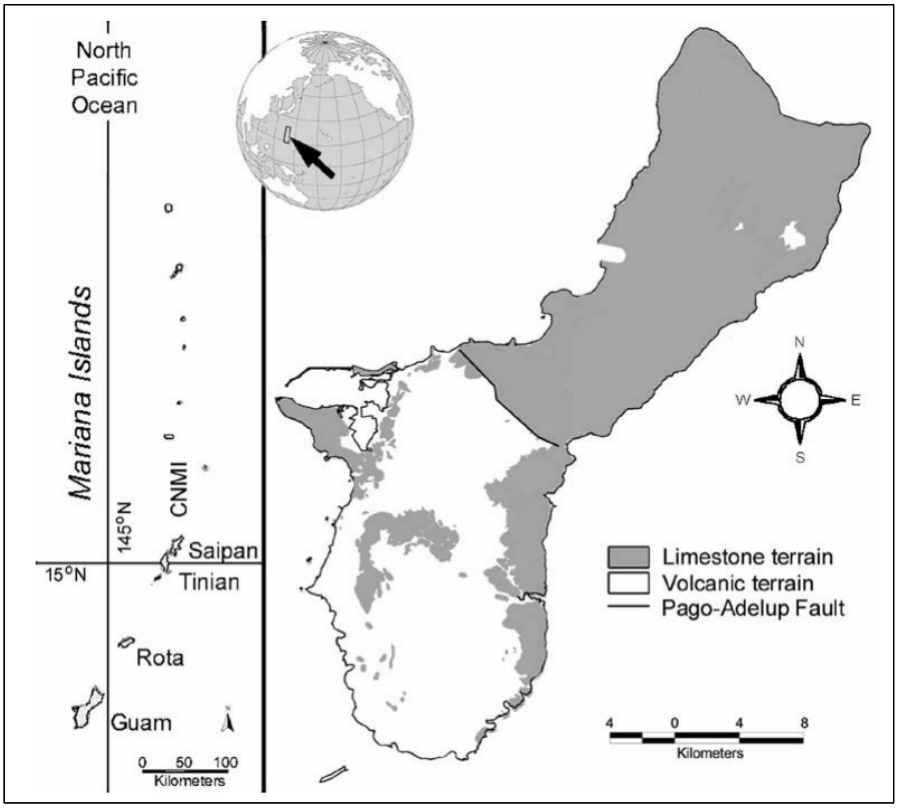

Figure 1-2 Mariana Islands Vicinity; Terrain of Island of Guam. (Image courtesy of Water & Environmental Research Institute of the Western Pacific University of Guam)

2 Existing Conditions

2.1 Hazard Assessment

Many hazards affect northern and southern Guam differently due to the two distinct geological features of the two regions, while some hazards have impacts throughout Guam. Hazards identified based on existing data and information include:

- Coastal erosion is problematic along Guam's 78 miles of coastline, most significant in southern Gaum (south of Tumon and Pago Bays).

- Climate related hazards include:
  - Total storm trends and typhoon intensifications show increases of roughly 5.4% and with intensities and increasing by 9.3% respectively, when compared to the period between 1986-2005 (NOAA, 2018)
  - Sea level rise (SLR) increases the consequences of tropical cyclones and is projected to increase
  - Degraded ecosystem health risk is increased due to more extreme water level and temperature fluctuations; and
  - ENSO specific hazards, including:
    - Guam experiences more drought during the El Niño phase.
    - Extreme El Niño events have increased since 1970.

    - Without significant changes in human activity (anthropogenic forcing), El Niño events are projected to increase in frequency and intensity in the future, potentially resulting in increased droughts and profound socioeconomic consequences; and
- El Niño-driven droughts reduce available water supply.
- Flooding related hazards include:
  - Riverine floods along low lying coastal and urban reaches
  - Flash floods; and
  - Coastal storm surge.
- High wind events during storms damage infrastructure and agriculture due to corrosive salt spray.
- Hazardous materials leach into streams and aquifers due to:
  - Leaking septic tanks and sewage spills.
  - Industrial spills.
  - Agricultural runoff.
  - Storm water; and
  - Coastal contamination.

2.2 Topography and Soils

Guam can be divided into two geologic regions. The southern portion is mountainous with steep slopes and volcanic streams. Soils are unstable clay-sand and volcanic rock. The northern portion is predominately flat limestone with steep coastal cliffs along the plateau edges and narrow coastal plains inland. Limestone is highly porous with the NGLA underneath. Sinkholes exist in both the north and south regions and are more prevalent in the northern limestone topography.

2.3 Vegetation

Southern Guam consists of non-vegetated areas or savanna grasses (swordgrass and mission grass) along the numerous mountain stream beds. Associated plant communities of Southern Guam's grasslands, ravine forests, and coastal areas provide habitat to the endangered Gallinula chloropus guami (Mariana common moorhen), Aerodramus bartschi (Mariana swiftlet), Erotmochelys imbricata (hawksbill turtle) and threatened Pteropus mariannus mariannus (Mariana fruit bat) and Chelonia mydas (green sea turtle). (NRCS)

Northern Guam has five main vegetation types associated with limestone soils; Breadfruit, banyan, Mammea, Cordia, nunu and aggag. Figure 2-1 illustrates the vegetation types (HMP 2019). Vegetation in the north is dominated by thick secondary scrub and urban vegetation (i.e., lawns and ornamental trees and shrubs) inland, and by strand and limestone forests in coastal areas. The high elevation of the limestone plateau prevents the root zone from reaching the freshwater lens. In the south, vegetation is dominated by savanna and patches of forest, mostly riverine forests that form along valleys and ravines. The low-lying portions of river valleys are occupied by swamp forests, marshes, and occasional cultivated clearings. (Digital Atlas of Guam)

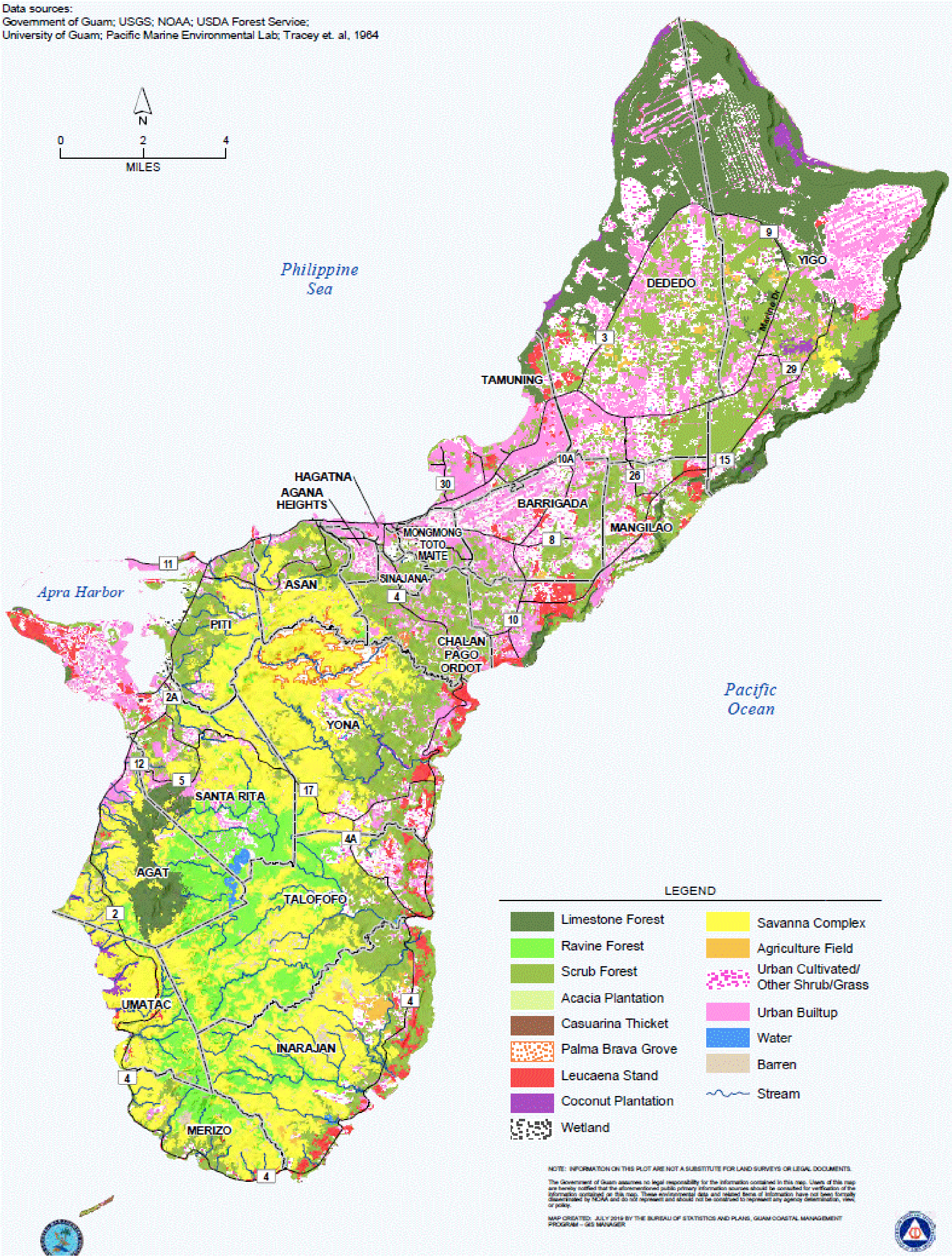

Figure 2-1. Vegetation Types of Guam

2.4 Climate Conditions, Variability, and Change

Climate

Guam has a tropical rainforest climate, though its driest month of March almost averages dry enough to qualify as a tropical monsoon climate. The weather is generally hot and humid throughout the year with little seasonal temperature variation. Hence, Guam is known to have equable temperatures year-round. Trade winds are fairly constant throughout the year, but there is often a weak westerly monsoon influence in summer. Guam has two distinct seasons: Wet and dry season. The dry season runs from January through May and June being the transitional period. The wet season runs from July through November with an average annual rainfall between 1981 and 2010 of around 98 inches. The wettest month on record at Guam Airport has been August 1997 with 38.49 inches and the driest was February 2015 with 0.15 inches. The wettest calendar year has been 1976 with 131.70 inches and the driest was in 1998 with 57.88 inches. The most rainfall in a single day occurred on October 15, 1953, when 15.48 inches fell.

The mean high temperature is 86 °F and mean low is 76 °. Temperatures rarely exceed 90 °F or fall below 70 °F. The relative humidity commonly exceeds 84 percent at night throughout the year, but the average monthly humidity hovers near 66 percent. The highest temperature ever recorded in Guam was 96 °F on April 18, 1971, and April 1, 1990. A record low of 69 °F was set on February 1, 2021, while the lowest recorded temperature was 65 °, set on February 8, 1973. Figure 2-2 below illustrates the range of temperatures seen in Guam.

Climate data for Guam International Airport (1991–2020 normals, extremes 1945–present) [hide]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °F (°C)	94 (34)	93 (34)	93 (34)	96 (36)	94 (34)	95 (35)	95 (35)	94 (34)	94 (34)	93 (34)	92 (33)	91 (33)	96 (36)
Average high °F (°C)	85.7 (29.8)	85.7 (29.8)	86.7 (30.4)	87.9 (31.1)	88.5 (31.4)	88.5 (31.4)	87.7 (30.9)	87.0 (30.6)	87.0 (30.6)	87.2 (30.7)	87.4 (30.8)	86.6 (30.3)	87.2 (30.7)
Daily mean °F (°C)	80.3 (26.8)	80.1 (26.7)	81.0 (27.2)	82.3 (27.9)	83.0 (28.3)	83.1 (28.4)	82.2 (27.9)	81.5 (27.5)	81.5 (27.5)	81.7 (27.6)	82.2 (27.9)	81.6 (27.6)	81.7 (27.6)
Average low °F (°C)	75.0 (23.9)	74.6 (23.7)	75.4 (24.1)	76.7 (24.8)	77.5 (25.3)	77.7 (25.4)	76.8 (24.9)	76.1 (24.5)	76.0 (24.4)	76.3 (24.6)	77.0 (25.0)	76.5 (24.7)	76.3 (24.6)
Record low °F (°C)	66 (19)	65 (18)	66 (19)	68 (20)	70 (21)	70 (21)	70 (21)	70 (21)	70 (21)	67 (19)	68 (20)	68 (20)	65 (18)
Average precipitation inches (mm)	5.34 (136)	4.15 (105)	2.77 (70)	3.50 (89)	4.45 (113)	6.51 (165)	12.25 (311)	17.66 (449)	15.17 (385)	12.73 (323)	8.29 (211)	5.30 (135)	98.12 (2,492)
Average precipitation days (≥ 0.01 in)	20.1	18.0	18.3	18.9	19.7	23.2	26.0	25.9	25.1	25.4	23.9	22.7	267.2
Average relative humidity (%)	83.7	81.9	83.1	82.0	82.7	82.7	87.3	88.7	88.8	88.3	86.6	83.0	84.9
Mean monthly sunshine hours	176.0	173.7	216.4	214.0	219.9	193.8	156.1	142.2	132.7	132.6	135.0	143.4	2,035.8
Percent possible sunshine	50	53	58	57	56	50	39	37	36	36	39	41	46

Source: NOAA (relative humidity and sun 1961–1990)[34][35][36]

Figure 2-2. Climate Data for Guam International Airport (Source: https://en.wikipedia.org/wiki/Guam)

Guam can be categorized into two distinct regions, northern and southern, due to its unique geography. A flat limestone plateau in the northern region provides a permeable surface for rainfall to infiltrate and recharge the Northern Guam Lens Aquifer and is the largest source of drinking water for most of the population. The southern portion of the island contains a mountain range on the west coast and more than 45 rivers that discharge into the ocean. Much of the south is covered by grassland. Guam is enclosed by a fringing reef interrupted only at a few of the bays.

The tropical monsoon climate brings an average rainfall of 98 inches during the wet season (July – November). Guam lies within 180 nautical miles to the southeast of the main zone of typhoon activity, known as Typhoon Alley. As such, the island is affected by the winds, storm surges, and rains of near-passing typhoons and suffered direct contact with typhoons in the past. On average, Guam is impacted by one to three tropical storms per year (NWS 2020).

Guam's climate, to include typhoon activity, is affected by the El Niño Southern Oscillation (ENSO), a climate phenomenon with three phases: El Niño, La Niña, and ENSO-neutral. El Niño and La Niña are opposite phases that involve changes in both the ocean and atmosphere. The ENSO-neutral phase is in the middle of the continuum between El Niño and La Niña. The El Niño phase brings about lower sea levels and reduced rainfall near Guam. The La Niña phase brings about higher sea levels and more typical rainfall patterns near Guam. During the ENSO-neutral phase, conditions are generally closer to average for the area. The El Niño Southern Oscillation (ENSO) is a Pacific wide oceanic condition that is quantified by higher water temperatures in the eastern Pacific. ENSO patterns in the Western Pacific are generally the reverse of those conditions that occurs in the Eastern Pacific. When a strong El Niño occurs on the west coast of the United States, cooler water temperatures prevail near the Northern Mariana Islands. Figure 4 presents a summary of conditions experienced during such an event. It is noted that the reverse occurs during a La Niña event in the eastern Pacific, although there is a decreased risk of tropical events near the Northern Mariana Islands (NOAA, 2019).

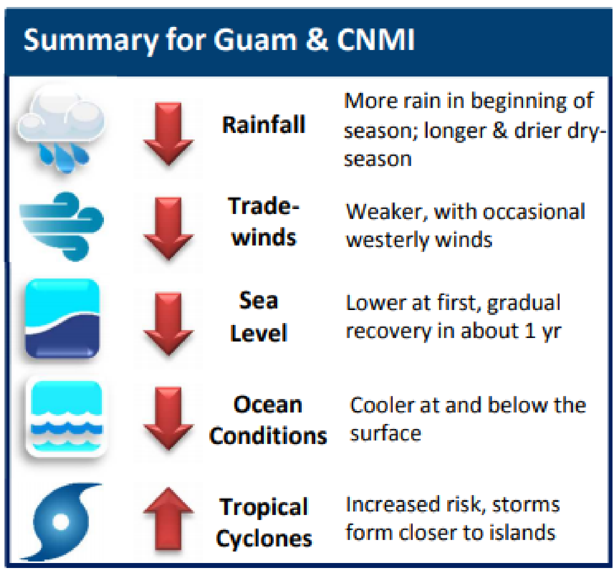

Figure 2-3 Impacts on Western Pacific

Climate is strongly correlated to ENSO fluctuations. During El Nino years, easterly trade winds are reduced which allows warmer western Pacific waters and higher sea levels to migrate eastward. This reduces sea levels in the western Pacific, reduces the warm oceanic pool, and is typically followed by drought. El Nino has a wet and dry phase in the western Pacific, which commences with higher rainfall, tropical storm, and typhoon activity, then migrates into drought. The driest year on record over recent decades preceded the strong El Nino event in 1997.

During El Nino events strong typhoons can develop southwest of Hawaii and travel to the Mariana Islands, allowing storms to develop strength. El Nino events are projected to intensify in the Pacific due to climate change (NOAA, 2018). El Nino events not only bring increased tropical storms; they also bring subsequent droughts and are therefore a key driver in weather hazards in the Mariana Islands. Figure 5 illustrates the three ENSO phases of neutral, El Nino (warm ocean temperatures), and La Nina (cooler ocean temperatures) climate conditions.

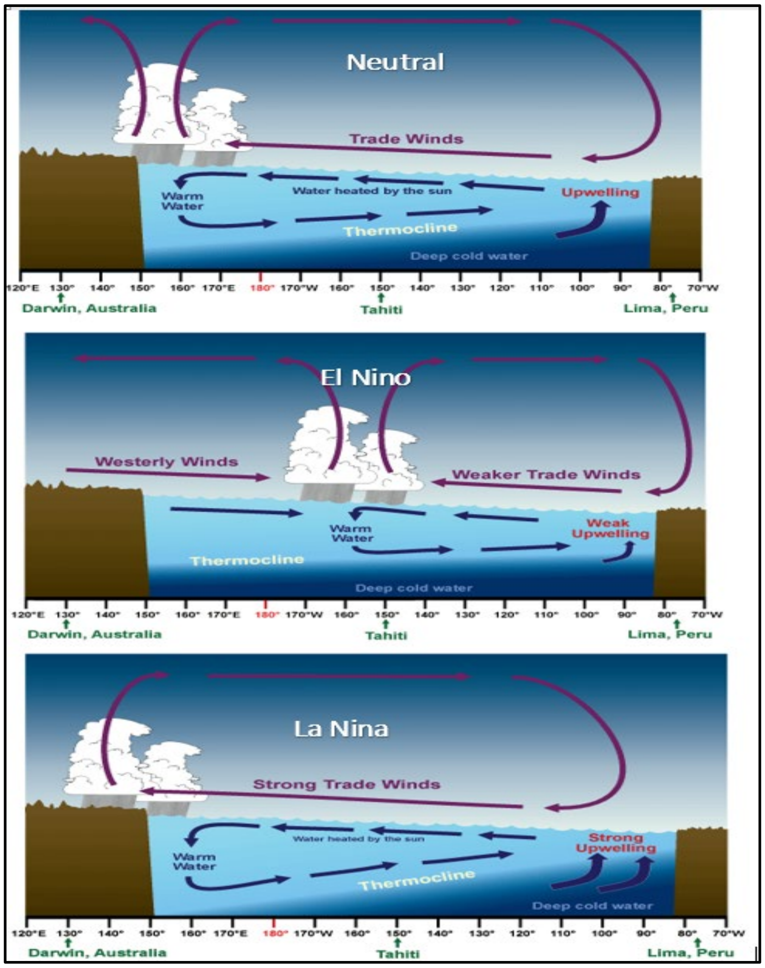

Figure 2-4 ENSO fluctuations in the Pacific: Neutral, El Nino, and La Nina (source: NOAA)

Wind

The Mariana Islands have a tropical marine climate and lie within the trade wind latitudes but are also impacted by monsoons. The prevailing winds near the Mariana Islands are easterly trade winds, which approach from the northeast through east-southeast sector. Trade winds occur nearly 80 percent of the time and are strongest and most consistent during the dry season from January through May. Wind direction is more variable during the primary typhoon season from July through December.

Trade winds are pronounced during January through May when winds blow from the Northeast more than 90% of the time. Wind directions are far more variable during July through October when tropical cyclones can impact the area. More rain falls in the upper slopes of the islands than in the coastal areas. There are distinct wet and dry seasons, the letter extending from about December to June although the onset of each season is not abruptly marked. Periodic rains can be expected during the dry season. Two main storm systems contribute to the climatic character of the islands; small-scale storms that are locally influenced or large-scale systems such as tropical storms or typhoons. The small-scale systems may only impact areas of a few square miles while larger systems may impact more than a quarter million square miles and can persist for more than a week.

The seasonal trend of winds is presented in the box-and-whisker plot in Figure 6. This plot shows the mean value as the star, the median as the red line, the blue box contains the values between the first and third quartile (25th percentile to 75th percentile), the dashed lines to the whisker indicate values between the expected minimum and maximum values and the black crosses indicate the outliers in the dataset.

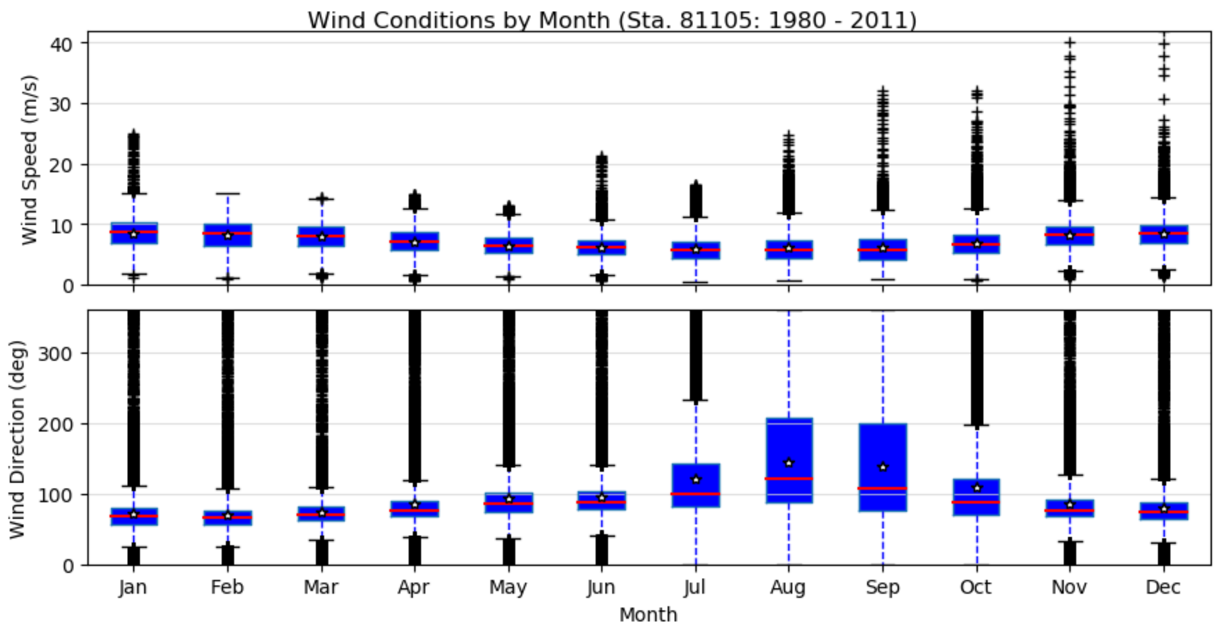

Figure 2-5 Seasonal Variation of Local Winds

Precipitation

Engineering and Construction Bulletin (ECB) Number 2108-14 outlines guidance for incorporating Climate Change Impacts to Inland Hydrology in Civil Works, Designs, and Projects. The ECB requires application of several tools available on Climate Preparedness and Resilience CoP Applications Portal at the URL provided here, (https://maps.crrel.usace.army.mil/projects/rcc/portal.html), however those tools do not cover the geographic region of Guam. The intent of the requirements of the EBC, which include an analysis and comprehensive literature review of observed and projected climatic trends, has been met based on the information presented while using the best available data from websites created by NOAA/NWS were used for this analysis.

Annual precipitation deviation from normal are more difficult to quantify. ENSO cycles as well as tropical storm activity can vary in duration and frequency and disrupt normal rainfall trends. Figure 7 illustrates the latest 29-year normal and observed precipitation deviations. A 2.1-inch reduction in annual precipitation is shown in observed rainfall compared to normal but is an insignificantly difference. However, increased oceanic and atmospheric temperatures and concentrations of carbon dioxide may lead to an increase in weather extremes such as rainfall intensity, droughts, and storms. Rainfall intensity and typhoon intensity are projected to increase (IPCC, 2019). Average annual precipitation is 98.1 inches. (NOAA NOWDATA).

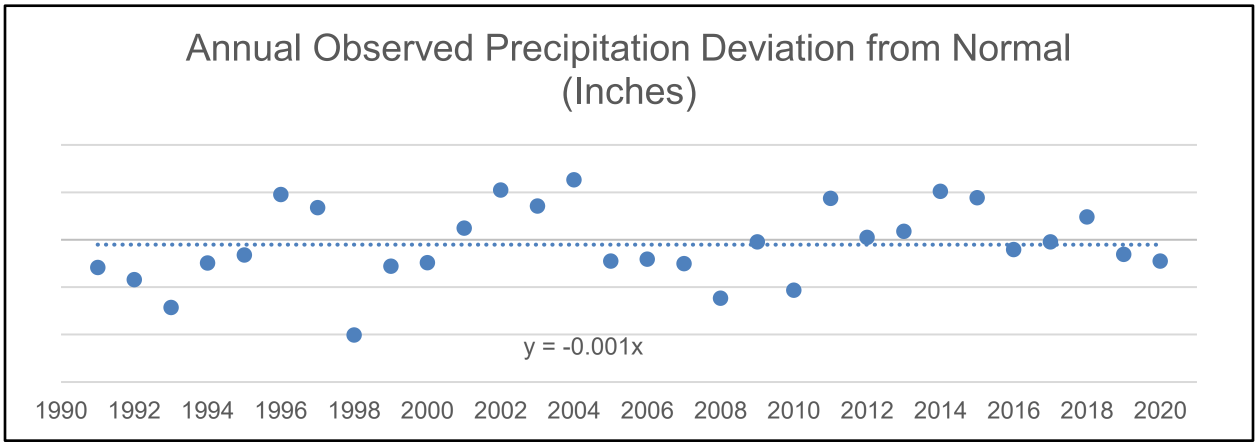

Figure 2-6 Departures from Normal, Annual Precipitation for Guam (Source: NOAA NOWDATA)

Climate impacts sea level, coastal storm surge, tropical cyclone intensity, agriculture, transportation, power, and economy and is significantly tied to El Nino Southern Oscillation (ENSO) fluctuations. ENSO consists of three phases, Neutral, El Nino and La Nina, with average durations between 9-18 months. The relationship between El Nino and La Nina cycles and the Southern Oscillation is a relationship between oceanic sea surface temperatures (SSTs) and the atmospheric pressure gradient, respectively. In neutral conditions the Pacific trade winds are driven westward owing to changes in the atmospheric pressure gradient across the Pacific, where lower atmospheric pressures in the western Pacific and higher pressure to the east drive trade winds and warmer Sea Surface Temperatures (SSTs) westward. Consequently, cooler SSTs are observed in the eastern Pacific. SST's transfer heat to the atmosphere, which, in turn, change the pressure gradient. In other words, the pressure gradient affects the SST's and the SST's affect the pressure gradient. This circulation is referred to as the Walker Circulation. Under El Nino conditions, trade winds weaken, allowing warmer western Pacific waters to migrate eastward. This results in lower sea levels and SSTs in the western Pacific and higher sea levels and SSTs in the eastern Pacific. Sea surface elevations can fluctuate from El Nino and La Nina events by as much as 0.7 to 1.0 feet (IPRC, 2014). During El Nino the western Pacific experiences reduced rainfall and drought conditions, while the eastern Pacific experiences wetter conditions. Under La Nina conditions, trade winds increase, resulting in significant pooling of warm water and higher SSTs in the western Pacific, increased sea levels, and increased convection. Correspondingly, lower SST's, lower sea levels, and reduced convection occurs in the eastern Pacific (NOAA, 2021).

2.5 Typhoons

A tropical cyclone is a generic term for a warm-core non-frontal cyclonic system over tropical or sub-tropical waters. A tropical storm is a tropical cyclone with maximum sustained winds between 39-73 mph. A tropical cyclone, or typhoon as they are known in the Western Pacific, is one with sustained winds greater than 73 mph. Typhoons occur from July to January and are generated very near to the Mariana Islands. Typhoon strength winds can impact the islands within 72 hours after initial storm formation. Wind speeds during typhoons can be 120 mph or greater. The Mariana Islands lie within one of the most active tropical cyclone regions in the world and experience increased risk of storms during El Nino years. Sustained winds of 170 miles-per-hour (mph) and gusts of 200 mph were documented during the October 24-25th 2018 passage of Super Typhoon Yutu through the Mariana Islands. From tropical storm track information, two tropical events impact the Mariana Islands yearly. Figure 8 shows the paths for all tropical events from 2000 through 2020 passing within 250 nautical miles from Guam.

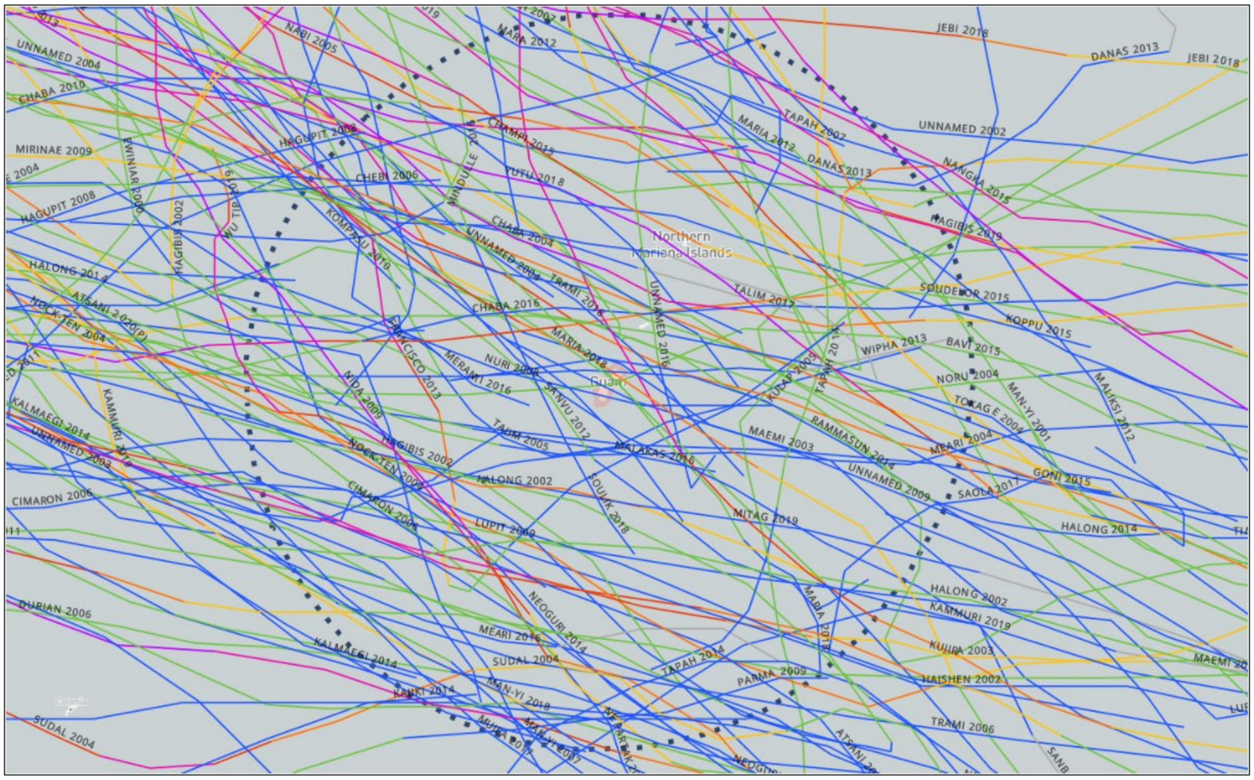

Figure 2-7 Tropical Events from 2000 to 2020 Passing Within 250 Nautical Miles from Guam

The effects and duration of typical typhoons are investigated by evaluating the combined storm surge (nontidal residuals) and offshore wave height. It is observed that the total storm duration is approximately one day while the peak of the waves lasting 1 – 2 hours. The nontidal residual is highly dependent on both the distance the storm passes from the island and the direction that it passes.

The NOAA National Hurricane Center (NHC) produces hurricane forecast and modeling utilizing the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) models. FEMA utilizes these maps in their HURREVAC programs for emergency planning and are downloadable (NOAA NHC, 2021). Below is a Maximum Of the Maximum, MOM, inundation map for Guam based on Mean-High-High-Water (MHHW). Figure 9 and Figure 10 below are the inundation MOM maps depicting the maximum envelope of water for an existing condition, worst-case typhoon.

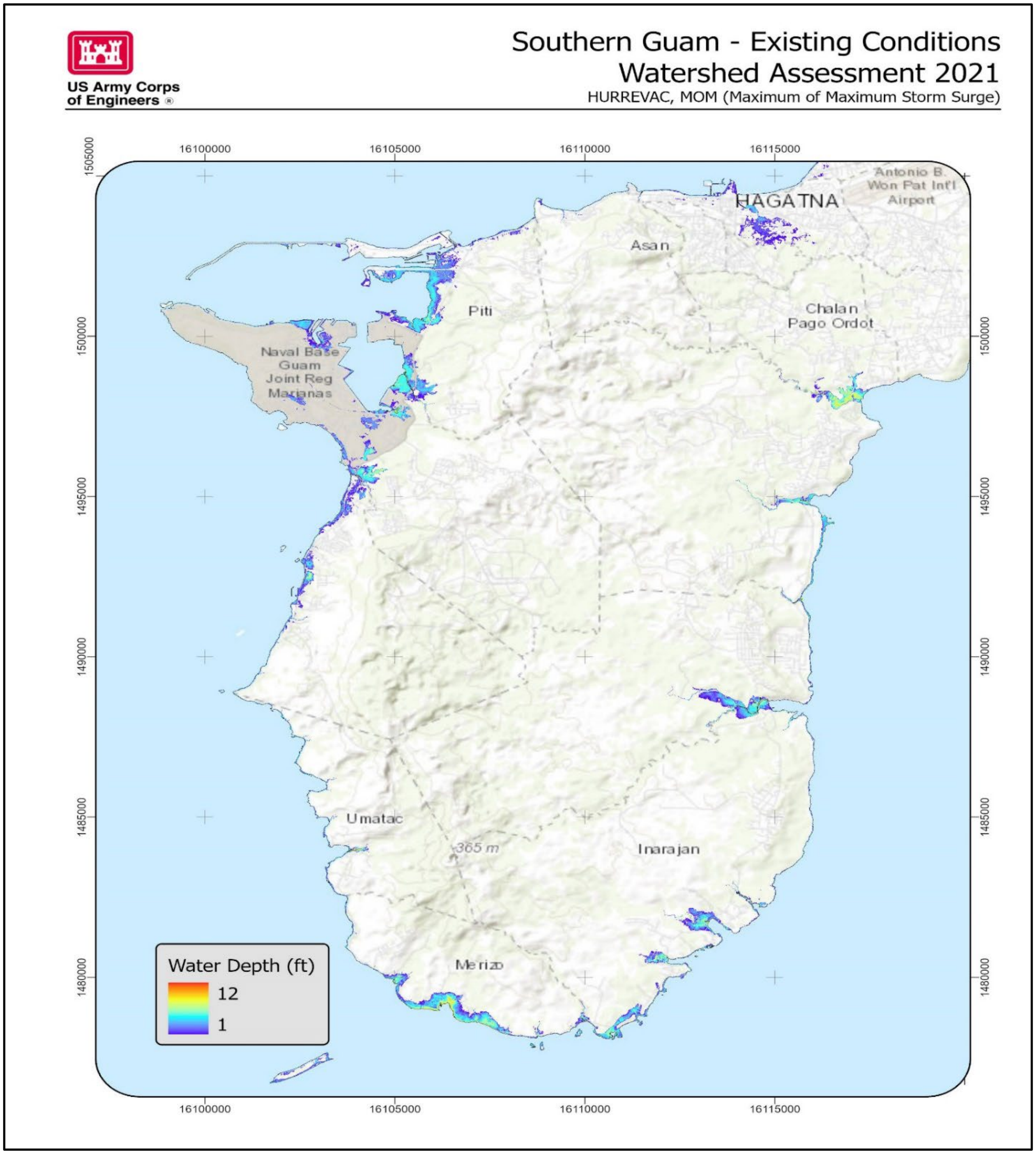

Figure 2-8 Southern Guam Typhoon Inundation - Existing Conditions (HURREVAC MOM) (ESRI)

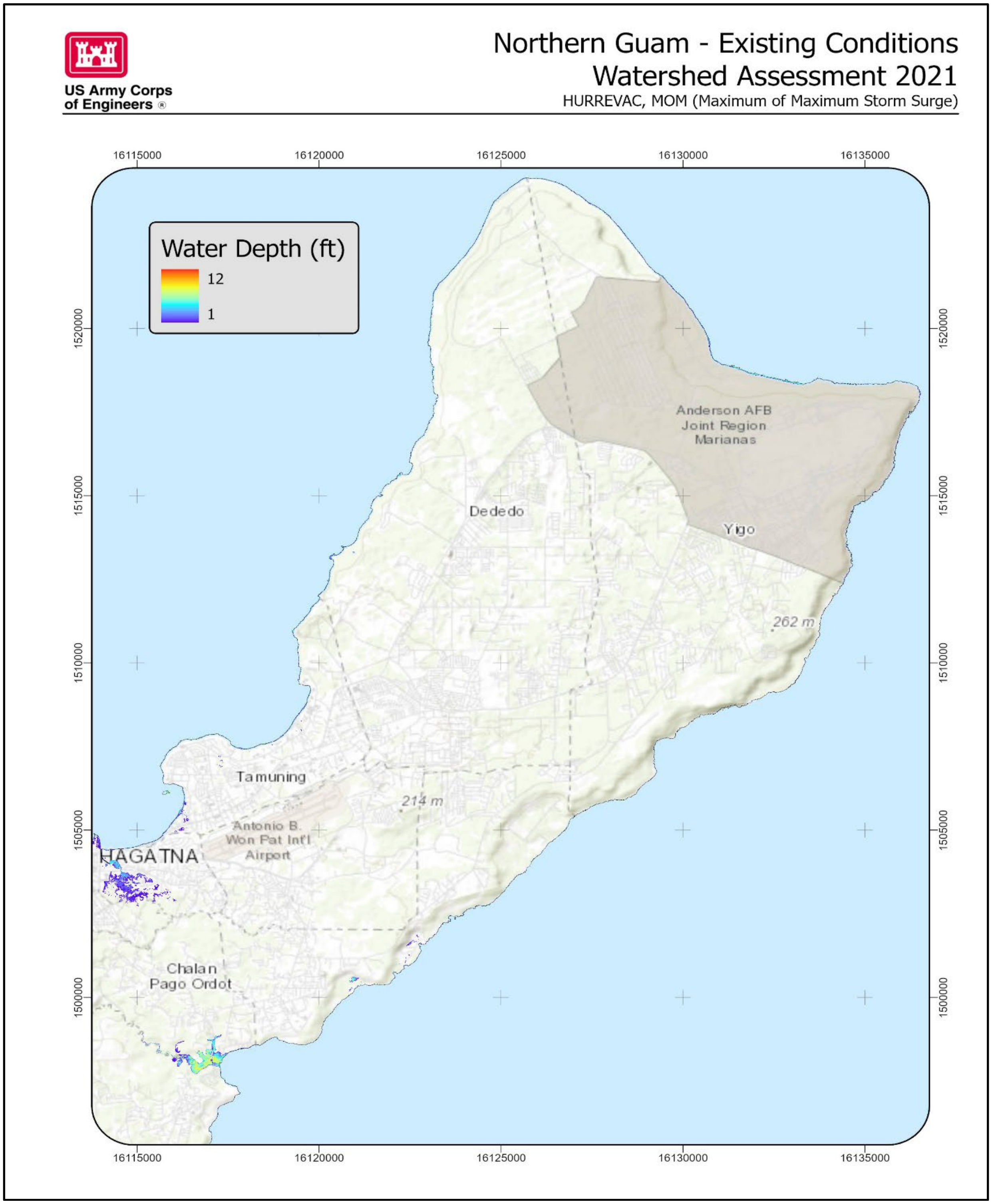

Figure 2-9 Northern Guam Typhoon Inundation - Existing Conditions (HURREVAC MOM) (ESRI)

2.6 Coastal Waves

There are five distinct wave patterns within the region of Guam and the Northern Mariana Islands that contribute to coastal flooding. Local "trade winds" generate waves from the east, long period swell energy from the north, local wind generated waves from the north, long period swell energy from the west or southwest and waves associated with tropical cyclones (Fletcher, 2007). The most common condition is trade wind generated wave from the east. Figure 2-9 presents the return period of long-period swell events based on a local WIS station (WIS 81105).

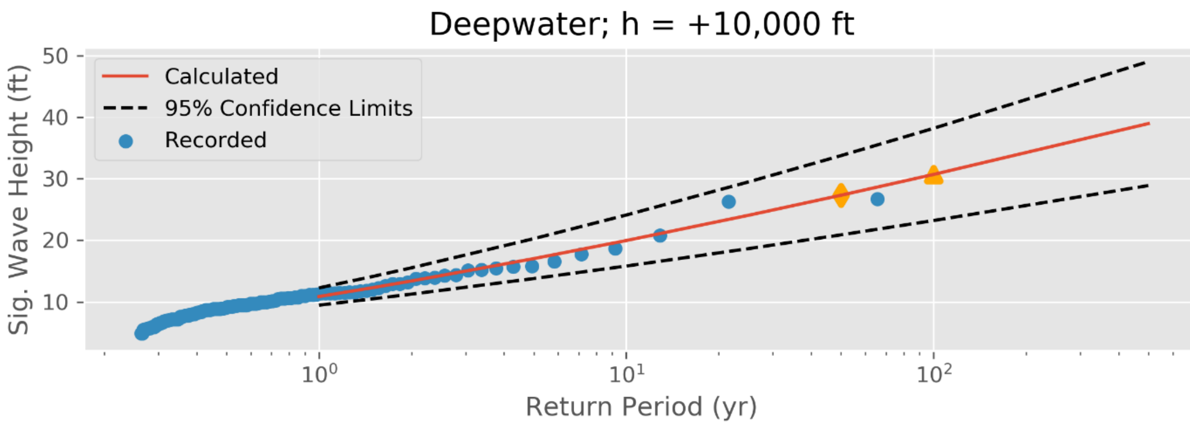

Figure 2-10 Extreme Event Analysis in Deepwater

2.7 Coastal and Riverine Flooding

The Federal Emergency Management Agency (FEMA) coastal and estuarine flood zones for a 1% annual chance of exceedance (ACE) are shown in Figure 12 and Figure 13. The inundation maps are expressed as the 1% ACE wave run-up over mean sea level (the equivalent for the Guam local datum) for coastal (V) (A) and estuarine flood zones. VE or AE zones include base flood elevation (BFE) without the wave run-up calculation (FEMA, April 2006). A zone marked V/VE designates a wave run-up that is greater than three feet above a 1% ACE still water elevation (SWEL or BFE). A SWEL assumes a static water line without shoaling or dune effects incorporated in modeling wave run-up. The SWEL is a flood water surface above high tide. An A/AE/AO zone designates a wave run-up depth that is 1-1.5 feet above the SWEL (AO designated sheet flow at 1-1.5 feet of depth). If this zone is adjacent to a V/VE zone it is typically due to raised topography at the location or due to reef or engineered protection. Coastal flooding is escalated by development and impervious roads and infrastructure.

Seventy days of riverine flooding events have been recorded since 1950 on Guam with $1.5 M in damages. Most flooding is related to tropical storms and cyclones, and antecedent conditions created by large storms which can lead to flooding from a subsequent light rainfall event. In November of 2001, rainfall of only 0.87 inches over a 6-hour period caused depths of 2 ft at the Guam Waterworks pump station in Upper Tumon. Nine flash flood events are recorded with estimated damages of $6.5 M (NOAA NCEI).

During a 10-year period, 35 fatalities and 41 injuries have occurred due to high surf and storm surge (NOAA, NCEI). The population often focuses on local storm events and can be caught without warning when distant storms or ocean circulation produce coastal storm surge under calm weather conditions. Typhoons are the source of the largest frequent wave events. Coastal flooding dominates damages and life loss in Guam. Flooding is focused along the coast and low-lying coastal communities, and to riverine overbanks. Critical infrastructure such as roads and harbors are in these low-lying areas which drive consequences. Disruptions to ports and harbors during storm surge disrupts critical imports (food and fuel) and exports. The predominate limestone (karst) geology in Northern Guam is comprised of sinkholes, depressions, disappearing streams, and caves. Karst terrains are known for pirating surface flow to storage below. This storage attenuates and lags flow, reaching base level to become a freshwater (lens) aquifer resting above saltwater (basal aquifer), or bedrock (para basal aquifer), or the flow recharges to the surface in springs. The undefined drainage from Chalan Pago Ordot to Hagatna is a Northern Guam exception and FEMA has analyzed this basin to fall within the 1% ACE flood hazard zone (A). This hazard zone is highly developed and impacts Maimai Route, Guelo Yan Guela Street, Lower Hagatna developments, and others. Other developments in the headwaters of Talofofo River in southern Guam are also within the FEMA 1% flood hazard zone. Developments within the Namo and Aplacho River floodplains, near the Guam Naval Base, are also vulnerable.

Southern Guam has regions of exposed volcanic basement rock and therefore more surface run-off than Northern Guam. Figure 12 and Figure 13 depict the South and North Guam 1% annual chance of exceedance (ACE) hazard zones for coastal storm surge (V/VE) above the 1 % still water elevation or base flood elevation (SWEL, or BFE) and 1% ACE hazard zones for riverine flooding (A/AE) based on FEMA Flood Insurance Studies (FEMA FIS, 1998).

Storm surge hazards are highest along the western shorelines near Hagatna and Agate and the southern region of Guam. Riverine flooding poses the most infrastructure impacts along lower reaches within estuarine zones where coastal backwater and urban runoff combine to impact roadways and businesses. These areas include but are not limited to Talofofo River and upper tributaries, Ylig River, Inarajan River, and the Hagatna River, and the undefined channels in the upper basin near the Chalan Pago Ordot development.

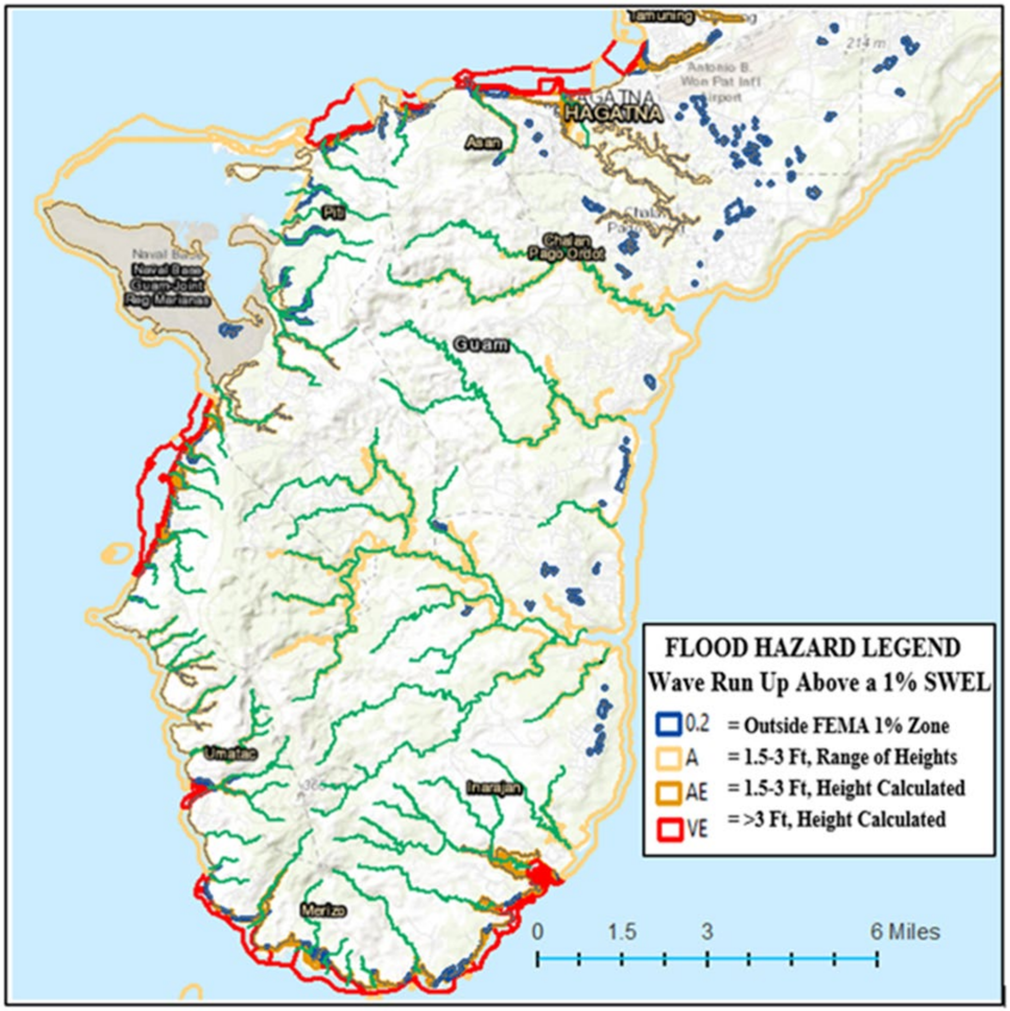

Figure 2-11 FEMA 1% ACE Coastal Wave Run Up and Riverine Flood Hazard Zones

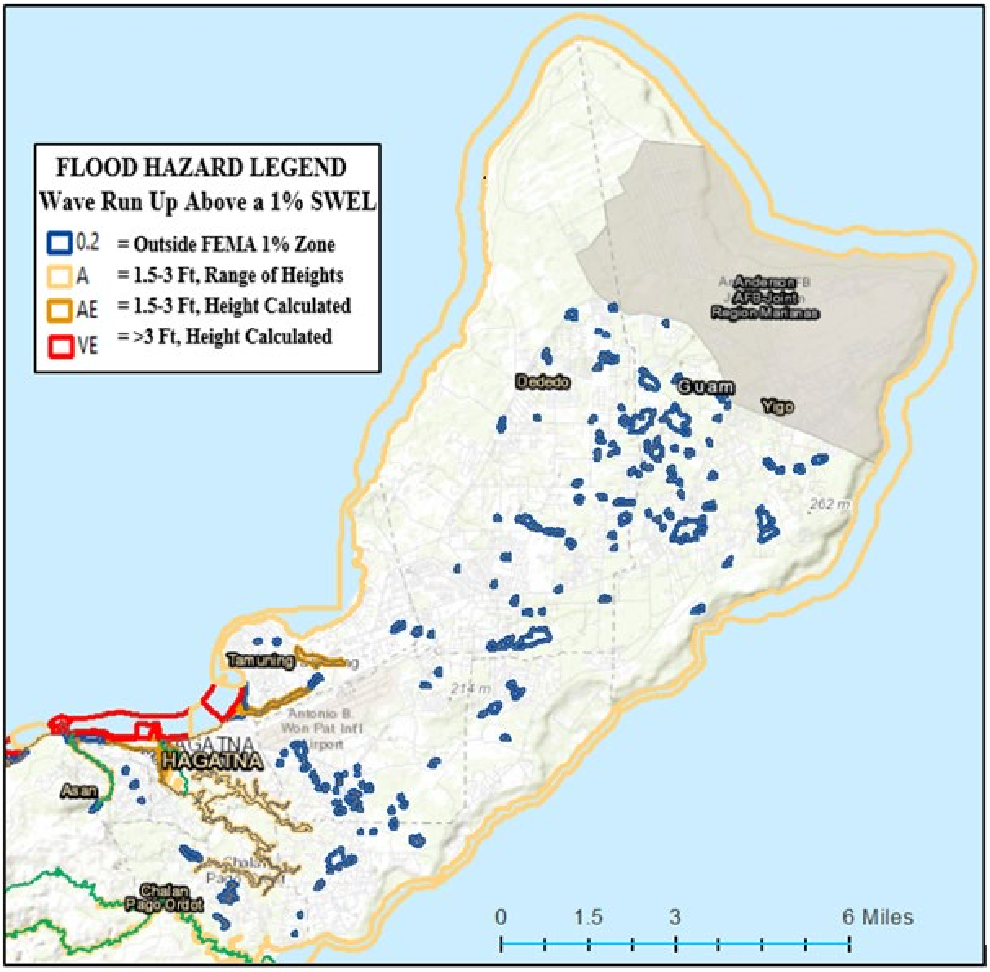

Figure 2-12 FEMA 1% ACE Coastal Wave Run Up and Riverine Flood Hazard Zones

2.8 Seismicity

The Guam and the Northern Mariana Islands are part of a geologic structure known as the Izu–Bonin–Mariana Arc system, and range in age from 5 million years old in the north to 30 million years old in the south (Guam). The land mass of Guam rests along a tectonically complex zone near the triple junction of the Philippine, Caroline, and Pacific Plates. The island chain arose as a result of the western edge of the Pacific Plate moving westward and plunging downward below the Mariana plate, a region which is the most volcanically active convergent plate boundary on Earth. This subduction region, just east of the island chain, forms the noted Mariana Trench, the deepest part of the Earth's oceans and lowest part of the surface of the Earth's crust. In this region, water trapped in the extensive faulting of the Pacific Plate, is heated by the higher temperatures of depth during its subduction, the pressure from the expanding steam results in the hydrothermal activity in the area and the volcanic activity which formed the Mariana Islands (Wikipedia).

Figure 2-12 illustrates the major subduction zones in the western Pacific region. A USGS list of western Pacific earthquakes with magnitudes above 8.0 between 1900-2014 yields 14 historic earthquakes having a potential of triggering a local tsunami that would impact the vicinity of the Guam and the Marianas are illustrated in Figure 2-13.

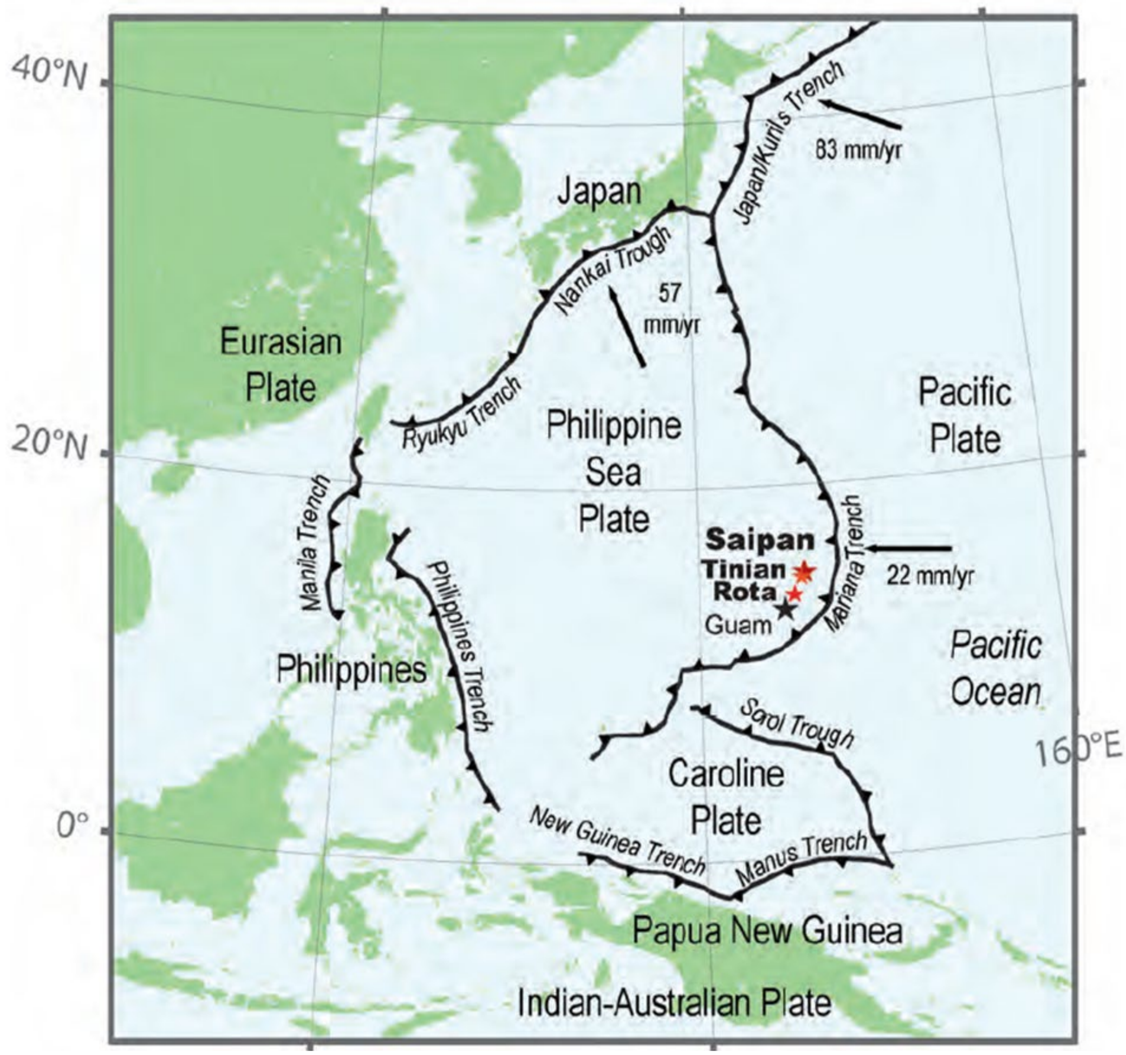

Figure 2-13 Regional Setting of Guam and Proximity to Major Subduction Zones (NOAA OAR, 2014)

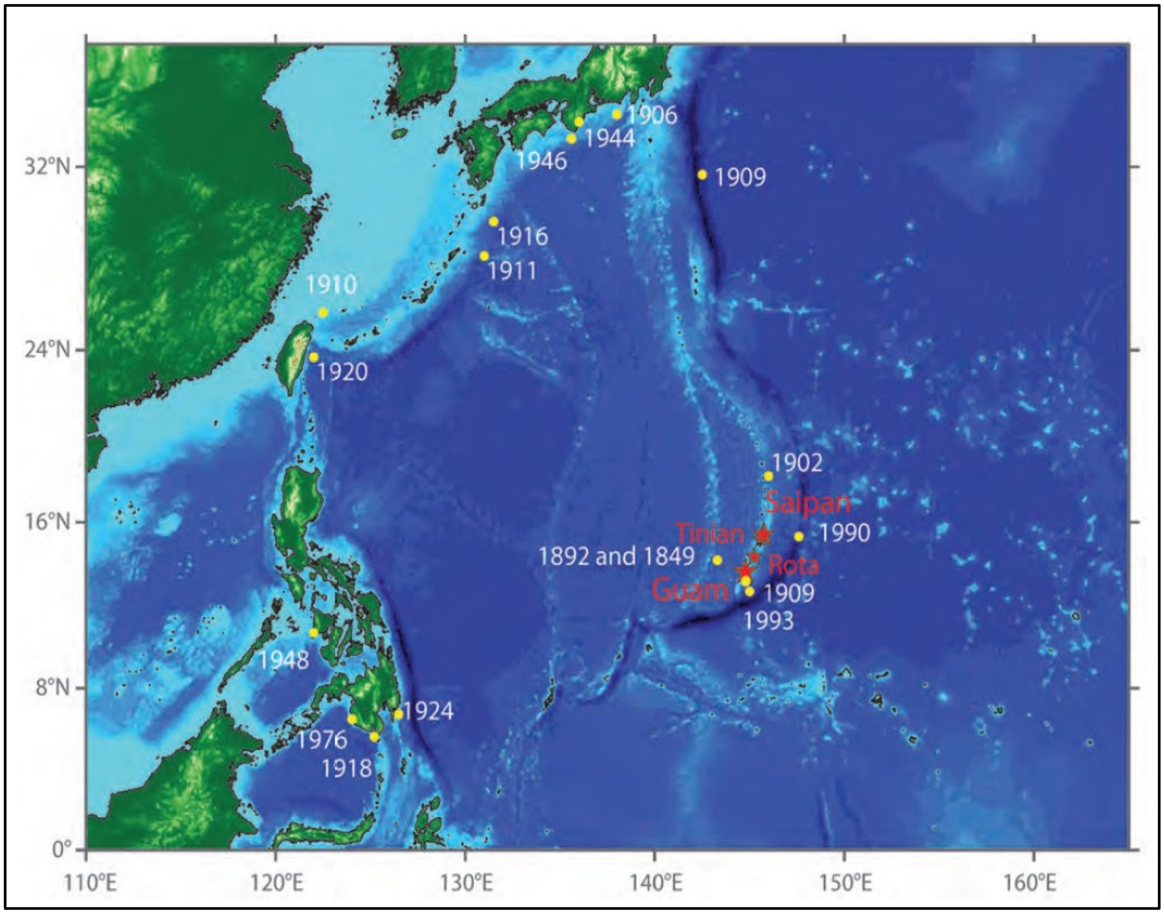

Figure 2-14 USGS Recorded Earthquakes > M 8.0 Since 1900 (NOAA OAR, 2014)

2.9 Tsunamis

Many coastal communities and territories of the United States are at risk for tsunamis, and their infrequent occurrence gives communities a false sense of security. While tsunami hazards are infrequent, their consequences are extremely high. When they occur, the population may have only minutes to hours to respond and reach a safe location. Tsunami sources include earthquakes, volcano's, sub-marine landslides, seamount collapse, and meteorite strike. A tsunami generated close to the shoreline is termed a "near-field" tsunami, and a tsunami generated far from the source of impact is termed a "far-field" tsunami. Generally, it takes a magnitude >7.0 to generate a near-field damaging tsunami and >8.0 for a far-field tsunami (USGS b, 2019). For example, a far-field earthquake centered in Chile would provide hours of notice while a near-field generated tsunami (Mariana Trench) may only provide minutes of notice. In some cases, a community may not feel an earthquake from a far-field earthquake or from a sub-marine landslide and therefore, be caught without warning. A local tsunami wave may arrive within minutes, emphasizing individuals need to understand natural cues such as ground shaking and shoreline draw down and immediately move to high ground. Alerts and warnings may not arrive in time.

After the 2004 Indian Ocean tsunami, which caused over 200,000 deaths, Congress passed two laws aimed to address potential tsunami damage: P.L. 1009-13 in 2005 (expanding tsunami detection networks) and P.L. 109-424 in 2006 (requesting NOAA and the National Tsunami

Hazard Mitigation Program [NTHMP] to strengthen the nation's preparation, warning, and education efforts). NOAA receives annual funds for the NTHMP and each state/territory requests funds annually from the national program to run their local programs. NOAA also sponsors the Tsunami Ready Community which is a voluntary program for states but does not require adherence to any methodology nor to administer enforcement.

There are two tsunami warning centers (TWC), Palmer Alaska (National Tsunami Warning Center serving Continental US and Alaska and Canada) and Honolulu Hawaii (Pacific Tsunami Warning Center serving Hawaii, British Virgin Island, US Pacific, and Caribbean Territories). Tsunami alert systems and warning systems are categorically different. For example, a siren or audio alert alone does not provide information and direction. A warning system (NWS and TWC) provides information, direction, and updates. Sirens can confuse locals as to what hazard is imminent or may not be heard if inside, outside of an audible radius, or during heavy rainfall. Siren parts often fail and are difficult to replace (remote locations). Radio, social media, texts, and NOAA weather radio will provide more warning information than an alarm. NOAA's Center for Tsunami Research Pacific Marine Environmental Lab (PMEL) positions Deep-ocean Assessment and Reporting Tsunami (DART) buoys strategically throughout the Pacific. Pressure and temperature signals are picked up and transmitted through buoys transducers to satellites and then to the TWC for dissemination to the NWS and public. DART buoy operations are not without failures. DART buoy performance operates within a 60-90 percent working range and are often damaged in winter storms (Personal Communication, USGS Nathan Wood). Figure 2-15 illustrates buoy locations monitored by NOAA/TWC.

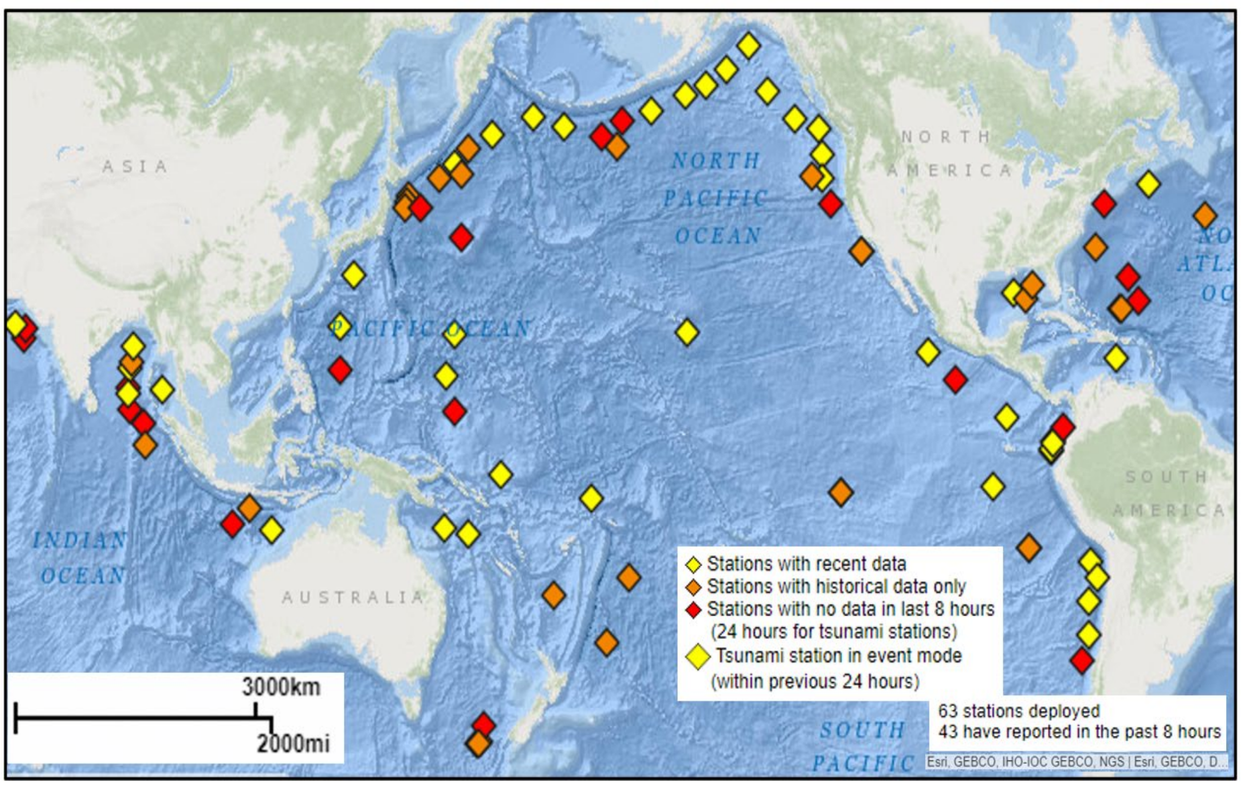

Figure 2-15. DART Buoy Locations (NOAA, National Data Buoy Center, real time data)

Over the last 161 years, approximately six validated tsunami events have been confirmed on Guam (NOAA NCEI). Wave run up was not observed across the entire island uniformly for the events and maximum recorded wave heights have ranged from one quarter of a foot (from a 6.9 magnitude [M] earthquake in 2010) to 22 feet (a 7.5 M earthquake in 1849). Damages from some of the events, such as 1849, included 22-foot waves at Agat, a quarter mile of inundation in Umatac Bay, flooded villages, destroyed homes and bridges, extensive sand boils, and a fatality near the Talafofo River. Evidence of a sub-marine landslide was found in Apra Harbor (Lander et al, 2002). The 1993 tsunami caused over $200 M in damages from an 8.1 magnitude earthquake in the Mariana Trench. Wave heights up to eight feet were reported. Apra harbor saw minor rise; however it was reported that one man whose truck was parked 15 yards from the waterline reported the water rising to chest level within 10 minutes and was trapped in his car. He was only able to escape after rolling down a rear truck window and swimming to shore.

The 2011 Tohoku earthquake (Japan/Kuril Trench) tsunami flooded Saipan, triggering surges in Apra Harbor and damaged a U.S. Navy vessel in port. The Apra Harbor (Guam) gage recorded a 4.3-foot wave surge, and the Pago Bay tide gage recorded a 1.6-foot surge within 3.5 hours of the earthquake. (NOAA OAR, 2014). The 1993 tsunami occurred during Typhoon Steve. Multiple hazards can occur simultaneously, and it is possible a sheltering center safe from coastal or riverine flooding may not be in a safe zone for tsunamis.

A tsunami from a far field earthquake such as Cascadia is possible. The risk for a near field event like the 1993 and 1849 earthquake, sourced from the Mariana Trench or east Philippine source, are potentials for tsunamigenic events that pose the greatest risk (NOAA/OAR 2010). Of the six credible observed tsunamis only the 1849 tsunami is believed to be the only one to have caused a fatality in the region.

The inundation map below, in Figure 16 and Figure 17, are NOAA/OAR modeled probable maximum tsunami (PMT) inundation maps for north and south Guam.

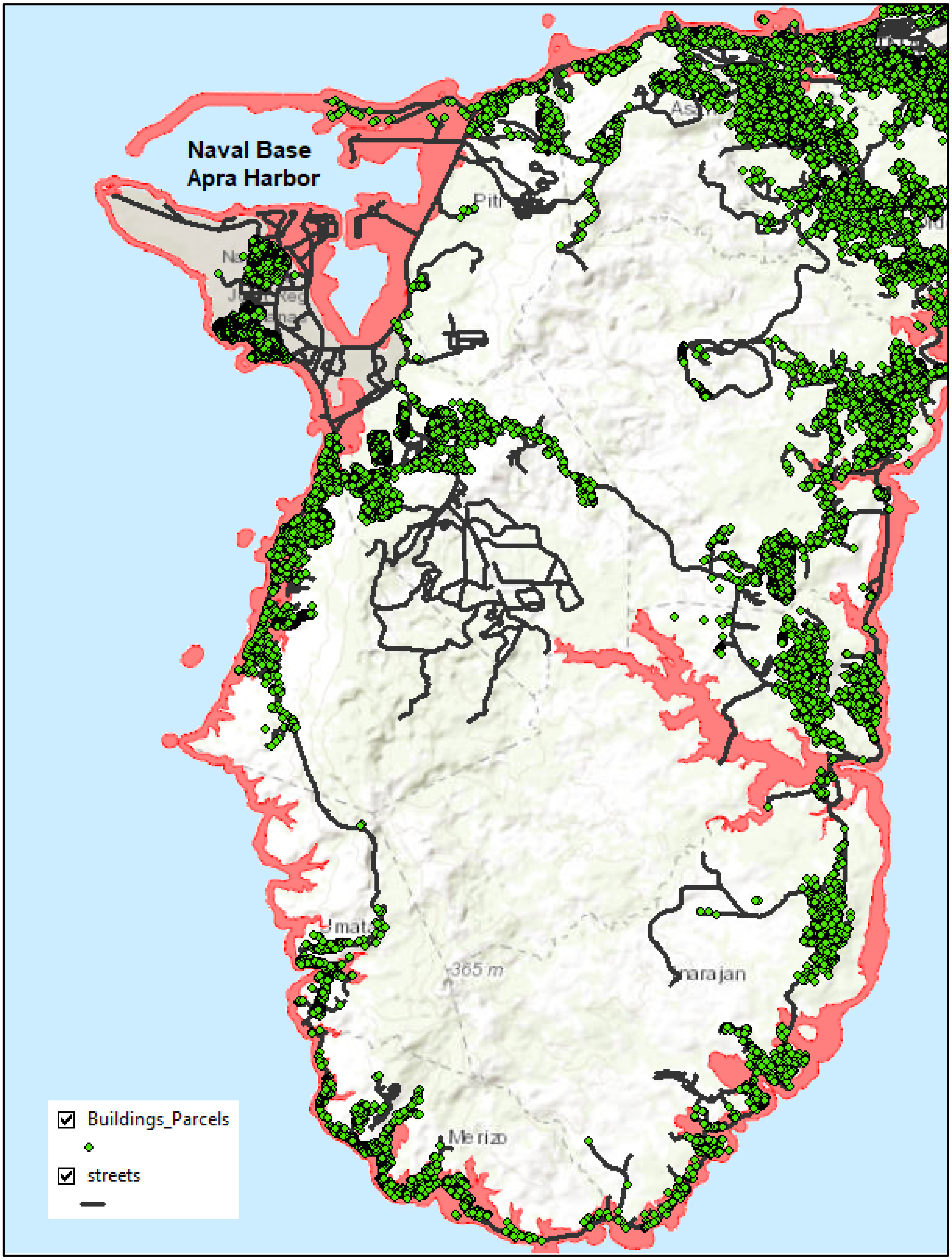

Figure 2-16 PMT Southern Guam (ESRI)

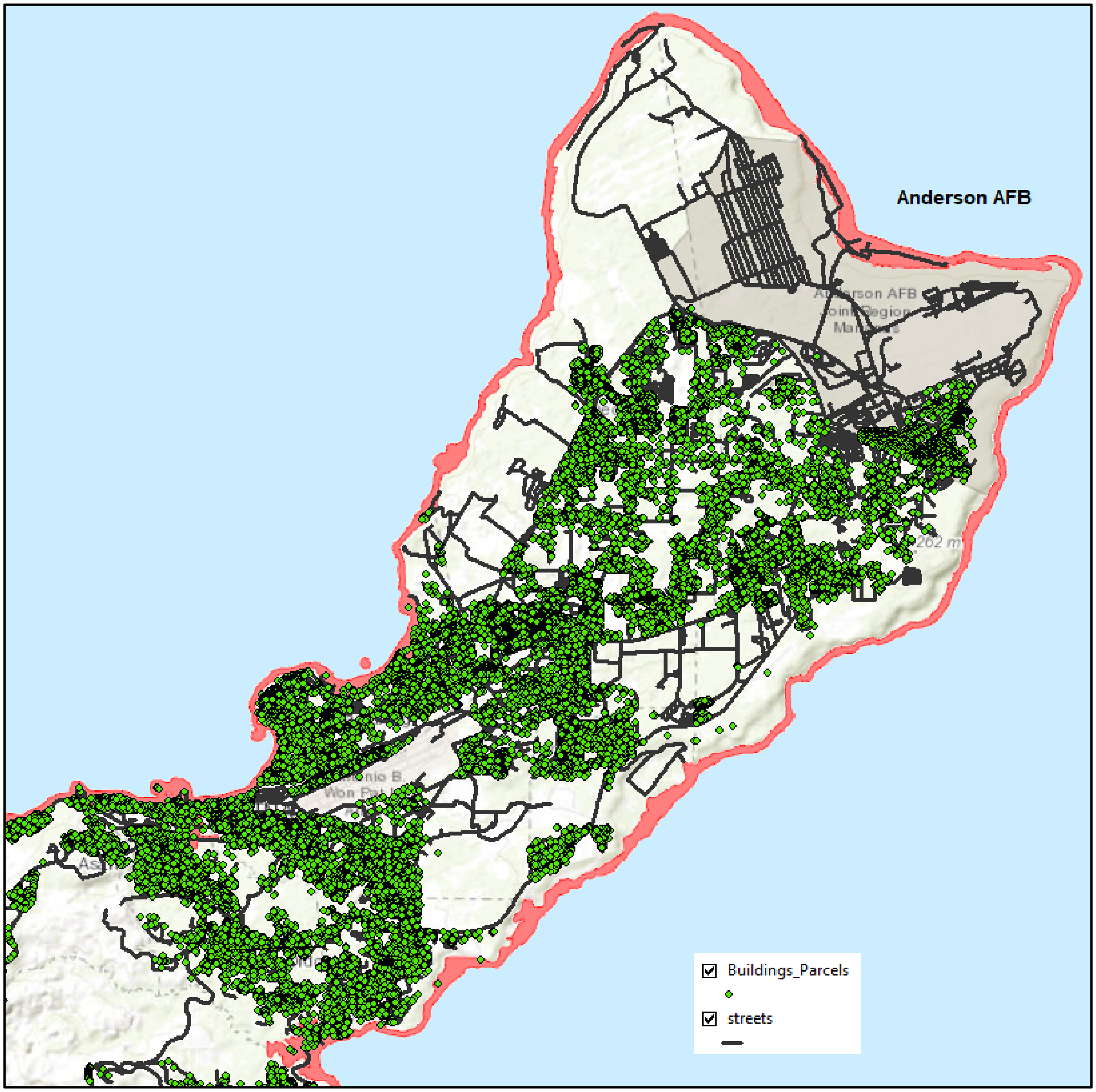

Figure 2-17 PMT Northern Guam (ESRI)

Table 1 lists critical infrastructure that lies within FEMA 1% ACE coastal and riverine flood zones, HURREVAC (MOM inundation) existing and FWOP, and tsunami (PMT inundation) hazard zones. FEMA and PMT hazard zones were analyzed under existing conditions only. Inventory for infrastructure is based on the 2010 Census and further analysis from SPK Economics.

Table 1. Infrastructure Impacts from Coastal and Riverine Flooding

.FACILITY TYPE	PMT-TSUNAMI ZONE (OR WITHIN 100 FT) EXISTING CONDITIONS	1% ACE FEMA FLOOD (OR WITHIN 100 FT) EXISITNG CONDITIONS	HURREVAC MOM ZONE (OR WITHIN 100 FT) EXISTING CONDITIONS	HURREVAC MOM ZONE (OR WITHIN 100 FT) FWOP RSLC = 3 FT
EVACUATION SHELTER, INARAJAN COMMUNITY CTR	X	X	within roughly 180 FT	within roughly 180 FT
EVACUATION SHELTER, MERIZO COMMUNITY CTR	X	X	X	X
EVACUATION SHELTER, INAJARAN ELEMENTARY SCHOOL	X			
EVACUATION SHELTER, ASAN_MIANA COMMUNITY CTR	X			
EVACUATION SHELTER, UMATAC COMMUNITY CTR	X		X	X
EVACUATION SHELTER, FRANCISCO Q. SANCHEZ ELEMENTARY (2 bldg'S)	X			
MEDICAL CLINIC AND US NAVAL HOSPITAL	SLIGHTLY OVER 100 FT			
GUAM MEMORIAL HOSPITAL	SLIGHTLY OVER 100 FT	SLIGHTLY OVER 100 FT		
POWER PLANT, TANGUSSON, DEDEO	X			
GOVERNMENT BLDGs, (count)	GIS format cannot analyze	16	4	4
FACILITIES & RESIDENTIAL, (count)	GIS format cannot analyze	3042	623	623

3 Vulnerability and Exposure: Future Without Project Condition

3.1 Climate

As stated, Average annual rainfall volumes range from 80 inches per year (lowlands) to 110 inches per year (mountainous) in Guam.

Guam has a tropical maritime climate with a wet (July through December) and dry season. The seasonal temperature variance is approximately five degrees Fahrenheit. The average annual temperature is 81.7 degrees Fahrenheit with minimum annual temperatures and maximum annual temperatures of 76.3- and 87.2-degrees Fahrenheit respectively, based on NOAA climate normals. Average annual precipitation is 98.1 inches. (NOAA NOWDATA).

Trends in observed annualized monthly maximum temperatures compared to NOAA normals (1991-2020) reflect a 4.8-degree Fahrenheit increase in maximum temperatures over a 29-year period. See the temperature graph in Figure 3.1

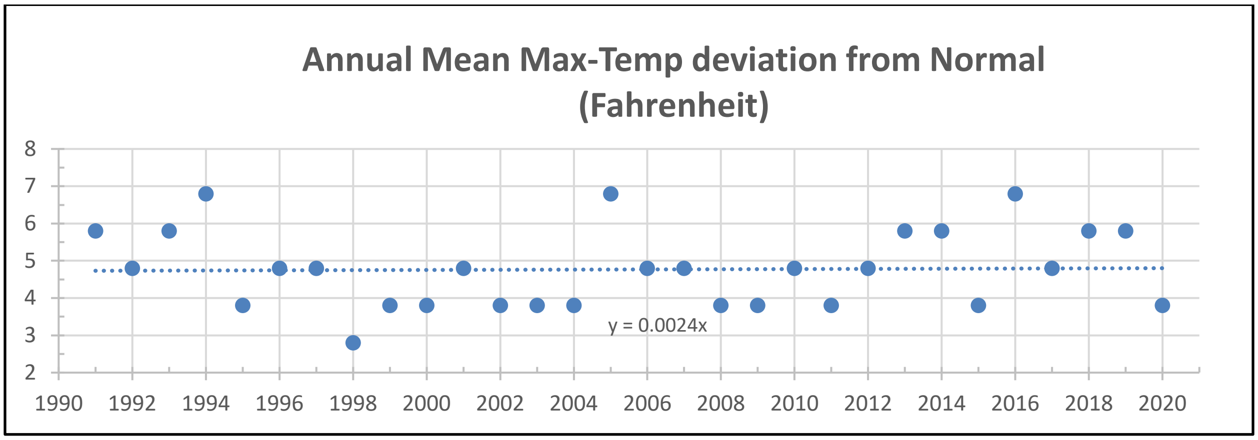

Figure 3-1. Increase in Maximum Temperature for Guam (NOAA NOWDATA)

Annual precipitation deviation from normal are more difficult to quantify. ENSO cycles as well as tropical storm activity can vary in duration and frequency and disrupt normal rainfall trends. Figure 3.2 below illustrates the latest 29-year normal and observed precipitation deviations. A 2.1-inch reduction in annual precipitation is shown in observed rainfall compared to normal but is an insignificantly difference. However, increased oceanic and atmospheric temperatures and concentrations of carbon dioxide will lead to an increase in weather extremes such as rainfall intensity, droughts, and storms. Rainfall intensity and typhoon intensity are projected to increase (IPCC, 2019).

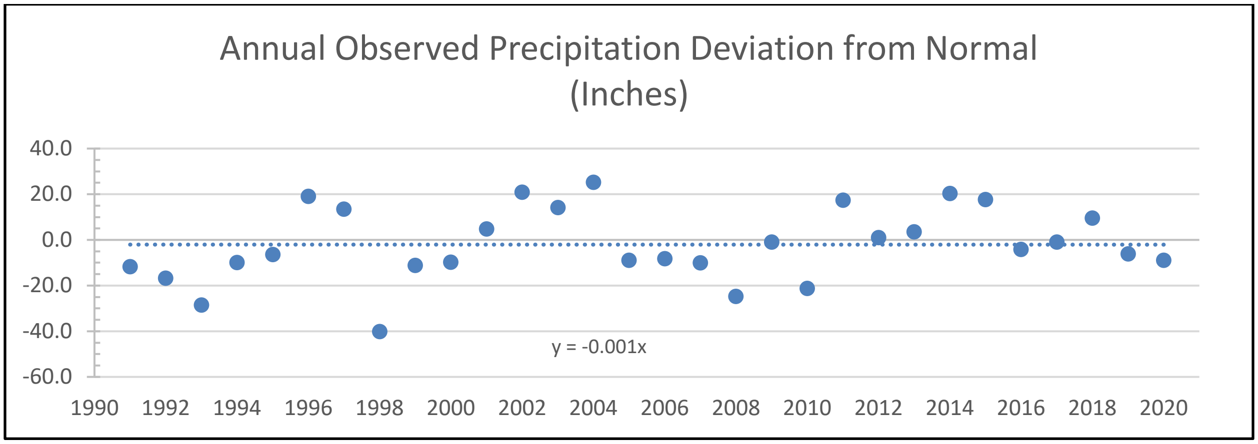

Figure 3-2. Departures for Normal, Annual Precipitation for Guam (NOAA NOWDATA)

Based upon projected trends, mean temperatures, number of hot days, maximum temperatures, sea level rise (SLR), regional sea level change (RSLC), and rainfall intensity are projected to increase. The western North Pacific climate has experienced 60 years of increased temperatures with anticipated 1.1° F to 1.3° F increases in temperature by 2030, a 1.9° F to 2.6° F increase by 2055, and a 2.7° F to 5.1° F by 2090. Changes to mean annual rainfall are not projected to change significantly, however rainfall intensities and dry and wet extremes are projected to increase. Tropical cyclone intensity models have predicted a 10.9% increase in super typhoons by the end of the century. Based on expected increases in El Nino events and typhoon intensity, existing flooding, and wind damage to coastal and island wide infrastructure will be exacerbated.

3.2 Relative Sea Level Change

Sea levels have been rising gradually throughout the study area during the entire period of record. The nearest NOAA tidal gauge is on the island of Guam in Apra Harbor (Station ID: 1630000). This gauge is not USACE compliant to use for a sea level change analysis due to an apparent datum shift caused by a local earthquake in 1992.

In Guam, eustatic water levels, tectonic activity and land subsidence all contributes to relative sea level change (RSLC). Figure 18 illustrates the low, intermediate, and high regional sea level change RSLC estimates based on the Apra Harbor gage. The extrapolated historic rate is represented by the blue line. The NRC Curves I and III predicted rates are represented by the green and red lines, respectively. This 100-year analysis is based on a 2030 base year. 1992 is the base year for calculations of sea level change in accordance with the established USACE methodology. While not USACE policy, NOAA recommends use of the intermediate or high curves in planning, therefore incorporating a worst-case scenario for planning and accommodation for future high tide, storm surge, wave, and wave run up conditions. RSLC is anticipated to range between 2.2-4.5 feet by 2070 and approximately 4.0-11.0 feet by 2130.

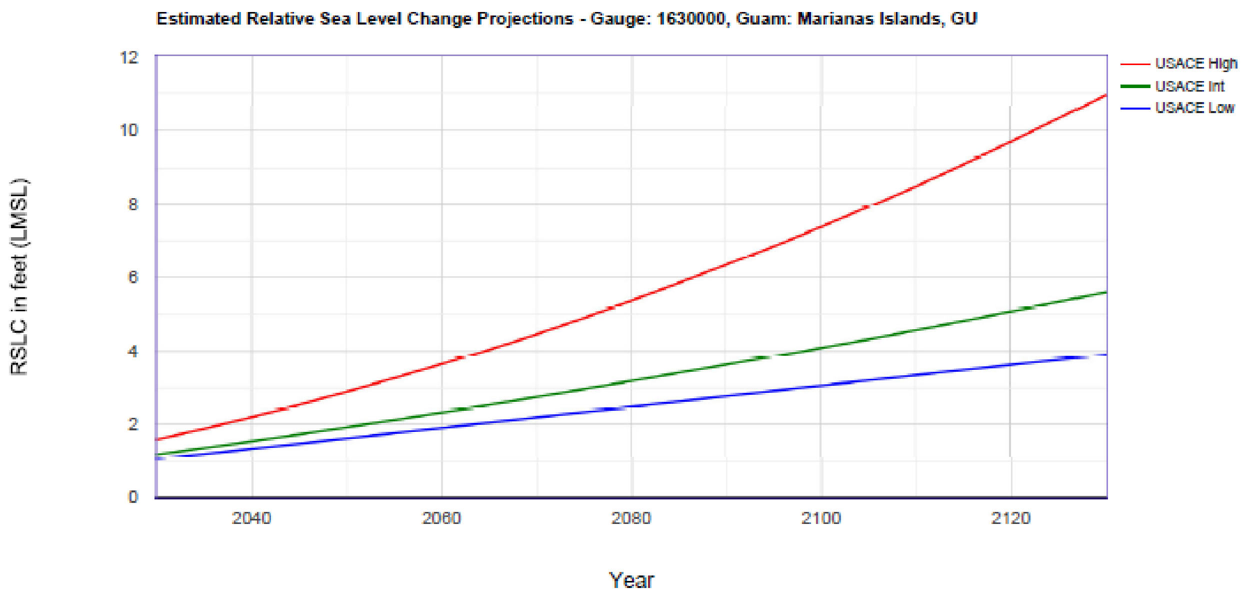

Figure 3-3 Projected Relative Sea Level Change for Guam

RSLC impacts that enhance coastal storm surge and flood damage were analyzed using HURREVAC data for existing and future conditions. NOAA Sea Level Rise (SLR) inundation depth raster files (digital maps) from the RSLC calculations for Guam (above) were added to HURREVAC storm surge depth raster files to estimate future coastal damage potential (NOAA SLR Viewer).

3.3 Future Conditions

Tropical cyclone intensity is projected to increase by 1-10% with currently projected 3.6˚ Fahrenheit temperature increase (2˚Celsius), with rainfall increase of 10 to 15% (NOAA, 2013). However, the increase in intensity (reaching a major hurricane category) has increased by 9.3% and is projected to increase by 10.9% (NOAA/University Princeton, 2018). Higher ocean temperatures are a driver for typhoon intensity and duration. Extended storm duration produces heavier rainfall volumes, extended wind and salt spray damage, higher risk to property and infrastructure, increased coastal erosion, and presents a sheltering and emergency supply challenge. Adding sea level to present coastal flooding conditions will inundate areas and roads that were once community safe zones. Longer duration storms mean longer periods without power and water.

Extended storm duration produces heavier rainfall volumes, extended wind and salt spray damage, higher risk to property and infrastructure, and presents a sheltering and emergency supply challenge. Adding sea level rise by the expected three feet over the next 50 years will inundate areas and roads that were once a community safe zone. Longer duration storms mean longer periods without power and water.

To assess the impacts of coastal flooding from typhoon driven storm surge, NOAA SLR raster files (gridded terrain map) were added to MOM inundation raster files. Horizontal and vertical datums were matched and the high curve from the USACE regional sea level change (RSLC) value was used to select the appropriate SLR inundation raster representing the year 2070. The USACE high curve was chosen to assume the worst-case scenario for planning purposes.

By utilizing the USACE RSLC value of three feet, the future conditions mapping therefore includes subsidence adjustments for the year 2070. Figure 3-2 and Figure 3-3 illustrate a worst-case hypothetical storm surge from a typhoon that includes RSLC in 2070. Figure 3-4 and Figure 3-5 illustrate the storm surge difference for clarity. Abrupt elevation changes from Guam's bluffs act as a control on inundation. Most low coastal zones experience similar inundation footprints from tidal surges and typhoons, but with increased depths.

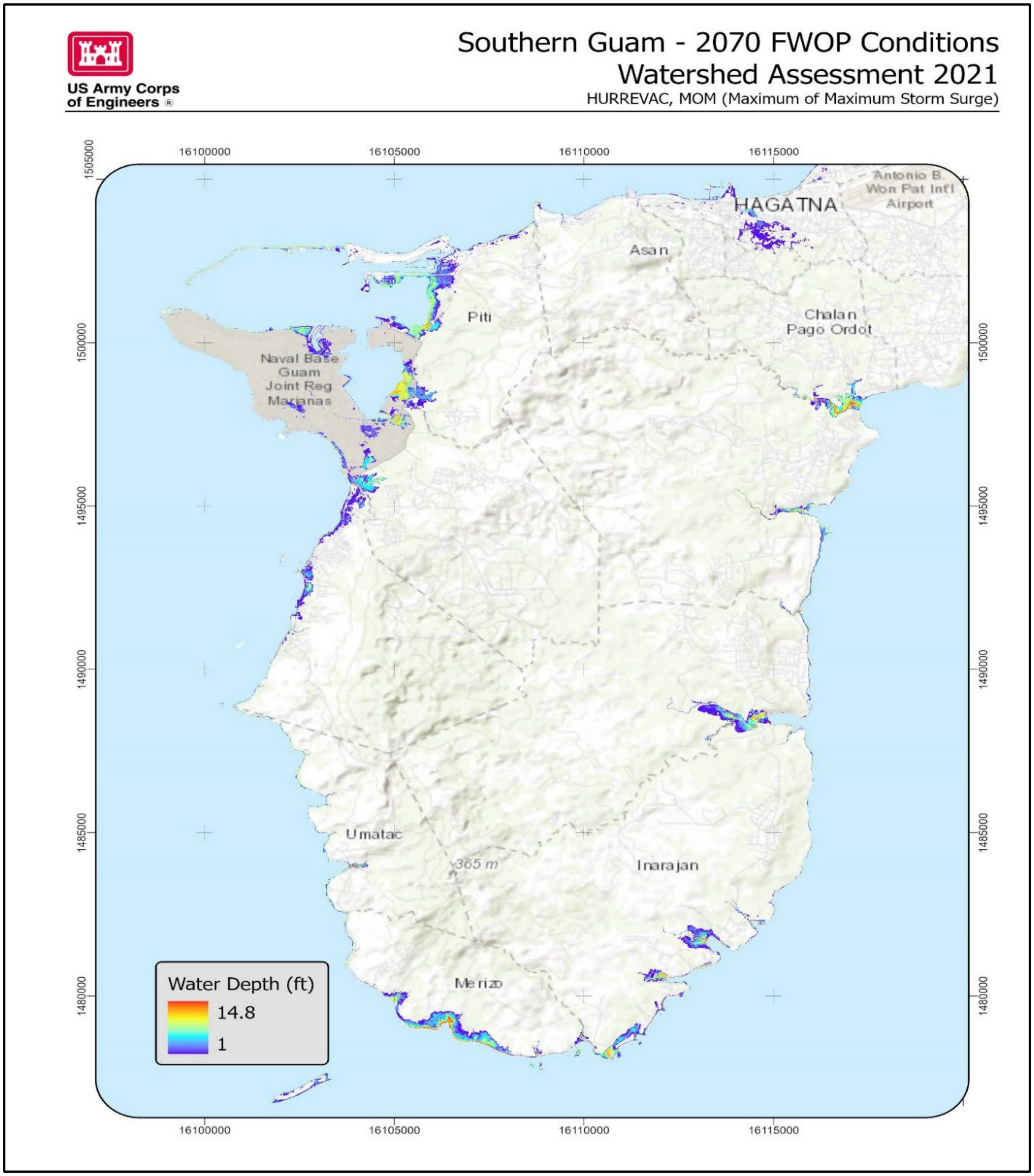

Figure 3-4 Southern Guam Typhoon Inundation – Future Conditions 2070 (HURREVAC MOM and NOAA SLR viewer) (ESRI)

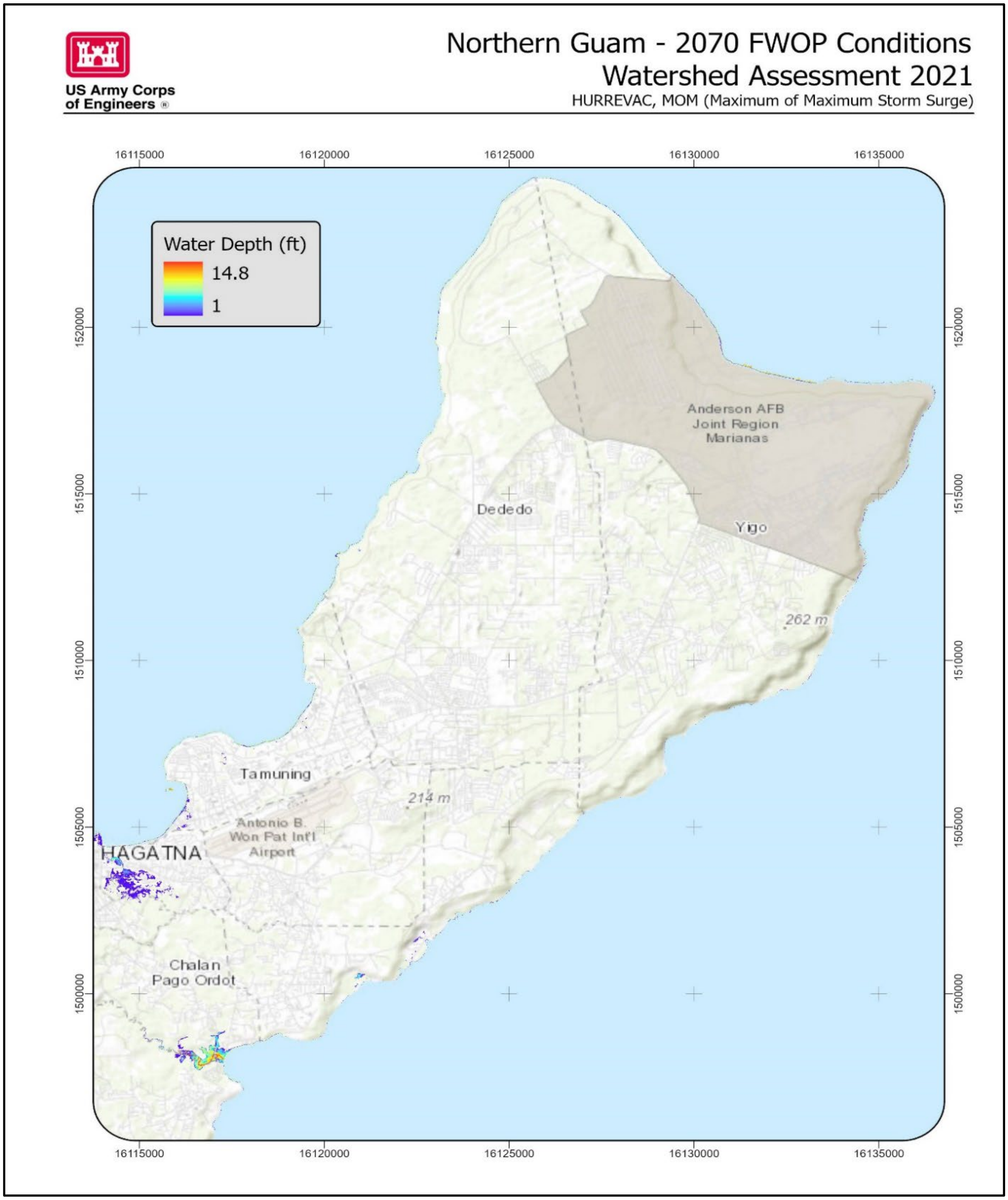

Figure 3-5 Southern Guam Typhoon Inundation – Future Conditions 2070 (HURREVAC MOM and NOAA SLR viewer) (ESRI)

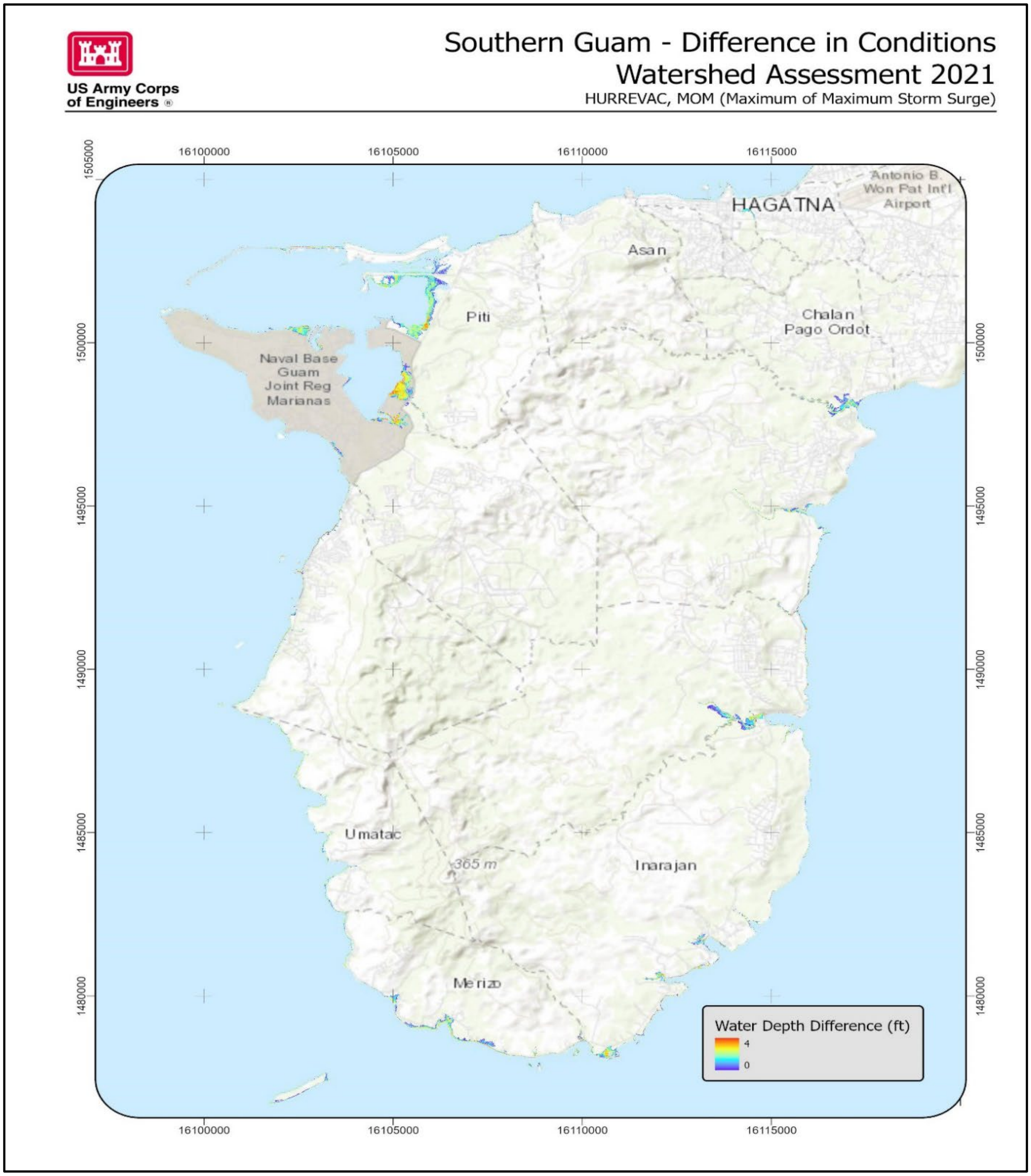

Figure 3-6 Northern Guam Typhoon Inundation – Difference from Existing and 2070 Conditions (HURREVAC MOM)

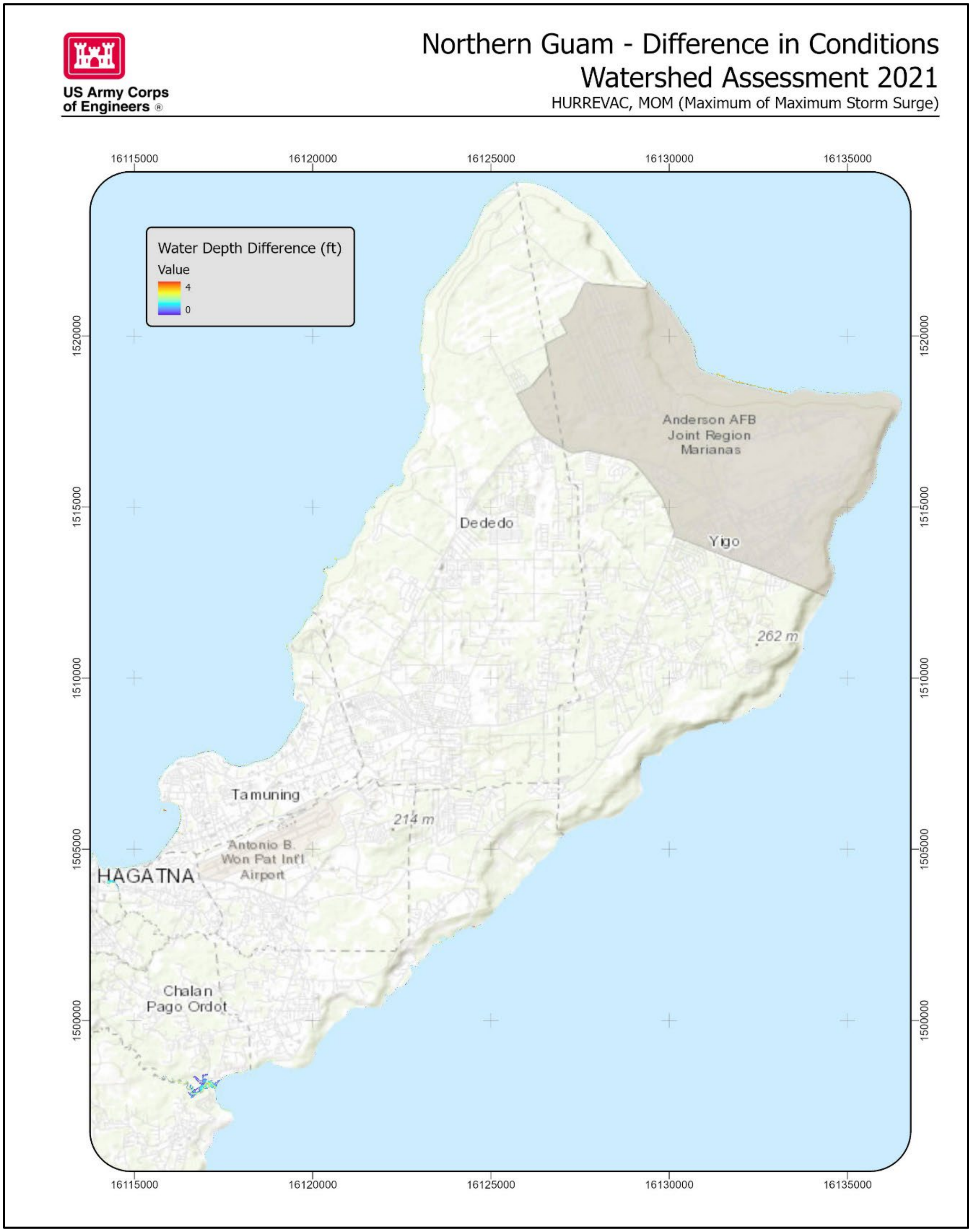

Figure 3-7 Northern Guam Typhoon Inundation – Difference from Existing and 2070 Conditions (HURREVAC MOM)

3.4 Riverine Erosion

Approximately six pounds of soil are lost for every pound of food eaten in the U.S. To re-establish the six inches of soil required to grow crops takes 3,000 years, and worldwide soil is being eroded 18 times faster than it is being built up in nature (NRCS, May 2021 online). Within the 19 distinct sub-watersheds, Figure 23, in Guam the soils in northern Guam are thin and sourced from exposed limestone, however limestone erodes more slowly and through different processes than clays and silts in southern Guam. Limestone erodes slowly by chemical dissolution and does not present the erosional and sedimentation impacts like the less cohesive silty soils in southern Guam. In southern Guam, the Agfayan and Akina (Badland Complex) soil parent material is volcanic and constitute most of the soils in southern Guam. Badland soils are highly acidic due to aluminum silicates and are unfavorable for most farming. Akina soils are highly erodible and although clay soils such as Agfayan are common, they are thin and reside on steep slopes and therefore prone to erosion (USDA, 1988). Guam has roughly 33,800 acres of moderately erodible soils that reside on slopes greater than 30 percent (NRCS). These watersheds are predominantly located in Southern Guam. Figure 24 depicts USDA defined moderately erodible soils in watersheds (shown in pink), on slopes greater than 30 percent (USDA SSURGO, 1985). Figure 25 illustrates the same conditions in addition to 2016 fire zones (red), marine protected areas (shown in blue), and impervious zones (greater than 14 percent, green). Impervious land use and fire increase runoff and prevent infiltration, which increase flood wave velocities and exacerbate erosion. Burn areas act to create erosive environments regardless of soil type.

Below the Santa Rita Mountain the Agat watershed is a vulnerable watershed due to heavy population, erosive soils, prior fire damage, and impervious cover. Similarly, the Atantano River in the Apra watershed drains below Santa Rita Mountain into the Naval Base near the harbor. The Sasa, Laguas, and Aguada watersheds contain erodible soils on steep slopes but are less developed and contain more forest.

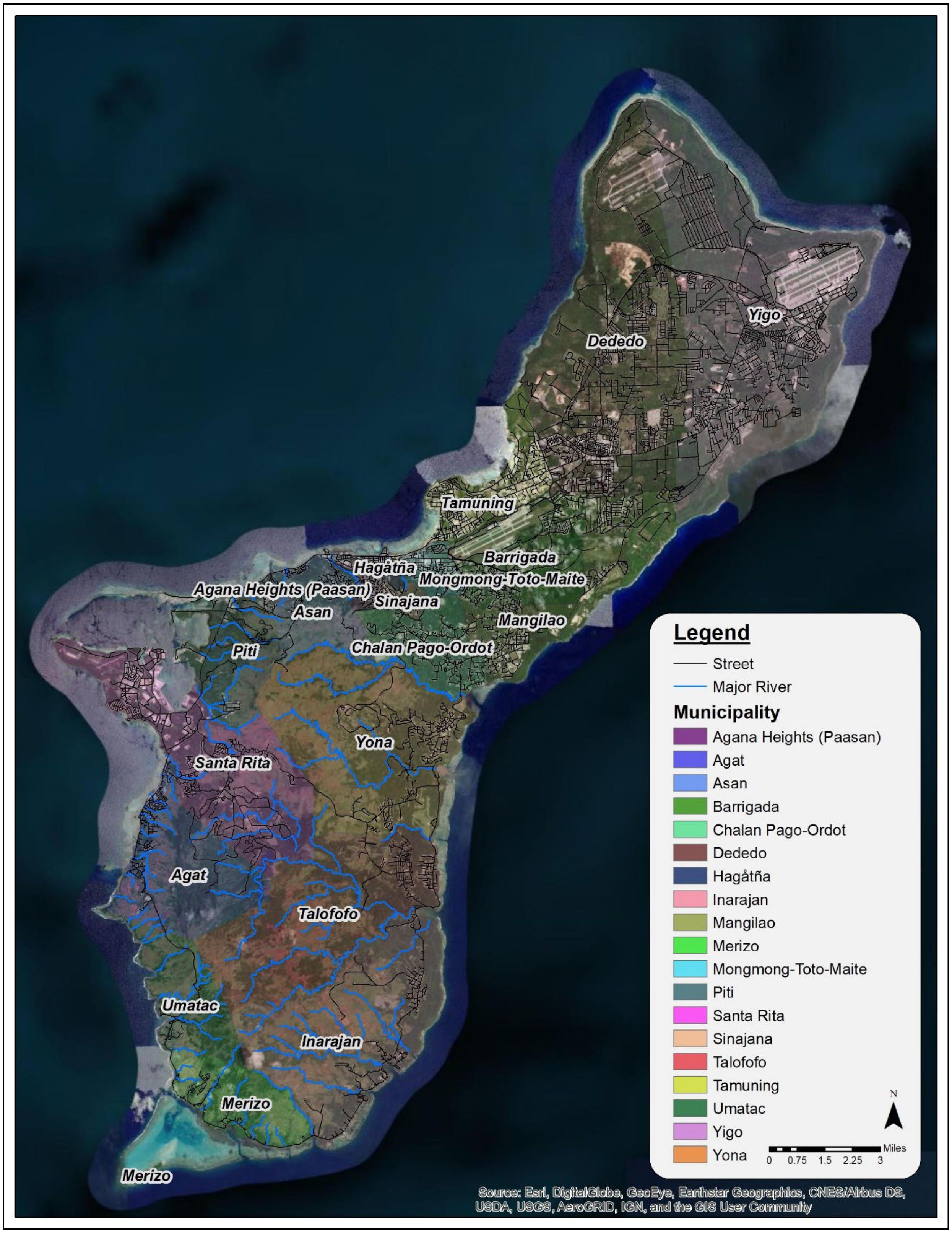

Figure 3-8 Island of Guam, Watersheds Defined

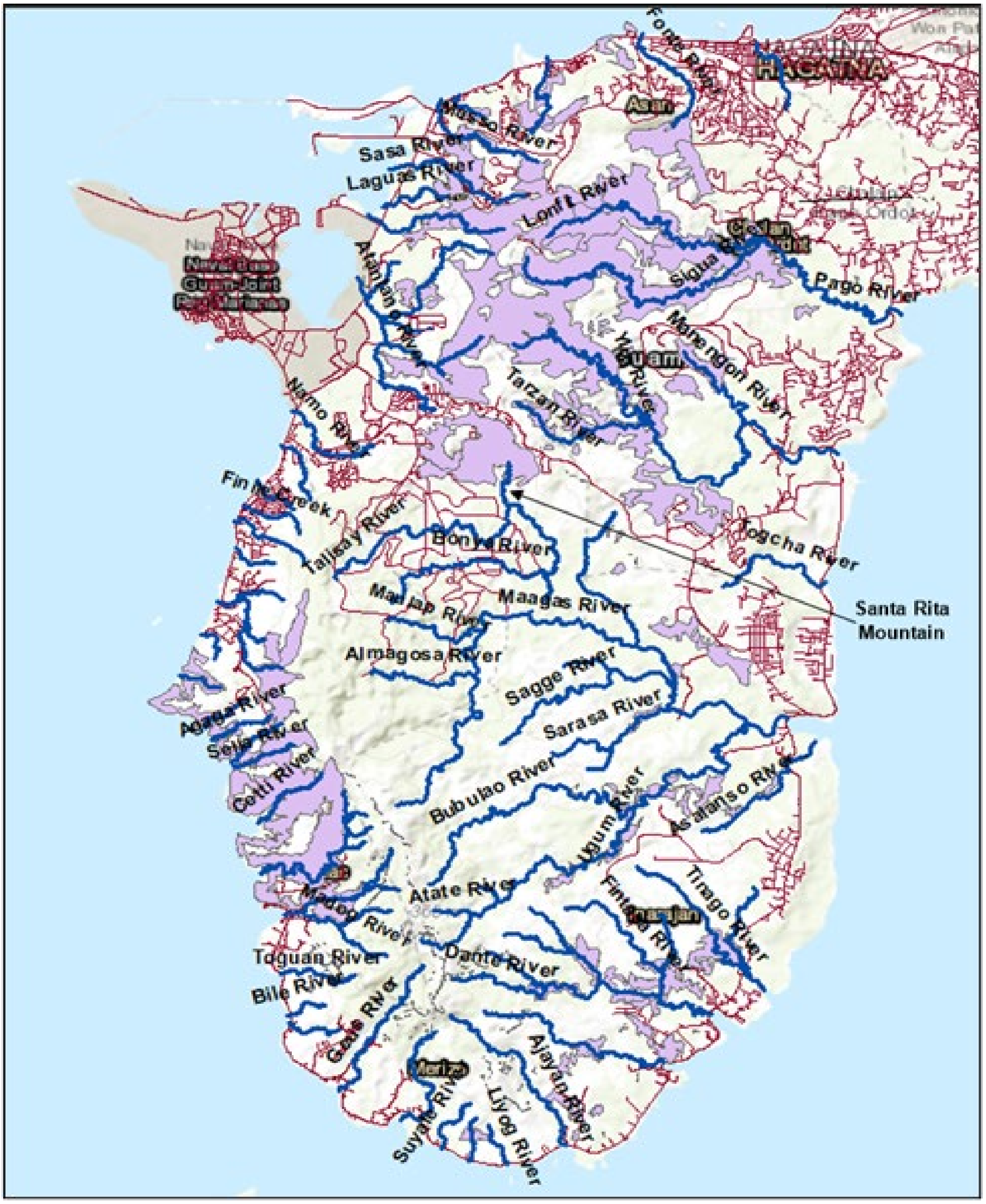

Figure 3-9 Moderate Erodibility Locations with Steep Slopes (Purple), South Guam (ESRI)

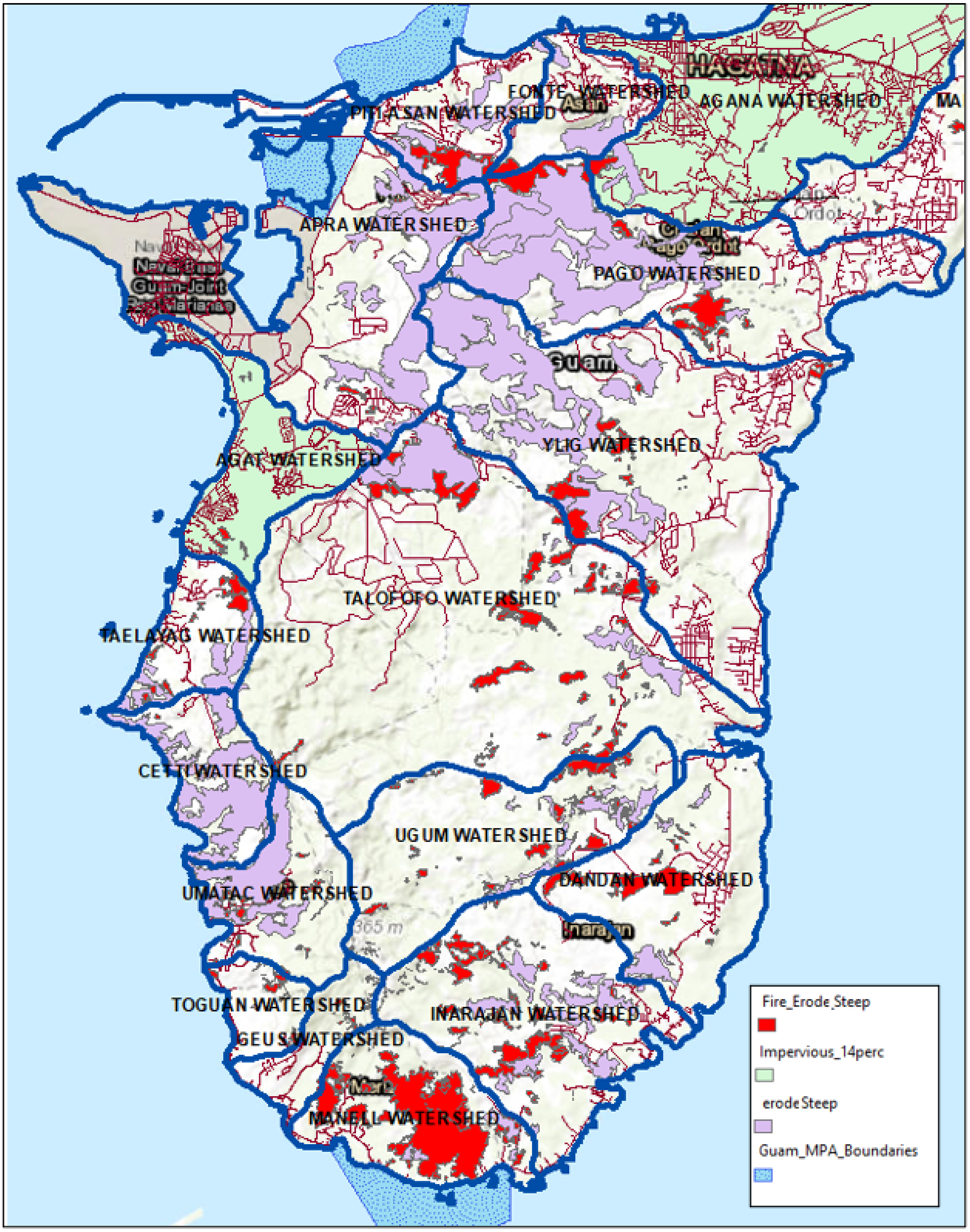

Figure 3-10 Vulnerable Erosion Watersheds (with Fire Zones in Red), South Guam (ESRI)

Most of southern Guam's watersheds are affected by moderately erodible soils on steep slopes. Additionally, many of these same watersheds have experienced fire damage. While addressing all impacted streams of the territory is not within the scope of this assessment, the table below lists watersheds which are significantly impacted due to impervious land cover, sedimentation to harbors or reefs (NOAA Coastal Management Program, CMP), or combinations of these erosion vulnerabilities. Building counts within each watershed (2010 Census) are listed for reference. Figure 26 describes the importance of land use and conservation related to impacts on soil degradation and erosion worldwide.

Table 1 Erosion of Vulnerable Watersheds

Watershed	Erodible with Slopes >30 percent	Fire Affected	Impervious Cover >14 percent	Impacts CMP_Waters or Harbor	Building Count (2010 Census)
Agana	X	X	X	X	7916
Fonte	X	X			2141
Piti-Asan	X	X		X	835
Agat	X	Small area		X	2141
Apra	X	Small area		X	1343
Cetti	X	Small area			18
DanDan	X	X			473
Inarajan	X	X			422
Geus		X			305
Manell	Small areas. Sumay & Ajayan River only	X		X	272
Pago	X	X			1344
Taelayag	X	Small area			330
Talafofo	X	Small area			332
Ugum	Small area	Small area			1
Umatac	X	Small area			218
Ylig	X	Small area			2192

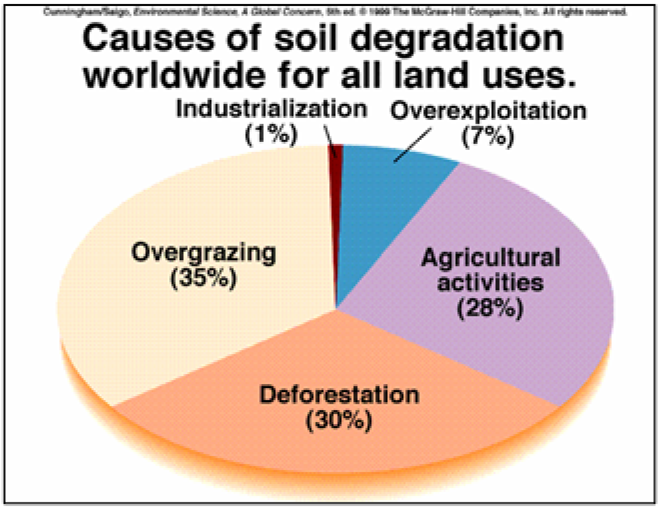

Figure 3-11 Worldwide Drivers for Soil Degradation

3.5 Erosion

Erosion and associated sedimentation are one of the primary threats to Guam's terrestrial and aquatic environments. Erosion is increased by any activity that reduces vegetation cover. Intense rain events, steep terrain, narrow river cross sections, changes in river direction, areas of existing bank erosion, and mass wasting all increase the potential for sediment to be introduced to and carried by rivers. Soil conditions, such as type, permeability, and moisture, greatly affect how land may be used, determine the potential for vegetation and habitat, and influence overland runoff that causes erosion and landslides. Coastal erosion in Guam can be caused by winds; ocean currents; storm surges; high surf; seismic activity; changes in the geometry of tidal inlets, river outlets, and bay entrances; human-made structures and human activities, such as shore protection structures and dredging; and/or local scour around structures. Human-built structures, such as properly engineered shore protection structures, can greatly increase the rate of coastal erosion in adjacent properties that are not armored while preventing any beach profile from accreting parallel to the wall. Cleared areas that are exposed to prevalent winds and open ocean waves often have a higher potential to experience heavy coastal erosion than highly vegetated areas where structures are set-back farther inland. The erosion of coastal cliffs can threaten the safety of land uses at the top of the cliffs. Coastal erosion can lead to sediment transport onto nearby reefs, reducing sunlight necessary for growth, and deposition of contaminants contained in eroded soils which can lead to the decline of the health of these reefs. Erosion may negatively impact vegetation, sea grass communities, beaches, and benthic organisms. (Guam HMP 2019)

La Niña and El Niño events also contribute, with El Niño causing lower sea levels but increased tropical cyclone activity, while La Niña causes less tropical cyclone activity, but higher background sea levels. In addition, sea level rise affects coastal erosion. Sea levels appear to have risen about 8 inches over the last century, with greater rises over the last two decades. Sea level rise estimates of 3 ft by the end of the century and intensification of storms will magnify erosion and shoreline recession. The impacts will damage coastal roadways, require critical infrastructure hardening or relocation, stress ecosystems, and increase land recession. Present erosion rates can be as high as 23-inches per year and 50-inches per year at Sagna Bay and Apaca Point respectively (2019, Guam Homeland Security).

The entire coastline of Guam has the potential for coastal erosion hazards. The western coast of Guam has experienced the most coastal erosion to date due to tropical cyclones and monsoon surges that have produced high waves.

In Guam, soil forms from different parent materials: volcanic rock, limestone, and bottomland/coastal deposits. The three basic types are further subdivided based on pedological characteristics into distinct varieties called soil series.

Volcanic soils are generally very shallow to deep and well drained. They dominate southern mountainous terrain and are typically found in steep settings.

Limestone soils are generally very shallow and well drained. They cover parts of northern Guam where limestone forms the land surface (and most of the northern Guam). They are typically found in level to moderately sloping settings.

Bottomland (or strandline) soils are deep and very deep, and poorly drained. They are found in valley bottoms and coastal plains.

Soil is an integral part of a healthy terrestrial ecosystem and a truly precious resource that must be conserved. As Guam deals with a growing population and rapid urban development, issues related to soil erosion and soil and water pollution are becoming critical. (Digital Atlas of Northern Guam)

In Guam, anthropogenic fire burns up to 10% of the island's area, mostly in the island's tropical savanna. The complex interactions of fire, vegetation, erosion, and sedimentation, while conceptually well understood, have not been investigated in Guam with sufficient detail to inform resource managers. (D. Minton 2005)

3.6 Tsunamis

Climate change is not expected to result in an appreciable (if any) increase in future tsunami vulnerability. Tsunami generation is not directly tied to measurable climate change. However, the low probability of tsunami hazards allows for a false sense of safety and complacency. Education, tabletop drills, signage, and preparation are critical. Tsunami wave amplitudes can be orders of magnitude higher than probable maximum hurricane waves and vulnerable residents need information for where safe zones are available. For low tsunami magnitude events, the predicted high curve for a 2.8-foot RSLC by 2070 means higher wave amplitudes and greater run up depths than those experienced under existing conditions. Climate change planning should consider safe zone re-evaluations from these RSLC impacts.

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Marines' move from Okinawa to Guam

https://www.stripes.com/news/marines-move-from-okinawa-to-guam-could-begin-as-early-as-october-2024-report-says-1.581201#:~:text=The%20Marine%20Corps'%20Asia%2DPacific,from%20elsewhere%20around%20the%20globe

Military Installation on Guam

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