Engineering Analysis
Appendix C

Guam
Watershed Plan

US Army Corps
of Engineers
Honolulu District

July 2022

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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 30). 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.

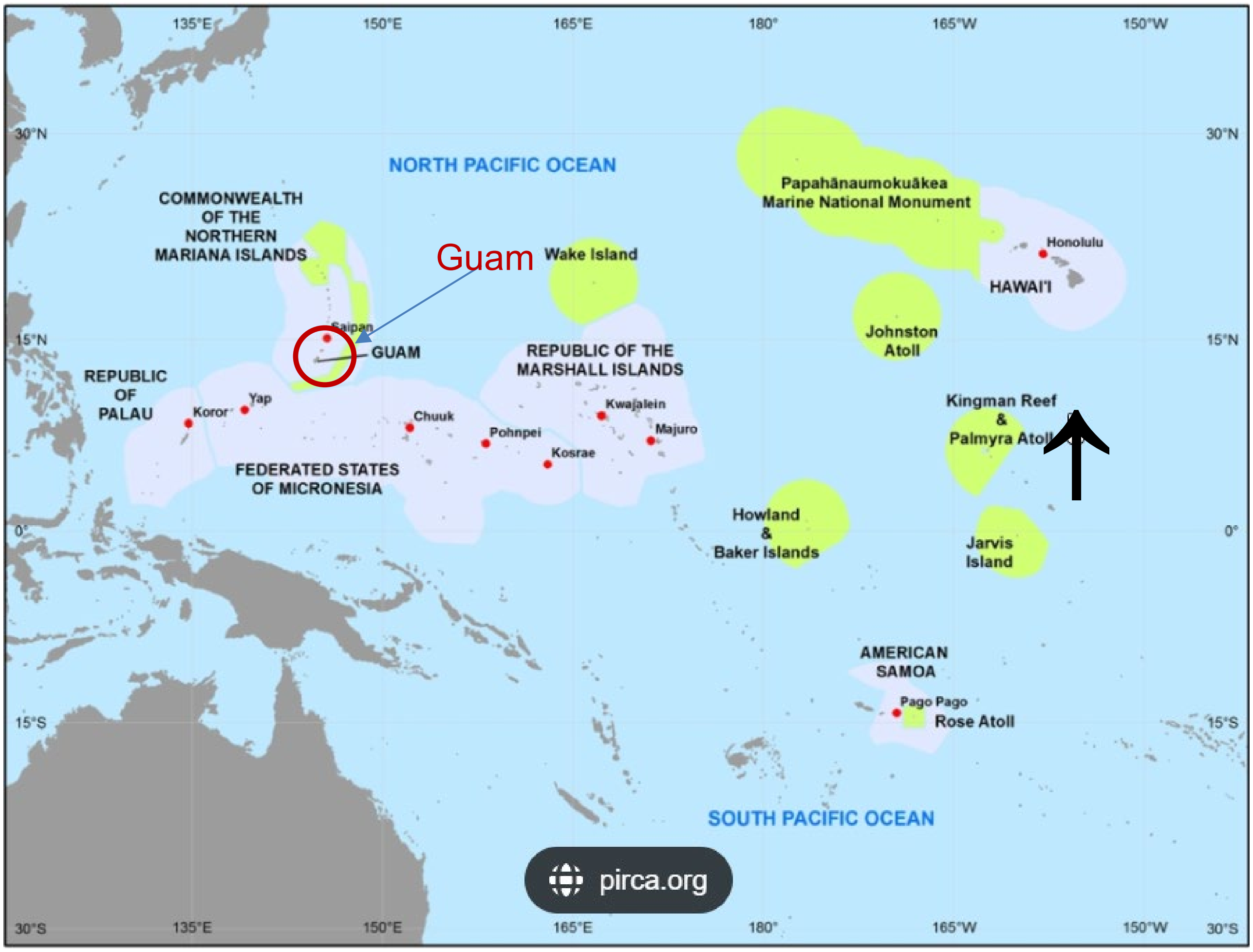


Figure 1. Map of the U.S. Pacific Islands Region (PIRCA.org 2018)

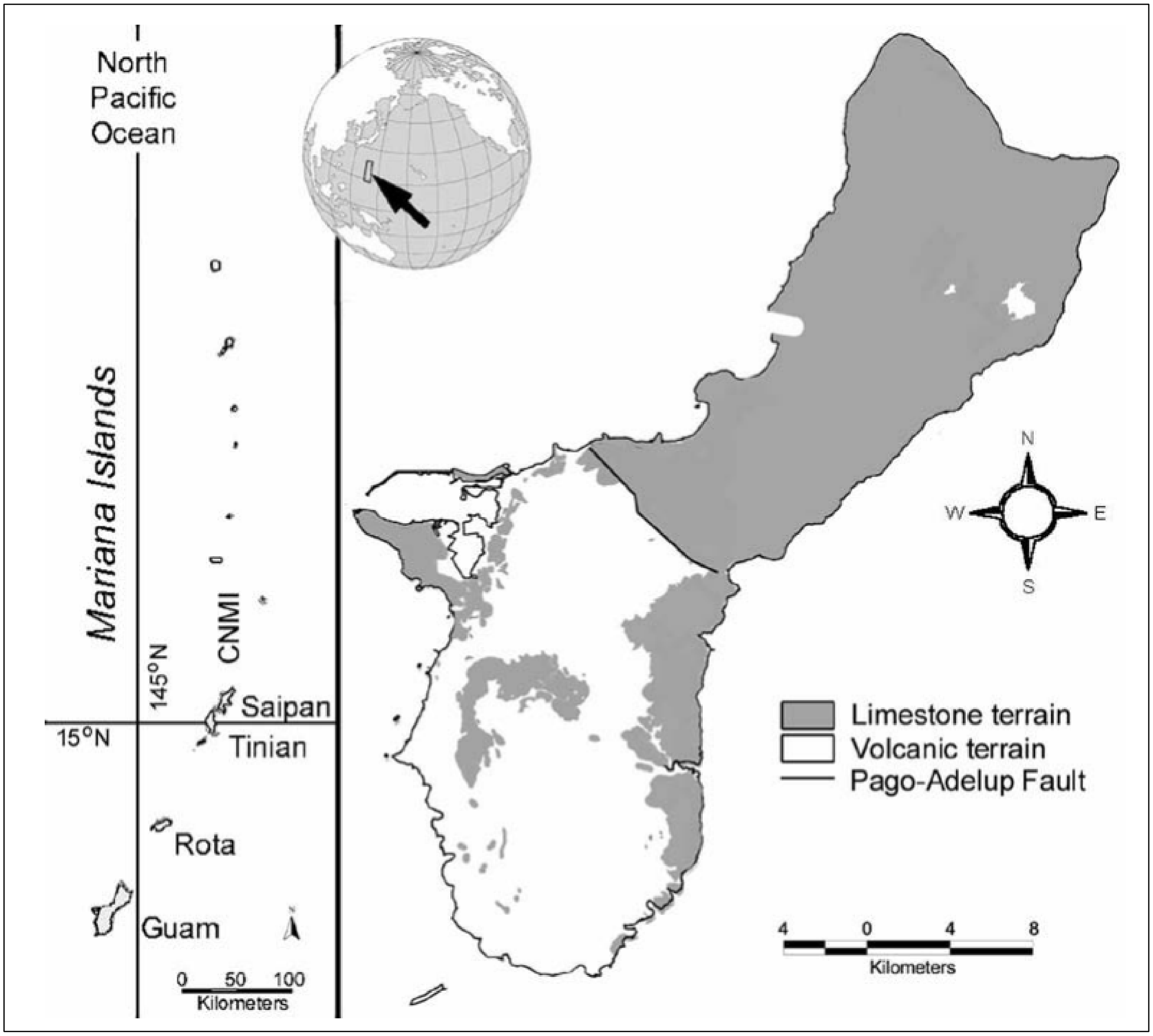


Figure 2 Mariana Islands Vicinity; Terrain of Island of Guam. (Image courtesy of Water & Environmental Research Institute of the Western Pacific University of Guam)

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:

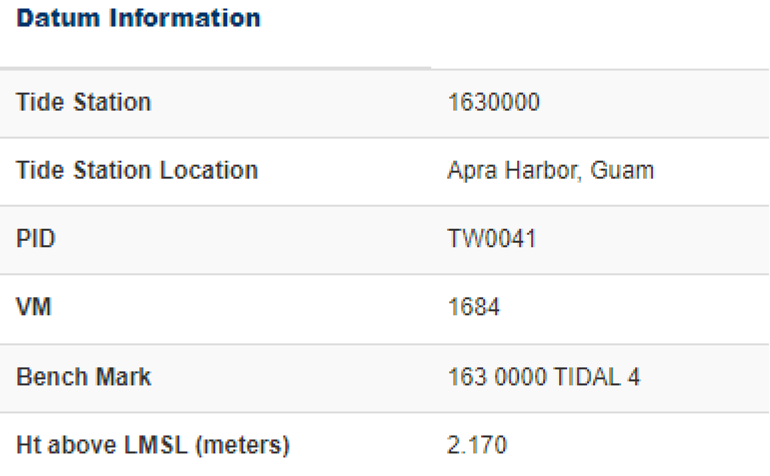
- Coastal erosion is problematic along Guam's 78 miles of coastline, most significant in southern Gaum (south of Tumon and Pago Bays).
- Climate related hazards include:
  - Total storm trends and typhoon intensifications show increases of roughly 5.4% and with intensities and increasing by 9.3% respectively, 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 Datum and Projection

The Guam Vertical Datum of 2004 (GUVD04) consists of a leveling network on the island of Guam affixed to a single origin point on the island. Datum information below can be sourced at the following URL and is shown below in Figure 3:

https://ngs.noaa.gov/datums/vertical/.guam-vertical-datum-2004.shtml



Datum Information

Tide Station	1630000
Tide Station Location	Apra Harbor, Guam
PID	TW0041
VM	1684
Bench Mark	163 0000 TIDAL 4
Ht above LMSL (meters)	2.170

Figure 3. Guam Vertical Datum.

Information on Tidal Benchmark Datums located at Apra Harbor, Guam (Station Number 1630000), and Pago Bay, Guam (Station Number 1631428) can be found at the following URLs:
https://tidesandcurrents.noaa.gov/datums.html?id=1630000

https://tidesandcurrents.noaa.gov/datums.html?id=1631428&name=Pago%20Bay,%20Guam,%20United%20States%20of%20Ame&state=ca

For more information on the development of geodetic vertical datums please refer to the document labeled “Development of Comprehensive Geodetic Vertical Datums for the United States Pacific Territories of American Samoa, Guam, and the Northern Marianas” at the URL below:

https://www.ngs.noaa.gov/PUBS_LIB/2009DevelopmentOfComprehensiveGeodeticVerticalDatumsForTheUSPacTerritoriesASGUNM)SaLIS.pdf#:~:text=American%20Samoa%20Vertical%20Datum%202002%20%28ASVD02%29%20Definition%20The,for%20the%20American%20Samoa%20Vertical%20Datum%202002%20%28ASVD02%29.

2.3 Elevation Data

Light Detection and Ranging (LiDAR) data were collected across the island of Guam by NOAA Office for Coastal Management (OCM) in 2012 and 2013 for the U.S. Geological Survey (USGS). The data is in North Atlantic Datum 1983 (NAD83) MA11, vertically referenced to GUVD04, has a vertical accuracy of +/- 8 centimeters (cm), and horizontal accuracy of +/- 0.11 m.

LiDAR data were also collected by USACE and the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) in 2007 for the Government of Guam. This data includes hydrographic and topographic data depicting the elevations above and below the immediate coastal water. The topographic lidar data are vertically referenced to Mean Sea Level (MSL) and the bathymetric lidar data are referenced to Mean Lower Low Water (MLLW). The data set has a horizontal accuracy of +/- 0.75 m and a vertical accuracy of Flood Hazard Study for Upper Namo River - Final 31 March 2020 10 +/- 20 cm. The data was collected so that the horizontal and vertical datum could be specified by the user. For this project, the selected projection was the Universal Transverse Mercator (UTM) coordinate system, zone 55N. Horizontal coordinates reference the NAD83 in meters. The vertical control datum is the Guam Vertical Datum of 2004 (GUVD04), in meters.

The Digital Atlas of Southern Guam and the Digital Atlas of Northern Guam, by WERI and IREI, provide public access to geospatial data that covers the entire island of Guam. The website address is: http://south.hydroguam.net/ and http://north.hydroguam.net/. Several files were downloaded and used as a resource for this study, including files on geology, climate, soil, surface water, land cover, and infrastructure.

2.4 Topography and Soils

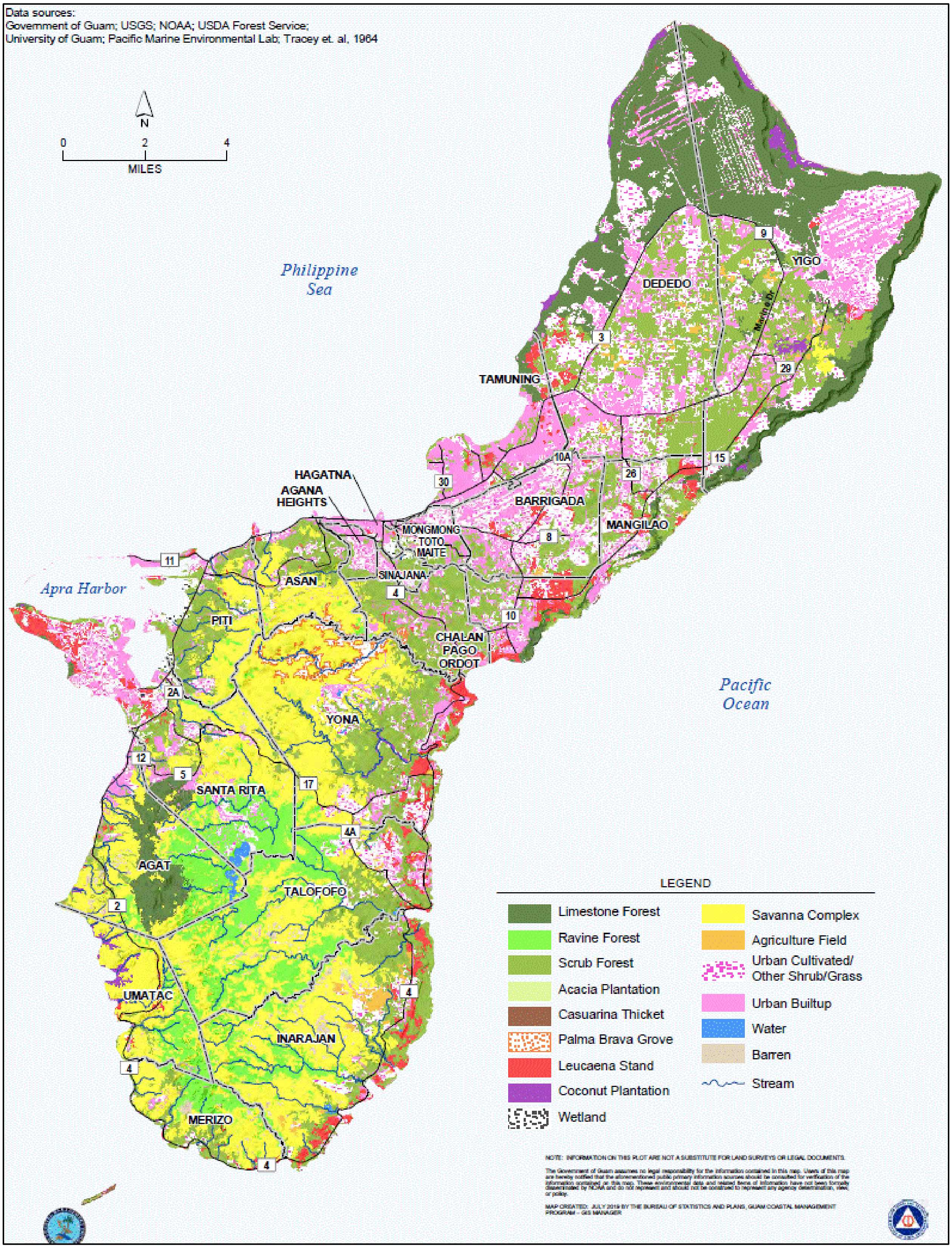
Guam can be divided into two geologic regions. The southern portion is mountainous with steep slopes and volcanic streams. Soils are unstable clay-sand and volcanic rock. The northern portion is predominately flat limestone with steep coastal cliffs along the plateau edges and narrow coastal plains inland. 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. (USDA SSURGO 1985. http://SoilDataMart.nrcs.usda.gov)

2.5 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, 2012)

Northern Guam has five main vegetation types associated with limestone soils: Breadfruit, banyan, Mammea, Cordia, nunu and aggag. Figure 4 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, 2020)


Data sources:
Government of Guam; USGS; NOAA; USDA Forest Service;
University of Guam; Pacific Marine Environmental Lab; Tracey et. al, 1964

NOTE: INFORMATION ON THIS PLOT ARE NOT A SUBSTITUTE FOR LAND SURVEYS OR LEGAL DOCUMENTS.

The Government of Guam assumes no legal responsibility for the information contained in this map. Users of this map are hereby notified that the aforementioned public primary information sources should be consulted for verification of the information contained on this map. These environmental data and related items of information have not been formally disseminated by NOAA and do not represent and should not be construed to represent any agency determination, view, or policy.

MAP CREATED: JULY 2019 BY THE BUREAU OF STATISTICS AND PLANS, GUAM COASTAL MANAGEMENT PROGRAM – GIS MANAGER

Figure 4. Detailed Vegetation Map of Guam

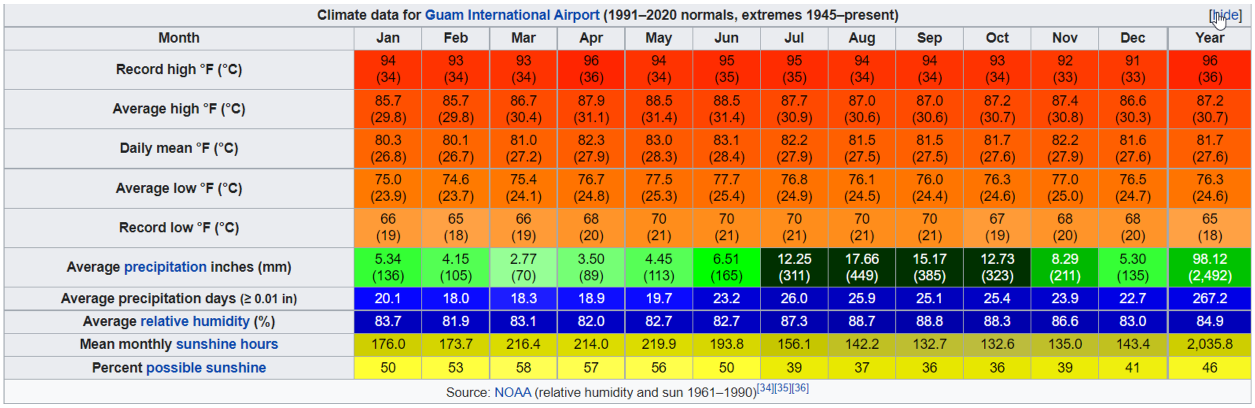
2.6 Climate Conditions, Variability, and Change

2.6.1 Climate

Engineering and Construction Bulletin (ECB) 2018 -14 (USACE, 2022), Engineering Regulation 1100-2-8162, and Engineering Technical Letter (ETL) 1110-2-3 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 ECB, 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.

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 °F. 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 5 below illustrates the range of temperatures seen in Guam.



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

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 5. Climate Data for Guam International Airport (Source: https://en.wikipedia.org/wiki/Guam retrieved April 2022)

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 6 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).

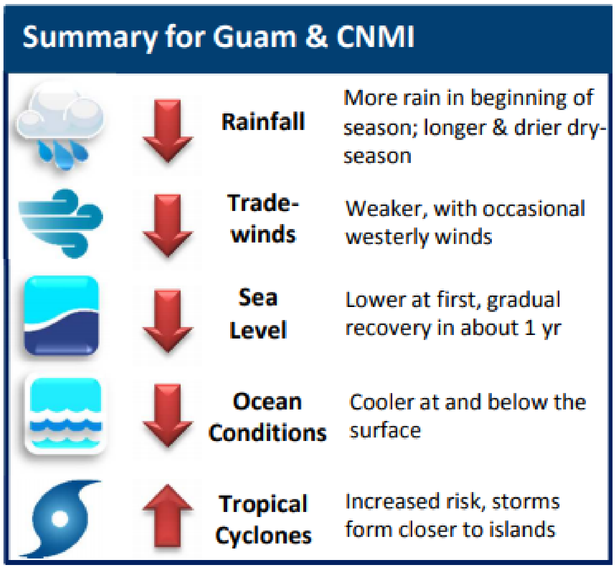


Figure 6. Impacts of El Niño Southern Oscillation on Western Pacific

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 7 illustrates the three ENSO phases of neutral, El Nino (warm ocean temperatures), and La Nina (cooler ocean temperatures) climate conditions and Figure 8 offers a perspective view of ENSO.

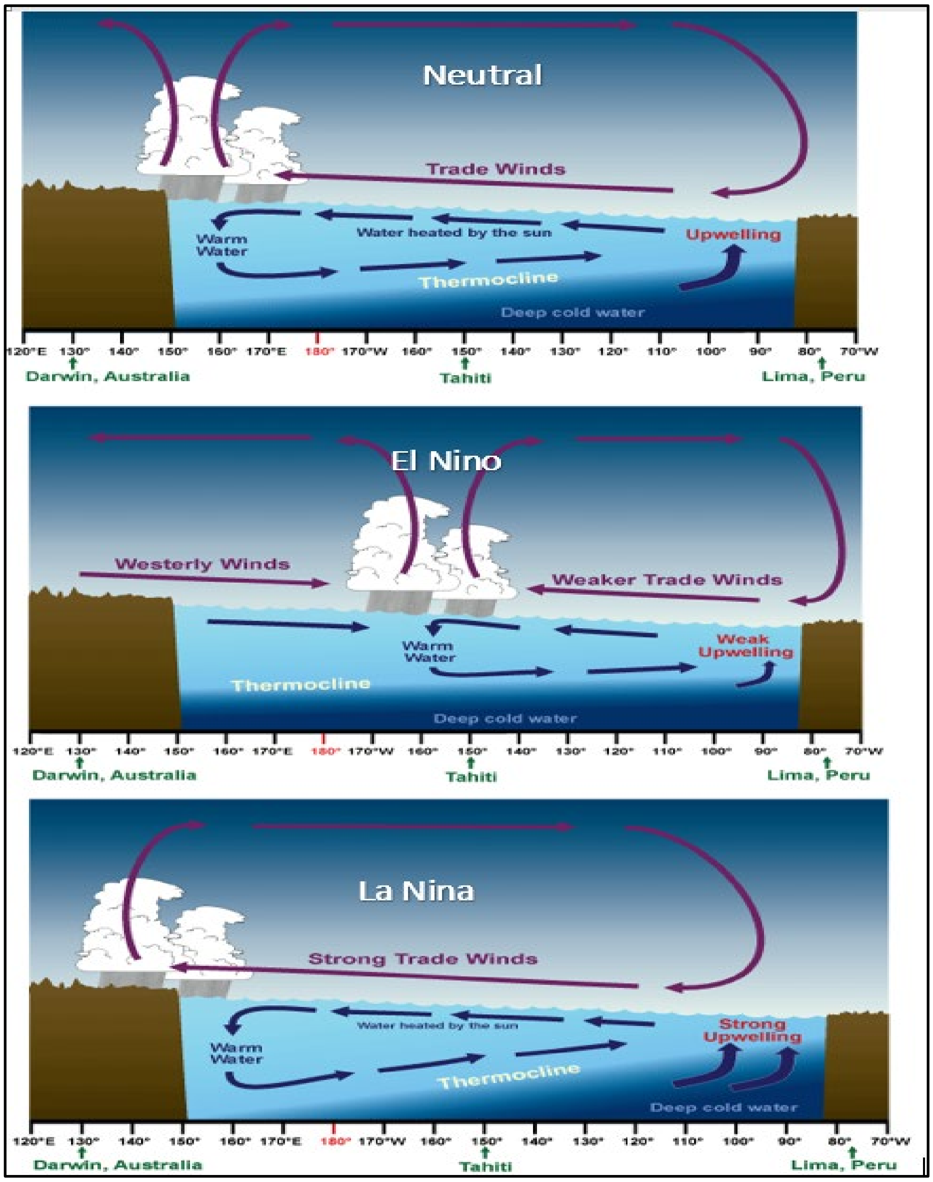


Figure 7. ENSO fluctuations in the Pacific, viewed from the Equator: Neutral, El Nino, and La Nina (source: NOAA)

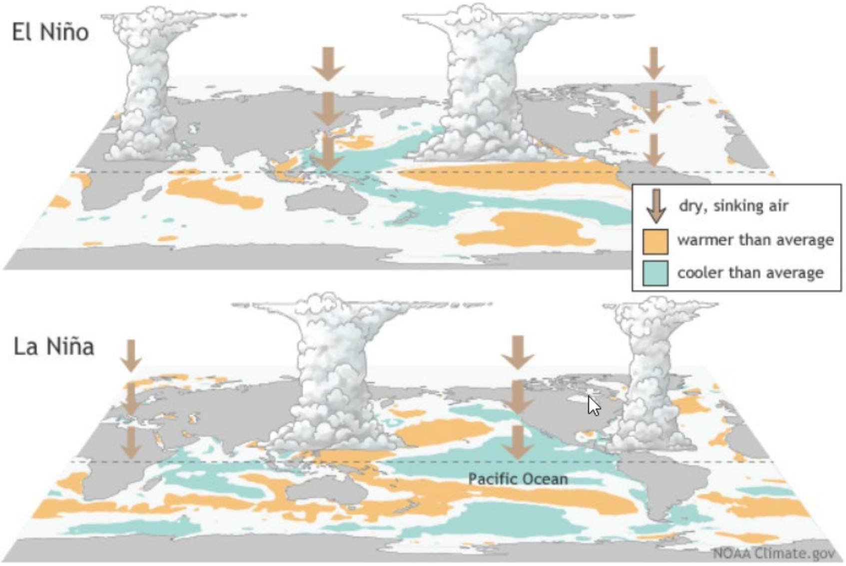


Figure 8. Perspective view of ENSO fluctuations

Changes in climate describe the phenomena of impacts to 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).

2.6.2 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 9. 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.

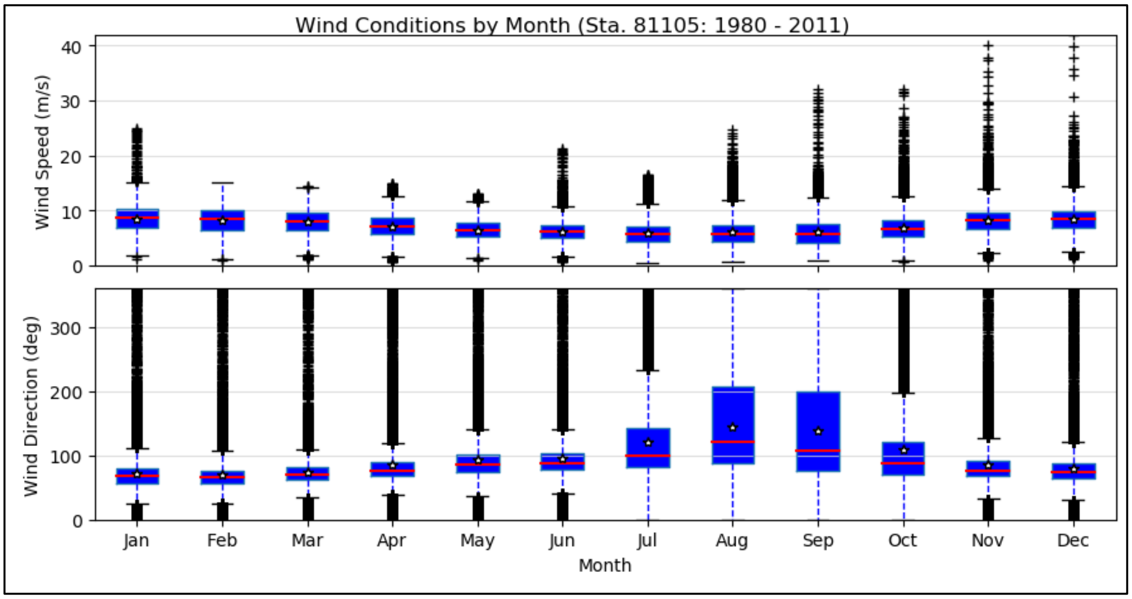


Figure 9. Seasonal Variation of Local Winds (Wave Information Station 81105)

2.6.3 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.

Average annual precipitation has been evaluated to be 98.1 inches. (NOAA NOWDATA retrieved May 2021).). However, annual precipitation deviation from normal are more difficult to quantify. ENSO cycles and tropical storm activity can vary in duration and frequency and can disrupt normal rainfall trends. Figure 10 illustrates the latest 29-year normal and observed precipitation deviations. The graphic below illustrates an insignificant trend in the reduction in annual 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. IPCC reports that rainfall intensity and typhoon intensity are projected to increase (IPCC, 2019).

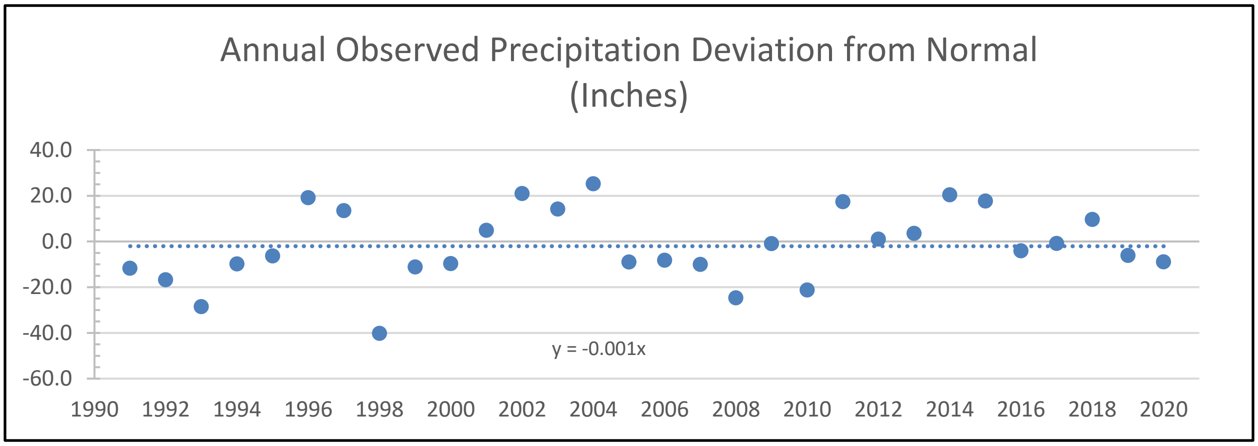


Figure 10. Departures from Normal, Annual Precipitation for Guam

2.6.4 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 typhoon, as they are known in the Western Pacific, is a tropical cyclone 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 11 shows the paths for all tropical events from 2000 through 2020 passing within 250 nautical miles from Guam.

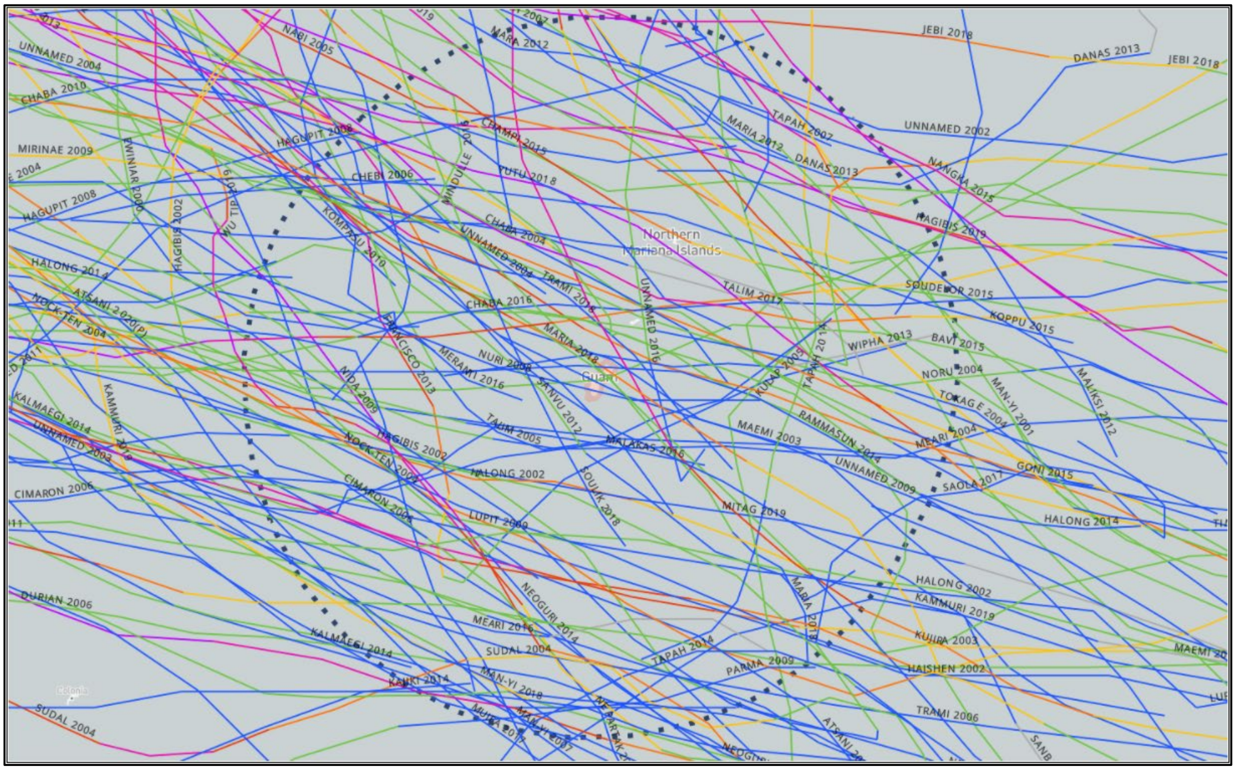


Figure 11. Tropical Events from 2000 to 2020 Passing Within 250 Nautical Miles from Guam

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 as shown in Figure 12 (USACE,2021). The nontidal residual is highly dependent on both the distance the storm passes from the island and the direction that it passes.

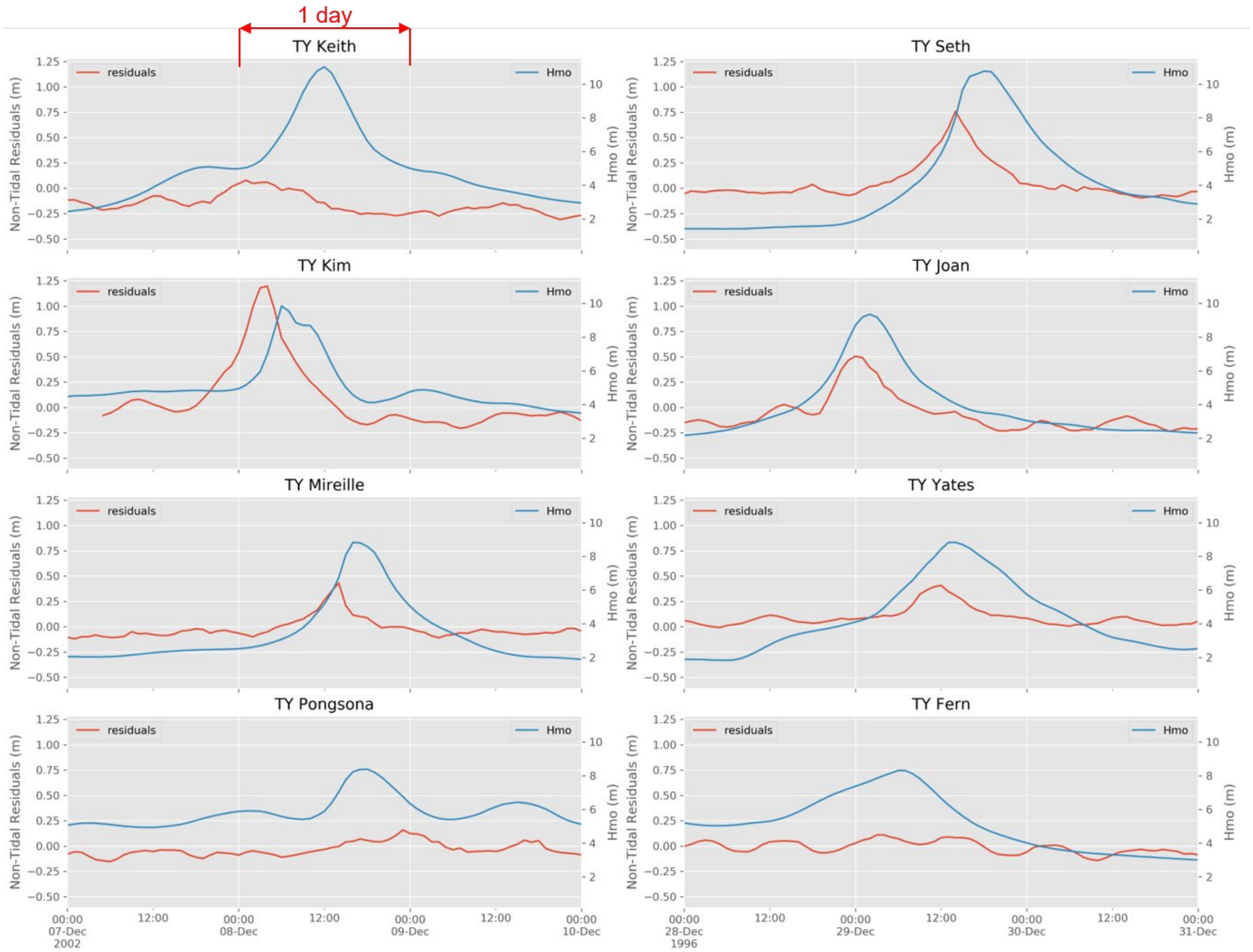


Figure 12. Typhoon Storm Duration Characteristics

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 13 and Figure 14 below are the inundation MOM maps depicting the maximum envelope of water for an existing condition, worst-case typhoon.

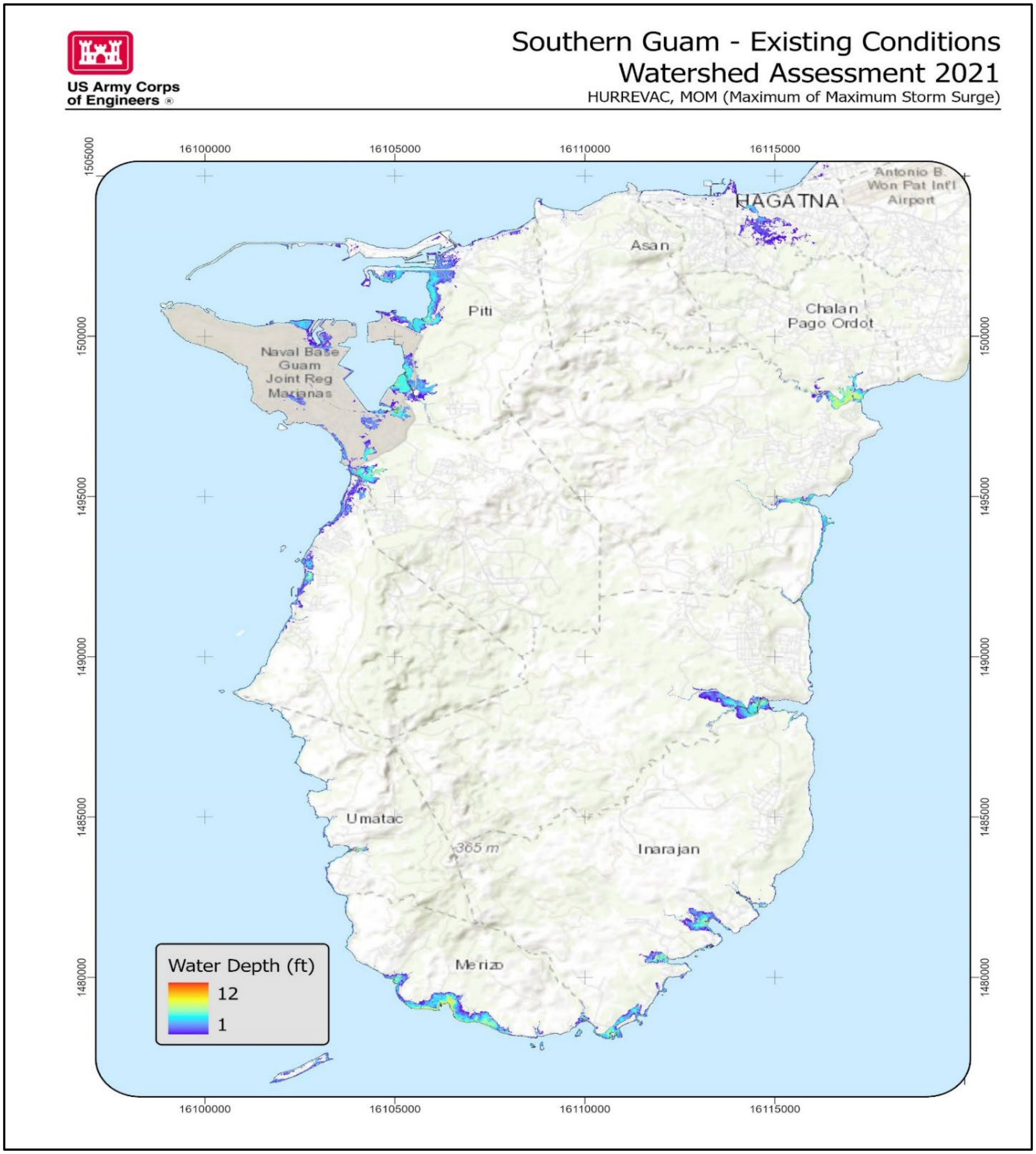


Figure 13. Southern Guam Typhoon Inundation - Existing Conditions (HURREVAC MOM) (ESRI)

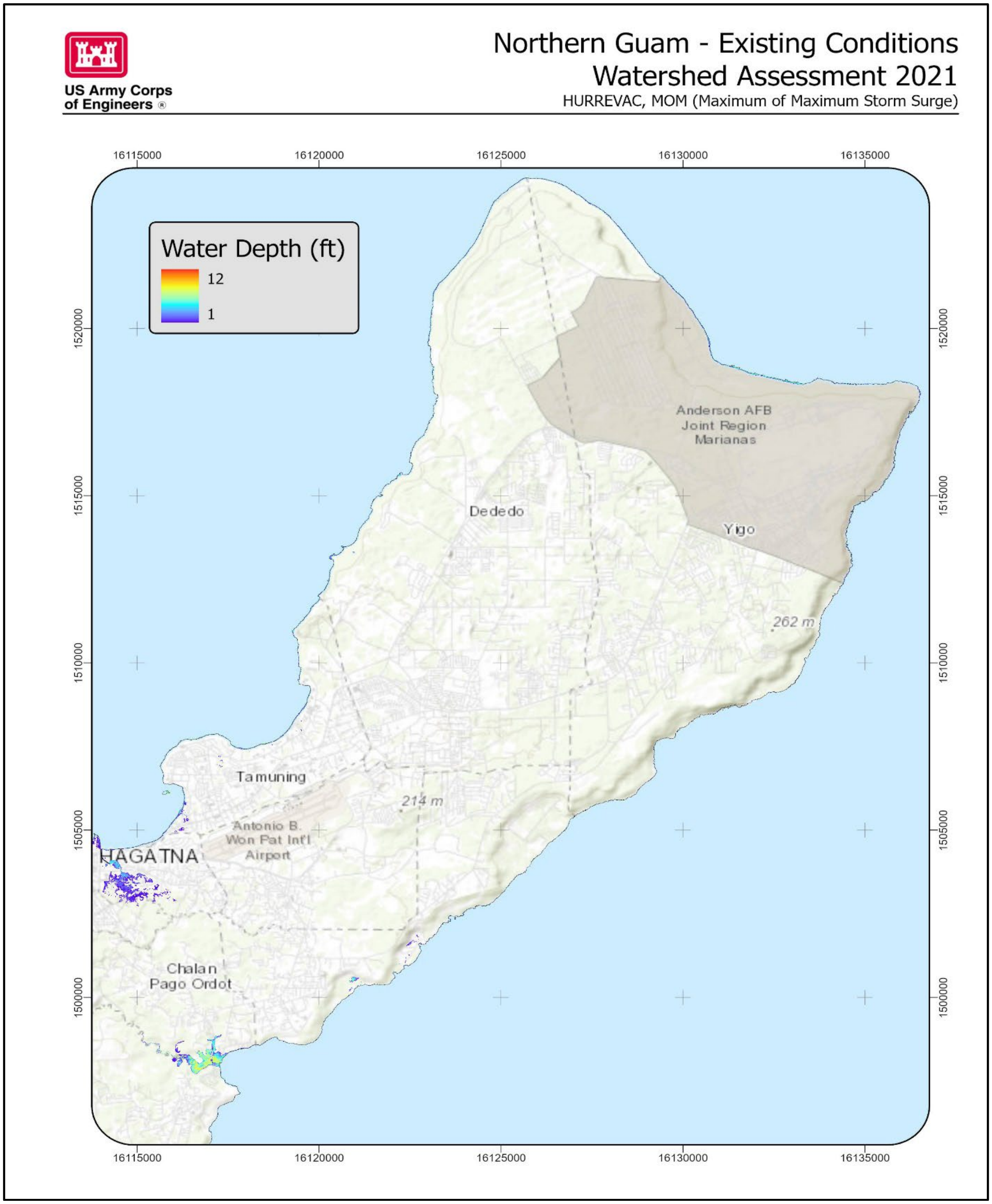


Figure 14. Northern Guam Typhoon Inundation - Existing Conditions (HURREVAC MOM) (ESRI)

2.7 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. Wave Information Studies (WIS) Station ST81420 is approximately 142 nautical miles northwest from the island in water depths greater than 10,000 ft. Basic wave statistics developed at this virtual location are shown in Table 1. The wave height climate is graphically shown in the wave rose in Figure 15.

Table 1. Wave Statistics for WIS Station ST81420

Statistic	Value
Average wave height:	6.44 ft
Standard deviation of wave height:	2.28 ft
Average wave period:	9.68 sec
Standard deviation of wave period:	1.47 sec
Maximum wave height:	36.15 ft
Period associated w/ max wave height:	14.13 sec
Direction associated w/ max wave height:	92.0 deg
Date associated w/ max wave height:	11/2/1997 12:00
Total number of wave records:	280,511

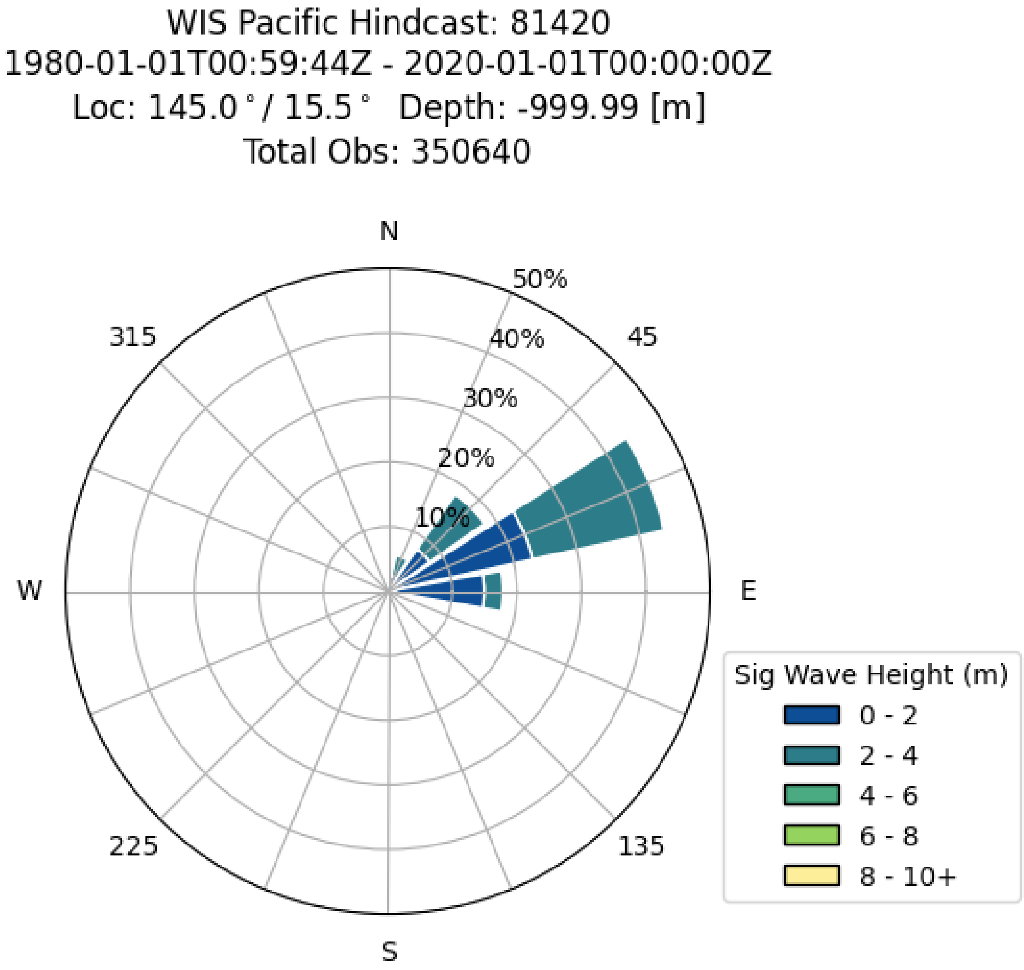


Figure 15. Wave Rose for WIS Station ST81420

2.8 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 16 and Figure 17 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.

Compound flooding refers to a phenomenon in which two or more flooding sources occur simultaneously or subsequently within a short period of time. In terms of coastal flooding, a compound flooding event is flooding caused by the interaction of the open ocean, atmosphere, and watersheds. As Guam is made up from a portion of a submerged mountain range and has very steep terrain and the alluvial fans are very short we believe there are insignificant areas where the phenomenon of compound flooding exists.

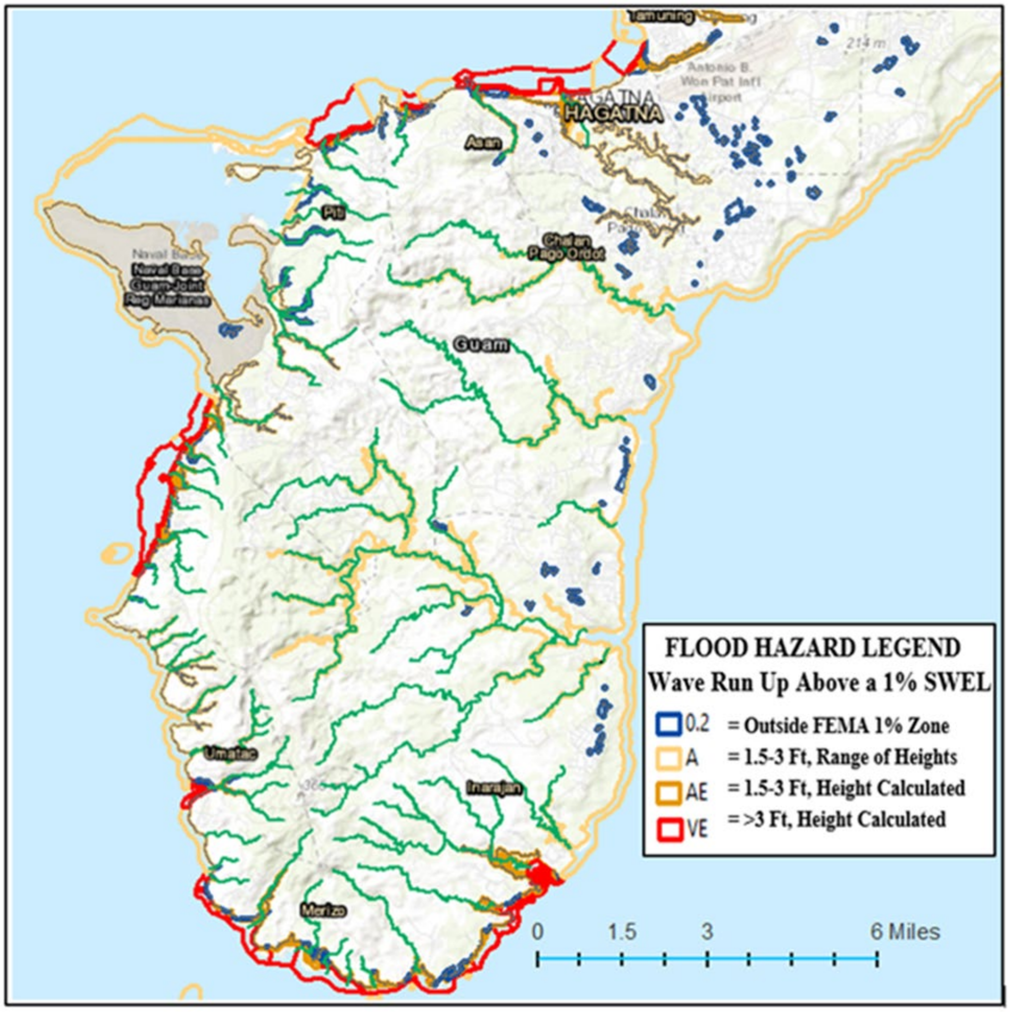


Figure 16. FEMA 1% ACE Coastal Wave Run Up and Riverine Flood Hazard Zones

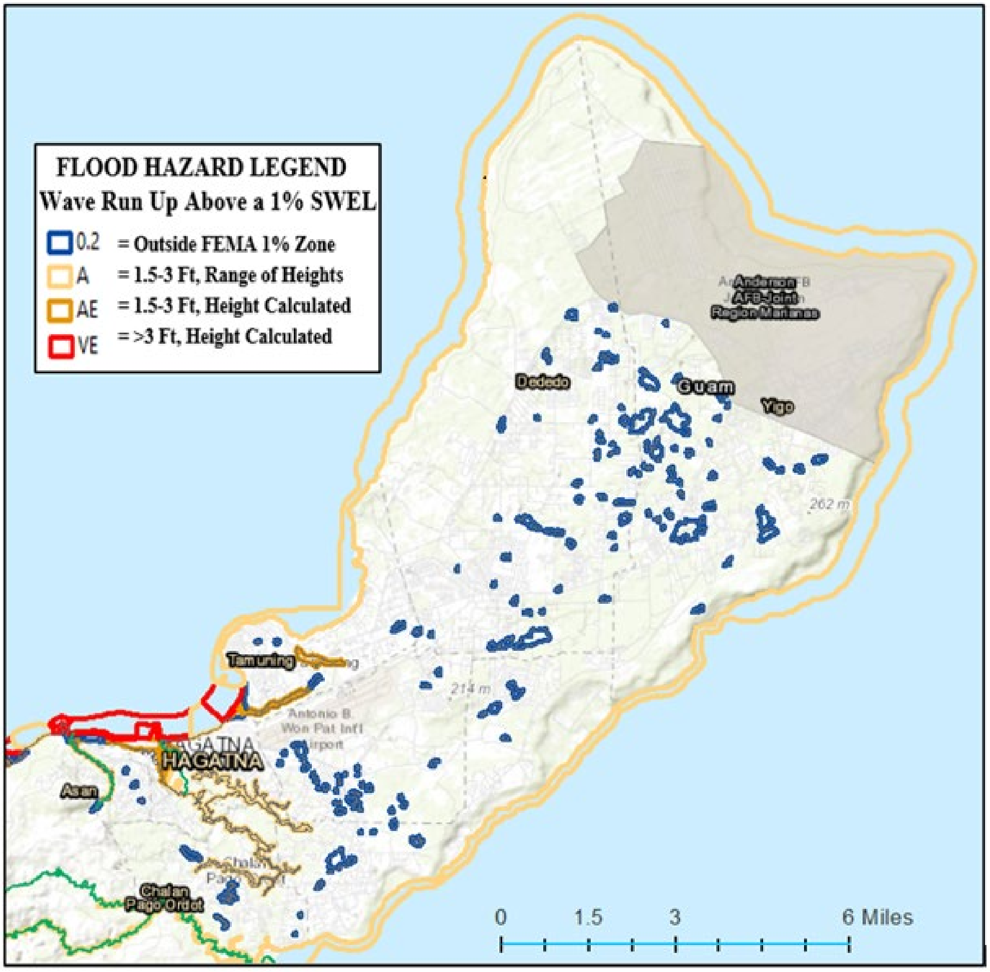
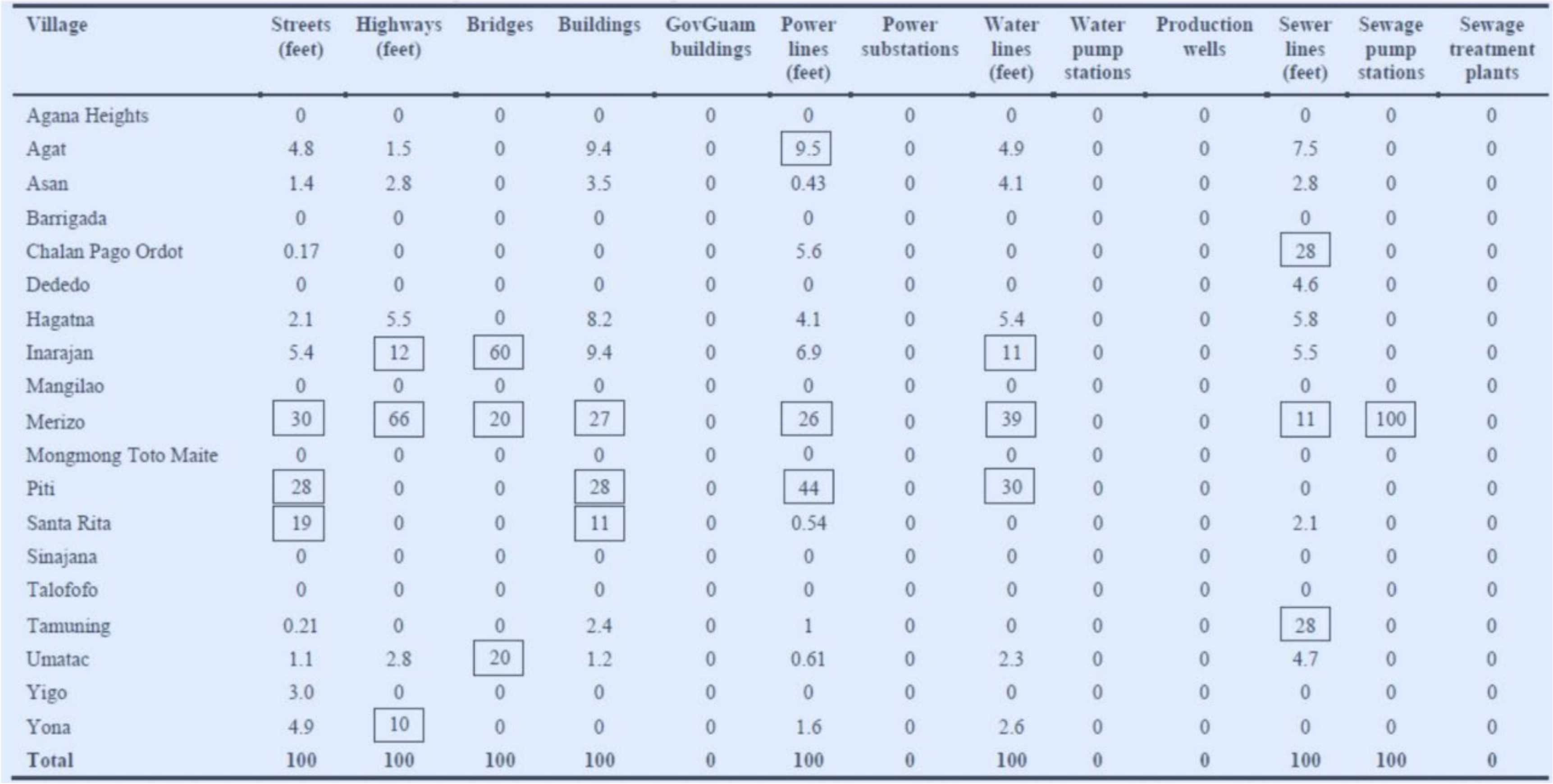


Figure 17. FEMA 1% ACE Coastal Wave Run Up and Riverine Flood Hazard Zones

The Vulnerability Assessment of Built Infrastructure near Coastal Bays using three Sea Level Rise Scenarios determined the southern watersheds of Merizo and Inarajan, and the western watershed Piti, will have the highest amount of impacted infrastructure under a three-foot SLR scenario. Table 2 is an excerpt from the report.

Table 2.Percentage of infrastructure impacted within each municipality under a three-foot SLR scenario. (Table from Guam BSP)



Village	Streets (feet)	Highways (feet)	Bridges	Buildings	GovGuam buildings	Power lines (feet)	Power substations	Water lines (feet)	Water pump stations	Production wells	Sewer lines (feet)	Sewage pump stations	Sewage treatment plants
Agana Heights	0	0	0	0	0	0	0	0	0	0	0	0	0
Agat	4.8	1.5	0	9.4	0	9.5	0	4.9	0	0	7.5	0	0
Asan	1.4	2.8	0	3.5	0	0.43	0	4.1	0	0	2.8	0	0
Barrigada	0	0	0	0	0	0	0	0	0	0	0	0	0
Chalan Pago Ordot	0.17	0	0	0	0	5.6	0	0	0	0	28	0	0
Dededo	0	0	0	0	0	0	0	0	0	0	4.6	0	0
Hagatna	2.1	5.5	0	8.2	0	4.1	0	5.4	0	0	5.8	0	0
Inarajan	5.4	12	60	9.4	0	6.9	0	11	0	0	5.5	0	0
Mangilao	0	0	0	0	0	0	0	0	0	0	0	0	0
Merizo	30	66	20	27	0	26	0	39	0	0	11	100	0
Mongmong Toto Maite	0	0	0	0	0	0	0	0	0	0	0	0	0
Piti	28	0	0	28	0	44	0	30	0	0	0	0	0
Santa Rita	19	0	0	11	0	0.54	0	0	0	0	2.1	0	0
Sinajana	0	0	0	0	0	0	0	0	0	0	0	0	0
Talofofo	0	0	0	0	0	0	0	0	0	0	0	0	0
Tamuning	0.21	0	0	2.4	0	1	0	0	0	0	28	0	0
Umatac	1.1	2.8	20	1.2	0	0.61	0	2.3	0	0	4.7	0	0
Yigo	3.0	0	0	0	0	0	0	0	0	0	0	0	0
Yona	4.9	10	0	0	0	1.6	0	2.6	0	0	0	0	0
Total	**100**	**100**	**100**	**100**	**0**	**100**	**0**	**100**	**0**	**0**	**100**	**100**	**0**

2.9 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 because 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, 2021).

Figure 18 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 19.

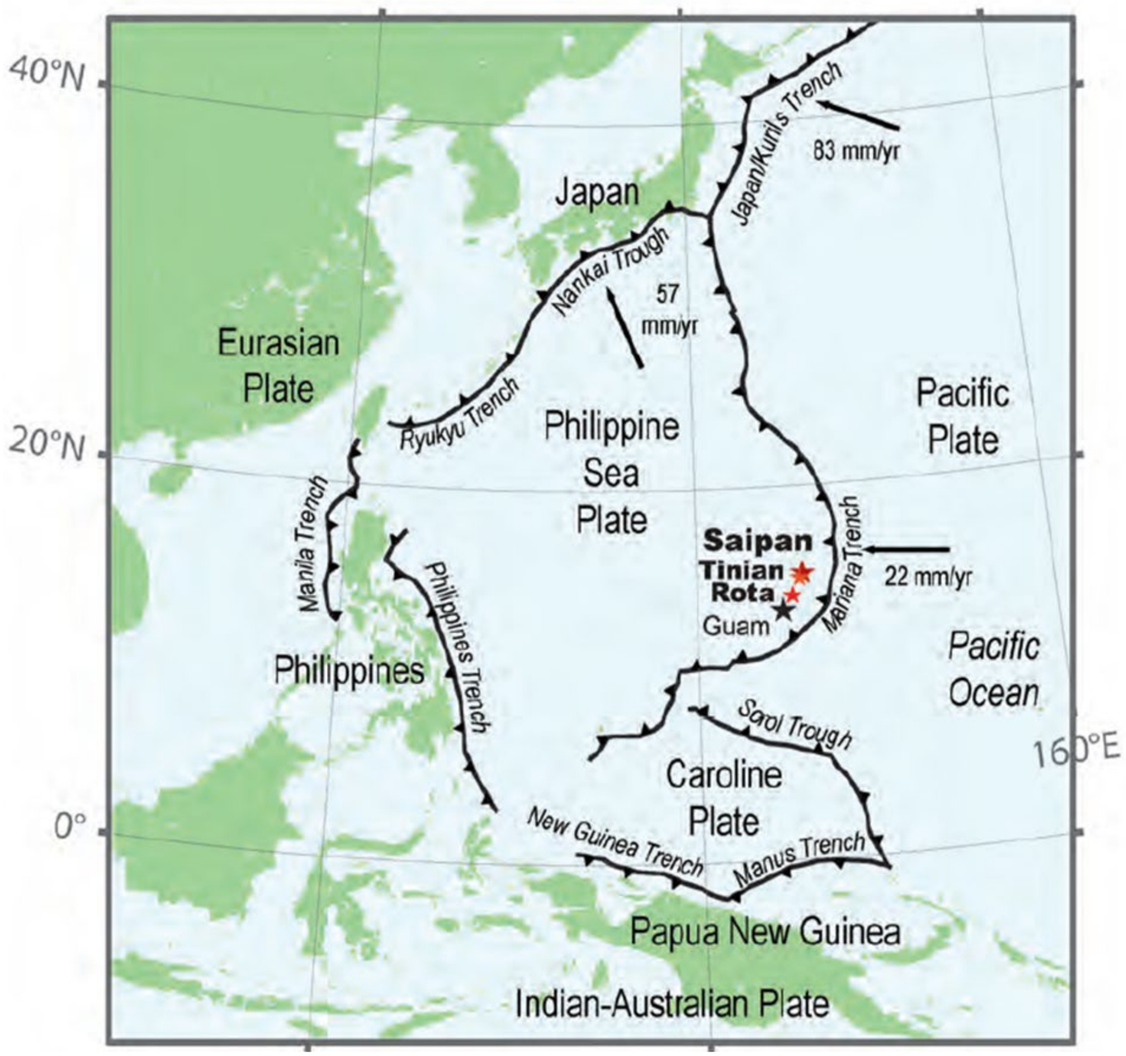


Figure 18. Regional Setting of Guam and Proximity to Major Subduction Zones (NOAA OAR, 2014)

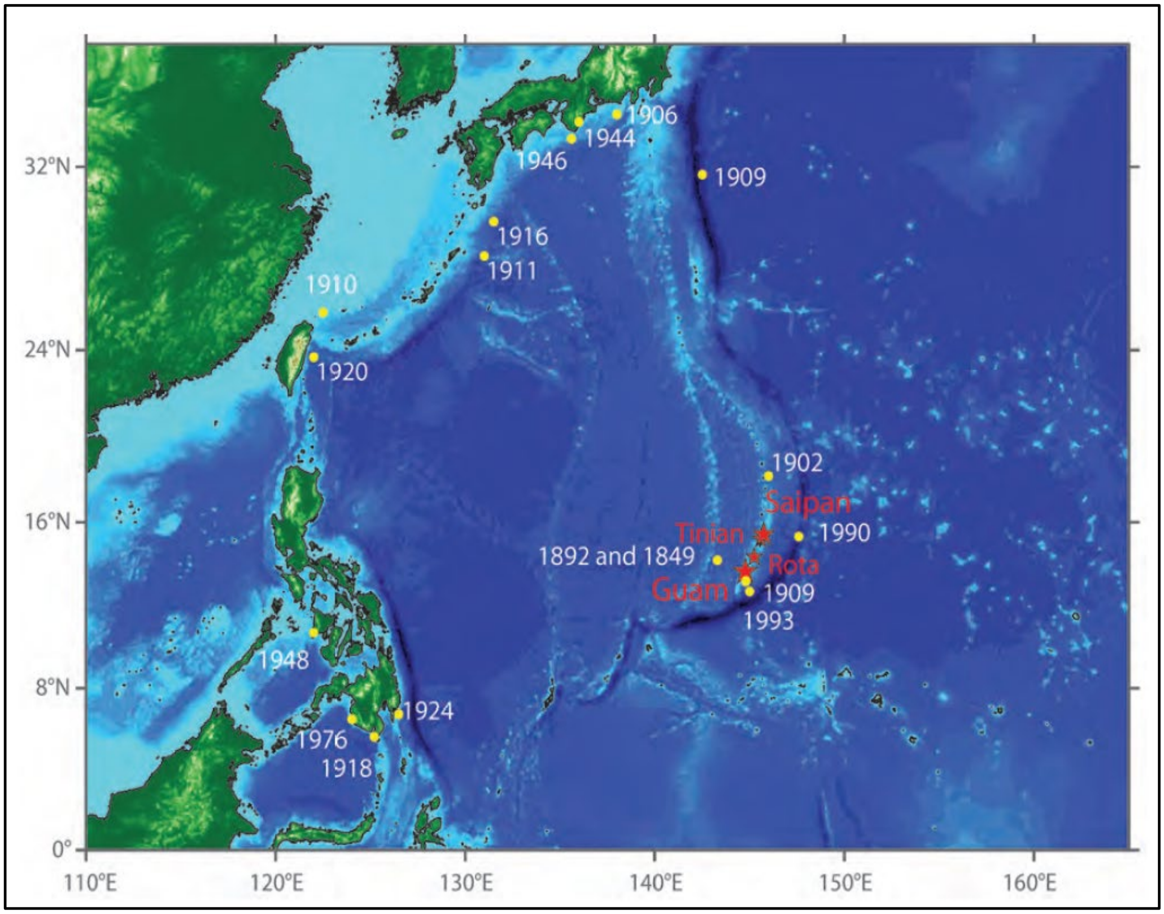


Figure 19. USGS Recorded Earthquakes > M 8.0 Since 1900 (NOAA OAR, 2014)

2.10 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 20 illustrates buoy locations monitored by NOAA/TWC.

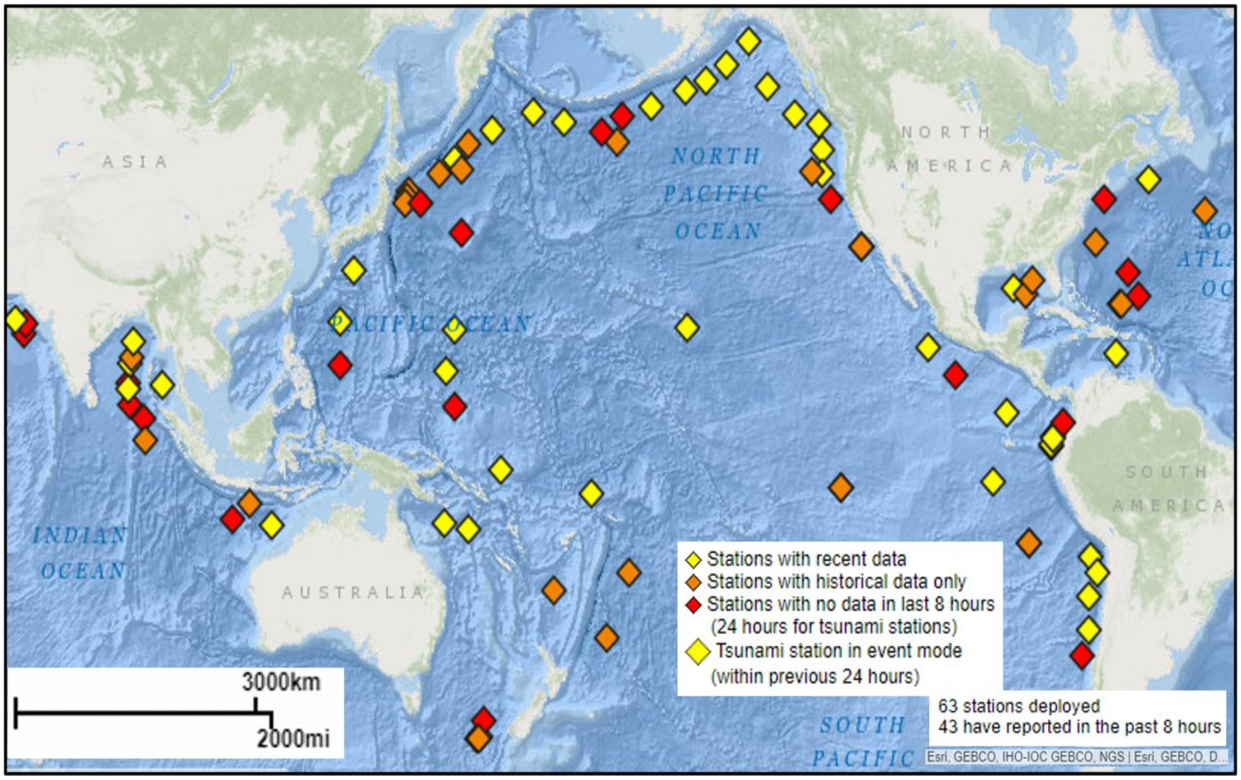


Figure 20. DART Buoy Locations (NOAA, National Data Buoy Center, real time data)

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 21 and Figure 22, are NOAA/OAR modeled probable maximum tsunami (PMT) inundation maps for north and south Guam.

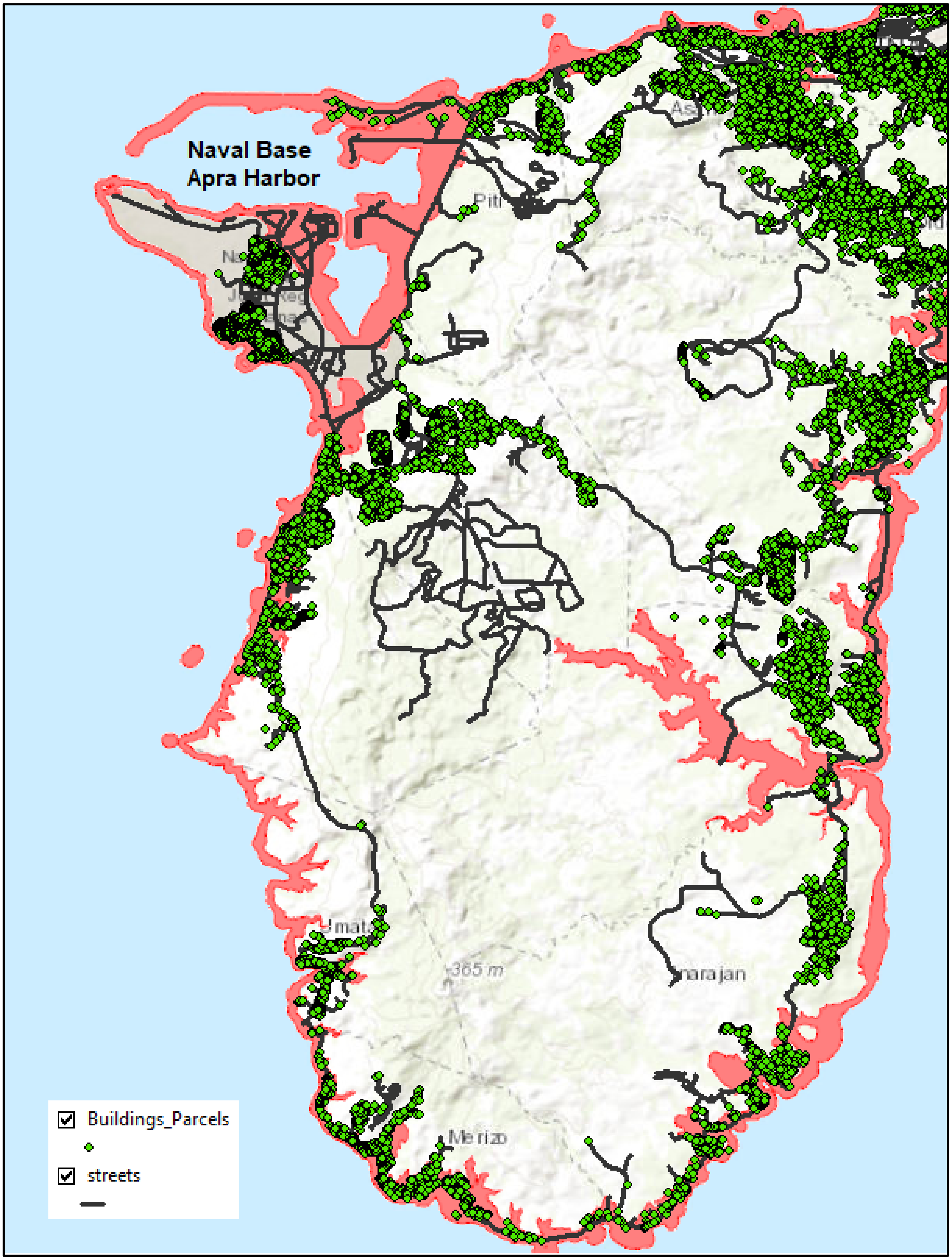


Figure 21. PMT Southern Guam (ESRI)

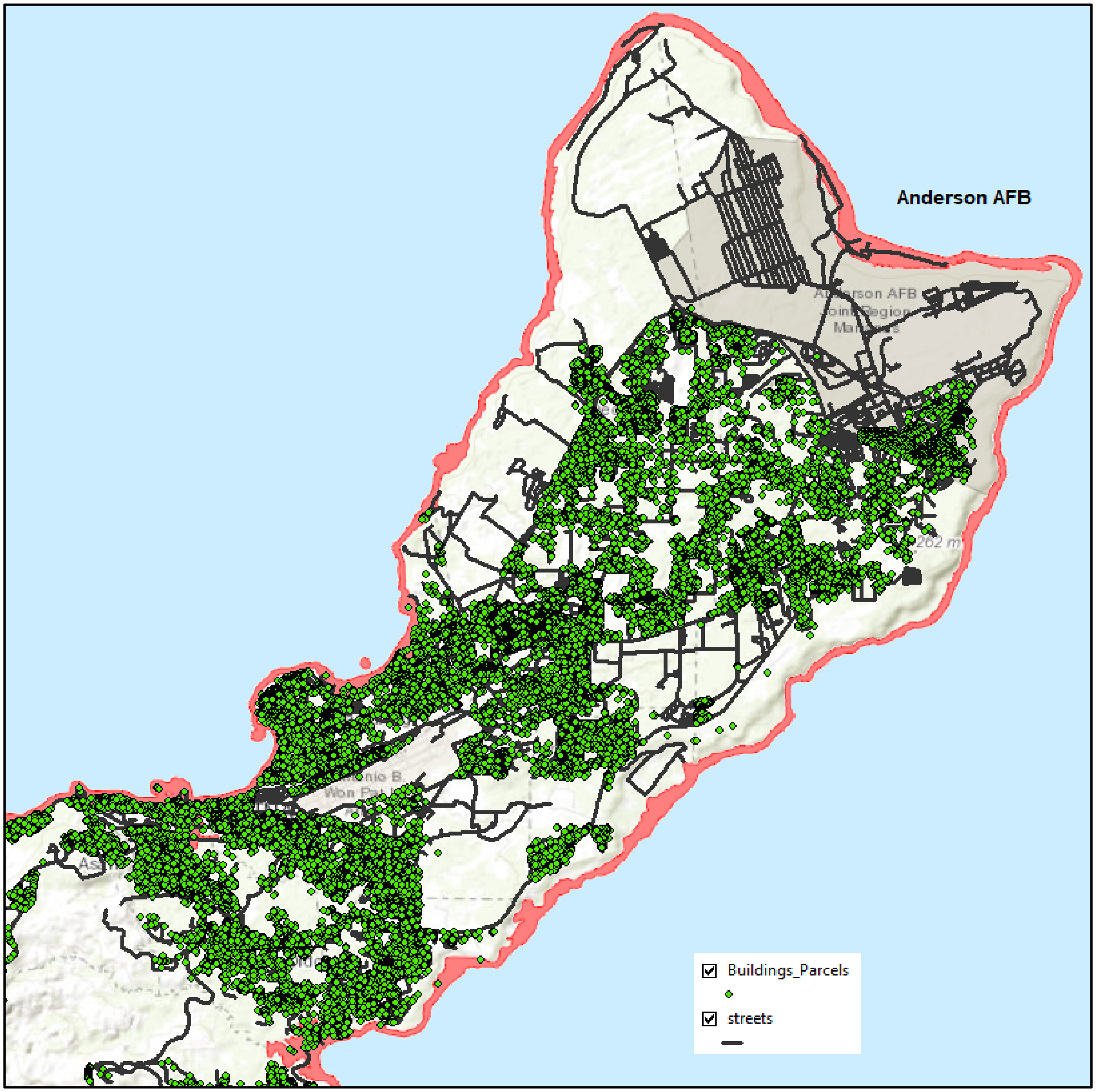


Figure 22. PMT Northern Guam (ESRI)

Table 2 lists critical infrastructure that lies within FEMA 1% ACE coastal and riverine flood zones, HURREVAC (MOM inundation) existing and Future Without Project (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. FEMA Flood Insurance Rate Maps (FIRM) are available for Guam at the URL Provided below.
https://hazards-fema.maps.arcgis.com/apps/webappviewer/index.html?id=8b0adb51996444d4879338b5529aa9cd

Table 3. 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

USACE projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of natural climate variability over their operating life spans. However, recent scientific evidence shows that in some places and for some impacts relevant to

USACE operations, climate change is shifting the climatological baseline about which that natural climate variability occurs and may be changing the range of that variability as well. This is relevant to USACE because the assumptions of stationary climatic baselines and a fixed range of natural variability as captured in the historic hydrologic record may no longer be appropriate for long-term projections of the climatologic parameters, which are important in hydrologic assessments for inland watersheds (USACE, 2020).

To evaluate the impacts of climate change on the study area's hydrometeorology a qualitative climate assessment is carried out in accordance with ECB 2018-14, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. As indicated by the flow chart in Figure 23, the qualitive assessment includes a literature review examining trends in historic, observed, and projected, future temperature, precipitation, and streamflow. The literature review is conducted at both the western Pacific (regional) and Island (local) scale. The assessment requires a quantitative evaluation of trends and nonstationarities in observed hydrometeorological records relevant to the study area and purpose. The final component of the ECB 2018-14 analysis is a review of projected climate changed hydrology and a screening level vulnerability assessment specific to the USACE business lines associated with the study objective.

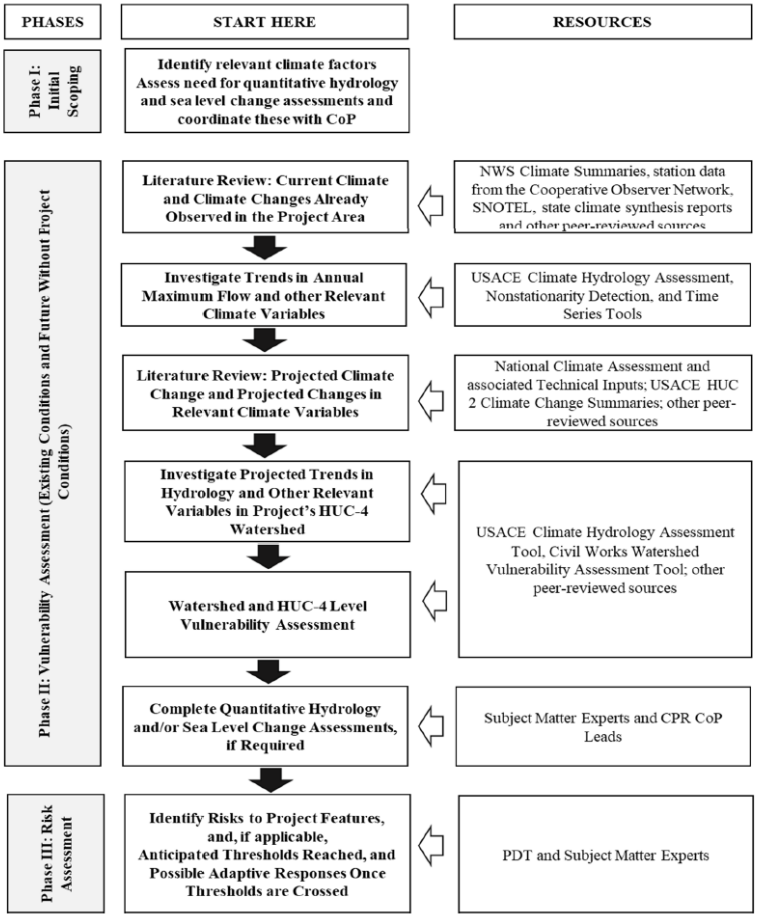
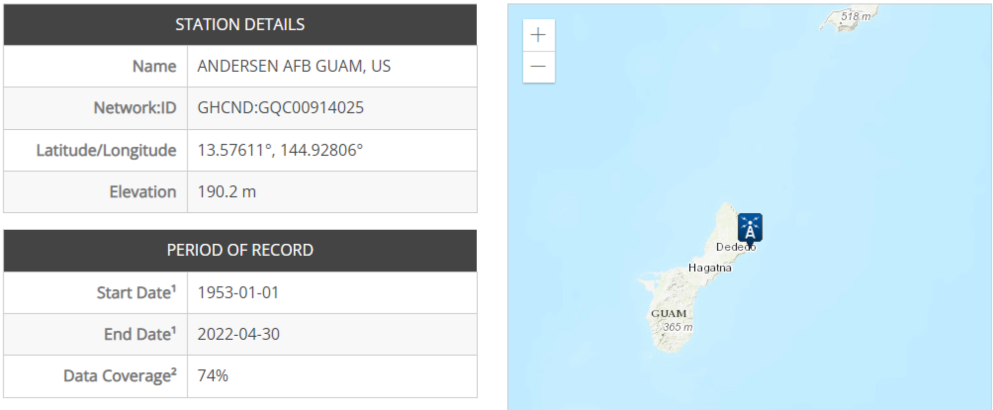


Figure 23. Flow chart describing steps for a qualitative assessment of impacts of climate change in hydrologic analyses (USACE[1], 2022).

3.1 Literature Review

To summarize trends in observed and projected temperature, precipitation, and streamflow the *Climate Science Special Report from the Fourth National Climate Assessment* (NCA4) (USGCRP, 2018) and the USACE's synthesis of *Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of* Engineers- Hawaii *Region* (USACE (2015)) are referenced but do not explicitly describe Guam. Other sources used in developing this report include the 2021 report labeled "2021: Climate Change in the Commonwealth of the Northern Mariana Islands: Indicators and Considerations for Key Sectors" by Grezni, Z. et all. Although this document focuses on climate change for the Commonwealth of the Northern Mariana Islands, CNMI, this document evaluates projections of temperature and precipitation using data measured at Andersen Air Force Base from 1953 to 2002 as shown in Figure 24 below as a proxy of climate conditions at CMNI. Other sources used in developing this report are referenced.



STATION DETAILS	
Name	ANDERSEN AFB GUAM, US
Network:ID	GHCND:GQC00914025
Latitude/Longitude	13.57611°, 144.92806°
Elevation	190.2 m

PERIOD OF RECORD	
Start Date¹	1953-01-01
End Date¹	2022-04-30
Data Coverage²	74%

Figure 24. ANDERSEN AFB GUAM, US. NOAA Gauge ID-GHCND:GQC00914025

3.2 Observed Temperature Trends

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.

Figure 25 illustrates the annual number of hot days in Guam. The figure shows days with temperatures at or above 88°F recorded at the Andersen Air Force Base weather station have increased, with 5 days per year exceeding 88°F on average in the 1950s, compared to 36 days per year on average in the 1990s. Similarly, there has been a drop in the annual number of cool nights (below 74°F) observed at Andersen as displayed in Figure 26. The Average air temperature (Figure 27) shows temperatures have risen overall.

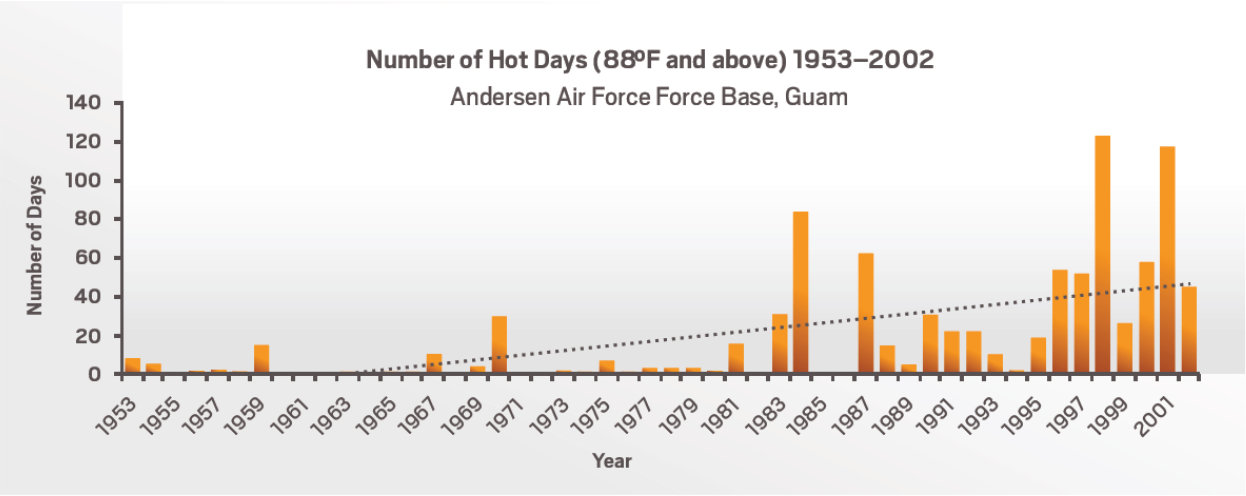


Figure 25. Number of Hot Days

Note: Figure 25 presents the Annual number of days with maximum temperature 88°F or hotter (at or above the 95th percentile of the data record) at Andersen Air Force Base in Guam from 1953 to 2002. The trendline (black, dotted line) shows there has been a long-term increase in the annual number of hot days. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1953–2002 (NOAA 2020c).

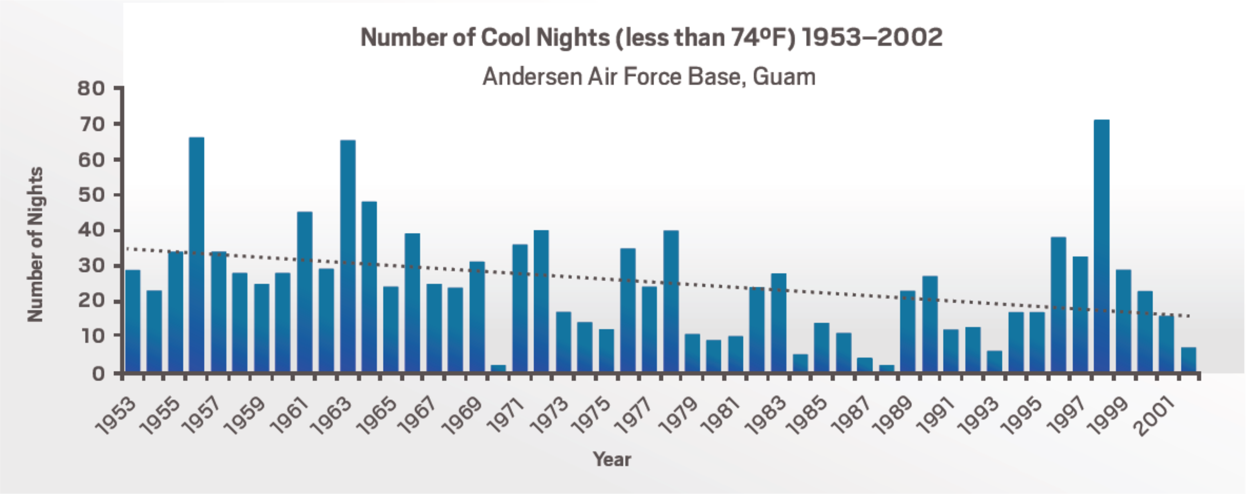


Figure 26. Number of Cool Nights

Note: Figure 26. Annual number of nights with minimum temperature less than 74°F —the 10th percentile of the data record—at Andersen Air Force Base in Guam from 1953 to 2002. The trendline (black, dotted line) shows a decrease on average in the frequency of cool nights during 1953–2002. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c).

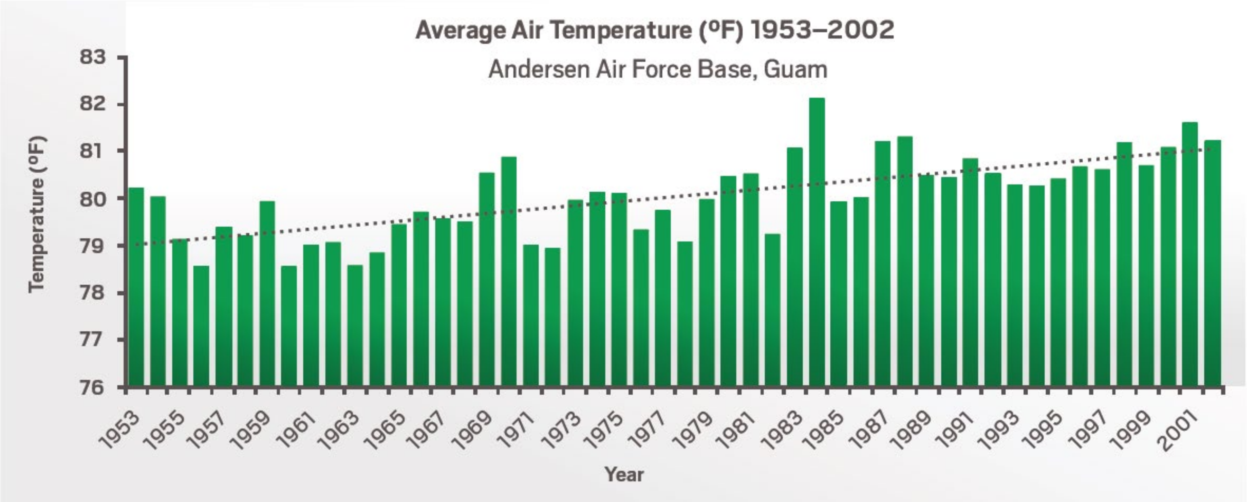


Figure 27. Average Air Temperature
Note: Figure 27 illustrates the Average annual air temperature at Andersen Air Force Base in Guam 1953–2002. The long-term linear trend indicated by the black, dotted line shows an increase over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1953–2002 (NOAA 2020c; Menne et al. 2012).

Average daily temperatures in Guam are projected to rise by 2.7–3.6°F under a low warming scenario and by 5.4–6.3°F under a high scenario by 2080–2099 (Zhang et al. 2016; Wang et al. 2016). Model projections for Guam indicate hot days over 90°F may increase to 257 days per year under a high scenario by the end of this century. In other words, more than 70% of days in the year are expected to see temperatures over 90°F (Zhang et al. 2016).

3.3 Observed Precipitation Trends

Rainfall patterns in the Marianas are closely tied to Eastern Hemisphere monsoons and the El Nino–Southern Oscillation (ENSO). As a result, annual rainfall varies dramatically. Figure 28 shows rainfall patterns reacting to ENSO at Andersen Air Force Base in Guam. The driest year on record at Andersen Air Force Base was 1998, when rainfall was more than 39 inches below normal due to a strong El Nino (Marra and Kruk 2017). 1976 was the wettest year on record, with more than 49 inches of rainfall over average.

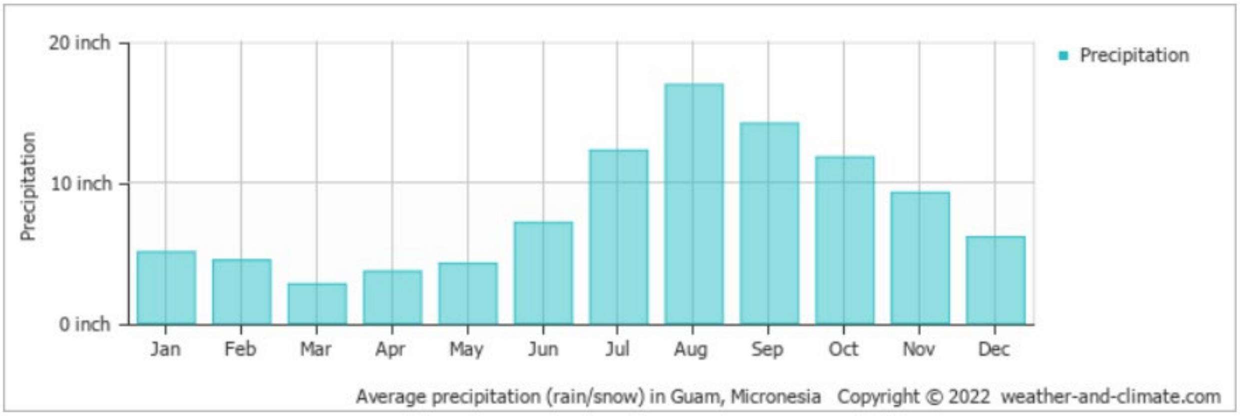


Figure 28. Average Monthly Precipitation in Guam. [https://weather-and-climate.com/average-monthly-precipitation-Rainfall-inches,Guam-fm,Micronesiarage monthly rainfall and snow in Guam, Micronesia (inches) (weather-and-climate.com)](https://weather-and-climate.com/average-monthly-precipitation-Rainfall-inches,Guam-fm,Micronesia)

Average annual rainfall volumes range from 80 inches per year (lowlands) to 110 inches per year (mountainous) in Guamwhile the average annual precipitation is 98.1 inches. (NOAA NOWDATA retrieved May 2021). 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 14 percent increase in super typhoons by the end of the century. (Hannam, 2015). 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.

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 29 below illustrates the latest 29-year normal and observed precipitation deviations. Trends show a minor reduction in annual precipitation in observed rainfall compared to the mean. 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).

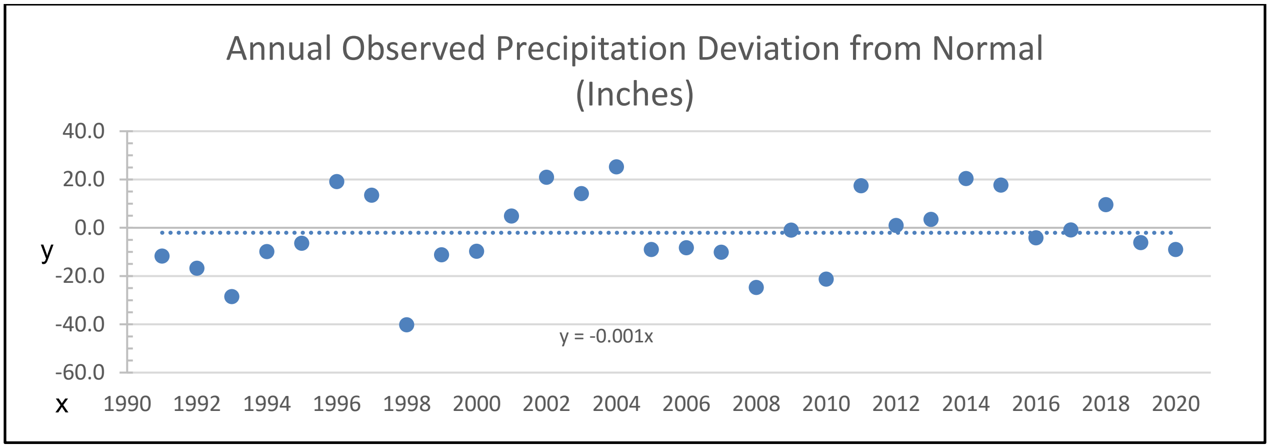


Figure 29. Departures for Normal, Annual Precipitation for Guam (NOAA NOWDATA retrieved May 2021)

Based upon projected trends, mean temperatures, number of hot days, maximum temperatures, relative 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.

3.4 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. Figure 30 illustrates the relative sea level trends and the impact of the 1992 earthquake for gauge 1630000. For more information on this gauge please follow the URL provided: https://tidesandcurrents.noaa.gov/datums.html?id=1630000.

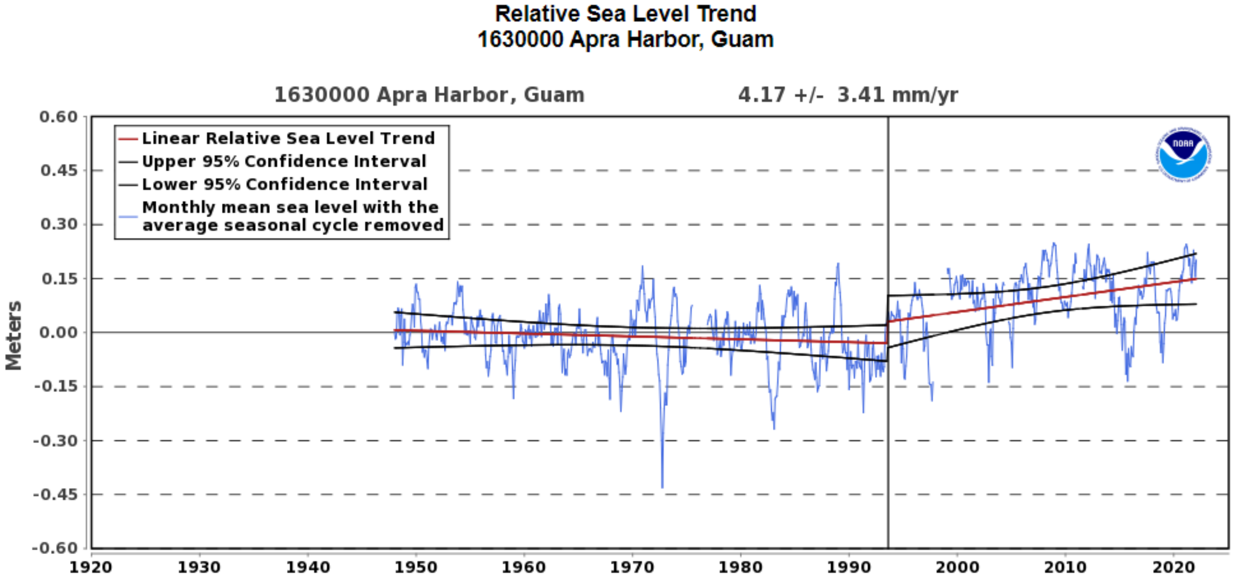


Figure 30. RLSC Apra Harbor, Guam

In Guam, eustatic water levels, tectonic activity and land subsidence all contributes to relative sea level change (RSLC). Figure 32 illustrates the low, intermediate, and high regional sea level change RSLC estimates based on the Apra Harbor gage. 1992 is the base year for calculations of sea level change in accordance with the established USACE methodology. It is noted that this 1992 year is based on tidal epoch and is unrelated to economic analysis. The curves are based on a historic rate of 0.00886 ft/yr developed by the USACE Honolulu District. The NRC Curves I and III predicted rates are represented by the green and red lines, respectively. This 100-year forecast period is based on a 2022 base year. RSLC is anticipated to range between 1.1-7.2 feet by 2122. 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. A comparison of USACE and NOAA curves can be found in Figure 25. These curves utilize local mean sea level, which is defined as the height of the sea with respect to a land benchmark.

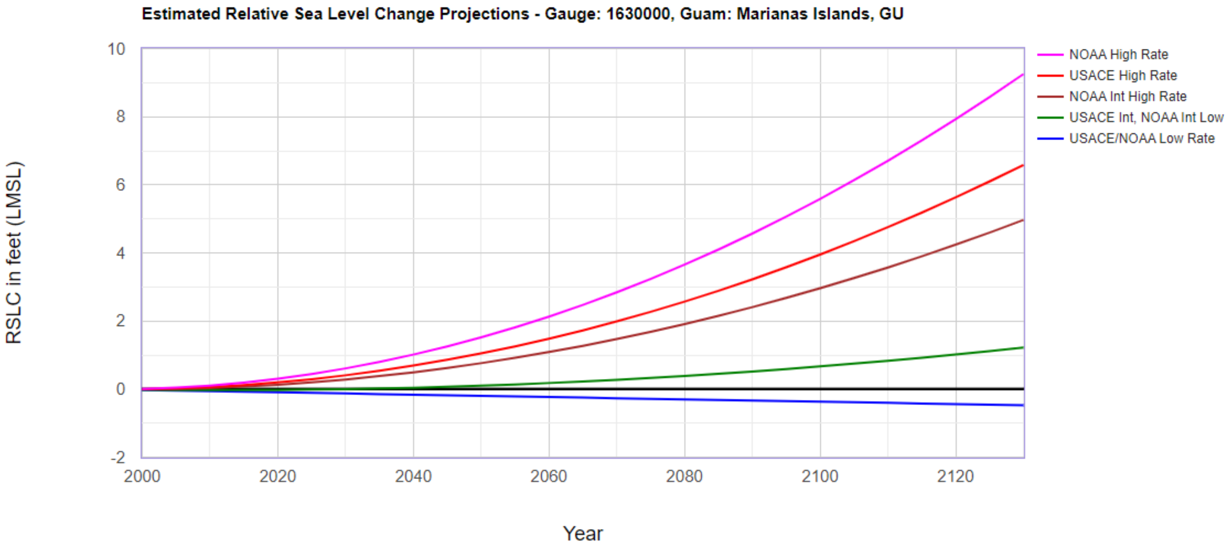


Figure 31. Projected Relative Sea Level Change for Guam - USACE and NOAA RSLC Curves

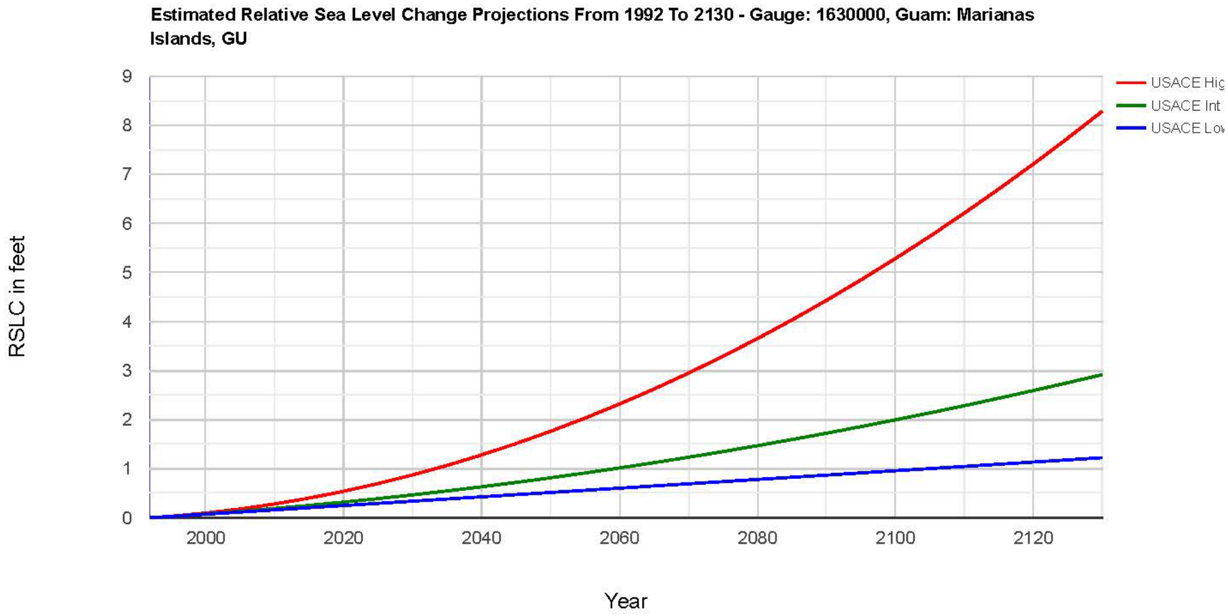


Figure 32. Projected Relative Sea Level Change for Guam

RSLC impacts that enhance coastal storm surge and flood damage were analyzed HURREVAC data for existing and future conditions. To quantify the RSLC impact alone to Guam a digital terrain model was created from the LiDAR described in section 2.3 of this report along with the 100 year horizon RSLC of 7.2 feet of rise from estimates illustrated in Figure 32. Using ArcGIS raster calculations inundation from RSLC is illustrated in Figure 33 through Figure 36. For more information, please follow the URL provided: https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html

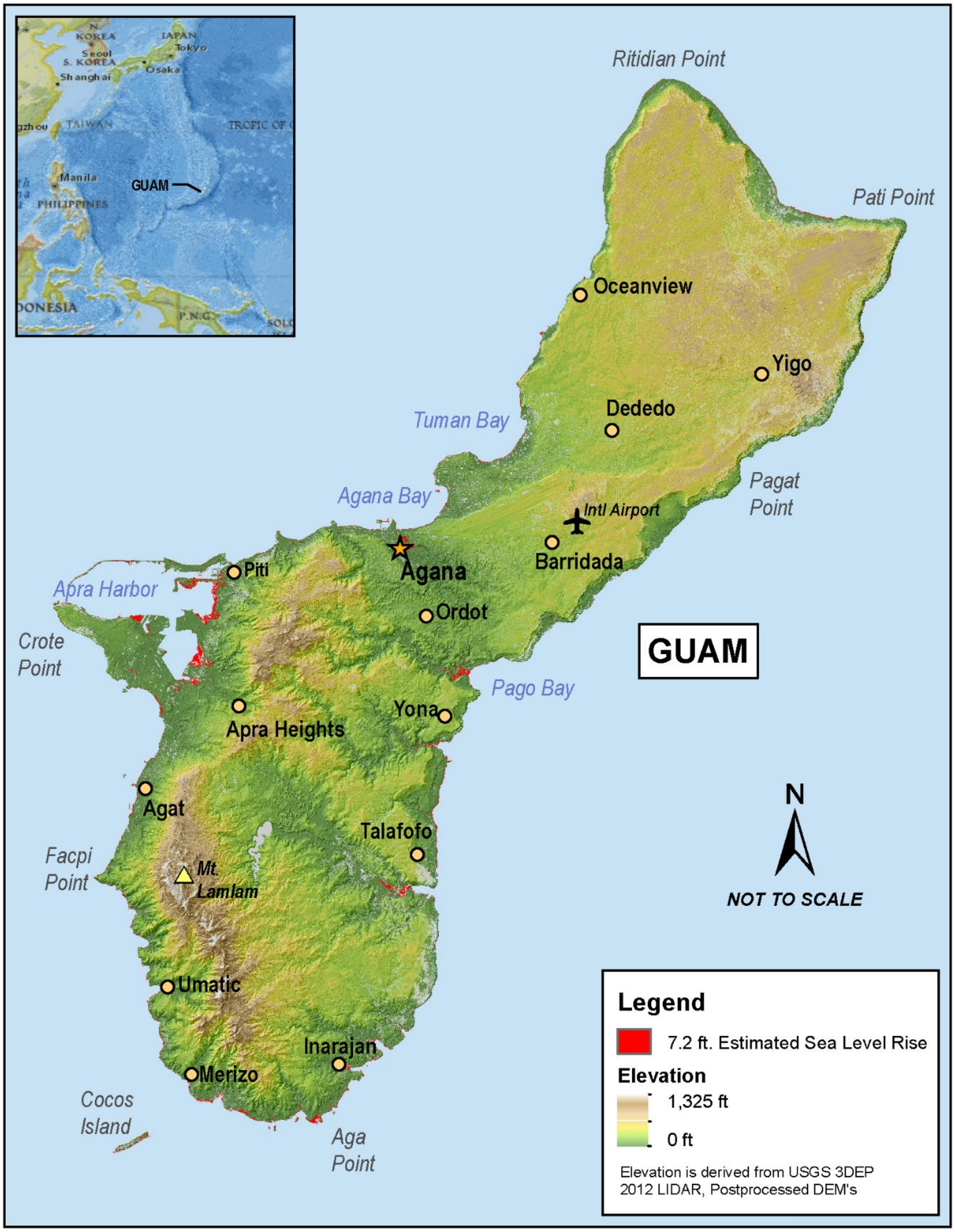


Figure 33. Estimated RSLC Impact - 100 Year Horizon (1 of 4)

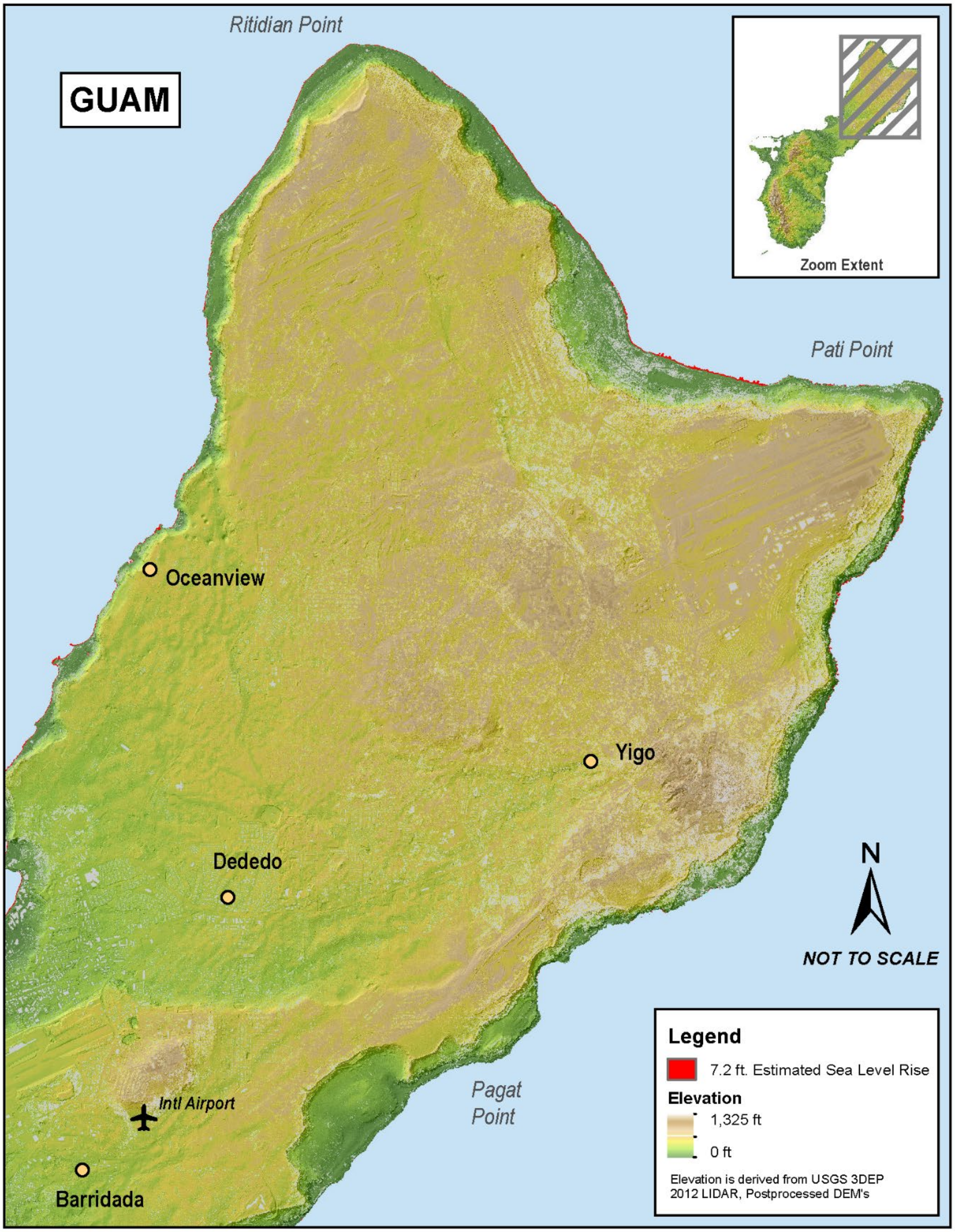


Figure 34. Estimated RSLC Impact - 100 Year Horizon (2 of 4)

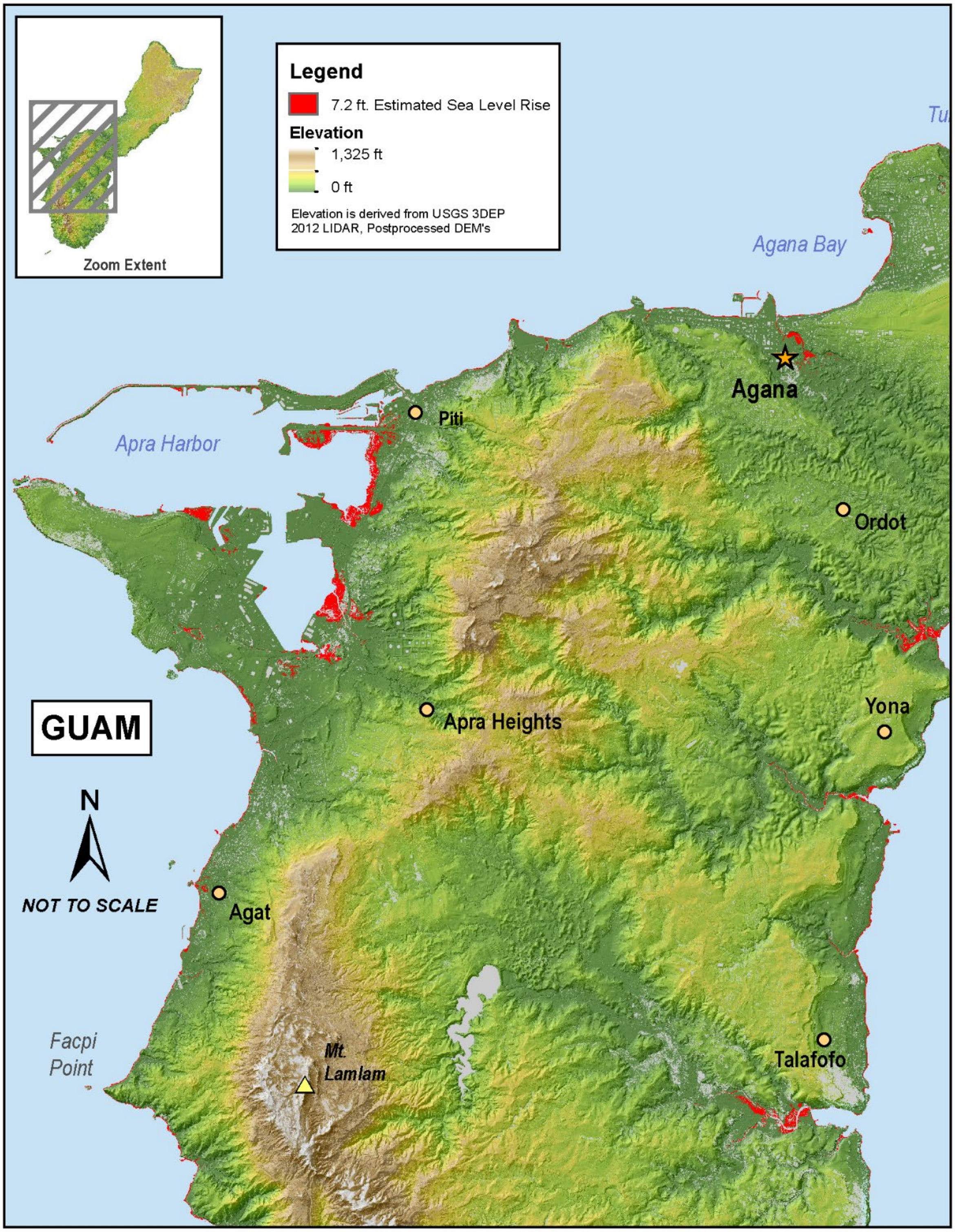


Figure 35. Estimated RSLC Impact - 100 Year Horizon (3 of 4)

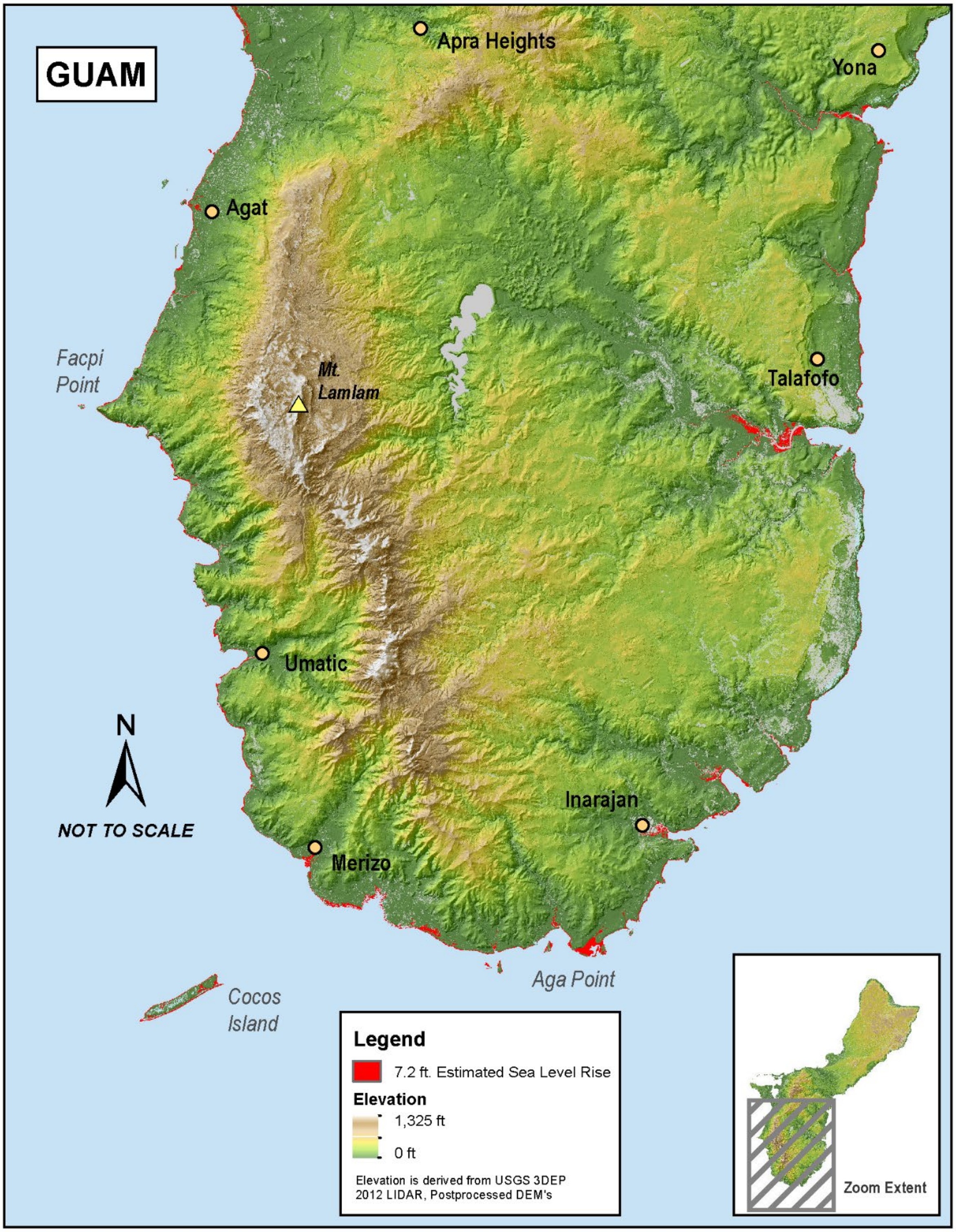


Figure 36. Estimated RSLC Impact - 100 Year Horizon (4 of 4)

To estimate the future coastal damage, potential RLSC estimates from Figure 32 and the NOAA Sea Level Rise (SLR) inundation depth raster files (digital maps) for Guam were added to the HURREVAC storm surge depth raster files to create 2070 impacts to Guam (NOAA SLR Viewer). Figure 37 and Figure 38 illustrate the impact.

By utilizing the USACE RSLC value of three feet, the future conditions mapping therefore includes subsidence adjustments for the year 2070. Figure 37 and Figure 38 illustrate a worst-case hypothetical storm surge from a typhoon that includes RSLC in 2070. Figure 39 and Figure 40 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.

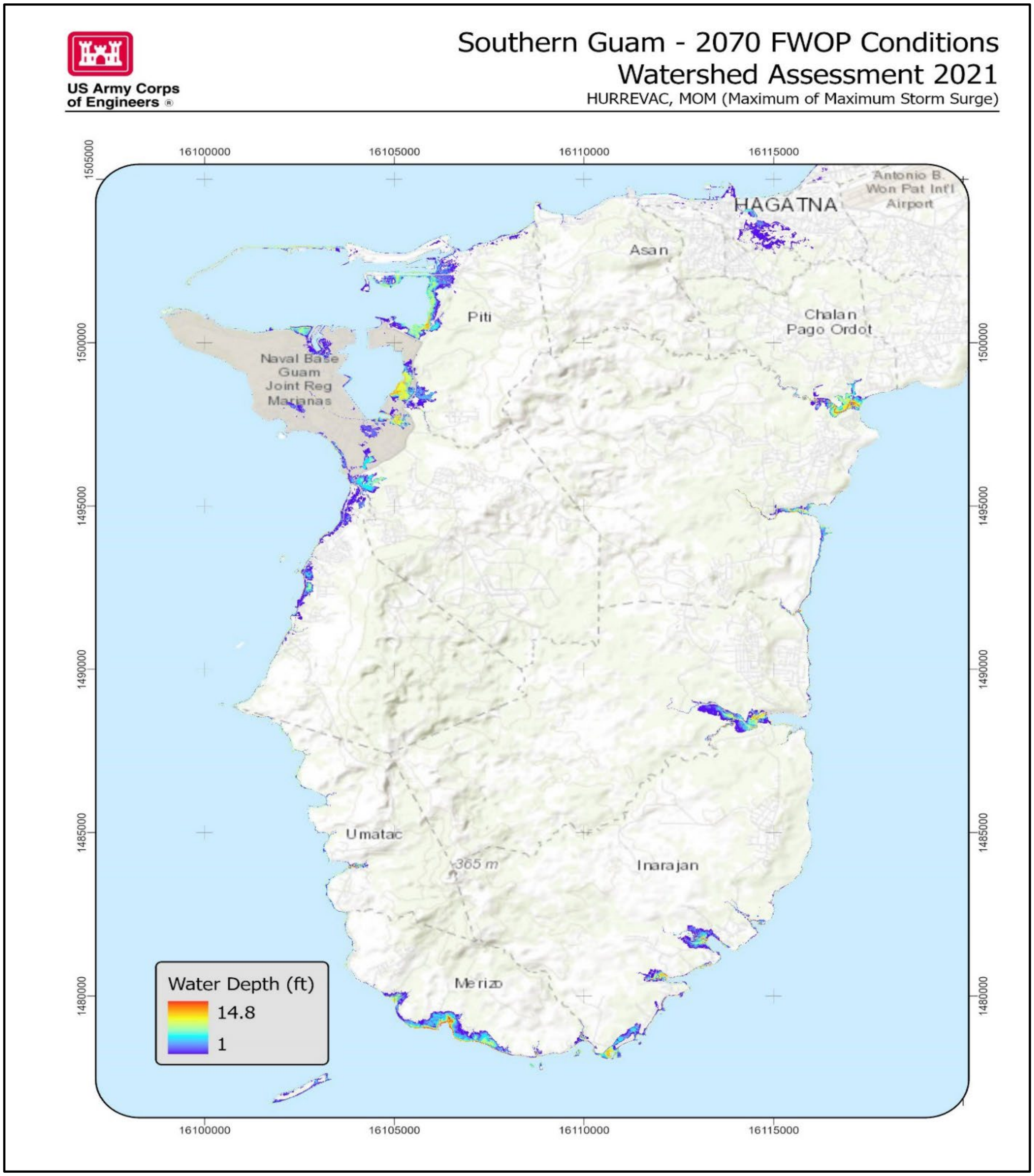


Figure 37. Southern Guam Typhoon Inundation – Future Conditions 2070 (HURREVAC MOM and NOAA SLR viewer) (ESRI)

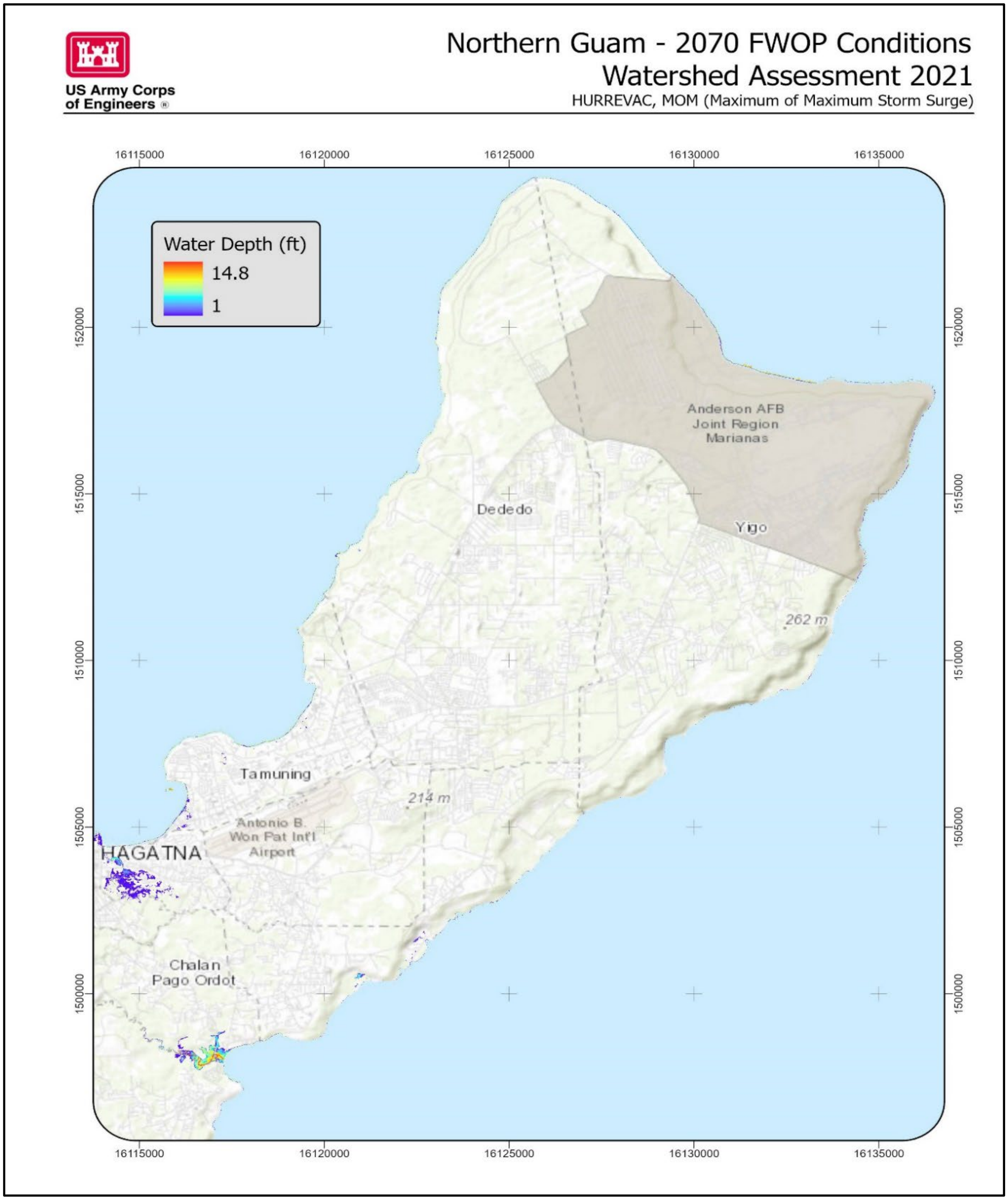


Figure 38. Northern Guam Typhoon Inundation – Future Conditions 2070 (HURREVAC MOM and NOAA SLR viewer) (ESRI)

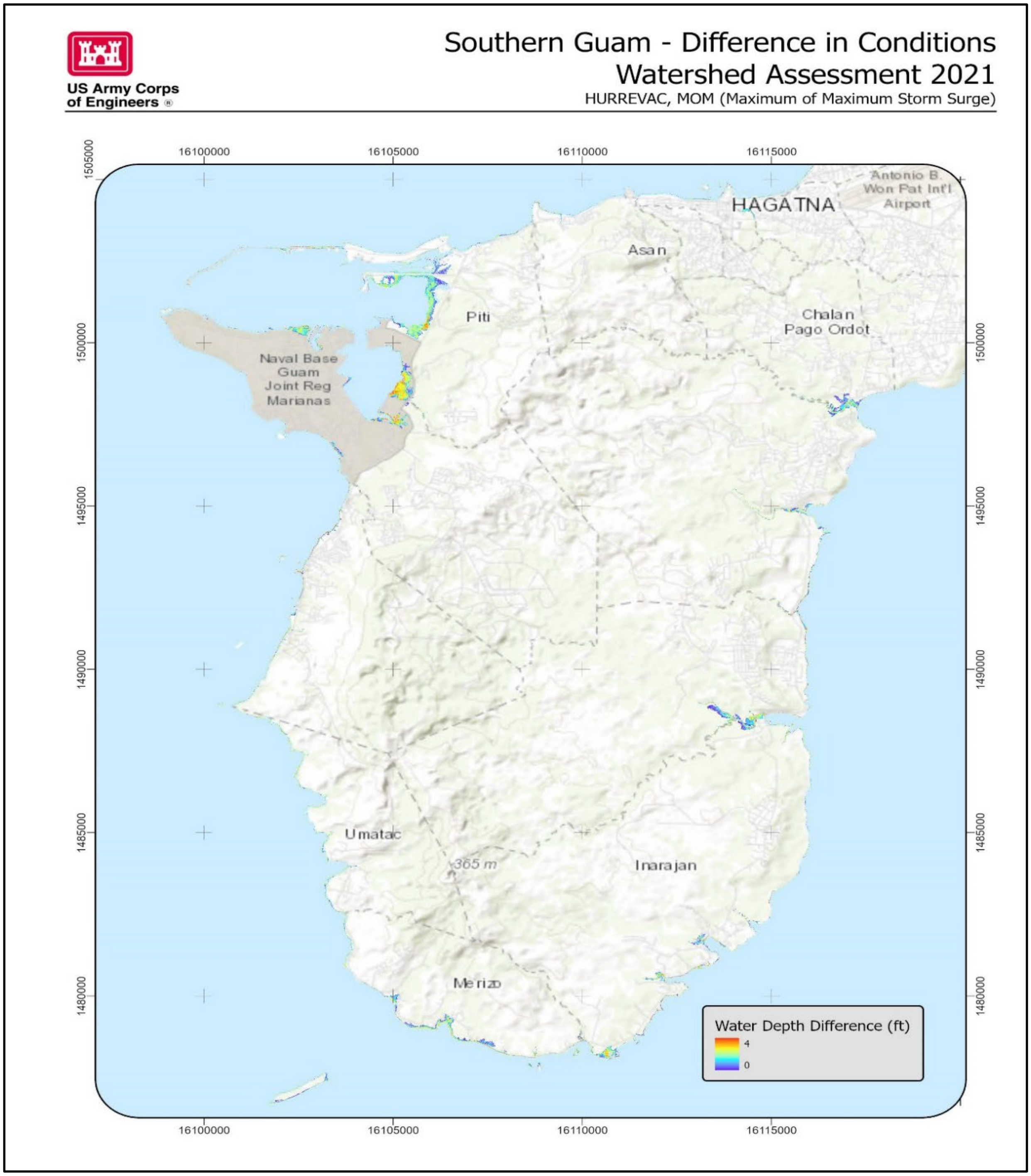


Figure 39. Southern Guam Typhoon Inundation – Difference from Existing and 2070 Conditions (HURREVAC MOM)

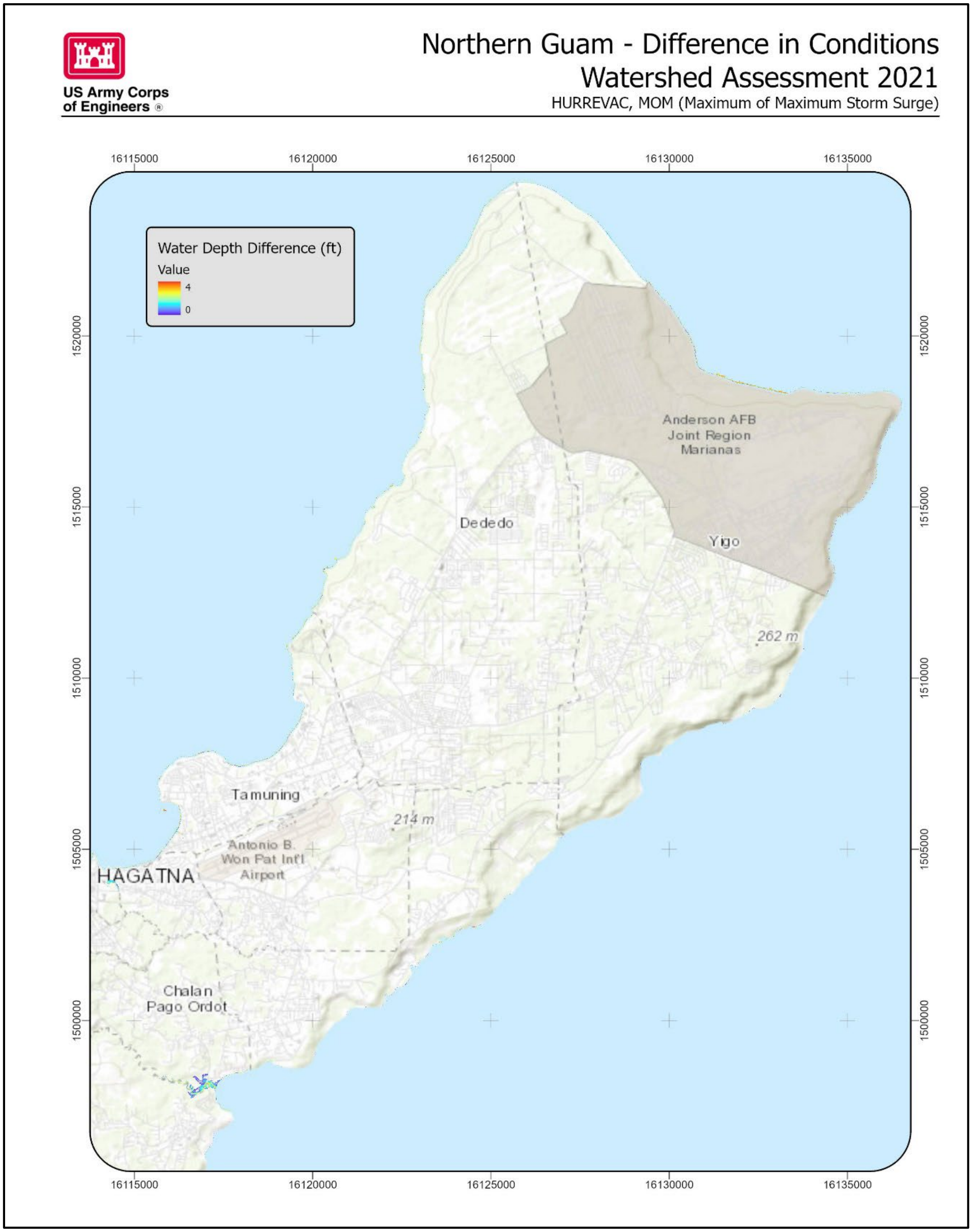


Figure 40. Northern Guam Typhoon Inundation – Difference from Existing and 2070 Conditions (HURREVAC MOM)

3.5 Assessment of Climate Change Impacts to Inland Hydrology

The focus of the inland hydrology assessment is the flood risk management business line and the high flow regime. Large-scale floods can instigate streambank erosion and are critical to any future project performance. Consequently, the focus of the first order statistical analysis conducted as part of this assessment is on peak flow. Observed data is analyzed using the annual instantaneous peak flow records on the Island. Projected, future streamflow data cannot be visualized using the Vulnerability Assessment Tool as these products have only been developed for Hydrologic Unit Codes (HUC)'s within the Continental US.

3.5.1 First Order Statistical Analysis – Observed Streamflow Gauges Analyzed

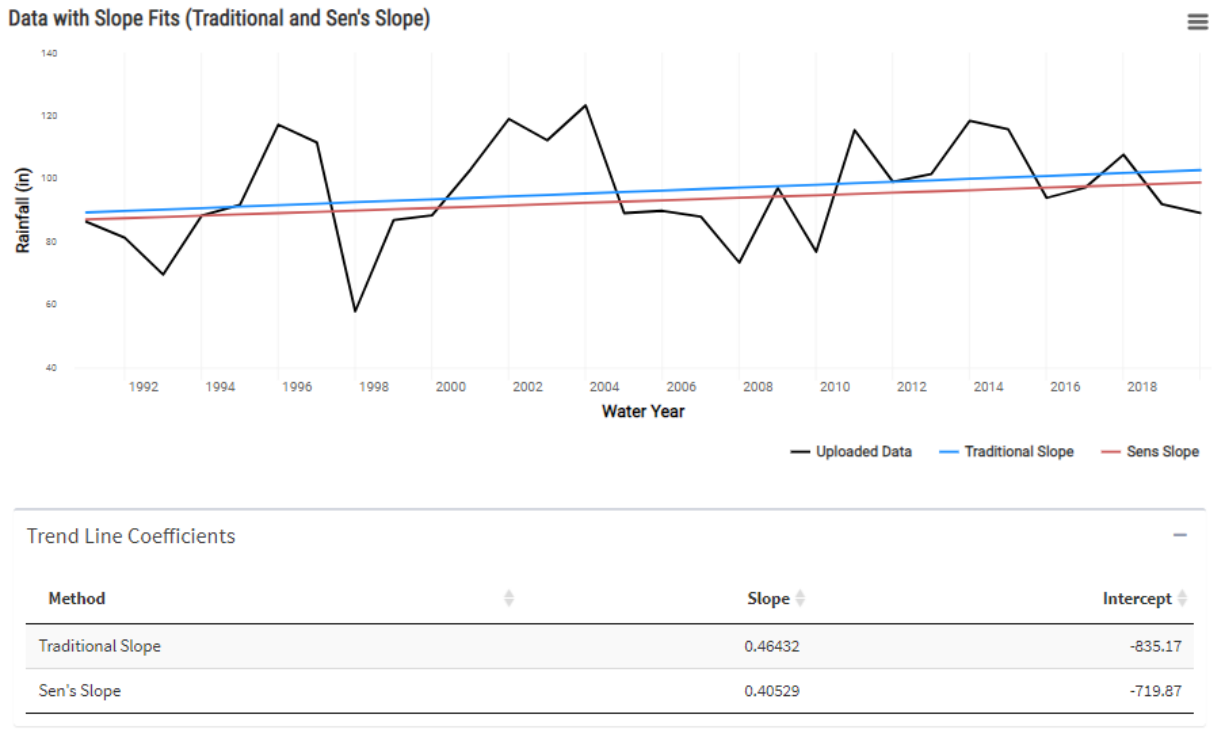
ECB 2018-14 requires a first order statistical analysis of timeseries relevant to the study purpose. First order statistical analysis encompasses a range of easily applied statistical tests including trend analysis and nonstationarity analysis. The focus of first order statistical analysis is trend and nonstationarity in annual instantaneous peak streamflow data, observed at the nine USGS stream Gauges on the Island of Guam HUC 22010000. Annual peak streamflow is appropriate for this analysis because infrequent, large-scale floods can instigate streambank erosion. Nonstationarity analysis of peak streamflow can detect changes, gradual or abrupt, in hydrologic processes over the period of record and an analysis was conducted for the nine gauges listed in Table 3 below:

Table 4. USGS Stream Gauges at Guam.

Site Number	Station Name	Drainage Area (sqm)	Period of Record	30 Years of Continuous Record?
16809600	La Sa Fua River near Umatac	1.03	1954 – 1958 1977 – 1983 2001 - 2019	No
16816000	Umatac River at Umatac	2.08	1954 - 1976 2002 - 2011	No
16840000	Tinaga River near Inarajan	1.91	1953 - 1985	Yes-but old
16847000	Imong River near Agat	1.92	1961 - 1993 1998 - 1999 2001 - 2004 2006 - 2019	No
16848100	Almagosa River near Agat	1.32	1972 - 1991 1998 - 2019	No
16848500	Maulap River near Agat	1.18	1972 – 1993 1998 – 2015 2017 – 2020	No
16854500	Ugum River above Talofofo Falls, nr Talofofo	5.92	1977 - 1994 1998 – 2020	No
16858000	Ylig River near Yona	6.53	1953 - 1955 1957 - 1985 1998 - 1990	No
16865000	Pago River near Ordot	5.57	1952 - 1955 1957 - 1982 1999 - 2019	No

3.5.2 Nonstationary & Trend Analysis

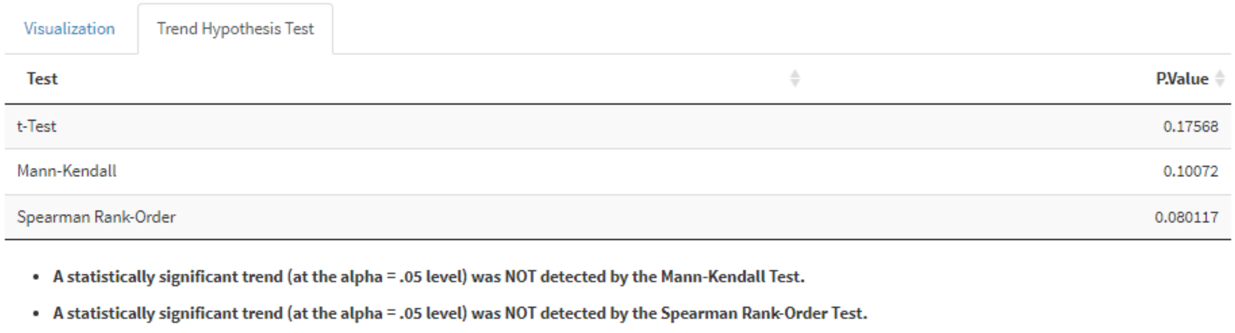
ETL 1100-2-3, Guidance for Detection of Nonstationarities in Annual Maximum Discharges is applied to evaluate the assumption of stationarity in the study area. The USACE Nonstationary Detection (NSD) Tool were applied to assess whether the annual instantaneous peak streamflow records collected at the gauge locations listed above are representative of stationary hydrologic conditions. For trend analysis, a p-value threshold of 0.05 is adopted to be indicative of statistical significance. Results described in this document have been created using the tools available in the Time Series Toolbox (TST) located at https://climate-test.sec.usace.army.mil/tst_app/. Analysis using the precipitation data shown in Figure 10 using the Time Series toolbox. Shown below, the results show only a slightly positive trend (Figure 41) in precipitation but not statistically significant as seen in Figure 42. Temperature was also analyzed in a similar manner using the TST. Temperature also shows no significant trend over the period of record analyzed as illustrated in Figure 43 while Figure 44 illustrates that there is no statistically significant trends for Temperature.



Method	Slope	Intercept
Traditional Slope	0.46432	-835.17
Sen's Slope	0.40529	-719.87

Source: Guam_Annual_Precip.csv

Figure 41. Time Series Toolbox -Annual Precipitation Trends

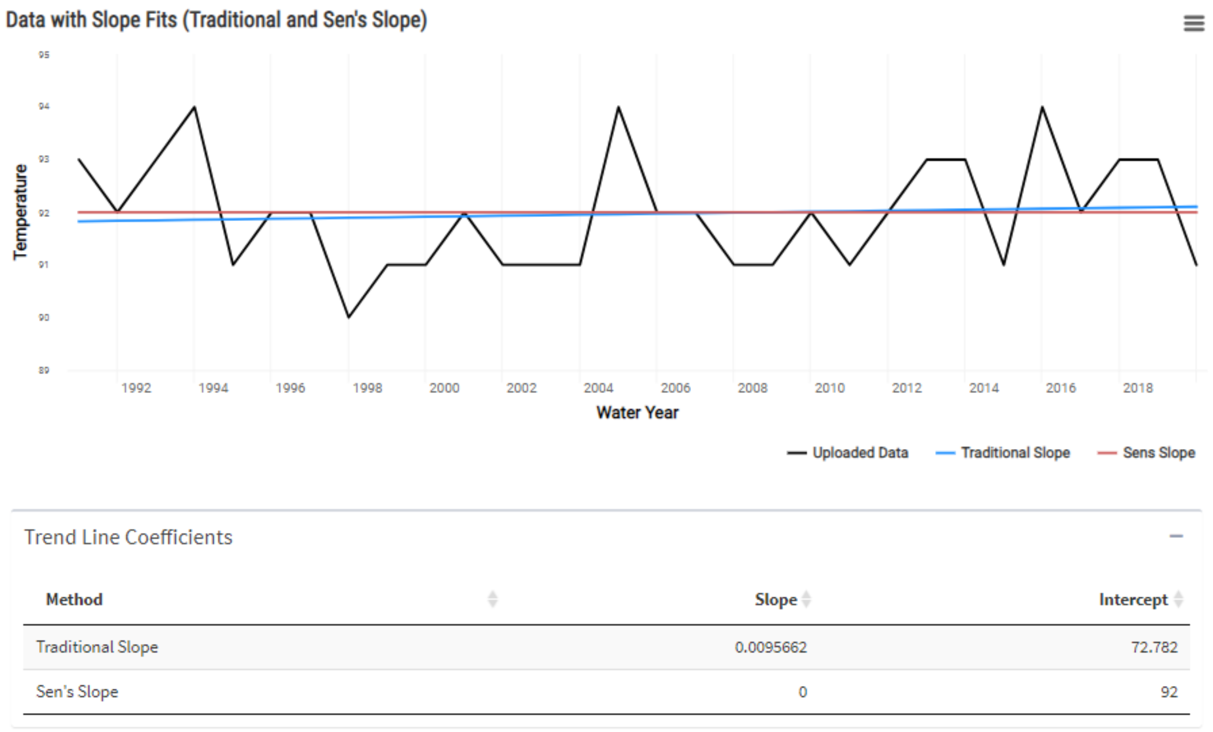


Test	P.Value
t-Test	0.17568
Mann-Kendall	0.10072
Spearman Rank-Order	0.080117

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Source: Guam_Annual_Precip.csv

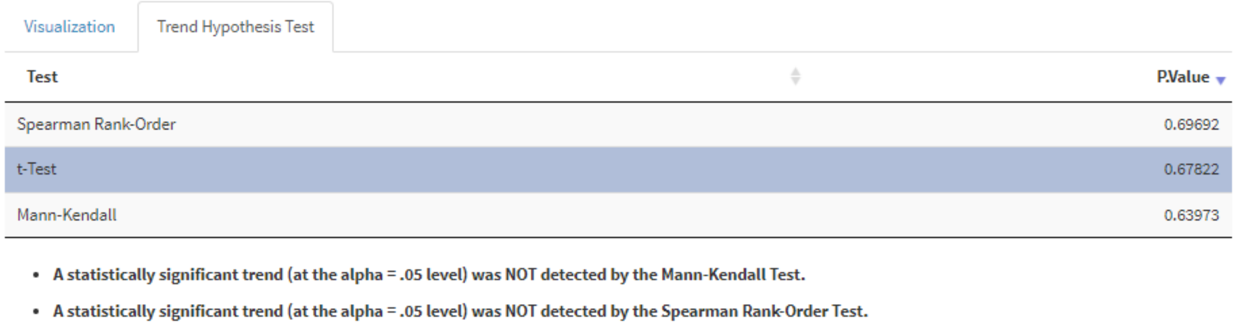
Figure 42. Time Series Toolbox - Annual Precipitation P-Values



Method	Slope	Intercept
Traditional Slope	0.0095662	72.782
Sen's Slope	0	92

Source: Guam_Annual_Temp.csv

Figure 43. Time Series Toolbox -Annual High Temperature Trends



Test	P.Value
Spearman Rank-Order	0.69692
t-Test	0.67822
Mann-Kendall	0.63973

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Source: Guam_Annual_Temp.csv

Figure 44. Time Series Toolbox- Annual High Temperature P-Values

For a nonstationarity to be considered strong it must demonstrate a degree of consensus and robustness. To show consensus the nonstationarity must trigger two or more tests within a range of five years for the same statistic (distribution, mean, etc.). To demonstrate robustness, it must trigger two or more tests within a range of five years for different statistics. A strong nonstationarity must also show significant change in the magnitude of the standard deviation and/or mean (USACE, 2017). Although most of these datasets do not have 30 years of continuous record the summary results of the Nonstationarity test and the Trends Analysis are described in
Table 5 and Table 5 below. All graphics resulting from the application of the TST supporting these analyses are located as plates in the back of this document.

Table 5. Nonstationary Test Results

Site Number	Station Name	Nonstationary (NS) Test Results
16809600	La Sa Fua River near Umatac	-NS analysis for the 2001-2019 period - No nonstationarities detected. - No statistically significant trends were detected
16816000	Umatac River at Umatac	NS analysis for the full period of record- No nonstationarities detected. -1954 – 1976 - No statistically significant trends were detected
16840000	Tinaga River near Inarajan	NS detected in 1972. Analysis for the 1953-1972 or 1972-1985 period detected- No nonstationarities detected.
16847000	Imong River near Agat	NS detected in 1993, 1999, & 2001. Analysis for the 1961- 1993 or 2001-2019 period detected- No nonstationarities.
16848100	Almagosa River near Agat	NS detected in 1972 & 1991. Analysis for the 1961-1993 or 2004-2019 period detected- No nonstationarities.
16848500	Maulap River near Agat	NS detected in 1999 & 2014. Analysis for the 1972-1994 or 1999-2020 period detected- No nonstationarities.
16854500	Ugum River above Talofofo Falls, nr Talofofo	NS analysis for the full period of record- No nonstationarities detected.
16858000	Ylig River near Yona	NS analysis for the full period of record- No nonstationarities detected.
16865000	Pago River near Ordot	NS detected in 1973 & 2000. Analysis for the 1952-1975 or 2001-2019 period detected- No nonstationarities.

Table 6. Trends Analysis Results

Site Number	Station Name	Trend Analysis
16809600	La Sa Fua River near Umatac	2001-2019 - No statistically significant trends were detected. - Analysis shows a mildly rising trend.
16816000	Umatac River at Umatac	1954-1976 - No statistically significant trends were detected. - Analysis shows a mildly rising trend.
16840000	Tinaga River near Inarajan	1953-1972 - No statistically significant trends were detected. - Analysis shows a mildly rising trend. 1972-1985 - No statistically significant trends were detected. - Analysis shows a mildly mixed trend.
16847000	Imong River near Agat	1961-1993 - No statistically significant trends were detected. - Analysis shows a mildly negative trend. 2001-2019 - No statistically significant trends were detected. - Analysis shows a mildly negative trend.
16848100	Almagosa River near Agat	1961-1993 - No statistically significant trends were detected. - Analysis shows a mildly negative trend. 2004-2019 - No statistically significant trends were detected. - Analysis shows a mildly negative trend.
16848500	Maulap River near Agat	1972-1994 - No statistically significant trends were detected. - Analysis shows a mildly negative trend. 1998-2015 - No statistically significant trends were detected. - Analysis shows a mildly mixed trend.
16854500	Ugum River above Talofofo Falls, nr Talofofo	1977-1994 - No statistically significant trends were detected. - Analysis shows a mildly mixed trend. 1998-2020 - No statistically significant trends were detected. - Analysis shows a mildly mixed trend.
16858000	Ylig River near Yona	1957-1984 - No statistically significant trends were detected. - Analysis shows a mildly negative trend.
16865000	Pago River near Ordot	1956-1982 - No statistically significant trends were detected. - Analysis shows a mildly negative trend. 2001-2019 - No statistically significant trends were detected. - Analysis shows a mildly mixed trend.

3.6 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). A study covering 850 typhoons in the region found the intensity of the damaging storms has increased by about 10 per cent since the 1970s, said Wei Mei, a climate scientist at the Scripps Institution of Oceanography at the University of California, San Diego, and a co-author of the study published in the journal Science Advances. Using 20 models and a mid-range projection of carbon dioxide emissions, the researchers found the peak intensity of storms such as super Typhoon Haiyan, which tore through the Philippines in November 2013, will become even stronger and more common.

Such storms will be 14 percent stronger by 2100, equivalent to adding another category to the current top severity rating of 5, the study found. (Hannam, 2015). 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.

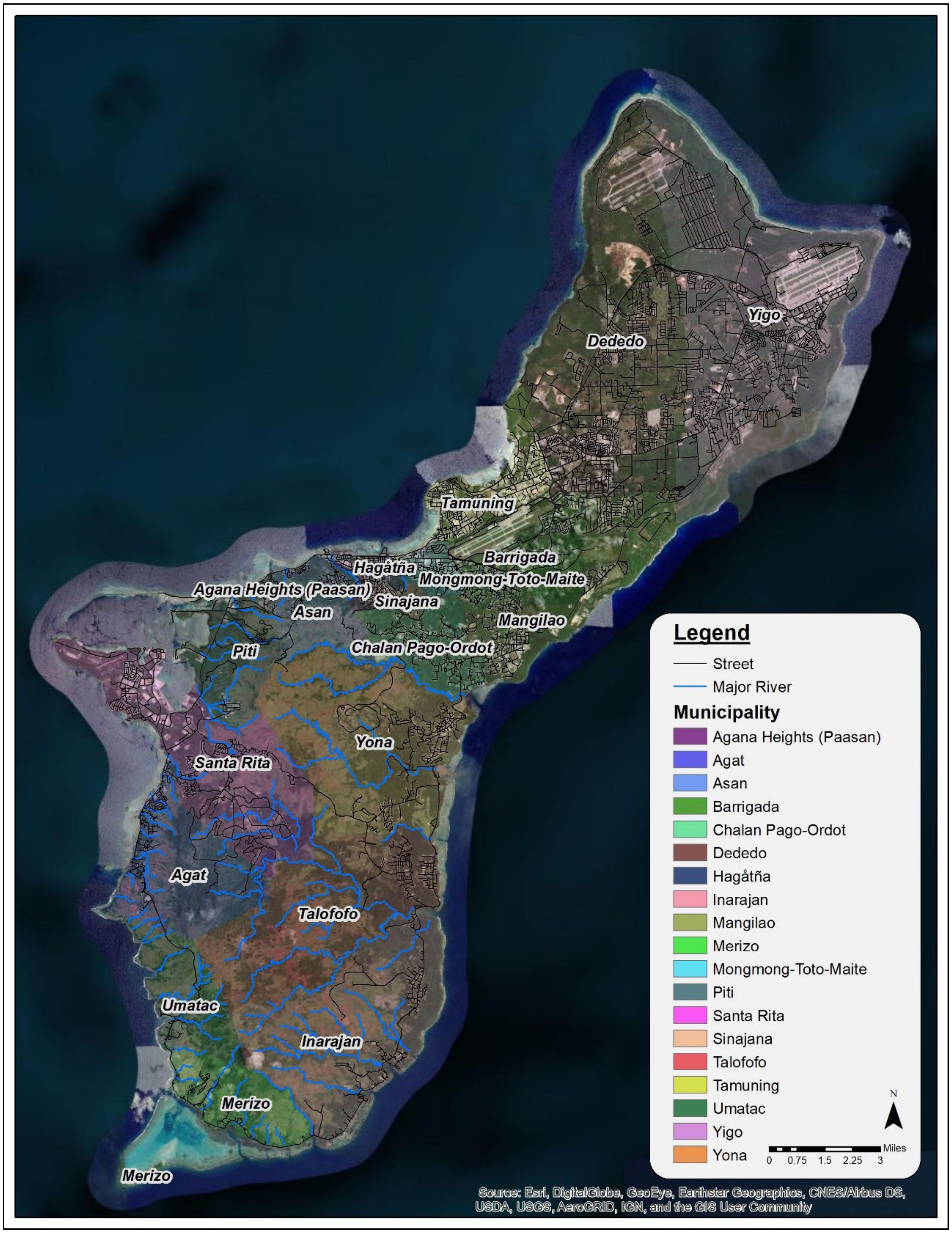
Extended storm duration produces heavier rainfall volumes, extended wind and salt spray damage, higher risk to property and infrastructure, and presents a sheltering and emergency supply challenge (Grenci et al., 2020). Adding sea level rise by the expected three feet over the next 50 years will inundate 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 37 and Figure 38 illustrate a worst-case hypothetical storm surge from a typhoon that includes RSLC in 2070. Figure 39 and Figure 40 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.

3.7 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 in Guam (Figure 45), 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 46 depicts USDA defined moderately erodible soils in watersheds (shown in pink), on slopes greater than 30 percent (USDA SSURGO, 1985). Figure 47 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.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 45. Island of Guam, Watersheds Defined

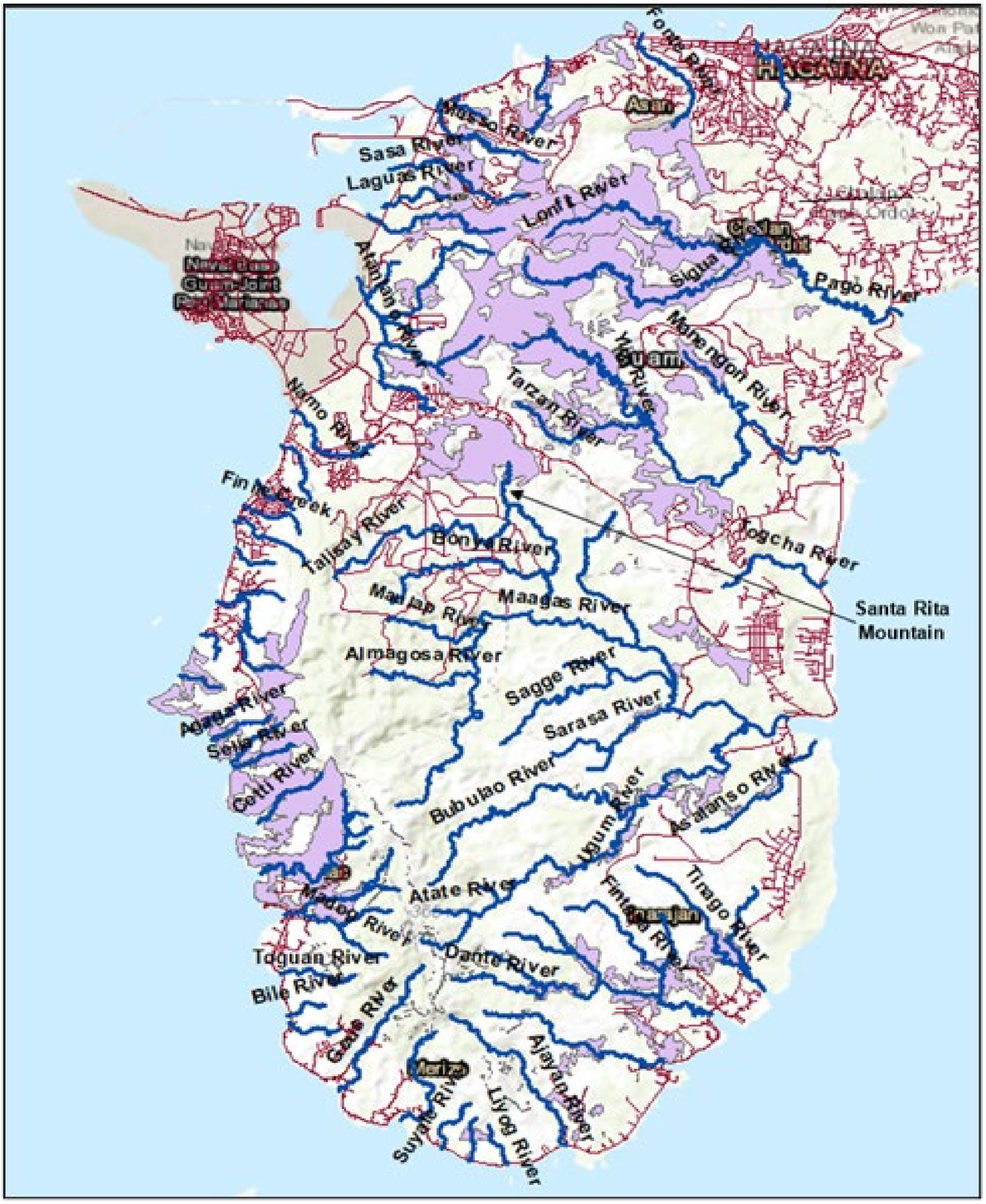


Figure 46. Moderate Erodibility Locations with Steep Slopes (Purple), South Guam (ESRI)

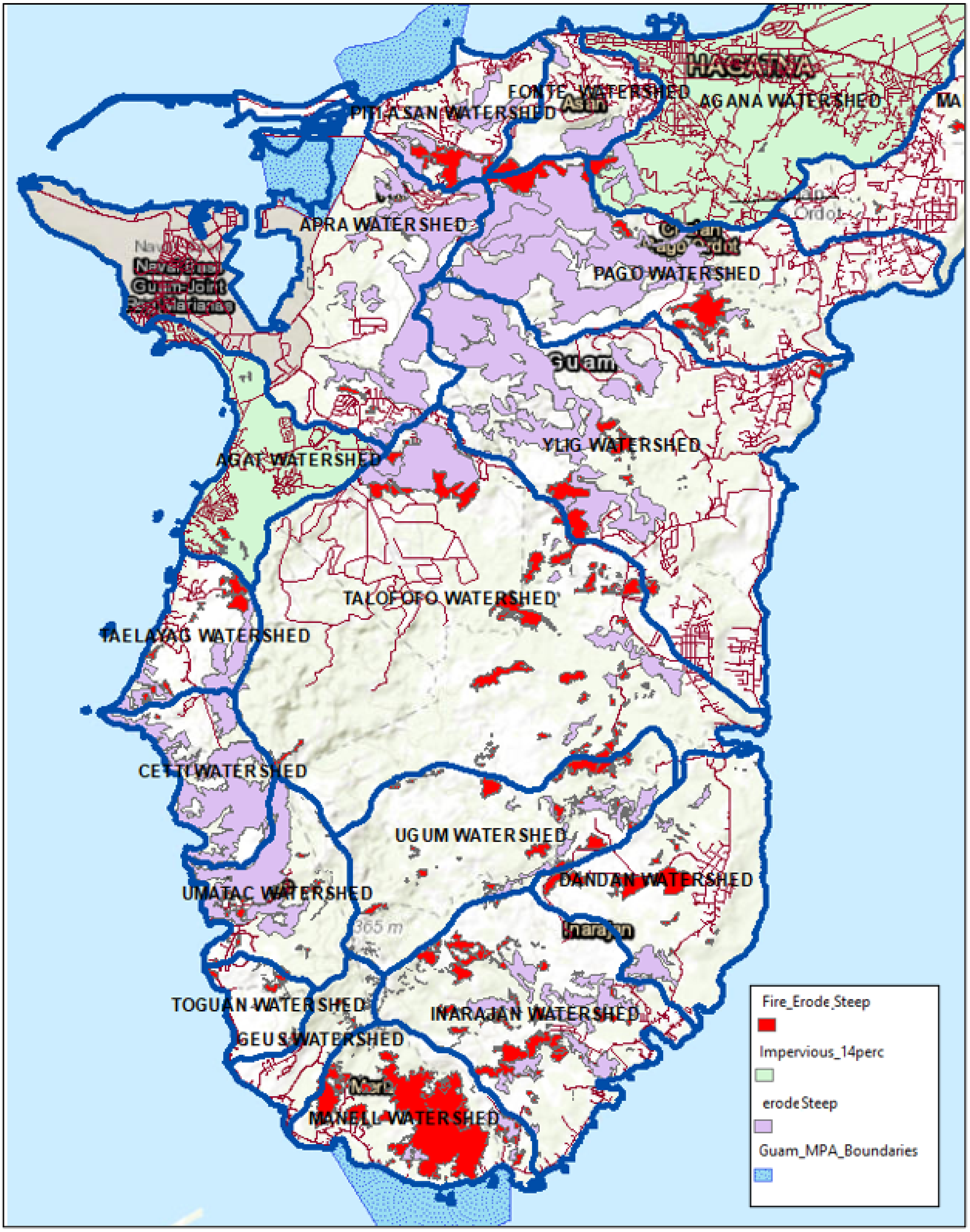
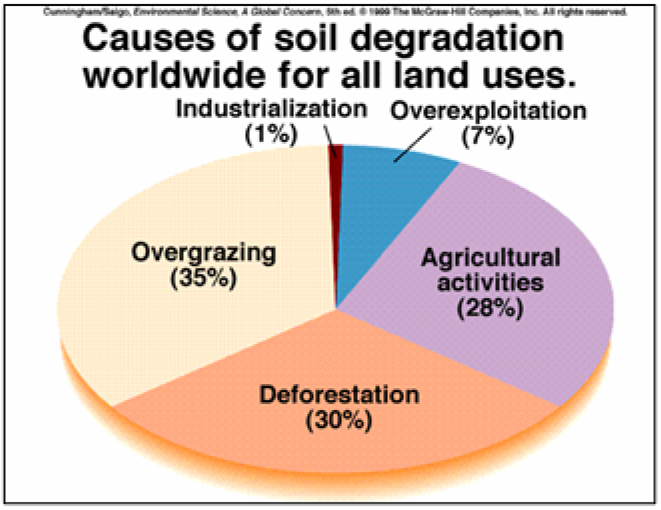


Figure 47. Vulnerable Erosion Watersheds (with Fire Zones in Red), South Guam (ESRI)

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, Table 6 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 48 describes the importance of land use and conservation related to impacts on soil degradation and erosion worldwide.

Table 7. 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


Cunningham/Saigo, *Environmental Science, A Global Concern*, 5th ed. © 1999 The McGraw-Hill Companies, Inc. All rights reserved.

Causes of soil degradation worldwide for all land uses.

Figure 48. Worldwide Drivers for Soil Degradation

3.8 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. These conditions determine the potential for vegetation and habitat and influence overland runoff that causes erosion and landslides (USDA, SCS. 1988)

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 and are identified below:

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

2. 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.

3. 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)

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. 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).

3.9 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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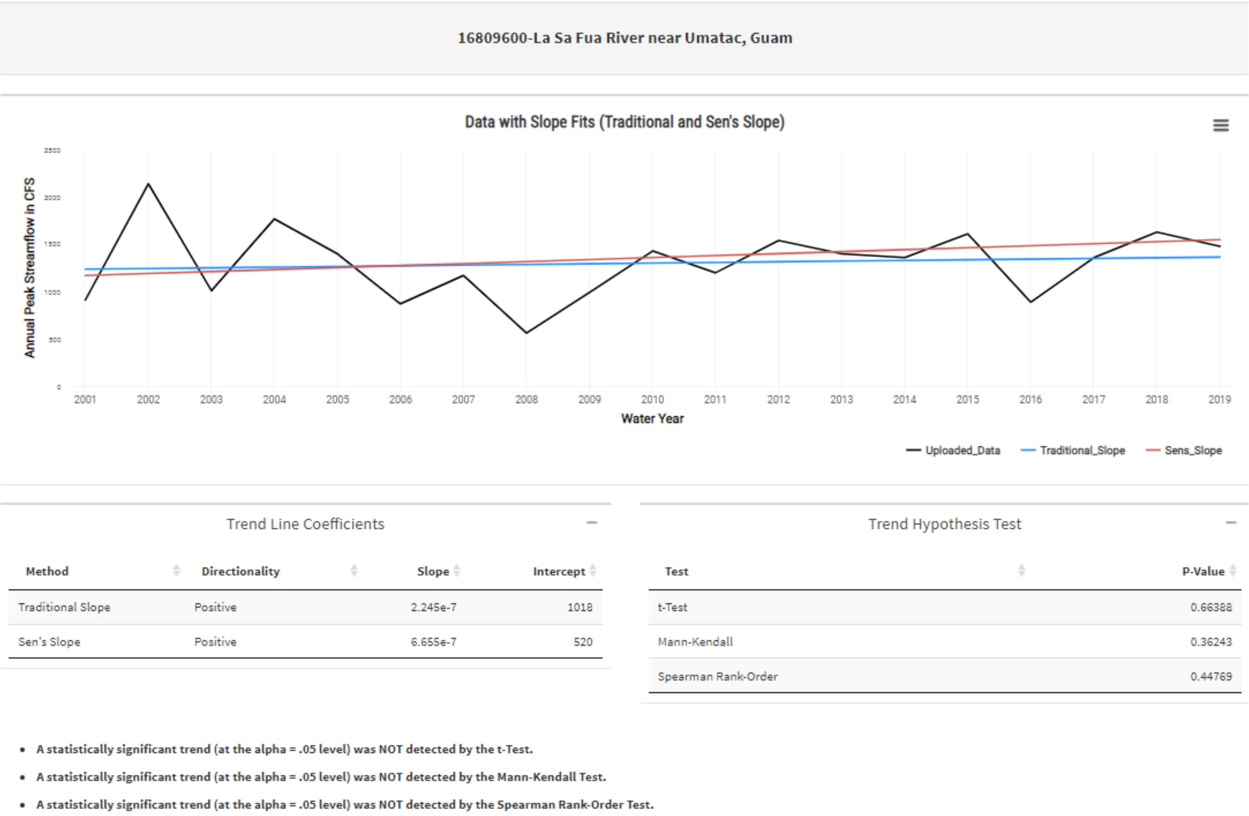
5 Plates

16809600-La Sa Fua River near Umatac, Guam

No nonstationarities detected!

Plate 1.Nonstationarity Analysis of Maximum Annual Flow, La Sa Fua River near Umatac, Guam (2001-2019)



16809600-La Sa Fua River near Umatac, Guam

Data with Slope Fits (Traditional and Sen's Slope)

Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Positive	2.245e-7	1018
Sen's Slope	Positive	6.655e-7	520

Trend Hypothesis Test

Test	P-Value
t-Test	0.66388
Mann-Kendall	0.36243
Spearman Rank-Order	0.44769

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 2. Trend Analysis of Maximum Annual Flow, La Sa Fua River near Umatac, Guam (2001-2019)

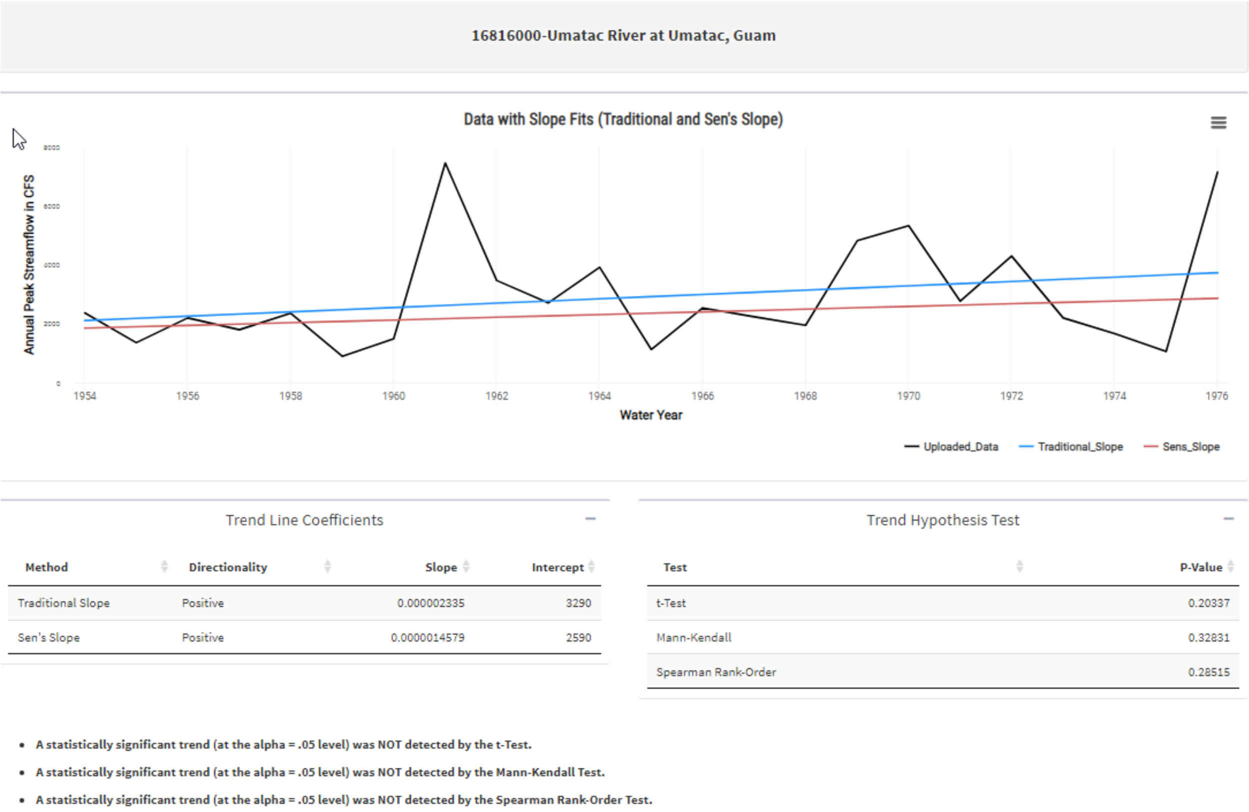
16816000-Umatac River at Umatac, Guam

Time Series with Nonstationarities Detected using All Tests

No nonstationarities detected!

Segment Statistics Using All Tests

Plate 3. Nonstationarity Analysis of Maximum Annual Flow, Umatac River at Umatac, Guam (1954-2011)



16816000-Umatac River at Umatac, Guam

Trend Line Coefficients

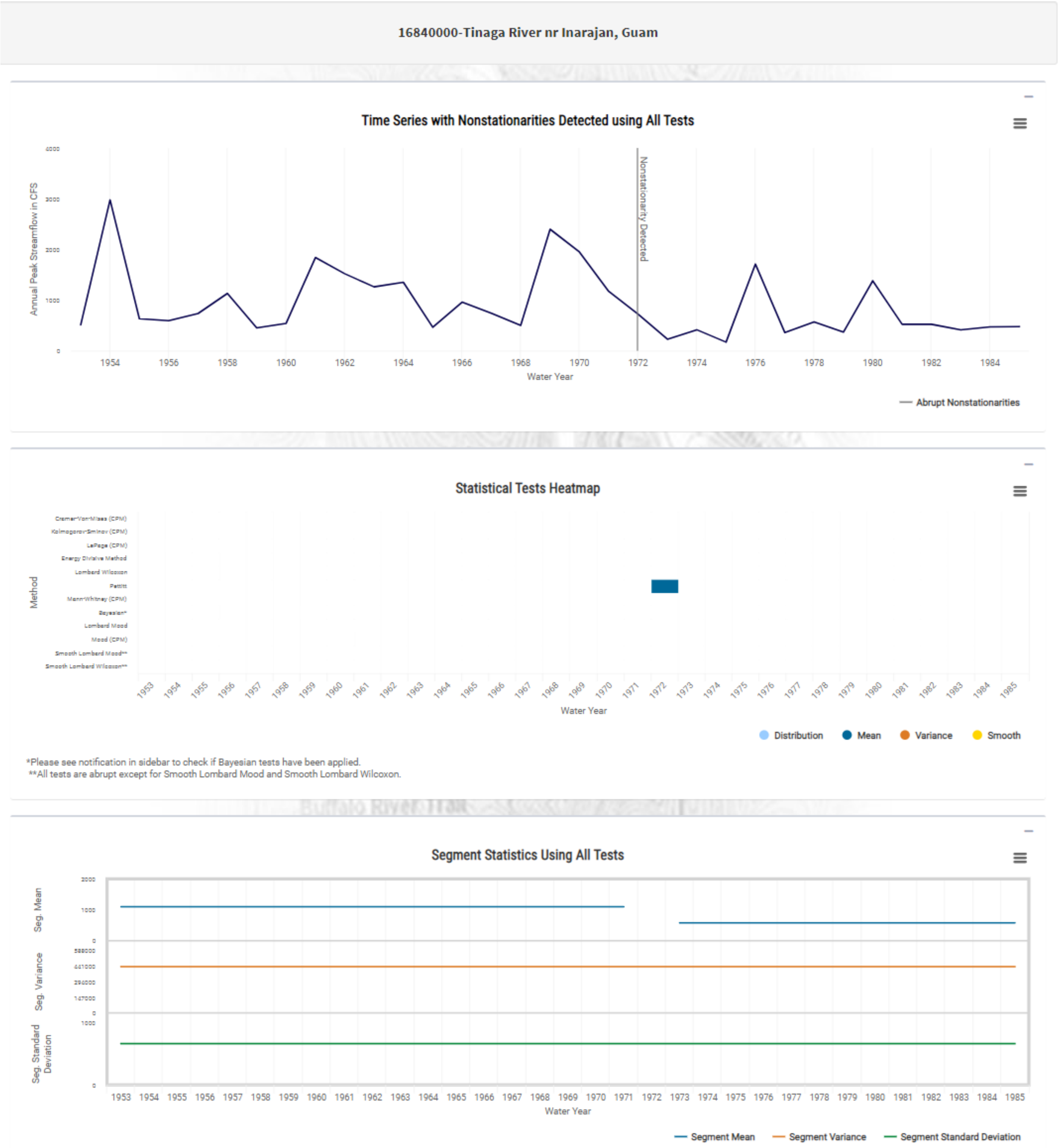
Method	Directionality	Slope	Intercept
Traditional Slope	Positive	0.000002335	3290
Sen's Slope	Positive	0.0000014579	2590

Trend Hypothesis Test

Test	P-Value
t-Test	0.20337
Mann-Kendall	0.32831
Spearman Rank-Order	0.28515

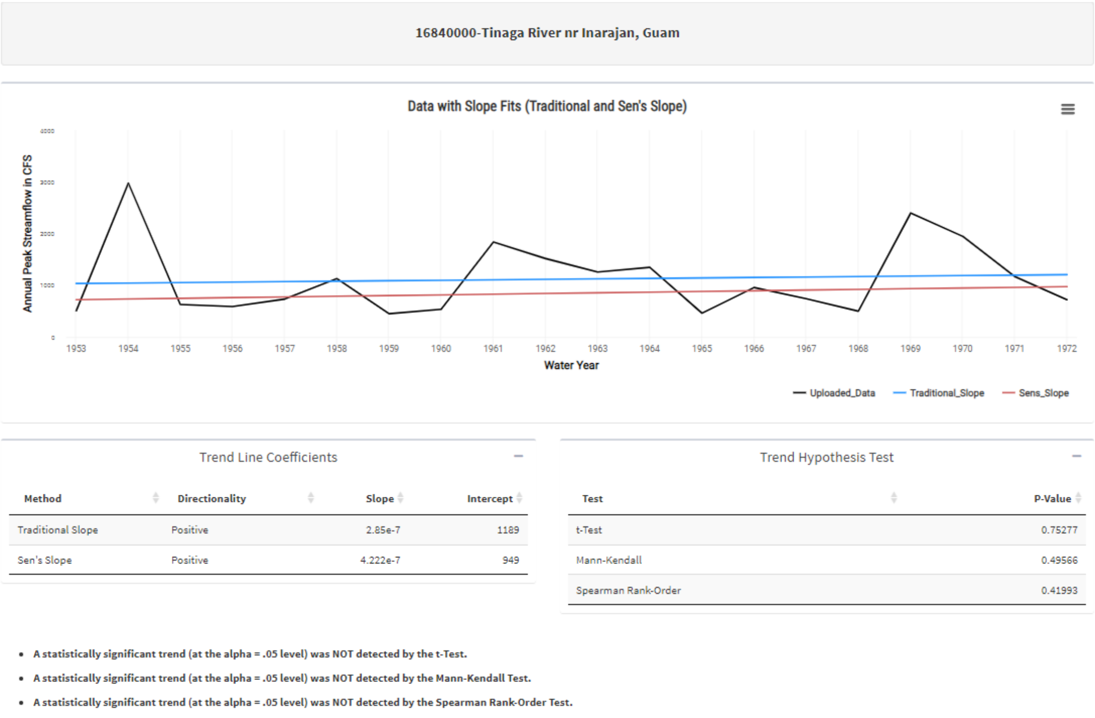
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 4. Trend Analysis of Maximum Annual Flow, Umatac River at Umatac, Guam (1954-2011)


16840000-Tinaga River nr Inarajan, Guam

*Please see notification in sidebar to check if Bayesian tests have been applied.
**All tests are abrupt except for Smooth Lombard Mood and Smooth Lombard Wilcoxon.

Plate 5. Nonstationarity Analysis of Maximum Annual Flow, Tinaga River near Inarajan, Guam (1953-1985)

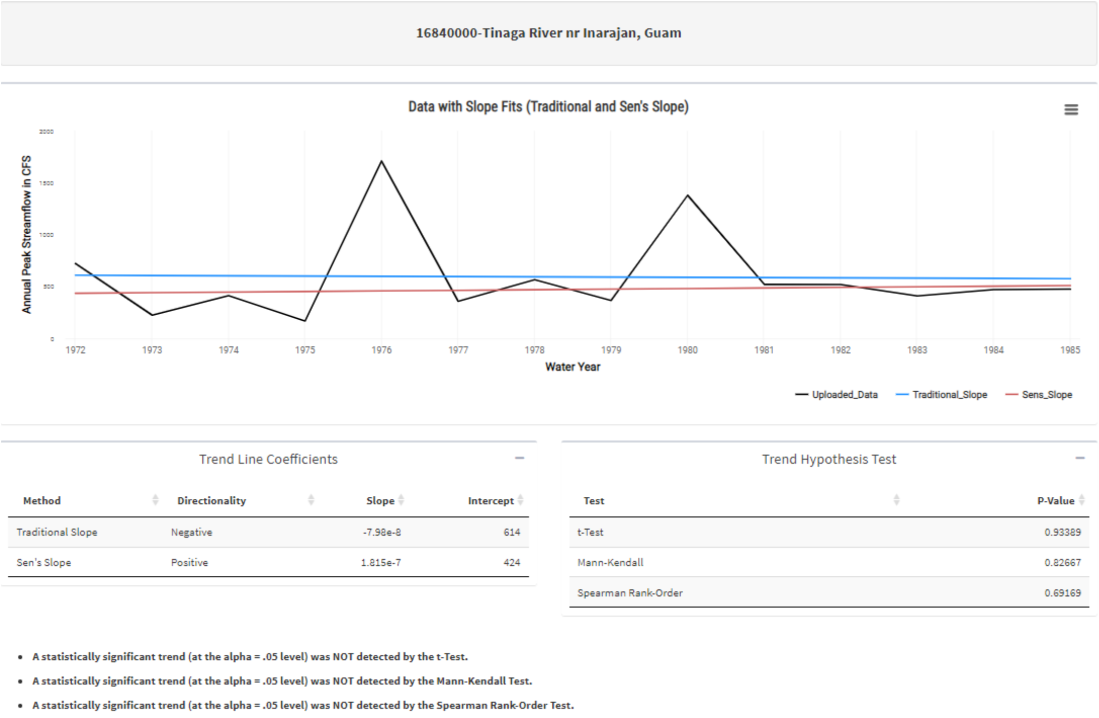


Method	Directionality	Slope	Intercept
Traditional Slope	Positive	2.85e-7	1189
Sen's Slope	Positive	4.222e-7	949

Test	P-Value
t-Test	0.75277
Mann-Kendall	0.49566
Spearman Rank-Order	0.41993

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 6. Trend Analysis of Maximum Annual Flow, Tinaga River near Inarajan, Guam (1953-1972)

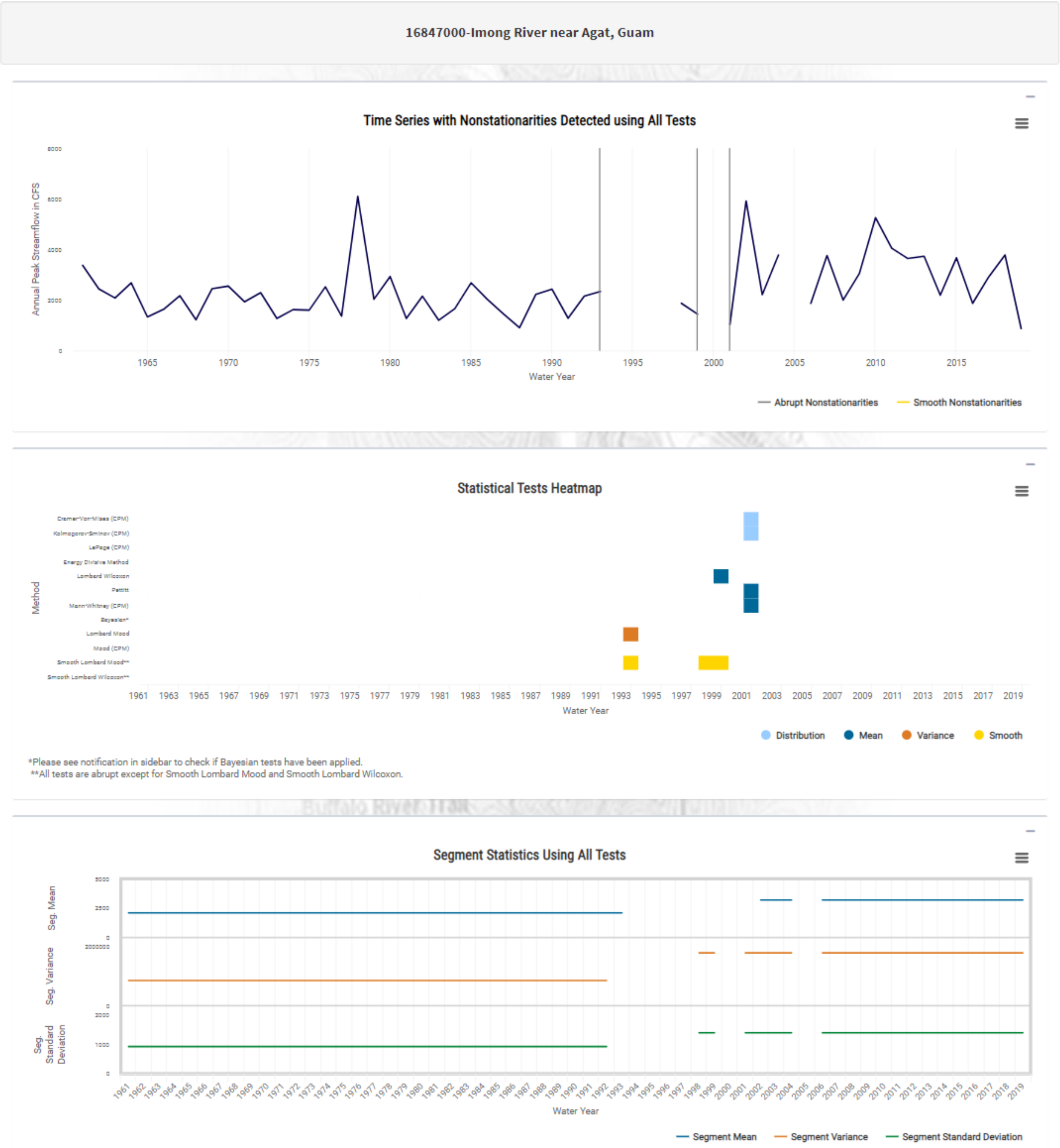


Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-7.98e-8	614
Sen's Slope	Positive	1.815e-7	424

Test	P-Value
t-Test	0.93389
Mann-Kendall	0.82667
Spearman Rank-Order	0.69169

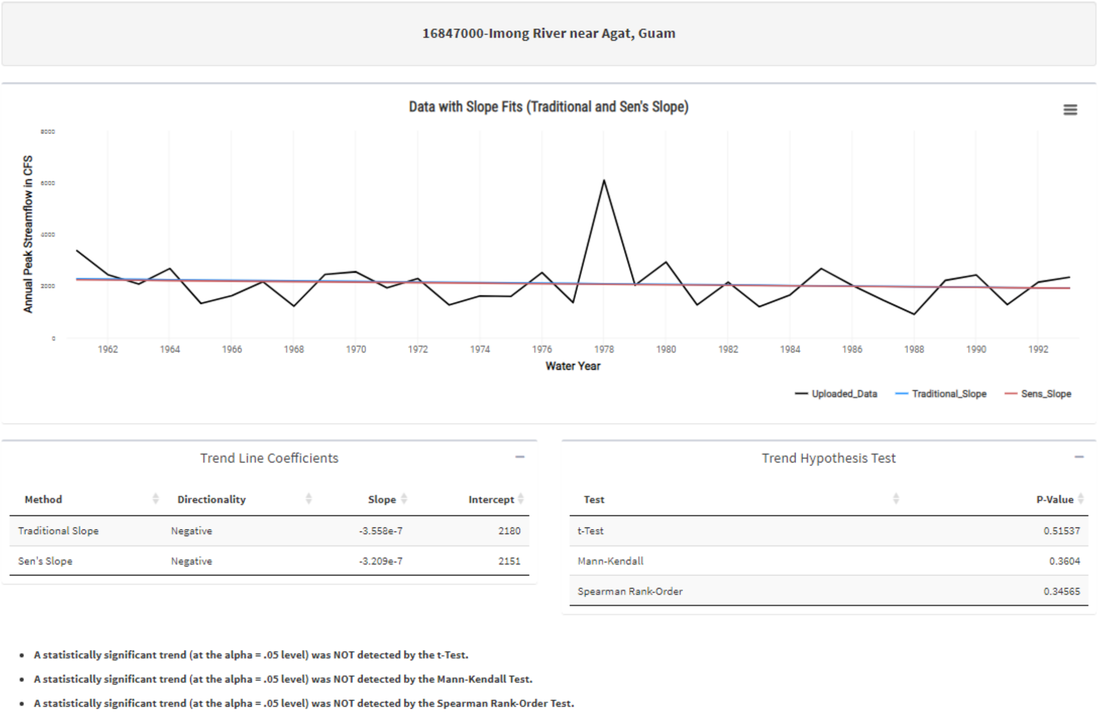
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 7. Trend Analysis of Maximum Annual Flow, Tinaga River near Inarajan, Guam (1972-1985)



*Please see notification in sidebar to check if Bayesian tests have been applied.
**All tests are abrupt except for Smooth Lombard Mood and Smooth Lombard Wilcoxon.

Plate 8. Nonstationarity Analysis of Maximum Annual Flow, Imong River near Agat, Guam (1961-2019)



16847000-Imong River near Agat, Guam

Trend Line Coefficients

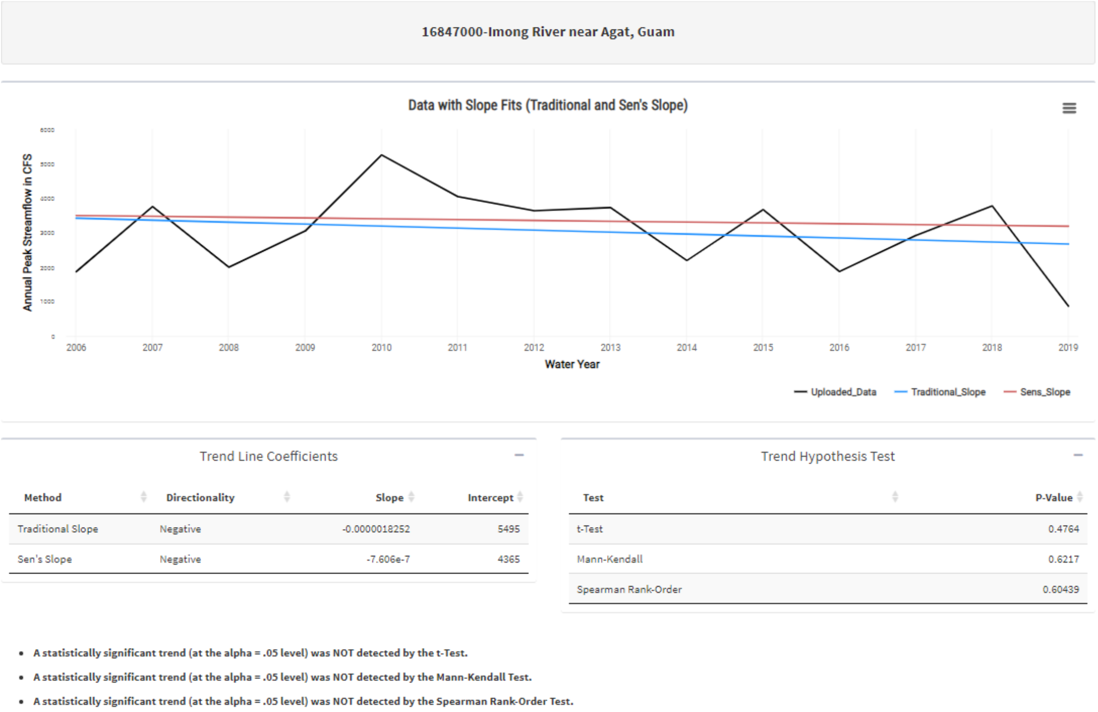
Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-3.558e-7	2180
Sen's Slope	Negative	-3.209e-7	2151

Trend Hypothesis Test

Test	P-Value
t-Test	0.51537
Mann-Kendall	0.3604
Spearman Rank-Order	0.34565

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 9. Trend Analysis of Maximum Annual Flow, Imong River near Agat, Guam (1961-1993)



16847000-Imong River near Agat, Guam

Trend Line Coefficients

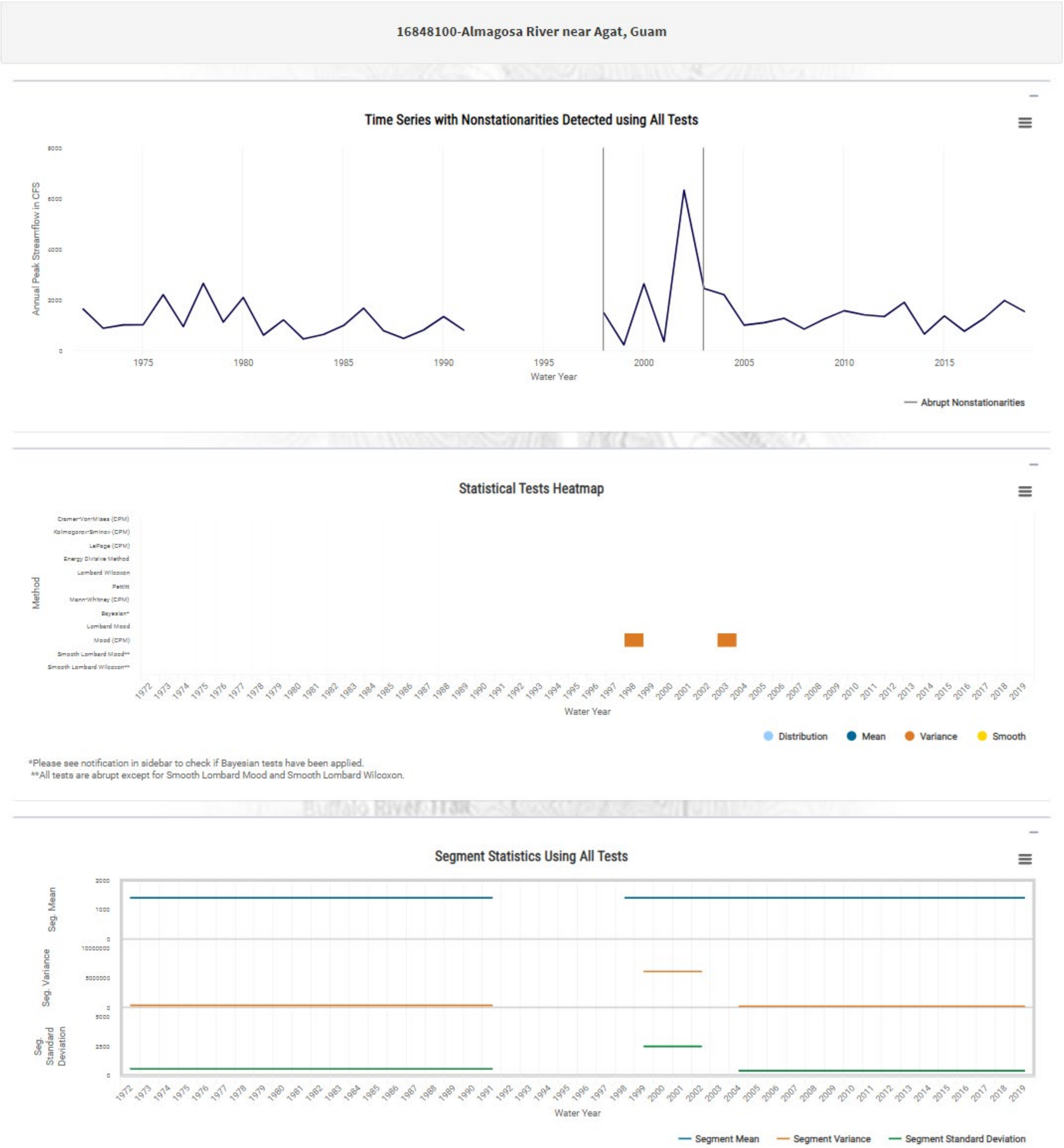
Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-0.0000018252	5495
Sen's Slope	Negative	-7.606e-7	4365

Trend Hypothesis Test

Test	P-Value
t-Test	0.4764
Mann-Kendall	0.6217
Spearman Rank-Order	0.60439

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 10. Trend Analysis of Maximum Annual Flow, Imong River near Agat, Guam (2006-2019)



16848100-Almagosa River near Agat, Guam

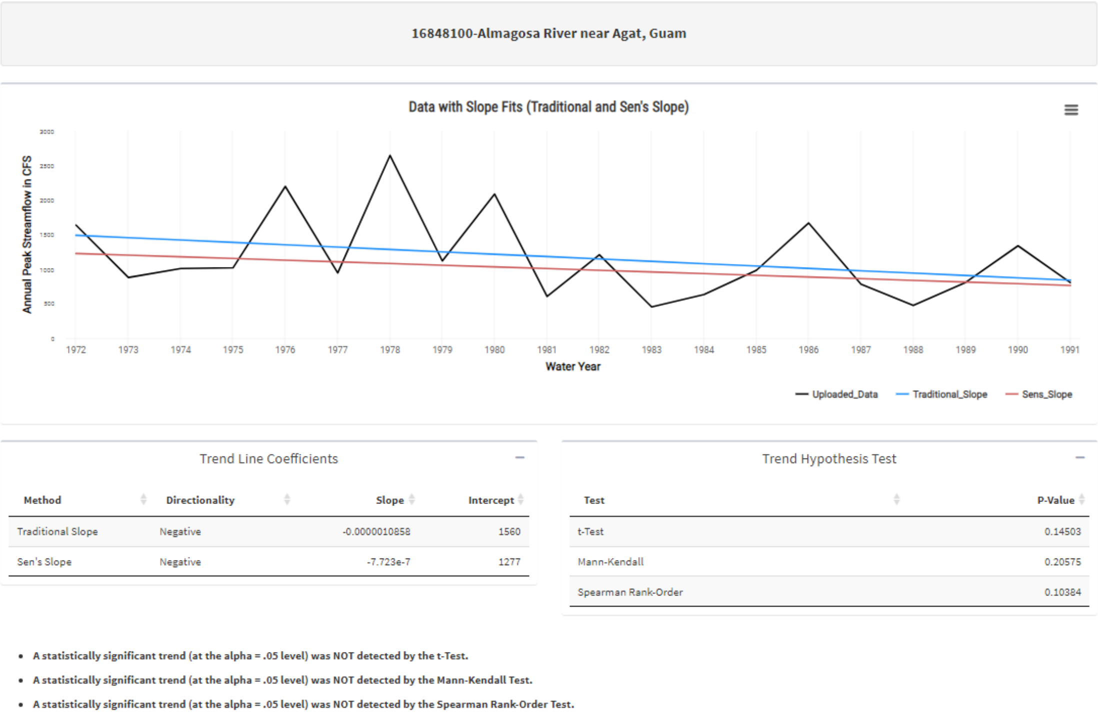
Time Series with Nonstationarities Detected using All Tests

Statistical Tests Heatmap

*Please see notification in sidebar to check if Bayesian tests have been applied.
**All tests are abrupt except for Smooth Lombard Mood and Smooth Lombard Wilcoxon.

Segment Statistics Using All Tests

Plate 11. Nonstationarity Analysis of Maximum Annual Flow, Almagosa River near Agat, Guam (1972-2019)



16848100-Almagosa River near Agat, Guam

Data with Slope Fits (Traditional and Sen's Slope)

Trend Line Coefficients

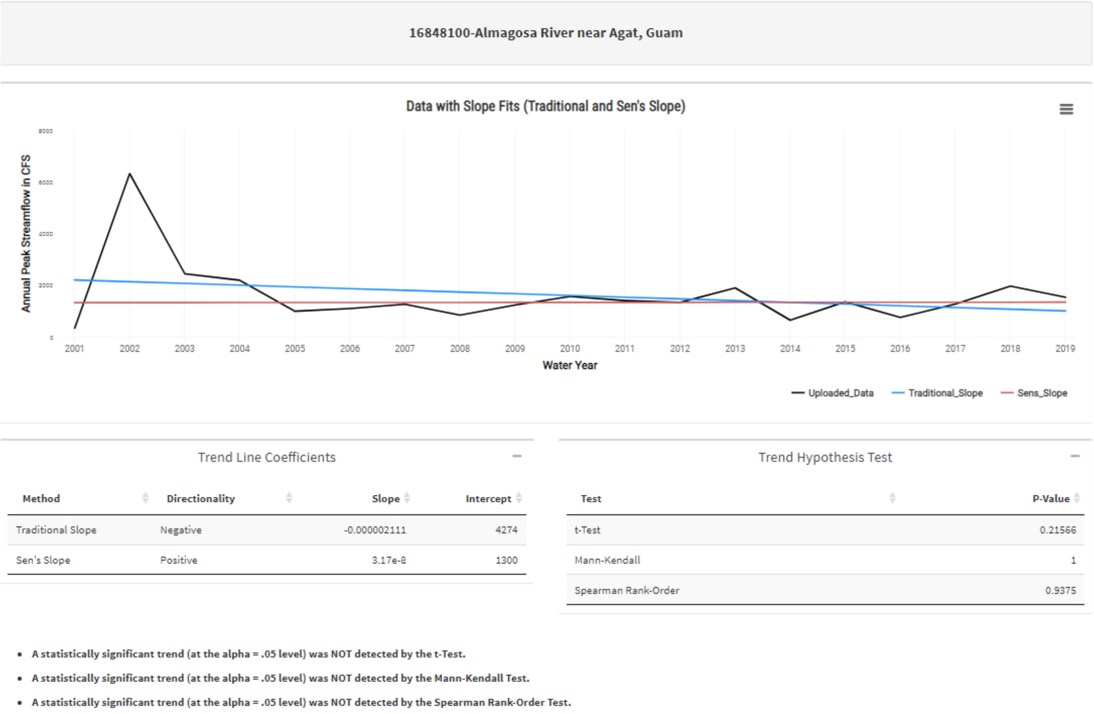
Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-0.0000010858	1560
Sen's Slope	Negative	-7.723e-7	1277

Trend Hypothesis Test

Test	P-Value
t-Test	0.14503
Mann-Kendall	0.20575
Spearman Rank-Order	0.10384

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 12. Trend Analysis of Maximum Annual Flow, Almagosa River near Agat, Guam (1972-1991)



16848100-Almagosa River near Agat, Guam

Data with Slope Fits (Traditional and Sen's Slope)

Trend Line Coefficients

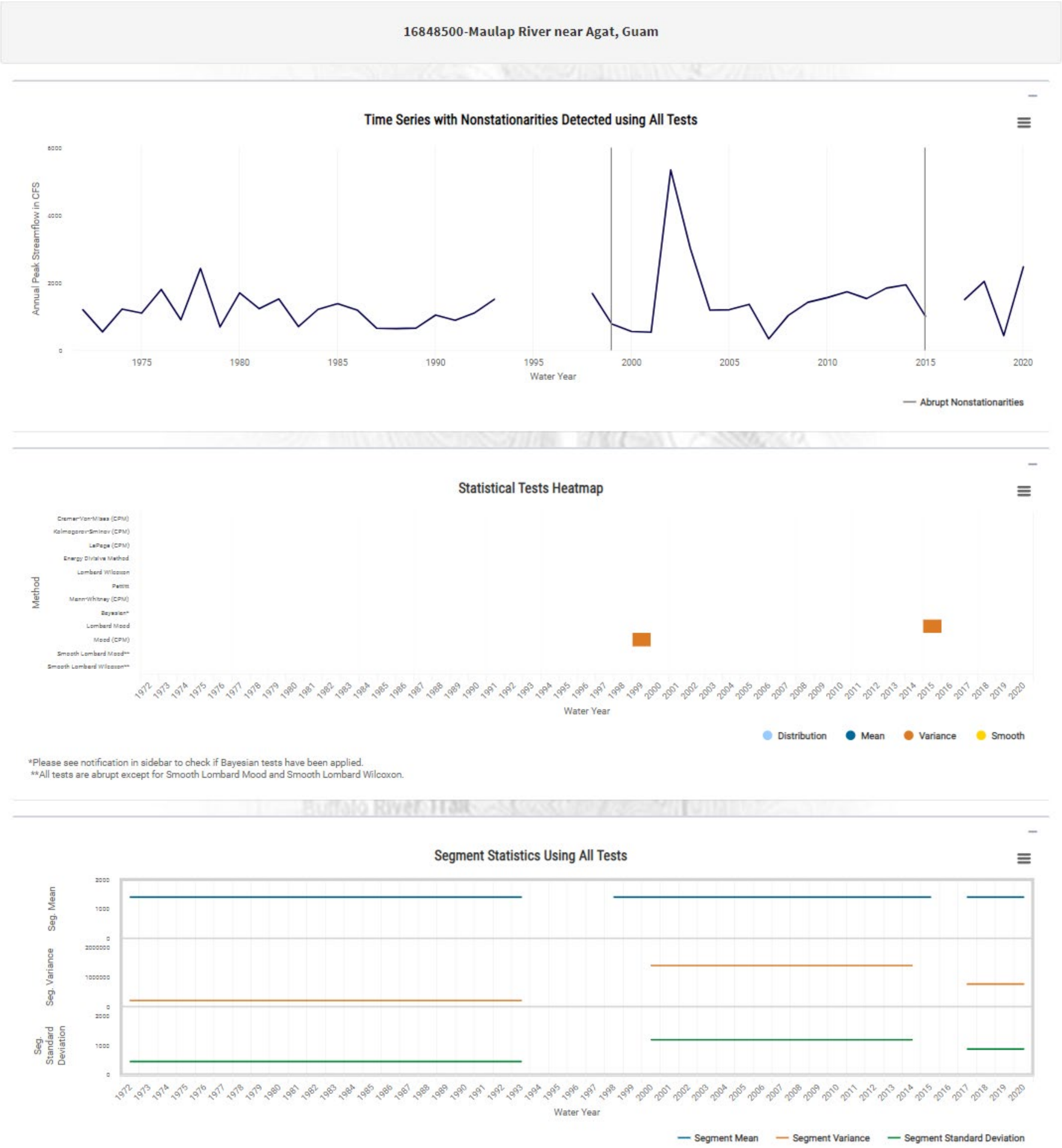
Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-0.000002111	4274
Sen's Slope	Positive	3.17e-8	1300

Trend Hypothesis Test

Test	P-Value
t-Test	0.21566
Mann-Kendall	1
Spearman Rank-Order	0.9375

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

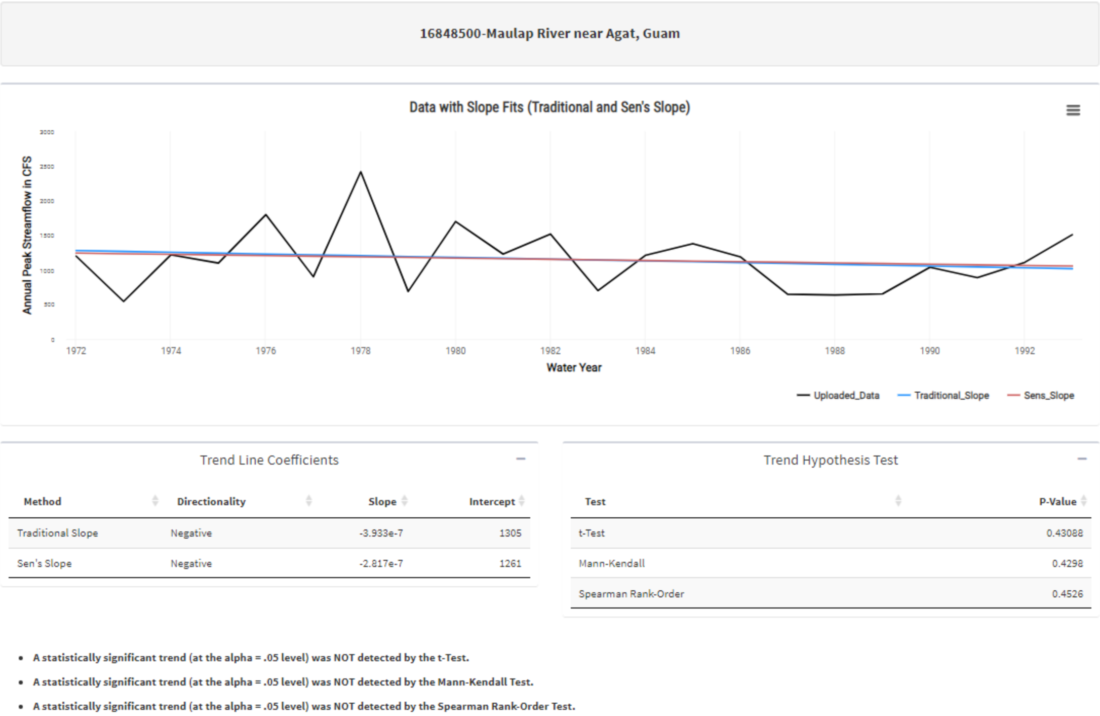
Plate 13. Trend Analysis of Maximum Annual Flow, Almagosa River near Agat, Guam (2001-2019)



16848500-Maulap River near Agat, Guam

*Please see notification in sidebar to check if Bayesian tests have been applied.
**All tests are abrupt except for Smooth Lombard Mood and Smooth Lombard Wilcoxon.

Plate 14. Nonstationarity Analysis of Maximum Annual Flow, Maulup River near Agat, Guam (1972-2020)



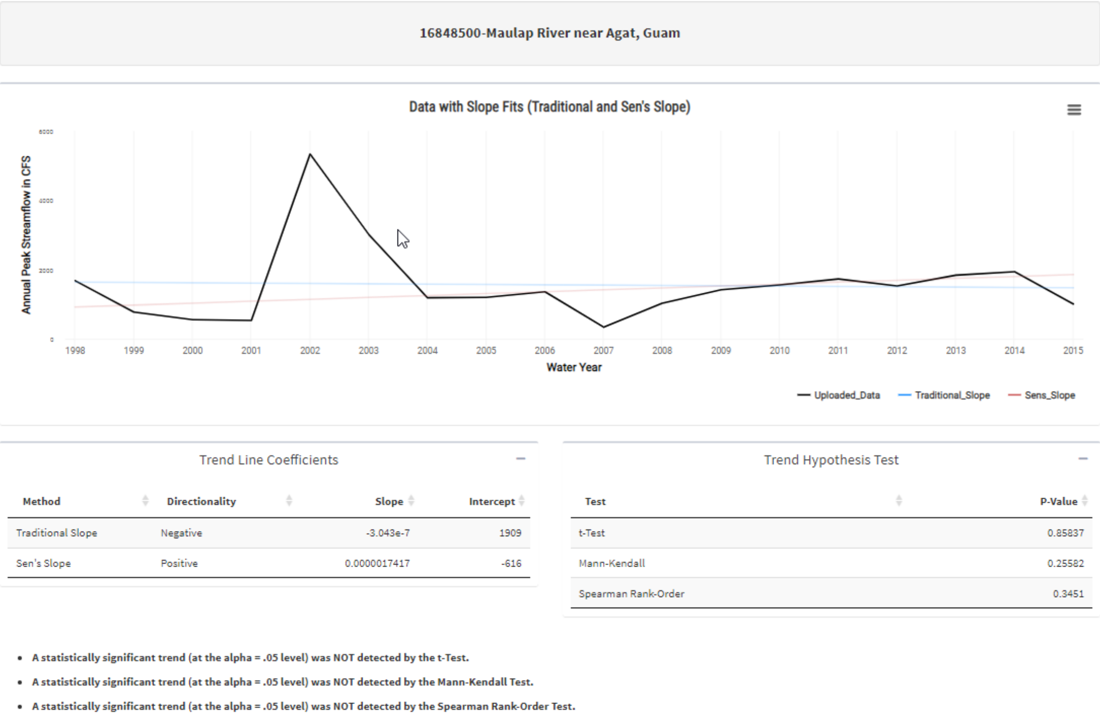
16848500-Maulap River near Agat, Guam

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-3.933e-7	1305
Sen's Slope	Negative	-2.817e-7	1261

Test	P-Value
t-Test	0.43088
Mann-Kendall	0.4298
Spearman Rank-Order	0.4526

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 15. Trend Analysis of Maximum Annual Flow, Maulup River near Agat, Guam (1972-1994)



16848500-Maulap River near Agat, Guam

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-3.043e-7	1909
Sen's Slope	Positive	0.0000017417	-616

Test	P-Value
t-Test	0.85837
Mann-Kendall	0.25582
Spearman Rank-Order	0.3451

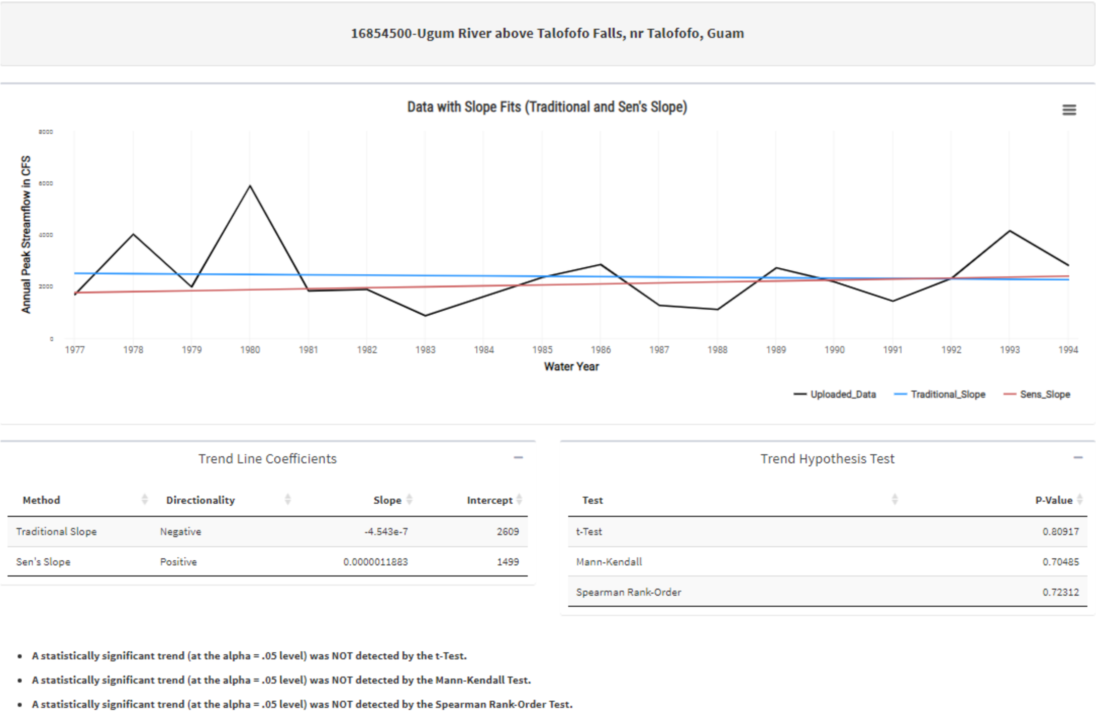
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 16. Trend Analysis of Maximum Annual Flow, Maulup River near Agat, Guam (1998-2015)

16854500-Ugum River above Talofofo Falls, nr Talofofo, Guam

No nonstationarities detected!

Plate 17. Nonstationarity Analysis of Maximum Annual Flow, Ugum River above Talofofo Falls Near Talofofo, Guam (1977-2020)

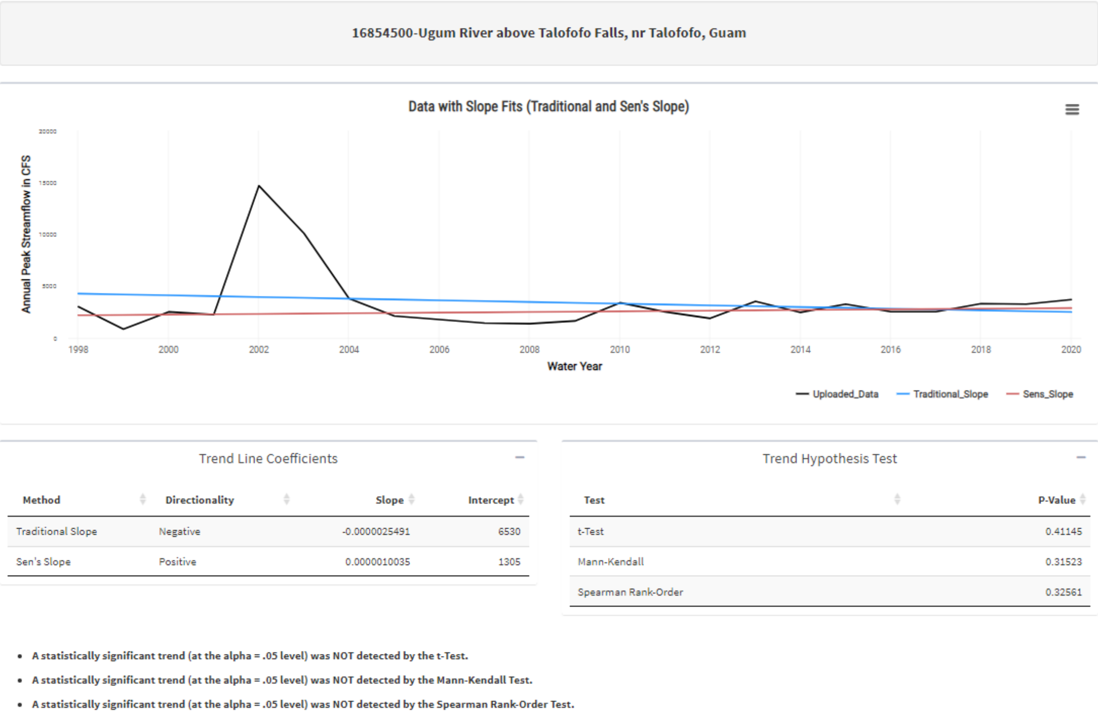


Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-4.543e-7	2609
Sen's Slope	Positive	0.0000011883	1499

Test	P-Value
t-Test	0.80917
Mann-Kendall	0.70485
Spearman Rank-Order	0.72312

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 18. Trend Analysis of Maximum Annual Flow, Ugum River above Talofofo Falls Near Talofofo, Guam (1977-1994)



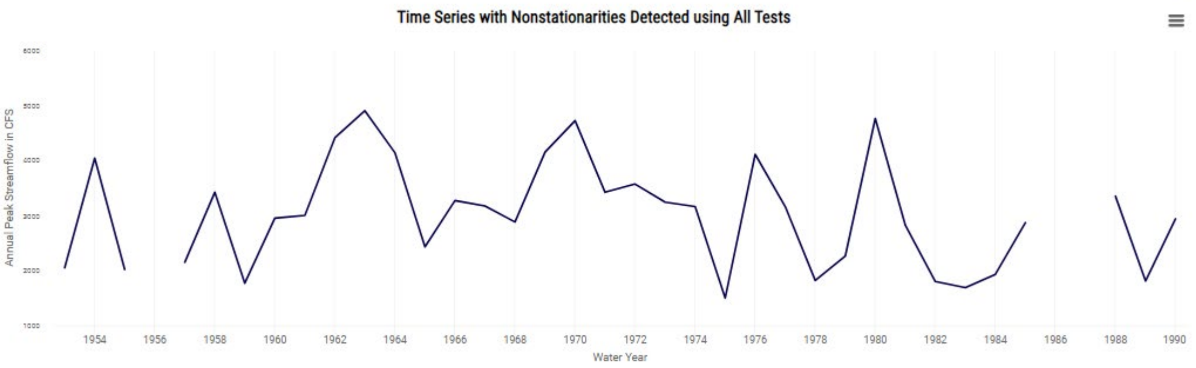
Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-0.0000025491	6530
Sen's Slope	Positive	0.0000010035	1305

Test	P-Value
t-Test	0.41145
Mann-Kendall	0.31523
Spearman Rank-Order	0.32561

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 19. Trend Analysis of Maximum Annual Flow, Ugum River above Talofofo Falls Near Talofofo, Guam (1998-2020)

16858000-Ylig River near Yona, Guam



No nonstationarities detected!

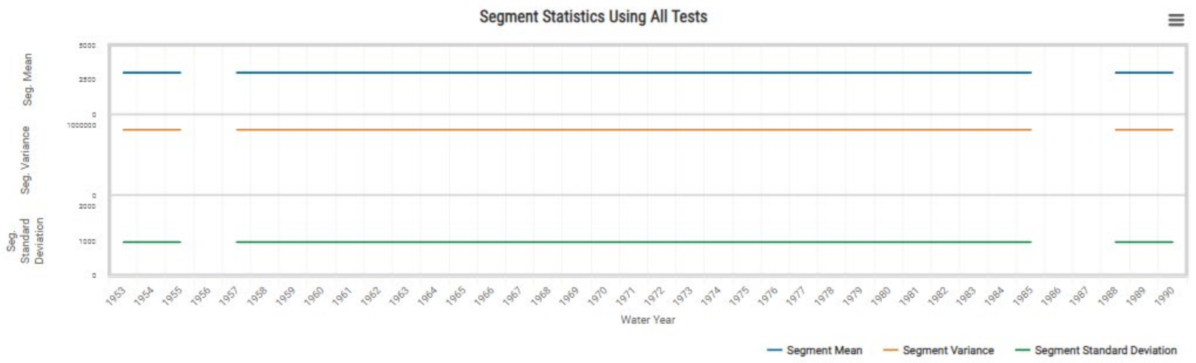
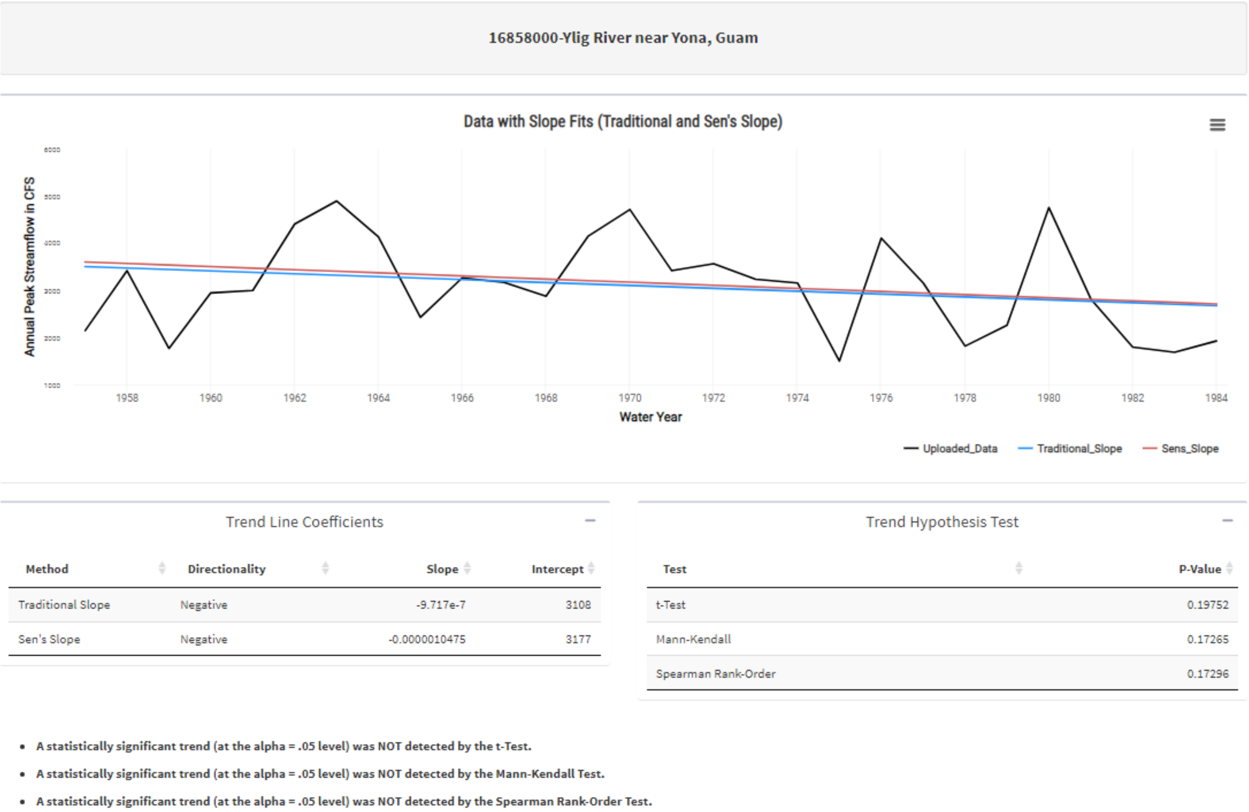


Plate 20. Nonstationarity Analysis of Maximum Annual Flow, Ylig River Near Yona, Guam (1953-1990)



16858000-Ylig River near Yona, Guam

Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-9.717e-7	3108
Sen's Slope	Negative	-0.0000010475	3177

Trend Hypothesis Test

Test	P-Value
t-Test	0.19752
Mann-Kendall	0.17265
Spearman Rank-Order	0.17296

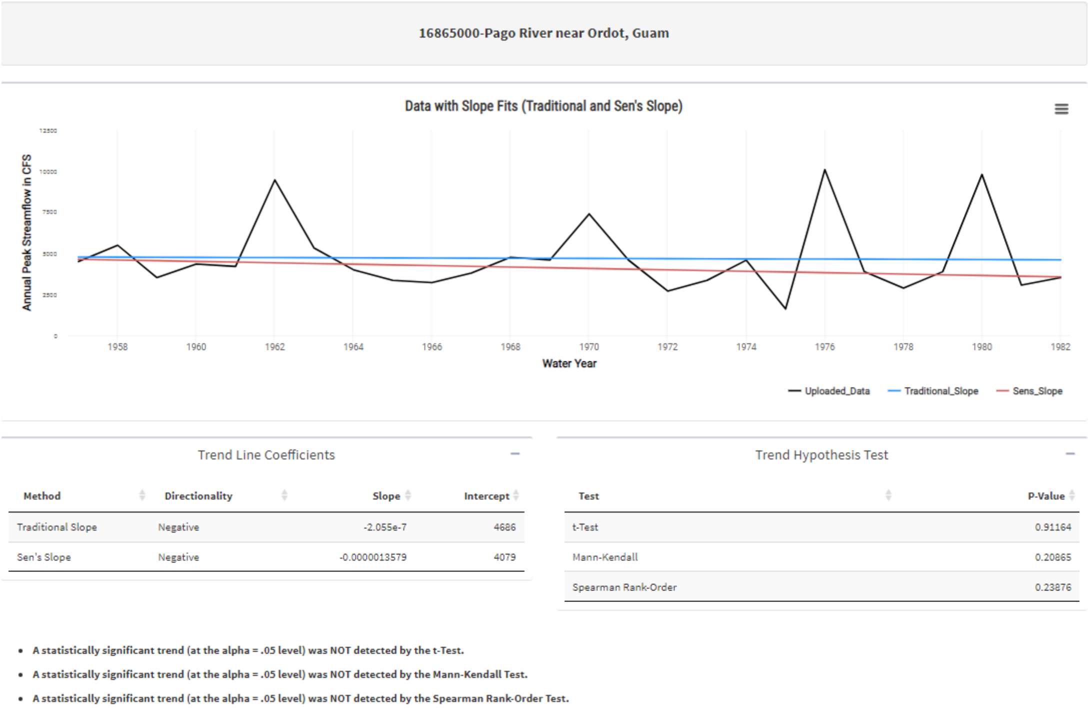
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Plate 21. Trend Analysis of Maximum Annual Flow, Ylig River Near Yona, Guam (1957-1984)

16865000-Pago River near Ordot, Guam

*Please see notification in sidebar to check if Bayesian tests have been applied.
**All tests are abrupt except for Smooth Lombard Mood and Smooth Lombard Wilcoxon.

Plate 22. Nonstationarity Analysis of Maximum Annual Flow, Pago River Near Ordot, Guam (1952-2019)

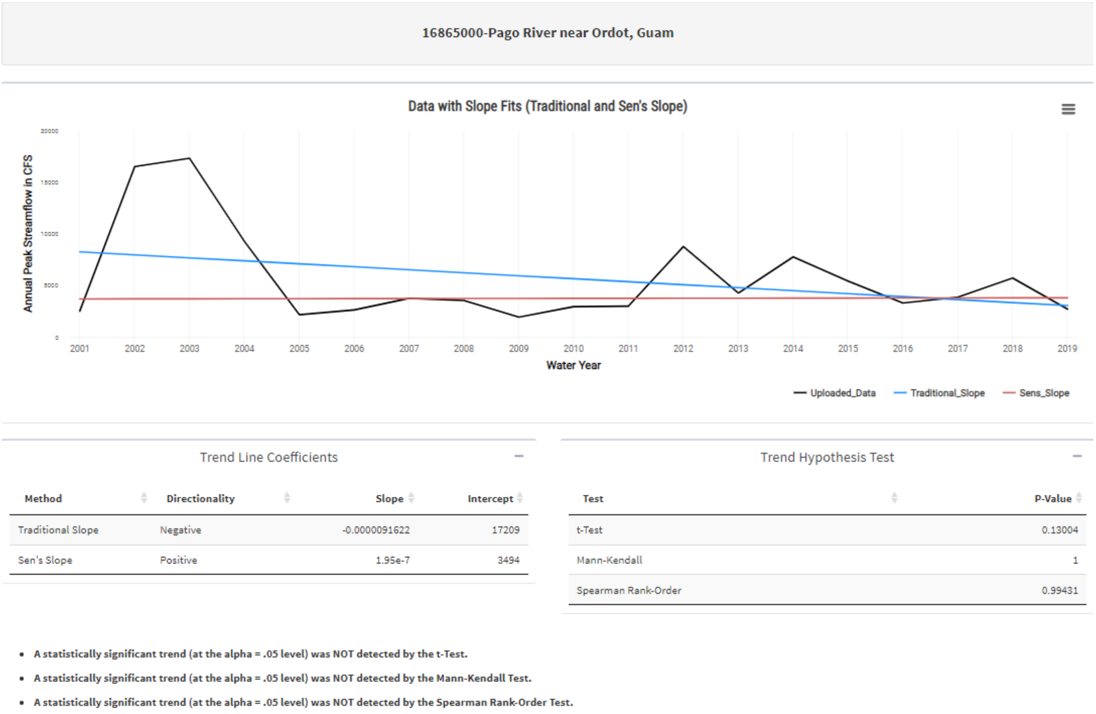


Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-2.055e-7	4686
Sen's Slope	Negative	-0.0000013579	4079

Test	P-Value
t-Test	0.91164
Mann-Kendall	0.20865
Spearman Rank-Order	0.23876

- A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.
- A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.
- A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.

Plate 23. Trend Analysis of Maximum Annual Flow, Pago River Near Ordot, Guam (1957-1982)



Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-0.0000091622	17209
Sen's Slope	Positive	1.95e-7	3494

Test	P-Value
t-Test	0.13004
Mann-Kendall	1
Spearman Rank-Order	0.99431

- A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.
- A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.
- A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.

Plate 24. Trend Analysis of Maximum Annual Flow, Pago River Near Ordot, Guam (2001-2019)