Wind and Wave Analysis

Summer's End Marina

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Executive Summary

Water Environment Consultants, LLC (WEC) was contracted by Technomarine USA to complete a study to define the extreme wind, wave and water level conditions at the Summer's End project site on St. John, USVI. WEC reviewed readily available wave information from the US Army Corps of Engineers (USACE), water level information from the National Oceanic and Atmospheric Administration (NOAA) and the Federal Emergency Management Agency (FEMA), and wind speeds from the American Society of Civil Engineers (ASCE). WEC conducted two-dimensional wave modeling to estimate the waves that can occur in Coral Harbor during extreme hurricane events. WEC also evaluated potential extreme current conditions that may occur during hurricane events. The results of the analysis are summarized in the tables below.

Table ES-1. Tidal water level datums

Datum	Description	Elevation (ft MLLW)
HAT	Highest Astronomical Tide	1.24
MHHW	Mean Higher-High Water	0.82
MHW	Mean High Water	0.78
MTL	Mean Tide Level	0.42
MSL	Mean Sea Level	0.39
DTL	Mean Diurnal Tide Level	0.41
MLW	Mean Low Water	0.06
MLLW	Mean Lower-Low Water	0
VIVD09	Virgin Islands Vertical Datum of 2009	0.37
LAT	Lowest Astronomical Tide	-0.37

Table ES-2. Extreme stillwater and wave setup elevations

Event return period (yrs)	Stillwater elevation[1] (ft MSL)	Wave setup[2] (ft)	Stillwater + setup (ft MSL)
10	3.5	1.1	4.6
25	4.5	1.2	5.7
50	5.2	1.3	6.5
100	6	3.2	9.2

Notes:
1. 25-yr stillwater interpolated based on logarithmic trend of other data points.
2.10, 25 and 50-yr setup calculated by SWAN model (see Section 5). 100-yr wave setup is from FIS study

Table ES-3. Extreme wind speeds

Return Period (yr)	3-sec wind speed (mph)	1-min wind speed (mph)	Hourly wind speed (mph)
10	74	55	44
25	112	83	67
50	130	96	78
100	143	106	85

Table ES-4. CGWAVE modeled swell heights

Return Period (yrs)	Offshore Swell (ft)	Marina Site Swell (ft)
10	29.2	3.2
25	35.8	3.9
50	40.7	4.5

Table ES-5. SWAN modeled wind wave heights and periods

Return Period (yrs)	1-hour Wind Speed (mph)	Direction	Hs (ft)	Tp (s)
10	44	ESE	2.3	2.3
	44	SE	2.3	2.3
	44	SSE	2.0	2.2
25	67	ESE	3.2	2.6
	67	SE	3.3	2.6
	67	SSE	3.1	2.5
50	78	ESE	3.7	2.7
	78	SE	3.8	2.7
	78	SSE	3.8	2.7

Table ES-6. Extreme depth-averaged current velocities

Return Period (yrs)	V (m/s)
10	0.6
25	0.9
50	1.1

1 Introduction

Water Environment Consultants, LLC (WEC) was contracted by Technomarine USA to complete a study to define the extreme wind, wave and water level conditions at the Summer's End project site on St. John, USVI (Figures 1-1 and 1-2). WEC was contracted to:

- Review and analyze available information from the Federal Emergency Management Agency to determine appropriate extreme wind and water levels at the project site;
- Review available Wave Information Study (WIS) hindcast data and determine extreme offshore wave conditions associated with 25 and 50-yr return period events;
- Conduct two-dimensional wave modeling to calculate the transformation of the offshore waves into Coral Bay and determine the 25 and 50-yr return period event wave heights; and
- Prepare a short report summarizing the study methods and results, to be provided in PDF format.

This report summarizes the results in the following sections:

- Section 2, Historic Storm Events – describes the effects of several major hurricanes that have affected the site since 1989;
- Section 3, Water Levels – summarizes astronomical tides and extreme water levels that may occur from hurricane events;
- Section 4, Extreme Wind Speeds – provides estimates of extreme wind speeds that may occur during hurricane events;
- Section 4, Extreme Waves – describes extreme offshores waves and estimates the extreme waves at the project site caused by offshore swell and locally generated wind waves; and
- Section 5, Currents - describes the currents that may occur at the project site.

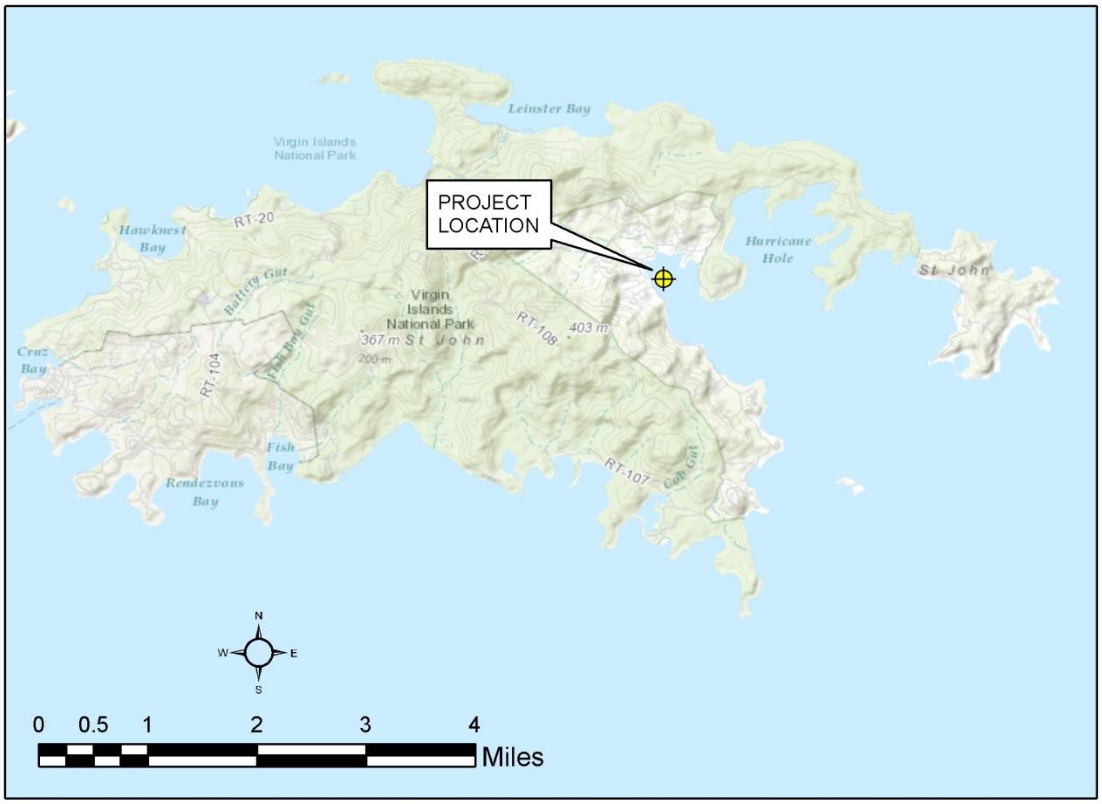

Figure 1-1. Project location map

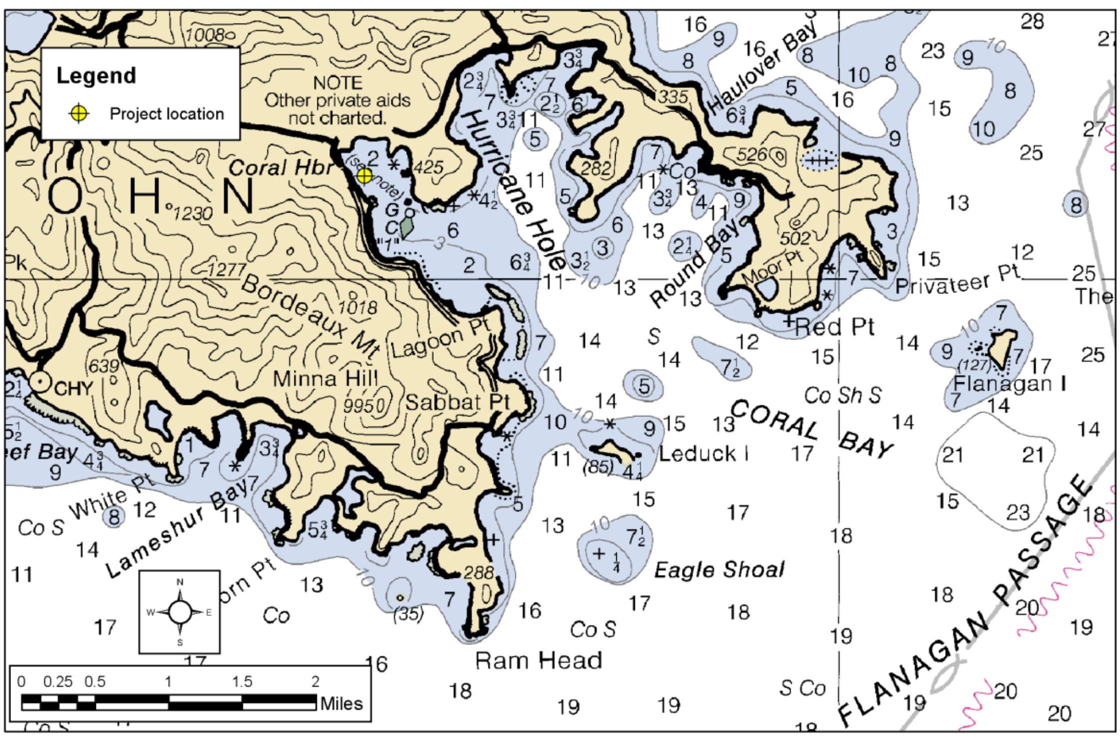

Figure 1-2. Navigation chart

2 Historic Storm Events

Four major hurricanes are described by the Federal Emergency Management Agency (FEMA) in their 2007 Flood Insurance Study for the USVI, including Hurricanes Hugo, Marilyn, Bertha and Lenny.

2.1 Hurricane Hugo, 1989

Hurricane Hugo was a Category 4 hurricane when it struck the Virgin Islands (National Oceanic and Atmospheric Administration [NOAA] 2007). Hugo caused severe coastal flooding the in Virgin Islands due to storm surges of as much as 11 ft (FEMA 2007). The storm passed directly over St. Croix, where the greatest damage occurred within the USVI. WEC did not find any official surge, wave or damage estimates for Coral Harbor in NOAA or FEMA documents. David Lyman posted to his web site his personal account of enduring Hugo while onboard is boat in Coral Bay (Lyman 2016):

> "There had been 55 boats anchored in Coral Bay when Hurricane Hugo arrived that September night in 1989. When the storm was over that next morning, there were just 5 boats still riding to their anchors...Many boats were blown ashore as other boats' mooring lines chaffed through or snapped, or small anchors dragged, entangling two, three or four boats in a mess as they were driven up on the beach by the wind, lifted by waves and surge far above the water line. When the hurricane left boats were stacked three and four deep, 10 feet from the water's edge."

Lyman estimated wave heights in the bay exceeding 10 feet, although measured wave heights or maximum water levels are not available. His photographs of boats beached along the shoreline of the harbor (Figure 2-1) are evidence that damaging wind, surge and waves can occur in the harbor during hurricane events.

Figure 2-1. Boats on Coral Harbor shoreline following Hugo (Source: Lyman 2016)

2.2 Hurricane Marilyn, 1995

Hurricane Marilyn was nearly a category 3 hurricane when it struck the USVI (FEMA 2007). Storm surge in the USVI reached 6 to 7 feet, with an isolated surge of 11.7 feet reported in St Croix. The eye passed over St. Thomas, where approximately 80 percent of homes and businesses were destroyed. On St.

John, approximately 30 percent of homes were destroyed (FEMA 2007). The approximate high water mark observed by the US Geological Survey in Coral Bay was 5.3 feet MSL (Torres-Sierra 1998).

2.3 Hurricane Bertha, 1996

The USVI were declared federal disaster areas following this storm. Bertha damaged almost 2,500 homes on St. Thomas and St. John.

2.4 Hurricane Lenny, 1999

Hurricane Lenny was unusual because of its extended west-to-east storm track. The hurricane caused an estimated 15 to 20 foot storm surge in Frederiksted on St. Croix. The National Ocean Service gage in Lime Tree Bay recorded a surge of 2.9 feet. A NOAA gage on St. Thomas recorded a surge of 1.8 feet.

3 Water Levels

3.1 Astronomical Tides

The NOAA published tidal datums for Lameshur Bay, St John (Station 9751381) are listed in Table 3-1. This is the closest tidal station to the project site. The mean tide range is small: Mean High Water (MHW) is approximately 0.7 feet above Mean Low Water (MLW). Also, note that the basis for the Virgin Islands Vertical Datum of 2009 (VIVD09) is Local Mean Sea Level for the National Tidal Datum Epoch 1983-2001.

Table 3-1. Tidal water level datums

Datum	Description	Elevation (ft MLLW)
HAT	Highest Astronomical Tide	1.24
MHHW	Mean Higher-High Water	0.82
MHW	Mean High Water	0.78
MTL	Mean Tide Level	0.42
MSL	Mean Sea Level	0.39
DTL	Mean Diurnal Tide Level	0.41
MLW	Mean Low Water	0.06
MLLW	Mean Lower-Low Water	0
VIVD09	Virgin Islands Vertical Datum of 2009	0.37
LAT	Lowest Astronomical Tide	-0.37

3.2 Extreme Water Levels

Extreme water levels from hurricane events have been evaluated by FEMA and are listed in the FIS for St. John (FEMA 2007). As noted in the FIS, there is a higher probability of landfalling storms on the south coast of St. John than the north coast because the prevailing storm direction is from the east and southeast. However, the bathymetry surrounding the island is steep, which limits the amount of surge caused by storms.

FEMA modeled hurricane storm surge at St. John using the ADCIRC hydrodynamic model and the PBL wind model. FEMA then analyzed coastal wave and water level elevations at specific cross-shore transects along the St. John shoreline. The closest transect location is J34, located in Coral Harbor, as shown in Figure 3-1. The reported extreme stillwater elevations for this transect are listed in Table 3-2 (note that WEC added an interpolated water level value for the 25-year return period, which is not included in the FIS). The stillwater elevation is the water level produced by the storm pressure and wind stress effects. In addition, wave setup adds an additional component of storm surge. The 1-percent-annual-chance (i.e., 100-year return period) stillwater plus wave setup listed in the FIS is 9.2 feet above local mean sea level (MSL), which includes a wave setup of 3.2 feet. WEC used the SWAN wave model (see Section 5 of this report) to calculate the wave setup component for the 10, 25 and 50-year return period events. Based on the SWAN model results, the FIS estimate of 3.2 of wave setup is conservative (i.e., high). The Base Flood Elevations for the project area are shown by FEMA Flood Insurance Rate Map in Figure 3-2.

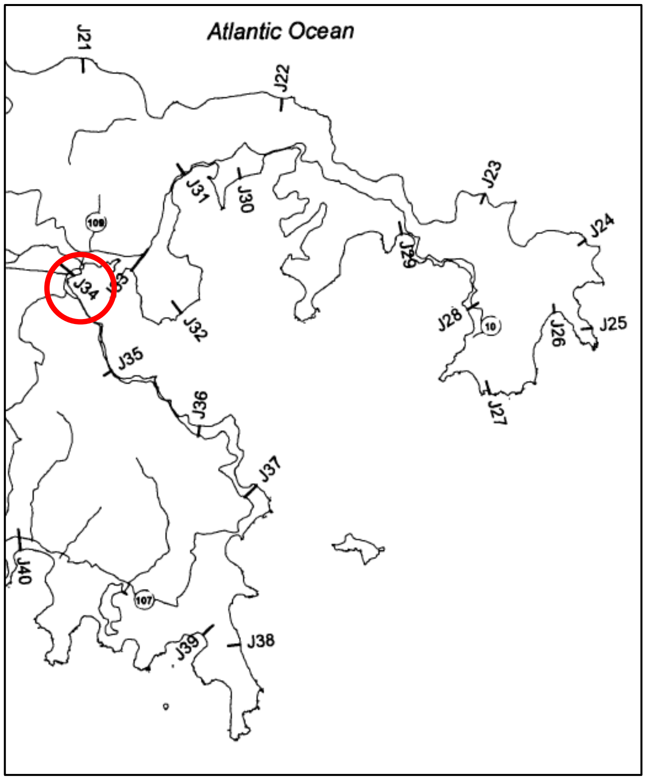

Figure 3-1. FIS transect location map (closest transect circled in red)

Table 3-2. Extreme stillwater and wave setup elevations

Event return period (yrs)	Stillwater elevation[1] (ft MSL)	Wave setup[2] (ft)	Stillwater + setup (ft MSL)
10	3.5	1.1	4.6
25	4.5	1.2	5.7
50	5.2	1.3	6.5
100	6	3.2	9.2

Notes:
1. 25-yr stillwater interpolated based on logarithmic trend of other data points.
2.10, 25 and 50-yr setup calculated by SWAN model (see Section 4). 100-yr wave setup is from FIS study

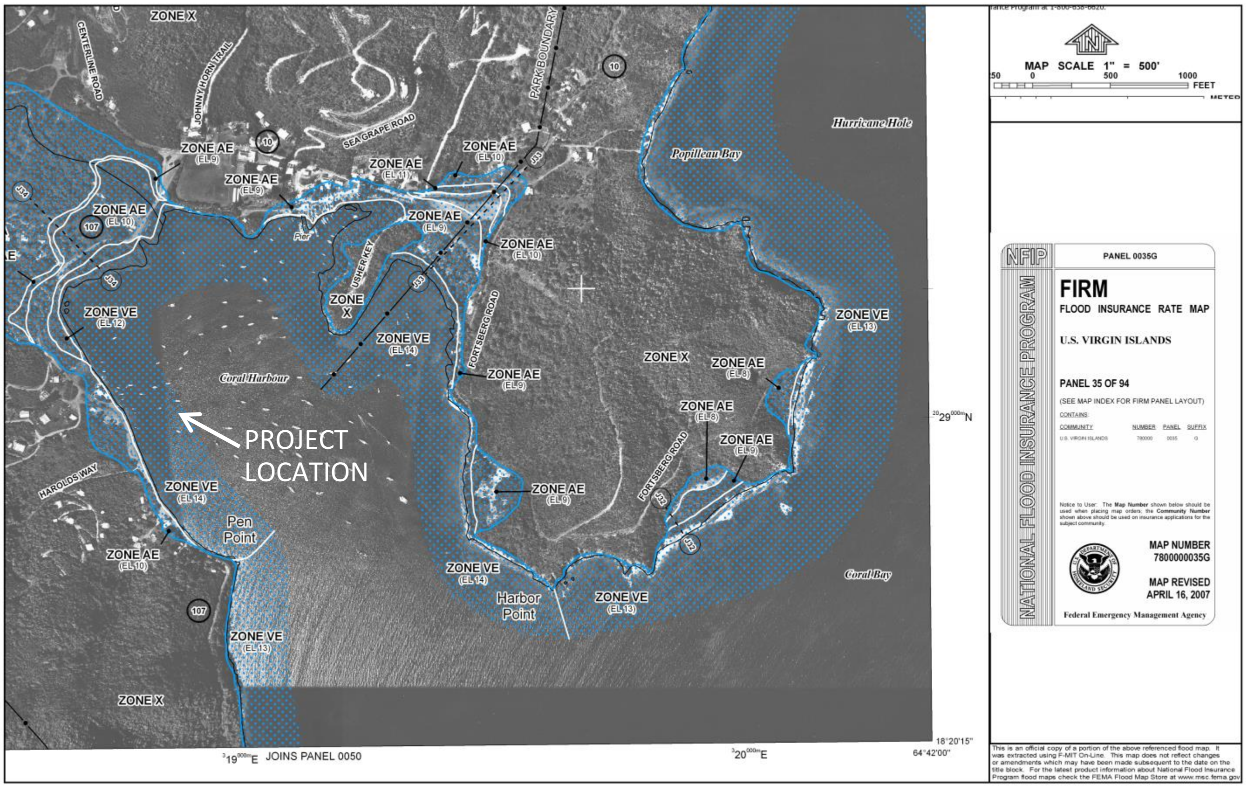

Figure 3-2. Flood Insurance Rate Map

3.3 Historical Sea Level Rise

Long-term water level monitoring by NOAA at Charlotte Amalie, VI indicates that the long-term historical trend in sea level rise (SLR) is approximately 0.65 ft per 100 years. SLR is expected to continue at a rate at least as high as the historical rate, and it may accelerate (although the degree of SLR acceleration is highly uncertain).

4 Extreme Wind Speeds

The most current design wind speeds are given by the national load standard, American Society of Civil Engineers (ASCE) 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE 2010). The ASCE 7-10 extreme wind speeds for the Virgin Islands, given as 3-sec peak gust values, are listed in Table 4-1. The Technomarine design criteria require 1-minute duration wind speeds. Therefore, the wind speed durations were adjusted to 1-minute wind speeds using the methods from the US Army Corps of Engineers (USACE) Coastal Engineering Manual (USACE 2006).

Table 4-1. Extreme wind speeds

Return Period (yr)	3-sec wind speed (mph)	1-min wind speed (mph)	Hourly wind speed (mph)
10	74	55	44
25	112	83	67
50	130	96	78
100	143	106	85

It is our understanding that Technomarine typically uses wind speed design criteria that correspond to the Saffir Simpson Hurricane Wind Scale. For the maximum wind speed with full occupancy, Technomarine typically assumes a Category 1 hurricane (sustained winds of 74-95 mph). For the maximum wind speed without boats, Technomarine typically assumes a Category 3 hurricane (sustained winds of 111-129 mph). For this site the Category 1 wind speed range corresponds roughly to a return period between 20 and 50 years. The Category 3 wind speed range corresponds to return periods greater than 100 years.

5 Extreme Waves

Coral Harbor is less than a half a mile wide, and the local fetch affecting the proposed marina is very short in most directions. The only significant fetch is to the south southeast, and extreme waves from this direction will be from locally generated wind waves and offshore swell during hurricane events. This section includes an assessment of extreme offshore waves and numerical modeling to estimate wind waves and swell in Coral Bay.

5.1 Offshore Waves

The USACE Engineering Research and Development Center (ERDC) provides high-quality coastal wave hindcast model estimates through the Wave Information Study (WIS) program. WIS data were obtained from the USACE for the WIS station closest to the project site (Station 61022), which is approximately 53 miles southeast of the project site (Figure 5-1).

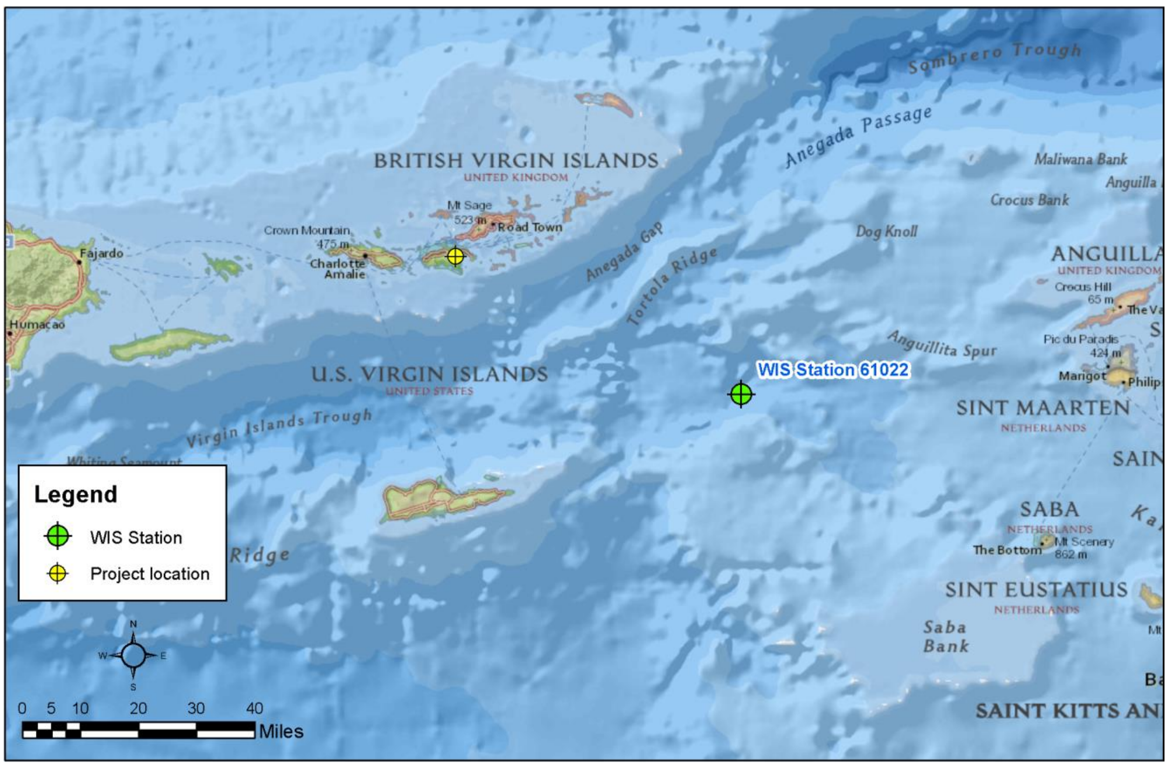

Figure 5-1. WIS station location

ERDC completed an extreme value analysis of the largest 33 events in the hindcast record, as shown in Figure 5-2. The resulting estimates of extreme significant wave heights for various return periods are summarized in Table 5-1. The peak periods for the largest six events (i.e., those equal to or greater than the 10-year return period event) range from 11.6 to 14.5 seconds. For these extreme events, longer wave periods are not directly correlated with higher wave heights, and therefore the design should assume that the wave periods for extreme events may range from 11 to 15 seconds.

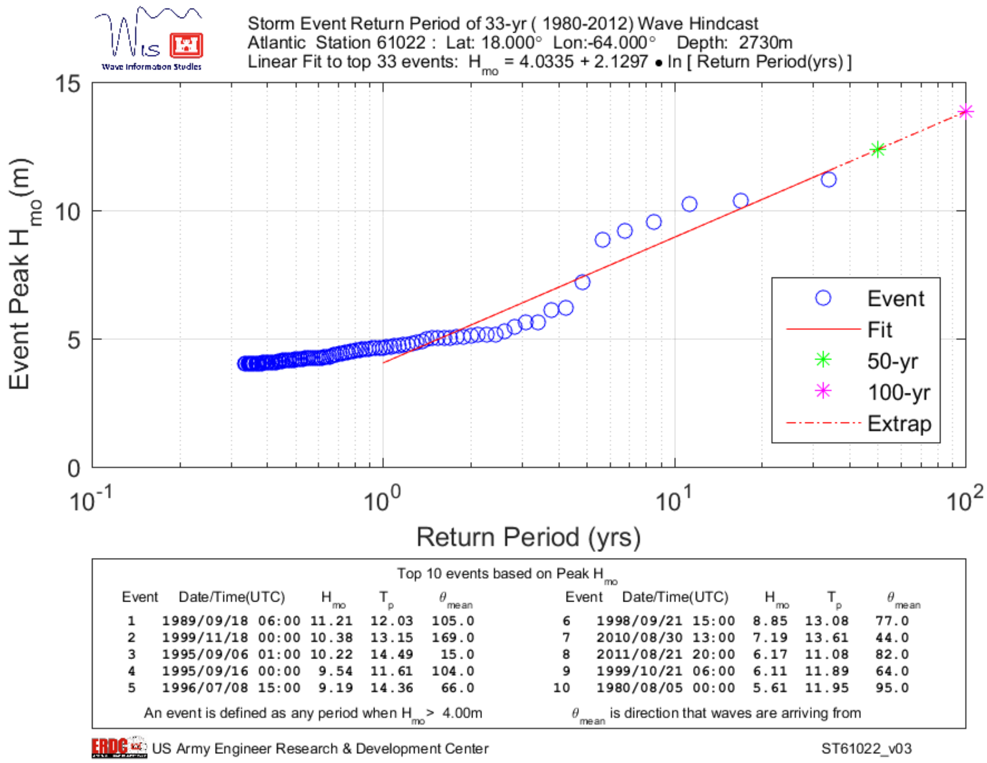

Figure 5-2. Extreme wave height analysis plot (Source: USACE 2016)

Table 5-1. Extreme offshore wave heights

Return Period (yr)	Hmo (m)	Hmo (ft)
10	8.9	29.3
25	10.9	35.7
50	12.4	40.6
100	13.8	45.4

5.2 Marina Site Waves

Coral Harbor is well protected from ocean waves, but some wave energy will enter the harbor from the south southeast. WEC used two-dimensional numerical wave models to estimate the waves that will enter the harbor. WEC used CGWAVE to model the refraction, diffraction, shoaling and reflection of swell as it travels from the ocean, through Coral Bay and into Coral Harbor. WEC also used SWAN to model the wind wave growth from the local fetches. During extreme hurricane events, the site will be subjected to the combination of both the swell and wind waves.

5.2.1 Swell

CGWAVE (Panchang & Xu 1995) is a two-dimensional finite element model based on the elliptic mild-slope wave equation. CGWAVE includes processes include refraction and shoaling as waves propagate towards the project site from deeper waters offshore, as well as reflection and diffraction as waves encounter the shoreline.

WEC set up the CGWAVE model of Coral Bay using the local bathymetry surveyed at the project site combined with bathymetry digitized from the NOAA navigation chart for the USVI (chart #25641). The model includes a wave reflection coefficient of 0.25 assigned to the shoreline areas. Typical wave reflection coefficients range from 0.1 for flat beaches to 0.45 for rubble mound structures and 0.9 for vertical walls. An intermediate value was used here given the steep shorelines throughout most of the study area. WEC modeled a range of wave periods, 10 to 15 seconds, representative of the possible range of swell from extreme hurricane events. Modeled wave directions included east southeast, southeast and south southeast.

Example output from the CGWAVE model is shown in Figures 5-3 and 5-4. As shown by these figures, the bathymetry causes the swell traveling up Coral Bay to refract (i.e., bend) toward Harbor Point and toward the headland between Sanders Bay and Johnson Bay. Most of the wave energy is refracted towards these shorelines before reaching Coral Harbor. The wave refraction patterns are dependent on the wave length (a function of wave period), as shown by the slight differences between Figure 5-3 (a 13-second wave period) and Figure 5-4 (a 15-second wave period). The maximum modeled wave heights reaching the south side of the proposed marina are approximately 11 percent of the offshore wave height. Table 5-2 summarizes the modeled swell heights approaching the marina.

Table 5-2. CGWAVE modeled swell heights

Return Period (yrs)	Offshore Swell (ft)	Marina Site Swell (ft)
10	29.2	3.2
25	35.8	3.9
50	40.7	4.5

5.2.2 Wind Waves

The SWAN (Simulating WAves Nearshore) model was used to estimate the extreme wind waves that can occur from wind wave growth over the fetch to the southeast of the project site during hurricane events. SWAN is a two-dimensional steady-state spectral wave transformation model that simulates the growth and transformation waves in the nearshore region. The wave model simulates the following wave processes: wave propagation, shoaling, and refraction; wind wave growth; and wave dissipation from white capping, bottom friction, and depth-induced breaking. The SWAN wave model was set up using bathymetry digitized from the NOAA navigation chart for the USVI (chart #25641). The model was then used to simulate waves during winds from the east southeast, southeast and south southeast directions.

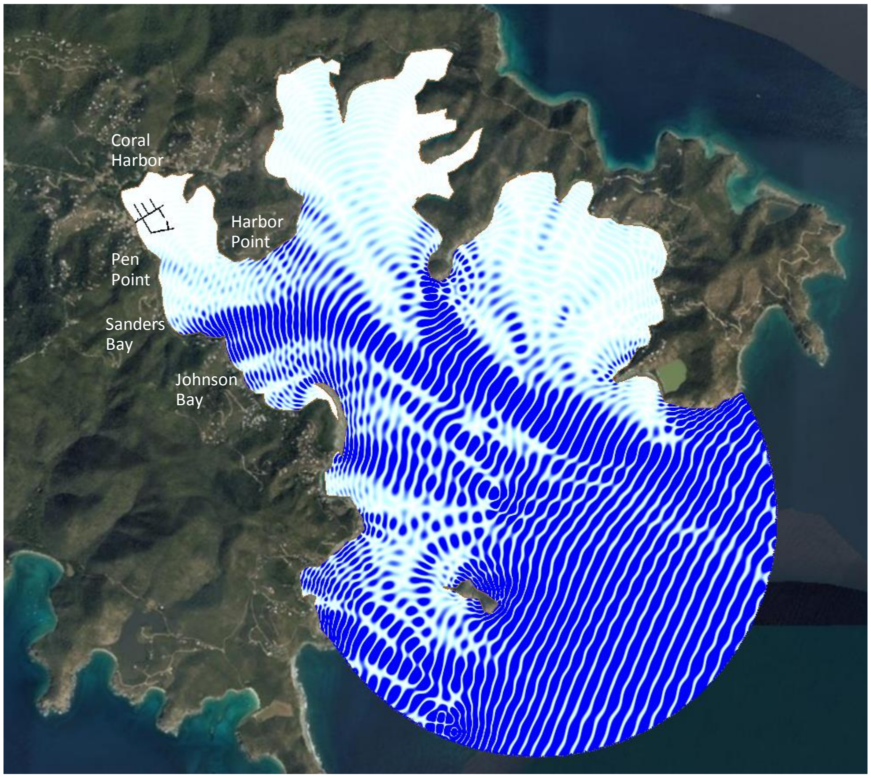

Figure 5-3. CGWAVE model results for 13-second period wave from ESE

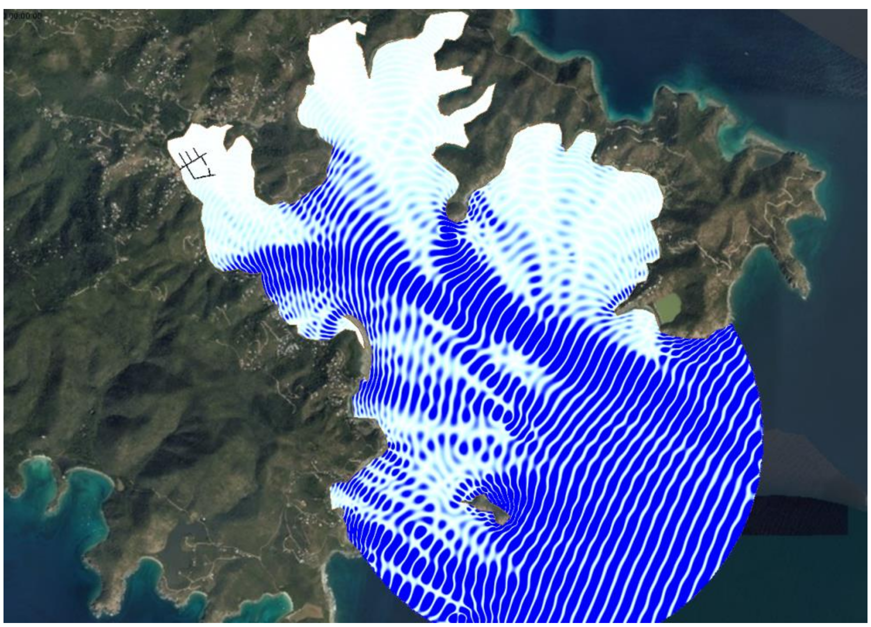

Figure 5-4. CGWAVE model results for 15-second period wave from ESE

Example SWAN modeled significant wave heights are shown in Figure 5-5 for the 50-year return period wind from the south southeast direction. The results for the various wave cases are shown in Table 5-3. In addition, the model was used to simulate the combined swell and wind wave conditions for the purposes of estimating wave setup in the harbor. The results for estimated wave setup are included in the water level estimates in Section 3.

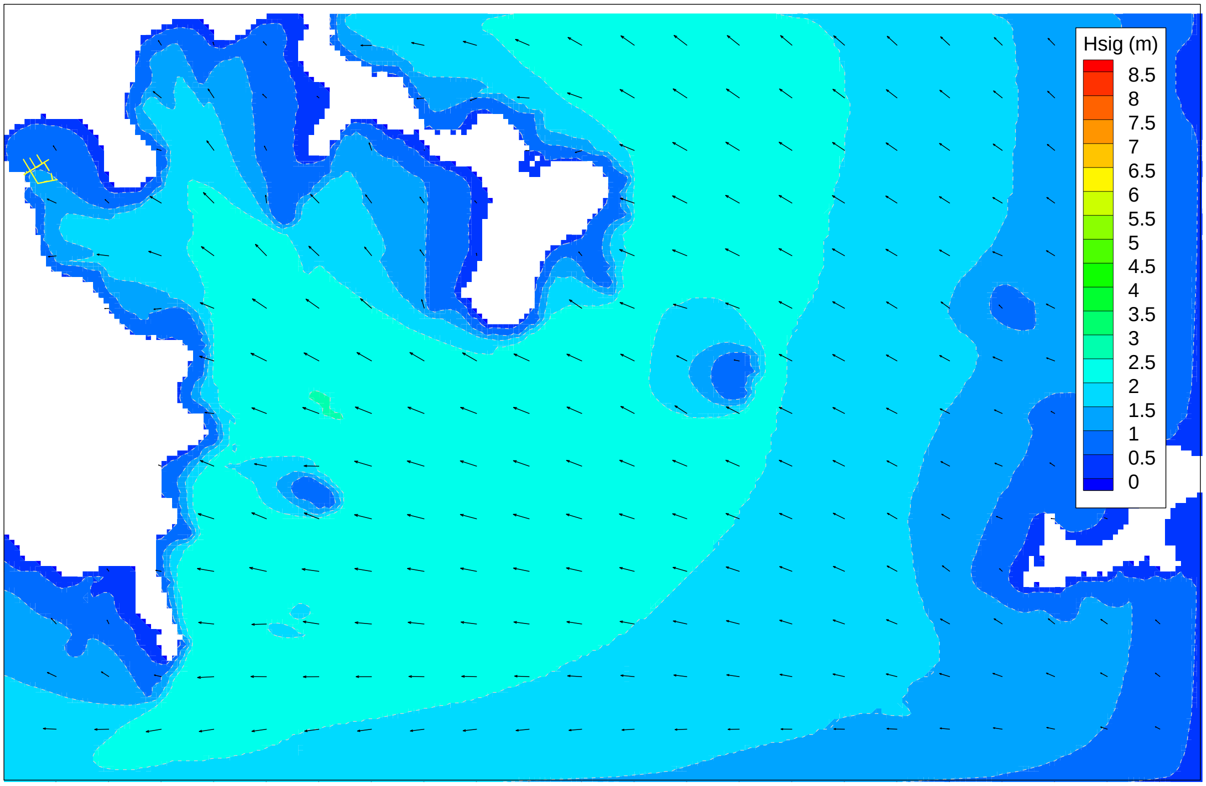

Figure 5-5. SWAN model results for 50-year return period wind from ESE

Table 5-3. SWAN modeled wind wave heights and periods

Return Period (yrs)	1-hour Wind Speed (mph)	Direction	Hs (ft)	Tp (s)
10	44	ESE	2.3	2.3
	44	SE	2.3	2.3
	44	SSE	2.0	2.2
25	67	ESE	3.2	2.6
	67	SE	3.3	2.6
	67	SSE	3.1	2.5
50	78	ESE	3.7	2.7
	78	SE	3.8	2.7
	78	SSE	3.8	2.7

5.2.3 Extreme Wave Conditions

The project site is an area where both offshore and local waves can exist and are propagating in the same direction. As described in *Guidance for Coastal Flood Hazard Analyses and Mapping in Sheltered Waters - Technical Memorandum* (FEMA 2008), for this scenario, the combined (swell and sea) wave height and combined wave period can be estimated as:

$$H \approx \sqrt{H_1^2 + H_2^2}$$

and

$$T \approx \frac{T_1 H_1^2 + T_2 H_2^2}{H_1^2 + H_2^2}$$

The estimated effective combined wave conditions are summarized in Table 5-4. The wave periods in this table include a range of values to account for the fact that the swell from the extreme storms may range from 11 to 15 seconds.

Table 5-4. Combined swell and wind wave heights and periods

Return Period (yrs)	Hs (ft)	Tp (s)
10	3.9	8.0 - 10.7
25	5.1	7.5 - 9.8
50	5.9	7.5 - 9.9

6 Currents

Currents during typical astronomical tides and winds were measured at the project site using a current meter and were found to be on the order of 0.1 m/s (Applied Technology and Management et al. 2014). Although typical wind and tide currents are small, extreme winds can result in much larger current speeds. The currents generated by hurricane wind speeds are complex and include currents it the direction of the surface wind, and as the wind generates a setup in the water levels, it also results in bottom currents in the opposite direction as the wind direction (Sheppard 2003). A three-dimensional hydrodynamic model would provide more accurate estimates of these currents under extreme wind conditions, but that level of analysis is beyond the scope of this study.

To provide a conservative estimate for this analysis, the bottom current in the opposite direction is neglected, and it is assumed that a fully-developed equilibrium logarithmic current profile forms in the direction of the wind (something that may or may not happen during hurricane conditions). An equation for depth-averaged alongshore current velocity is given by Dean and Dalrymple (1991):

$$V = \sqrt{\frac{8k\sin\theta}{f}}W\tan h\left(\frac{kf\sin\theta}{8}\frac{Wt}{h}\right)$$

where

W is the wind speed,
θ is the angle to the shoreline,
t is time;
h is the water depth,
f is the Darcy-Weisbach friction factor, and
k is the friction factor on the order of 10^{-6}.

The calculated depth-averaged current velocities reach equilibrium within 1 to 2 hours. These velocities are listed in Table 6-1. The resultant velocities are approximately 3 percent of the wind speed.

Table 6-1. Extreme depth-averaged current velocities

Return Period (yrs)	V (m/s)
10	0.6
25	0.9
50	1.1

References

Applied Technology & Management, Inc., Bioimpact, Inc., and Cairone and Kaupp, Inc. 2014. Earth Change Plan & Environmental Assessment Report for the Development of the Upland Areas of the St. John Marina, Coral Bay, St. John, USVI. April 2014.

ASCE. 2010. Minimum Design Loads of Buildings and Other Structures. ASCE Standard ASCE 7-10.

Dean, R.G. and R.A. Dalrymple. 1991. Water Wave Mechanics for Engineers and Scientists. World Scientific. p 162.

FEMA. 2007. Flood Insurance Study, U.S. Virgin Islands. Flood Insurance Study number 780000V000A. Revised April 16, 2007.

FEMA. 2008. Guidance for Coastal Flood Hazard Analyses and Mapping in Sheltered Waters - Technical Memorandum.

Panchang, V. G. and B. Xu, 1995. "CGWAVE: A Coastal Wave Transformation Model for Arbitrary Domains," Technical Report, Dept. of Civil and Environmental Engineering, University of Maine, Oct. 1995.

Lyman. D. 2016. Experiencing Hurricane Hugo. Available: http://www.dhlyman.com/DHLyman.com/Hurricane_Hugo.html (April 2016)

National Oceanic and Atmospheric Administration. 2007. Errata Sheet to the Service Assessment Report Hurricane Hugo September 10-22, 1989.

Sheppard. M. 2003. Wind Generated Currents in Shallow Water. Research project completed for Florida Department of Transportation. Available: http://www.dot.state.fl.us/rddesign/Drainage/Research/CE/Wind-Generated-Currents.pdf (April 2016)

Torres-Sierra, H. Storm-Tide Elevations Caused by Hurricane Marilyn on the U.S. Virgin Islands, September 15-16, 1995. U.S. Geological Survey Open-File Report 96-44.

USACE. 2008. Coastal Engineering Manual. Engineering Manual EM-1110-2-1100.