

Draft Environmental Impact Statement Infrastructure Improvements at the Yap International Airport and the Yap Seaport

Yap State, Federated States of Micronesia

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SOUTHWEST DIVISION

Metocean and Numerical Modeling Report

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Yap Harbor Channel Improvements

Yap Island
Federated States of Micronesia

30 May 2025



EXECUTIVE SUMMARY

The Port of Yap is located in Tamil Harbor in Colonia, the capital city of Yap Island, a state in the Federated States of Micronesia (FSM). Receiving domestic and international goods, the port facilities comprise a +800-foot contiguous wharf (split into two berths), two small barge slips located on the east (170 foot) and west (100 foot) ends of the primary wharf face, and a landing craft Ro-Ro (Roll-on, Roll-off) ramp south of the east barge slip. Tamil Harbor is accessed from deep water through a natural channel from the island's fringing outer reef. Channel improvements projects have previously widened and deepened the natural channel to facilitate shipping.

The objective of this report is to characterize the metocean (metrological and oceanographic) conditions through data gathering, numerical modeling, and analysis and to inform the design of improvements of Yap Port.

Metocean Characteristics

Site characteristics define the physical, meteorological, and oceanographic conditions of Yap Port and the surrounding waters. Data used in the characterization includes field collected data, historical measured data, and site specific numerically modeled parameters. The report details bathymetry, water temperature and salinity, and precipitation and sediment transport, along with statistics for water levels, currents and wind speed/direction, and storm conditions.

Due to the complex nature of the waters surrounding Tamil Harbor, the fringing reef, and shallow flats, it is challenging to predict the oceanographic conditions under a range of scenarios from ambient to storm/typhoon. The collection of field data, specifically wave and current direction and magnitude, allows the characterization of the oceanographic conditions. Numerical modeling is used as a tool to characterize oceanographic conditions that are unknown, to extend prediction of parameters where none exist, or to extrapolate extreme values. Field data is used to calibrate the numerical models, greatly increasing confidence in the modeled results.

Hydrodynamic and Spectral Wave Modeling

For the Yap Channel Improvements, a coupled hydrodynamic (HD) and spectral wave (SW) model was developed to predict the ambient conditions and to define extreme conditions for the design of the wharf improvements. A flexible mesh domain that covers the entire Yap Island with finer mesh resolution (approximately 200 feet) at Yap Port was adopted. To facilitate the simulation of ambient scenarios, a representative year based on 43 years of offshore wave information from the CSIRO CAWCR (Durrant et al. 2019) hindcast model was selected. Year 2022 was selected as the representative average year due to data availability and abundance of satellite wave altimetry information, essential for model validation and confidence. Additionally, the year 2022 also has relatively small deviation from the modeled long-term average wave energy. 2022 falls under the La Niña period, indicating higher than average water levels. This is expected to result in more wave penetration and more energetic wave climate at the port.

Hourly water level observations collected from tide gauges were downloaded from the University of Hawaii Sea Level Center (UHSLC) Station Explorer to facilitate model validation through comparison between the modelled and observed surface elevations. Satellite wave altimetry observations were extracted from the Copernicus Marine Environment Monitoring Service (CMEMS) multi-year satellite wave products. Resulting significant wave height values from the modelled representative year were validated by comparing them with the significant wave heights derived from the four satellite altimetry measurements.

Time-series data of ambient conditions was extracted from the model at two points at the port, one at the center of the turning basin, four points on the channel, and one point at an offshore location. A detailed assessment of wave exceedance at the extraction points was also performed for the simulated

representative year. Monthly distribution of significant wave height was plotted (average and maximum) at each extraction point.

The majority of waves extracted near the port come from the east-southeast direction. As the port is sheltered by the landmass from the south, these are likely diffracted waves with minimal wave height and energy. In contrast, waves at the turning basin primarily come from the south and are relatively stronger and more energetic. Nonetheless, the waves at and near the port area are likely a combination of broken swells or locally generated wind waves. Relatively calm waves are expected across the port and the turning basin for the entire year where wave heights of less than 0.8 feet are modeled.

The channel is open to deep water with notably energetic offshore waves, heights can reach more than 9 feet in height. Wave heights at the channel entrance averaging 3 feet can be experienced, mainly from the east and east-southeast directions. The waves dissipate as these penetrate towards the harbor due to the presence of reef on both sides of the channel. The reduction in wave heights is noticeable as waves move further north. By the time waves are halfway to the turning basin they have reduced in height by around 50 to 70%.

Wave periods have a significant impact on vessel navigation. In mariners' terms, waves with periods of up to 2 seconds are known as ripples, from 2 to 5 seconds are called chop, from 5 to 15 seconds are called sea state, and from 15 to 30 seconds are called swell. A ship whose length waterline is equal to the wave length and wave height is less than the freeboard will only experience less severe functionality degradation in rough seas (pounding, slamming, wetness of the deck, excessive rolling and pitching, emergence of propeller at the surface, etc.); whereas a ship whose length waterline is smaller than wave length and wave height exceeds the freeboard will encounter severe functionality degradation of the ship's system in rough sea conditions.

At the offshore location, most waves are sea states and these transition to chops as you move closer into the harbor, more specifically when offshore waves break across the reef. At the port, chops consist of 50 to 60% of waves, with sea state waves typically having very small wave heights of less than 0.2 feet.

Maximum values for significant wave heights are observed to occur between April and October. This is coincidental with the typhoon season in the Pacific, which usually begins in April and ends in November, where the most severe typhoons usually occur in August and September. Additionally, mean sea level (MSL) between the months of May to September also tends to be higher than average, which may result in stronger waves being able to penetrate and travel towards the port area. In contrast, strong waves are expected to occur in the channel entrance and offshore areas from October until April. This period coincides with the island's defined winter season.

Ebb and flood describe the movement of currents during the rise and fall of tide levels. The current patterns within Yap Harbor and the entrance channel were extracted from the hydrodynamic model. Currents near Yap Port are generally weak under ambient conditions. At the vicinity of the port area, currents are envisaged to be regularly less than 0.1 knot, flowing towards the NW at flood, and SW at ebb. In the turning basin, the currents are flowing northward at flood, and southward during ebb, peaking at around 0.2 knot.

Stronger currents are predicted along the channel alignment. Ebb currents were also observed to be stronger than flood currents. Comparing the currents at the extraction points, the entrance bend encounters the strongest currents exceeding 0.5 knots. This value can be exceeded at other locations with the strongest modeled currents being 0.8 knot, at a point approximately 0.2 mile SE of the bend. This point is within the shallowest section of the channel with a recorded depth of 55.6 feet. Currents in the deep water offshore areas remain relatively low, less than 0.15 knot.

Typhoon Modeling

Eight different typhoons were selected based on availability of data and recorded storm surge at Port of Yap and modeled. Water level data was extracted from the model results within the port and were compared to the recorded water levels during each typhoon. Maximum modeled water levels for each storm ranged

from 2.34 m to 1.24 m, MLLW. Typhoon Sudal of 2004 both modeled and recorded the greatest water surface elevation. The largest error between measured and modeled water surface elevations is 0.52 m for Typhoon Hagupit of 2014. Wave data, including maximum significant wave height and maximum peak period, was extracted from the model results at a selected point near the port. Most waves were broken by the reef system during the typhoons and resulted in significant wave heights ranging from 1.6 to 0.1 m. Of the typhoons, Typhoon Sudal of 2004, produced the largest modeled wave at the port. Maximum significant peak wave periods at the port during the typhoons ranged between 20.0 and 13.4 s. Typhoon Maysak of 2015 produced the largest modeled peak wave period at the port. Maximum current speeds at the port during the typhoons ranged between 0.09 and 0.03 m/s. Typhoon Haima of 2016 produced the largest modeled current speed at the port.

Comparing the typhoon events to the ambient condition modeling, inside of Tamil Harbor and at the port, there is very little propagation from storm events. The most significant factor during typhoon conditions will be wind speed impacting ships moored at the berth.

Harbor Tranquility

A harbor agitation model was developed to further resolve the wave transformation into Tamil harbor during extreme events. This was undertaken using the MIKE 3 Wave Model FM, a phase resolving non-hydrostatic wave model that is based on the 3D Navier-Stokes equations and with free surface described as a height function. The port is naturally sheltered by both land mass and shallow reefs.

The scenarios chosen to simulate the extreme events were based on the offshore wave height and peak wave period generated by Typhoon Mitag (2002), where significant wave heights greater than 20 m and peak period in the order of 16 s at the model boundary were simulated during the typhoon wave simulation. The eye-walls of the typhoons went past the vicinity of the project site and created wave heights that were almost doubled that simulated for 2013 Haiyan and 2015 Maysak; additionally, the long wave period is expected to result in more wave penetration into the port compared to short period wind waves.

The simulation of shortlisted typhoons indicates that the dominant wave direction offshore Yap in a typhonic environment is in 90°-120°. While a southerly wave will be more critical to the port due to co-direction with the channel that facilitates higher wave penetration, the likelihood of this hypothetical scenario is considered to be low given the orientation of the island as well as evidence from historical typhoon tracks.

The modeled results suggest that wave propagation into Yap Port is limited for the scenarios considered. While wave propagation can be seen in the model results, waves dissipated relatively quickly with nearly negligible resultant wave heights at the port.

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1 INTRODUCTION

The Port of Yap is located in Tamil Harbor in Colonia, the capital city of Yap Island, a state in the Federated States of Micronesia (FSM). Receiving domestic and international goods, the port facilities comprise a +800-foot contiguous wharf (split into two berths), two small barge slips located on the east (170 foot) and west (100 foot) ends of the primary wharf face, and a landing craft Ro-Ro (Roll-on, Roll-off) ramp south of the east barge slip. Tamil Harbor is accessed from deep water through a natural channel from the island's fringing outer reef. Channel improvements projects have previously widened and deepened the natural channel to facilitate shipping. Refer to Figure 1-1.

The objective of this report is to characterize the metocean (metrological and oceanographic) conditions through data gathering, numerical modeling, and analysis to inform the design of improvements of Yap Port. This metocean report provides the baseline oceanographic and meteorological conditions that will guide the design of marine infrastructure improvements.

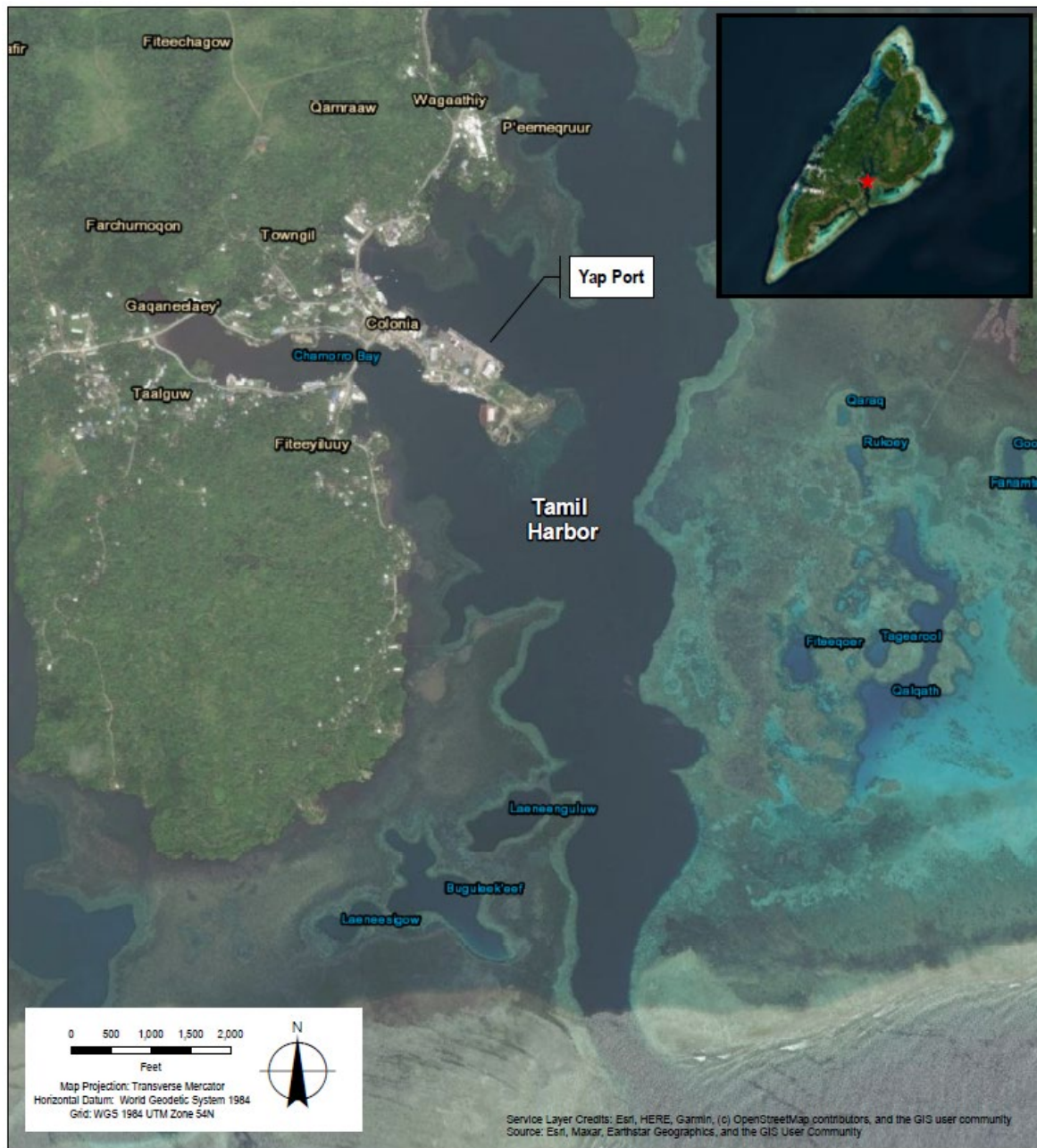


Figure 1-1 Port of Yap

2 DESKTOP METOCEAN STUDY

The site characteristics define the physical, meteorological, and oceanographic conditions of Yap Island and the surrounding waters. Data used in the characterization includes field collected data, historical measured data, and site specific numerically modeled parameters.

2.1 Project Datum

The planar coordinate system adopted is the Universal Transverse Mercator System (UTM), Zone 54 North. The vertical datum is mean lower low water (MLLW).

2.2 Bathymetry

Tamil Harbor and the surrounding waters of Yap Port have been hydrographically surveyed a number of times. The most recent multibeam survey was conducted from May 5, 2023 to May 15, 2023. Figure 2-1 and Figure 2-2 show the bathymetric contours around the port and the approach channel. Elevation values are referenced to MLLW vertical datum. Within the entrance channel, the lowest elevation depths are approximately -180 feet (MLLW), with a gradual decrease in depth through the channel to approximately -120 feet (MLLW). Around the existing wharf area, the depth decreases to -110 feet (MLLW) to -50 feet (MLLW), with a rapid loss of depth towards the shoreline. Although the channel has been modified in places for shipping, it is a naturally occurring deep water inlet; therefore, outside of the areas of previous dredging, the channel sides are naturally steep, ending in very shallow reef flats.

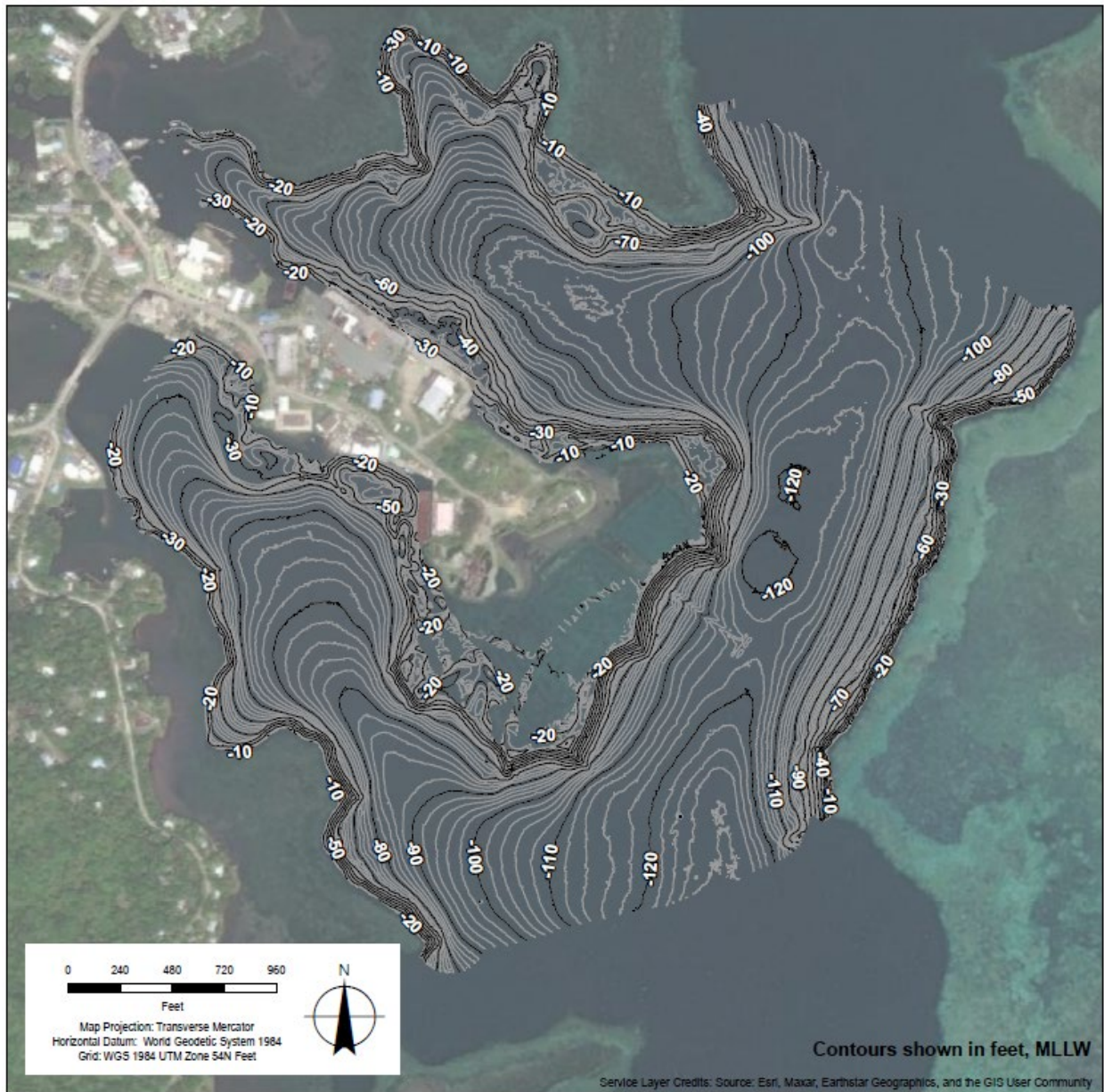


Figure 2-1 Yap Harbor Bathymetry (Surveyed May 2023 by Sea Engineering, Inc.)

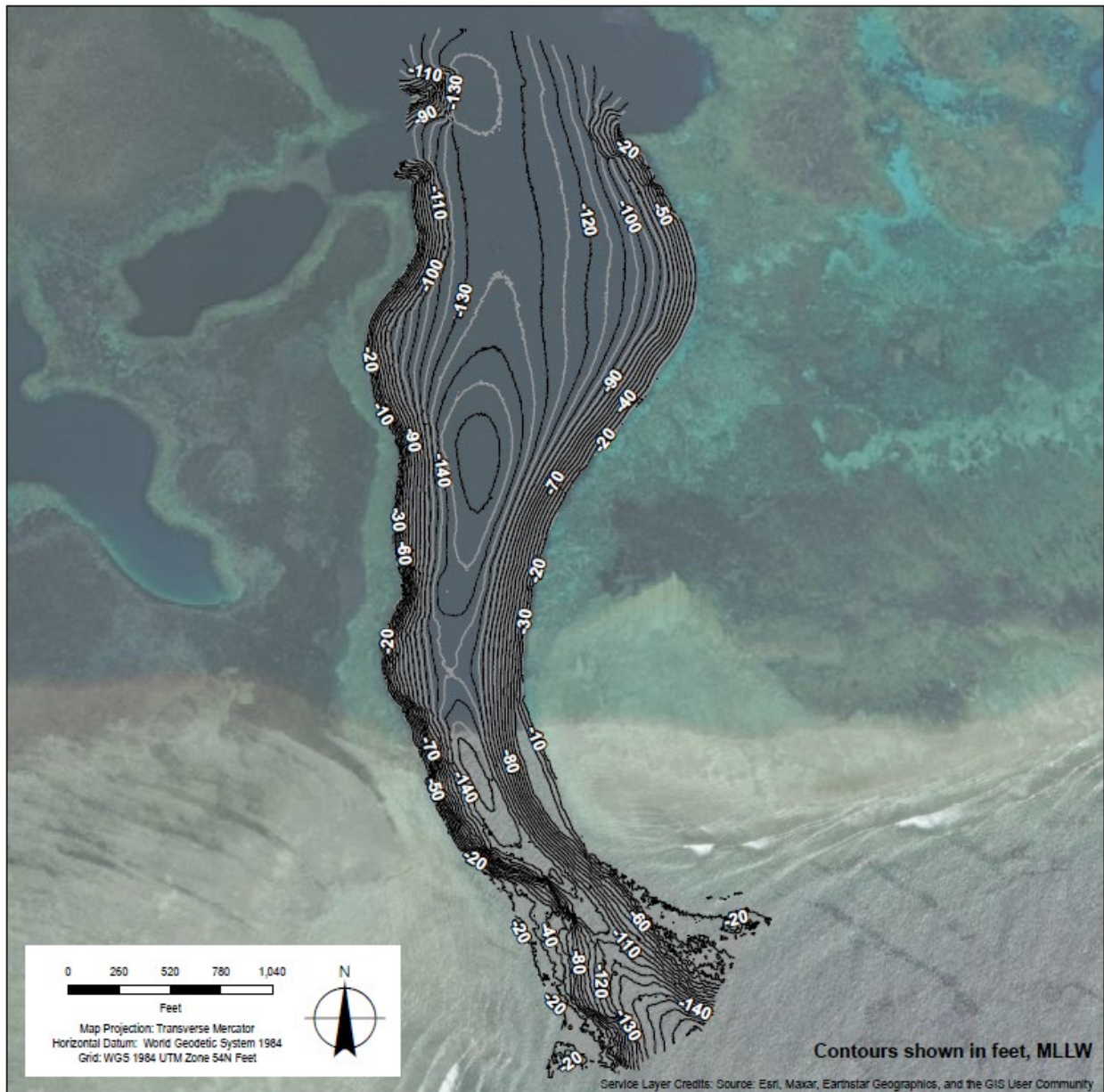


Figure 2-2 Yap Channel Bathymetry (Surveyed May 2023 by Sea Engineering, Inc.)

All three bathymetric sources are consistent, indicating little change to the alignment or depth of the channel, outside of man-made actions. The outermost end of the island peninsula where the Port of Yap is located appears to have been utilized as a dredge disposal/material reclaim source over the years. Historical aerial imaging shows the change in the peninsula (near the wastewater facility). Refer to Figure 2-3.



Figure 2-3 Historical Change in Colonia Peninsula (left: 2/8/2005, middle: 3/31/2013, right: 8/9/2022. Source: Google Earth)

2.3 Climate

The climate in Yap is tropical. Mean daily air temperature is approximately 82°F (28°C). There is little seasonal variability in temperature. The wetter season extends from May to November, with a greater than 54% chance of precipitation. Rainfall and sea temperatures can vary significantly between years as a result of El Niño Southern Oscillation (ENSO). El Niño years are drier and La Niña years are, on average, wetter.

2.4 Water Temperature and Salinity

Water temperature and salinity data was extracted from the Multi Observation Global Ocean (ARMOR3D L4) platform maintained by the Copernicus Marine Service for a point offshore of Yap. Monthly averages for the previous 4.5-year period (January 2019 to June 2023) were plotted to characterize the typical ocean water temperature and salinity fluctuations over time (Figure 2-4). During this period, the ocean surface temperature varied from 27.6°C to 30.5°C, with an average value of 29.3°C. The surface temperature is seasonal in nature with minimums occurring around February and maximums occurring in the summer months. Ocean surface salinity varied from 33.9 practical salinity units (PSU) to 34.3 PSU, with an average value of 34.1 PSU.

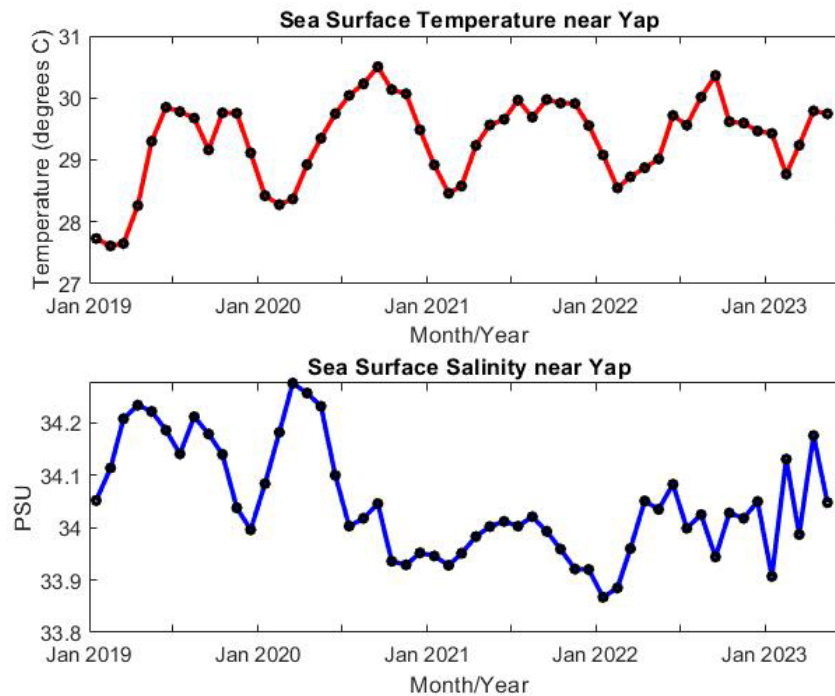


Figure 2-4 Ocean Surface Temperature and Salinity

2.5 Precipitation

Daily precipitation data from 1951 to 2023 was downloaded from the Global Historical Climatology Network for the Yap International Airport (NOAA NCEI n.d.). The Island of Yap is located on the edge of the Pacific Warm Pool and is subject to the intertropical convergence zone. Yap typically receives around 126 inches of rainfall per year, and an average of 10.2 inches of rainfall per month (Figure 2-5). During the wet season, June and August, Yap receives an average rainfall of 13.8 inches, with an average of 8.9 inches of rainfall for the remainder of the year.

Wet and dry years were defined as above or below the annual average. Annual total precipitation for 2000 to 2022 is shown in Figure 2-6, relative to the annual average. During this time period, 11 of the 23 years were drier than average, and the remaining 12 years were wetter than average. More recently, 2021 and 2022 were wetter than the average year, with about 132 inches and 137 inches of precipitation, respectively.

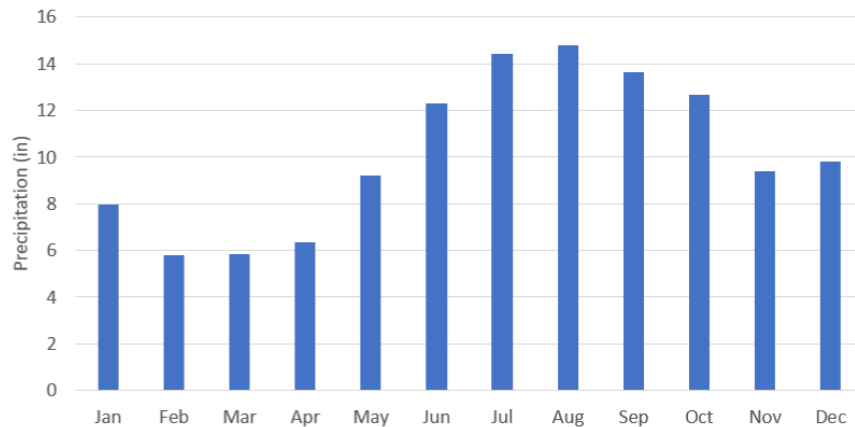


Figure 2-5 Monthly Average Precipitation Data for Yap International Airport from 1951-2023

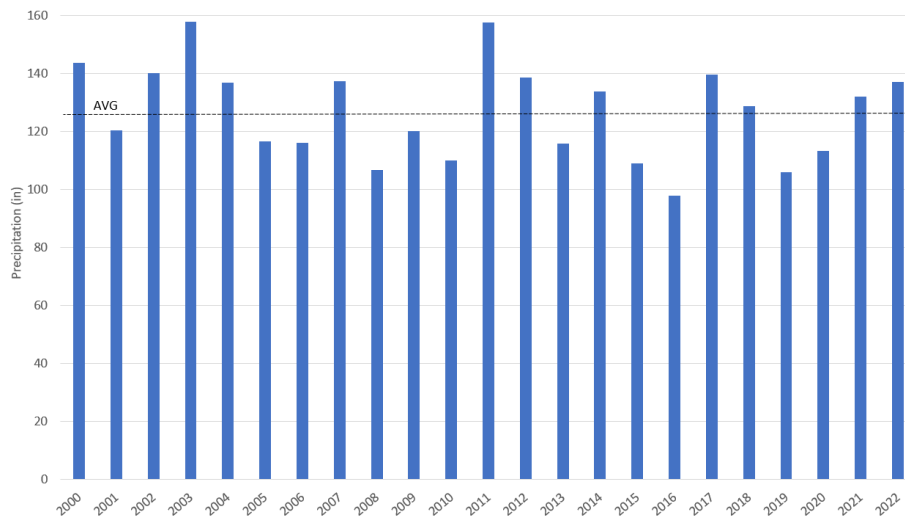


Figure 2-6 Total Annual Precipitation Data for Yap International Airport from 2000-2023

(average shown as black dash line)

2.6 Water Levels

Water levels include normally occurring tides, seasonal and long-term water elevation change, and extreme extent fluctuations such as storm surge and tsunami.

2.6.1 Tides

The University of Hawaii Sea Level Center (UHSLC) operates and maintains a network of tide stations throughout the Pacific Ocean. The representative tide gauge for the site is located near the wharf (UHSLC ID 008) and contains a data record as far back as 1969 (Caldwell et al. 2015). The water levels for the project site are mixed semi-diurnal, meaning that there are two high tides and two low tides of differing values per lunar day. The tidal range, or the difference between the typical high tide (mean higher high water, MHHW) and typical low tide (MLLW) is approximately 4.6 feet.

UHSLC provides water level datums for each tide station, which are presented below in Table 2-1. It is important to note that MLLW is referenced to the station datum, a local benchmark.

Table 2-1 Water Level Datums for Yap

Datum	Water Level (m, MLLW)	Water Level (ft, MLLW)
Highest Observed Water Level (04/09/2004)	2.56	8.39
Highest Astronomical Tide (HAT) (09/18/1993)	1.39	4.55
Mean Higher-High Water (MHHW)	1.11	3.63
Mean High Water (MHW)	1.05	3.44
Mean Tide Level (MTL)	0.63	2.05
Mean Sea Level (MSL)	0.62	2.03
Mean Diurnal Tide Level (DTL)	0.56	1.82
Mean Low Water (MLW)	0.21	0.66
Mean Lower-Low Water (MLLW)	0.0	0.0
Lowest Astronomical Tide (LAT) (12/31/1986)	-0.49	-1.62
Lowest Observed Water Level (09/29/2019)	-1.91	-6.27
Station Datum	-0.74	-2.44

**Values are shown relative to MLLW, which is referenced to the Station Datum*

2.6.2 Sea Level Trends

Sea level trends at Yap Harbor were examined using water level data spanning from 1970 to 2023 to better understand historic and seasonal trends, independent of storm surge induced by typhoons. The water level data record is fairly complete since 1970; however, notable data gaps exist in 2005 (5 months), 2006 (6 months), 2007 (8 months), 2020 (10 months), 2021 (10 months), and 2022 (5 months).

The mean sea level (MSL) trend analysis indicates that sea levels at Yap Harbor have risen approximately 5.4 inches since 1970, with 3.0 inches of sea level rise (SLR) in the last 20 years (2003 to 2023). The rate of SLR during these time periods are 0.10 inch/year and 0.15 inch/year for the 1970 to 2023 and 2003 to 2023 time periods, respectively. This is generally consistent with the climate analysis and projections presented by UHSLC (Caldwell et al. 2015), which reports an SLR of about 4.7 inches since 1969. The historic MSL trend is presented below in Figure 2-7.

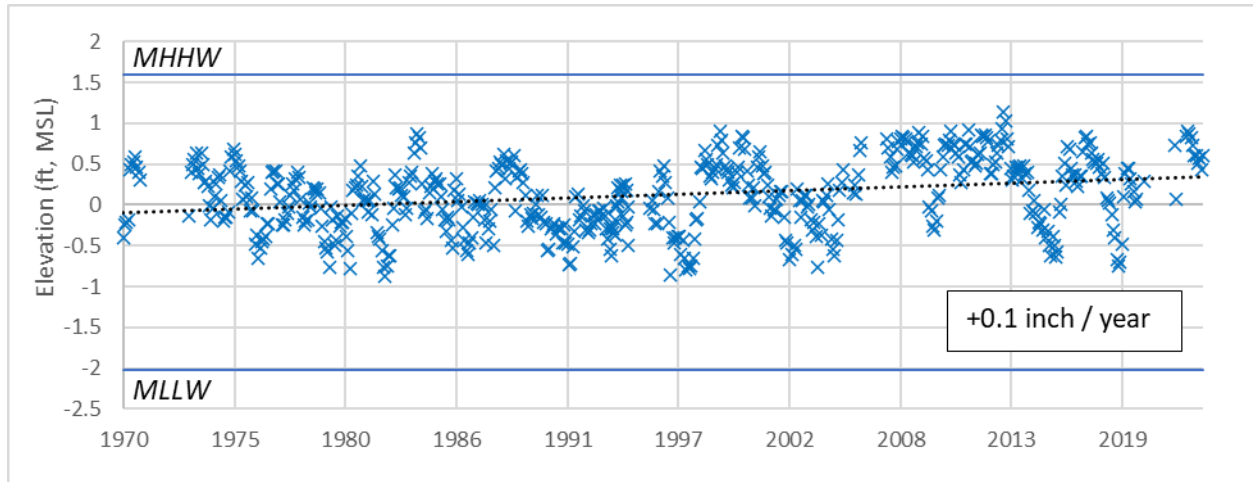


Figure 2-7 MSL Trends for Yap Harbor

In order to examine seasonal water level trends, the monthly MSL was derived for the 1970 to 2023 and 2003 to 2023 time periods. The analysis revealed that water levels tend to be highest during the May to September months, with the monthly MSL range being 0.4 and 0.6 feet for the 1970 to 2023 and 2003 to 2023 time periods, respectively. For both time periods, the MSL is lowest during January. The relative rise in sea levels is also present over the last 20 years, as can be seen in Figure 2-8. However, it should be noted that these seasonal trends include the El Niño and La Niña climatic oscillations, which will be discussed in the following section.

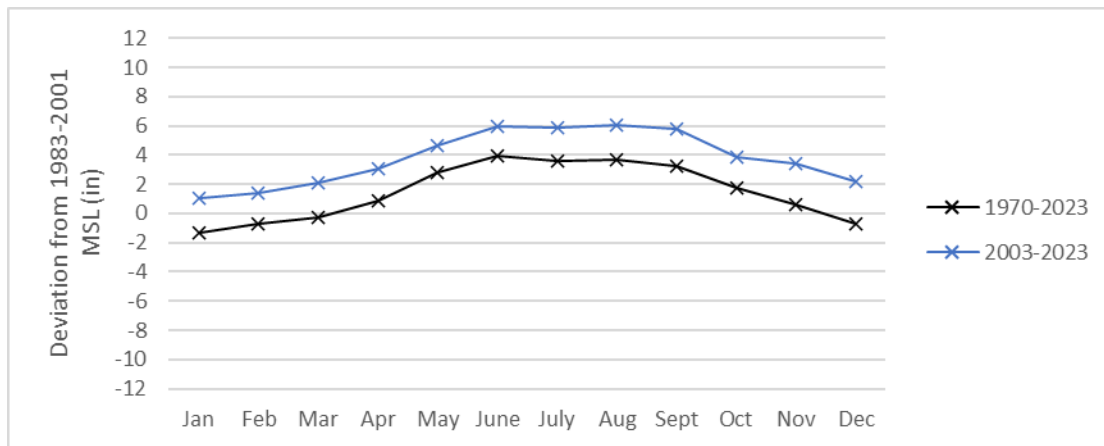


Figure 2-8 MSL Trends by Month

2.6.2.1 Climatic Oscillation

ENSO is a periodic fluctuation in sea surface temperature and the air pressure of the overlying atmosphere across the equatorial Pacific Ocean that occurs about every 2 to 7 years (NOAA NCEI 2023). These fluctuations have been recognized as El Niño for warm events and La Niña for cool events that occur in the eastern tropical Pacific Ocean. These events are characterized by a five consecutive, 3-month running mean of sea surface temperature (SST) anomalies taking place in the equatorial Pacific Ocean that is above or below the threshold of $\pm 0.5^{\circ}\text{C}$ (NOAA NCEI 2023). This standard of measure is known as the

Oceanic Niño Index (ONI). These occurrences can have a substantial global effect on rainfall distribution, sea surface temperatures, and weather patterns.

Table 2-2 ENSO Type from 1951 to Present (ONI)

Year Range	ENSO	Year Range	ENSO
1951 – 1954	El Niño	1994 – 1995	El Niño
1954 – 1956	La Niña	1995 – 1996	El Niño
1957 – 1959	El Niño	1997 – 1998	El Niño
1963 – 1964	El Niño	1998 – 2001	La Niña
1965 – 1966	La Niña	2002 – 2003	El Niño
1968 – 1970	El Niño	2004 – 2005	El Niño
1970 – 1973	El Niño	2005 – 2006	La Niña
1973 – 1976	El Niño	2006 – 2007	El Niño
1976 – 1978	La Niña	2007 – 2009	La Niña
1979 – 1980	El Niño	2009 – 2010	El Niño
1982 – 1983	La Niña	2010 – 2012	La Niña
1983 – 1985	La Niña	2014 – 2016	El Niño
1986 – 1988	La Niña	2016 – 2018	La Niña
1988 – 1989	El Niño	2018 – 2019	El Niño
1991 – 1992	La Niña	2020 – 2023	La Niña

An occurrence of an El Niño event would have a significant impact on Yap's ocean and weather conditions. Sea levels decrease a few inches to a foot along the island but is typically followed by a gradual recovery to normal water levels after a year (NOAA n.d.). Yap will typically experience cooler SST at and below the surface (NOAA n.d.). Rainfall in the area steadily decreases during an El Niño event, resulting in longer and drier dry seasons (NOAA n.d.). The normal easterly trade winds are weaker during this event and will occasionally switch to westerly winds (NOAA n.d.). There is typically a reduced risk of tropical cyclones, but since storms are more likely to form closer to the island, this can increase flooding and sediment runoff from the land (NOAA n.d.).

The El Niño and La Niña climatic oscillations also impact water levels in the Yap Harbor. Among the FSM, El Niño periods are typically characterized by cooler water temperatures and lower-than-usual sea levels (Grecni et al. 2023). Whereas La Niña periods are typically characterized by heightened sea levels. Of the 51-year data record, 12 years were considered to be La Niña and 10 years were considered to be El Niño. Seasonally, months considered to be in an El Niño cycle can deviate about 6 inches below the MSL (1983-2001 epoch), with the lowest water levels occurring in January and February. Whereas the La Niña cycle can lead to increased water levels around 7 inches higher than the MSL, peaking in the June to August months.

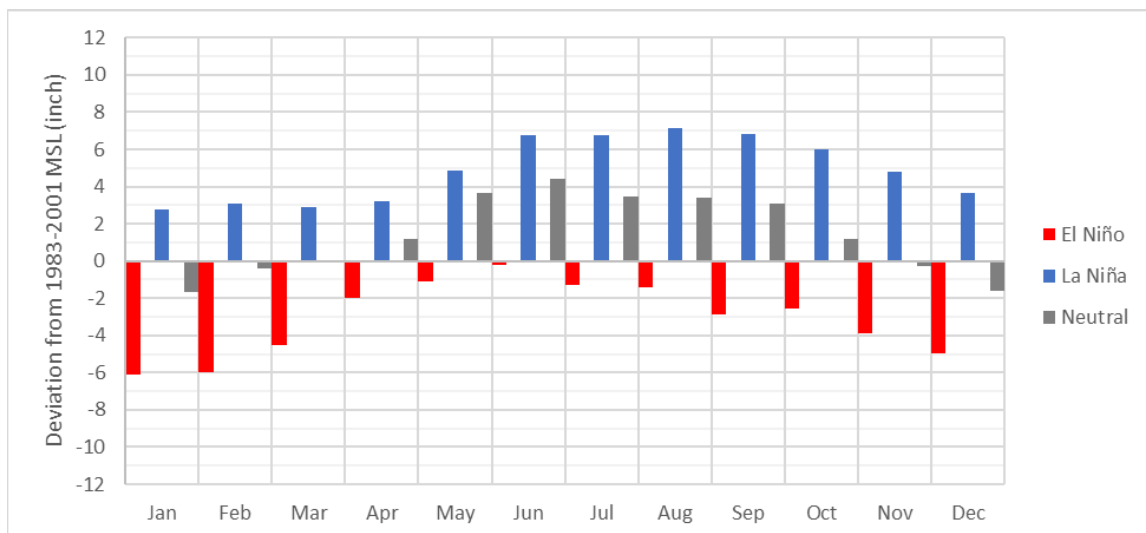


Figure 2-9 Seasonal MSL Trends, El Niño vs La Niña

2.6.3 Extreme Water Levels

Ocean water levels typically vary within predictable astronomical tide ranges. However, sea level anomalies may occur that increase water levels above the predicted tides. These anomalies may occur with ENSO (as discussed in the previous section) or large storm events and can result in elevated water levels.

An extreme value analysis (EVA) of the water level record from 1969 to 2023 was undertaken to estimate extreme water levels at various return intervals. The data was fit to a Gumbel distribution and the analysis was undertaken for two separate time periods: 1) the full data record (1969 to 2023), and 2) the past 30 years (1993 to 2023). The results are presented below in Table 2-3. The extreme water levels estimated include storm surge associated with typhoon activity and may not accurately represent storm surge associated with individual storms. Further analysis of typhoon conditions is provided in Section 2.8. The annual extreme water level for both time periods is well aligned; however, the 1993 to 2023 estimates are more conservative, increasing with the return period. The 100-year extreme water level estimates for both time periods display a difference of approximately 0.6 feet.

Table 2-3 Extreme Water Level Estimates for Yap

Return Period (years)	Annual Exceedance Probability	Water Level (ft, MLLW)	
		1969-2023	1993-2023
100	1%	7.3	8.0
10	10%	6.0	6.4
2	50%	4.9	5.1
1	99%	3.8	3.8

*Values are shown relative to MLLW, which is referenced to the Station Datum

2.6.4 Sea Level Rise

SLR projections are provided in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC 2021) for a range of probabilistic scenarios. The IPCC presents SLR scenarios for five Shared Socioeconomic Pathways (SSPs), which represent various greenhouse gas emission futures, and are provided for low (SSP1-1.9) to high (SSP5-8.5) greenhouse gas emissions. SLR projections for Yap are

not available; therefore, the representative station for which SLR projections are provided is Palau (Malakal). The probabilistic SLR are presented below in Figure 2-10 and Table 2-4.

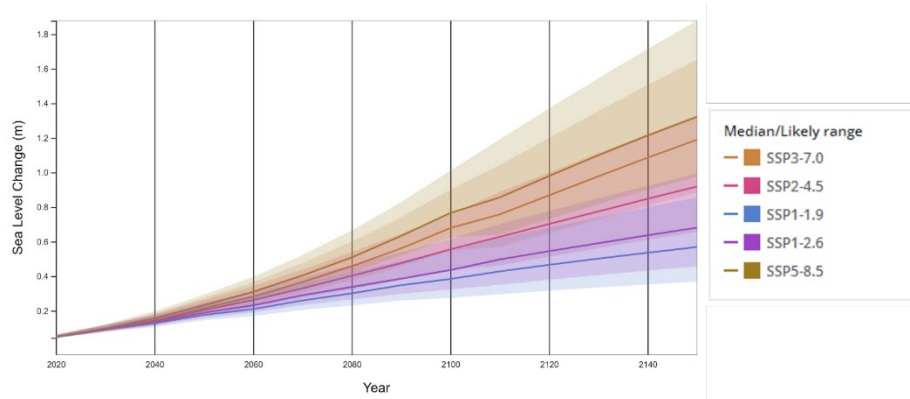


Figure 2-10 SLR Projections for Palau (IPCC 2021)

Table 2-4 50th Percentile SLR Projections for Palau (IPCC 2021)

Year	Sea Level Rise (ft)				
	SSP 1-1.9	SSP 1-2.6	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5
2030	0.30	0.30	0.31	0.31	0.32
2050	0.58	0.62	0.67	0.71	0.76
2070	0.85	0.95	1.08	1.20	1.33
2100	1.26	1.43	1.82	2.23	2.51

2.7 Wind Speed and Direction

2.7.1 Ambient Wind

Wind data was extracted from the Yap International Airport (Sta. FMW00040308), covering a 71-year timespan of 1952 to 2023 (NOAA NCEI 2001). This station is located approximately 4 miles southwest of the wharf at an elevation of approximately 44 feet. The predominant wind direction is from the east and north-east with the majority of wind speeds ranging between 10 to 15 knots (Figure 2-11). The summer and fall months generate more winds from the westerly direction, with the largest wind speeds, consistent with typhoon season (June to November). The winter and spring months generate more easterly and north-easterly winds, primarily ranging from 5 to 15 knots.

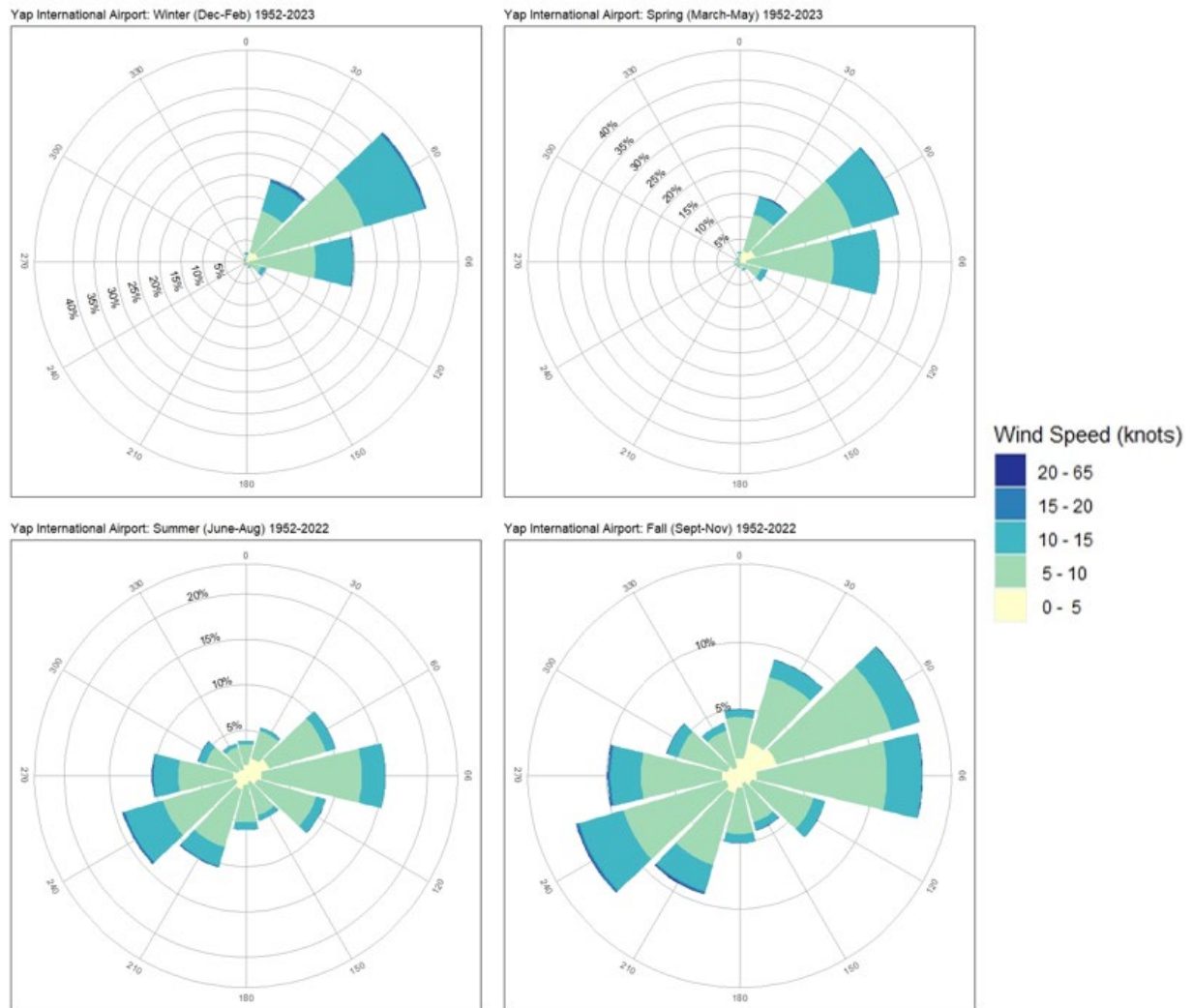


Figure 2-11 Seasonal Wind Roses for Yap International Airport (1952-2023)

Table 2-5 Frequency of 10-Minute Wind Speed and Direction for Yap International Airport (1996-2023)

		Wind Speed (knots)				
		0 – 5	5 – 10	10 – 15	15 – 20	20-65
Wind Direction (degree)	0	0.8%	1.9%	0.4%	0.0%	0.0%
	30	2.4%	6.8%	3.3%	0.3%	0.1%
	60	3.0%	16.5%	7.5%	0.3%	0.0%
	90	1.3%	14.1%	6.2%	0.1%	0.0%
	120	0.7%	4.8%	1.1%	0.0%	0.0%
	150	0.4%	2.3%	0.5%	0.0%	0.0%
	180	0.5%	2.1%	0.4%	0.0%	0.0%
	210	0.8%	3.0%	1.1%	0.1%	0.0%
	240	0.6%	4.1%	1.9%	0.1%	0.0%
	270	0.7%	3.1%	1.2%	0.1%	0.0%
	300	0.5%	2.0%	0.5%	0.0%	0.0%
	330	0.4%	1.5%	0.3%	0.0%	0.0%

2.7.2 Extreme Winds

To evaluate extreme wind events, hourly wind data spanning from 1952 to 2023 was subjected to an EVA. The EVA approach consisted of extracting the annual maxima and fitting the data to a Gumbel distribution. This is a common approach when estimating the probability distribution of extreme events. Additionally, it was necessary to evaluate the impact of data gaps prior to 1993, thus the EVA was undertaken for the entirety of the dataset (1952 to 2023) and for the last 30 years (1993 to 2023). The omnidirectional EVA results are presented below in Table 2-6 for various return periods and exceedance probabilities. The extreme wind speeds for both time periods examined are relatively well aligned through the 50-year return period. At the 100-year return period there is a 1.3-knot difference and a 2.6-knot difference at the 500-year return period.

Table 2-6 Omnidirectional Extreme Wind Speed Estimates for Yap

Return Period (years)	Annual Exceedance Probability	Wind Speed (knots)	
		1952-2023	1993-2023
10	10%	36.4	35.9
20	5%	40.5	40.6
50	2%	45.9	46.7
100	1%	49.9	51.2
500	0.2%	59.2	61.8

A directional EVA was also undertaken to examine the extreme wind speeds for various wind directions. The results are presented below in Table 2-7. This analysis revealed that the highest wind speeds are generated from the north to northeast (0-60 degrees) and south to southeast. The wind direction with the highest 100-year and 500-year wind speeds was north (0 degrees), being 56.8 knots and 69.1 knots, respectively.

Table 2-7 Directional Extreme Wind Estimates for Yap International Airport (1993-2023)

Return Period (years)	Wind Speed (knots) and Direction (degree)											
	0	30	60	90	120	150	180	210	240	270	300	330

10	39.0	34.1	34.3	25.6	27.2	31.8	27.6	30.2	29.1	31.2	22.3	24.8
20	44.4	39.1	38.5	27.5	30.2	36.7	31.0	34.2	32.3	35.3	24.3	27.7
50	51.5	45.6	44.0	30.0	34.2	43.0	35.5	39.3	36.4	40.6	26.8	31.5
100	56.8	50.4	48.1	31.9	37.2	47.8	38.9	43.1	39.5	44.6	28.8	34.4
500	69.1	61.6	57.6	36.2	44.1	58.7	46.7	51.9	46.7	53.8	33.3	41.0

2.8 Current Direction and Magnitude

Currents within Tamil Harbor are largely driven by tides; however, wind can also drive surface currents. Hydrodynamic conditions close to the port and in the entrance channel are assessed through the use of a numerical model and measured data, detailed in Section 4.

2.9 Waves Height, Period, and Direction

2.9.1 Wind Waves

Wind waves typically contribute to sea state, which is the term applied to steep, short-period waves generated either from local storms, strong pressure gradients, or from the diurnal sea breezes. Wind waves within Tamil Harbor and the approach channel will be fetch limited due to the shallow fringing reef, which protects the inner Island waters from deepwater swell. The characterization of wave conditions inside of the fringing reef is assessed using a numerical model, as detailed in Section 6, and through collection of measured data, described in Section 3.

2.9.2 Swell Waves

Swell waves originate many hundreds of miles away in the Pacific Ocean. To evaluate the potential propagation of these waves into Tamil Harbor and also around the entrance channel, a 30-year offshore wave hindcast for Yap was downloaded from Waves and Coasts of the Pacific (WACOP) (Bosserele et al. 2015). The hindcast station is located offshore of the southeast Yap coastline. From the wave hindcast, the predominant wave direction is from the east with wave heights ranging from calm to approximately 10 feet (3 m) (Figure 2-12). The impact of offshore swell wave propagation into the channel is analyzed through numerical modelling, detailed in Section 4.2.2.

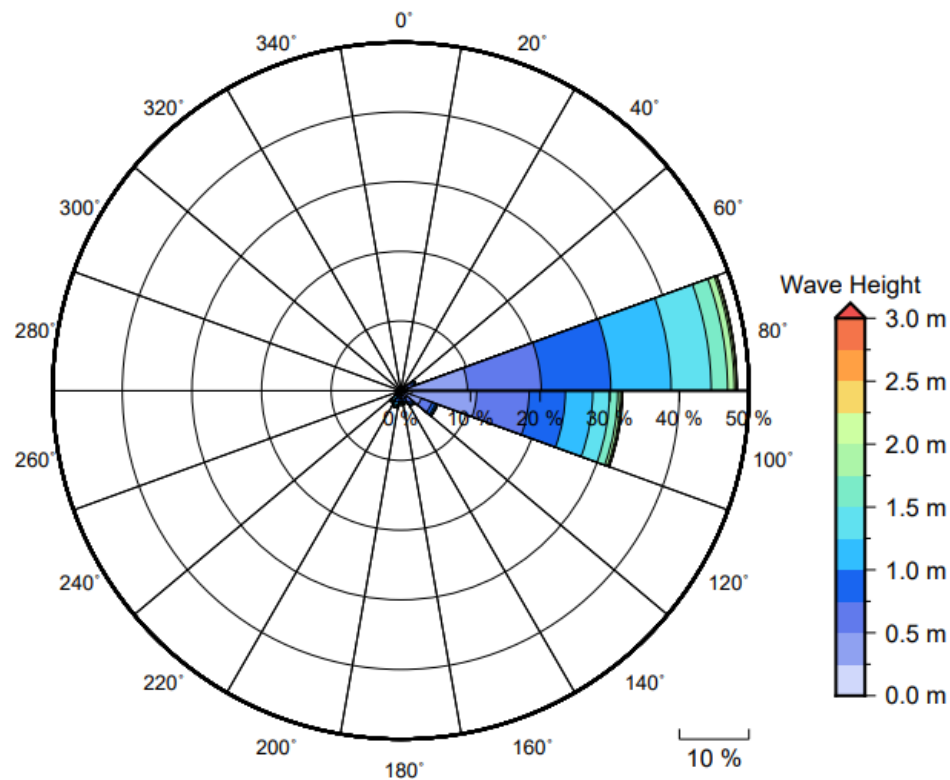


Figure 2-12 Wave Rose for Yap (Bossierelle et al. 2015)

2.10 Sediment Transport

While there are limited available studies on sediment transport within the harbor, based on the bathymetric surveys and the seabed (limestone and coral), sediment transport is expected to be low. Visual and below water inspection indicates low to very low turbidity, which is also an indicator of sediment load in the water (suspended sediment) and, therefore, low potential for transport. Exceptions include where sediment is introduced into the harbor and surrounding waters, such as deposition of materials around the wastewater treatment facility and/or end of the Colonia peninsula. Additionally, there is evidence of sediment build-up along the face of the existing Yap wharf. Further site investigation is needed to confirm the source of this sediment and, therefore, the likelihood of further deposition.

2.11 Typhoon and Storm Conditions

The location of Yap Island in the north Pacific Ocean exposes the project site to frequent extreme typhoon events. Historical records of extreme storm events were queried through the Historical Hurricane Track database maintained by the NOAA (NOAA OCM n.d.). All storms passing within a 150-mile radius of the project site were filtered for further examination. Since 1947, there have been a total of 127 named tropical storms and typhoons that have passed within a 150-mile radius of the project site (Figure 2-13).

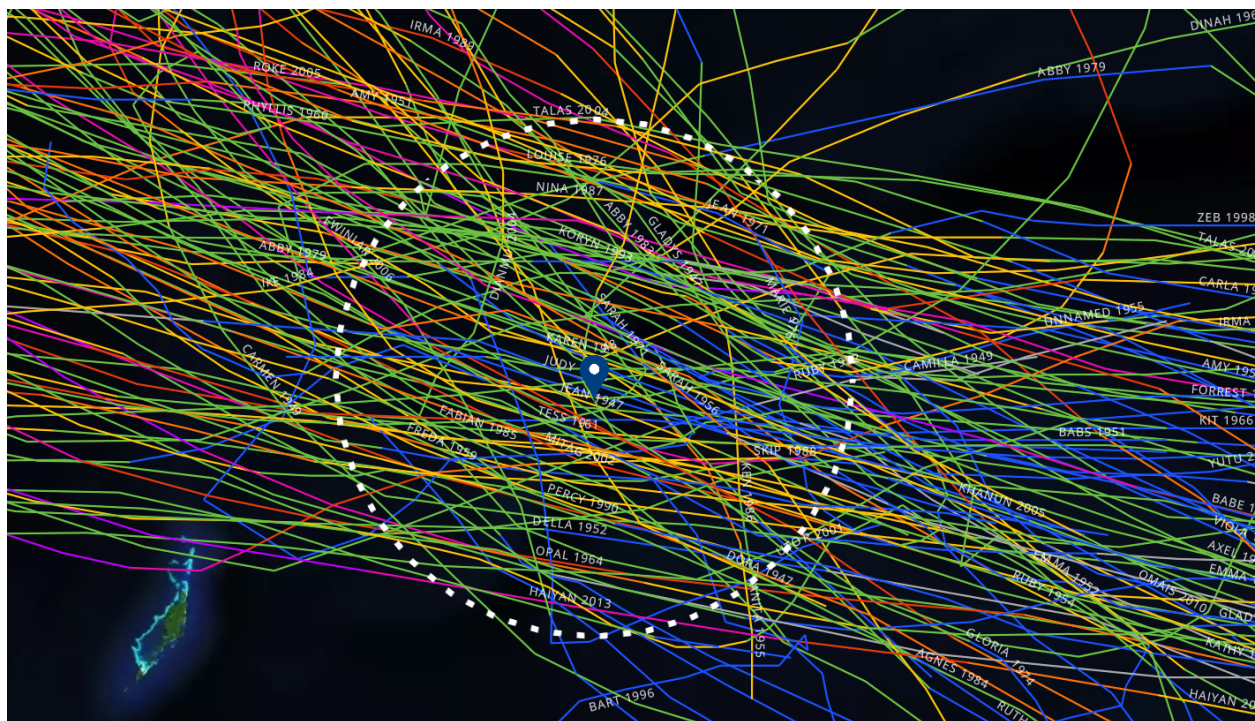


Figure 2-13 All Named Tropical Storms and Typhoons Passing the Project Site

2.11.1 Distribution of Storm Intensities

The 127 storms displayed graphically in Figure 2-13 were further investigated to characterize the intensity of the storms while in the vicinity of the Island of Yap. International Best Track Archive for Climate Stewardship (IBTrACS) data was downloaded from the NOAA National Centers for Environmental Information (NCEI) (Knapp et al. 2010; Knapp et al. 2018). The IBTrACS data contains information on the storm's wind speed, pressure, structure, and trajectory among other various observations.

The data was sorted and filtered to isolate the wind speed observations captured within the 150-mile radius of the project site. The breakdown by Saffir-Simpson storm classification based on maximum sustained wind speed is presented in Table 2-8.

Table 2-8 Distribution of Storm Intensities

Classification	Wind Speed Range	Storm Count	Percentage
Tropical Storm	35-64 knots	60	47.2%
Category 1	64-82 knots	29	22.8%
Category 2	83-95 knots	13	10.2%
Category 3	96-113 knots	8	6.3%
Category 4	114-135 knots	8	6.3%
Category 5	>135 knots	4	3.1%
No valid wind data*		5	3.9%
Total:		127	100%

*Storms that contained invalid or blank IBTrACS wind speed data.

The majority of passing storms are within the Tropical Storm wind speed intensity limits while passing within 150 miles of Yap Island. Major typhoons (classified as Category 3 or higher) compose just over 15% of the total passing typhoon events since 1947. The most severe storms in terms of sustained winds were Typhoons Haiyan and Maysak occurring in 2013 and 2015, respectively. Both storms recorded 150-knot sustained wind speeds while passing Yap Island. A summary tabulation of the four Category 5 typhoons is provided in Table 2-9 below.

Table 2-9 Category 5 Typhoons Passing Yap Island

Typhoon Name	Year of Occurrence	Maximum Recorded Wind Speed
Maysak	2015	150
Haiyan	2013	150
Ophelia	1958	140
Wilma	1952	140

2.11.2 Typhoon Surge Severity

A useful metric to examine while evaluating the severity of extreme coastal storm events is the magnitude of the storm surge. The water level records presented in Section 2.4 near the project site were queried to investigate the storm surge induced by passing storms. Only storm events from 1970 forward were included due to limitations of the water level period of record. The maximum water surface elevation was extracted for each storm event while it was passing in proximity to the site. A summary table of the top 10 most severe named storms with respect to storm surge is provided in Table 2-10 below.

Table 2-10 Measured Storm Surge by Storm Event

Name of Storm	Year	Maximum Water Surface Elevation	
		Meters (MHHW)	Feet (MHHW)
Sudal	2004	1.45	4.76
Mitag	2002	1.08	3.54
Hagupit	2014	0.80	2.62
Haiyan	2013	0.79	2.59
Nancy	1970	0.61	2.00
Vera	1979	0.58	1.90
Haima	2016	0.44	1.44
Ike	1984	0.44	1.44
Utor	2001	0.33	1.08
Zeb	1998	0.33	1.08

Typhoon Sudal in 2004 caused the highest water level captured in the approximately 53-year record at the UHSLC Yap station (Caldwell et al. 2015). Many reports consider this storm to be one of the most severe to ever impact Yap. Typhoon trajectory, path, and linger duration relation to land and hemisphere of occurrence can significantly influence the resulting storm surge that is observed. This is evident in the case of Typhoon Maysak, which occurred in 2015 and passed Yap as a Category 5 storm but did not produce a significant enough surge signal to be included in Table 2-10. Typhoon Mysak passed to the north of Yap causing widespread wind damage and surge on the north and western shorelines of the island but did not produce a significant surge effect near the project area. The most dramatic water surface elevations at the project site generally occur alongside storms that pass to the south of Yap.

2.11.3 Tropical Storm Trajectory

The impact of a tropical typhoon is influenced by the storm's trajectory relative to the landmass or site of interest. To coincide with water level measurements, all storms from 1970 forward were assigned a geographic position (e.g., north, south, etc.) while passing Yap to quantify the predominant passing direction of historical events and to examine if this influences the resulting surge. A summary table of these events based on storm center location while passing Yap is provided in Table 2-11 below.

Table 2-11 Storm Trajectory Counts

Storm Position while Passing Yap	Storm Count	Percentage
North	19	30.6%
Northeast	19	30.6%
South	11	17.7%
Southeast	1	1.6%
Southwest	12	19.4%
Total:	62	100%

Storms passing Yap are split between the northern and southern sectors in roughly a 60/40 fashion. To visualize any difference in surge effects inside of the harbor that could be attributed to the passing storm position, box and whisker plots of the maximum storm surge grouped by passing position is presented in Figure 2-14 below.

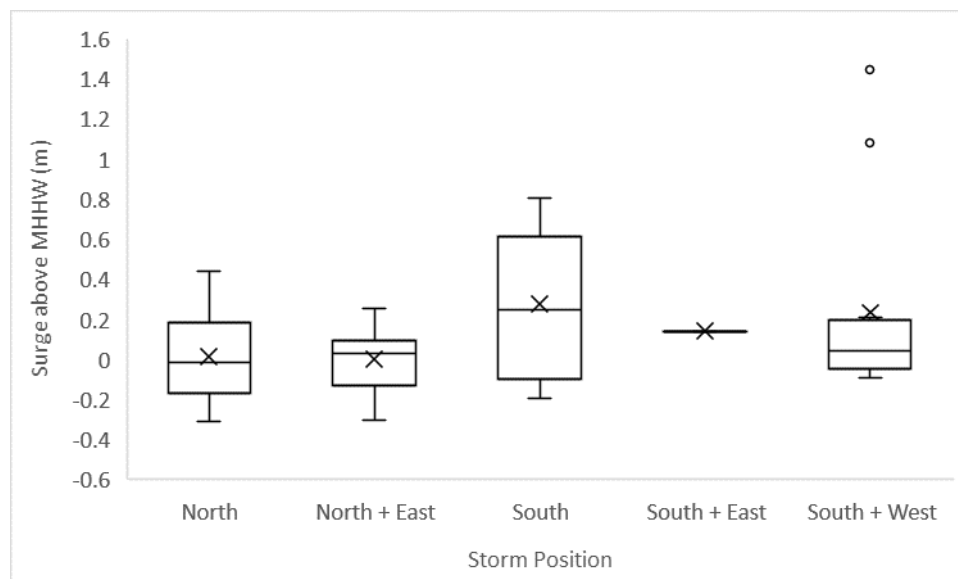


Figure 2-14 Storm Intensity by Passing Position

Storms passing in the southern sectors of Yap compose the maximum surges within the water level period of record. The mean surges for storms passing to the north are smaller in magnitude than storms that pass to the south of the island.

The impact of specific typhoon conditions on Tamil Harbor, the port, and the entrance approach is explored further through numerical modeling, detailed in Section 5.

2.12 Tsunami Hazard

Tsunamis are long-period waves generated when significant volumes of ocean water are abruptly displaced due to various events. The force of gravity then acts to restore the displaced water to its original equilibrium position, resulting in the propagation of a wave that can travel vast distances radially from the source. Tsunamis most commonly result from large earthquakes beneath the ocean floor. These seismic events cause sudden movements of massive rock slabs, displacing a significant volume of water above them. Less frequently, tsunamis can be triggered by volcanic explosions or submarine landslides.

Tsunamis carry a significant amount of energy and can transport it over vast distances travelling at speeds up to 250 meters per second. As these waves approach shallow water, they tend to shoal resulting in a substantial increase in height which can penetrate inland for hundreds of meters or even kilometers, causing property damage and human casualties. Coastal areas are particularly exposed to this hazard with recent events in Japan and the Pacific Islands highlighting their potential destructiveness.

2.12.1 General hazard description

As the westernmost state of the FSM, Yap faces a variety of threats that render it highly vulnerable. Situated in an area known as 'Typhoon Alley', Yap is prone to disturbances from earthquakes, tsunamis, and droughts due to the impact of the ENSO. Being close to both the Yap Trench and the Mariana Trench, Yap State is particularly susceptible to seismic activity, with four significant earthquakes recorded in recent times. Although there have been no documented instances of significant tsunami damage, the state's predominantly low-lying terrain would likely result in substantial harm in the event of a tsunami. (McNamara, S., & Stitz, C., 2010).

ThinkHazard!, a web-based tool developed by the Global Facility for Disaster Reduction and Recovery (GFDRR), classifies the FSM's tsunami hazard level as medium (Think Hazard, n.d.). This designation suggests that there is approximately a 10% probability of a potentially damaging tsunami occurring within the next 50 years (equivalent to a return period of ~500 years).

Yap's vulnerability to tsunamis is closely tied to its physical geography and bathymetry. The main Yap Island group includes four large and several smaller, high volcanic islands surrounded by flatlands and a fringing reef. Mangrove forests are also widespread, covering about 10% of the total land area of the island. These flatlands, fringing reefs, and mangrove forests serve as a natural buffer against direct wave impact, mitigating the immediate threat posed by tsunamis. However, despite this natural defense, the site's proximity to the Yap and Philippine Trench remains a significant concern. Moreover, the deep ocean surrounding the site provides an unimpeded pathway for the rapid transmission of tsunami waves.

2.12.2 Tsunami Observations in Yap

Tsunami records from NCEI were also searched for tsunamigenic events and runups. The Global Historical Tsunami Database encompasses tsunami events from 2000 B.C. to 2024. Development in instrumental seismology in the 1960s allowed more precise capturing of seismological events. This is why there are more seismic events recorded during the latter years of the data, and not because seismic activity has increased from the 1960's.

Events occurring within Yap were extracted from the NCEI database and presented in Figure 2-15. There were 14 observed runups in the NCEI database for this area. It should be noted that the first three records in 1912 and 1925 are only based on eyewitness anecdotes, while subsequent records are based on tide gauge measurements at Yap Island. Details of each tsunami observation are tabulated below in Table 2-12

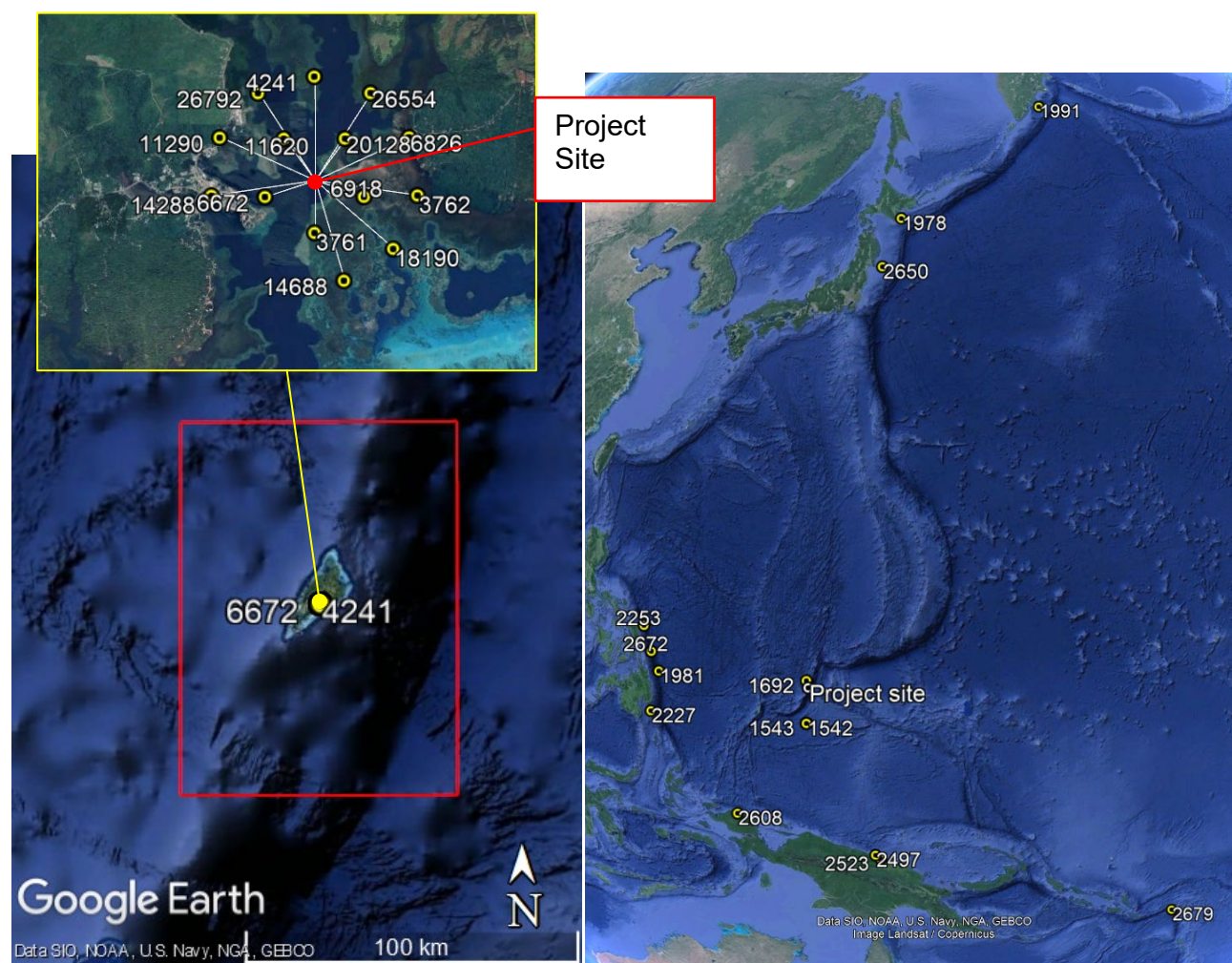


Figure 2-15 NCEI Database Tsunami Observation at Yap (left) and Corresponding Tsunamigenic Sources (right)

Table 2-12 Tsunami Observations at Yap and its Source Location

Year	Obs. ID	Location	Water Height (m)	Distance From Source (km)	Tsunami Source Location	Source ID	Earthquake Magnitude, M_i
1912	3761	Yap Island ¹	No data	278.8	Caroline Islands	1542	6.9
1912	3762	Yap Island	No data	NaN	Yap Island	1543	NaN
1925	4241	Yap Island	No data	55.4	Caroline Islands	1692	NaN
1952	6672	Yap Island	0.1	3658.9	SE. Hokkaido, Japan	1978	8.1
1952	6826	Yap Island	0.04	1194.9	E. of Mindanao, Philippines	1981	7.8
1952	6918	Yap Island	0.1	5186.5	Kamchatka, Russia	1991	9
1972	11290	Yap Island	0.09	1314.3	Mindanao, Philippines	2227	7.4
1975	11620	Yap Island	0.06	1367.9	Philippine Trench	2253	7.6
1998	14288	Yap Island	0.02	1463.6	Papua New Guinea	2497	7
2002	14688	Yap Island	0.03	1510.2	Bismarck Sea	2523	7.6
2009	18190	Yap Island	0.04	1242.7	North coast of Indonesia	2608	7.6
2011	20128	Yap Island	0.2	3216.2	Honshu, Japan	2650	9.1

Year	Obs. ID	Location	Water Height (m)	Distance From Source (km)	Tsunami Source Location	Source ID	Earthquake Magnitude, M_1
2012	26554	Yap Island	0.02	1267.7	Philippines	2672	7.6
2013	26792	Yap Island	0.02	3735.9	Santa Cruz, Philippines	2679	7.9

¹ Recorded at the following coordinates: (9.517°, 138.133°)

Among the tsunami observations, the highest water height was 0.2 m. The distance of the tsunami observations ranged from 55 km to as far as 5,186 km. Only one value was recorded for the arrival hours of a maximum tsunami wave, 11 hours from event 2650 (Honshu, Japan). This indicates that tsunami observations have so far originated several hours away before reaching Yap. Among the 14 tsunami observations, three originated from the Yap Trench, four from the Philippines, three from Papua New Guinea, one from the Solomon Islands, two from Japan, and one from Russia as also shown in Figure 2-15.

The farthest source was Event 1991, which occurred in the Kamchatka Peninsula in the Russian Far East. The nearest source was Event 1692, which is just the Yap Trench. Lastly, the highest tsunami observation of 0.2 m was from Event 2650, the infamous 2011 Tōhoku 9.1 magnitude earthquake that caused a maximum water height of 39.26 m in Japan. However, the observed tsunami amplitude at Yap Harbor was just 0.2 m arriving 11 hours after the initial earthquake.

2.12.3 Probabilistic Tsunami Hazard Assessment

To quantify tsunami risks within Southwest Pacific Nations, Thomas and Burbidge (2009) performed a probabilistic tsunami hazard assessment considering major plate boundaries surrounding the Pacific Ocean. These sources not only include proximate sources like the Philippine Trench, New Guinea Trench, and Yap Trench, but also Transpacific sources such as the Cascadia Trough, Middle America Trench, etc.

The study finds that the maximum amplitude at Yap ranges from 1.8 m (5.9 feet) to 2.6 m (8.5 feet) for a 2000-year return period event. The study also performed de-aggregation to identify the weighted contribution of each source to the estimated tsunami amplitudes as shown in Figure 2-16. From the figure, it is envisaged that 2000-yr RP tsunami events will likely originate from earthquakes occurring across several regions, including the Philippines Trench, the southern part of the Mariana Trench, and the New Guinea Trench. This seems to be consistent with historical records showing earthquakes originating from the Philippine Trench, Papua New Guinea, and Japan, as the predominant source of tsunami observations at Yap.

Additionally, Thomas and Burbidge (2009) also generated return period curves at the different output points shown in Figure 2-16.

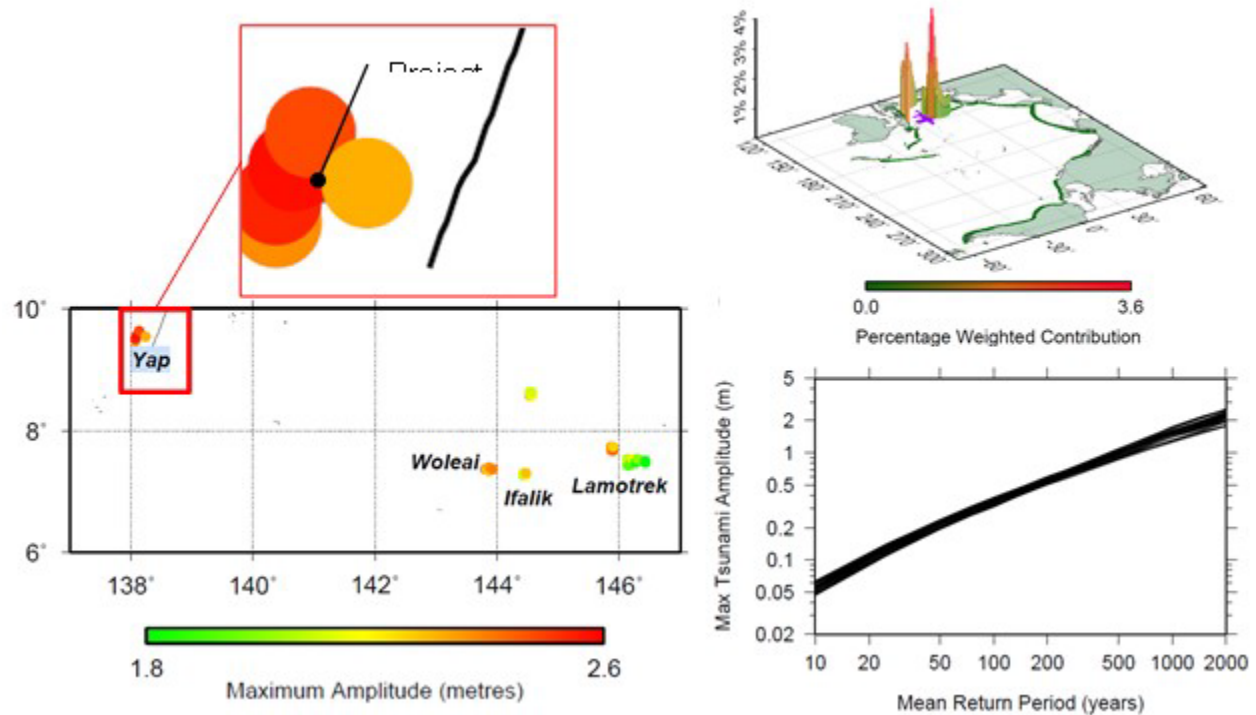


Figure 2-16 Model extraction points and maximum amplitudes at Yap - top-pan, Tsunami hazard sources for Yap for 2000-yr return period – lower left pan, Hazard curves of output points across Yap - lower right (excerpt from Thomas & Burbidge, 2009)

2.12.4 Summary

Several sources of information related to tsunami hazards in Yap were reviewed, including historical databases and relevant literature. A summary of the tsunami related information from different sources are presented in Table 2-13, including estimates of tsunami amplitude from Thomas and Burbidge (2009) and maximum observed tsunami amplitude from the NCEI database.

Table 2-13 Estimated Tsunami Amplitudes at Various Return Periods

Data Source	Est. RP (yr)	Est. tsunami amplitude (m)	Remarks
Thomas and Burbidge (2009)	10	0.05 – 0.06	Model output points are located in areas where water depth is at least 50-100m. Actual tsunami amplitude at the wharf will likely be different from this “offshore” value as the tsunami waveform transforms as it approaches shallow water and as it is affected by local site geography.
	20	0.09 – 0.12	
	50	0.19 – 0.24	
	100	0.3 – 0.4	
	200	0.5 – 0.6	
	500	0.9 – 1.1	
	1000	1.3 – 1.8	
	2000	1.6 – 2.6	
NCEI database (max observed)	-	0.2	Max observed tsunami amplitude at the Yap tide gauge recorded during the 2011 Tohoku Earthquake in Japan. Estimated record length of 54 yrs (1970-2023)
ThinkHazard!	-	-	Classified Yap as having medium tsunami risk, suggesting an approximately 10% probability of potentially damaging tsunami occurring within the next 50 years.

3 FIELD DATA COLLECTION

Due to the complex nature of the waters surrounding the Port of Yap, the fringing reef, and shallow flats, it is challenging to predict the oceanographic conditions under a range of scenarios from ambient to storm/typhoon. The collection of field data, specifically wave and current direction and magnitude, allows the characterization of the oceanographic conditions. Since data can only be collected in a relatively short time frame (unlike the record lengths described in Section 2), numerical models (described in Sections 4 and 5) are used to predict conditions outside of the data collection time period. The field data is used to validate the numerical models, greatly increasing confidence in the modeled results.

The main objective of the instrument deployment is to collect wave and current data in the vicinity of Yap Port. Three instruments were deployed at the port area: one surface buoy to measure waves (Sofar Spotter buoy) and two Nortek acoustic doppler current profilers (ADCPs) placed on the seafloor that measure currents throughout the water column as well as waves. The measurement period is 12 months, with interim data retrieval at 3 months. In addition to the surface buoy and ADCPs, a boat-mounted ADCP, pointed downward, was used to measure currents along transects surveyed across the entrance channel.

3.1 Instruments

Three instruments were deployed at the port area: two Nortek ADCPs placed on the seafloor that measure both currents throughout the water column and waves, and one surface buoy to measure waves (Sofar Spotter buoy). The instruments were serviced at 3-month intervals to change batteries, download data, and clean housings and moorings. In addition, a vessel mounted ADCP conducted transects across the navigation channel to collect representative current velocities across the tidal regime.

The ADCPs were deployed approximately 100 to 150 m and 1 to 1.2 km offshore to the east of the wharf, water depths at the deployment sites were 20 to 30 m. The spotter buoy was deployed on the west side of the outer channel through the reef on a relatively flat portion of the reef between 10 to 20 m deep.

3.1.1 ADCP

ADCPs are marine instruments that use the Doppler Effect to measure water particle movement. The instruments emit acoustic beams, and acoustic backscatter from particulates in the water column is shifted to higher and lower frequencies depending on the relative motion of the particulates to the acoustic beams. By separating the backscatter return by time, different layers of the water column can be measured. For this study, 1-m vertical measurement bins are planned. In common with all transducer-generated acoustics, the acoustic beams have associated side lobe patterns. At the sea surface, reflections of the side lobes cause noise that contaminates the data. As a result, the top 6% of the water column is typically not useable data. Also, the acoustic measurement begins at 5 feet (1.5 m) above the instrument. ADCPs are also able to measure the surface wave conditions. The ADCPs used in this study are Nortek Signature500, which transmit at an acoustic frequency of 500 kHz and have a maximum range of approximately 70 m.

3.1.2 Spotter Buoy

Sofar's Spotter buoy is a small, solar-powered oceanographic sensing buoy that collects wave, wind, sea surface temperature, and barometric pressure data. Spotter buoys transmit data in real time via 24/7 satellite telemetry; data is also stored internally and is available for download upon retrieval. Spotter buoys have different data modes for parameter collection. Bulk wave statistics may be recorded and reported based on a 30-minute sampling interval. A wave partition mode allows the spotter to calculate bulk wave

statistics and sea/swell partition data based on a 1-hour sample period, or spotter buoys may be configured to transmit the variance density spectrum and directional moments as a function of frequency every 6 hours based on a 60-minute sampling period.

3.1.3 Boat Mounted ADCP

The boat-mounted current meter was a Teledyne ADCP (Sentinel V50 or Workhorse Monitor 300 kHz). The operating frequencies were 500 kHz and 300 kHz with accuracies $\pm 0.3-0.5\%$. The ADCPs were equipped with a bottom-tracking module. Bottom tracking measures speed-over-ground in marine applications by using long acoustic pulses scattered by the bottom. The bottom tracking mode provides greater measurement accuracies because the ADCP measures both the water motion and its own motion in the same reference frame defined by its five acoustic beams.

3.2 Data Collection

3.2.1 Deployment Summary

Two ADCPs and one spotter buoy was deployed in the channel shown in Figure 3-1 and Figure 3-2, for 3-month durations. One ADCP was placed a next to the pier and is referred to as the “Pierside” location, while another was placed in the turning basin, referred to as the “Turning Basin” location. A summary of the deployments including the locations, depth and deployment dates in shown in Table 3-1. A summary of the data collected for each location and deployment will be summarized in the following subsections.

Table 3-1 ADCP Deployment Log

	Deployment Date	Recovery Date	Latitude	Longitude	Depth, m
Pierside Deployment 1	1/12/2024	4/19/2024	9° 30' 54.3129" N	138° 7' 37.559" E	22.9
Pierside Deployment 2	4/22/2024	8/26/2024	9° 30' 54.3129" N	138° 7' 37.559" E	22.9
Pierside Deployment 3	8/27/2024	1/7/2025	9° 30' 54.32" N	138° 7' 37.57" E	24.0
Pierside Deployment 4	1/12/2025	5/14/2025	9° 30' 54.32" N	138° 7' 37.57" E	24.0
Turning Basin Deployment 1	1/12/2024	4/19/2024	09° 30' 59.95" N	138° 7' 56.82" E	31.9
Turning Basin Deployment 2	4/22/2024	8/26/2024	09° 30' 59.95" N	138° 7' 56.82" E	31.9
Turning Basin Deployment 3	8/27/2024	1/7/2025	09° 30' 59.95" N	138° 7' 56.82" E	33.0
Turning Basin Deployment 4	1/12/2025	5/14/2025	09° 30' 59.95" N	138° 7' 56.82" E	33.0
Spotter Buoy	1/12/2024	4/19/2024	9° 29' 59.28" N	138° 7' 57.43" E	30.5
Spotter Buoy	4/22/2024	8/26/2024	9° 29' 59.28" N	138° 7' 57.43" E	30.5
Spotter Buoy	8/27/2024	1/7/2025	9° 29' 59.28" N	138° 7' 57.43" E	30.5
Spotter Buoy	1/12/2025	5/14/2025	9° 29' 59.28" N	138° 7' 57.43" E	30.5



Figure 3-1 ADCP deployment locations.



Figure 3-2 Location of the Spotter Buoy

It should be noted that due to the short-wave periods observed, the data is outside of the directional limits for both the ADCPs and surface spotter buoy. Directionality for current data was also not well resolved due to the depth and low current magnitudes. This data is described in further detail in the following sections.

3.2.1.1 Deployment 1

Data retrieved from the first deployment covered a complete time period of 1/12/2024 to 4/19/2024. Due to technical issues with the instrumentation, the boat mounted ADCP data was not able to be processed and, therefore, is not included in Deployment 1.

Currents

The currents measured during the first deployment for both the pierside and turning basin locations are averaged over the whole water column. Observed current velocities were fairly low at both locations, less than 0.16 m/s (0.3 knots). The pierside location had slightly higher current speeds, but was still representative of a calm environment. It is important to note that this data collection period did not capture any extreme events. The mean and maximum current speeds averaged over the water column are summarized in Table 3-2.

Table 3-2 Mean and Maximum Currents Measured at the Pierside and Turning Basin Locations – First Deployment

Pierside		Turning Basin	
Mean (m)	Max (m/s)	Mean (m)	Max (m/s)
0.01	0.06	0.03	0.16

Waves

The ADCP wave data from the first pierside and turning basin deployment is summarized in Figure 3-3. The pierside location reported slightly higher waves heights than that of the turning basin. At the pierside location, the majority of the wave heights were below 0.2 m, but occasional larger waves above 0.4 m were observed. The wave periods mostly stayed between 1-2 seconds, indicating that they were localized wind generated waves, or wind chop. At the turning basin site, the majority of the wave heights were 0.1 m with occasional larger waves, but still below approximately 0.4 m. Similar to the pierside site, wave periods were low and ranged from 1-2 seconds, again indicating locally generated wind waves.

The spotter buoy site was more exposed the ocean waves, and the wave height shown in Figure 3-3 reflects that. Wave heights remain small, generally below 0.3 m. The periods, however, reflect the greater exposure to swell, as mean periods ranged from 2 to 5 seconds. Overall, the spotter buoy reflected the largest wave heights.

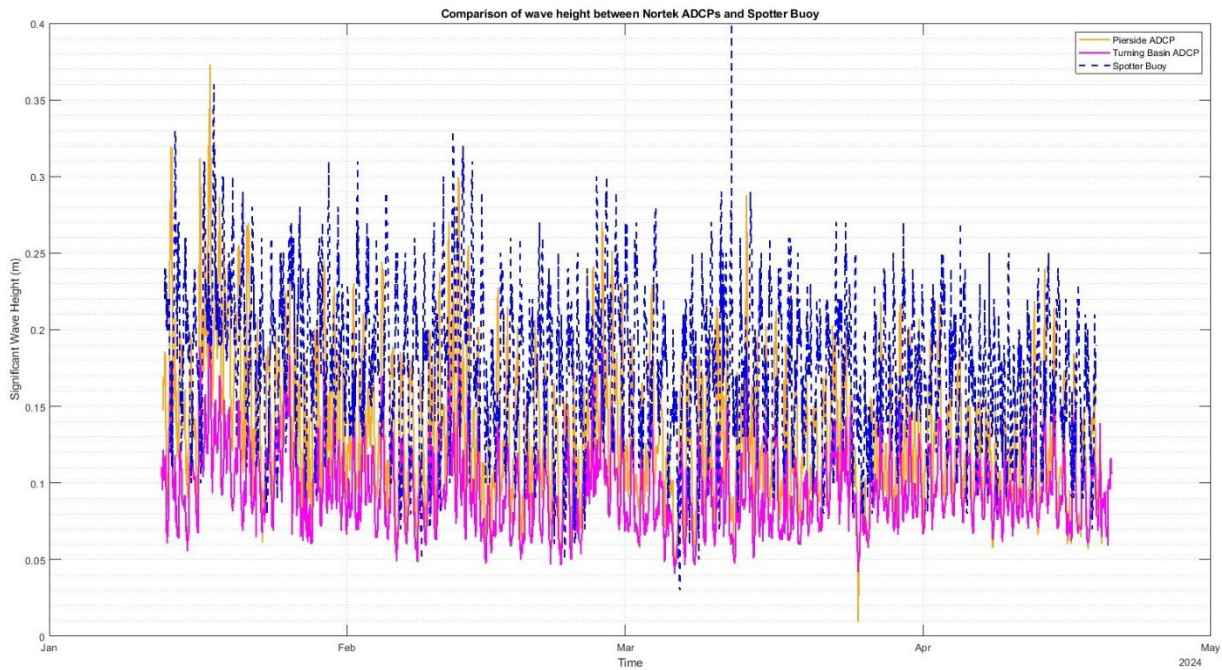


Figure 3-3. Turning Basin, Pierside, and Spotter Bouy Significant Wave Height

3.2.1.2 Deployment 2

Data retrieved from the first deployment covered a complete time period of 4/22/2024 to 8/26/2024. ADCP 1 was relocated to the outer channel and ADCP 2 (Figure 3-4) was deployed in the same location within the Turning Basin. The purpose of the instrument relocation was to better define site conditions and increase confidence in model results.

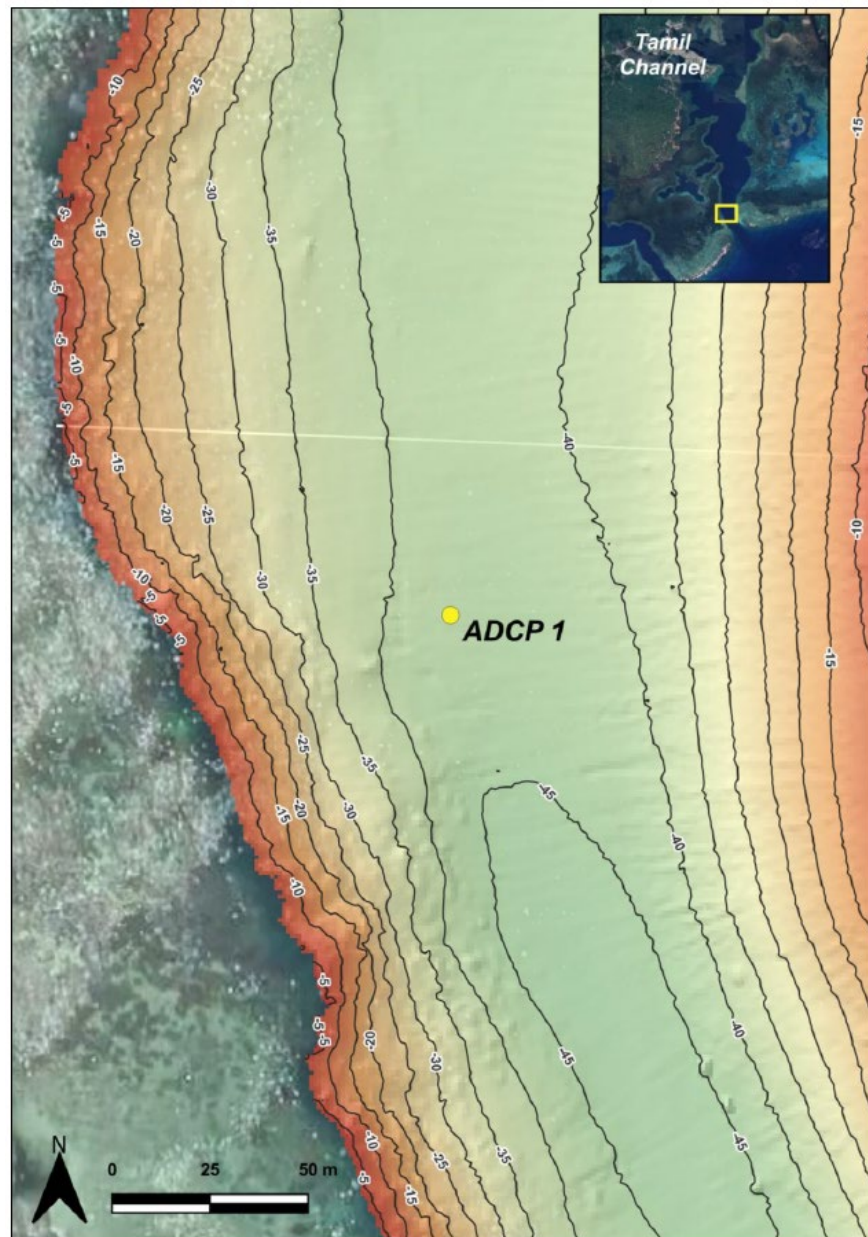


Figure 3-4. ADCP 1 Deployment 2 Location

At ADCP 1, the current speeds in the channel reached a maximum of 0.11 m/s (0.21 knots), while the average current speed for the deployment duration was 0.012 m/s (0.02 knots). Speeds in the turning basin reached a maximum of 0.28 m/s (0.54 knots), with the average current speed for the deployment being 0.021 m/s (0.04 knots). This data is summarized below in Table 3-3.

Table 3-3. Mean and Maximum Currents Measured at ADCP 1 and ADCP 2

Channel (ADCP 1)		Turning Basin (ADCP 2)	
Mean (m/s)	Max (m/s)	Mean (m/s)	Max (m/s)
0.01	0.11	0.02	0.28

Wave data recorded at the ADCP's and spotter buoy indicates that the wave climate in the area is calm. At ADCP 1, the average Hs for the deployment period was 0.080 m, with an average Tp of 1.88 s. The maximum Hs recorded was 0.27 m at 1.94 s. At ADCP 2, the average Hs for the deployment period was 0.07 m, with an average Tp of 2.4 s. The maximum Hs recorded was 0.24 m at 1.80 s. The maximum significant wave height at the Spotter buoy was 0.25 m with an associated peak period of 1.5 s and direction of 235 degrees. The average significant wave height recorded from January to August was 0.09 m. This data is summarized below in Table 3-4.

Table 3-4. Mean and Maximum Wave Heights Measured at ADCP 1, ADCP 2, and Spotter Buoy

Channel (ADCP 1)		Turning Basin (ADCP 2)		Spotter	
Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)
0.08	0.27	0.07	0.24	0.09	0.25

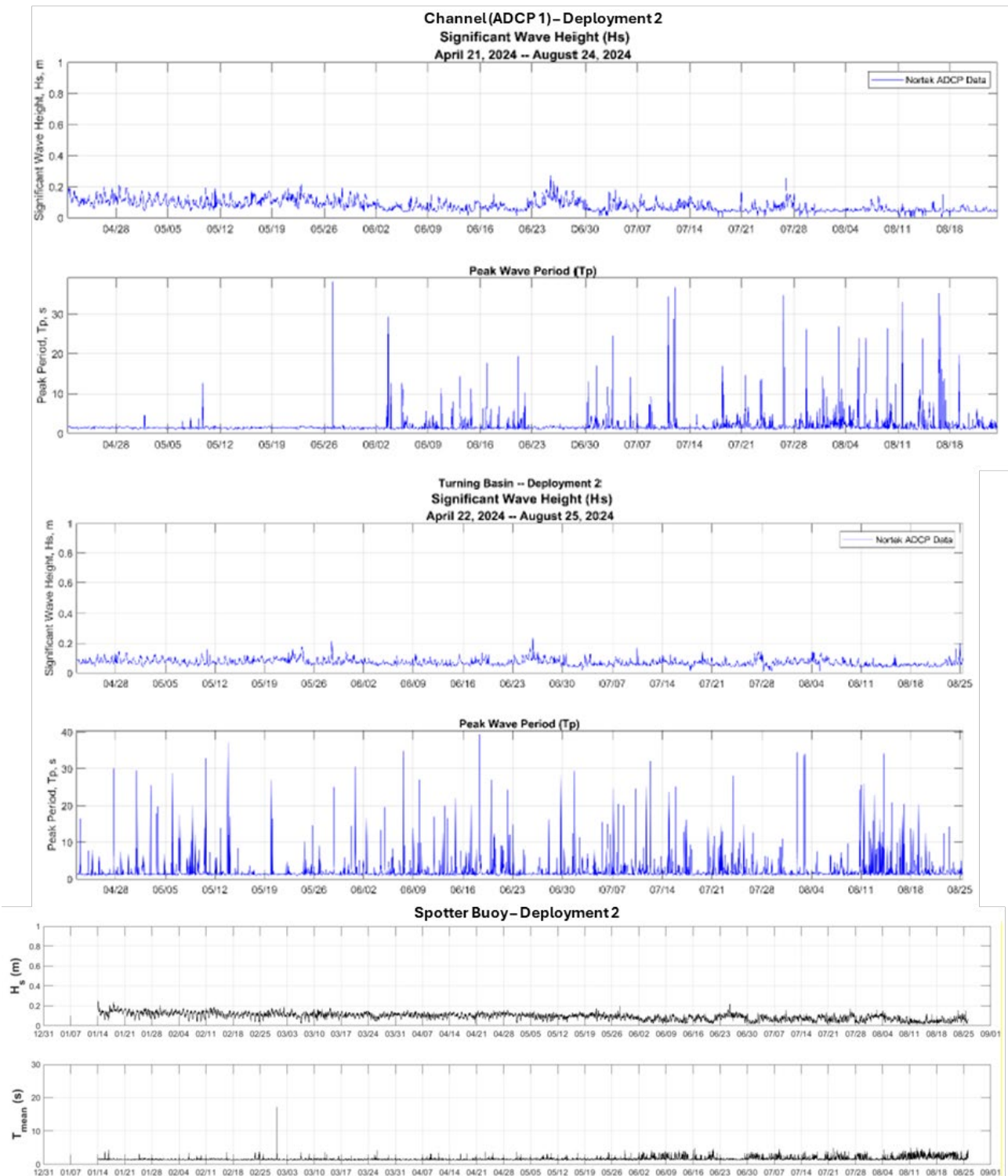


Figure 3-5. Deployment 2 - Wave height and period for ADCP 1 (top), ADCP 2 (middle), and Spotter Buoy (bottom)

3.2.1.3 Deployment 3

Data retrieved from the first deployment covered a complete time period of 8/27/2024 to 1/7/2025. The instruments were deployed in approximately the same locations as deployment 2. At ADCP 1 the typical speeds were 0.1-0.2 m/s with peak speeds being 0.3-0.4 m/s, rarely exceeding 0.4 m/s. The average current speed (depth averaged) was 0.12 m/s (0.23 knots) with a maximum of 0.5 m/s (0.97 knots). At ADCP 2, generally less than 0.04 m/s. The current speeds in the turning basin reached a maximum of 0.11 m/s (0.21 knots), while the average current speed for the deployment duration was 0.03 m/s (0.06 knots). This data is summarized below in Table 3-5.

Table 3-5. Mean and Maximum Currents Measured at ADCP 1 and ADCP 2

Channel (ADCP 1)		Turning Basin (ADCP 2)	
Mean (m/s)	Max (m/s)	Mean (m/s)	Max (m/s)
0.12	0.50	0.03	0.11

At ADCP 1, the average Hs for the deployment period was 0.2 m, with an average Tp of 4.55 s. The maximum Hs recorded was 0.6 m at 5.2 s. At ADCP 2, the average Hs for the deployment period was consistent with deployment 2, being 0.07 m, with an average Tp of 2.4 s. The maximum Hs recorded was 0.21 m at 1.67 s. The maximum significant wave height at the Spotter buoy was 0.37 m with an associated peak period of 3.1 s. The average significant wave height recorded from January to August was 0.14 m. This data is summarized below in Table 3-6.

Table 3-6. Mean and Maximum Wave Heights Measured at ADCP 1, ADCP 2, and Spotter Buoy

Channel (ADCP 1)		Turning Basin (ADCP 2)		Spotter	
Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)
0.20	0.60	0.07	0.21	0.14	0.37

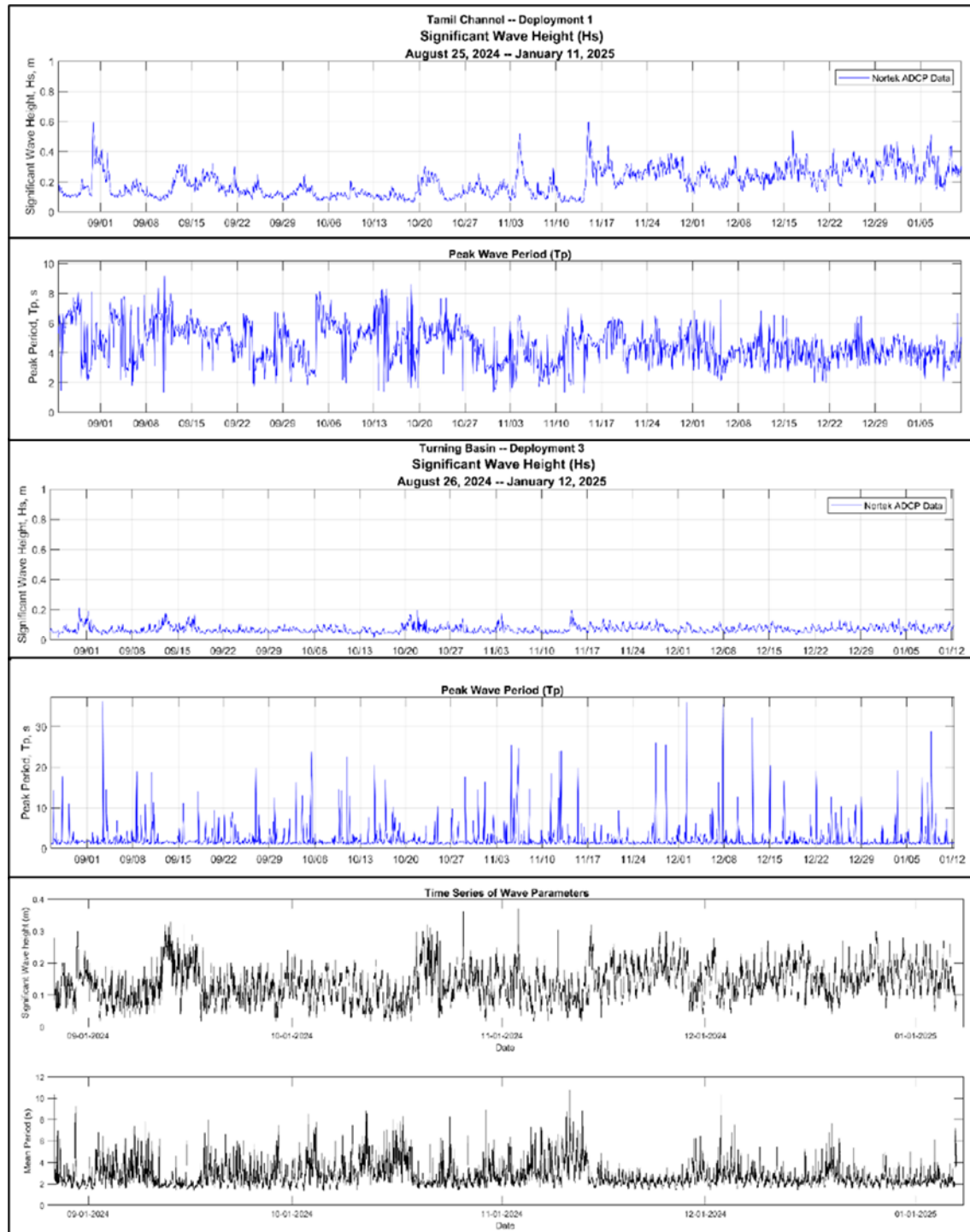


Figure 3-6. Deployment 3 - Significant wave height and period for ADCP 1 (top), ADCP 2 (middle), and spotter buoy (bottom)

3.2.1.4 Deployment 4

Data retrieved from the first deployment covered a complete time period of 1/12/2025 to 5/14/2025. The instruments were deployed in approximately the same locations as deployment 3. At ADCP 1 the typical speeds were 0.1 m/s with peak speeds being 0.2 m/s. The average current speed (depth averaged) was 0.11 m/s (0.2 knots) with a maximum of 0.42 m/s (0.8 knots). At ADCP 2, the current speeds were generally less than 0.04 m/s. The current speeds in the turning basin reached a maximum of 0.06 m/s (0.1 knots), while the average current speed for the deployment duration was 0.02 m/s (0.04 knots). This data is summarized below in Table 3-7.

Table 3-7. Mean and Maximum Currents Measured at ADCP 1 and ADCP 2

Channel (ADCP 1)		Turning Basin (ADCP 2)	
Mean (m/s)	Max (m/s)	Mean (m/s)	Max (m/s)
0.11	0.42	0.02	0.06

At ADCP 1, the average Hs for the deployment period was 0.28 m. The maximum Hs recorded was 0.7 m at 5.3 s. At ADCP 2, the average Hs for the deployment period was 0.08 m. The maximum Hs recorded was 0.2 m at 1.8 s. The maximum significant wave height at the Spotter buoy was 0.66 m with an associated average period of 25.6 s on February 12th, 2025. The average significant wave height recorded from January to August was 0.17 m. This data is summarized below in Table 3-8.

Table 3-8. Mean and Maximum Wave Heights Measured at ADCP 1, ADCP 2, and Spotter Buoy

Channel (ADCP 1)		Turning Basin (ADCP 2)		Spotter	
Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)
0.28	0.67	0.08	0.17	0.17	0.66

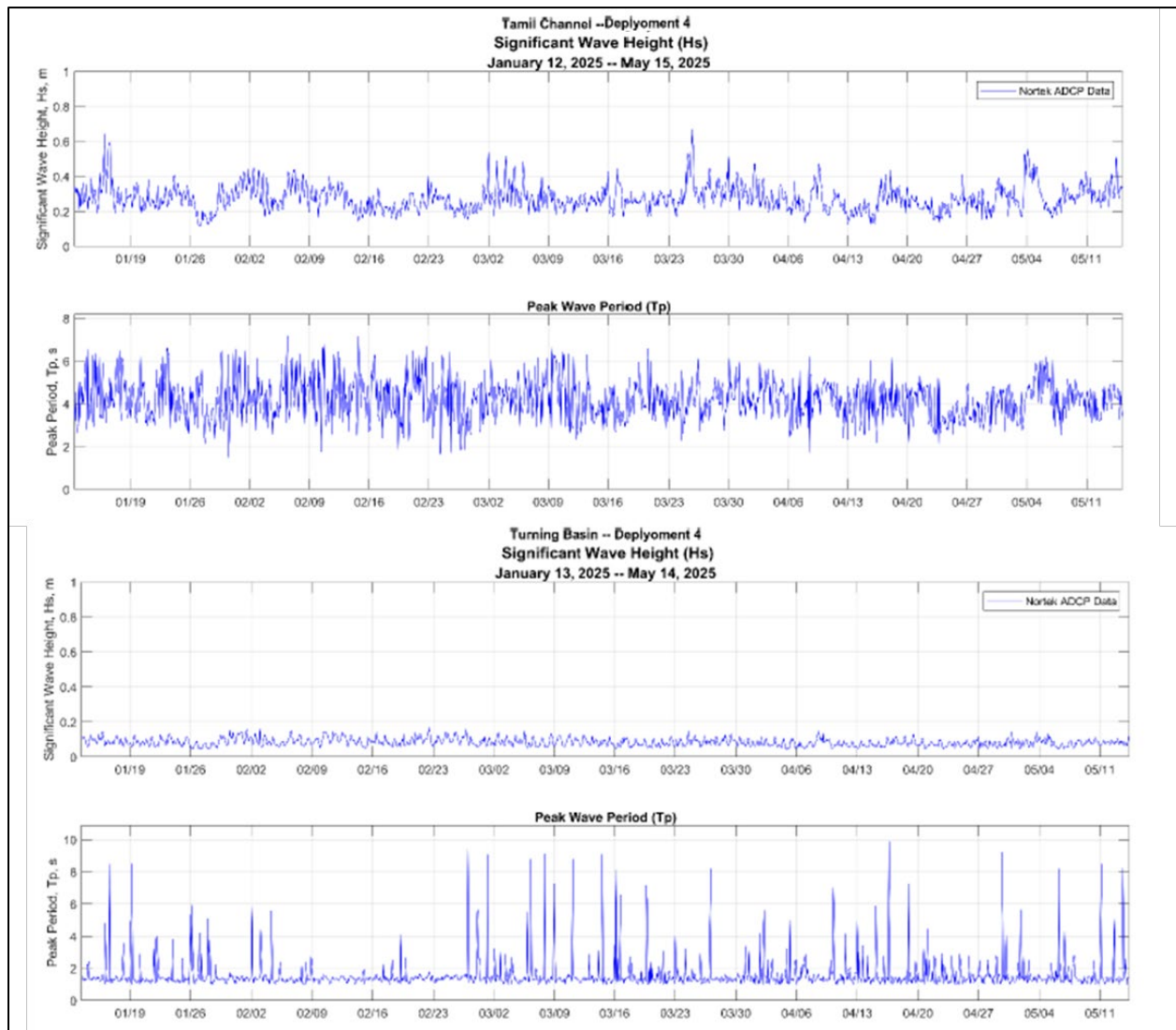


Figure 3-7. Deployment 4 - Significant wave height and period for ADCP 1 (top) and ADCP 2 (bottom)

4 HYDRODYNAMIC AND SPECTRAL WAVE NUMERICAL MODELING

Numerical modeling is used as a tool to characterize oceanographic conditions that are unknown to extend prediction of parameters where none exist or to extrapolate extreme values. For the Yap Channel Improvements, a coupled hydrodynamic (HD) and spectral wave (SW) model was developed to predict the ambient conditions and to define extreme conditions for the design of the wharf improvements.

4.1 Approach

An HD and SW model was developed to hindcast the ambient and extreme wave climate at the proposed project location. The modelling approach is outlined in Figure 4-1. The MIKE 21 Coupled Model Flow Model was deployed in this modelling exercise. The model is a dynamic modelling system for applications within coastal, estuarine, and river environments. Its primary components, the HD and the SW modules can simulate the mutual interaction between waves and currents through dynamic coupling (feedback).

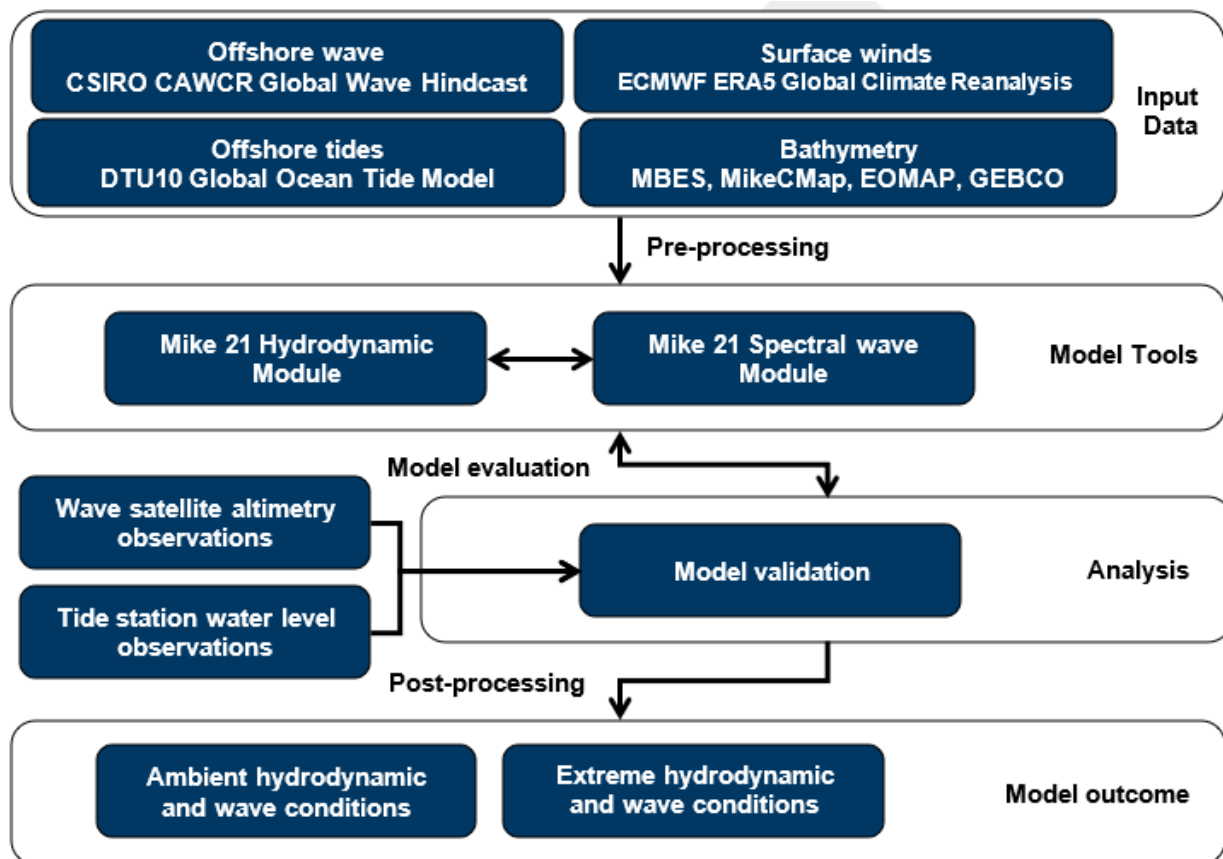


Figure 4-1 Modelling Flowchart

4.1.1 Model Domain

A flexible mesh domain was adopted covering the entire Yap Island, with finer mesh resolution (approximately 200 feet) at the location of Yap Port. The modelling domain is presented in Figure 4-2, together with a close-up at the vicinity of Yap Port.

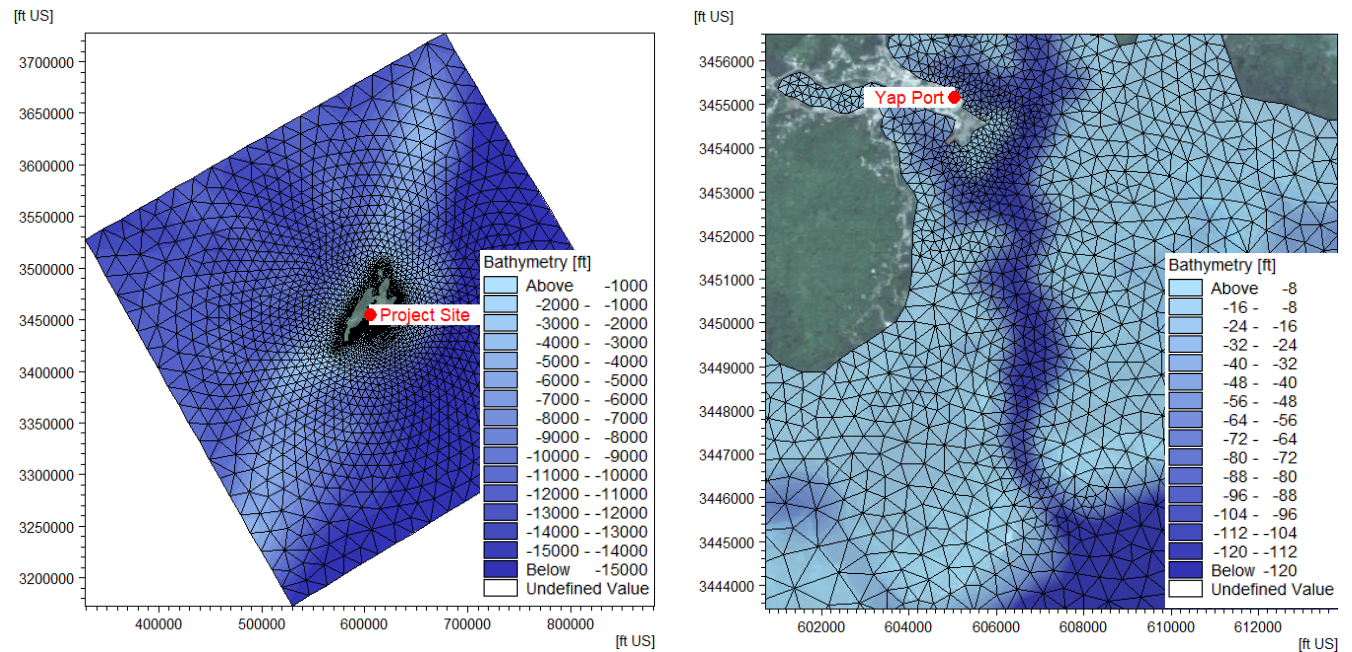


Figure 4-2 Modelling Domain (left) and Closeup at Yap Port (right) [datum: MLLW]

4.1.2 Representative Sample

To facilitate the simulation of ambient scenarios, a representative year based on 43 years of offshore wave information from the CSIRO CAWCR (Durrant et al. 2019) hindcast model was selected. It is time consuming and inefficient to run a numerical model for every possible scenario and year of hindcast data available. Therefore, representative years were selected from the offshore data to be used in the simulation. Figure 4-3 shows the location of the offshore extraction point for the representative years analysis.

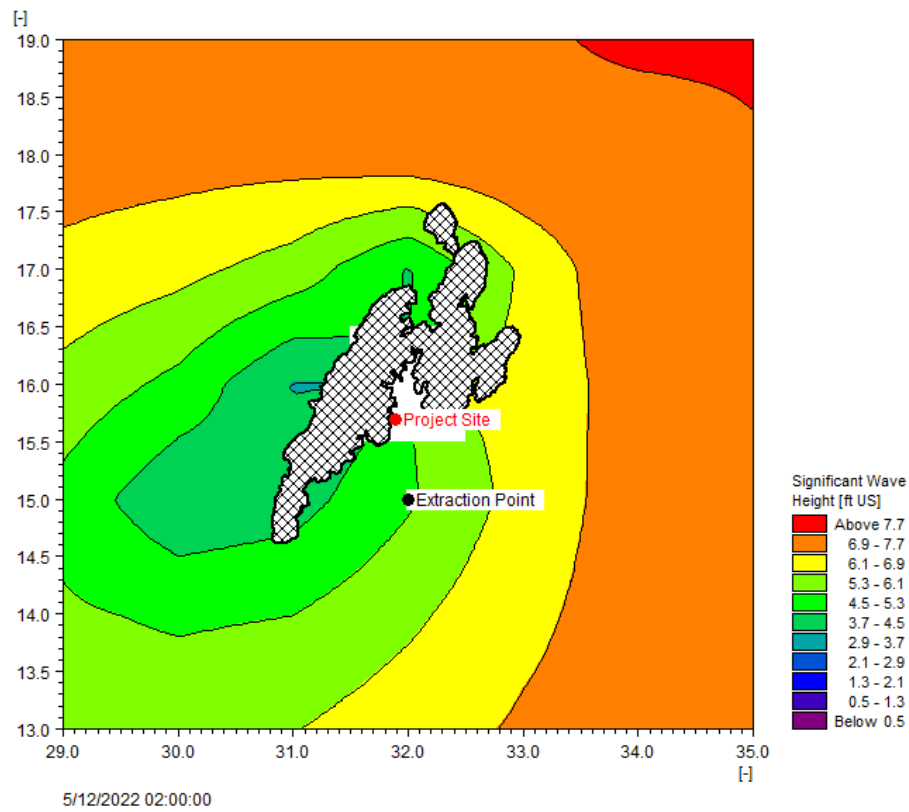


Figure 4-3 Offshore Extraction Point Location for Characterization of Representative Years

The selected representative years are 1990, 2011, and 2002, which describe the high wave, low wave, and average wave energy years, respectively. An ensemble of the wave frequency plots for the 43-year dataset is shown in Figure 4-4, overlain by the frequency plots for the selected representative years and the average of the dataset. Wave heights for the year 2002 closely match the dataset average, while wave heights for the years 2011 and 1990 tend to trend lower and higher than average, respectively. However, it is opted to select the year 2022 as the representative average year instead of 2002 due to data availability and abundance of satellite wave altimetry information, essential for model validation and confidence. Additionally, the year 2022 also has relatively small deviation from the modeled long-term average wave energy.

Water levels can also influence the wave conditions at Yap Port since a large fraction of waves are expected to break along the reefs protecting the harbor. In this regard, the ENSO classification of the selected years was also identified in the table. It was noted that the selected representative year of 2022 falls under the La Niña period, indicating higher than average water levels. This is expected to result in more wave penetration and more energetic wave climate at the port. Table 4-1 shows the wave energy power values at selected candidate years.

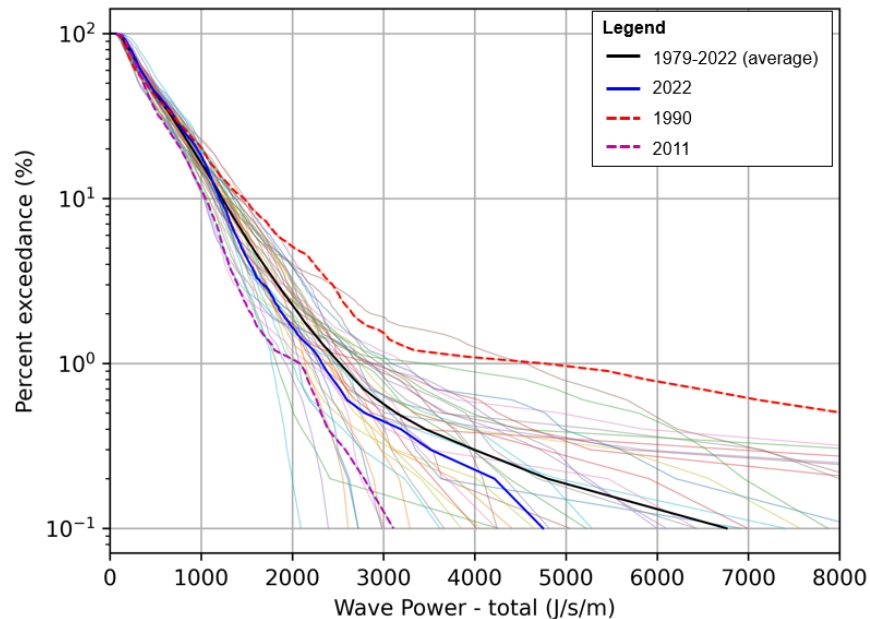


Figure 4-4 Percent Exceedance Plot for Waves at Extraction Point

Table 4-1 Annual Average Wave Power for Each Candidate Year Together with ENSO Classification

Year	Description	Average Wave Power, J/s/m	ENSO
2002	Average	606.6	El Niño
2022	Representative	600.9	La Niña
1990	High	718.9	Average / Transition
2011	Low	504.9	La Niña

To simulate the typical hydrodynamic and wave conditions at the site, the coupled HD+SW simulation for the whole duration of the selected representative year was performed. Table 4-2 summarizes the selected modelling scenario based on the selected representative year.

Table 4-2 Simulation Scenario for Ambient Conditions Modelling

Simulation	Model Ramp-Up Dates	Simulation Dates	Remarks
Representative year (2022)	2021/12/29 to 2021/12/31 (3 days)	2022/01/01 to 2022/12/31 (1 year)	1-year simulation of ambient hydrodynamic and wave conditions for the representative year. Frequency distribution of offshore wave energy expected to be close to the 43-year average. Water levels are expected to be higher than average (La Niña season). Simulation results were validated against significant wave heights derived from wave-satellite altimetry measurements and water levels observed from the tide station.

4.1.3 Boundary Conditions

Boundary conditions refer to the forcing conditions at the boundaries of the model domain. These can be water elevations, offshore wave conditions, winds, or other parameters for different types of numerical models. The boundary conditions adopted for the ambient year simulations are summarized in Table 4-3.

Table 4-3 Boundary Conditions for Ambient Condition Modelling

Parameter	Boundary Conditions
Tide	Tide levels extracted from 0.125° x 0.125° DTU10 Global Tide Model (Cheng & Andersen 2010) at the ocean boundaries of the modelling domain. Tide currents extracted from 0.25° x 0.25° DTU10 Global Tide Model at the ocean boundaries of the modelling domain.
Wave	Bimodal wave (wind and swell) time series extracted from the CSIRO CAWCR hindcast dataset at the ocean boundaries of the modelling domain.
Wind	2D wind field and mean sea level pressure time series extracted from the ERA5 reanalysis dataset applied to the entire modelling domain.

4.1.4 Bathymetry

Accurate bathymetry is essential for a numerical model, particularly in shallow areas. Due to the large area covered by the model, four different sources of bathymetry data were used.

- **GEBCO** – A coarse bathymetry data retrieved from the General Bathymetric Chart of the Oceans (GEBCO) with a resolution of 15 arc-seconds for the regional model.
- **Mike C-Map** – Seabed elevation data from digitized nautical charts.
- **MBES** – 2023 multi-beam bathymetric survey performed by Sea Engineering, Inc. (Site specific data collected for this Project).
- **EOMAP SDB** – Satellite-derived bathymetry (SDB) procured from EOMAP.

The different sources were collated and processed, ensuring that all sources have the same horizontal (WGS 84 / UTM Zone 54) and vertical (MLLW) datum. Figure 4-5 and Figure 4-6 illustrate the extent of the bathymetric data.

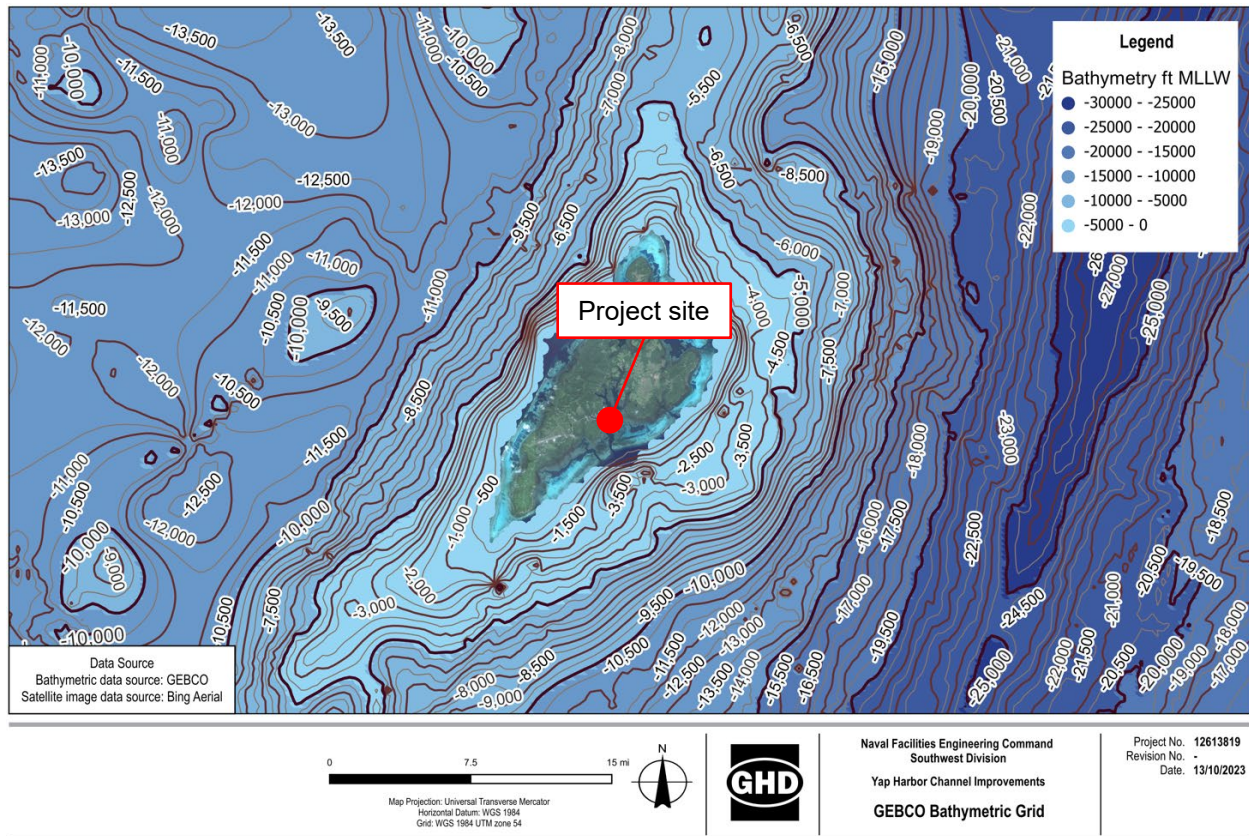


Figure 4-5 Offshore Bathymetry of Yap Island, Excerpt from GEBCO
 (horizontal datum: WGS 84 / UTM Zone 54, vertical datum: ft MLLW)

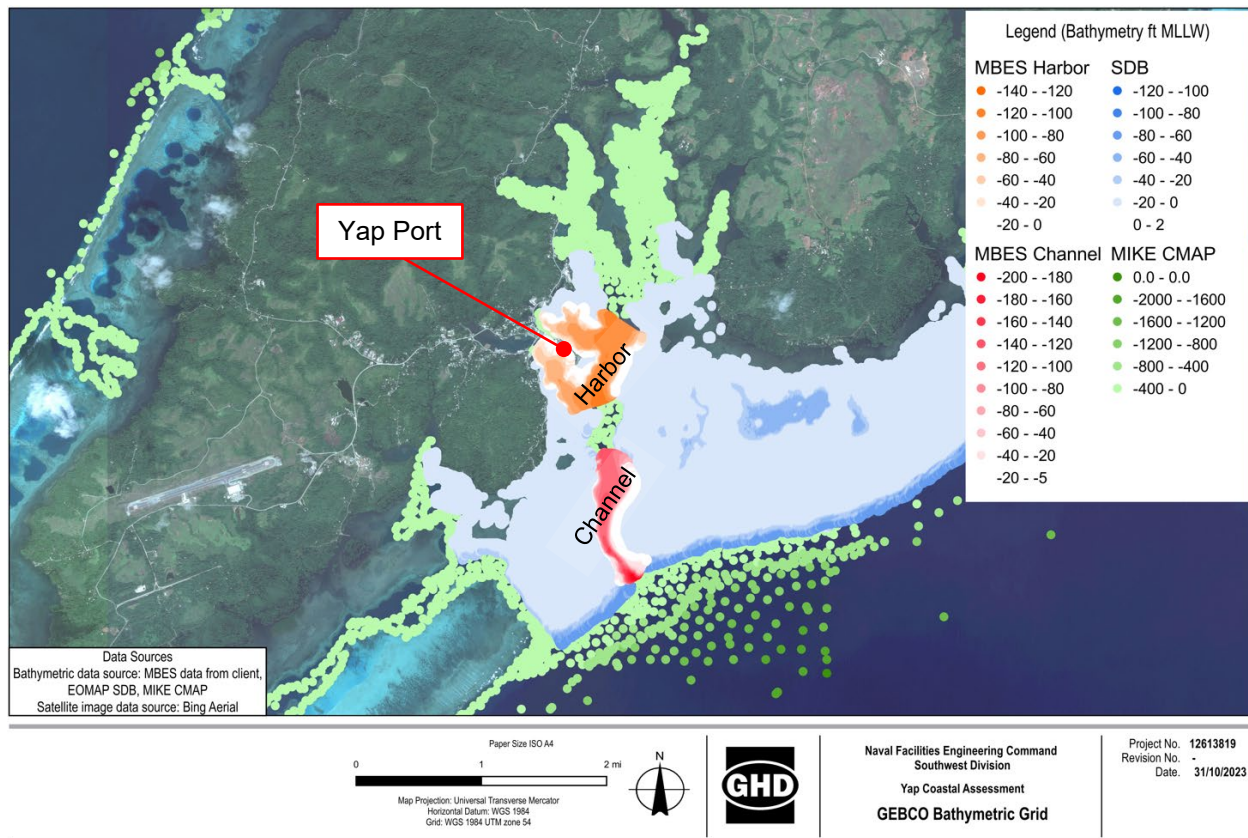


Figure 4-6 Additional Bathymetric Data Sources Closer to the Project Site, Consolidated to a Single Horizontal and Vertical Datum
(Horizontal datum: WGS 84 / UTM Zone 54, vertical datum: ft MLLW)

4.1.5 Model Validation

4.1.5.1 Statistical Metrics

Model validation was carried out against the quantitative indices summarized in Table 4-4. The validation compares the simulated results from the numerical models with the available actual measured data at the site. The validation focused on water levels and waves.

Table 4-4 Metrics for Evaluating Model Performance

Metric	Equations
Root Mean Squared Error (RMSE). An aggregate measure that includes both bias and dynamical behavior. It is often used as an overall measure of comparison.	$RMSE = \sqrt{\frac{\sum_{i=1}^n (O_i - P_i)^2}{n}}$
Mean Error (ME). The measure of general offset between measurements and simulated values. A positive value of ME denotes positive bias, meaning the simulated values tend to underestimate the variable and a negative value denotes overestimation.	$ME = \frac{\sum_{i=1}^n O_i - P_i}{n}$

Metric	Equations
Coefficient of Determination (R²). R ² is the square of Pearson's product-moment correlation coefficient ranging from 0 to 1 with larger values indicating a better fit.	$R^2 = \frac{[\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (P_i - \bar{P})^2}$
Coefficient of efficiency (NSE). NSE is a widely used metric in evaluating model performance. It ranges from negative infinity to 1 with larger values indicating a better fit.	$NSE = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$
Index of Agreement (IOA, d). The IOA is a measure of the average differences between predicted and observed values relative to the range of values in the observation dataset. It is bounded between the values of 0 and 1, with values close to 0 describing models with large relative differences (i.e., poor validation) and values close to 1 describing models with small relative differences (i.e., good validation). Willmott et al. (1985) suggest that IOA values that are meaningfully greater than 0.5 represent good model performance, with values approaching 1 representing excellent performance.	$IOA = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (P_i - \bar{O} + O_i - \bar{O})^2}$

4.1.5.2 Validation of Water Levels

Hourly water level observations collected from tide gauges were downloaded from the UHSLC Station Explorer to facilitate model validation through comparison between the modelled and observed surface elevations. Data processing of high-frequency tide gauge measurements automatically removes most sensor and transmission errors, converts the data into hourly observations, and chooses the best sensor gauge for each station (UHSLC Station Explorer 2023). The nearest available data on tidal planes is from Tide Gauge ID 008. Hourly water level data for the representative year was compared with the surface elevation recorded by the model at the tide station's location. This comparison is shown in Figure 4-7. The comparison result shows high R² value, which secures the reliability of the ambient model.

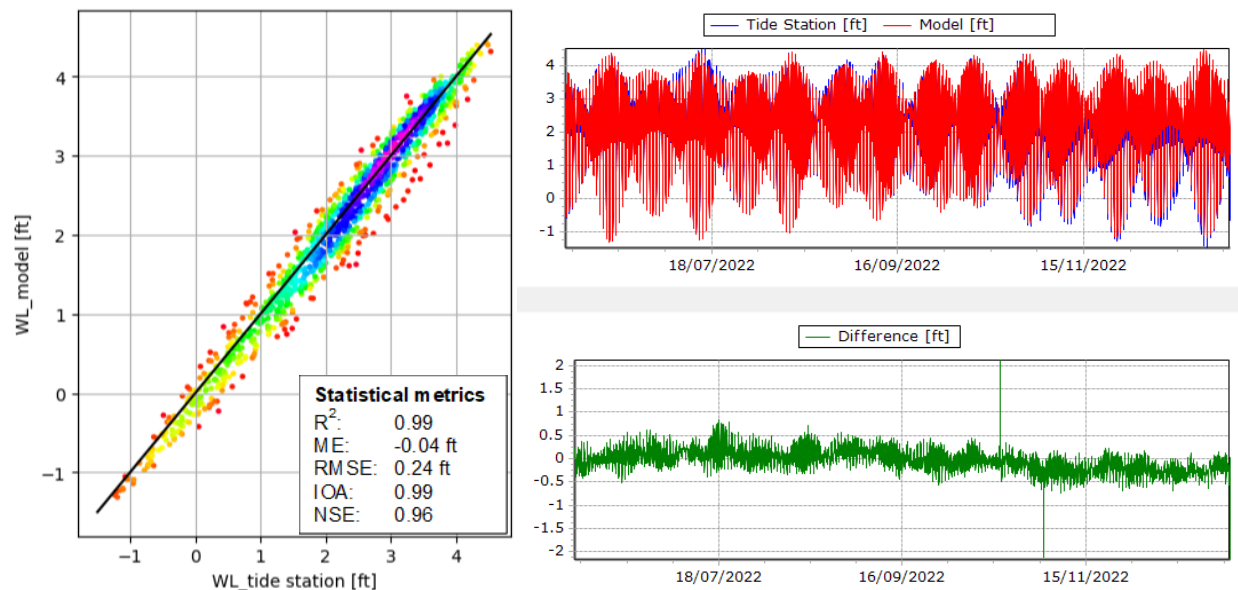


Figure 4-7 Model Validation Results – Water Levels at Tide Station Extraction Point for the Representative Year 2022

4.1.5.3 Validation of Offshore Wave Heights

Satellite wave altimetry observations were extracted from the CMEMS multi-year satellite wave products. Satellite data from SARAL-ALtiKa, Jason-3, CryoSAT-2, and CFOSAT missions were extracted for the

modelled validation timeframe. Resulting significant wave height values from the modelled representative year were validated by comparing these with the significant wave heights derived from the four satellite altimetry measurements. Figure 4-8 shows the satellite wave altimetry observation tracks with respect to the project site.

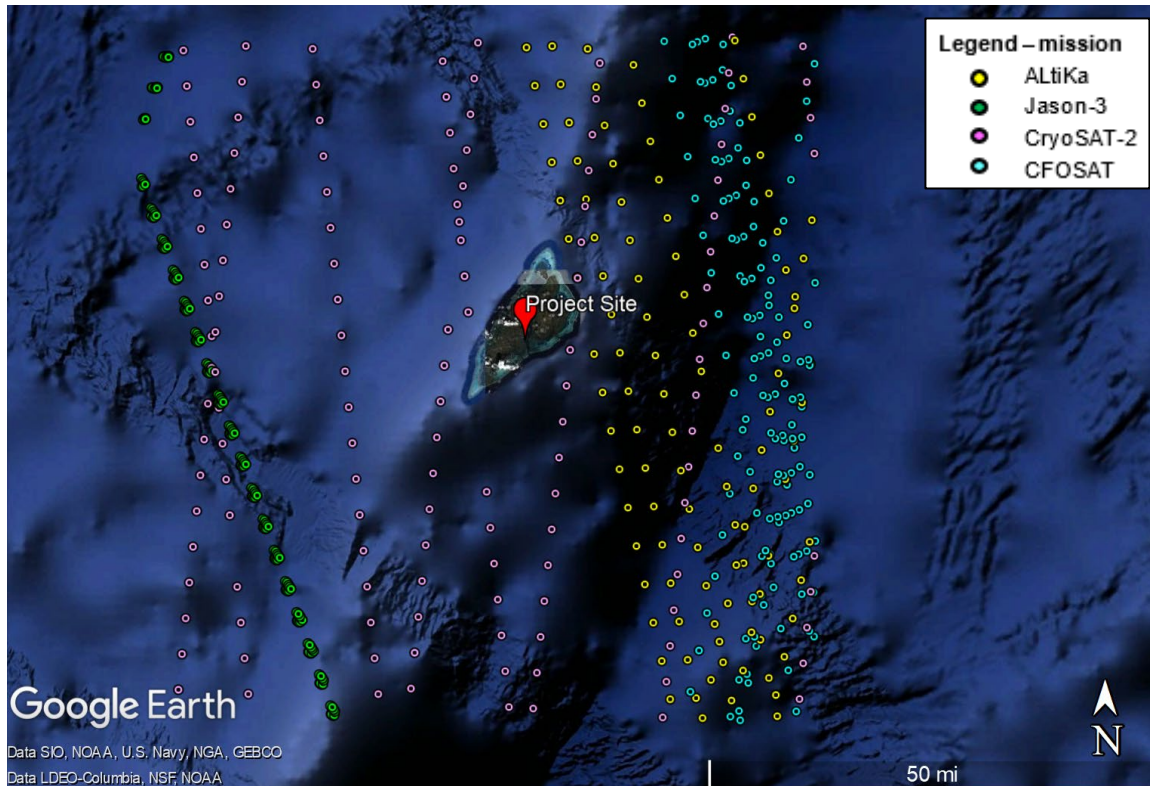


Figure 4-8 Satellite Image of the Site Vicinity Overlain by Wave Satellite Altimetry Observation Points

The comparison between modelled results and satellite observations are presented in Figure 4-9. The validation confirms the suitability of the numerical model, which achieved satisfactory R^2 , NSE, and IOA values against satellite observations for use in the evaluation of the Yap Channel Improvements Project.

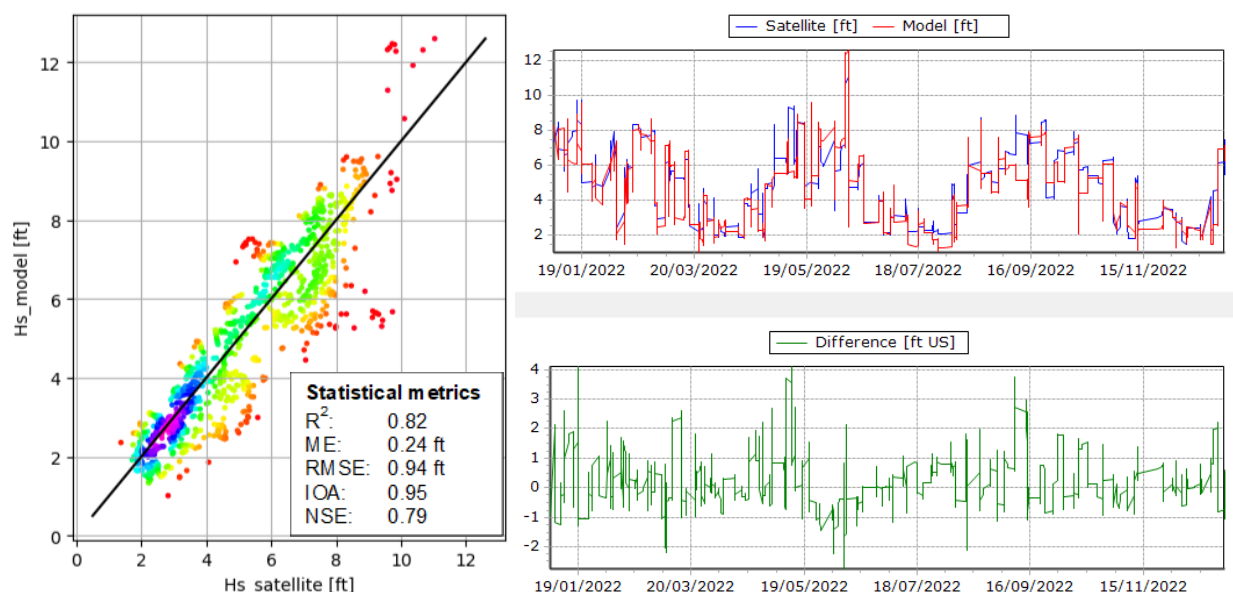


Figure 4-9 Model Validation Results – Offshore Significant Wave Heights for the Representative Year 2022

4.1.5.4 Validation of Nearshore Wave Heights and Currents

The results of the field data collection conducted by Sea Engineering was received June 2024. From here, the parameters obtained from the numerical model and measured field data were compared using the statistical metrics described above, as shown in Table 4-5.

Table 4-5 Comparison of Parameters Between the Average Values from the Model and Field Data Measurements

Measurement locations	Parameter	Index of Agreement	Average (model)	Average (measured)
Pierside	Hs	0.55	0.18	0.13
	Tp	0.23	1.49	1.5
	current speed	0.36	0.002	0.01
Turning Basin	Hs	0.4	0.14	0.1
	Tp	0.2	1.65	1.76
	current speed	0.37	0.01	0.03
Spotter Buoy	Hs	0.60	0.04	0.05
	Tp	0.37	7.02	20.5

The measured data at the pierside and turning basin ADCP sites revealed that the waves at these locations are primarily wind chop with $T_p < 2$ seconds. This is due to locally generated wind waves which are coming from the NE and NNE directions. The spotter buoy also revealed primarily wind chop both measured and model results. In terms of general observations, it was evident that higher Hs was recorded for periods with higher tide levels, while lower Hs was recorded for periods with lower tide level. Figure 4-10 shows the plot of time series of the observed and simulated wave heights at the spotter buoy.

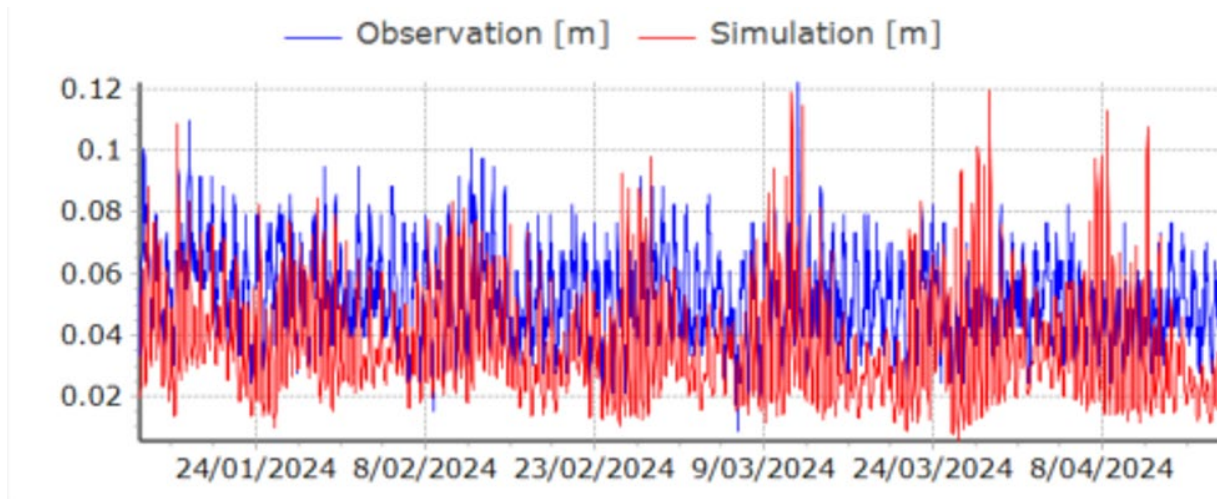


Figure 4-10 Time series plot of the observed and simulated wave heights at the spotter buoy location

As shown in Table 4-5, the index of agreement between the observed and simulated wave heights at the spotter buoy is 0.60. It also shows an average difference of 0.018 m, which indicates that the model fits the measured data well. Figure 4-11 shows a scatter plot of the observed and simulated data.

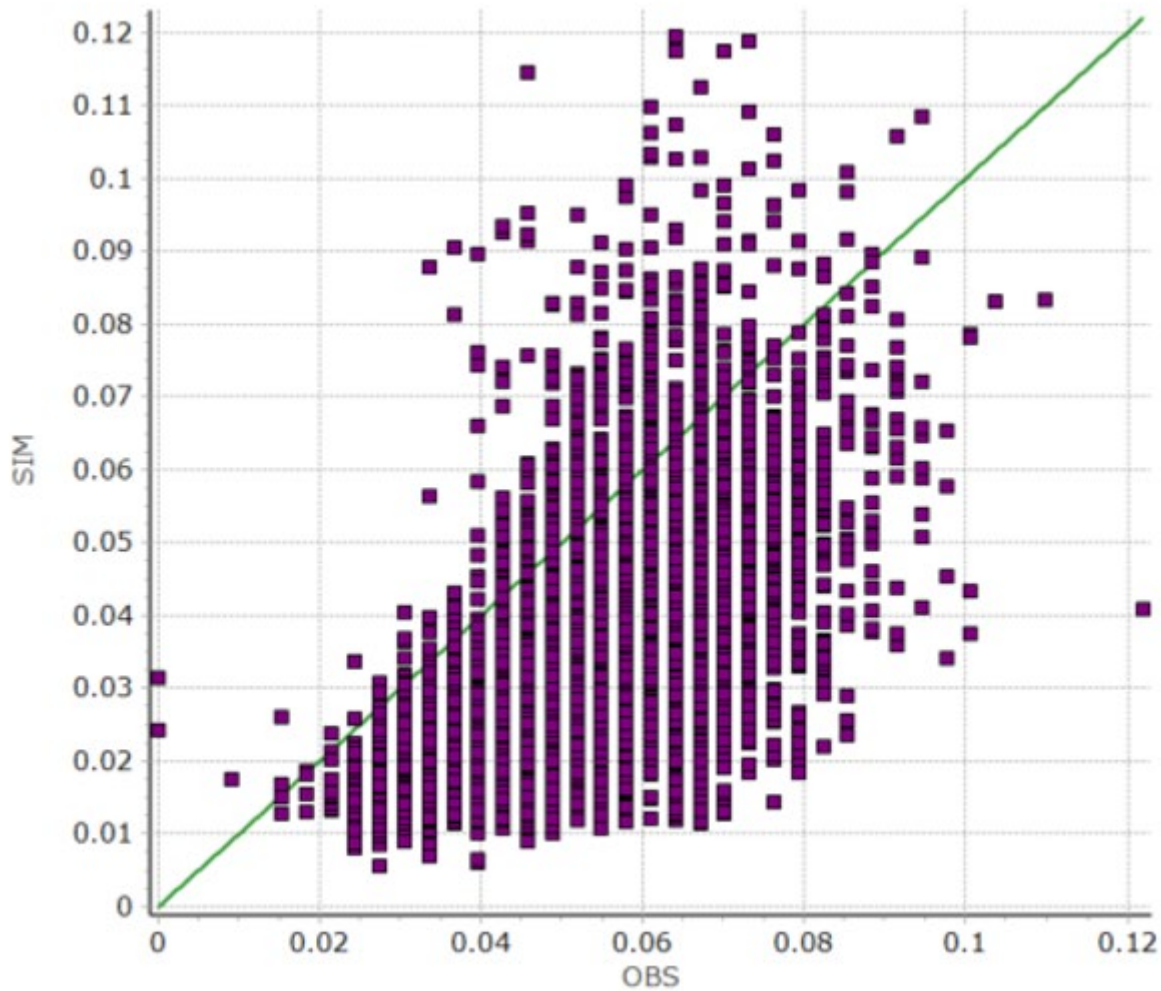


Figure 4-11 Scatter Plot Representing the Relationship Between the Observed and Simulated Wave Heights at the Spotter Buoy Location

4.2 Ambient Condition Results

4.2.1 Model Extraction Points

The time-series data used in the analysis for the production simulations of ambient conditions are extracted at points plotted in Figure 4-12. The extraction points are composed of two points at the port, one at the center of the turning basin, four points on the channel, and one point at an offshore location. The location and elevation at these points are summarized in Table 4-6. Data can be extracted from any location within the numerical model; hence, the usefulness of the tool for analysis.

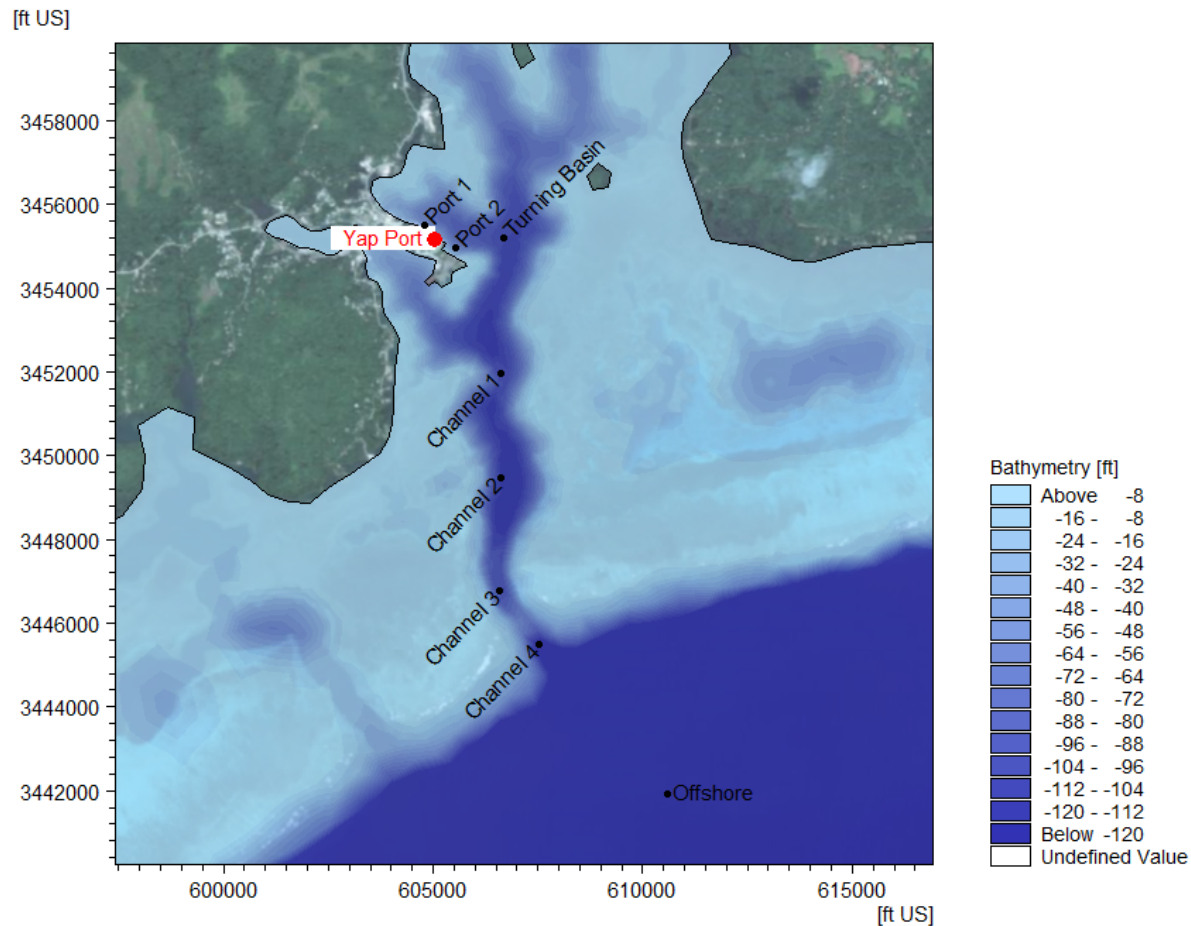


Figure 4-12 Model Extraction Points for Ambient Conditions Modelling

Table 4-6 Location and Elevation of Model Extraction Points (horizontal datum: WGS 84 / UTM Zone 54)

Extraction Point	Eastings (ft)	Northings (ft)	Model Seabed Elevation (ft MLLW)
Port 1	604793.7	3455521.1	-50.5
Port 2	605553.0	3454959.5	-54.9
Turning Basin	606675.3	3455187.9	-111.0
Channel 1	606610.2	3451980.1	-108.0
Channel 2	606610.0	3449480.6	-120.7
Channel 3	606586.3	3446767.2	-99.4
Channel 4	607513.3	3445486.6	-130.6
Offshore	610589.5	3441934.3	-1449.9

4.2.2 Wave Height and Frequency

Wave data (significant wave height, peak period, and mean wave direction) were extracted from the numerical model for the representative year. Figure 4-13 shows a spatial distribution of the mean and maximum envelope significant wave height at the project site from the modelled results. The mean values represent the typical wave condition at the site, while the maximum envelope values represent the condition during periods of stronger waves.

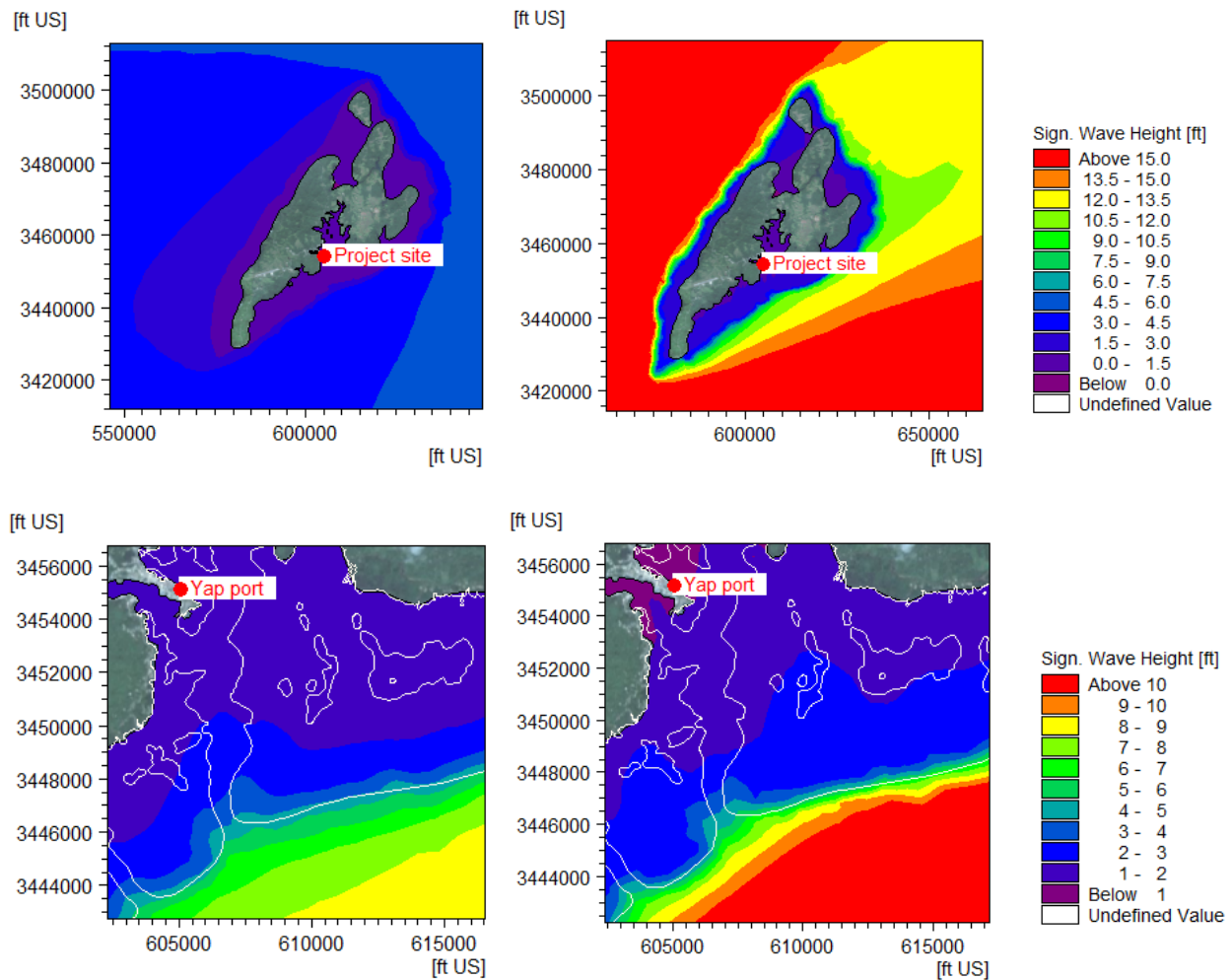


Figure 4-13 Mean (left) and Maximum (right) Envelope of Modelled Significant Wave Height

The annual wave rose information for the representative year at the port and channel areas entering Yap Port are illustrated in Figure 4-14 and Figure 4-15, respectively. For convention, the wave spokes point to the direction where the waves come from. Additionally, wave-direction frequency tables are presented in Table 4-7 and Table 4-8.

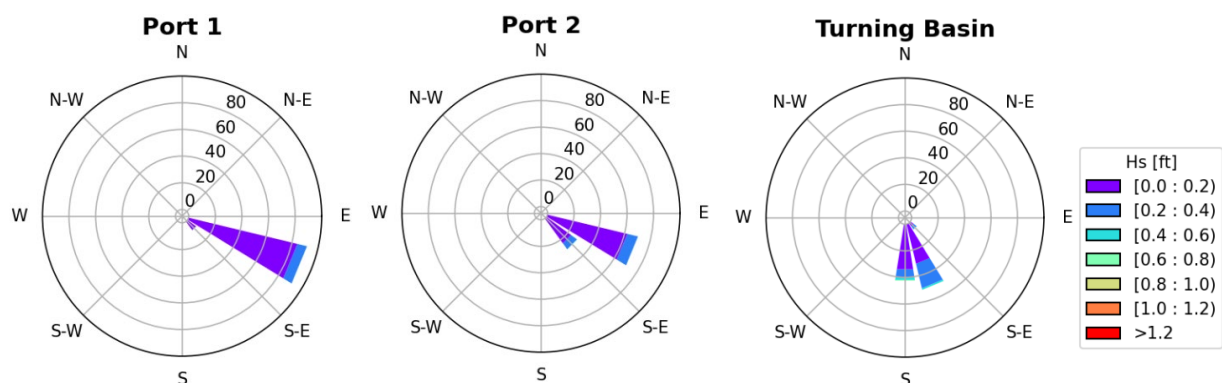


Figure 4-14 Annual Wave Rose at Yap Harbor Extraction Points

Based on Figure 4-14, the majority of waves extracted near the port come from the east-southeast direction. As the port is sheltered by the landmass from the south, these are likely diffracted waves with minimal wave height and energy. In contrast, waves at the turning basin primarily come from the south and are relatively stronger and more energetic. Nonetheless, the waves at and near the port area are likely a combination of broken swells or locally generated wind waves. Relatively calm waves are expected across the port and the turning basin for the entire year where wave heights of less than 0.8 feet are modeled.

Table 4-7 Wave Height – Direction Frequency Table at Yap Harbor Extraction Points

Point	Hs (ft)	Frequency (%)				
		E	ESE	SE	SSE	S
Port 1	0.0 – 0.2	0.2	84.2	7.9	-	-
	0.2 – 0.4	-	7.4	0.2	-	-
	0.4 – 0.6	-	0.1	-	-	-
Port 2	0.0 – 0.2	0.7	62.0	23.1	-	-
	0.2 – 0.4	-	8.3	5.5	-	-
	0.4 – 0.6	-	0.1	0.3	-	-
Turning Basin	0.0 – 0.2	-	-	3.0	30.7	34.3
	0.2 – 0.4	-	-	2.7	19.0	6.3
	0.4 – 0.6	-	-	10.3	1.2	1.8
	0.6 – 0.8	-	-	-	0.1	0.5

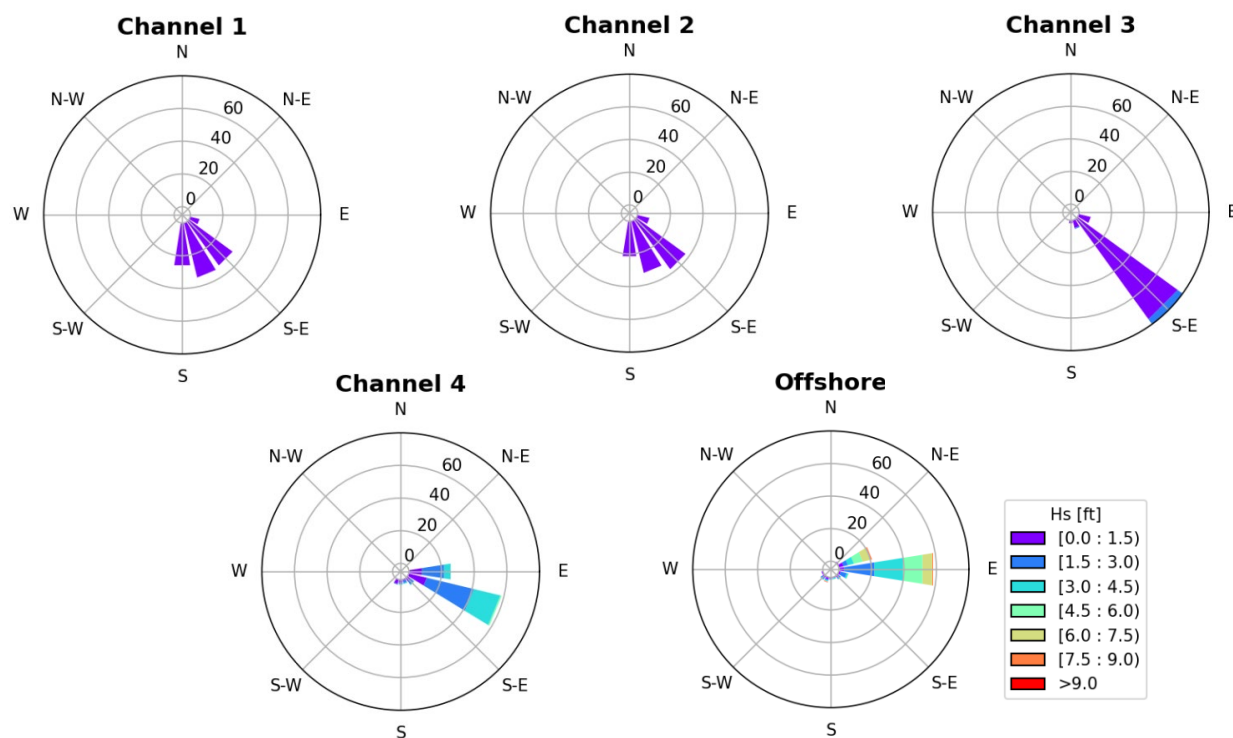


Figure 4-15 Annual Wave Rose at Yap Channel and Offshore Extraction Points

On the other hand, waves are observed to be higher along the channel. The channel feeds from the offshore waves where the heights are notably energetic and can reach more than 9 feet in height. Extracted at Channel 4, which is at the channel entrance, wave heights averaging to 3 feet can be experienced, mainly from the east and east-southeast directions. The waves dissipate as these penetrate towards the harbor

due to the presence of reef from both sides of the channel. The reduction in wave heights is noticeable as waves move further north. At Channel 1, the waves are already significantly calmer compared to Channel 4, with wave heights reduced by around 50 to 70%.

Table 4-8 Wave Height – Direction Frequency Table at Yap Channel and Offshore Extraction Points

Point	Hs (ft)	Frequency (%)									
		NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
Channel 1	0.0 – 1.5	-	-	0.1	6.0	33.3	34.5	26.2	-	-	-
Channel 2	0.0 – 1.5	-	-	0.4	7.6	37.4	32.6	21.7	0.2	-	-
Channel 3	0.0 – 1.5	-	0.3	0.6	7.7	76.2	4.9	1.9	0.2	-	-
Channel 4	1.5 – 3.0	-	-	-	-	7.6	0.7	-	-	-	-
	0.0 – 1.5	-	0.2	8.1	11.5	2.4	0.9	1.9	2.8	-	-
	1.5 – 3.0	-	-	13.7	29.6	2.5	1.4	0.8	0.5	-	-
	3.0 – 4.5	-	-	4.2	16.8	0.4	0.6	0.3	-	-	-
	4.5 – 6.0	-	-	-	0.8	0.2	0.1	0.5	-	-	-
	6.0 – 7.5	-	-	-	0.1	-	-	-	-	-	-
	7.5 – 9.0	-	-	-	-	-	-	-	-	-	-
Offshore	0.0 – 1.5	0.8	3.0	3.2	1.3	1.1	0.5	0.6	1.4	1.3	1.0
	1.5 – 3.0	-	2.8	18.9	3.8	1.3	0.1	0.5	0.7	1.3	-
	3.0 – 4.5	-	3.8	17.8	1.0	0.3	0.6	0.3	0.4	0.3	-
	4.5 – 6.0	-	5.6	12.1	0.2	0.1	0.1	-	0.3	-	-
	6.0 – 7.5	-	4.7	6.1	0.1	-	0.1	-	-	-	-
	7.5 – 9.0	-	1.2	0.5	-	-	-	-	0.3	-	-
	9.0 – 10.5	-	-	-	-	-	-	-	0.2	0.1	-
	10.5 – 12.0	-	-	-	-	-	-	-	0.1	-	-

4.2.3 Wave Exceedance

A detailed assessment of wave exceedance at the extraction points was performed using the simulated representative year. Wave height exceedances for points within the project site are presented in Figure 4-16.

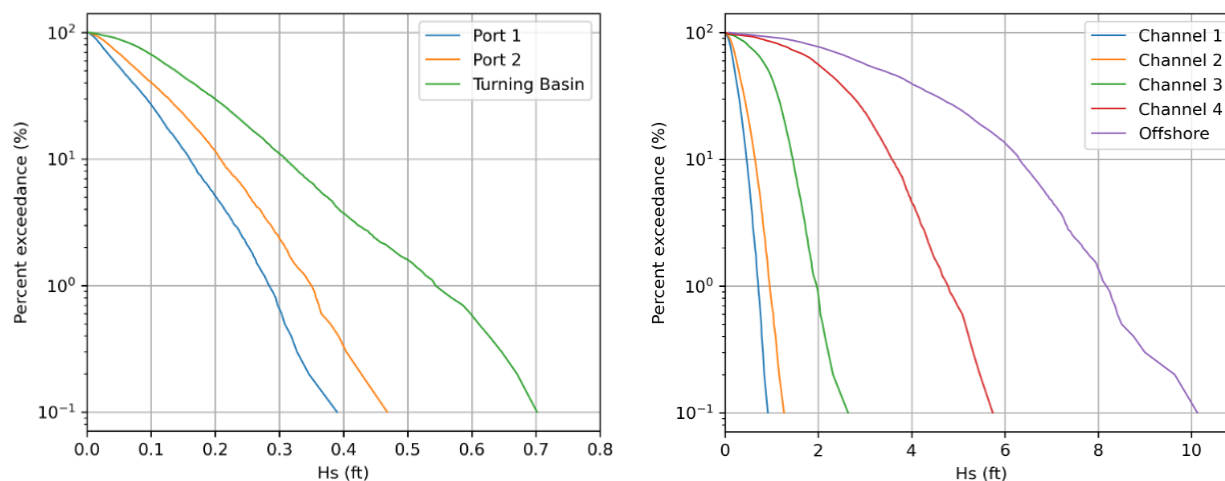


Figure 4-16 Wave Height Exceedance Curve for Extraction Points Along Harbor (left) and Channel and Offshore (right)

The wave height exceedance table presented in Table 4-9 shows the corresponding significant wave heights at selected percentile values for all identified extraction points.

Table 4-9 Wave Height Exceedance Table

Point	Hs(ft)							
	P97.5	P75	P50	P25	P2.5	P1	Mean	Max
Port 1	0.00	0.03	0.05	0.10	0.24	0.28	0.07	0.50
Port 2	0.01	0.04	0.08	0.14	0.30	0.35	0.10	0.55
Turning Basin	0.02	0.08	0.14	0.22	0.45	0.54	0.16	0.87
Channel 1	0.03	0.13	0.21	0.34	0.62	0.72	0.24	1.05
Channel 2	0.04	0.18	0.29	0.46	0.85	0.96	0.34	1.50
Channel 3	0.05	0.57	0.93	1.21	1.76	1.97	0.90	3.01
Channel 4	0.08	1.38	2.16	2.95	4.31	4.78	2.18	6.67
Offshore	0.28	2.11	3.39	5.02	7.46	8.18	3.60	11.57

4.2.4 Wave Period

Wave periods have a significant impact on vessel navigation. In mariners' terms, waves with periods of up to 2 seconds are known as ripples, from 2 to 5 seconds are called chop, from 5 to 15 seconds are called sea state, and from 15 to 30 seconds are called swell. A ship whose length waterline is equal to the wave length and wave height is less than the freeboard will only experience less severe functionality degradation in rough seas (pounding, slamming, wetness of the deck, excessive rolling and pitching, emergence of propeller at the surface, etc.); whereas a ship whose length waterline is smaller than wave length and wave height exceeds the freeboard will encounter severe functionality degradation of the ship's system in rough sea conditions. Both conditions are presumed to be head-on seas.

Figure 4-17 presents a scatter plot of wave periods experienced at the harbor, channel, and offshore extraction points. Table 4-10 and Table 4-11 below show the frequency of different bins of significant wave heights and peak period. Peak period bins were subdivided into three categories: chops, sea states, and swells, consistent with the described mariners' terms above. At the offshore location, most waves are sea states and these transitions to chops as you move deeper into the harbor. At the location of the port, chops consist of 50 to 60% of waves, with sea state waves typically having very small wave heights of less than 0.2 feet. It is noted that the wave model cannot resolve ripples with wave periods less than 2 seconds. Nonetheless, it is envisaged that this will be of no consequence, as waves with such small periods are expected to have non-significant impact on port operations.

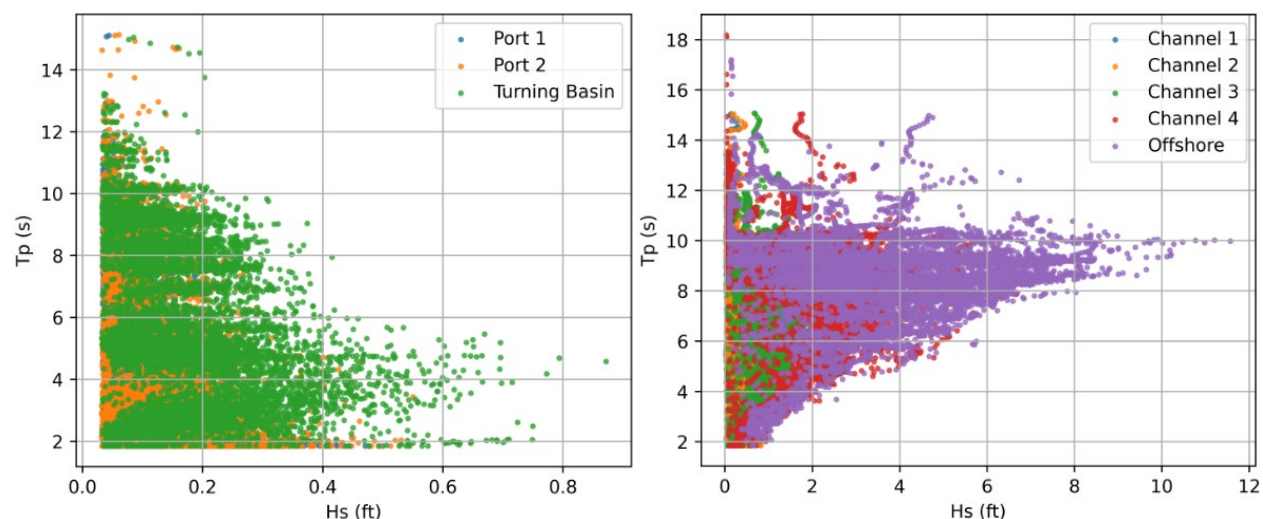


Figure 4-17 Wave Height – Period Characteristics Along Harbor (left) and Channel and Offshore (right)

Table 4-10 Wave Height – Wave Period Frequency Table at Yap Harbor Extraction Points

Point	Hs (ft)	Frequency (%)				
		Chop	Sea State			Swell
		2-5 s	5-8 s	8-12 s	12-15 s	>15 s
Port 1	0.0 – 0.2	58.1	18.1	16.0	-	-
	0.2 – 0.4	7.52	-	-	-	-
Port 2	0.4 – 0.6	0.1	-	-	-	-
	0.0 – 0.2	37.0	24.9	23.5	0.4	-
	0.2 – 0.4	11.9	1.8	0.1	-	-
Turning Basin	0.4 – 0.6	0.4	-	-	-	-
	0.0 – 0.2	27.5	21.4	18.9	0.3	-
	0.2 – 0.4	17.9	7.7	2.4	-	-
	0.4 – 0.6	3.1	0.3	-	-	-
	0.6 – 0.8	0.6	0.1	-	-	-

Table 4-11 Wave Height – Wave Period Frequency Table at Yap Channel and Offshore Extraction Points

Point	Hs (ft)	Frequency (%)				
		Chop	Sea State			Swell
		2-5 s	5-8 s	8-12 s	12-15 s	>15 s
Channel 1	0.0 – 1.5	36.3	34.8	28.4	0.6	-
Channel 2	0.0 – 1.5	31.0	31.7	36.3	1.0	-
Channel 3	0.0 – 1.5	20.0	24.7	46.0	1.1	-
	1.5 – 3.0	1.4	3.2	3.6	-	-
Channel 4	0.0 – 1.5	6.5	3.1	17.1	1.0	0.1
	1.5 – 3.0	2.9	18.2	26.8	0.4	-
	3.0 – 4.5	0.1	7.9	14.3	-	-
	4.5 – 6.0	-	0.5	1.1	-	-

Point	Hs (ft)	Frequency (%)				
		Chop	Sea State			Swell
		2-5 s	5-8 s	8-12 s	12-15 s	>15 s
Offshore	0.0 – 1.5	2.5	1.4	8.7	1.5	0.1
	1.5 – 3.0	1.5	6.4	21.2	0.3	-
	3.0 – 4.5	-	9.1	15.0	0.4	-
	4.5 – 6.0	-	6.4	11.7	0.3	-
	6.0 – 7.5	-	0.7	10.4	-	-
	7.5 – 9.0	-	-	2.1	-	-
	9.0 – 10.5	-	-	0.3	-	-
	10.5 – 12.0	-	-	0.1	-	-

4.2.5 Seasonal Trends

The monthly distribution of significant wave height was also investigated by plotting both the average and maximum significant wave heights at each extraction point, as presented in Figure 4-18. Near the port, the average significant wave heights do not significantly vary across the year, with average wave heights limited to around 0.1 feet. Higher waves are modeled in the turning basin, which can reach up to 0.2 feet on average. Meanwhile, maximum values for significant wave heights are observed to occur between April and October. This is coincidental with the typhoon season in the Pacific, which usually begins in April and ends in November, where the most severe typhoons usually occur in August and September. Additionally, MSL between the months of May to September also tends to be higher than average, which may result in stronger waves being able to penetrate and travel towards the port area.

In contrast, strong waves are expected to occur in the channel entrance and offshore areas from October until April. This period coincides with the island's defined winter season. Trends on observing stronger waves between these months are also consistent with the monthly wave height plots presented in the WACOP report (Bosselle et al. 2015).

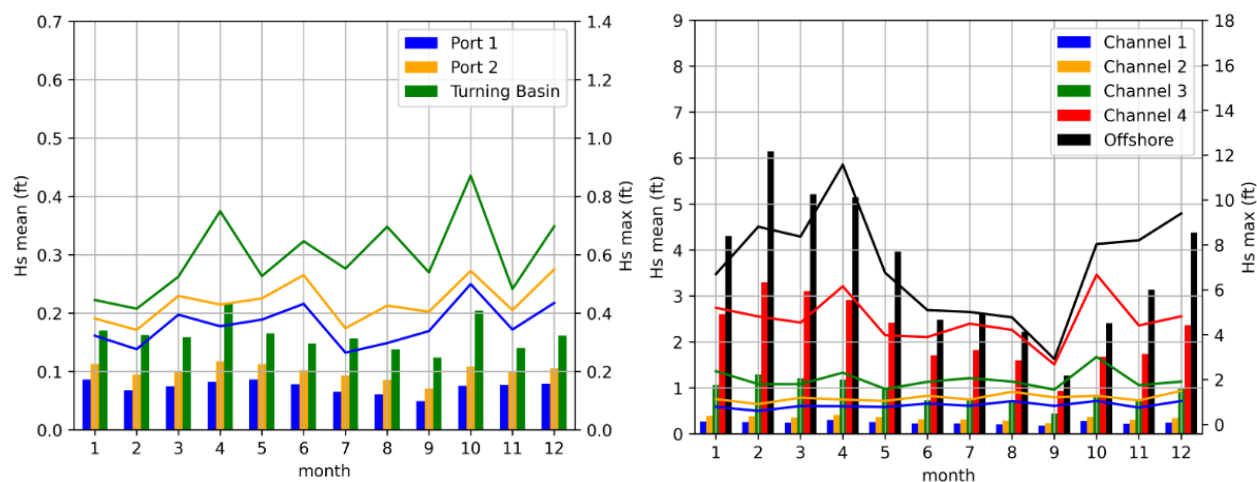


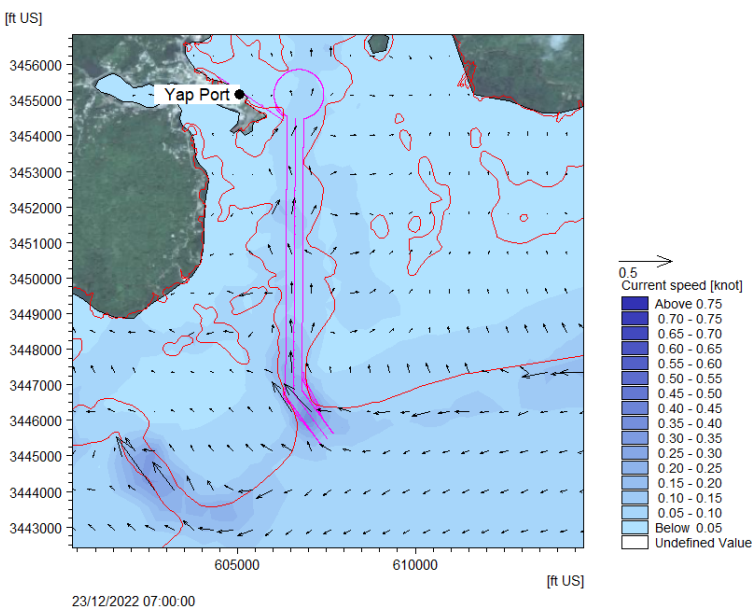
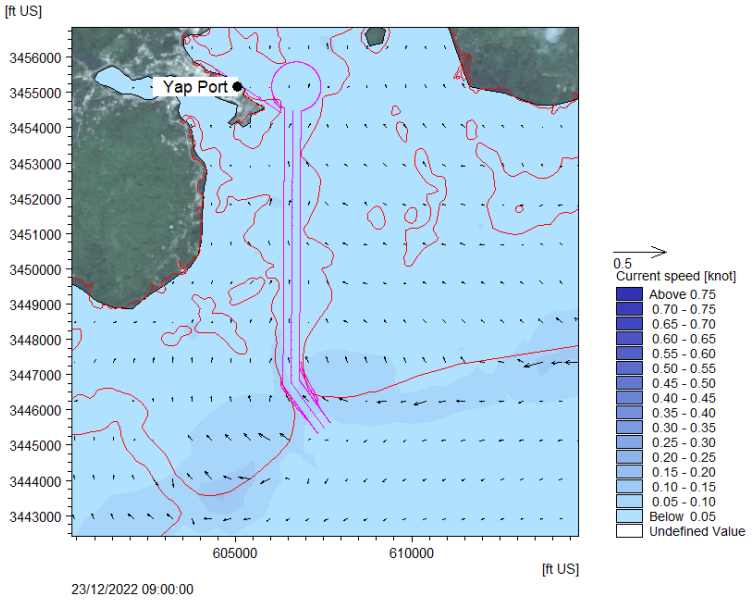
Figure 4-18 Monthly Average (bar) and Maximum (line) Significant Wave Height for Extraction Points Along Harbor (left) and Channel and Offshore (right)

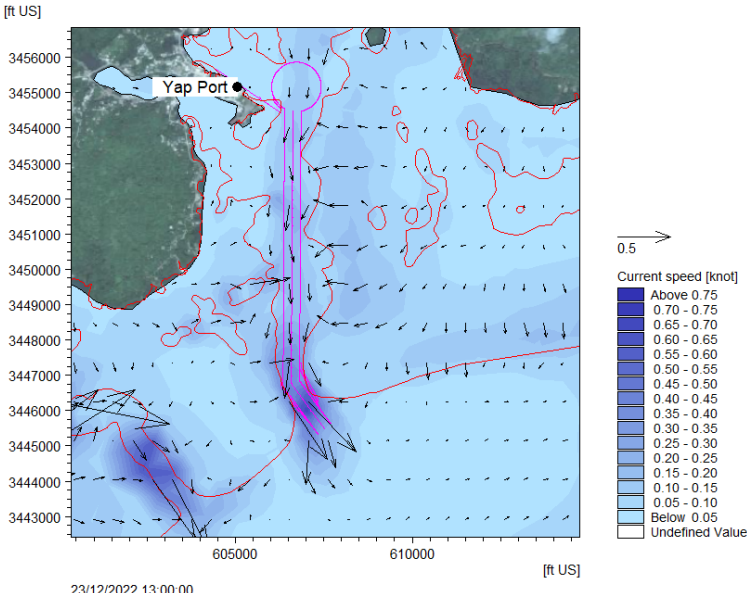
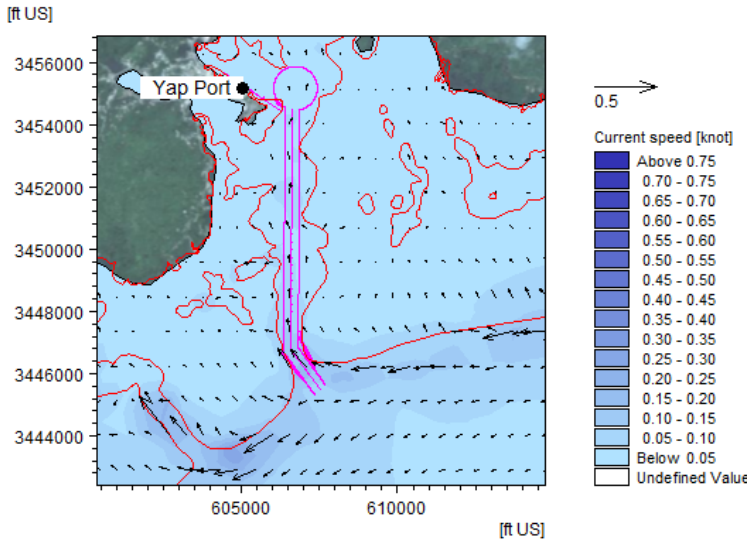
4.2.6 Currents

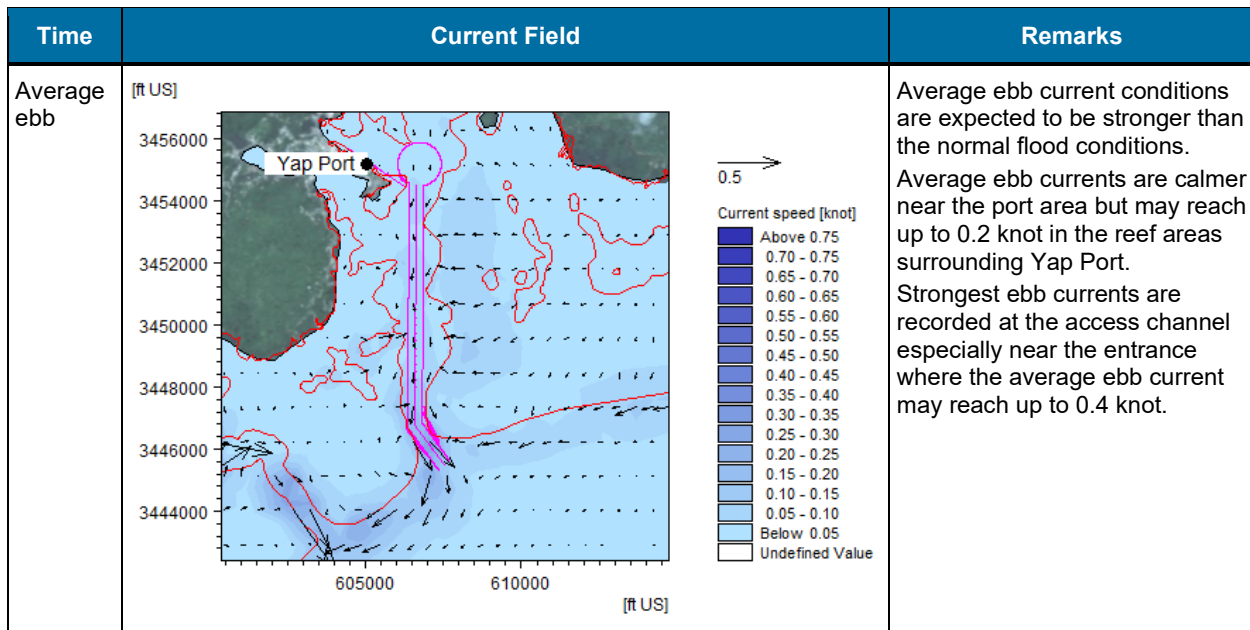
4.2.6.1 Ebb and Flood

Ebb and flood describe the movement of currents during the rise and fall of tide levels. To visualize the current patterns within the harbor and channel, snapshots of the hydrodynamic modelling results were extracted from the model. The period with the highest simulated tide level occurring during a spring tide was referenced for the analysis. The snapshots and corresponding discussions are outlined in Table 4-12.

Table 4-12 Ebb and Flood Current Behavior at Yap Island

Time	Current Field	Remarks
t = -2 hrs		Peak flood currents in the vicinity of Yap Port occurred 2 hours before the modeled spring high tide. Currents are generally flowing northward towards the port from the south access channel. Very weak currents (<0.1 knot) are generally expected near the port area. Stronger but still weak currents are observed in the turning basin. Currents capping at 0.6 knot are observed along the access channel, especially near the entrance and close to the bend.
t = 0 – high tide		Very weak currents are observed during peak spring high tide. Currents are flowing towards the north but very close to slack.

Time	Current Field	Remarks
t = +4 hrs	 23/12/2022 13:00:00	Peak ebb currents in the vicinity of Yap Port occurred 4 hours after the spring high tide. Currents flow southwards, out of the harbor and channel area. Weak currents (<0.1 knot) are observed near the port area while currents capping at 0.2 knot can be expected at the turning basin. Strongest currents reaching up to 0.8 knot was modeled along the access channel, near the entrance at the vicinity of the channel bend. Ebb currents are expected to be stronger relative to flood currents.
Average flood		Average flood current conditions near Yap Port and in the reef surrounding the port are expected to be very calm (<0.1 knot) throughout the year. Stronger flood currents may persist along the access channel but are generally less than 0.3 knot.



4.2.6.2 Current Roses

The annual current rose information for the representative year at Yap Port are presented in Figure 4-19 and Figure 4-20 for the harbor, channel, and offshore area, respectively. For convention, it is noted that the spokes are pointed in the direction where the currents are flowing towards, following mariners' convention. Additionally, current speed – direction frequency tables are generated in Table 4-13 and Table 4-14 for reference.

Currents near Yap Port are generally weak under ambient conditions. At the vicinity of the port area, currents are envisaged to be regularly less than 0.1 knot, flowing towards the NW at flood, and SW at ebb. In the turning basin, the currents are flowing northward at flood, and southward during ebb, peaking at around 0.2 knot.

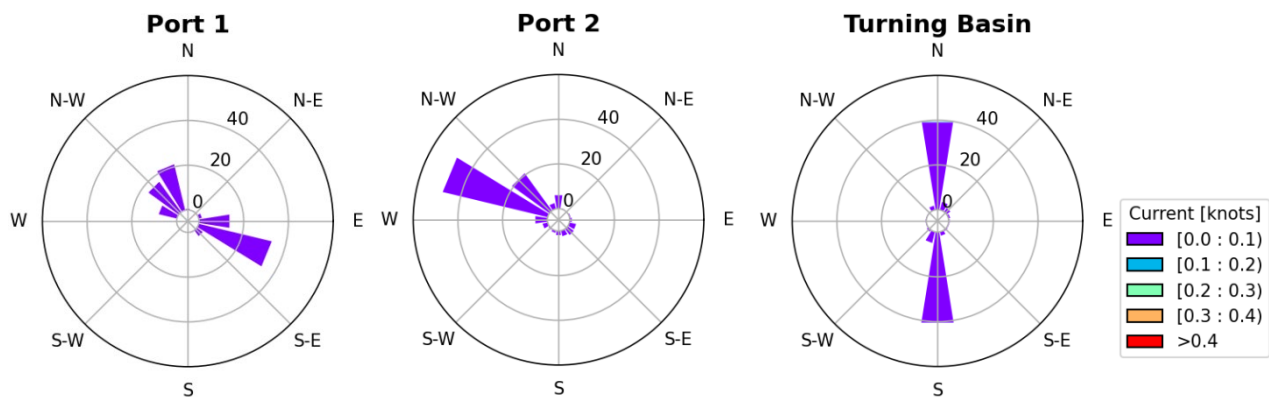


Figure 4-19 Annual Current Rose for Yap Harbor Extraction Points

Table 4-13 Current Speed – Direction Frequency Table at Yap Harbor Extraction Points

Point	Current speed (knot)	Frequency (%)															
		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Port 1	0.0 – 0.1	0.6	0.1	0.2	1.5	13.9	33.6	3.2	0.3	0.1	-	-	-	0.2	8.4	16.7	21.1
Port 2	0.0 – 0.1	6.1	0.3	-	0.5	0.9	3.1	3.4	2.6	1.9	1.0	0.5	2.4	5.5	48.3	20.7	2.7
Turning Basin	0.0 – 0.1	39.5	3.7	2.1	0.8	0.5	0.4	0.6	1.8	41.0	5.1	0.9	0.3	0.4	0.2	0.3	2.0
	0.1 – 0.2	0.3	-	-	-	-	-	-	-	0.1	-	-	-	-	-	-	-

In contrast, stronger currents are modeled along the channel alignment. Currents averaging 0.1 knot can be regularly encountered, but stronger currents were also modeled near the vicinity of Channel 3. Ebb currents were also observed to be stronger than flood currents. Comparing the currents at the extraction points, Channel 3 encounters the strongest currents exceeding 0.5 knot. This value can be exceeded at other locations with the strongest modeled currents being 0.8 knot, at a point approximately 0.2 mile SE of Channel 3. This point is within the shallowest section of the channel with a recorded depth of 55.6 feet. Currents in the offshore area remain relatively calm with currents and generally slower than 0.15 knot.

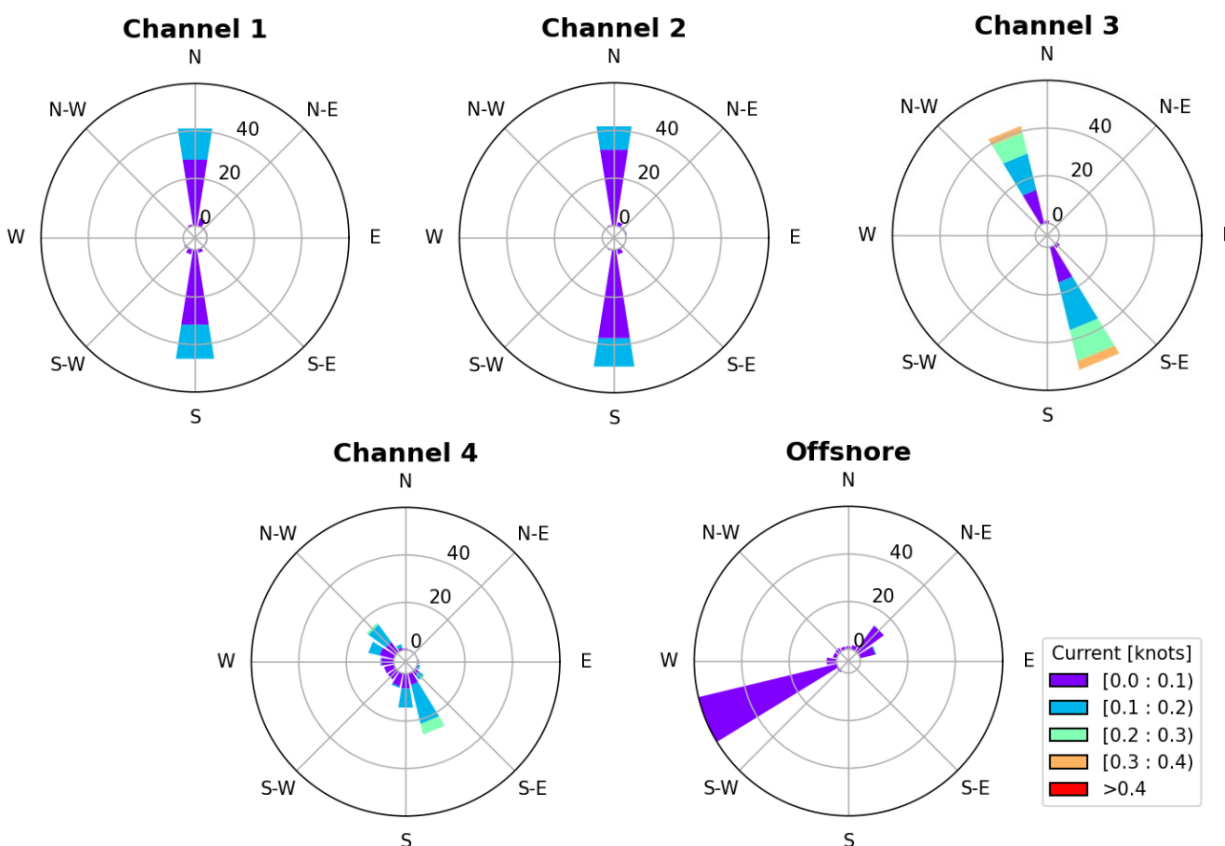


Figure 4-20 Annual Current Rose for Yap Channel and Offshore Extraction Points

Table 4-14 Current Speed – Direction Frequency Table at Yap Channel and Offshore Extraction Points

Point	Current speed (knot)	Frequency (%)															
		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Channel 1	0.0 – 0.1	28.2	3.4	0.5	0.5	0.3	0.4	0.4	1.6	31.6	2.2	0.7	0.2	0.2	0.1	0.3	0.8
	0.1 – 0.2	13.4	-	-	-	-	-	-	-	15.0	-	-	-	-	-	-	-
Channel 2	0.0 – 0.1	32.2	1.8	0.6	0.6	0.3	0.2	0.5	2.2	37.3	0.5	0.1	0.2	0.1	0.2	-	0.6
	0.1 – 0.2	10.1	-	-	-	-	-	-	-	12.4	-	-	-	-	-	-	-
Channel 3	0.0 – 0.1	1.1	0.3	0.2	0.2	0.1	0.2	1.6	15.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	14.5
	0.1 – 0.2	-	-	-	-	-	-	-	20.4	-	-	-	-	-	-	-	15.7
	0.2 – 0.3	-	-	-	-	-	-	-	13.6	-	-	-	-	-	-	-	9.1
	0.3 – 0.4	-	-	-	-	-	-	-	3.9	-	-	-	-	-	-	-	2.9
	0.4 – 0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.1
Channel 4	0.0 – 0.1	0.7	0.4	0.3	0.2	0.5	0.6	2.0	4.9	6.2	5.5	4.2	4.3	5.2	6.1	5.1	1.0
	0.1 – 0.2	0.1	-	-	0.1	0.3	0.8	2.2	16.5	8.3	0.8	0.1	0.1	0.5	5.0	9.1	1.6
	0.2 – 0.3	-	-	-	-	-	-	0.6	5.1	0.1	-	-	-	-	-	1.1	0.1
Offshore	0.0 – 0.1	1.3	1.9	13.4	6.6	0.1	0.1	0.0	0.1	0.1	-	0.9	61.3	4.2	1.7	1.8	1.3
	0.1 – 0.2	-	-	0.1	0.5	-	-	-	-	-	-	-	4.5	-	-	-	-

4.2.6.3 Current Speed Exceedances

A detailed assessment of current speed exceedance at the extraction points was undertaken using the simulated representative year. Current speed exceedance for the said points in the harbor, channel, and offshore of the project site are presented in Figure 4-21. Furthermore, the current speed exceedance values are presented in Table 4-15 to show the percentile values for all the identified extraction points.

For Port 1 and Port 2, very weak currents are expected, with maximum values of around 0.05 knot. Currents at the turning basin are slightly stronger peaking at 0.11 knot. The strongest currents are expected at the vicinity of Channel 3, near the channel bend, 0.41 knot. Farther from the channel, only mild currents are observed with currents not exceeding 0.15 knot at the offshore area.

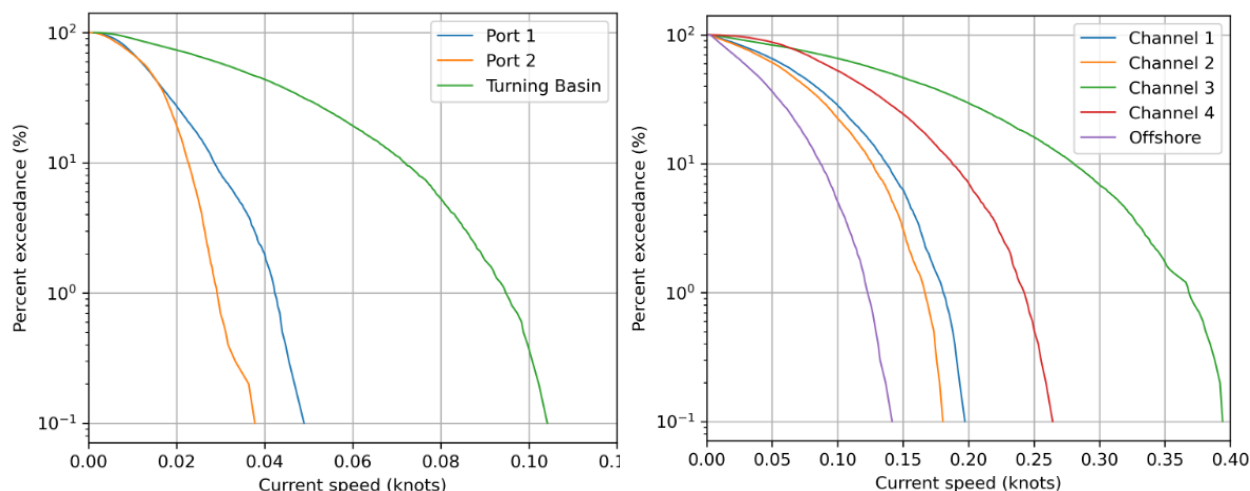


Figure 4-21 Current Speed Exceedance Curves for Yap Harbor (left) and Channel and Offshore (right) Extraction Points

Table 4-15 Current Speed Exceedance Table (knot)

Point	Current Speed (kn)							
	P97.5	P75	P50	P25	P2.5	P1	Mean	Max
Port 1	0.00	0.01	0.01	0.02	0.04	0.04	0.01	0.05
Port 2	0.00	0.01	0.01	0.02	0.03	0.03	0.01	0.04
Turning Basin	0.00	0.02	0.04	0.05	0.09	0.09	0.04	0.11
Channel 1	0.01	0.04	0.07	0.10	0.16	0.18	0.07	0.21
Channel 2	0.00	0.03	0.06	0.10	0.15	0.17	0.07	0.19
Channel 3	0.01	0.07	0.14	0.21	0.34	0.37	0.15	0.41
Channel 4	0.02	0.07	0.10	0.15	0.22	0.24	0.11	0.27
Offshore	0.00	0.02	0.04	0.06	0.11	0.12	0.04	0.15

5 TYPHOON MODELING

5.1 Typhoon Analysis and Selection

Typhoons for Yap Port were selected based on measured storm surge, available storm data, and the direction in which the typhoon passed the Project site. Typhoons that occurred after 2001 generally had enough storm data available to properly model the storm event. Table 5-1 lists the typhoons chosen for the models and their associated maximum measured storm surges and Figure 5-1 shows their paths. These typhoons were further modeled to inform for the harbor tranquility wave model.

Table 5-1 Measured Storm Surge for each Typhoon Modeled

Name of Storm	Year	Direction of Path from Yap	Maximum Water Surface Elevation	
			Meters (MLLW)	Feet (MLLW)
Sudal	2004	South & West	2.56	8.39
Mitag	2002	South & West	2.19	7.18
Hagupit	2014	South	1.91	6.27
Haiyan	2013	South	1.90	6.22
Haima	2016	North	1.55	5.08
Nok-Ten	2016	South & West	1.25	4.11
Maysak	2015	North	1.21	3.98
Omais	2010	North & East	1.16	3.79



Figure 5-1 Typhoons Selected for Analysis (NOAA OCM 2023)

5.2 Typhoon Mesh Construction

The mesh domain generated previously in Section 4.1.1 was utilized around Yap Island in conjunction with GEBCO bathymetry to produce the mesh presented in Figure 5-2. This mesh was utilized to run the eight identified typhoons.

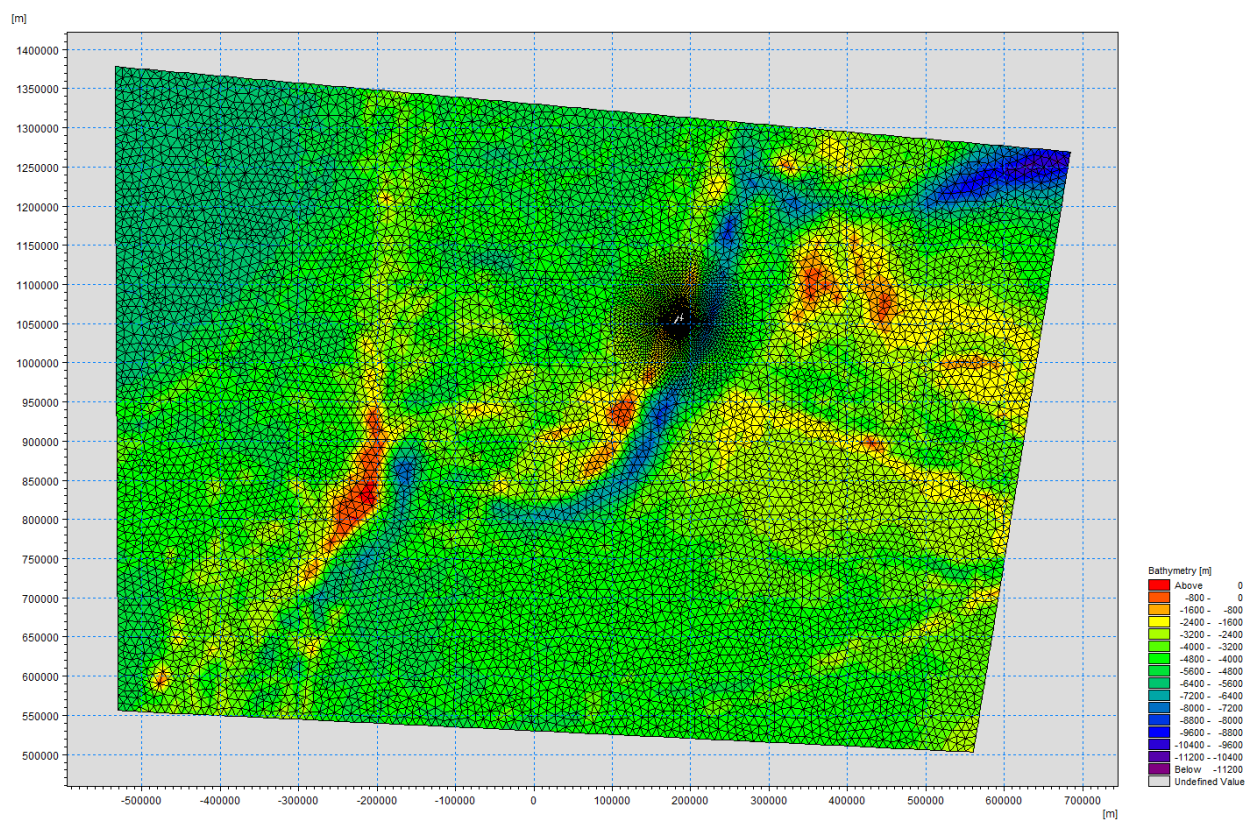


Figure 5-2: Typhoon Model Mesh

5.3 Typhoon Boundary Conditions

Boundary conditions refers to the forcing conditions at the boundaries of the model domain. These can be water elevations, offshore wave conditions, winds, or other parameters for different types of numerical models. The boundary conditions adopted for the typhoon simulations are summarized in Table 5-2.

Table 5-2 Boundary Conditions for Typhoon Condition Modelling

Parameter	Boundary Conditions
Tide	Tide levels extracted from 0.125° x 0.125° DTU10 Global Tide Model (Cheng & Andersen, 2010) at the ocean boundaries of the modelling domain. Tide currents extracted from 0.25° x 0.25° DTU10 Global Tide Model at the ocean boundaries of the modelling domain.
Wind	2D wind field and mean sea level pressure time series extracted from the IBTrACS dataset, for each typhoon, was applied to the entire modelling domain.

5.4 Typhoon Condition Results

The HD and SW model results are presented in the following section. Each scenario is based on the parameters and descriptions presented in the sections above. The results are presented by figures of the maximum water surface elevation, maximum current speed, maximum significant wave height, and maximum peak wave period in the port area for each typhoon.

5.4.1 Water Surface Elevations

Maximum modeled water surface elevations range from 2.34 to 1.24 m (MLLW) within the port area, as shown in Figure 5-3 through Figure 5-10. Based on recorded surge data near the port, the maximum error between measured and modeled storm surge elevations is 0.52 m.

5.4.1.1 Sudal 2004

The maximum modeled water surface elevation during Typhoon Sudal of 2004 was 2.34 m near the port.

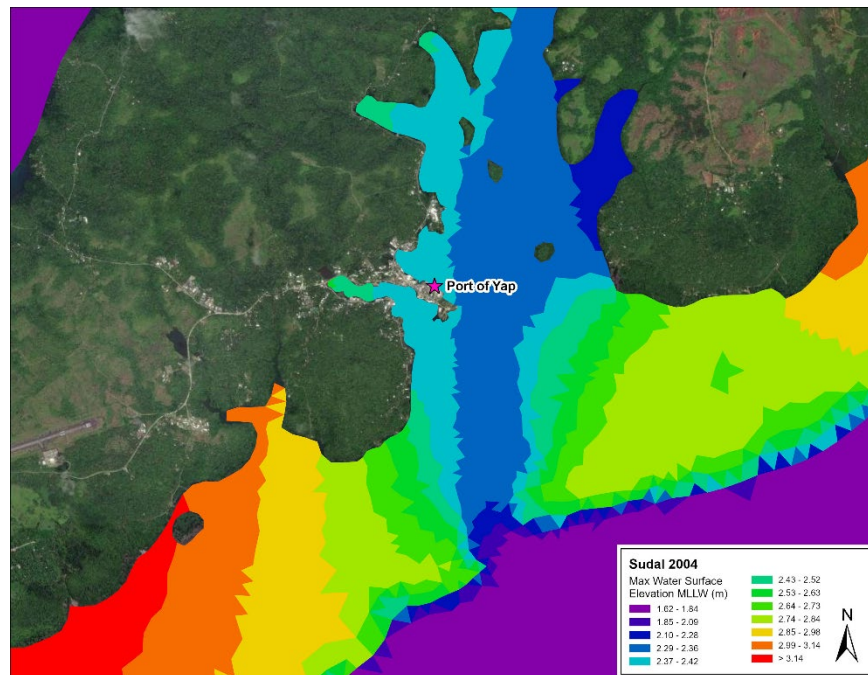


Figure 5-3 Maximum Water Surface Elevation – Sudal 2004

5.4.1.2 Mitag 2002

The maximum modeled water surface elevation during Typhoon Mitag of 2002 was 1.92 m near the port.

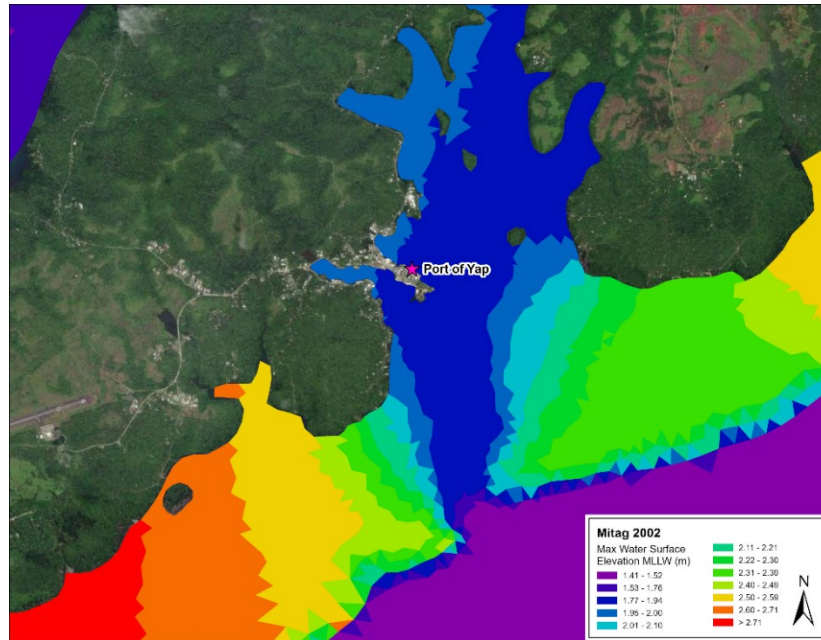


Figure 5-4 Maximum Water Surface Elevation – Mitag 2002

5.4.1.3 Hagupit 2014

The maximum modeled water surface elevation during Typhoon Hagupit of 2014 was 1.39 m near the port.

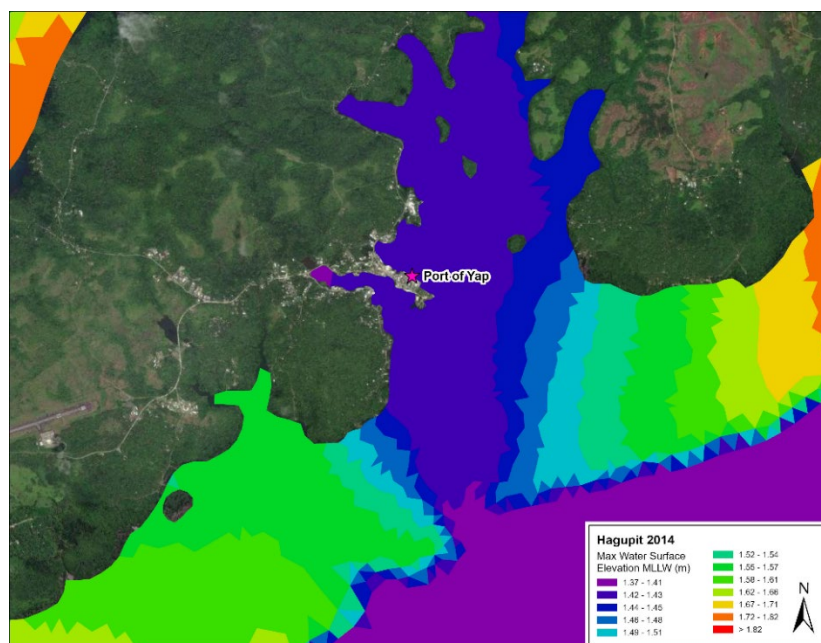


Figure 5-5 Maximum Water Surface Elevation – Hagupit 2014

5.4.1.4 Haiyan 2013

The maximum modeled water surface elevation during Typhoon Haiyan of 2013 was 1.41 m near the port.

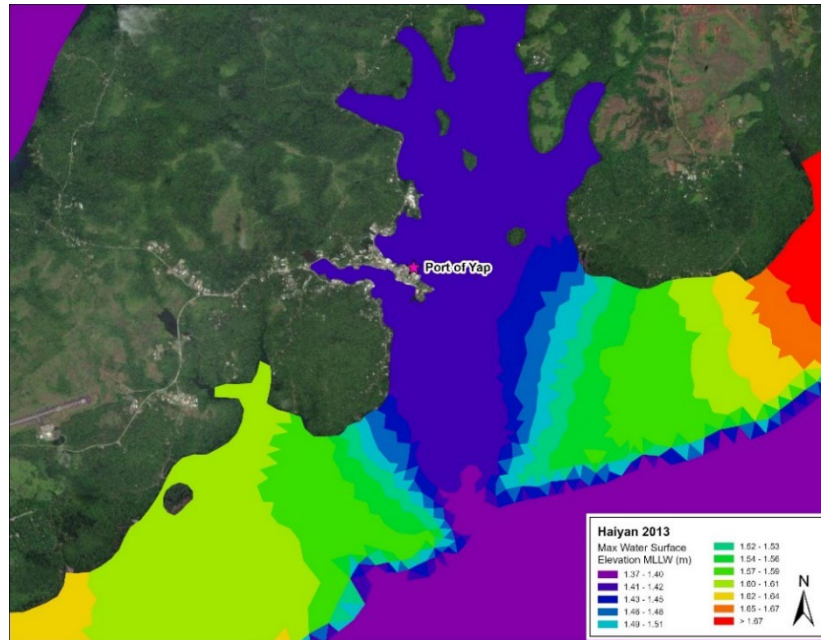


Figure 5-6 Maximum Water Surface Elevation – Haiyan 2013

5.4.1.5 Haima 2016

The maximum modeled water surface elevation during Typhoon Haima of 2016 was 1.43 m near the port.

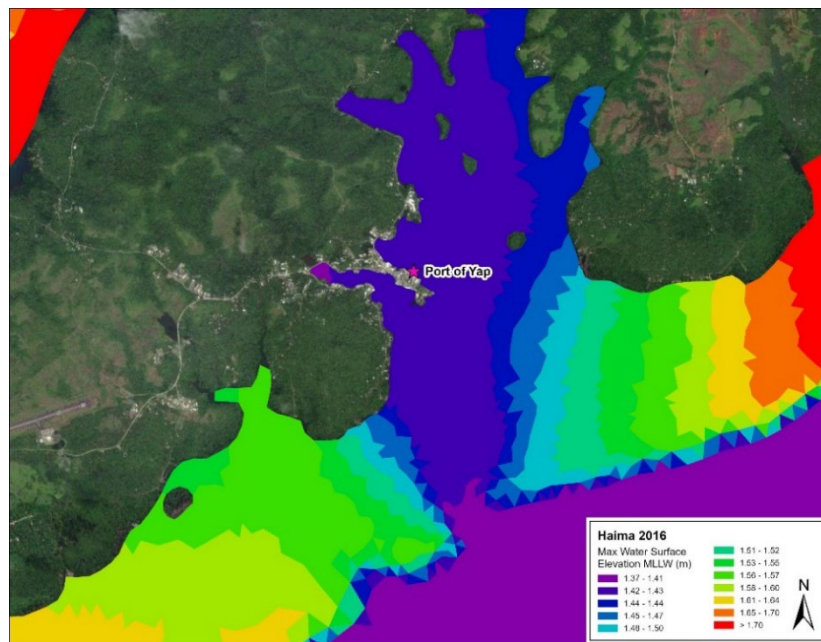


Figure 5-7 Maximum Water Surface Elevation – Haima 2016

5.4.1.6 Nock-Ten 2016

The maximum modeled water surface elevation during Typhoon Nock-Ten of 2016 was 1.36 m near the port.

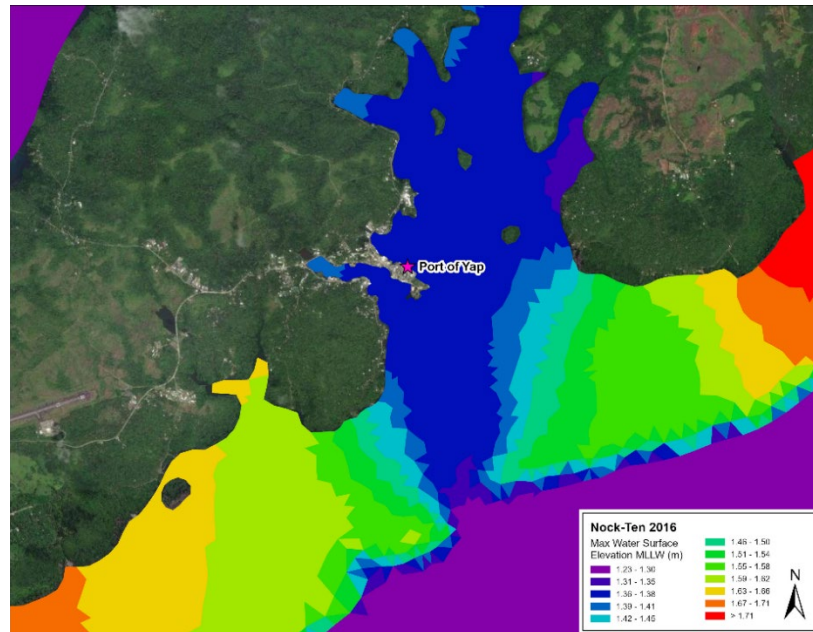


Figure 5-8 Maximum Water Surface Elevation – Nock-Ten 2016

5.4.1.7 Maysak 2015

The maximum modeled water surface elevation during Typhoon Maysak of 2015 was 1.26 m near the port.

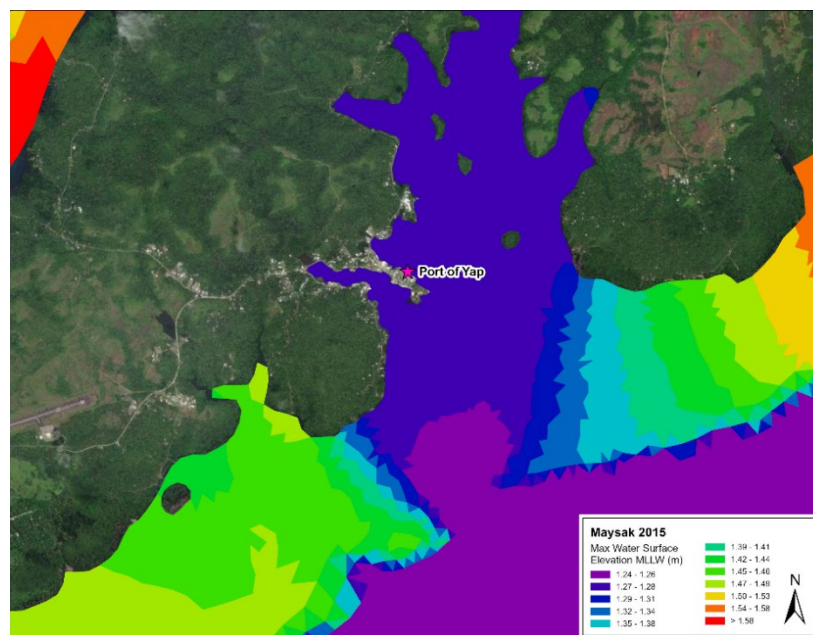


Figure 5-9 Maximum Water Surface Elevation – Maysak 2015

5.4.1.8 Omais 2010

The maximum modeled water surface elevation during Typhoon Omais of 2010 was 1.24 m near the port.

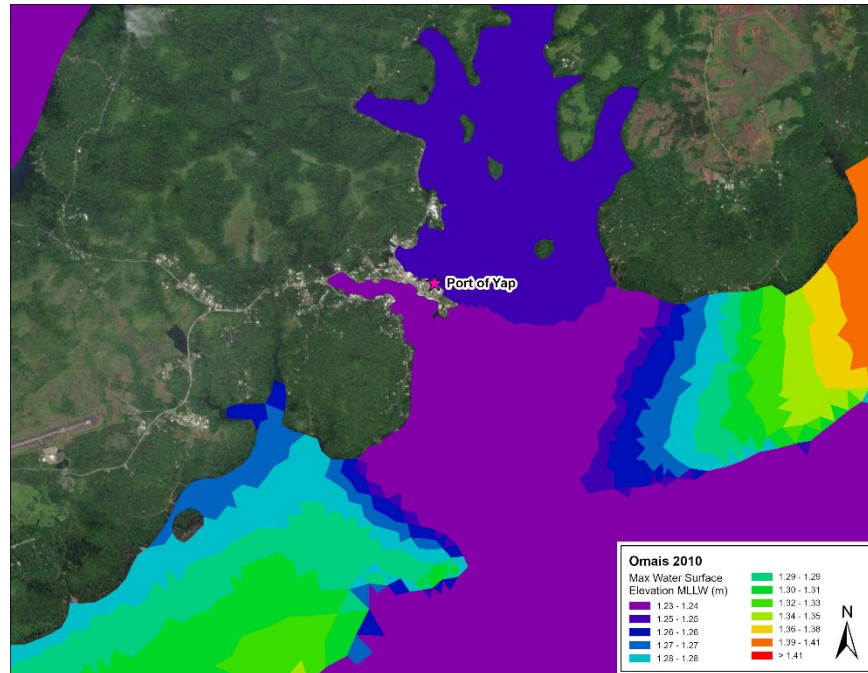


Figure 5-10 Maximum Water Surface Elevation – Omais 2010

5.4.2 Typhoon Currents

Maximum modeled current speeds range from 0.09 to 0.03 m/s within the port area, as shown in Figure 5-11 through Figure 5-18.

5.4.2.1 Sudal 2004

The maximum modeled current speed during Typhoon Sudal of 2004 was 0.08 m/s near the port.

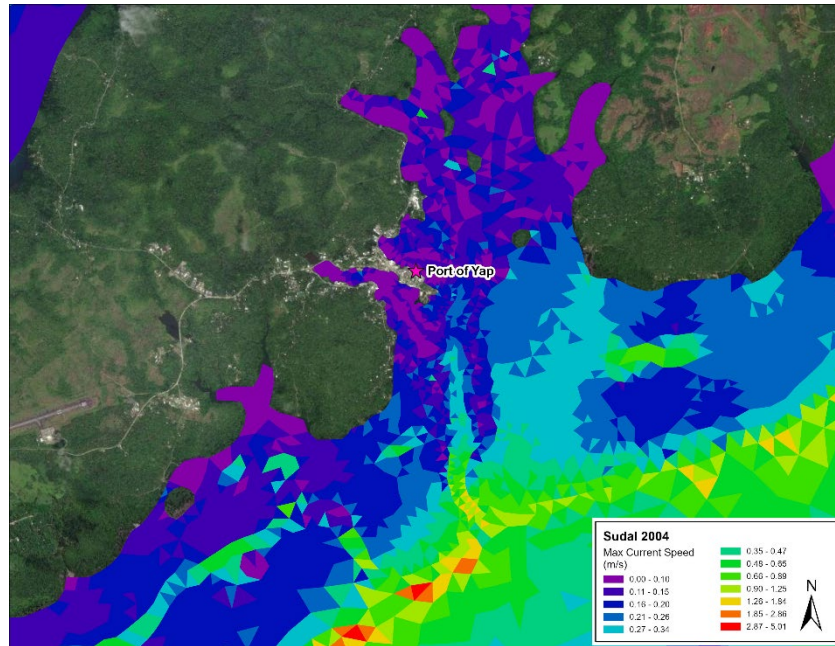


Figure 5-11 Maximum Current Speed – Sudal 2004

5.4.2.2 Mitag 2002

The maximum modeled current speed during Typhoon Mitag of 2002 was 0.08 m/s near the port.

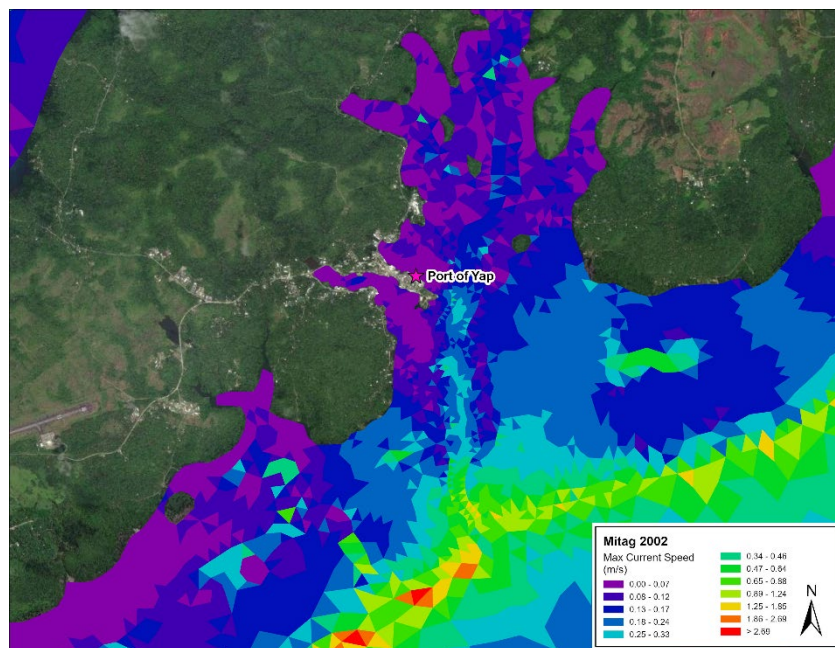


Figure 5-12 Maximum Current Speed – Mitag 2002

5.4.2.3 Hagupit 2014

The maximum modeled current speed during Typhoon Hagupit of 2014 was 0.06 m/s near the port.

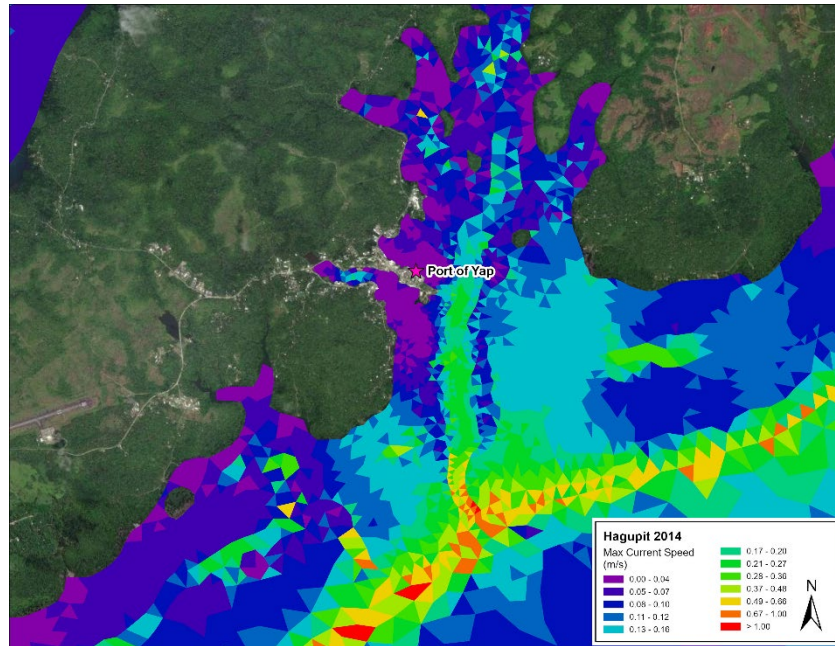


Figure 5-13 Maximum Current Speed – Hagupit 2014

5.4.2.4 Haiyan 2013

The maximum modeled current speed during Typhoon Haiyan of 2013 was 0.07 m/s near the port.

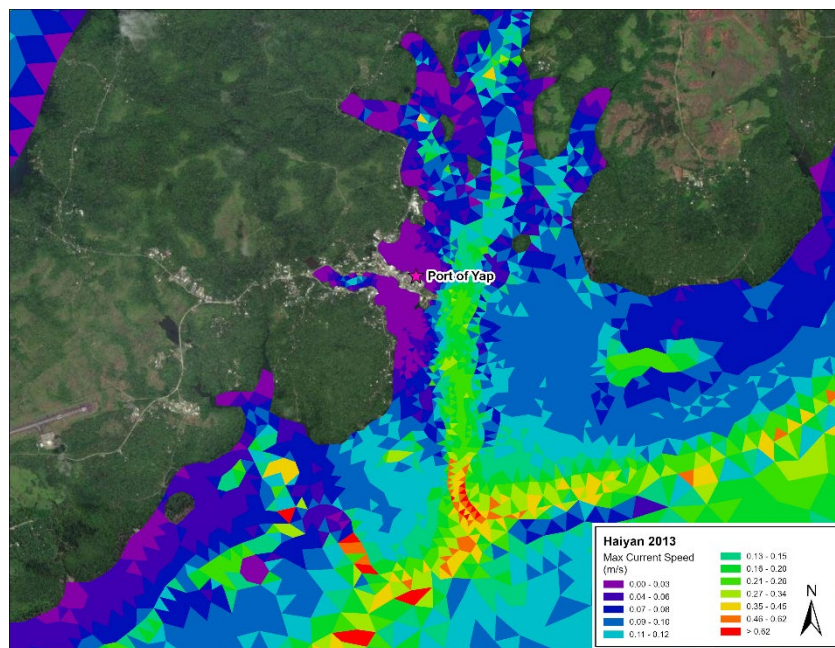


Figure 5-14 Maximum Current Speed – Haiyan 2013

5.4.2.5 Haima 2016

The maximum modeled current speed during Typhoon Haima of 2016 was 0.09 m/s near the port.

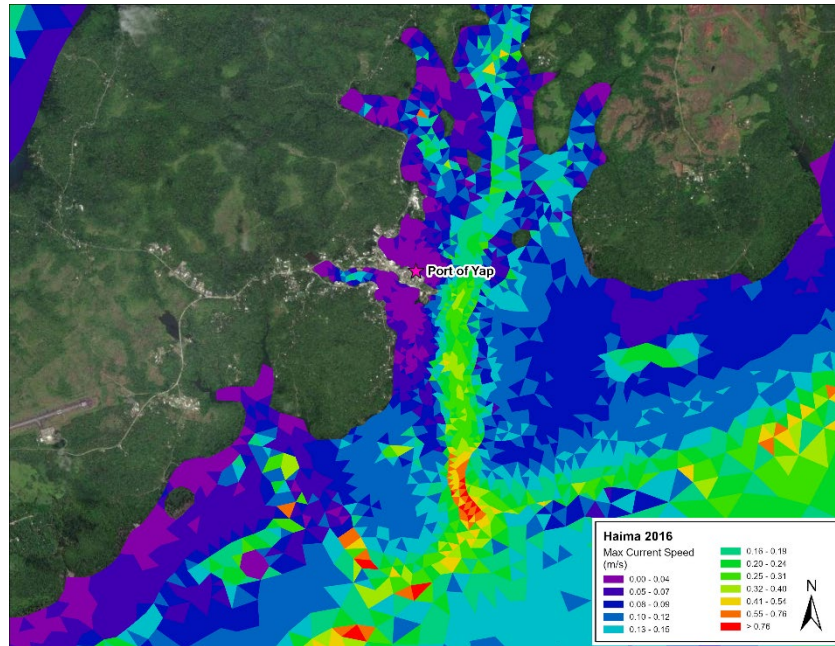


Figure 5-15 Maximum Current Speed – Haima 2016

5.4.2.6 Nock-Ten 2016

The maximum modeled current speed during Typhoon Nock-Ten of 2016 was 0.04 m/s near the port.

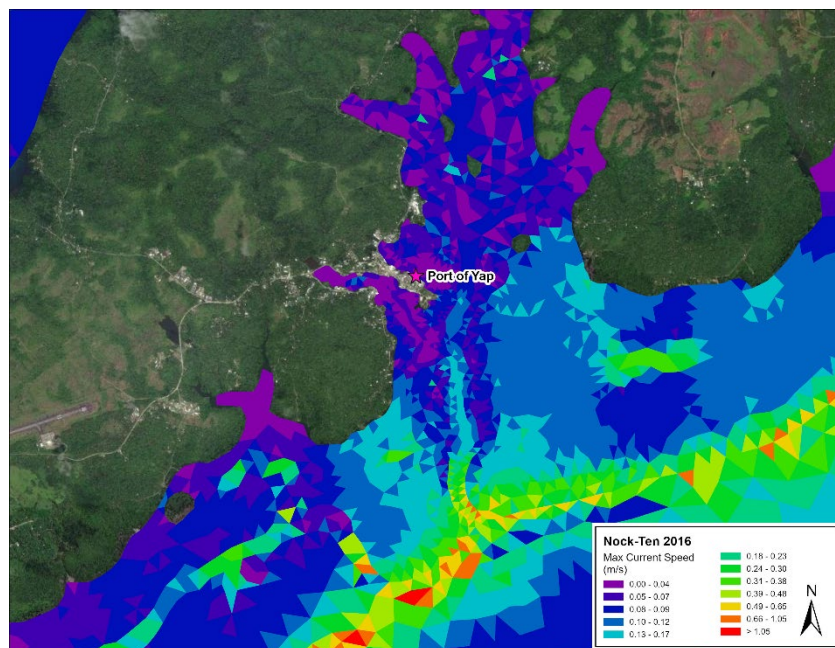


Figure 5-16: Maximum Current Speed – Nock-Ten 2016

5.4.2.7 Maysak 2015

The maximum modeled current speed during Typhoon Maysak of 2015 was 0.03 m/s near the port.

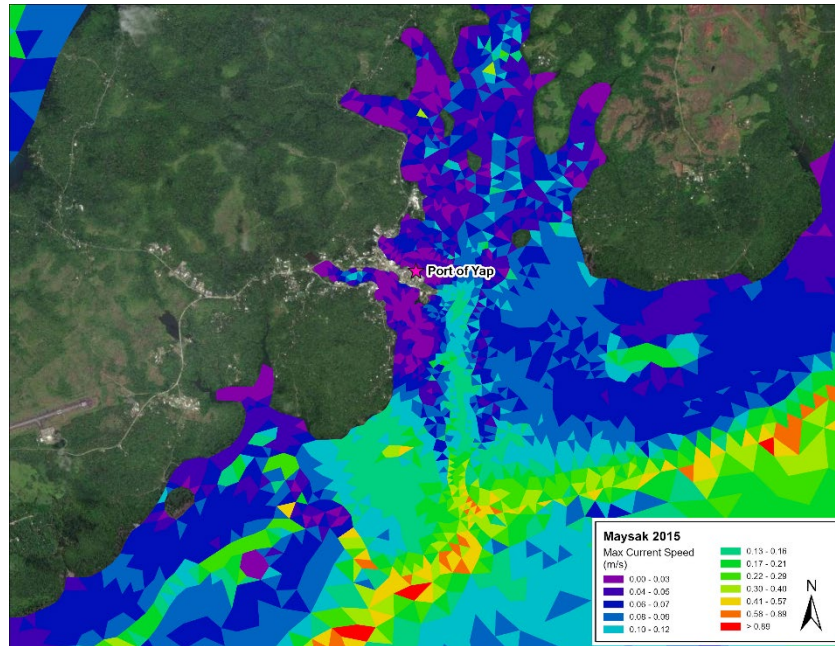


Figure 5-17 Maximum Current Speed – Maysak 2015

5.4.2.8 Omais 2010

The maximum modeled current speed during Typhoon Omais of 2010 was 0.06 m/s near the port.

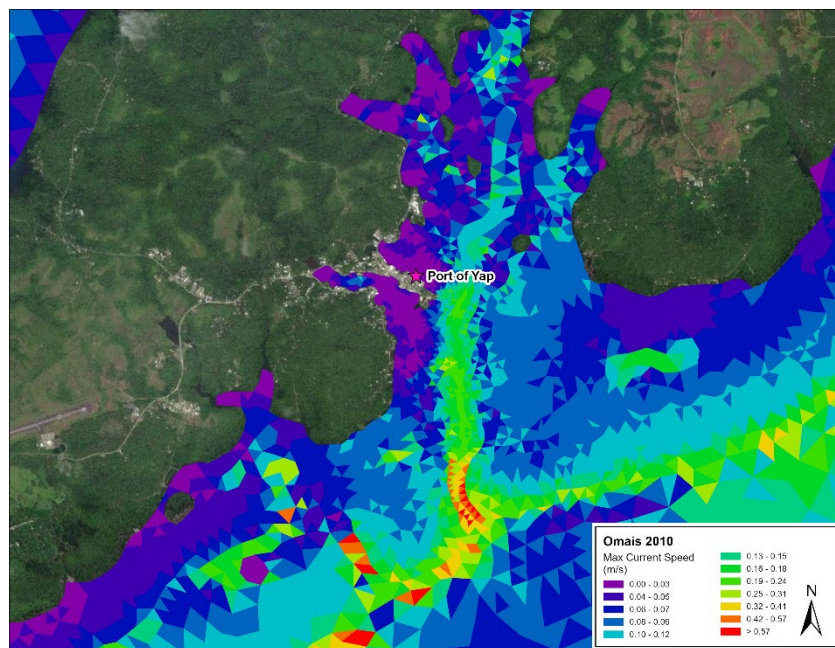


Figure 5-18 Maximum Current Speed – Omais 2010

5.4.3 Wave Conditions

5.4.3.1 Significant Wave Height

Maximum modeled significant wave heights range from 1.60 to 0.09 m within the port area, as shown in Figure 5-19 through Figure 5-34.

5.4.3.1.1 Sudal 2004

The maximum modeled significant wave height during Typhoon Sudal of 2004 was 1.60 m near the port.

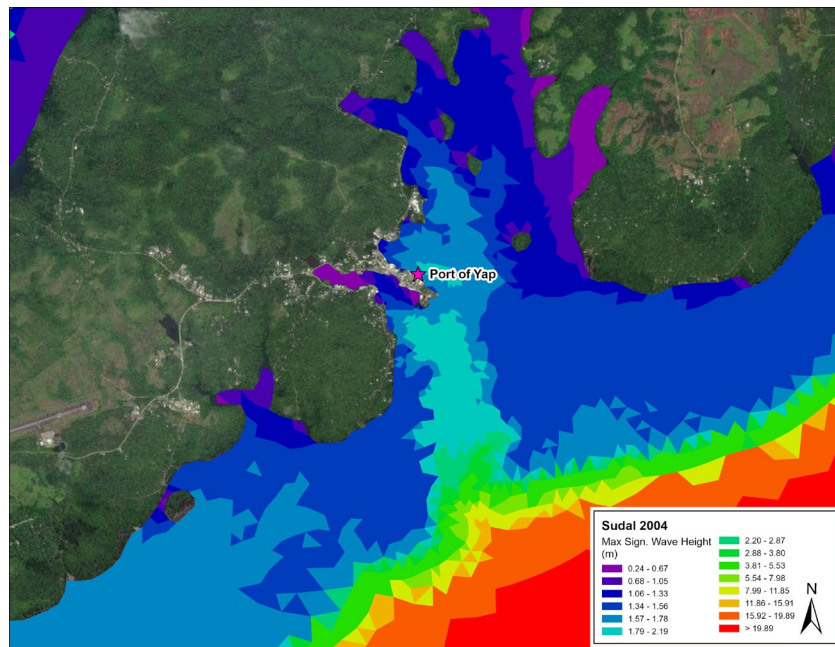


Figure 5-19 Maximum Significant Wave Height at the Port – Sudal 2004

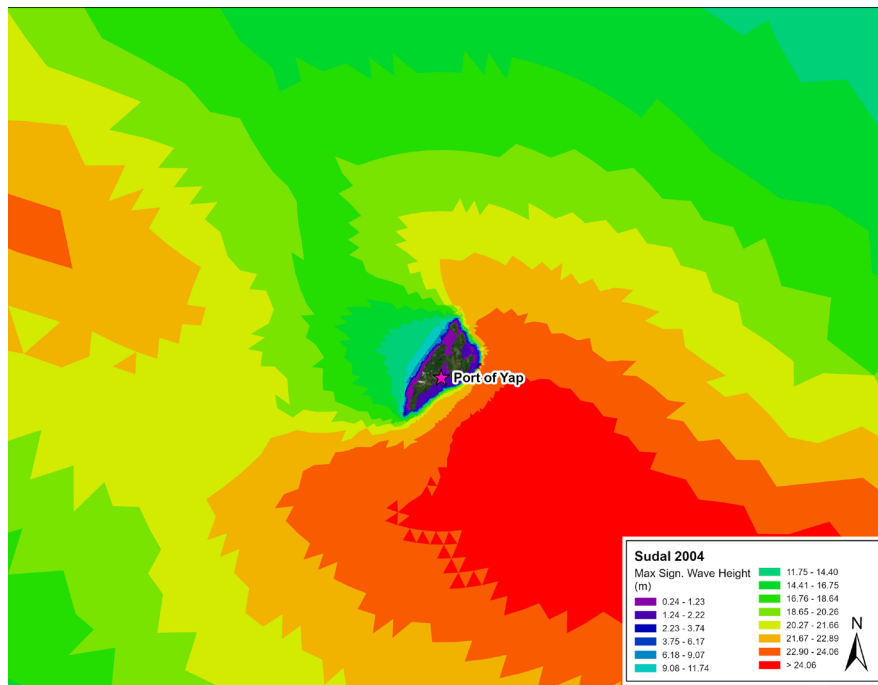


Figure 5-20 Maximum Significant Wave Height at Yap – Sudal 2004

5.4.3.1.2 Mitag 2002

The maximum modeled significant wave height during Typhoon Mitag of 2002 was 1.01 m near the port.

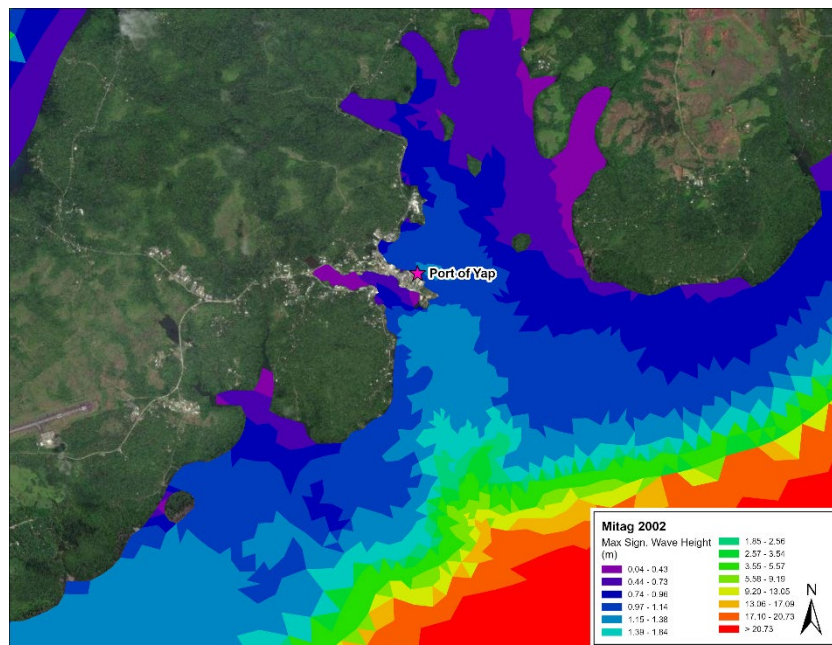


Figure 5-21 Maximum Significant Wave Height at the Port – Mitag 2002

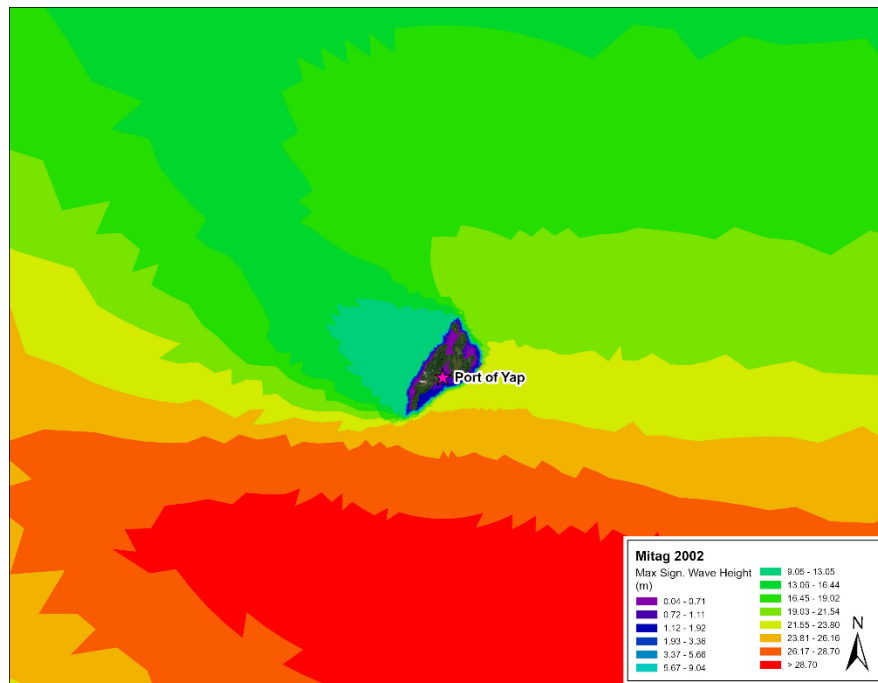


Figure 5-22 Maximum Significant Wave Height at Yap – Mitag 2002

5.4.3.1.3 Hagupit 2014

The maximum modeled significant wave height during Typhoon Hagupit of 2014 was 0.11 m near the port.

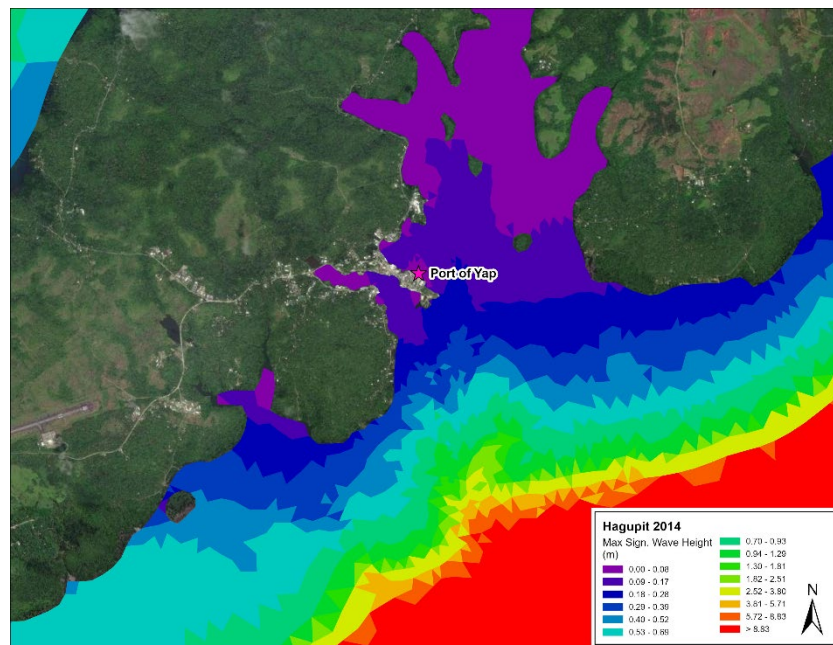


Figure 5-23 Maximum Significant Wave Height at the Port – Hagupit 2014

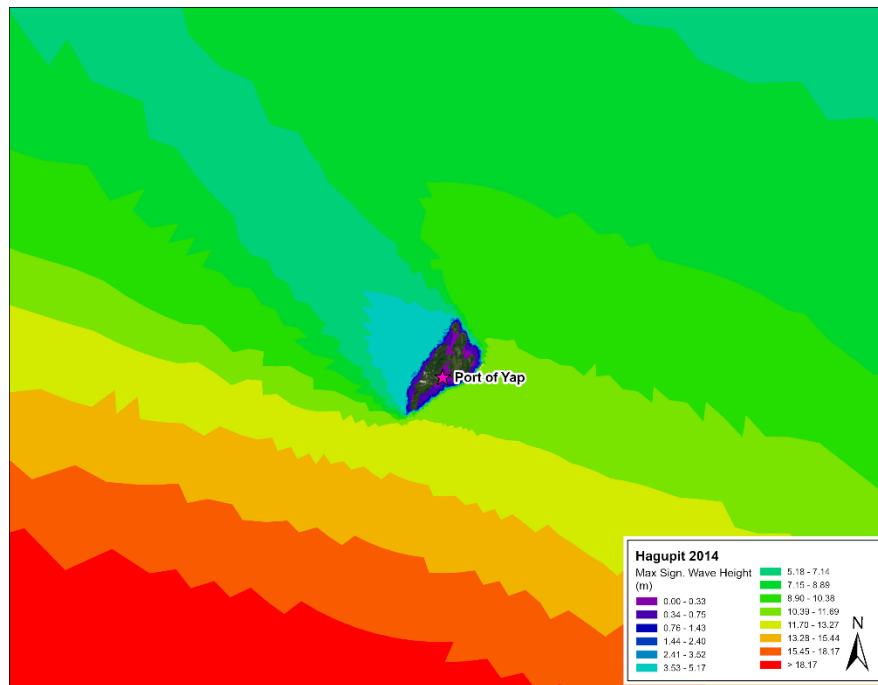


Figure 5-24 Maximum Significant Wave Height at Yap – Hagupit 2014

5.4.3.1.4 Haiyan 2013

The maximum modeled significant wave height during Typhoon Haiyan of 2013 was 0.09 m near the port.

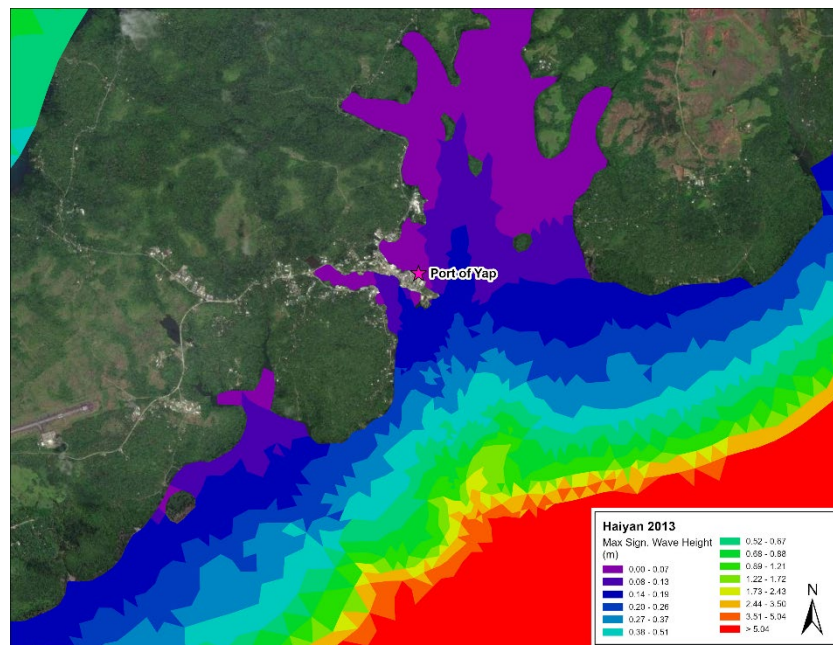


Figure 5-25 Maximum Significant Wave Height at the Port – Haiyan 2013

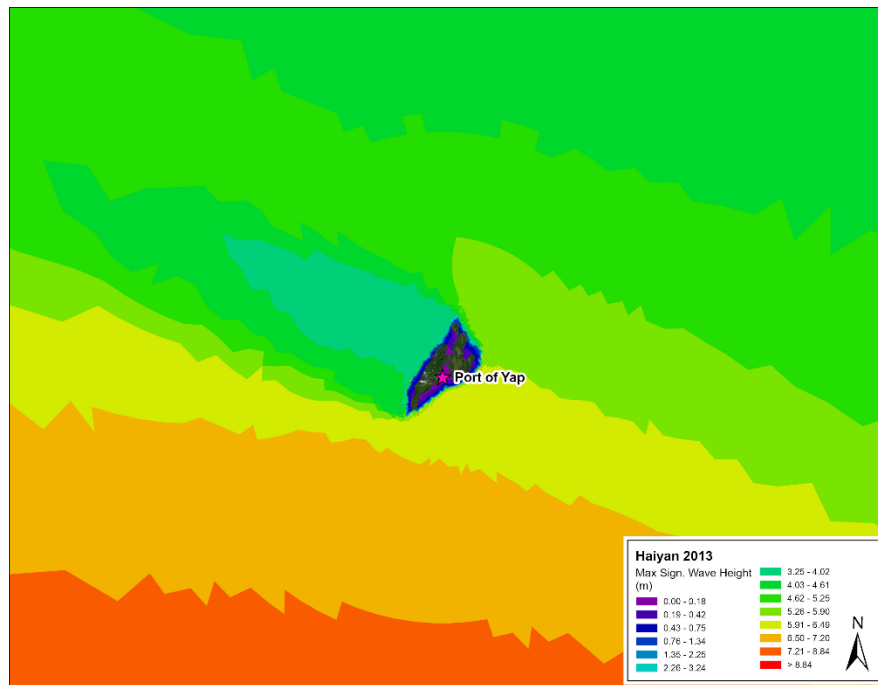


Figure 5-26 Maximum Significant Wave Height at Yap – Haiyan 2013

5.4.3.1.5 Haima 2016

The maximum modeled significant wave height during Typhoon Haima of 2016 was 0.12 m near the port.

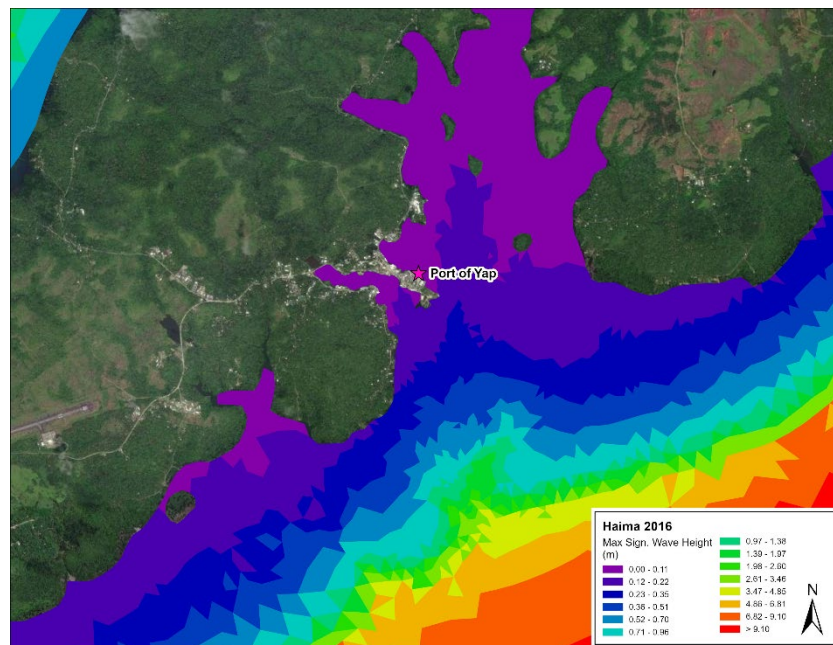


Figure 5-27 Maximum Significant Wave Height at the Port – Haima 2016

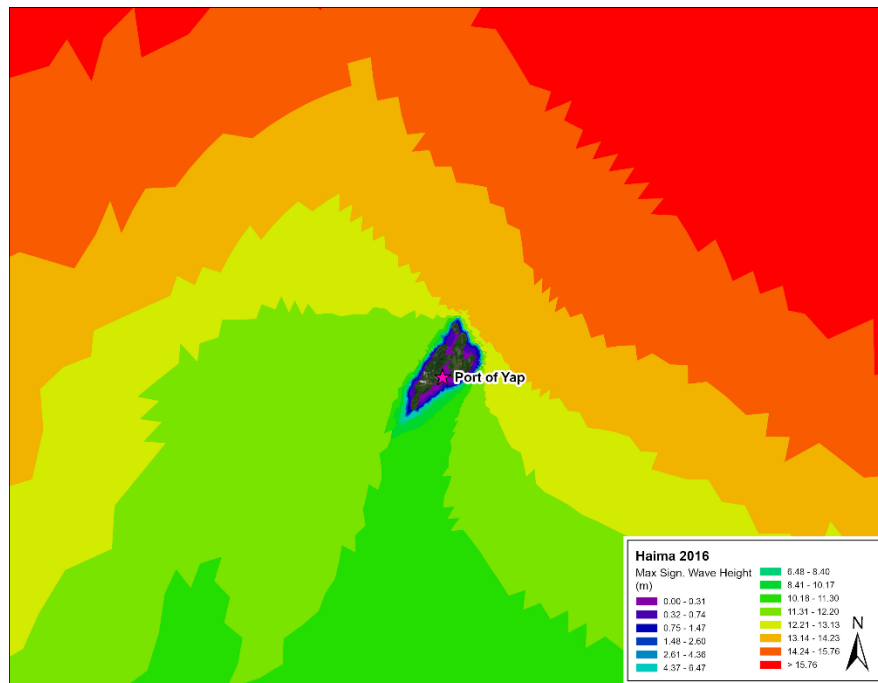


Figure 5-28 Maximum Significant Wave Height at Yap – Haima 2016

5.4.3.1.6 Nock-Ten 2016

The maximum modeled significant wave height during Typhoon Nock-Ten of 2016 was 0.80 m near the port.

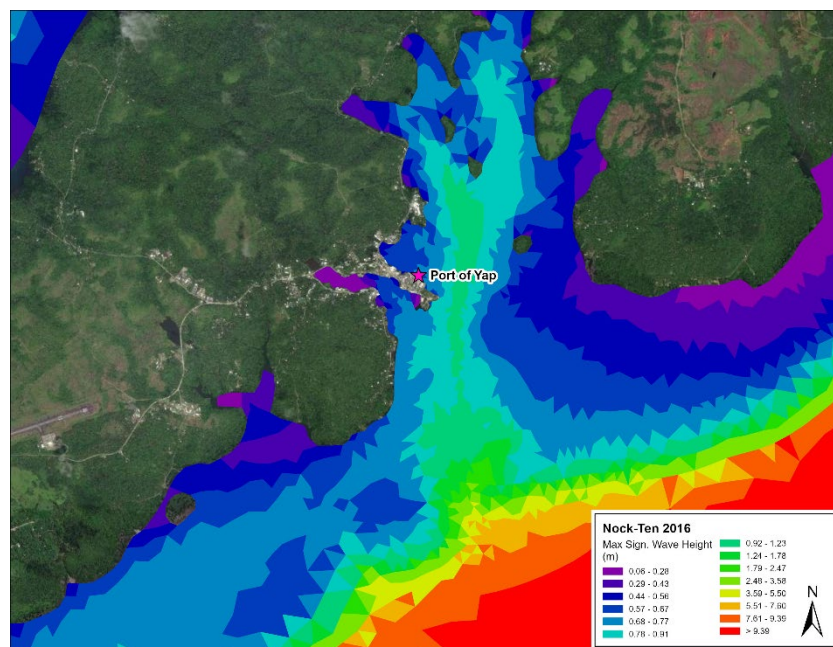


Figure 5-29 Maximum Significant Wave Height at the Port – Nock-Ten 2016

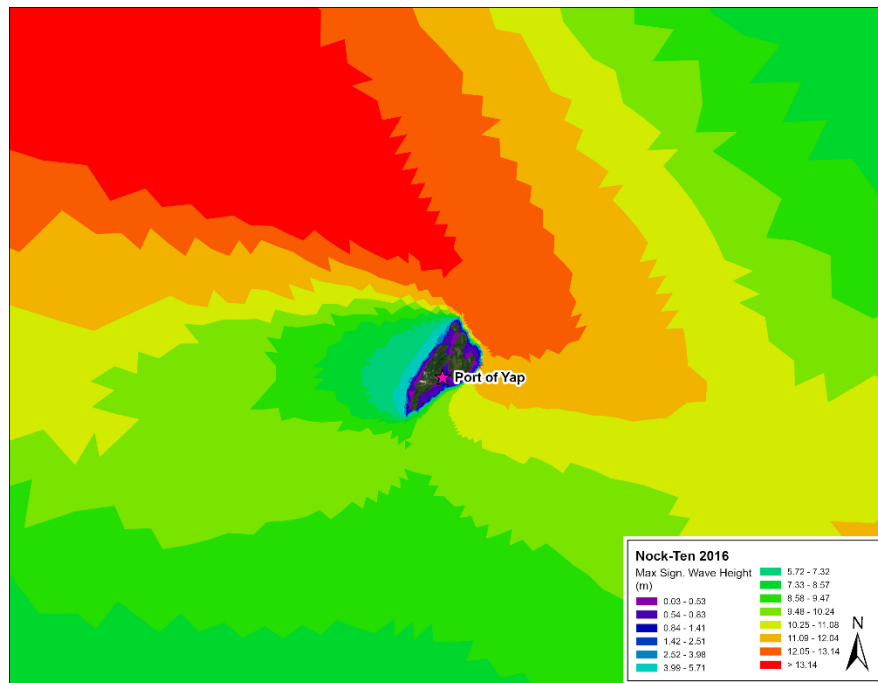


Figure 5-30 Maximum Significant Wave Height at Yap – Nock-Ten 2016

5.4.3.1.7 Maysak 2015

The maximum modeled significant wave height during Typhoon Maysak of 2015 was 0.53 m near the port.

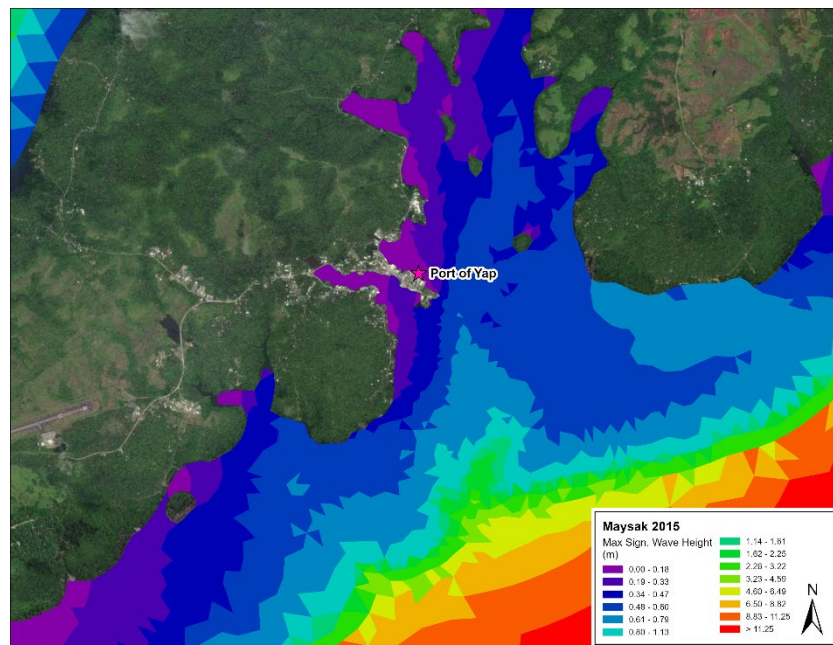


Figure 5-31 Maximum Significant Wave Height at the Port – Maysak 2015

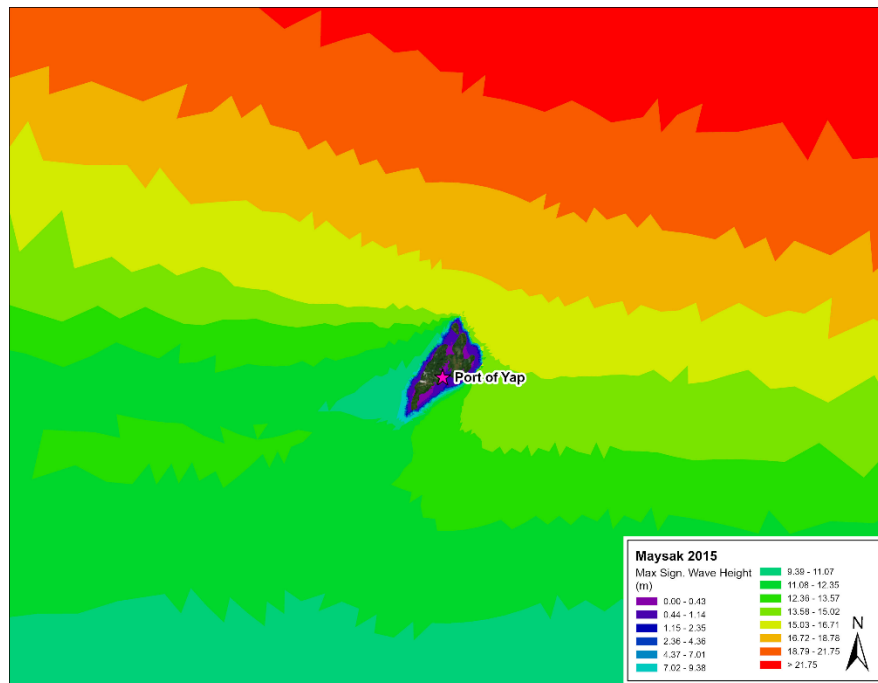


Figure 5-32 Maximum Significant Wave Height at Yap – Maysak 2015

5.4.3.1.8 Omais 2010

The maximum modeled significant wave height during Typhoon Omais of 2010 was 0.20 m near the port.

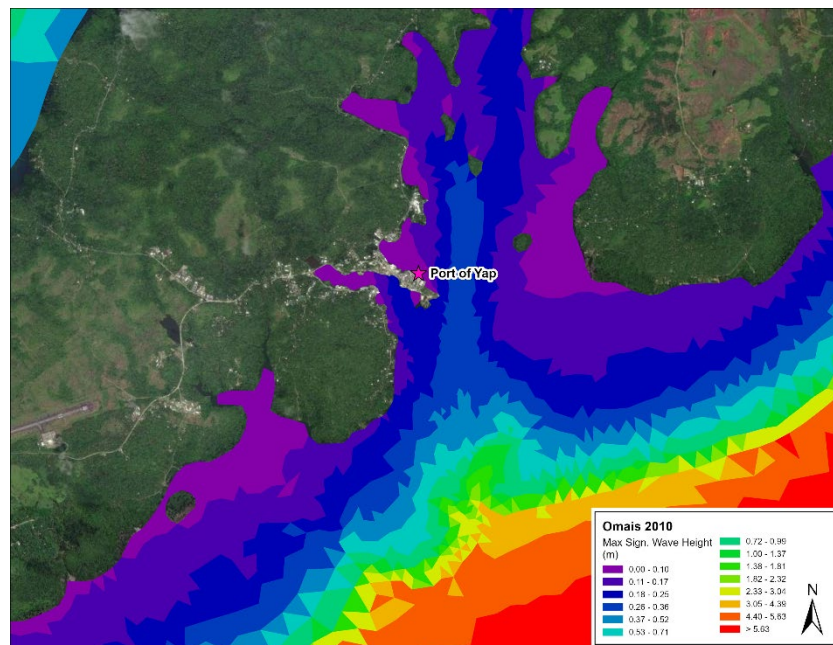


Figure 5-33 Maximum Significant Wave Height at the Port – Omais 2010

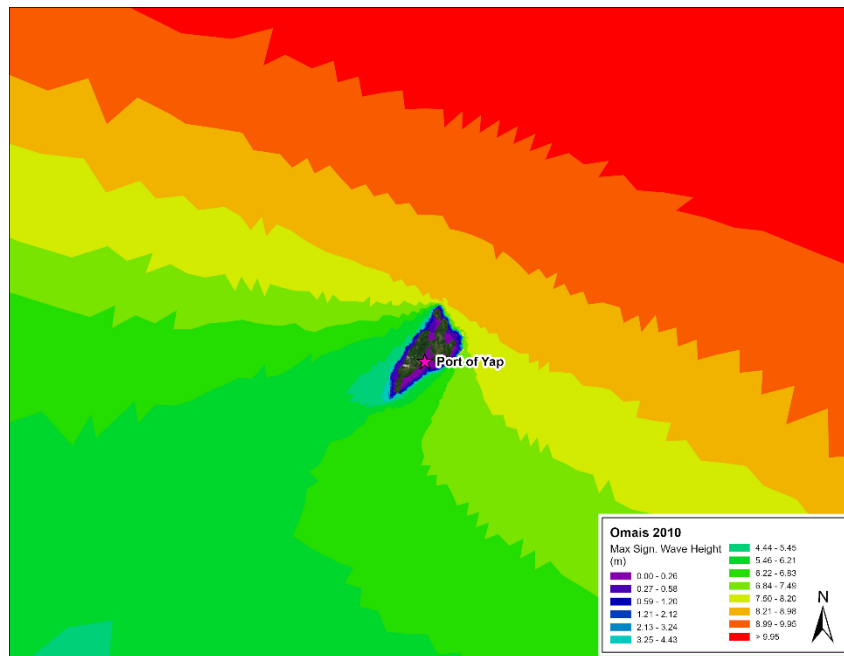


Figure 5-34 Maximum Significant Wave Height at Yap – Omais 2010

5.4.3.2 Peak Wave Period

Maximum modeled peak wave periods range from 20.0 to 13.4 s within the port area, as shown in Figure 5-35 through Figure 5-42.

5.4.3.2.1 Sudal 2004

The maximum modeled peak wave period during Typhoon Sudal of 2004 was 18.1 s near the port.

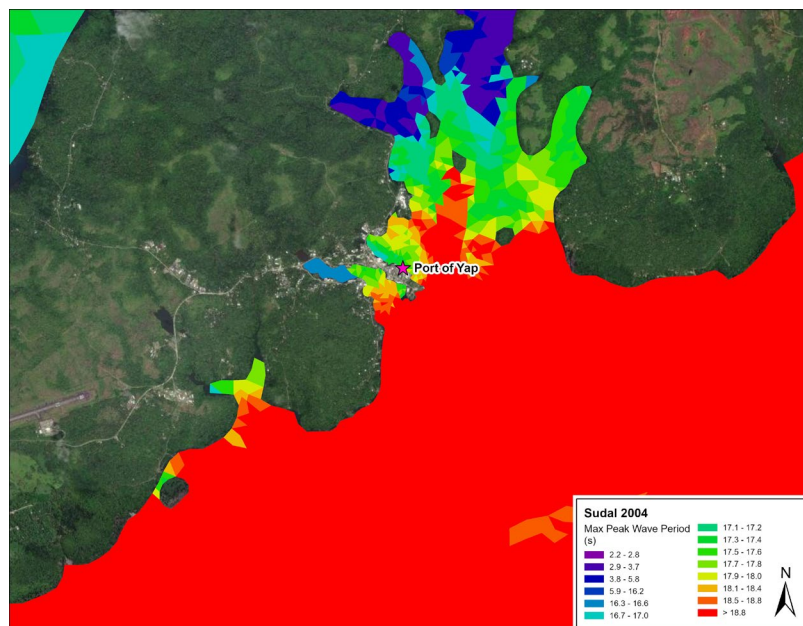


Figure 5-35 Maximum Peak Wave Period at the Port – Sudal 2004

5.4.3.2.2 Mitag 2002

The maximum modeled peak wave period during Typhoon Mitag of 2002 was 18.0 s near the port.

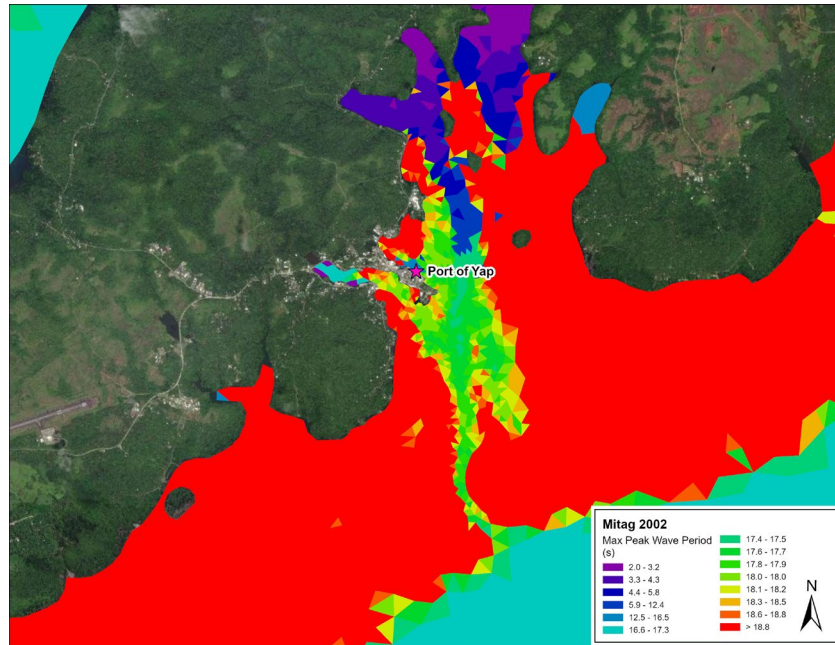


Figure 5-36 Maximum Peak Wave Period at the Port – Mitag 2002

5.4.3.2.3 Hagupit 2014

The maximum modeled peak wave period during Typhoon Hagupit of 2014 was 18.4 s near the port.

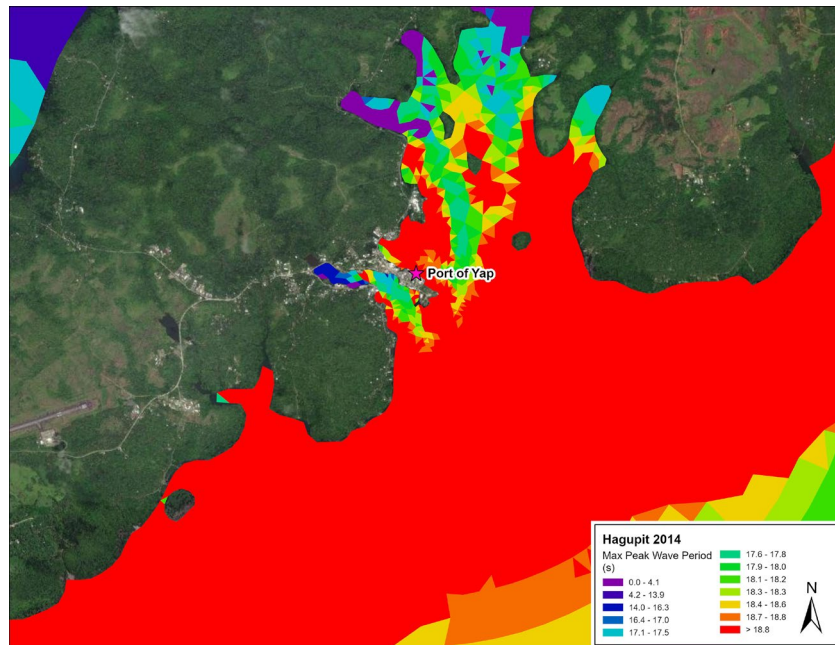


Figure 5-37 Maximum Peak Wave Period at the Port – Hagupit 2014

5.4.3.2.4 Haiyan 2013

The maximum modeled peak wave period during Typhoon Haiyan of 2013 was 17.7 s near the port.

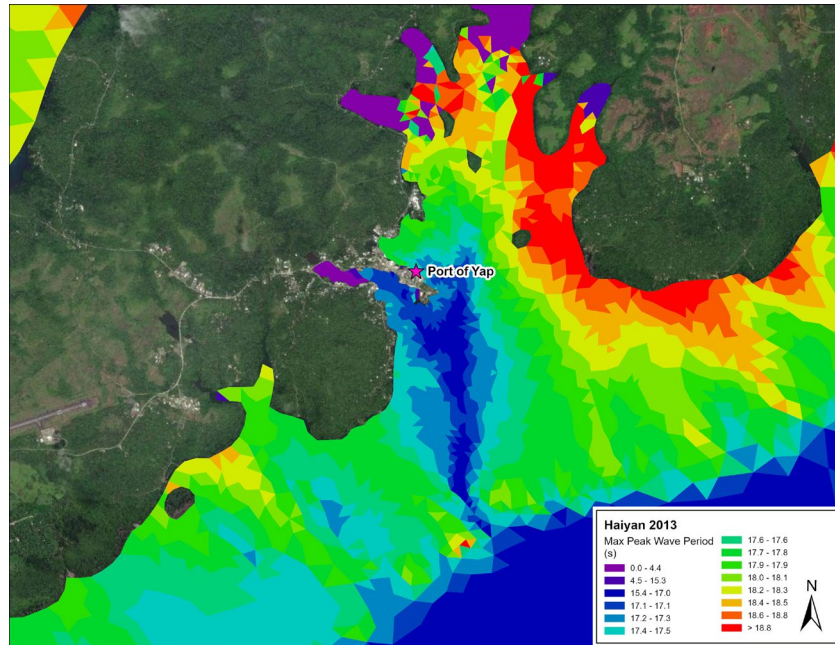


Figure 5-38 Maximum Peak Wave Period at the Port – Haiyan 2013

5.4.3.2.5 Haima 2016

The maximum modeled peak wave period during Typhoon Haima of 2016 was 16.2 s near the port.

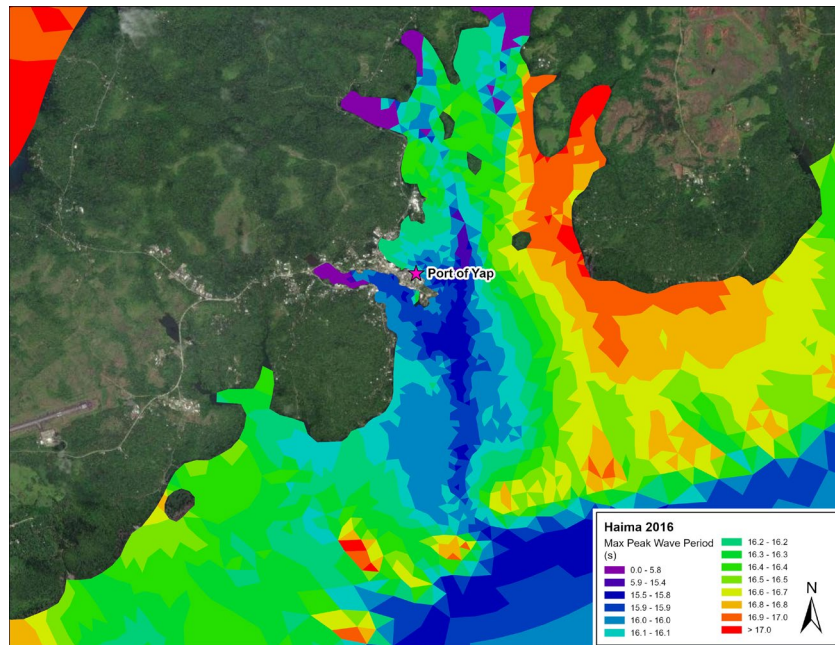


Figure 5-39 Maximum Peak Wave Period at the Port – Haima 2016

5.4.3.2.6 Nock-Ten 2016

The maximum modeled peak wave period during Typhoon Nock-Ten of 2016 was 14.7 s near the port.

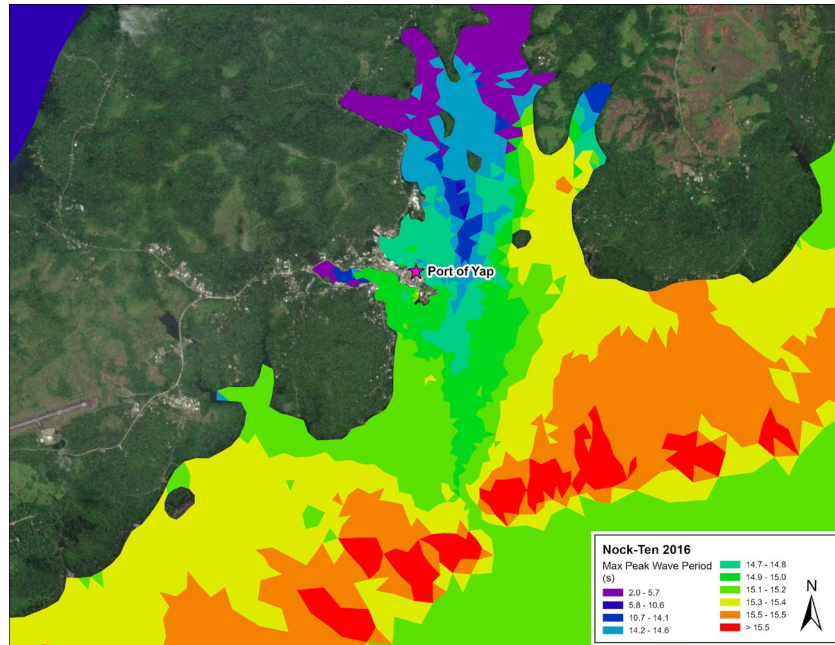


Figure 5-40 Maximum Peak Wave Period at the Port – Nock-Ten 2016

5.4.3.2.7 Maysak 2015

The maximum modeled peak wave period during Typhoon Maysak of 2015 was 20.0 s near the port.

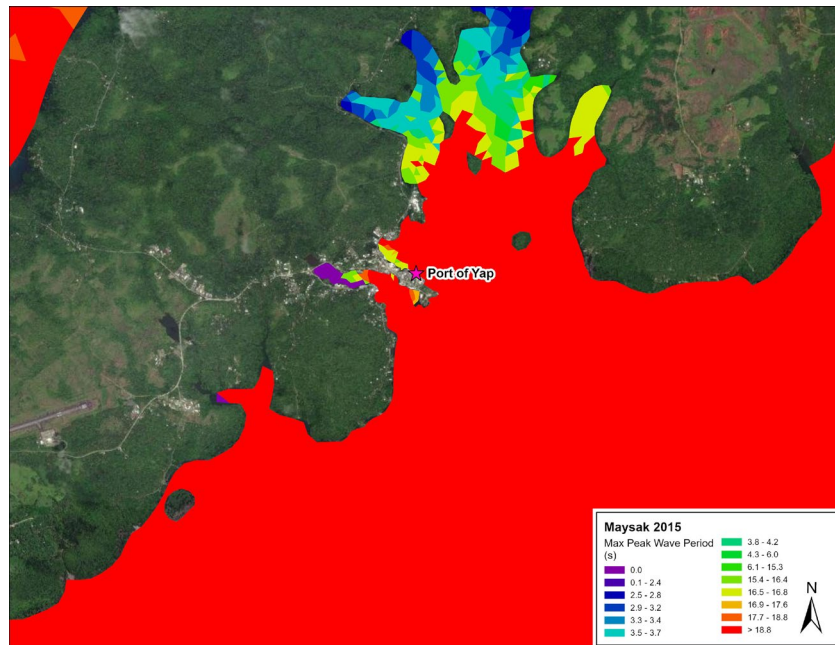


Figure 5-41 Maximum Peak Wave Period at the Port – Maysak 2015

5.4.3.2.8 Omais 2010

The maximum modeled peak wave period during Typhoon Omais of 2010 was 13.4 s near the port.

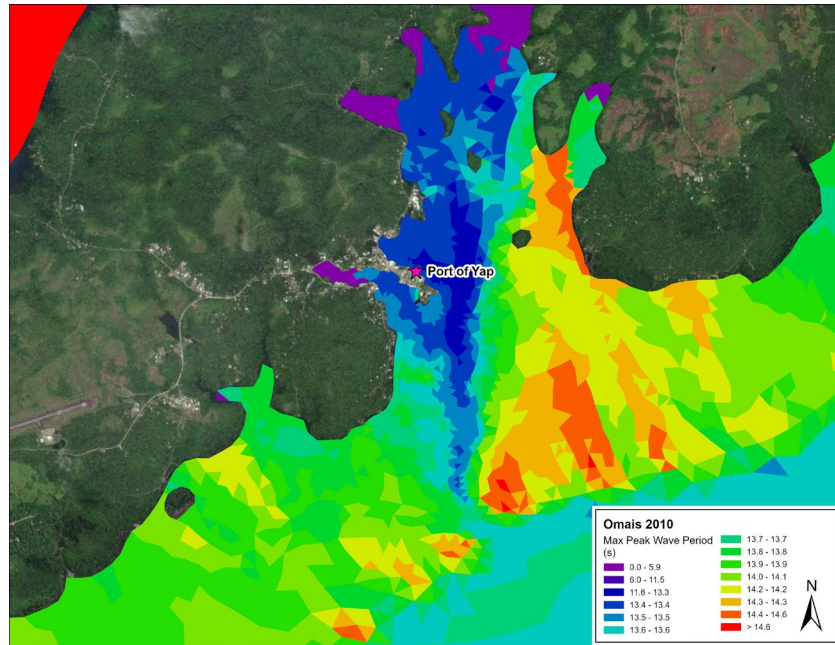


Figure 5-42 Maximum Peak Wave Period at the Port – Omais 2010

6 HARBOR TRANQUILITY

6.1 Approach

A harbor agitation model was developed to further examine the wave transformation into the harbor during extreme conditions. The objective of the harbor wave modeling is to understand the wave forcing components at the Yap Port. This was undertaken using the MIKE 3 Wave Model FM, a phase resolving non-hydrostatic wave model that is based on the 3D Navier-Stokes equations and with free surface described as a height function (DHI, 2023). The wave model was developed for the assessment of harbor layout and wave disturbance and allows for the use of a flexible unstructured mesh. The model is capable of simulating the processes of wave diffraction, reflection, and refraction at a small length scale (order of meters).

6.1.1 Model Domain

The model domain was informed by the results of the extreme (typhoon) modeling. The Yap Port is naturally sheltered by shallow reefs. Wave roses were extracted from an offshore boundary extraction point shown in Figure 6-1 and Figure 6-2. The typhoon modeling results indicate that waves enter the lagoon and harbor from an easterly-southeasterly direction. Thus, the domain, as shown in Figure 6-3, has been truncated to maximize wave reception from these directions. Parts of the reef further northeast and southeast that are obstructed by the surrounding land masses have been omitted.

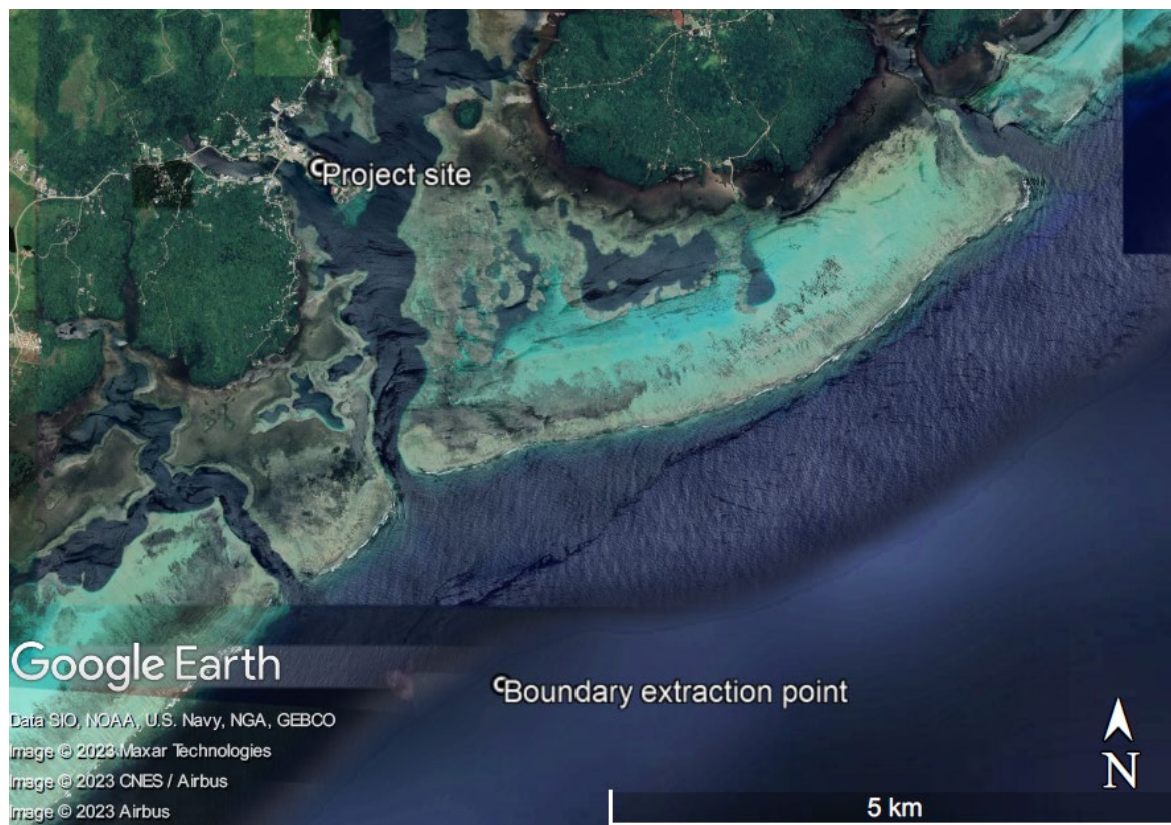


Figure 6-1. Offshore Boundary Extraction Point

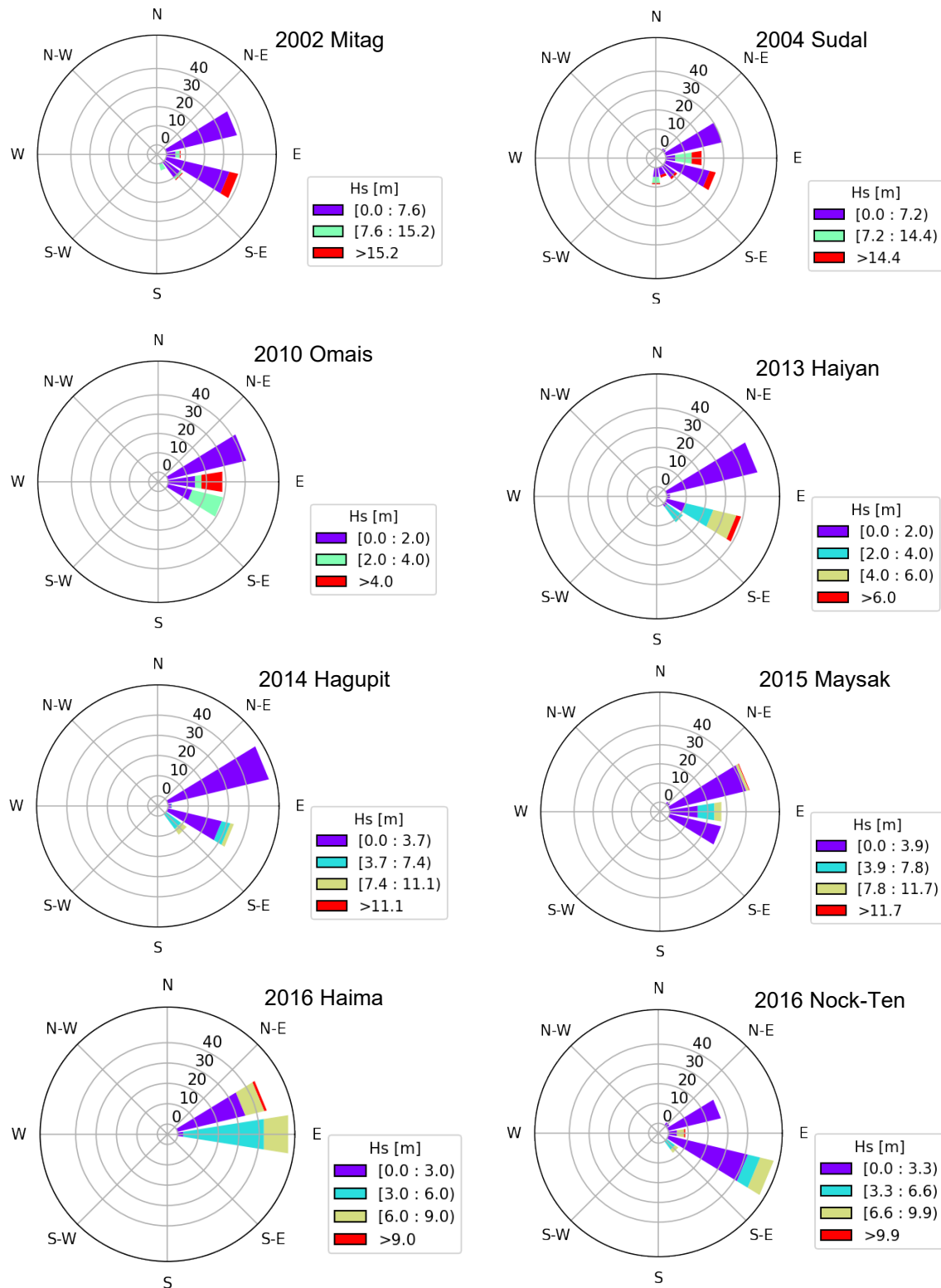


Figure 6-2 Typhoon Wave Roses at the Offshore Boundary Extraction Point



Figure 6-3 Wave 3 Model Domain

6.1.1.1 Mesh

An unstructured triangular mesh was developed for the project area. The shoreline data was extracted from the Office of Coast Survey through the NOAA. The mesh triangular area was constructed uniformly across the model domain. A vertical mesh consisting of ten equidistance layers was applied. Several production runs were conducted to evaluate the model's sensitivity to mesh resolution, with the finding that varying the resolution can optimize computational time. A coarser mesh at the offshore area would allow for less mesh elements and faster simulation times, while a finer mesh resolution on nearshore areas, steep bathymetry slopes, and at the navigation channel would help stabilize the model preventing simulation blow-ups. The domain covers an area of approximately 4,500 m by 7,000 m.

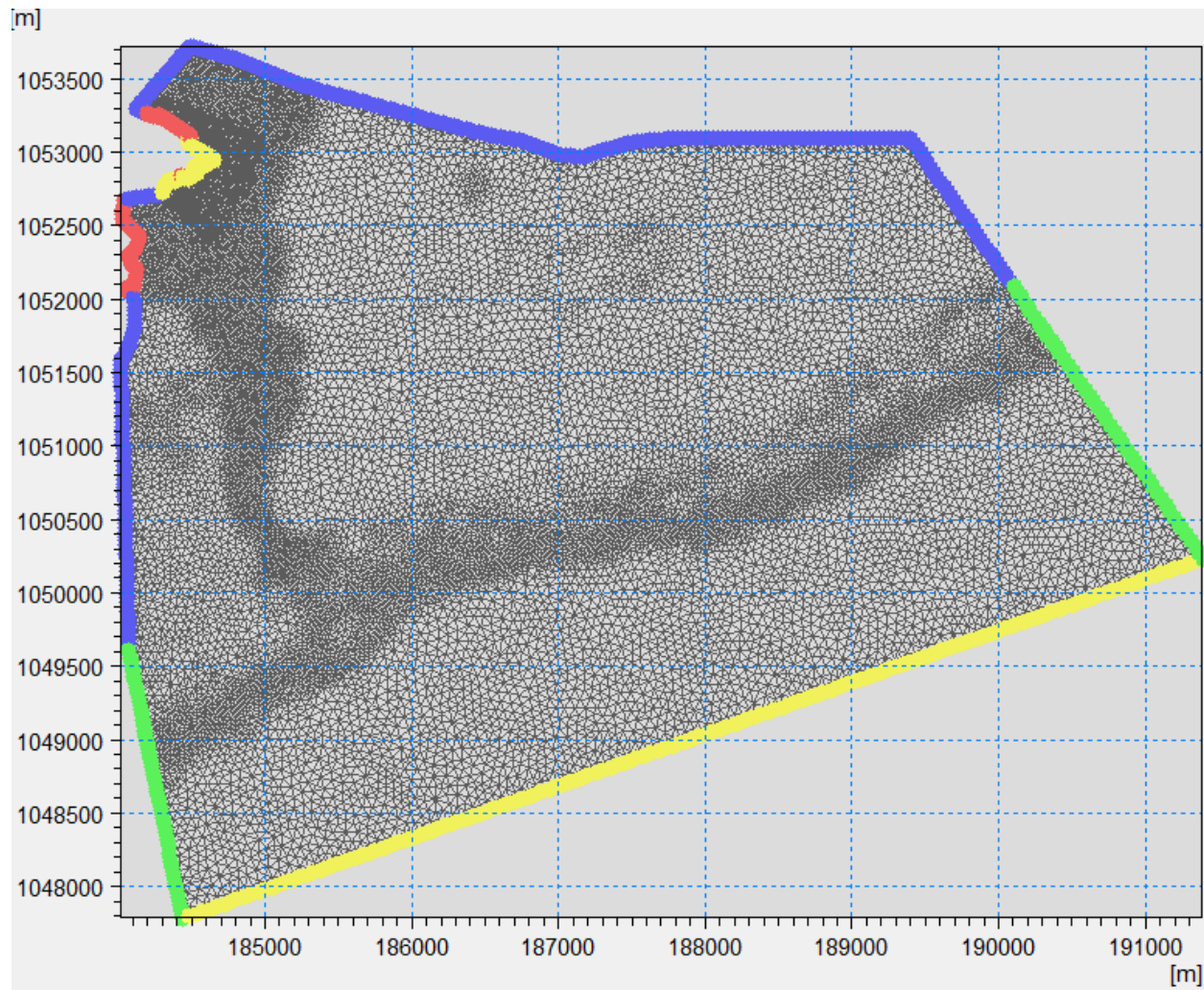


Figure 6-4 Model Unstructured Triangular Mesh

6.1.1.2 Bathymetry

The same bathymetry data sources discussed in Section 4.1.4 were used in generating the model bathymetry for the MIKE 3 Wave model. Bathymetry was edited as needed around the coastline and offshore area for model stability:

- Limited by insufficient density of scatter data, the resulting digital bathymetry surface contained artificial, abrupt slopes and high-spots. To overcome the limitation, artificial scatter points were introduced to increase the density of the data and to enable a smoother bathymetry surface to be generated, particularly around the edges of the reef and navigation channel.
- The offshore area at the model domain boundary has been flatlined to a depth of 50 m to stabilize the model boundary condition and to optimize simulation run time.

The bathymetry adopted in production simulation is shown below in Figure 6-5.

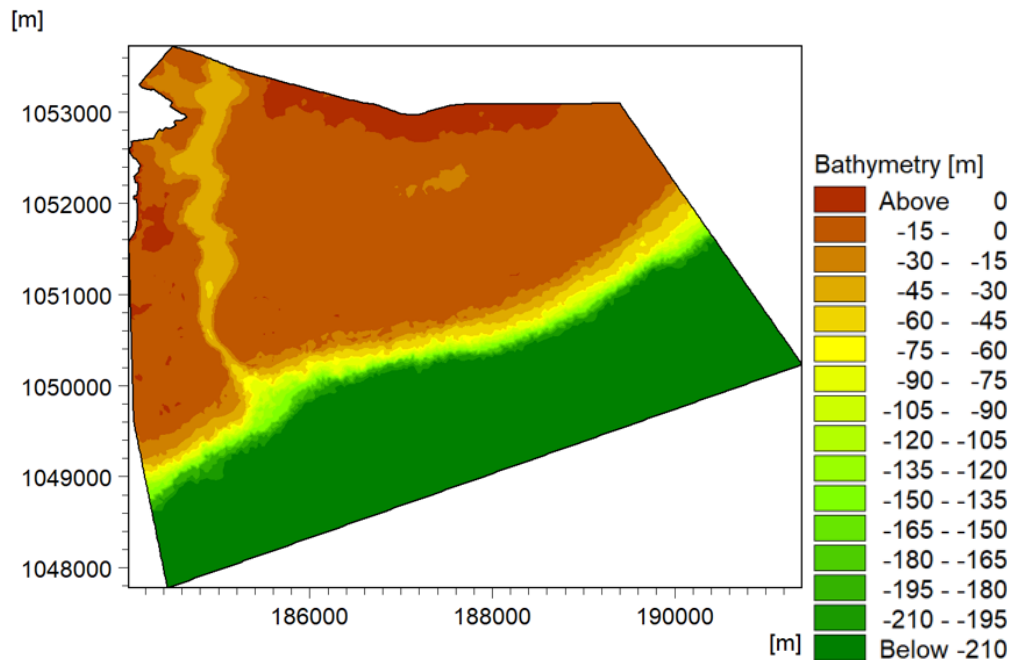


Figure 6-5 Model Bathymetry (m, MLLW)

6.1.2 Boundary Conditions

The boundary conditions of the MIKE 3 Wave model include land boundaries, a sponge layer, a porosity layer, and an internal wave generation zone. These boundaries are discussed in more detail below.

6.1.2.1 Sponge Layers and Porosity

The sponge layer provides numerical diffusion to dampen the reflected waves and eliminate instabilities generated near the model boundary and along the shoreline. A sponge layer was applied around the perimeter of the shoreline in all cases, with the exception of two segments of the shoreline in which a porosity layer was applied. A porosity layer allows for partial reflection and is used for cases of hardened shorelines or structures. The segments of shoreline in which a porosity layer was used include the structures surrounding the port and the adjacent shoreline to the west, as shown below in Figure 6-6. Both the sponge and porosity layers have a width of 200 m. The boundary conditions shown in Figure 6-6 show the sponge and porosity layers as Code 5, 6, and 7, respectively.

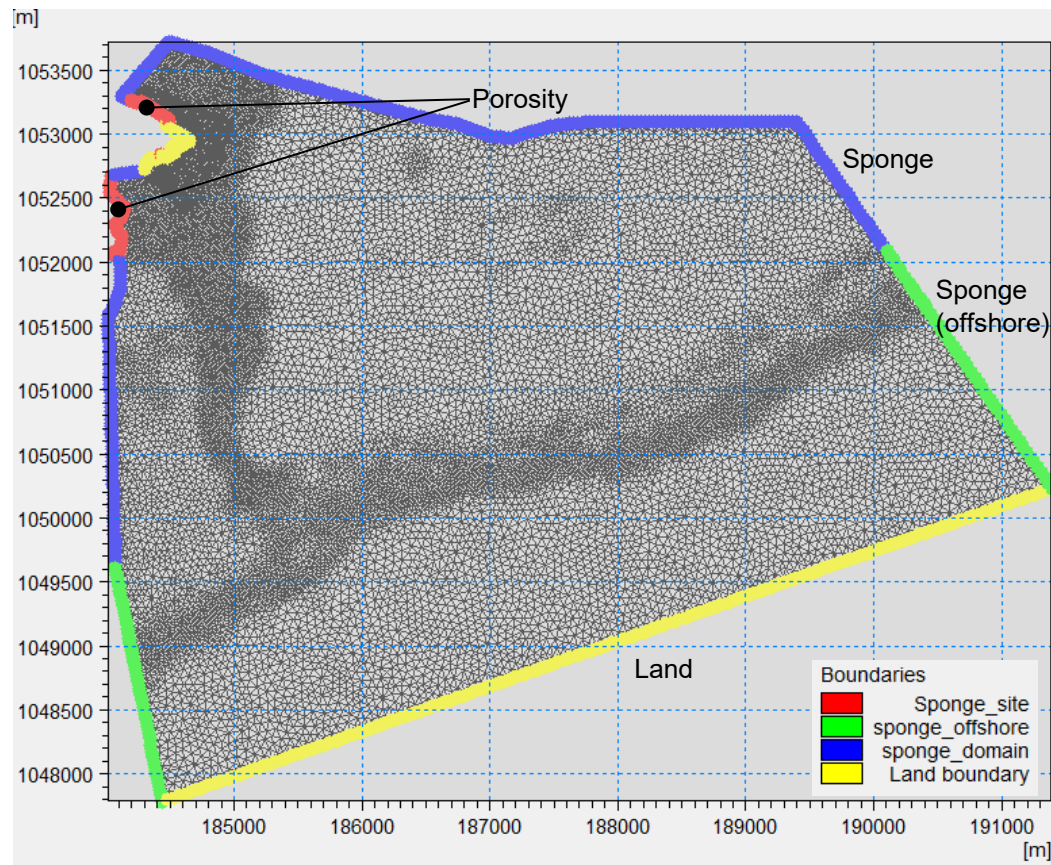


Figure 6-6 Boundary Conditions Displaying the Sponge Layer, Porosity Layer, and Land

6.1.2.2 Internal Wave Generation

Internal wave generation lines were defined at the boundary of the model, as shown below in Figure 6-7. The internal wave generation requires a relaxation zone, in which the width is equivalent to the wavelength of the boundary condition wave.

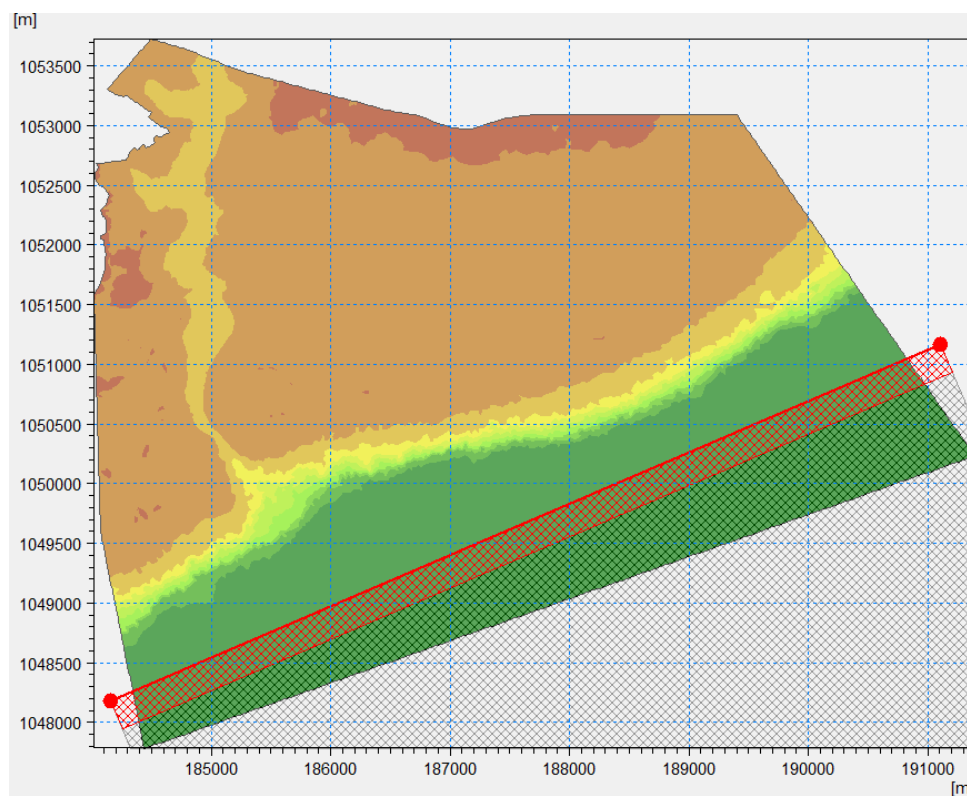


Figure 6-7 Internal Wave Generation Zone (relaxation zone shown by red hatch)

6.2 Model Scenarios

The extreme scenarios were developed through an examination of the typhoon modeling results. Significant wave height, peak period, and mean wave direction were extracted at the boundary of the Wave 3 model shown in Figure 6-1. Model results were used to evaluate the wave conditions both at the boundary of the Wave 3 domain and adjacent to the port.

In general, the peak wave conditions for the majority of typhoons are associated with relatively long period waves (i.e., >8 seconds), as evident in Table 6-1. Scenarios are most extreme when the storm passes south of the island, where the typhoon eye-wall introduces the most influence. Notwithstanding, as illustrated in Figure 6-8, the surrounding reef and shallow bathymetry of the island depleted most of these typhonic waves. This has resulted in the waves being experienced at the port being substantially dampened to below 1-m wave height and short peak periods (i.e. < 4 seconds). Such a short period indicates that wind waves will govern the extreme wave climate at the port. The MIKE 3 Wave was run on the critical typhoon condition with the highest significant wave height – 2002 Mitag.

Table 6-1 Wave Conditions Associated with the Peak Period for Each Typhoon

Name of Storm	Year	Direction of Path from Yap	Peak Period (s)	Significant Wave Height (m)	Mean Direction (degrees)
Mitag	2002	South & West	15.9	22.7	105.9
Sudal	2004	South & West	15.9	21.5	99.1
Omais	2010	North & East	13.6	5.9	85.4

Name of Storm	Year	Direction of Path from Yap	Peak Period (s)	Significant Wave Height (m)	Mean Direction (degrees)
Hagupit	2014	South	14.4	6.1	121.7
Haiyan	2013	South	15.6	11.1	124.5
Maysak	2015	North	16.2	11.8	75.9
Haima	2016	North	16.0	9.0	75.1
Nok-Ten	2016	South & West	13.6	10.0	94.3

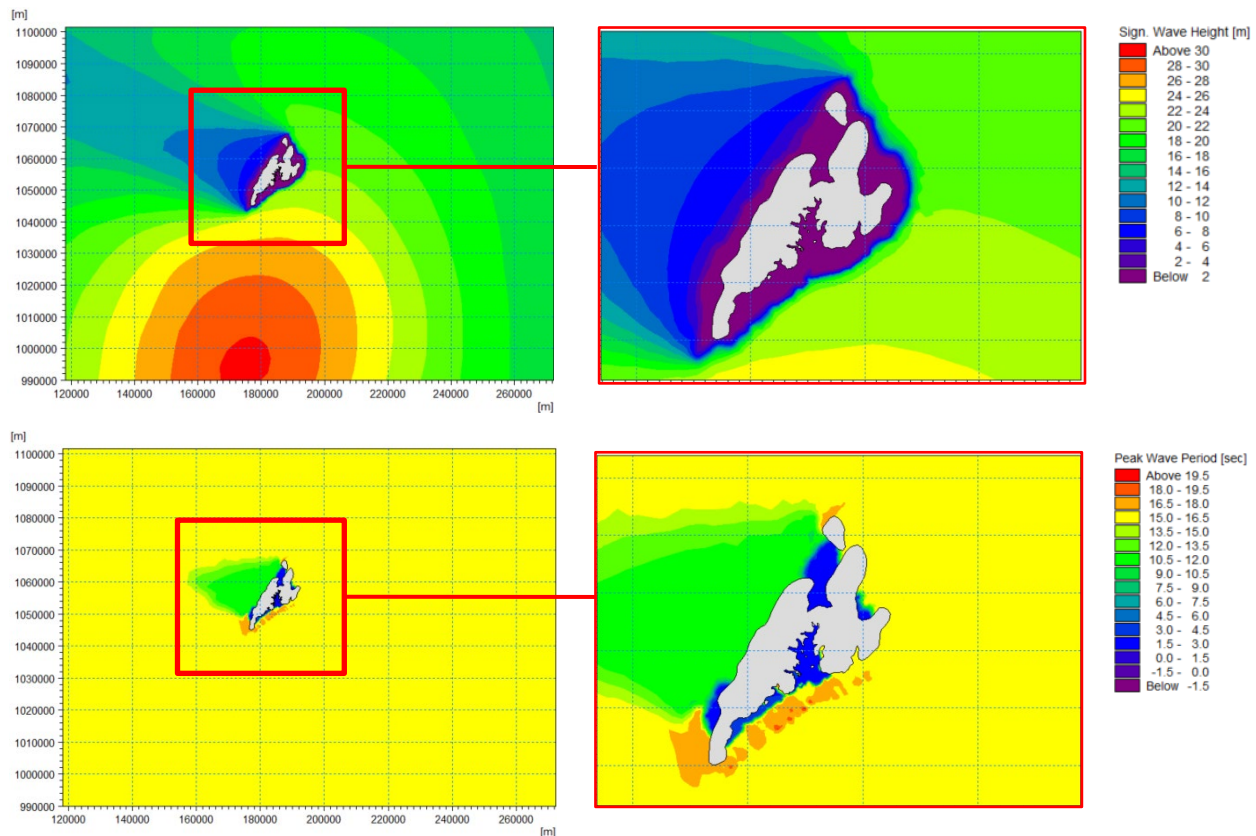


Figure 6-8 Peak Period Model Results for Typhoon Mitag at 2/03/2002 22:40:00

6.3 Model Extraction Points

The extraction points for the MIKE 3 Wave model comprise of two points. These points are located at the navigation channel entrance and adjacent to the port. The location of these points is shown below in Figure 6-9 and summarized Table 6-2. These points are utilized in extracting times-series for the model validation and results in the subsequent sections.

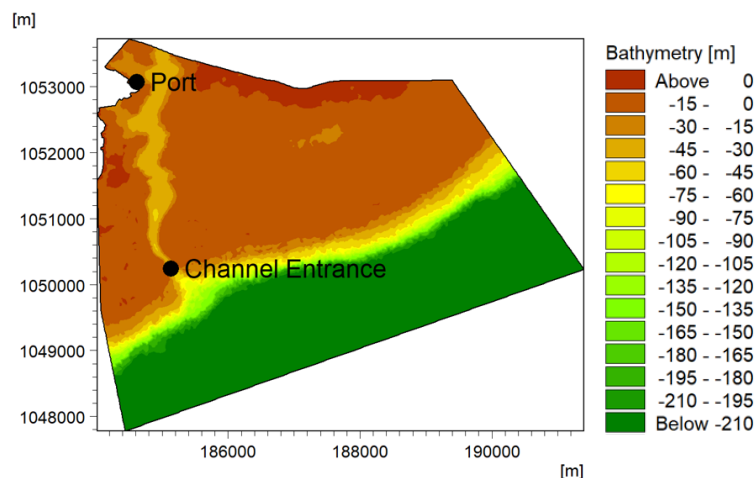


Figure 6-9 Model Extraction Points

Table 6-2 Wave 3 Model Extraction Points

Extraction Point	Eastings (m)	Northings (m)	Model Seabed Elevation	
			m, MLLW	ft, MLLW
Port	184616.013	1053076.052	-24	-79
Channel Entrance	185126.711	1050240.398	-42	-138

Northings and eastings are presented in UTM Zone 54N (meters)

6.4 Model Validation

6.4.1 Model Sensitivity

Various parameters were evaluated during the modelling process to aid the development of the model, such as the solution technique and bed roughness. Calibration of the harbor tranquility model was not undertaken due to a lack of sufficient data reflecting larger wave events (i.e., storm or typhoon). In-situ metocean data within the model domain was collected in 2024, however this data suggest wind chop, whereas this model is largely testing for longer period swell waves assumed to penetrate the outer reef during a typhoon. As such, results were extracted at the two points within the model for the purposes of sensitivity testing.

6.4.1.1 Solution Technique

The Wave 3 FM module allows for a specification of the HLLC Riemann solver factor, which accounts for the numerical dissipation of breaking waves. The Riemann solver allows for the robust and stable simulation of flows that involve shocks or discontinuities, which is required for modeling waves in the breaker zone or along porous structures (in the case of Yap, the reef area). The model documentation states that for simulations using a triangular element mesh, spurious noise can occur in the horizontal velocity field that can be removed by applying the HLLC solver with a Riemann factor of 0.05 or higher.

To evaluate the impact of the HLLC solver, HLLC factors of 0.05 and 0.9 were examined in the initial model runs. The model was forced with monochromatic wave conditions with 23-m wave heights and a 16 second period from 105 degrees.

The results indicate that wave dissipation is much greater with the HLLC solver factor set to the higher range at 0.9. The high range HLLC results at the channel displays substantially lower water surface elevation oscillation with negligible waves when compared to the low range HLLC, as illustrated below in Figure 6-10 and Figure 6-11

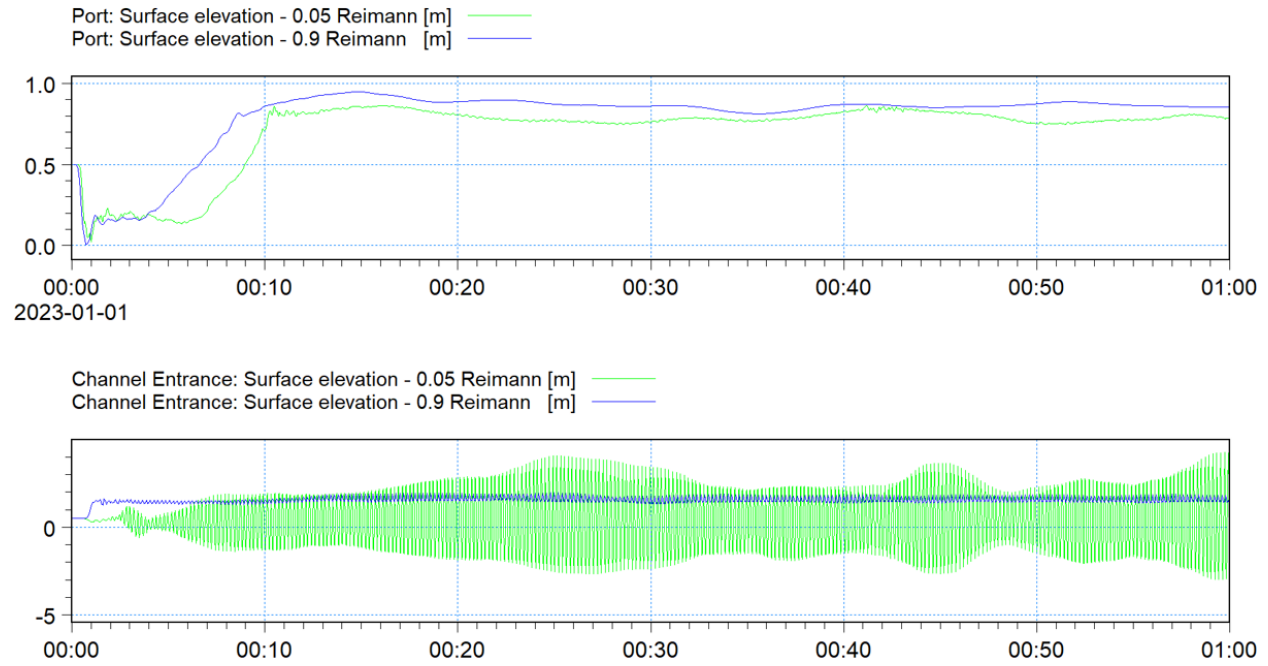


Figure 6-10 Modeled Water Surface Elevation

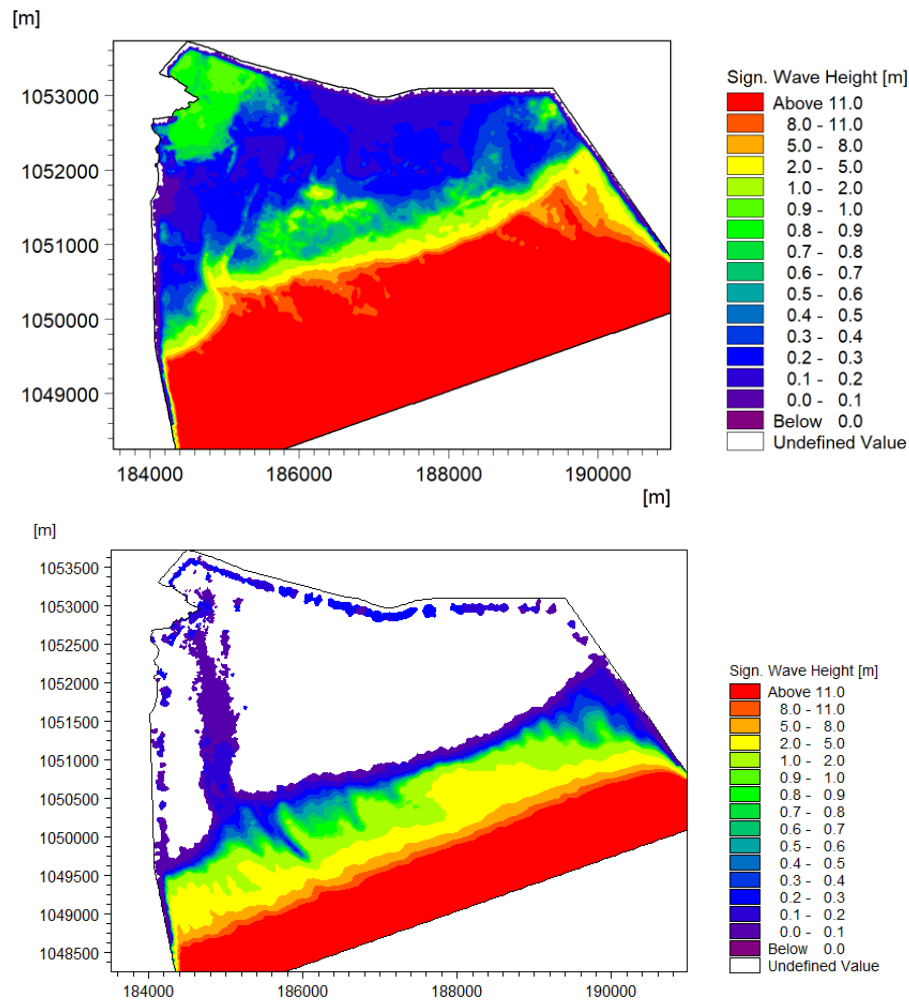


Figure 6-11 Modeled Significant Wave Height with Low HLLC Factor ((top) and High HLLC Factor (bottom)

6.4.1.2 Bed Resistance

The Wave 3 FM documentation states that bed resistance is relatively unimportant for short-period waves due to the idea that the area covered by most short-period waves is very small and there is usually not a sufficient distance for bed resistance to attain any significant effect on short wave propagation. The exception to this is very high waves combined with very shallow water. Long-period waves, however, may be more sensitive to the effects of bed resistance.

In reference to the characteristics of the typhoon waves at Yap and in order to test the model's sensitivity to bed resistance, the model was examined with monochromatic wave conditions with 23-m wave heights and a 16-second period from 105 degrees and with the low range and typical range of roughness heights. The low range of bed resistance was specified at 0.01 m, while the high range was specified as 0.3 m, which is within the normal range of roughness height (DHI, 2023).

The results indicate that bed resistance does not impact significant wave height or water surface elevation throughout the domain of the model. The difference in water surface elevation results between the low and high range of bed resistance was about 0.1 m, and these bed resistance factors had no impact on the timing of the waves from the boundary to arrive at the extraction point. Based on these results, bed resistance

was not included in the model parameters for the extreme scenarios. The results are presented below in Figure 6-13.

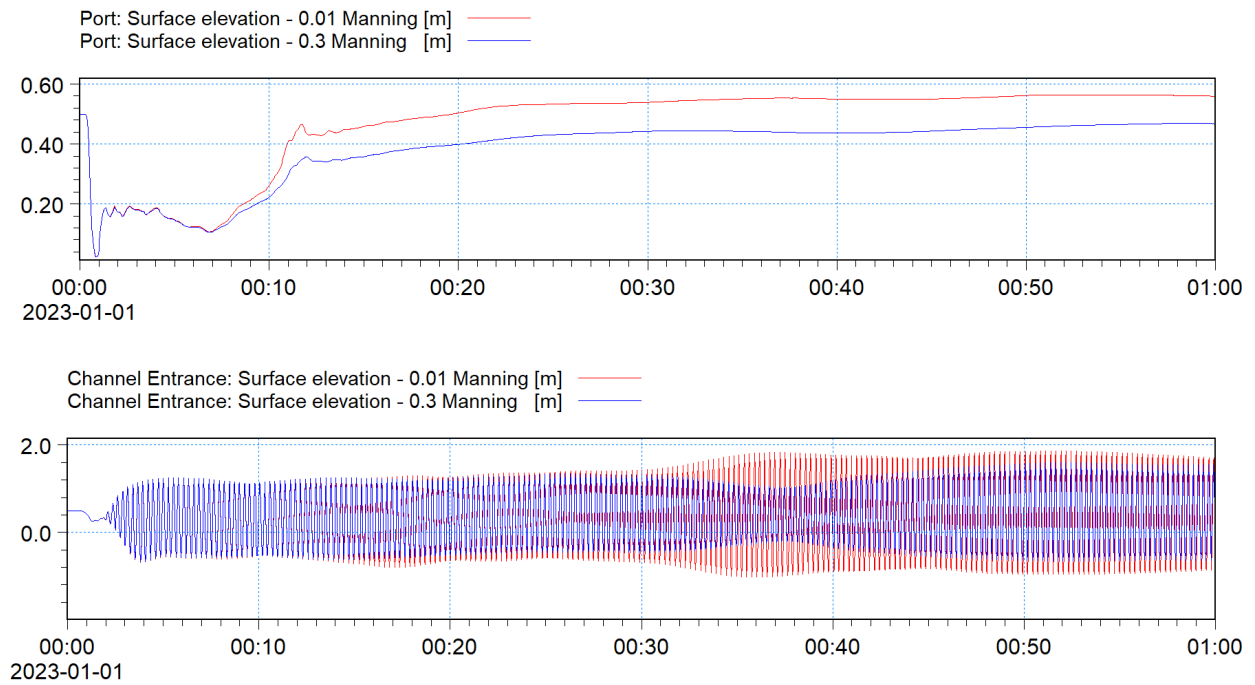


Figure 6-12 Modeled Water Surface Elevation

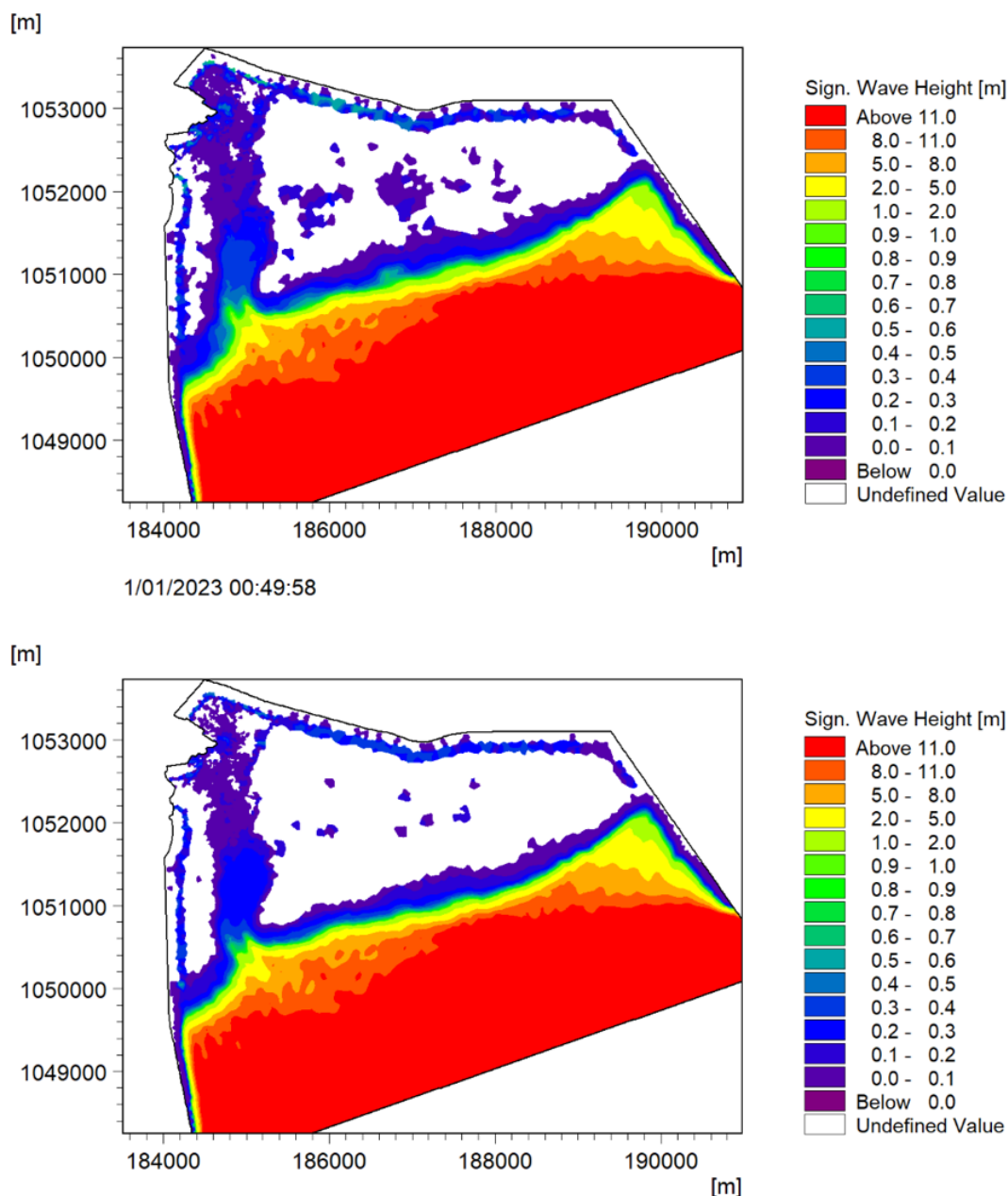


Figure 6-13. Modeled Significant Wave Height with Low Bed Resistance (top) and High Bed Resistance (bottom)

6.5 Results

Significant wave height and water surface elevation were extracted from the model and are discussed in this section. The Typhoon Mitag scenario was run using boundary waves of 22 m in height with a 16.0 second period and southeasterly direction (105 degrees).

The results indicate that waves originating from a southeasterly direction tend to dissipate quickly as they encounter shallow depths at the surrounding reef. The significant wave height at the entrance channel peaked at 3.4 m (11.1 feet), while minimal waves resulted at the port, in the order of 0.2 m (0.6 feet). The port extraction point appears to be well sheltered from offshore waves by the shallow reef. The channel,

although with much greater depth than the reef, also dissipates the waves to much lower levels before reaching the port given its limited opening width compared to wavelength.

Table 6-3 Maximum Significant Wave Height at Extraction Points for Typhoon Mitag

Extraction Point	Maximum Significant Wave Height	
	meter	feet
Port	0.2	0.6
Channel Entrance	3.4	11.1

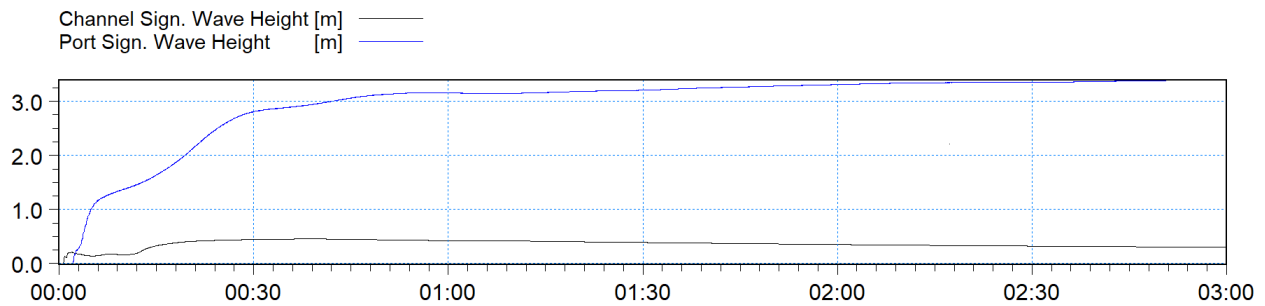


Figure 6-14 Modeled Significant Wave Height at Extraction Points for Typhoon Mitag

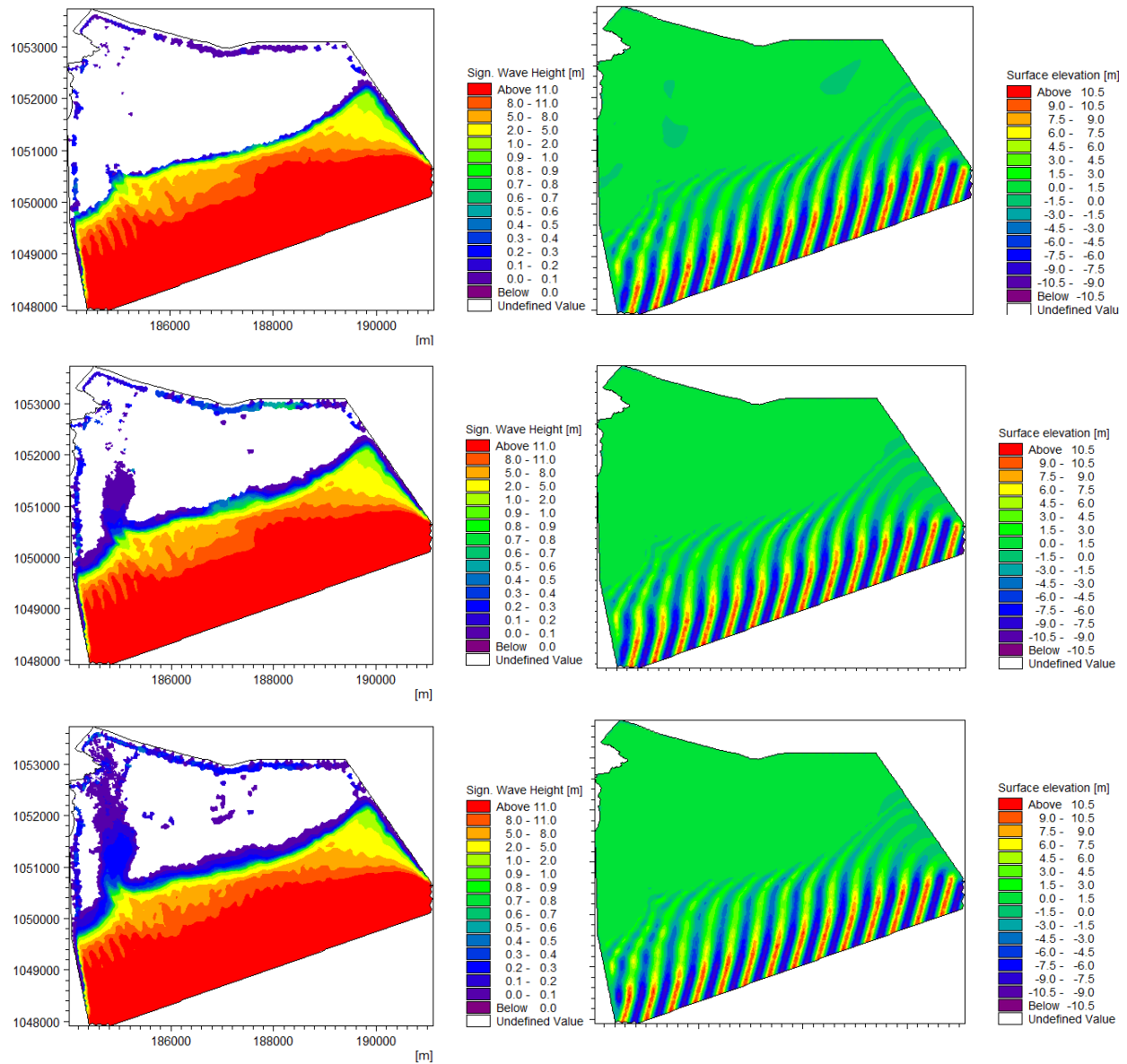


Figure 6-15. Significant Wave Height and Water Surface Elevation for Typhoon Mitag at the Time of Peak Wave Height for the Entrance (top) and Port (bottom) Extraction Points

7 DISCUSSION

The results of the metocean characterization and numerical modeling are intended for use in the design of wharf and navigation improvements. Site specific metocean data was collected in Yap throughout 2024 and data was used to validate the HD/SW numerical models, increasing confidence in the model results. These models, as well as the analysis performed in this report, can be used to hindcast future conditions and aid design of navigation improvements.

7.1 HD/SW Numerical Modeling

- A one-year simulation of the ambient hydrodynamic and wave climate was performed for year 2022, which aligns with available satellite data for validation, and the long-term average wave energy at the site. The selected period was also under the influence of La Niña period which entails slightly higher-than-average water level. This is anticipated to increase wave penetration at the site.
- Validation of the model results was performed considering offshore wave satellite altimetry measurements and water level data recorded from the Yap Port tide station. The model was able to satisfactorily capture both the significant wave height around the island, and the water levels at the port. In-situ field data collected in 2024 served to further validate the hydrodynamic and spectral wave models.
- Wave data, including significant wave height, peak period and mean wave direction was extracted from the model results at selected points. Offshore, ambient waves are energetic and regularly exceed 3 ft in height. However, at the Port, most of the waves are broken by the reef system resulting in a generally calm wave climate (Mean Hs of 0.1 ft).
- Similarly with the wave period, peak component of the wave spectrum at the offshore area generally has a peak wave period T_p between 5 to 15 seconds. However, most of these offshore sea-state waves break at the reef, resulting in approximately 50% of the waves at the Port having a T_p of less than 5s. Waves with period greater than 5s also generally have very low wave height Hs, less than 0.2 ft.
- Monthly distribution of wave height shows that the most energetic months are between January to May. Generally calmer wave climate can be experienced between June to October. The seasonal trend is not as prominent for the port area where Hs tends to remain below 1ft.
- Currents in the areas near the port are generally weak and not more than 0.1 knots in magnitude. Stronger currents can be observed along the Yap channel reaching as high as 0.8 knots, but around 0.4 knots on average.
- Currents at the port area also have very weak directionality indicating the reduced influence of tides in the currents. On the other hand, very strong directionality is observed along the turning basin and the Yap channel, with the flow directions generally following the channel alignment. In this case, flood currents travel northward to the site and ebb currents southward out of the harbor area.

7.2 Typhoon Modeling

- A simulation of the extreme hydrodynamic and wave climate was performed for eight different typhoons which were selected based on availability of data and recorded storm surge.

- Validation of the model results was performed considering water level data recorded from the Yap Port tide station. The model was able to satisfactorily capture the water levels at the port during the identified typhoons.
- Water level data was extracted from the model results within the Port and were compared to the recorded water levels during each typhoon. Maximum modeled water levels for each storm ranged from 2.34 m to 1.24 m, MLLW. Typhoon Sudal of 2004 both modeled and recorded the greatest water surface elevation. The largest error between measured and modeled water surface elevations is 0.52 m for Typhoon Hagupit of 2014.
- Wave data, including maximum significant wave height and maximum peak period, was extracted from the model results at a selected point near the Port. Most waves were broken by the reef system during the typhoons and resulted in significant wave heights ranging from 1.6 to 0.1 m. Of the typhoons, Typhoon Sudal of 2004, produced the largest modeled wave at the Port.
- Maximum significant peak wave periods at the Port during the typhoons ranged between 20.0 and 13.4 s. Typhoon Maysak of 2015 produced the largest modeled peak wave period at the Port.
- Maximum current speeds at the Port during the typhoons ranged between 0.09 and 0.03 m/s. Typhoon Haima of 2016 produced the largest modeled current speed at the Port. Current speeds during typhoons were generally similar to those in the ambient conditions model.

7.3 Harbor Tranquility

- A MIKE 3 Wave model was used to simulate wave agitation in the Yap Port during extreme events. The objective of the modeling is to understand the disturbance of water level at the Port during extreme events, to evaluate berth availability/downtime.
- The MIKE 3 Wave domain was orientated to maximize wave reception from a southeasterly wave approach, as the typhoon modeling results suggest that waves enter the lagoon from an easterly to a southeasterly direction. Several production runs, as well as sensitivity tests for various model parameters such as the Reinemann Solver, bed friction, and mesh size, were completed to better represent the likely wave conditions in the Port and to optimize the simulation times.
- The scenarios chosen to simulate the extreme events were based on the offshore wave height and peak wave period generated by Typhoon Mitag (2002), where significant wave heights greater than 20 m and peak period in the order of 16 s at the model boundary were simulated during the typhoon wave simulation. The eye-walls of the typhoons went past the vicinity of the project site, and created wave heights that were almost doubled that simulated for 2013 Haiyan and 2015 Maysak; additionally, the long wave period is expected to result in more wave penetration into the Port compared to short period wind waves. To establish the disturbance coefficient between the Port and offshore boundary, a monochromatic wave representing the Typhoon Mitag wave was applied at the boundary of the model.
- Regarding the wave direction at the boundary, the simulation of shortlisted Typhoons indicates that the dominant wave direction offshore Yap in a typhonic environment is in 90°-120°. While a southerly wave will be more critical to the Port due to co-direction with the channel that facilitates higher wave penetration, the likelihood of this hypothetical scenario is considered to be low given the orientation of the island as well as evidence from historical typhoon tracks.
- The modeled results suggest that wave propagation into Yap Port is limited for the scenarios considered. While wave propagation can be seen in the model results, waves dissipated relatively

quickly with nearly negligible wave heights resulted at the Port. The Mitag typhoon scenario, which represented a critical typhoon condition, indicated substantial wave dissipation is likely to take place within the reef area and the narrow Yap channel.

- While MIKE 3 Wave results suggest the penetration of offshore waves into the Port is limited, owing to the availability of fetch distance landward of the reef, short-period wind waves will likely be generated and experienced at the Port during typhonic conditions. Simulation of wind waves are not represented in MIKE 3 Wave and as such, local wave disturbance (or sea state) will be challenging for smaller craft.

8 CONCLUSIONS

This analysis included a desktop evaluation of metocean conditions and was followed by in-situ data collection and several coastal models to provide further insight into the typical and extreme metocean characteristics. The desktop evaluation revealed several data gaps that were facilitated by the field data collection, which began in January of 2024. The field data collection efforts also aimed to verify the desktop review and validate the numerical models. Field data collection included waves, water levels, and currents through the deployment of a spotter buoy, two seabed mounted ADCPs, and a vessel mounted ADCP.

A total of three models were built to further characterize the Project Site; a coupled HD and SW model, a typhoon model, and a harbor tranquility model. This numerical modeling effort aimed to characterize both the ambient and extreme (typhoon) conditions. The coupled HD and SW model focused on the representative annual ambient conditions, while the typhoon and harbor tranquility models served to predict the extreme conditions.

This analysis revealed that the Project Site, Yap (FSM), is a very tranquil environment outside of the influence of typhoons. The surrounding reef network and deep channel serves as protection offshore against waves while the wind climate is fairly moderate. The deep, straight channel in combination with a moderate tidal regime, results in low currents velocities. The combined efforts of the desktop evaluation, field data collection, and numerical modeling have led to the following conclusions for ambient conditions:

- **Water levels:** The water levels for the project site are mixed semi-diurnal, with two high tides and two low tides of differing values per lunar day. The tidal range, or the difference between the typical high tide (MHHW) and typical low tide (MLLW) is approximately 4.6 feet. El Niño periods are typically characterized by lower-than-usual sea while La Niña periods are typically characterized by heightened sea levels (Grecni et al. 2023). Seasonally, months considered to be in an El Niño cycle can deviate about 6 inches below the MSL (1983-2001 epoch), with the lowest water levels occurring in January and February. Whereas the La Niña cycle can lead to increased water levels around 7 inches higher than the MSL, peaking in the June to August months.
- **Wind:** Wind data from the Yap International Airport was examined for the 71-year data record. The predominant wind direction is from the east and north-east with the majority of wind speeds ranging between 10 to 15 knots. The summer and fall months generate more winds from the westerly direction, with the largest wind speeds, consistent with typhoon season (June to November). The winter and spring months generate more easterly and north-easterly winds, primarily ranging from 5 to 15 knots.
- **Waves:** Typical offshore waves regularly exceed 3 feet in height with periods in between 5 to 15 seconds. However, most of the waves are broken by the reef system, resulting in a generally calm wave climate (mean Hs of 0.1 ft, Tp less than 5 seconds) at the port. Monthly distribution of wave height shows that the most energetic months are between January to May.
- **Currents:** Currents around the port are generally weak (less than 0.1 knots) with low directionality. However, the turning basin and channel contain currents with more defined directionality, with the flow directions generally following the channel alignment.
- **Sediment transport:** Information on sediment transport within the harbor is very limited. However, based on the bathymetric surveys and the seabed (limestone and coral), sediment transport is expected to be low. Visual and below water inspection indicates low to very low turbidity, which is also an indicator of sediment load in the water (suspended sediment) and, therefore, low potential for transport. Exceptions include where sediment is introduced into the harbor and surrounding waters, such as deposition of materials around the wastewater treatment facility and/or end of the Colonia peninsula.

- **Tsunami:** Several data sources were reviewed to better understand Yap's exposure and vulnerability to tsunamis. The FSM have been classified as a medium risk to tsunamis, or in other words suggesting that there is approximately a 10% probability of a potentially damaging tsunami occurring within the next 50 years (equivalent to a return period of ~500 years) (Think Hazard, n.d.). A data record search revealed 14 observed runups in the NCEI database for this area with the highest water height being 0.6 feet. The estimated 500-year tsunami amplitude in offshore areas is 2.9 feet to 3.6 feet (0.9 to 1.1 m) (Thomas and Burbidge, 2009).

The primary conclusions of the metocean conditions during extreme conditions, or the resultant of passing typhoons, are as follows:

- **Typhoons:** Since 1947, there have been a total of 127 named tropical storms and typhoons that have passed within a 150-mile radius of the project site. Major typhoons, or Category 3 or above, comprise only 15% of those passing storms. Storms passing Yap are split between the northern and southern sectors of the Island in roughly a 60/40 fashion. It was found that storms passing in the southern sectors of Yap compose the maximum surges within the water level period of record.
- **Wind:** Extreme winds were estimated through an EVA of hourly wind data spanning from 1952 to 2023. Isolating the last 30 years of the data record, the estimated extreme (omnidirectional) winds range between approximately 36 knots and 51 knots for the 10-year and 100-year return periods, respectively.
- **Water levels:** An EVA of the water level record was undertaken and included sea level anomalies (i.e., El Niño) and storm surge associated with typhoon activity. For the past 30-year data record, these EWLs ranged from 3.8 feet and 8.0 feet (MLLW) for the annual return period and 100-year return period, respectively. This translates to approximately 0.2 feet and 4.4 feet above MHHW, respectively. Storm surge resulting from the top 10 most severe named typhoons was also isolated. Typhoon Sudal resulted in the highest storm surge, being approximately 4.8 feet above MHHW, which roughly aligns with the estimated 100-year water level.
- **Waves:** The most energetic wave conditions will generally be associated with passing typhoons. This study found that most offshore (typhoon generated) waves were broken by the reef system, resulting in a significant reduction between wave heights offshore and at the port. For instance, with 11-foot wave heights at the channel entrance, the resulting waves at the port were less than 1 foot (about 0.6 feet).
- **Currents:** The current magnitude at the port during typhoons were found to be only slightly above ambient, with the maximum modeled current of 0.2 knots during Typhoon Haima.

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