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Engineering – Hydrology – Stream Restoration – Water Resources

TECHNICAL MEMORANDUM

Date: 07 July 2024

To: Brett Vivyan, P.E.
Project Manager/Technical Director
GHD Inc.
713 3rd Street
Eureka, CA 95501

From: Jeffrey K. Anderson, P.E., M.S.

Re: Existing Condition Coastal Flood Assessment for the City of Arcata Sea Level Rise Vulnerability and Adaptation Planning Services Project, City of Arcata, Humboldt County

1 INTRODUCTION AND PURPOSE

GHD Inc. and Northern Hydrology & Engineering (NHE) are currently developing a City of Arcata Sea Level Rise Vulnerability and Adaptation Planning Services Project (Project) for the City of Arcata. This technical memorandum summarizes a coastal flood analysis conducted by NHE to support the Project.

The purpose of this analysis determines representative still water levels, wind setup, wave setup and runup values from locally generated wind-waves, and total water levels for the City of Arcata's shoreline in Arcata Bay (North Bay). Results are provided for a combination of wind speeds and water levels that span tidal datums to extreme annual exceedance probability events. Total water level estimates are provided for both natural and armored shoreline segments, with the difference between estimates being the inclusion of wave setup and runup for the armored shoreline.

This analysis was conducted in SI units (e.g. wave height in meters, wind speed as meters per second) but tabulated results will be presented in both SI and English units. Water levels or water surface elevations are referenced to the North American Vertical Datum of 1988 (NAVD88).

2 PROJECT SETTING AND LOCATION

2.1 Physical Setting

Humboldt Bay is a multi-basin, bar-built coastal lagoon located approximately 260 miles (418 km) north of San Francisco, California, is the second largest natural bay in California, and the only major harbor between San Francisco and Portland, Oregon (Costa and Glatzel 2002). Humboldt Bay consists of three basins, Arcata Bay (or North Bay), Entrance Bay and South Bay (Figure 1). North Bay is connected to Entrance Bay by a long narrow channel (North Bay Channel) that splits into multiple channels at the northern end of the channel, and South Bay and Entrance Bay are separated by a constriction between King Salmon and the South Bay spit. Humboldt Bay has a water surface area of approximately 25 mi^2 (65 km^2) at high tide, 8 mi^2 (21 km^2) at low tide, and about 70% of the bay is exposed tidal mudflat at low tide, with most of the mudflat contained in shallower North and South Bays (Costa and Glatzel 2002).

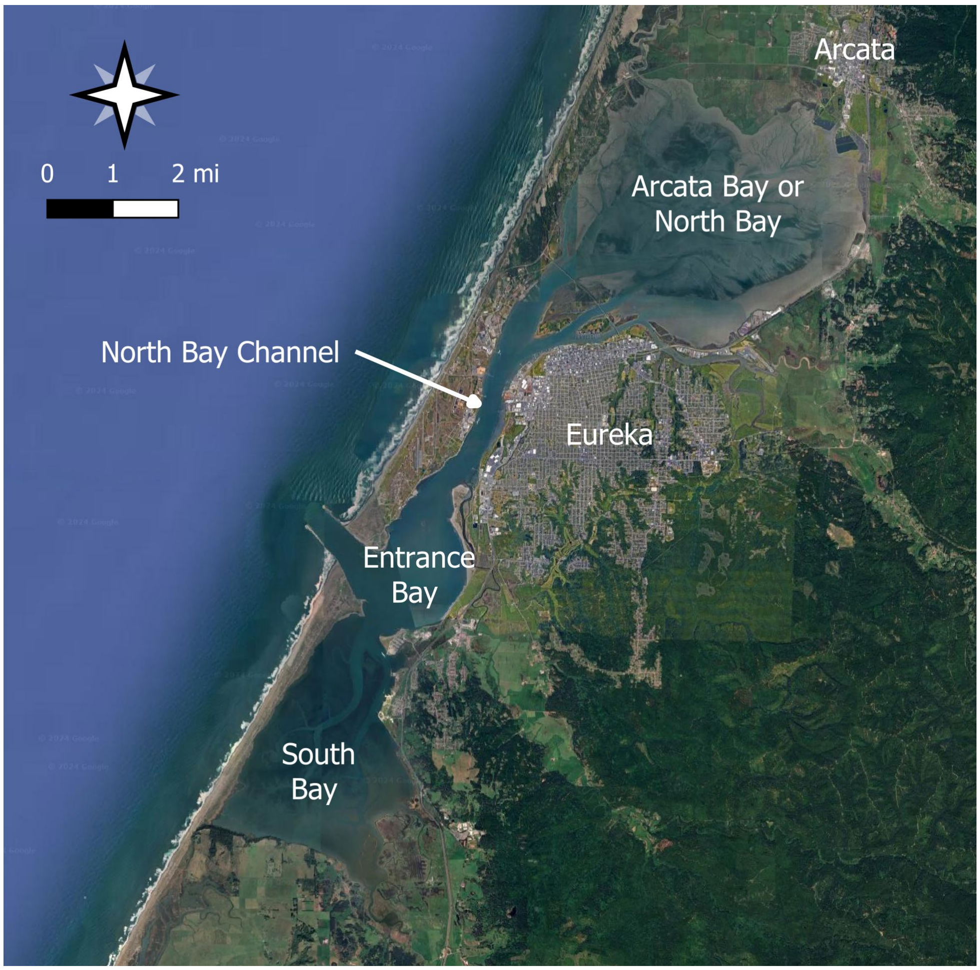

Figure 1. Humboldt Bay vicinity and location map.

Humboldt Bay lies within the 42 mile (67 km) long Eureka littoral cell (ELC) which is bounded by Trinidad Head to the north and False Cape to the south (see Figure 5). The region is known for its high erosion rates and fluvial sediment supply, which is generally attributed to a combination of unique land use, climate, geology and tectonics (Kelsey 1980; Mackey et al. 2011; Warrick et al. 2013). The ELC has an approximate 4,520 mi^2 (11,700 km^2) contributing watershed, and the two largest rivers (Eel River and Mad River) discharge directly into the ELC. In comparison, the Humboldt Bay watershed is relatively small at 223 mi^2 (578 km^2). The four largest Humboldt Bay streams are Jacoby Creek and Freshwater Creek that discharge into North Bay, Elk River that discharges into the northern end of Entrance Bay, and Salmon Creek that discharges into South Bay. Although the region's climate is relatively moderate (cool temps with moderate precipitation of 30-40 inches/year), the wave climate is quite extreme with large frequent swells emanating from both the North and South Pacific (Wheatcroft and Borgeld 2000; Costa and Glatzel 2002; George and Hill 2008).

The dominant forcing in Humboldt Bay are tides, followed by incident ocean waves that pass through the jetty into Entrance Bay, with wind and locally generated wind-waves having a secondary forcing in the shallow North and South Bays (Costa and Glatzel 2002). Due to the small watershed size and low freshwater flows, the circulation in Humboldt Bay is tidally dominated and the bay consists of well-mixed marine water. Seasonal estuarine conditions are generally associated with the sub-estuary regions of the bay tributaries (Costa and Glatzel 2002).

2.2 Project Location

This analysis assesses coastal flooding along a portion of the northern shoreline in Arcata Bay (North Bay). For this assessment the Project shoreline is defined as the portion shoreline that includes the City of Arcata Wastewater Treatment Facility (WWTF) oxidation ponds, treatment wetlands, enhancement wetlands and Klopp Lake levees, and the tidal wetlands/levees that make up the southern shoreline of the McDaniel Slough/Janes Creek restoration project (Figure 2). The Project shoreline consists of both natural and armored shoreline segments. The natural shoreline consists of tidal wetland segments, and rock revetments make up the armored shoreline. Most of the rock revetment in the Project shoreline armor the levees that surround the WWTF.

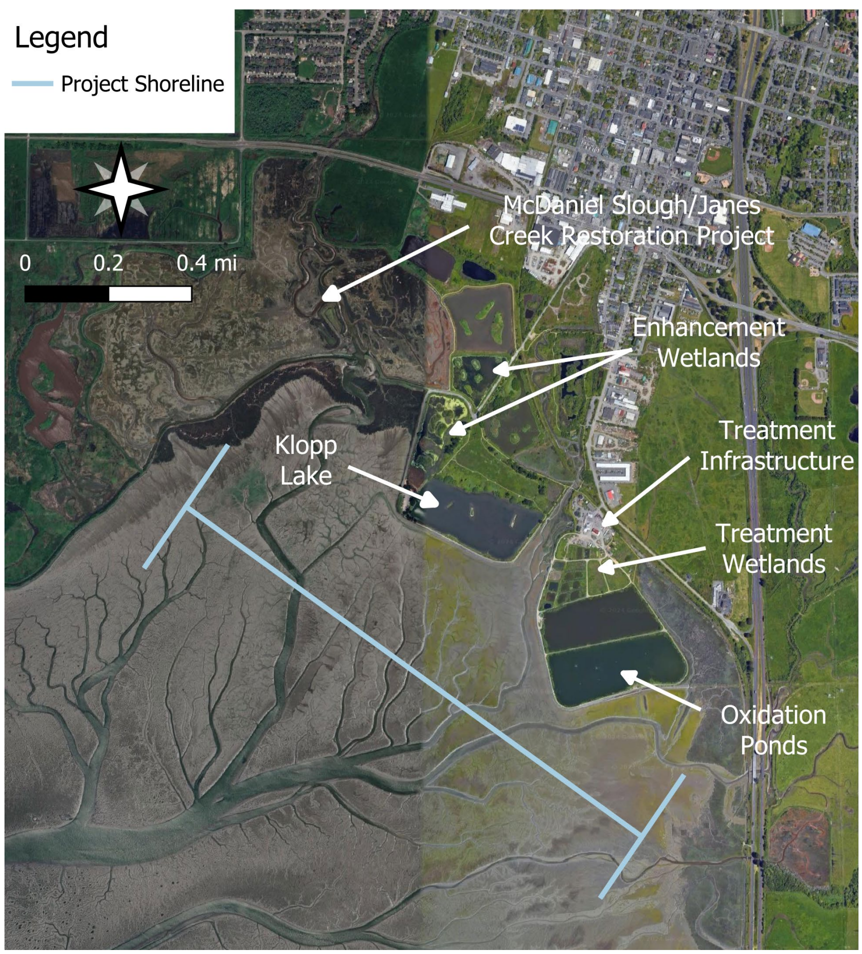

Figure 2. The City of Arcata Project shoreline in northern portion of Arcata Bay (North Bay).

2.3 Topography and Bathymetry

Project area topography and bathymetry was defined by the 2020 USGS Coastal National Elevation Database (CoNED) 1-meter topobathymetric digital elevation model (TBDEM) for the Northern California Coast (2020 USGS CoNED DEM). The 2020 USGS CoNED DEM (or Project DEM) consists of multiple topographic and bathymetric data sets ranging in dates from approximately 1986 to 2019 that have been aligned vertically and horizontally to a common reference system (OCM Partners 2024). Figure 3 shows the topography and bathymetry of the City of Arcata Project shoreline in North Bay.

According to the online metadata information (OCM Partners 2024), it appears the topographic data surrounding Humboldt Bay relied on the City of Eureka 2019 Humbold Bay LiDAR (24 September 2019 acquisition date). For this assessment, it was assumed the City of Eureka 2019 LiDAR represents ground elevations in 2019 at the time of the acquisition and has not been adjusted for vertical land motion either before or after the acquisition date. This distinction is important when comparing ground elevations to observed or modeled water surface elevations, and when considering future sea-level change.

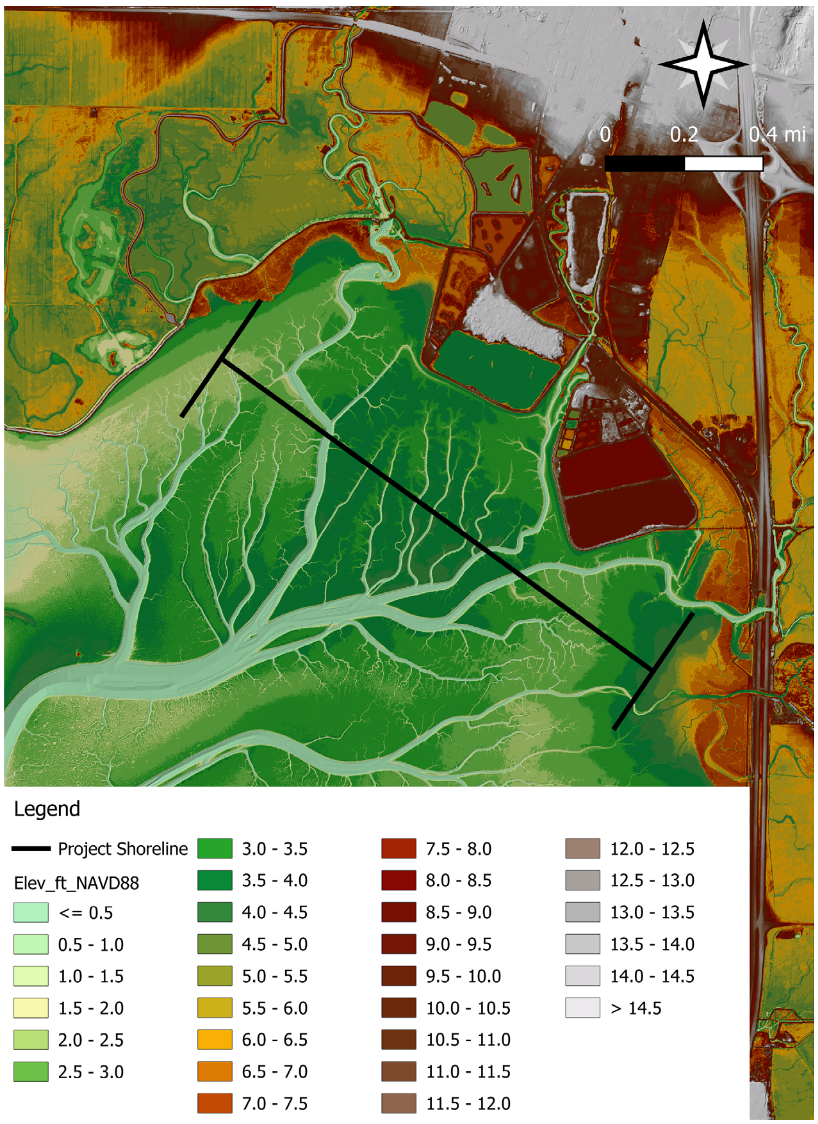

Figure 3. Project area topography and bathymetry in vicinity of the City of Arcata Project shoreline in North Bay. Topography and bathymetry based on 2020 USGS CoNED DEM.

2.4 FEMA Flood Hazard Maps

The Project shoreline is in a Federal Emergency Management Agency (FEMA) Special Flood Hazard Area for which 1% base flood elevations (BFE) have been determined from a detailed coastal flood hazard analysis for the open coast and Humboldt Bay (FEMA 2014 and 2018). FEMA determined a constant still water elevation of 10.2 ft NAVD88 for Humboldt Bay. The coastal analysis BFE represents the 1% total water level (TWL), which includes the still water elevation and increased elevation from wave setup and wave runup at the shoreline. To determine locally generated wind-waves in Humboldt Bay, FEMA assumed an extreme wind speed of 45 mph (20.1 mps).

Figure 4 shows the Project shoreline on Flood Insurance Rate Map (FIRM) map panels 06023C0835G, 06023C0845G, 06023C0852G and 06023C0855G. Within the Project shoreline, areas behind levees, revetments or far enough inland from the shoreline that wave runup does not apply are within an AE zone with a BFE of 10 ft (NAVD88). Areas in front of shoreline levees and revetments are mapped as VE zones with a BFE of 13 to 14-ft, due to wave setup and runup. It should be noted that areas within the McDaniel Slough/Janes Creek restoration area have BFE ranging from 11 to 12-ft due to wave growth landward of the levee.

The 1% flood elevations determined in this assessment can be considered refinements to the FEMA 1% BFEs for the Project shoreline. The 1% flood elevations are a composite water level estimate specific to the Project shoreline consisting of coastal extreme high-water levels (e.g. storm surge), wind effects (wind setup), wave effects (e.g. wave runup), and sea-level change adjustments.

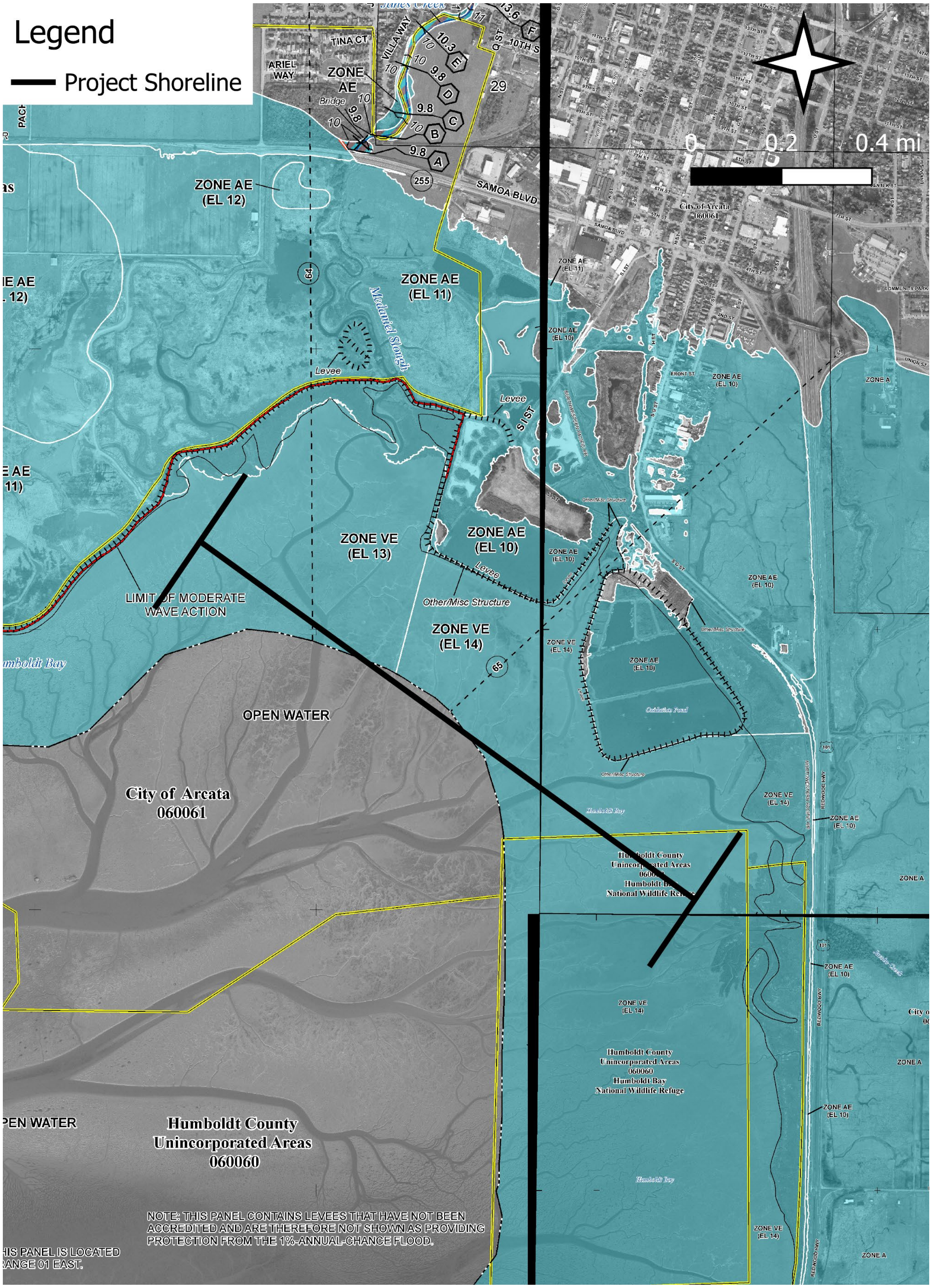

Figure 4. FEMA Base flood elevations (BFE) in ft (NAVD88) for the North Bay Project shoreline (FIRM map panels 06023C0835G, 06023C0845G, 06023C0852G and 06023C0855G).

3 HUMBOLDT BAY COASTAL HYDROLOGY AND FLOOD HAZARDS

This section describes the coastal hydrology in Humboldt Bay related to the general Project site location. Figure 5 shows Humboldt Bay within the context of the Eureka Littoral Cell, and the locations of Humboldt Bay tidal stations nearby weather stations.

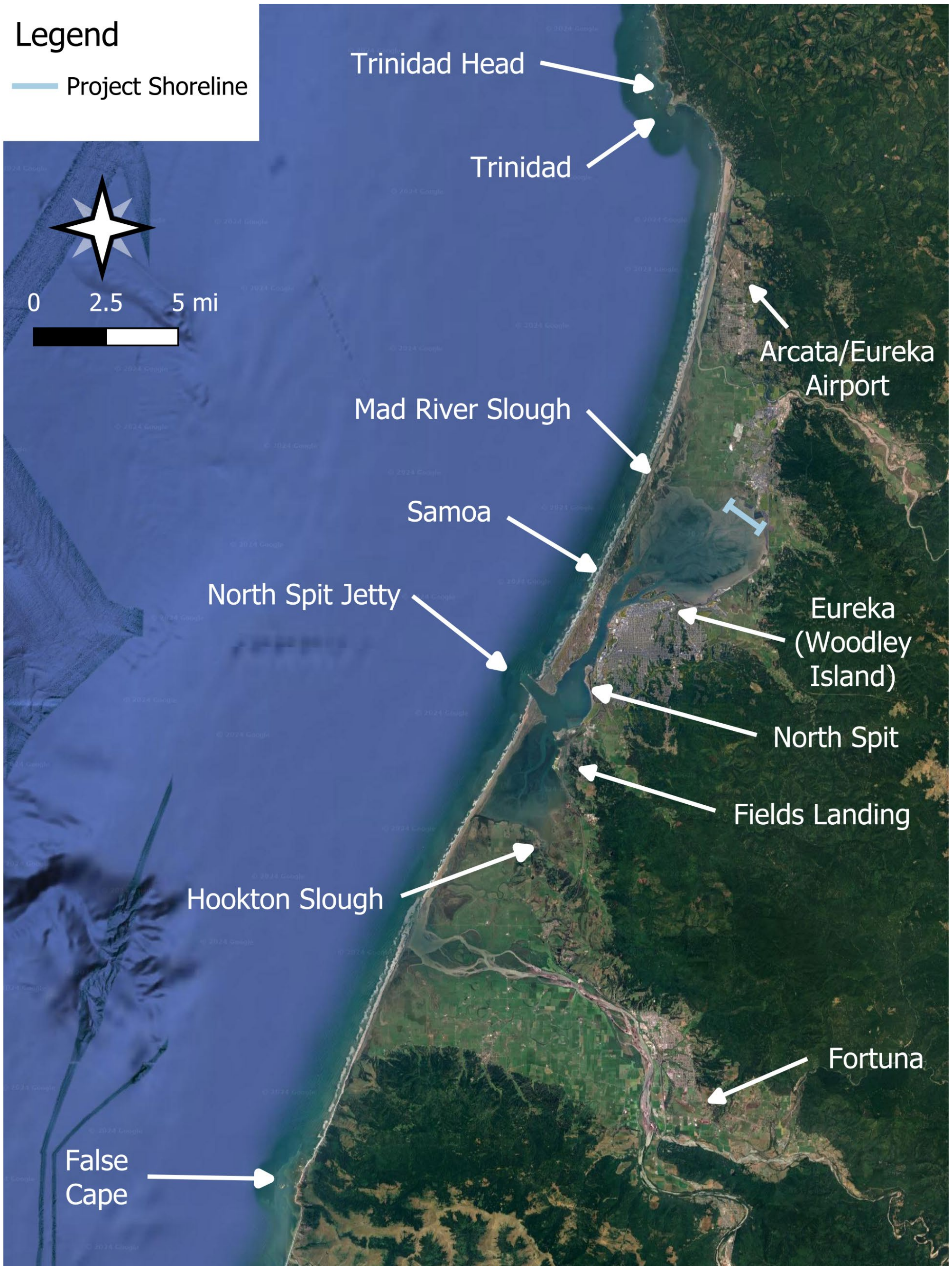

Figure 5. Location of NOAA tide stations in Humboldt Bay and Trinidad, weather stations in the Project area, and the extents of the Eureka Littoral Cell from Trinidad Head to the north and False Cape to the south. Crescent City tide station is located approximately 68 miles (109 km) north of the North Spit station.

3.1 Tide Levels and Tidal Datums

Humboldt Bay tides have a mixed semidiurnal pattern with two unequal high and low tides during each tidal (or lunar) day of duration 24 hours and 50 minutes. Continuous water level observations are available for the National Oceanic and Atmospheric Administration (NOAA) primary North Spit, CA tide station (Station ID: 9418767) with data spanning August 1977 to present. Tidal datums for the North Spit station and a secondary NOAA tide station in North Bay, Mad River Slough (Station ID: 9418865) are provided in Table 1 for the 1983-2001 tidal epoch. The location of the tidal stations relative to the Project shoreline are shown in Figure 5.

Table 1. Tidal datums and water levels reported by NOAA for North Spit and Mad River Slough tidal stations for the 1983-2001 tidal epoch; datums and elevations referenced to NAVD88.

		North Spit (NS) ID: 9418767		Mad River Slough (MRS) ID: 9418865	
Description	**Abbrev.**	**Value (m)**	**Value (ft)**	**Value (m)**	**Value (ft)**
Highest Observed Tide	HOT	2.910	9.54	NA	NA
Highest Astronomical Tide	HAT	2.592	8.50	NA	NA
Mean Higher High Water	MHHW	1.987	6.51	2.021	6.63
Mean High Water	MHW	1.770	5.80	1.800	5.90
Mean Tide Level	MTL	1.025	3.36	0.953	3.13
Mean Sea Level	MSL	1.025	3.36	0.990	3.25
Mean Low Water	MLW	0.280	0.91	0.105	0.34
North American Vertical Datum 1988	NAVD88	0.000	0.00	0.000	0.00
Mean Lower Low Water	MLLW	-0.103	-0.34	-0.305	-1.00
Lowest Astronomical Tide	LAT	-0.835	-2.74	NA	NA
Highest Observed Tide	LOT	-0.986	-3.24	NA	NA
Diurnal Tidal Range (MHHW – MLLW)	2.090	6.86	6.86	2.326	7.63

3.2 Sea-Level Change and Vertical Land Motion

Humboldt Bay has the highest rates of sea-level rise in California. (NHE 2018). Recently, Patton et al. (2023) updated relative sea-level (RSL) and vertical land motion (VLM) rates and standard errors (SE) for the Crescent City and Trinidad tide stations, and five stations in Humboldt Bay (Figure 5 and Table 2). RSL rates were refined by combining the individual station rates and the difference in rates between stations in a weighted least squares adjustment. The VLM rates were resolved by subtracting the regional (or absolute) sea-level (ReSL) rate of 1.99 mm/yr for the Pacific Northwest region (Montillet et al. 2018) from the adjusted RSL rates. Within Humboldt Bay there is a significant north to south longitudinal gradient in RSL and VLM rates, consisting of lower rates to the north and higher rates to the south. The North Spit (NS) and Mad River Slough (MRS) stations are the same in Table 1 and Table 2.

Table 2. Tide station relative sea level (RSL) and vertical land motion (VLM) rates and standard errors (SE) from Patton et al. (2023); VLM determined by differencing RSL and the regional (or absolute) sea level (ReSL) rate of 1.99 ± 0.16 mm/yr (Montillet et al., 2018).

Station and Abbreviation	NOAA Station ID	Relative Sea-Level (RSL) (mm/yr)		Vertical Land Motion (VLM) (mm/yr)	
		Rate	SE	Rate	SE
Crescent City (CC)	9419750	-0.84	0.14	2.83	0.21
Trinidad (TR)	9419059	2.86	1.10	-0.87	1.11
Mad River Slough (MRS)	9418865	2.53	0.41	-0.54	0.44
Samoa (SO)	9418817	3.92	0.35	-1.93	0.38
North Spit (NS)	9418767	5.20	0.17	-3.21	0.23
Fields Landing (FL)	9418723	4.65	0.33	-2.66	0.37
Hookton Slough (HS)	9418686	6.64	0.65	-4.65	0.67

3.3 Estimated Extreme Water Levels and Tidal Datum Still Water Levels

The coastal still water levels for this analysis came from the 2D hydrodynamic model developed as part of the Humboldt Bay sea-level rise modeling and inundation vulnerability mapping project (NHE 2015). Estimates of Year 2023 extreme high-water levels were determined at a representative grid cell location (adjacent to Klopp Lake) along the Project shoreline reach (Figure 2). The maximum daily water elevation (NAVD88) for each day of the 100-yr simulation was extracted from the results database resulting in 36,525 daily values for each selected grid cell.

Estimates of the mean higher high water (MHHW) tidal datum, and the mean monthly maximum water (MMMW) and mean annual maximum water (MAMW) levels were determined from the 36,525 daily maximum values. An estimate of mean high water (MHW) was provided by subtracting 21.7 cm (9.54 in) from MHHW (NHE 2015).

An extreme value analysis (EVA) was conducted on the daily maximum water levels at each grid cell using the peaks-over-threshold (POT) approach and Generalized Pareto Distribution (GPD). A theoretical definition, more detailed information, and an explanation of the parameter estimation process for the POT and GPD can be found in Coles (2001). The EVA and parameter estimation were conducted with the R package extRemes (Gilleland and Katz 2016). All model distribution parameters were determined with the maximum likelihood estimation approach (Coles 2001). For this analysis, the threshold value was set to 97% of the maximum daily data. To satisfy the independence requirement of the EVA analysis, a de-clustering time of 3 days was used. Using these threshold and de-clustering values results in an approximate mean number of exceedances per year of 3.9, which is consistent with recommendations for regional and global extreme sea level analysis (Arns et al. 2017).

Results of the tidal datum and still water level EVA for the Project shoreline are provided in Table 3. Water levels were adjusted for sea-level rise to represent Year 2023 estimates using a ReSL value of 1.99 mm/yr. For comparison results for the North Spit tide station grid cell location are also provided.

Costa and Glatzel (2002) noted that tidal amplification and phase lag occur within the bay based on distance from the entrance. Both the reported NOAA tidal datum values (Table 1) and the modeled tidal datum and EVA water levels (Table 3) show tidal amplification into North Bay, along with an increase in the diurnal tidal range (difference between MHHW and MLLW.

Table 3. Summary of tidal datum and extreme value analysis (EVA) still water levels for the Project shoreline and North Spit tide station for Year 2023. Water levels adjusted to Year 2023 using a ReSL value of 1.99 mm/yr.

Tidal Datum and Annual Exceedance Probability (%)	Annual Expected Number of Occurrences (#/yr)	Annual Average Recurrence Interval (yr)	Year 2023 Estimated Still Water Levels (NAVD88)			
			Project Shoreline		North Spit	
			Value (m)	Value (ft)	Value (m)	Value (ft)
MHW[1]			1.994	6.54	1.838	6.03
MHHW			2.176	7.14	2.055	6.74
MMMW			2.584	8.48	2.441	8.01
MAMW			2.896	9.50	2.753	9.03
99.0	0.99	1.01	2.836	9.30	2.694	8.84
95.0	0.95	1.053	2.841	9.32	2.699	8.86
90.9	0.91	1.1	2.847	9.34	2.705	8.87
80.0	0.80	1.25	2.862	9.39	2.721	8.93
66.7	0.67	1.5	2.885	9.46	2.742	9.00
50.0	0.50	2	2.918	9.57	2.776	9.11
20.0	0.20	5	3.017	9.90	2.872	9.42
10.0	0.10	10	3.082	10.11	2.937	9.64
5.0	0.05	20	3.142	10.31	2.996	9.83
4.0	0.04	25	3.160	10.37	3.014	9.89
2.0	0.02	50	3.211	10.54	3.065	10.05
1.0	0.01	100	3.258	10.69	3.111	10.21
0.5	0.005	200	3.300	10.83	3.152	10.34
0.2	0.002	500	3.349	10.99	3.201	10.50

[1] MHW was estimated by subtracting 21.7 cm (8.54 in) from MHHW (NHE 2015).

3.4 Winds

Humboldt Bay has distinct seasonal wind patterns, with winds from the north to northwest from March through October, and southeast to southwest winds from November to February (Costa and Glatzel 2002). Several weather stations exist in the Project vicinity with wind speed and direction data (Figure 5 and Table 4).

Table 4. Weather stations in Project vicinity with wind speed and direction data. Arcata/Eureka Airport data downloaded from NOAA Integrated Surface Data (ISD) database; data for other stations from Iowa Environmental Mesonet of Iowa State University.

Station Name	Station ID	Coordinates	Elevation	Period of Record	Notes
Arcata/Eureka Airport	ACV	40.97811°N, 124.10861°W	66 m (217 ft)	1949 to present	Wind analysis
Fortuna	FOT	40.55390°N, 124.13270°W	112 m (369 ft)	2011 to present	Wind rose
Eureka (Woodley Island)	EKA	40.80970°N, 124.16030°W	18 m (599 ft)	1948 to 2022	Wind rose
North Spit (9418767)	HBYC1	40.76700°N, 124.21700°W	7.6 m (25.9 ft)	2016 to present	Wind rose
Samoa - North Jetty Landing	NJLC1	40.76890°N, 124.23890°W	6 m (20 ft)	2020 to present	Wind rose

Hourly wind data for the stations listed in Table 4 were used to generate wind roses (Figure 6). The two land-based automated surface observation stations (ASOS) (Eureka/Arcata Airport and Fortuna) show an opposing northwest to southeast wind direction pattern, while the three stations located in Humboldt Bay (Eureka and North Spit) and nearshore (North Jetty Landing) show a stronger north to south pattern. This indicates that the topography of the easterly Northern Coast Range adjacent to Humboldt Bay may have a topographic steering effect on wind directions of the land-based stations.

An extreme 2-min wind speed and direction analysis was conducted by NHE for the Natural Shoreline Infrastructure project using the Arcata/Eureka Airport wind data (Appendix D, GHD et al. 2022). Reference to Appendix D can be made for a detailed discussion of the analysis methods and results.

Peak 2-min wind speeds (assuming a Gumbel distribution) differ by wind direction in Humboldt Bay (Figure 7). The fastest wind speeds are from the east-southeast (112.5°) to north (360°) directions, with peak winds from easterly directions being much lower. Consistent with the Arcata/Eureka Airport wind rose (Figure 6) maximum peak winds appear to come from two dominant and opposing directions, southeast (135°) and northwest (315°). The extreme wind speed analysis was based on a GPD-POT approach and used the maximum daily 2-min wind speed neglecting wind direction. Consequently, the resulting extreme wind speeds are applicable for any wind direction from approximately 112.5° to 360°. Table 5 lists the estimated 2-min extreme wind speeds affecting the Project shoreline.

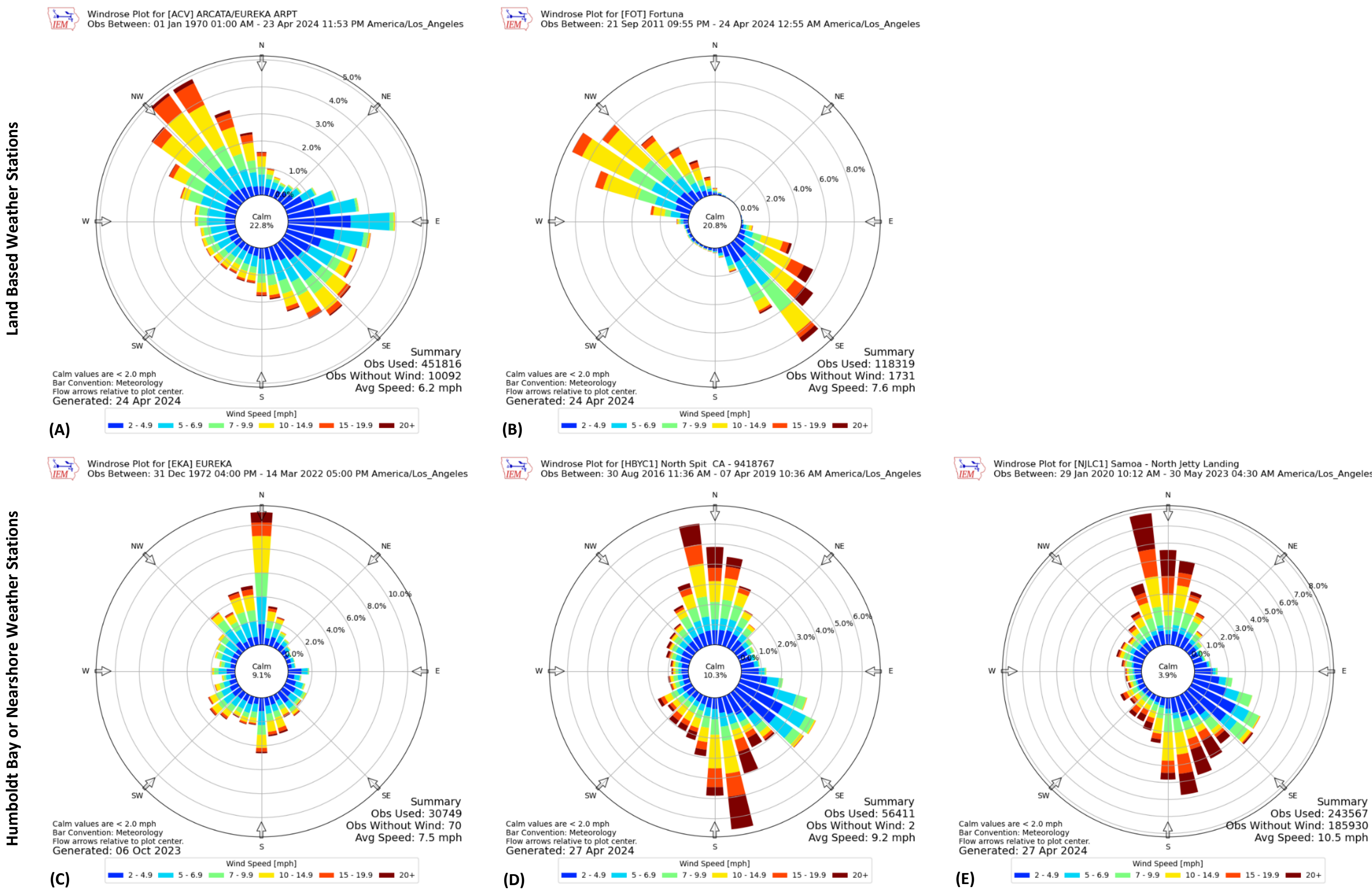

Figure 6. Wind rose for Arcata/Eureka Airport (A), Fortuna (B), Eureka (C), North Spit (D) and North Jetty Landing (E). Plots generated from Iowa Environmental Mesonet of Iowa State University.

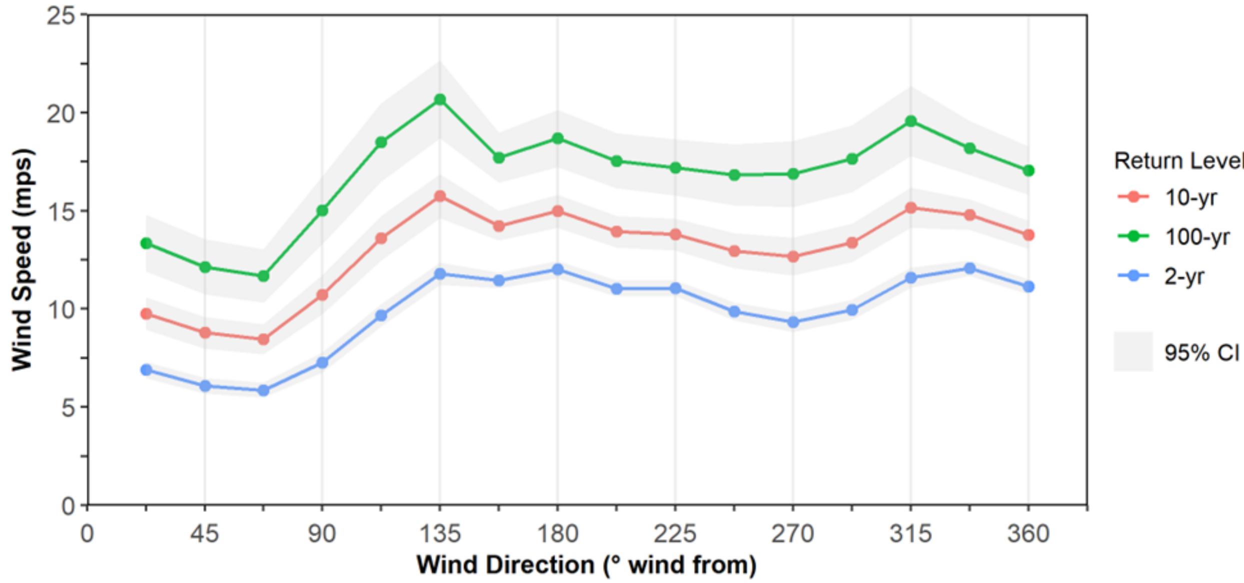

Figure 7. Peak 2-min wind speed estimates and 95% confidence intervals by wind direction from a Gumbel distribution for the 2-yr, 10-yr and 100-yr return levels (figure from Appendix D, GHD et al., 2022).

Table 5. Extreme 2-min wind speed estimates from the POT/GPD analysis of the Arcata/Eureka Airport data (Appendix D, GHD et al. 2022). Wind speeds have been adjusted to 2-min average duration and 10 m height.

Annual Exceedance Probability (%)	Annual Expected Number of Occurrences (#/yr)	Annual Average Recurrence Interval (yr)	Extreme 2-min Wind Speed (mps)		Extreme 2-min Wind Speed (mph)	
			Estimate	95% CI	Estimate	95% CI
~100	~1	~1	16.85	[15.90, 17.79]	37.7	[35.6, 39.8]
95.0	0.95	1.053	16.94	[15.98, 17.90]	37.9	[35.7, 40.0]
80.0	0.80	1.25	17.22	[16.22, 18.23]	38.5	[36.3, 40.8]
66.7	0.67	1.5	17.51	[16.46, 18.57]	39.2	[36.8, 41.5]
50.0	0.50	2	17.94	[16.82, 19.07]	40.1	[37.6, 42.7]
20.0	0.20	5	19.11	[17.69, 20.53]	42.7	[39.6, 45.9]
10.0	0.10	10	19.82	[18.11, 21.53]	44.3	[40.5, 48.2]
4.0	0.04	25	20.58	[18.38, 22.78]	46.0	[41.1, 51.0]
2.0	0.02	50	21.04	[18.39, 23.70]	47.1	[41.1, 53.0]
1.0	0.01	100	21.43	[18.25, 24.60]	47.9	[40.8, 55.0]
0.5	0.005	200	21.75	[17.97, 25.52]	48.6	[40.2, 57.1]
0.2	0.002	500	22.09	[17.38, 26.79]	49.4	[38.9, 59.9]

3.5 Wind Fetch Direction and Length

The Project shoreline is most vulnerable to wind setup and locally generated wind-waves in North Bay from southeast to southwest winds. Since waves in North Bay are fetch limited, the longest fetch length for a given constant wind speed will produce the largest wave heights. For this analysis, wave conditions were estimated at a single location with the longest fetch length and the resulting wind-waves can be considered maximums for the Project shoreline. For this assessment, wind setup and wind-wave heights and periods were estimated for winds from a west-southwest (240.3°) direction, which is the longest fetch with a length of 8.4 km (5.2 miles). Figure 8 shows fetch directions and lengths at 22.5° intervals and the longest fetch relative to the Project shoreline. It should be noted that the Project shoreline for the wind-wave analysis is the armored shoreline adjacent to Klopp Lake, and the longest fetch wave direction is 32.8° relative to the shore normal transect at this location.

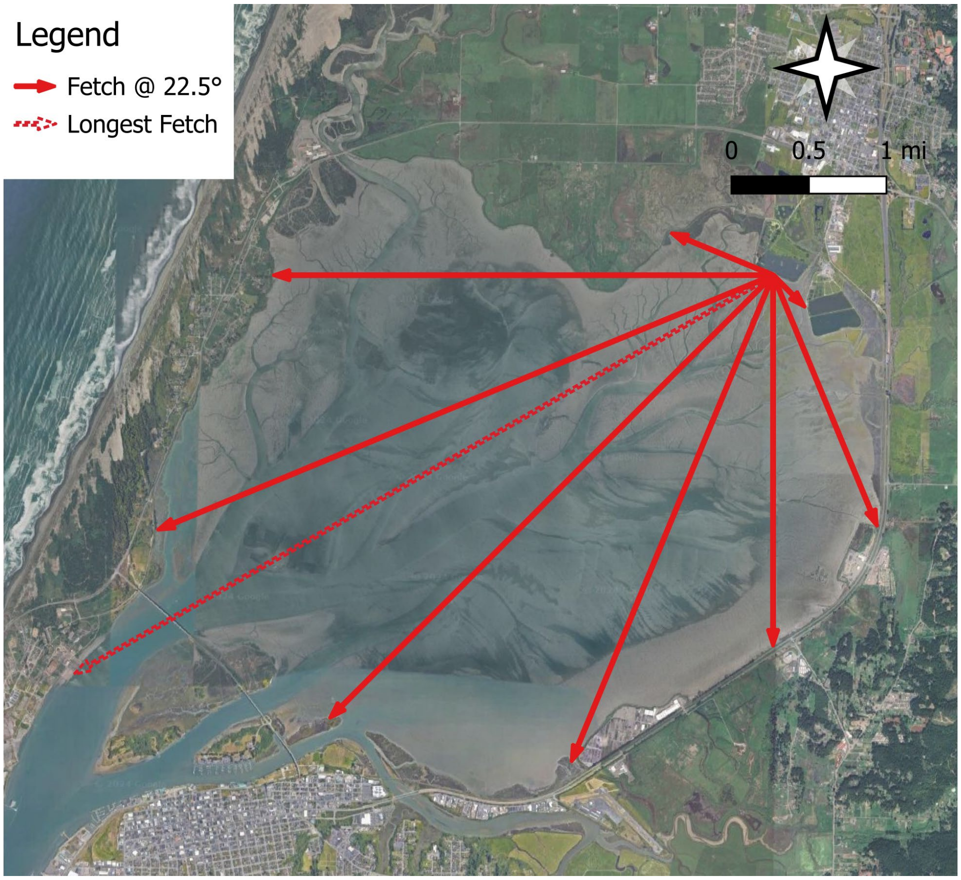

Figure 8. Fetch directions relative to the Project shoreline adjacent to Klopp Lake in North Bay.

3.6 Estimated Wind Setup

The Humboldt Bay hydrodynamic model (Figure 9) developed as part of the Natural Shoreline Infrastructure project (GHD et al. 2022) was used to estimate wind setup at the Project site for various wind speeds and directions. Reference to the GHD et al. (2022) report can be made for a description of the hydrodynamic model setup and parameters.

The tidal open boundary condition (Figure 10) for the analysis consisted of a 10-day period from the 100-yr hourly sea level height series (NHE 2015) derived for the Crescent City tide station (NOAA Station ID: 9419750). The 10-day period spanned 22 to 31 January 1983. During this 10-day period a large El Niño driven storm coincided with higher-than-normal astronomical tides producing the highest water levels of record at the Crescent City tide gauge. This 10-day series contains a large tidal height range spanning MHHW to above the 1% annual chance extreme high-water level event. The wind speeds and directions were held constant for each 10-day simulation.

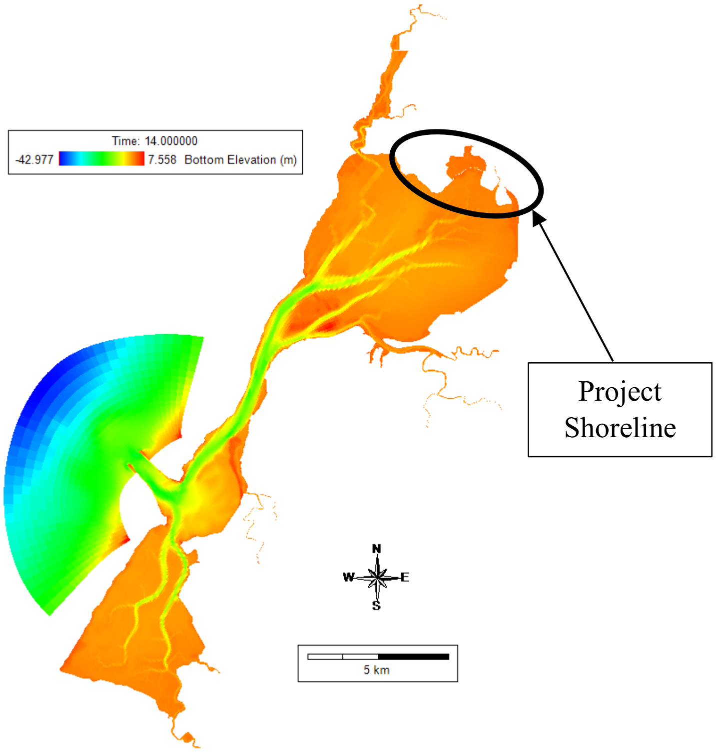

Figure 9. Humboldt Bay 3D circulation model domain. Bathymetry/topography based on grid cell elevations.

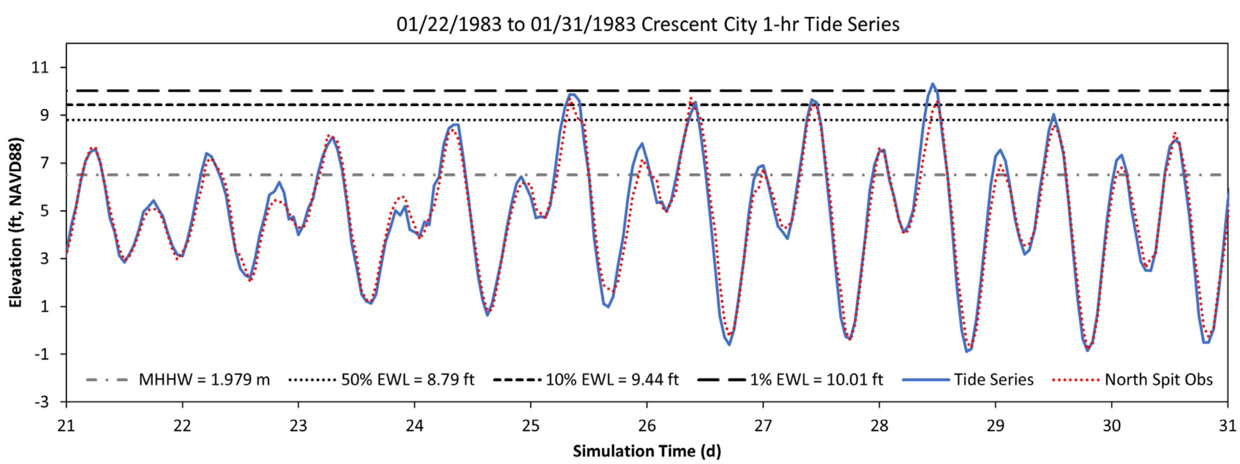

Figure 10. Tidal open boundary condition (blue line) used for model simulations. Tidal series based on Crescent City tide station (ID: 9419750). Observed North Spit tide station (ID: 9418767) observations (red dotted line) corrected for ~2 mm sea-level change from 1982 to 2012. MHHW is mean higher high water; #% EWL (e.g. 1% EWL) represents the #% annual chance extreme high-water level (e.g. 1% chance extreme high-water level).

Wind setup results at the Project shoreline were extracted at the peak water level near day 25.36 of the simulation which represents the approximate 1% extreme high-water level. Results of the wind setup analysis for a constant wind speed of 20 mps (44.7 mph) and different wind directions are listed in Table 6 and shown on Figure 11. The variation in wind setup by wind speed for the wind directions (180° to 270°) that produce the highest wind setup values are shown on Figure 12.

Table 6. Summary of wind setup for 20 mps (44.7 mph) wind speed and various directions at the Project shoreline. Wind setup estimate for the longest fetch is also provided (grey cell). Water levels were extracted at the approximate 1% extreme high-water level.

Wind Direction (from)	Wind Direction From (°)	Wind Speed (not adjusted) (mps)	Wind Speed (not adjusted) (mph)	~1% Water Level (m, NAVD88)	Wind Setup (m)	Wind Setup (ft)
No wind	No wind	20	44.7	3.165	0.000	0.00
East-Southeast	112.5	20	44.7	2.991	-0.174	-0.57
Southeast	135.0	20	44.7	3.105	-0.060	-0.20
South-Southeast	157.5	20	44.7	3.217	0.052	0.17
South	180.0	20	44.7	3.323	0.158	0.52
South-Southwest	202.5	20	44.7	3.394	0.228	0.75
Southwest	225.0	20	44.7	3.445	0.280	0.92
Longest Fetch[1]	240.3	20	44.7	NA	0.274	0.90
West-Southwest	247.5	20	44.7	3.427	0.262	0.86
West	270.0	20	44.7	3.397	0.232	0.76
West-Northwest	292.5	20	44.7	3.305	0.139	0.46
Northwest	315.0	20	44.7	3.194	0.029	0.09
North-Northwest	337.5	20	44.7	3.059	-0.107	-0.35
North	360	20	44.7	2.929	-0.237	-0.78

[1] Wind setup estimates for the longest fetch (240.3°) were determined by interpolating setup values between the southwest (225°) and west-southwest (247.5°) wind directions.

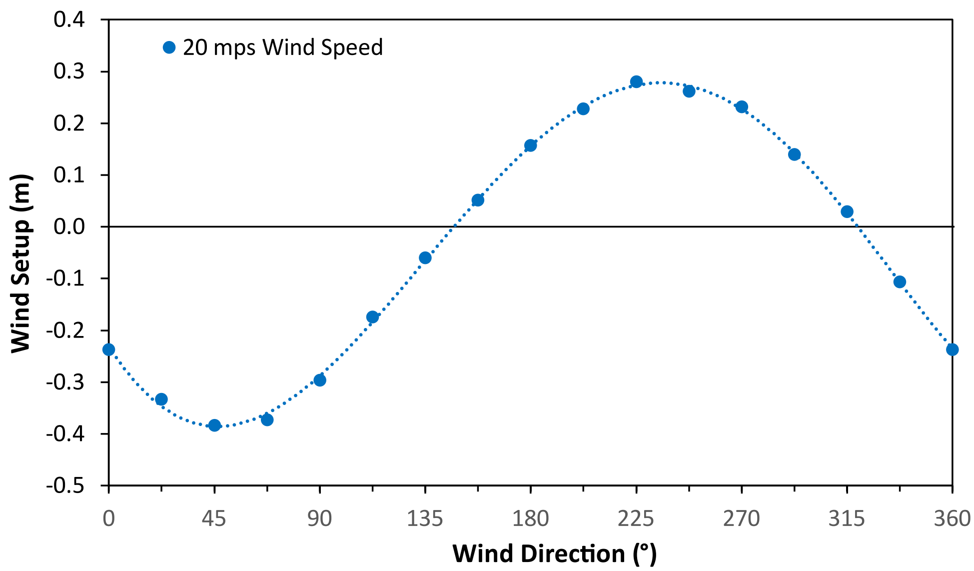

Figure 11. Wind setup by wind direction for a 20 mps (44.7 mph) wind speed at the Project shoreline.

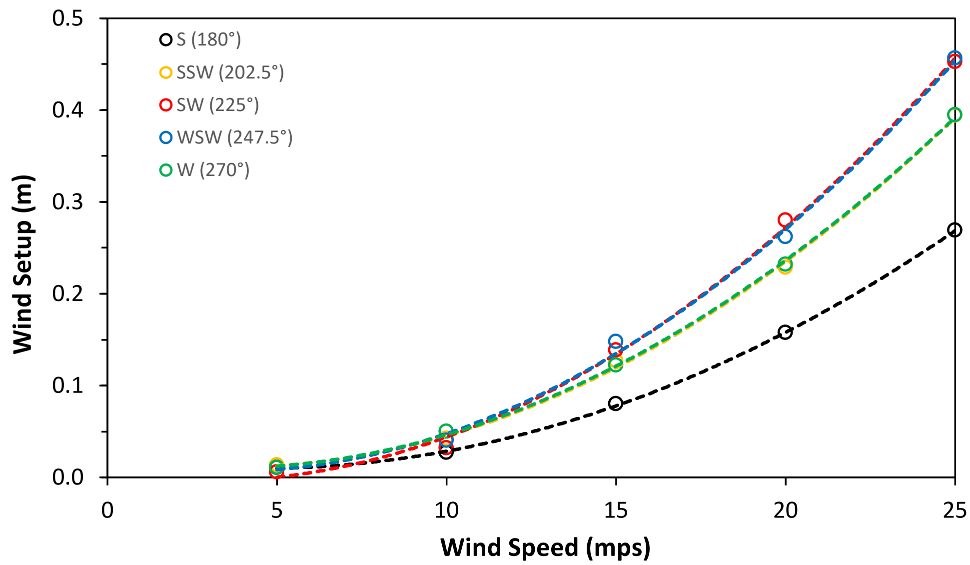

Figure 12. Wind setup by wind speed for wind directions from the south to west (180° to 270°).

Results for the 20 mps (44.7 mph) wind speed, which is close to the 10% adjusted wind speed (Table 5) of 19.8 mps (44.3 mph), indicate that winds from the south-southwest to northwest directions (157.5° to 315°) push water out of South Bay into North Bay and/or from the west to east shorelines of North Bay creating positive wind setup values up to a maximum of 0.28 m (0.9 ft). Winds from the other directions tend to push water out of North Bay into South Bay and/or away from the Project shoreline resulting in negative wind setup values down to a minimum of -0.24 m (-0.8 ft).

Wind setup values along the longest fetch direction (240.3°) are summarized in Table 7 for eight extreme wind speeds (95, 66.7, 50, 20, 10, 4, 2 and 1% exceedance probability). The longest fetch direction is between the two highest wind setup directions (225° to 247.5°). Consequently, conditions that produce the largest wind-waves and wave runup values along the Project shoreline also generate large wind setup values.

Table 7. Summary of wind setup values for the longest fetch (240.3°) relative to the Project shoreline for different extreme wind speeds. Wind setup estimates were determined by interpolating setup values between the southwest (225°) and west-southwest (247.5°) wind directions.

Annual Exceedance Probability (%)	Extreme 2-min wind speed (mps)	Adjusted Wind Speed (mps)	Adjusted Wind Speed (mph)	Wind Direction From (°)	Wind Setup (m)	Wind Setup (ft)
95	16.94	16.83	37.6	240.3	0.179	0.59
66.7	17.51	17.41	38.9	240.3	0.195	0.64
50	17.94	17.85	39.9	240.3	0.207	0.68
20	19.11	19.04	42.6	240.3	0.241	0.79
10	19.82	19.76	44.2	240.3	0.263	0.86
4	20.58	20.54	45.9	240.3	0.288	0.95
2	21.04	21.01	47.0	240.3	0.304	1.00
1	21.43	21.41	47.9	240.3	0.318	1.04

3.7 Wind-Waves for the Project Shoreline

3.7.1 Estimated Wind-Wave Height and Period

Wave heights and periods were determined along the longest fetch direction for eight extreme wind speeds (95, 66.7, 50, 20, 10, 2 and 1% exceedance probability) outlined in Table 5. Fetch-limited peak wave heights and periods were estimated using the simplified procedures for wind adjustments and wave prediction outlined in CEM (2015). This procedure adjusts wind speeds to fetch-limited conditions by (1) adjusting wind speed for duration and fetch length, and (2) applying a 1.2 factor for overwater wind speeds for fetch lengths less than 16 km (~10 mi). The fetch lengths, adjusted wind speeds, and predicted peak wave heights and periods for the five wind speeds are summarized in Table 8.

Table 8. Wind-wave analysis summary of adjusted wind speeds and predicted peak wind-wave heights and periods for eight extreme wind speeds for the Project shoreline. Wave conditions are along the longest fetch (west-southwest direction (240.3°), 8.359 km length) relative to the shoreline.

Annual Exceedance Probability (%)	Extreme 2-min wind speed (mps)	Adjusted Wind Speed (mps)	Adjusted Wind Speed (mph)	Peak Wave Height (m)	Peak Wave Height (ft)	Wave Period (s)
95	16.94	16.83	37.6	0.72	2.35	2.66
66.7	17.51	17.41	38.9	0.75	2.45	2.70
50	17.94	17.85	39.9	0.77	2.53	2.73
20	19.11	19.04	42.6	0.83	2.74	2.80
10	19.82	19.76	44.2	0.87	2.87	2.85
4	20.58	20.54	45.9	0.92	3.01	2.90
2	21.04	21.01	47.0	0.94	3.09	2.92
1	21.43	21.41	47.9	0.96	3.17	2.95

3.7.2 Estimated $R_{2\%}$ Wave Runup

The $R_{2\%}$ wave runup values were estimated for the Project shoreline following the Technical Advisory Committee for Water Retaining Structures (TAW) method (van der Meer 2002) as modified in FEMA (2005) and used in the Natural Shoreline Infrastructure project (Appendix E, GHD et al. 2022). The approach in Appendix E is consistent with the approach used by FEMA (2014) to determine wave runup in Humboldt Bay where the shoreline is composed of a natural shoreline (without fringing tidal wetland) or shoreline structures. Reference to Appendix E (GHD et al. 2022), FEMA (2005) or FEMA (2014) can be made for more information regarding the wave runup methodology.

As noted in FEMA (2005 and 2014), the TAW equation is based on wave tank measurements which accounts for wave setup landward of the shoreline or structure toe, and FEMA (2005) recommends reducing the dynamic setup to account for this. If the incident waves have not broken prior to reaching the structure toe, then wave setup is not included in the total runup, which is consistent with the approach used by FEMA (2014) for determining wave runup estimates in Humboldt Bay. For runup estimates where the toe water depths were less than 0.78 times the wave height, wave runup estimates were based on the broken wave height determined as 0.78 times the toe water depth; and the static wave setup was determined using the Direct Integration Method (DIM) as described in FEMA (2005 and 2014), but the dynamic setup was assumed zero. For the water elevations listed in Table 3 greater than MHHW, the water depth at the toe of the shoreline or structure is greater than 0.78 times the wave height, indicating that waves have not broken prior to reaching the toe and wave setup was assumed zero.

The Project shoreline consists of both armored (rock revetment) and natural shoreline segments, and the armored shorelines will produce the highest $R_{2\%}$ wave runup estimates. For this assessment, wave runup estimates were only determined for the armored shoreline, using the following representative rock revetment geometry:

- Crest elevation: 3.5 m (11.5 ft)
- Toe elevation: 1.2 m (3.9 ft)
- Structure slope: 1V:2H
- Crest width: assumed negligible

Since runup estimates are along the longest fetch affecting the Project shoreline, the $R_{2\%}$ wave runup values listed in Table 9 can be considered maximum values for each wind speed analyzed. For this assessment it was assumed that portions of Project shoreline consisting of natural shoreline segments will attenuate wave height and runup to values below the crest elevation.

Table 9. Summary of $R_{2\%}$ wave runup estimates for extreme wind speeds at the armored Project shoreline with rock revetment. Runup estimates are maximum values for the reported still water levels (tidal datums or exceedance probabilities (EP)). Wave conditions are along the longest fetch (west-southwest direction (240.3°), 8.359 km length) relative to the shoreline, and a 1V:2H revetment slope.

Annual Exceedance Probability (%)	Annual Average Recurrence Interval (yr)	Applicable Still Water Level	Adjusted Wind Speed (mps)	Adjusted Wind Speed (mph)	Wave Runup - $R_{2\%}$ (m)	Wave Runup - $R_{2\%}$ (ft)
95	1.053	>= MHHW	16.83	37.6	1.262	4.14
66.7	1.5	>= MHHW	17.41	38.9	1.306	4.29
50	2	>= MHHW	17.85	39.9	1.340	4.40
20	5	>= MHHW	19.04	42.6	1.433	4.70
10	10	>= MHHW	19.76	44.2	1.490	4.89
4	25	>= MHHW	20.54	45.9	1.551	5.09
2	50	>= MHHW	21.01	47.0	1.589	5.21
1	100	>= MHHW	21.41	47.9	1.621	5.32

3.8 Total Water Levels at Project Shoreline

Total water levels (TWL) at the Project shoreline are a combination of still water levels (tide levels plus storm surge), wind setup, and wave setup and runup from locally generated wind-waves. For this analysis, wave runup values include wave setup. Tabulated results of TWL estimates for the Project shoreline are provided in Table 10 for a combination of still water levels (MHHW, MMMW, and 95%, 50%, 10%, 4% and 1% exceedance probabilities) and wind speeds (95%, 50%, 10%, 4% and 1% exceedance probabilities). Two TWL estimates are provided. One can be used as a TWL estimate for natural shorelines and combines still water level and wind setup, but assumes the natural shoreline attenuates waves and wave runup to negligible values. The other TWL estimate applies to armored shoreline segments and includes still water level, wind setup and the $R_{2\%}$ wave runup values.

Table 10. Summary of total water levels (TWL) at the Project shoreline. An estimate of TWLs for a natural shoreline is provided by combining still water level and wind setup values (green cells). The TWL for an armored shoreline includes still water level, wind setup and $R_{2\%}$ wave runup (blue cells).

Annual Exceedance Probability (%) (Recurrence Interval (yr))		Still Water Level (m, NAVD88)	Wind Setup (m)	TWL (NAVD88) Estimate for Natural Shoreline		$R_{2\%}$ Wave Runup (m)	TWL (NAVD88) for Armored Shoreline	
Water Level	Wind Speed			Value (m)	Value (ft)		Value (m)	Value (ft)
MHHW	No wind	2.176	0.000	2.176	7.14	0.000	2.176	7.14
	95 (1.05-yr)		0.179	2.355	7.73	0.179	3.617	11.87
	50 (2-yr)		0.207	2.382	7.82	0.207	3.723	12.21
	10 (10-yr)		0.263	2.439	8.00	0.263	3.929	12.89
	4 (25-yr)		0.288	2.464	8.08	0.288	4.016	13.17
	1 (100-yr)		0.318	2.494	8.18	0.318	4.114	13.50
MMMW	No wind	2.584	0.000	2.584	8.48	0.000	2.584	8.48
	95 (1.05-yr)		0.179	2.763	9.06	0.179	4.025	13.20
	50 (2-yr)		0.207	2.790	9.15	0.207	4.130	13.55
	10 (10-yr)		0.263	2.847	9.34	0.263	4.337	14.23
	4 (25-yr)		0.288	2.872	9.42	0.288	4.423	14.51
	1 (100-yr)		0.318	2.901	9.52	0.318	4.522	14.84
95 (1.05-yr)	No wind	2.841	0.000	2.841	9.32	0.000	2.841	9.32
	95 (1.05-yr)		0.179	3.020	9.91	0.179	4.282	14.05
	50 (2-yr)		0.207	3.048	10.00	0.207	4.388	14.40
	10 (10-yr)		0.263	3.104	10.19	0.263	4.595	15.07
	4 (25-yr)		0.288	3.129	10.27	0.288	4.681	15.36
	1 (100-yr)		0.318	3.159	10.36	0.318	4.779	15.68
50 (2-yr)	No wind	2.918	0.000	2.918	9.57	0.000	2.918	9.57
	95 (1.05-yr)		0.179	3.098	10.16	0.179	4.359	14.30
	50 (2-yr)		0.207	3.125	10.25	0.207	4.465	14.65
	10 (10-yr)		0.263	3.182	10.44	0.263	4.672	15.33
	4 (25-yr)		0.288	3.207	10.52	0.288	4.758	15.61
	1 (100-yr)		0.318	3.236	10.62	0.318	4.857	15.93
10 (10-yr)	No wind	3.082	0.000	3.082	10.11	0.000	3.082	10.11
	95 (1.05-yr)		0.179	3.262	10.70	0.179	4.524	14.84
	50 (2-yr)		0.207	3.289	10.79	0.207	4.629	15.19
	10 (10-yr)		0.263	3.346	10.98	0.263	4.836	15.87
	4 (25-yr)		0.288	3.371	11.06	0.288	4.922	16.15
	1 (100-yr)		0.318	3.400	11.16	0.318	5.021	16.47
4 (25-yr)	No wind	3.160	0.000	3.160	10.37	0.000	3.160	10.37
	95 (1.05-yr)		0.179	3.339	10.95	0.179	4.601	15.09
	50 (2-yr)		0.207	3.366	11.04	0.207	4.706	15.44
	10 (10-yr)		0.263	3.423	11.23	0.263	4.913	16.12
	4 (25-yr)		0.288	3.448	11.31	0.288	4.999	16.40
	1 (100-yr)		0.318	3.477	11.41	0.318	5.098	16.73
1 (100-yr)	No wind	3.258	0.000	3.258	10.69	0.000	3.258	10.69
	95 (1.05-yr)		0.179	3.437	11.28	0.179	4.699	15.42
	50 (2-yr)		0.207	3.464	11.37	0.207	4.805	15.76
	10 (10-yr)		0.263	3.521	11.55	0.263	5.011	16.44
	4 (25-yr)		0.288	3.546	11.63	0.288	5.098	16.72
	1 (100-yr)		0.318	3.576	11.73	0.318	5.196	17.05

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