Reference Model Development

Wave Energy Resource and Site Characterization

Prepared by RE Vision Consulting, LLC on behalf of the U.S. Department of Energy

June 2010

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Report ID

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Introduction

In order to develop a solid understanding of the design requirements, reference site data-sets are developed. These reference sites correspond to real sites and capture valuable early adopter deployment sites. Design requirements must encompass a global view, if they are to allow engineers to optimize their device for a global market. The following provides an overview of the design requirements from a designer's perspective:

1. Statistical Information on Wave Characteristics suitable for Device Performance and Cyclic Fatigue Assessment
2. Extreme structural loading conditions
    a. 50-year and 100-year wave event
    b. 50-year and 100-year wind event
    c. 50-year and 100-year current event
3. Mooring considerations (water depth / seabed / sediments)

A first initial reference site was selected, near Eureka in Humboldt County, California. This initial selection was made because the site was identified as a promising future deployment site in previous studies and has a wave climate that is representative of other US west-coast deployment sites. Further, the availability of a wide range of oceanographic data-sets allows the team to obtain a high-fidelity data-set for design efforts undertaken. The initial focus is on a single US site, but eventually this scope will be expanded to include potential deployment sites in other parts of the US and eventually worldwide. This will allow capturing major differences in design considerations as a function of deployment location. The following is an initial short-list of representative US sites:

1. Eureka – California
2. Oregon – Reedsport
3. Yakutat – Alaska
4. Waimanalo Bay – Oahu, Hawaii
5. Cape Hatteras – North Carolina

An initial short-list of international sites is:

1. EMEC – Orkney, Ireland
2. Wave Hub – Southwest UK
3. Galway Bay – Deep water Offshore or other Irish deployment site exposed to Atlantic wave conditions

4. Portuguese pilot testing zone – Portugal

Future Work – Shallow Water

While this initial site only captures deep-water wave-data, it will need to be expanded to shallow water as different devices are being evaluated. Shallow-water wave characteristics require a different characterization because sea-bed effects start to play a dominant factor in device performance characterization and should be included in future versions of this document.

Future Work – Directional Data

To evaluate device performance for directionally sensitive devices and arrays, this work will need to be expanded to develop reference data-sets characterizing fully directional seas.

Status Summary

Statistical Analysis sea-states of US reference sites => Completed => Device Performance Assessments can be carried out.

Extreme Wave Events Analysis => Complete => Driving extreme loads can be assessed.

Remaining to be done

- Methodology Documentation
- Refine extreme current and wind assessment
- Compare to Offshore Standards
- Future Work (Shallow water and directional data)

Basic Wave Characteristic

To determine the significant wave height, wave energy period, and wave energy flux from a wave energy spectrum the two spectral moments needed are m_0 and m_{-1}, which are numerically calculated as:

$$m_0 = \sum_{i=1}^{N} S(f_i)\ \Delta f_i \qquad \text{(Equation 1)}$$

and

$$m_{-1} = \sum_{i=1}^{N} \frac{S(f_i)}{f_i}\ \Delta f_i \qquad \text{(Equation 2)}$$

From the zeroth-order moment, a spectrally derived **significant wave height** (H_{m0}) is calculated as:

$$H_{m0} = 4\sqrt{m_0} \qquad \text{(Equation 3)}$$

This accurately estimates the time-series derived significant wave height, which is the mean value of the highest third of the waves in a random seaway. Visually the significant wave height corresponds to the mean wave height one would estimate from observations, since the human eye does not perceive the smaller waves.

The **wave energy period** (T_e) is calculated from the above two spectral moments as:

$$T_e = \frac{m_{-1}}{m_0} \qquad \text{(Equation 4)}$$

The wave energy period represents the period of a single wave that would have the same energy as the overall sea-state.

The **peak wave period** (T_p) is the inverse of the frequency at which the wave spectrum has its highest energy density, and is also referred to as the dominant wave period. T_p is sometimes used to calculate power density, requiring a spectral factor which is only approximate. However, this is an inaccurate way to calculate power density, because the frequency distribution of energy in the spectrum is neglected.

Total wave energy flux, also referred to as **wave power density**, in Watts per meter propagating through a vertical plane in an irregular sea state at a given ocean depth, *d*, is determined from linear wave theory as follows:

$$P = \rho g \int_0^\infty c_G(f,d) \times S(f)\,df$$

$$= \frac{\rho g^2}{4\pi} \int_0^\infty \frac{S(f)}{f} \left[\left(1 + \frac{2k_f d}{\sinh(2k_f d)} \right) \tanh(k_f d) \right] df \qquad \text{(Equation 5)}$$

In deep water, this equation simplifies to:

$$P_0 = \frac{\rho g^2}{4\pi} m_{-1} = \frac{\rho g^2}{64\pi} T_e (H_{m0})^2 \qquad \text{(Equation 6)}$$

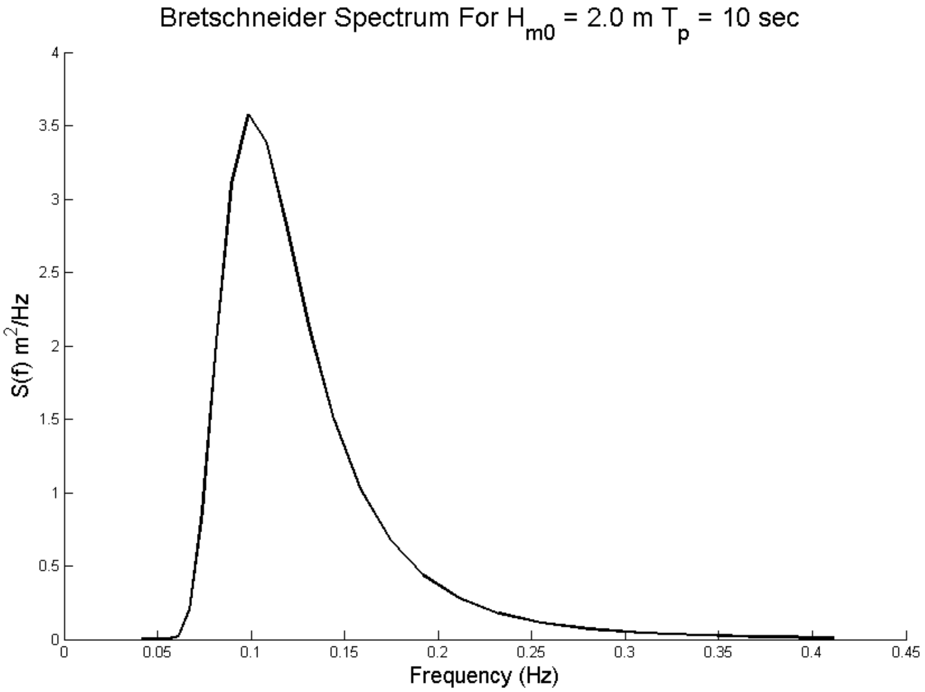
or simplified to yield kW/m:

$$P_0 = 0.49\, T_e (H_{m0})^2 \qquad \text{(Equation 7)}$$

It is important to understand the limitations of linear wave theory as it assumes that waves are sinusoidal in nature. As waves approach the near-shore environment, non-linear effects start to dominate. In those environments (i.e. < 20m) a higher order method that captures the non-linear behavior may be more appropriate to accurately calculate power density.

Spectral Distribution

The spectral distribution of energy is important, because it defines at which frequencies most of the energy in a sea-state occurs. Because most of the wave power conversion devices have a frequency dependent performance characteristic, the spectral distribution of wave energy is a site-specific phenomena, and it is important to characterize it accurately. Using wave spectra, the time-series can be reconstructed in the computational domain, which in turn can be used to evaluate device tuning strategies, which impact device performance to a significant extent. The following illustration shows an example of a typical wave energy spectrum.



Different spectral definitions have been developed for different regions around the world. A good starting point is usually the Bretschneider (or Generalized Pierson-Moskowitz) spectrum. The energy per unit area of the irregular wave consisting of the superposition of several frequency components is given by:

$$E = \rho g \sum_{k=1}^{N} S(\omega_k)\,\Delta\omega = \rho g \overline{\zeta(t)^2} = \rho g \sum_{k=1}^{N} \frac{\alpha(\omega_k)^2}{2} \qquad \text{(Equation 8)}$$

where ρ is the density of the fluid, g is the acceleration due to gravity, $S(\omega_k)$ is a component of the spectral density function and $\Delta\omega$ the component frequency interval. The component wave amplitudes are related to the spectral density components by the relation:

$$amp_k = \alpha(\omega_k) = \sqrt{2S(\omega_k)\Delta\omega} \qquad \text{(Equation 9)}$$

The resulting wave amplitude spectrum can then be used to generate a representative surface elevation time-series for time-domain simulations of wave energy conversion devices.

Methodology

In order to develop a more accurate site-specific representation of the wave climate and hence develop accurate site-specific performance assessments, methodology developed by EPRI was adapted to the Eureka, California site. The methodology uses a 52-month run of the Wavewatch III model by the NCEP, which generated a hindcast dataset that with broad geographical coverage in US waters. Utilizing both the methodology developed by EPRI and the Wavewatch III hindcast dataset, adding additional sites to the analysis can be done with relative ease.

The Wavewatch III model computes the full directional wave spectrum for thousands of grid points in the model domain. The Wavewatch III directional spectrum contained 24 directions (15 degree width) as well as 25 frequency divisions (totaling 600 wave spectra values per hindcast) making storage of the full directional spectrum unfeasible. Therefore, the full directional spectrum was only archived for 257 grid points worldwide. Archived grid points are consistent with NDBC deployments and have been used as deep-water calibration points to help regenerate unsaved spectrums.

However, at the tens of thousands of remaining grid points, Wavewatch III archives important sea state parameters: spectrally derived significant wave height (H_{m0}), peak wave period (T_p), mean direction of spectral peak energy (θ_p), wind fraction (wf). For operational forecasts and hindcasts, Wavewatch III archives these sea state parameters for the overall sea state as a whole, and also for the three highest component wave trains or partitions that constitute the overall sea state. NCEP performed a special, dedicated hindcast covering the 52-month period from February 2005 through July 2009, in which the sea state parameters (H_{m0}, T_p, θ_p, wf) were archived for all component wave trains (also referred to as "partitions") identified in the overall sea state at a given time step at a given grid point, and these were archived for all grid points and all time steps.

The method next uses the Wavewatch III hindcast full directional spectrum (1 of 257 locations) as a basis to reconstruct the actual wave spectrums at surrounding grid points where only sea state parameters have been archived. To reconstruct the spectrum, a theoretical Gamma spectrum (similar to the JONSWAP spectrum) was modified and then the formulation was applied to each sea state partition. The modified Gamma spectrum (defined below) has two spectral shape coefficients γ and k_B which have been optimized for the reference site on a monthly basis.

The modified Gamma spectrum is as follows:

$$S(f) = m_o n T_P (f/f_P)^{-n} exp\left(-\left(\frac{n}{n-1}\right)(f/f_P)^{1-n}\right) * G(f) \qquad \text{(Equation 10)}$$

where $G(f)$ is the peak enhancement function,

$$G(f) = \gamma^{exp\left(-(f-f_P)^2/(2\sigma^2 f_P{}^2)\right)} \qquad \text{(Equation 11)}$$

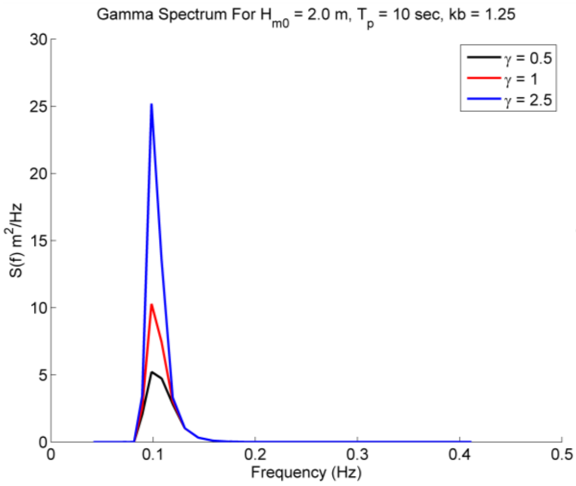
n is a modification to the gamma spectrum,

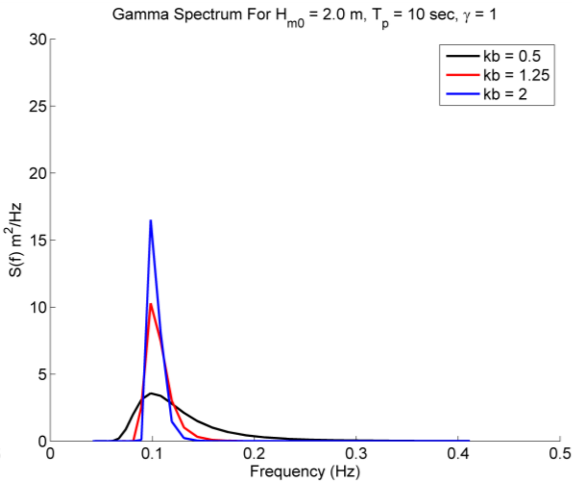
$$n = k_B T_P(1 - wf) + 5wf(10) \qquad \text{(Equation 12)}$$

with the parameters:

γ the peak enhancement factor,
k_B spectral shape parameter, and
wf the wind fraction.

As seen below, γ changes the peakedness of the spectrum increasing the values around the peak spectral period. The second parameter, k_B, compensates for shape or width change of the spectrum due to influence of the peak period. The wind fraction is an archived parameter from the Wavewatch III run and represents a percentage of the spectral energy forced by the wind.

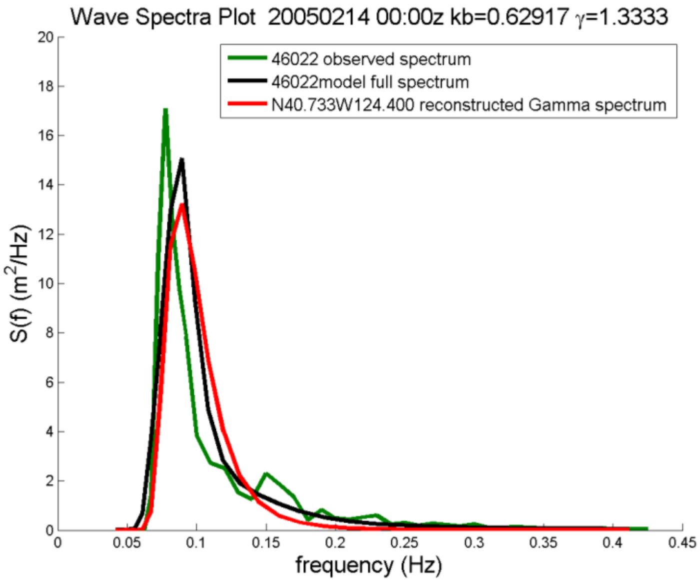




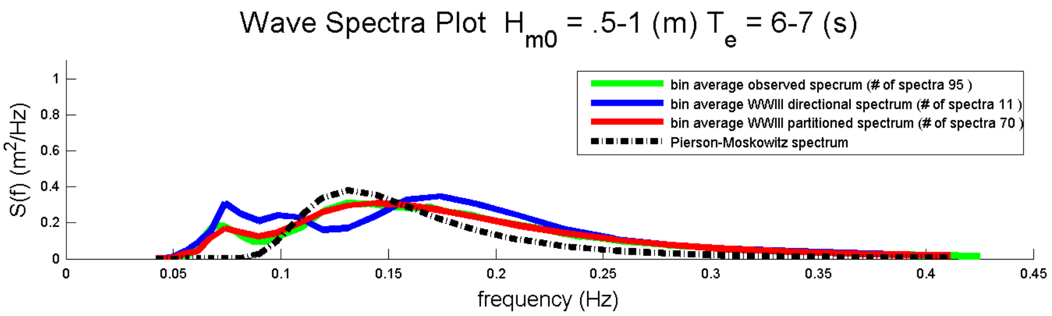
Through an iterative process, values for γ and k_B were found from wave partition data at a deep-water calibration point. The calibration points have both the full directional spectrum archived from Wavewatch III as well as the partitioned files containing sea-state parameters which were for all grid points. Values of γ and k_B for the modified gamma spectrum were calibrated to the Wavewatch III full spectrum. With calibrated spectral shape parameters for each region, the overall sea state spectra can be reconstructed to best fit the full hindcast spectra for that region from a selected deep-water calibration station.

Our deep-water calibration points were carefully selected making sure that the calibration point and the reference point were close by and more importantly under influence of the same wave climate. Because of this each calibration is only regionally applicable.

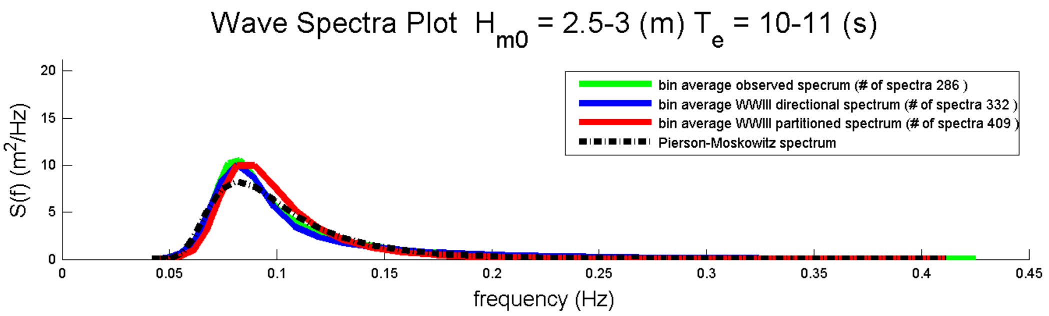
Since wave power density is directly proportional to the negative-first moment (m_{-1}) of the wave spectrum (see Equations 2 and 6), our calibration objective was to minimize the difference between the modified gamma spectra from the individual wave partitions and the full hindcast spectrum for the quantity $S(f)/f$, which is the quantity used to calculate m_{-1}. This was done by calculating the root-mean-square (RMS) difference in the quantity $S(f)/f$ between the reconstructed spectrum and the full hindcast spectrum over the entire range of frequencies used by Wavewatch III for time steps over 52 months. The spectrum for one time step is shown below for NDBC buoy 46022 which is collocated with our deep-water calibration point.



Above, the model full spectrum is from Wavewatch III full directional data, the reconstructed spectrum Gamma spectrum is from the Wavewatch III partitions, and the observed from buoy measurements. The method aggregates the RMS differences over all time steps to find optimal values for the shape coefficients (γ and k_B). To complete the analysis all the spectra for the 52 months are separated by their inherent sea-states, which are represented as different H_{m0} / T_e combinations. Once the different sea-states are separated, the spectra for each combination of the significant wave height and energy period can be found.



The wave spectra plot above demonstrates that significant improvement in fitting the observed spectrum over is made when using the modified gamma spectrum vs. the Pierson-Moskowitz spectrum for the given sea-state. For other sea-states, the addition of the parameter γ to the spectral formulation shows improvement capturing the observed spectral peak.



Within a given region, the nature of the wave-generating weather systems varies depending on the sea-state. Therefore, we apply our calibration process to each of the sea-states in our hindcast period from March 2005 through May 2009. Although February 2005 data were provided in the NOAA hindcast, it is evident from examining these data that wave conditions were “spinning up” in the first half of the month and that a steady state was not reached until the second half of the month, so February 2005 was excluded from our analysis.

Computed Outputs

Outputs are archived within a Matlab structure. This standard structure is intended for future re-use in device design efforts and provides a standard database. The following provides a list of variables that were developed for the reference site.

Table 1 - Archived Wave Resource Parameters

Variable	Size	Type	Description
Gam	12623x1	Double	calibrated γ parameter
Kb	12623x1	Double	calibrated Kb parameter
dteP	12623x1	Double	date from paritioned data file
Gspec_r	12623x25	Double	reconstructed Gamma spectrum
HmoP	12623x1	Double	reconstructed Hmo
TeP	12623x1	Double	reconstructed Te
P0P	12623x1	Double	reconstructed Power Denisty
m0P	12623x1	Double	reconstructed 1st moment
m_1P	12623x1	Double	reconstructed -1st moment
part	12623x13	Cell	WWIII paritioend data
MHmo	1	Double	max Hmo
MTe	1	Double	max Te
MP0	1	Double	max Power
aHmo	1	Double	average Hmo
aTe	1	Double	average Te
aP0	1	Double	average Power
dpth	1	Double	site depth
Te_bins	1*16	Cell	string of Te bin names
Hmo_bins	1*20	Cell	string of Hmo bin names
scat	16*20	Double	scatter matrix (# of occurences)
scat_ctr	1*2	cell of cell strings	centre values for Hmo and Te the scatter bins
	{1}	1x16	centre values for Hmo
	{2}	1x20	centre values for Te
freq	1*25	Double	WWIII frequency
freq_bw	1*25	Double	WWIII frequency bandwidth
rmsd	16*20	Double	root mean square difference for each bin average spectrum
bin	16*20	cell of cells	binned data:
	{1}	# spec in bin x 25	the spectra of all sea states in the bin
	{2}	# spec in bin x 1	the date-times of the above spectra
	{3}	1 x 25	the average bin spectrum
	{4}	1 x 5000	time sereies of water elevation from average bin spectrum

Extreme Event Analysis

Extreme events for wave, current and wind conditions need to be identified and specified for the reference site of interest. These extreme events provide a means to characterize extreme loads on structural components and hence provide an important design consideration.

Remaining need to be addressed:

- Confirmation that the 5-meter wind speed data and OSCAR ocean surface current data are appropriate for our purposes in wind and current extreme events
- Ocean currents at depth
- Compare results to extreme events from offshore sector (design standards)
- Identify uncertainties and related safety margins

Extreme event analysis relies upon long-term statistics gathered over 20 years or more. The long-term history provides the basis for a probabilistic model which can be extrapolated out to 50- and 100-year extreme events. In the absence of long-term data, the analysis techniques must be modified slightly and confidence in the result is more limited.

For the Eureka - Northern California site, the following data sources were utilized to generate extreme event models for wave, current, and wind conditions. NDBC station 46022 provided hourly wave and wind data from 1982 through 2009. The wave height has been recorded as *significant wave height*, which was calculated as the average of the highest one-third of all of the wave heights during the 20-minute sampling period. Wind speed was measured 5 meters above the water surface and two data channels were recorded: (1) the 8-minute average wind speed and (2) the peak 5-second gust speed measured during the 8-minute sample period. CDIP stations 094 and 128 provided daily maximum wave heights (measured crest-to-trough) from May 2007 to September 2010. Although these data span only three years, they serve as a point of comparison and validation of assumptions. Ocean *surface currents* for the region (126.2W-124.2W, 40.2N-42.2N) from 1992 through 2010 were obtained from the OSCAR Project Office. In these data, the mean and median current speeds were recorded every five days. Figure 1 illustrates the geographic location of these data sources.

The annual-maximum approach was employed to derive the probabilistic models for each environmental condition. In this approach, the entire sample population is divided into sample sets in which each set contains one year of measurements. Each year's maximum value is taken as the extreme for that year.

According to extreme-value theory, the distribution of the maximum values of the sets is the generalized extreme-value (GEV) distribution, which is given by the cumulative distribution function

$$F(x;\mu,\sigma,k) = \exp\left\{-\left[1 + k\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/k}\right\}$$

The parameters μ and k are called the location and shape parameters, respectively. They can be any real number. The parameter σ is called the scale and must be a positive real number [1].

A number of techniques exist for finding parameters to fit a data set. The maximum-likelihood technique attempts to maximize the probability that the observations were taken from the candidate distribution. The moments technique attempts to match the lower-order moments of the observed distribution and the candidate distribution. The least-squares technique minimizes the sum of squared differences between the observed and candidate distribution.

This work utilized Matlab's Statistics Toolbox to fit the GEV distribution by the maximum-likelihood technique. The *gevfit* function returns not only the parameters but also the 95% confidence interval for each parameter. Using nonlinear constrained optimization, it was possible to calculate the 95% confidence interval for the 50- and 100-year extreme events. Results are presented in Table 2.

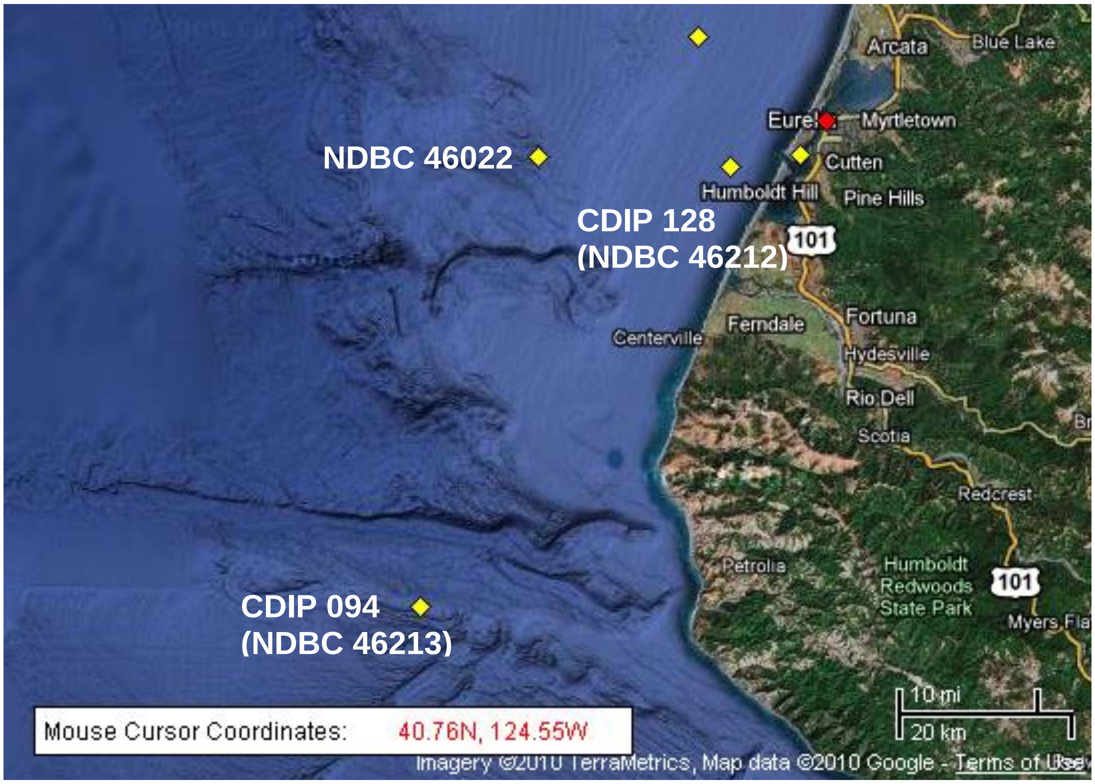


Figure 1. NDBC and CDIP stations near Eureka, CA used in extreme event analysis.

Table 2. 50- and 100-year extreme ocean events near Eureka, CA. The maximum-likelihood estimate (MLE) and 95% confidence interval are given.

Ocean Parameter	Observed Maximum	50-year MLE	50-year 95% CI	100-year MLE	100-year 95% CI
Wave height					
46022 significant wave height (m)	12	11.6	(10.9, 13.6)	11.9	(11.2, 14.5)
094 daily max wave (m)	15	20.1	(16.9, 25.2)	21.1	(17.5, 27.0)
128 daily max wave (m)	14.6	17.8	(15.4, 21.6)	18.7	(16.0, 23.0)
Wind Speed					
46022 8-min avg (m/s)	25	25.1	(24.0, 29.3)	25.6	(24.4, 31.2)
46022 5-sec gust (m/s)	31.2	31.3	(30.5, 34.7)	31.6	(30.8, 35.9)
Surface Current					
OSCAR mean (m/s)	0.36	0.46	(0.41, 0.54)	0.49	(0.43, 0.58)
OSCAR median (m/s)	0.38	0.54	(0.47, 0.64)	0.59	(0.50, 0.71)

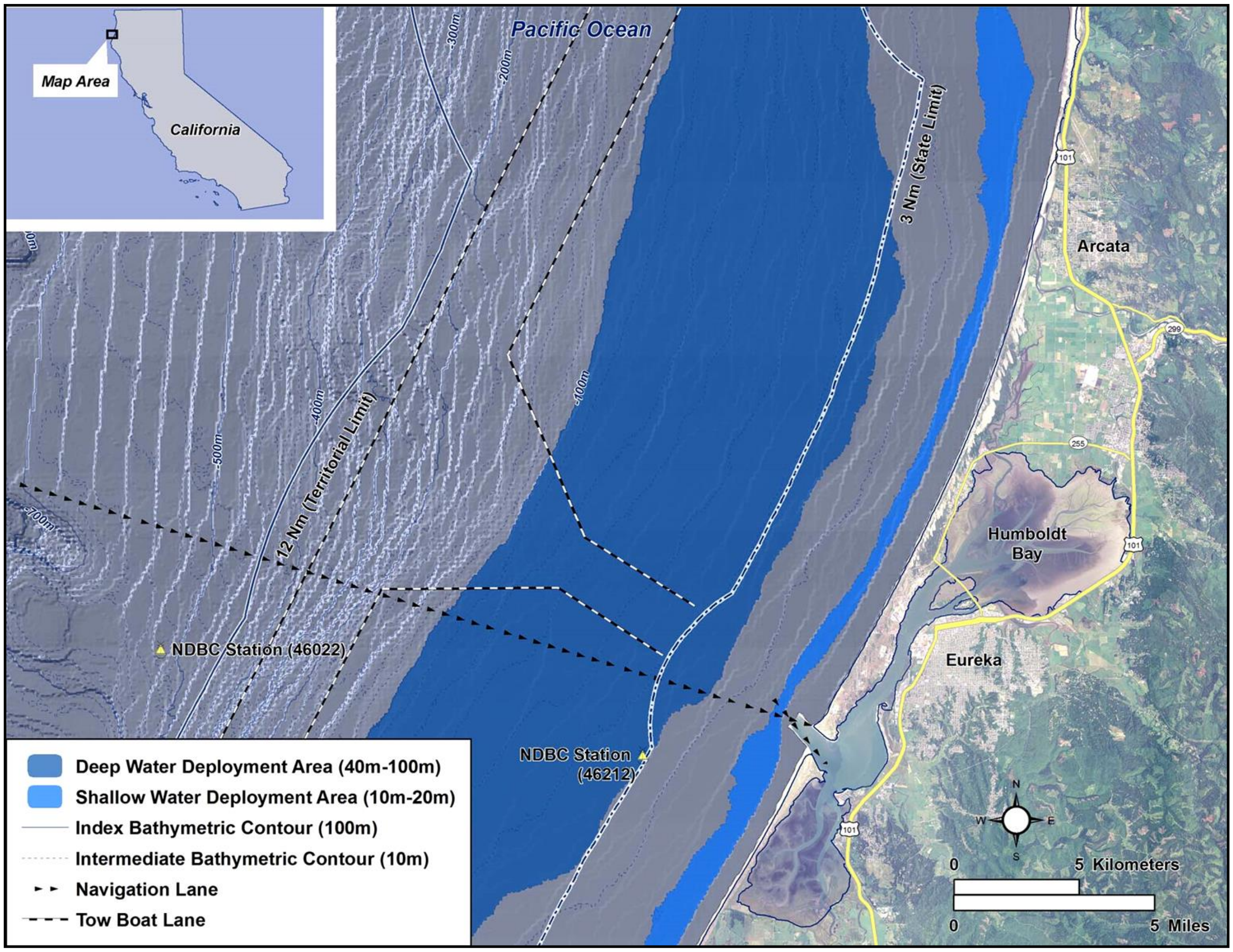
Recalling that significant wave height was calculated as the average of the highest one-third of all waves in the sample period, it is expected that some individual waves are greater in height. A rule-of-thumb explained by Ref. [1] is that the maximum individual wave height is approximately equal to twice the significant wave height. Thus, we can expect the peak-to-trough extreme wave height to be around 24 meters. This result is consistent with the results obtained for stations 094 and 128 which are direct measurements of the peak-to-trough wave height.

Note that the analysis procedure had to be modified slightly for stations 094 and 128. A three-year record is not long enough to fit a distribution to yearly maximums. Instead, the GEV was fit to the daily-maximums. This modified approach produces some error because the extreme-value theory assumes the random variables are independent and identically distributed (i.i.d.) but the daily-maximums will experience seasonal changes. To justify this approach, it was noted that Ref. [1] shows that the distribution of individual wave heights is very close to a Weibull distribution and that the Weibull distribution is contained within the generalized extreme-value family of curves. The 50- and 100-year extremes were then calculated by using the return period corresponding to the number of *days* in 50 or 100 years.

[1] Holthuijsen, Leo H. *Waves in Oceanic and Coastal Waters*. Cambridge University Press, 2007. ISBN 978-0-521-86028-4

Site Bathymetry and Sediments

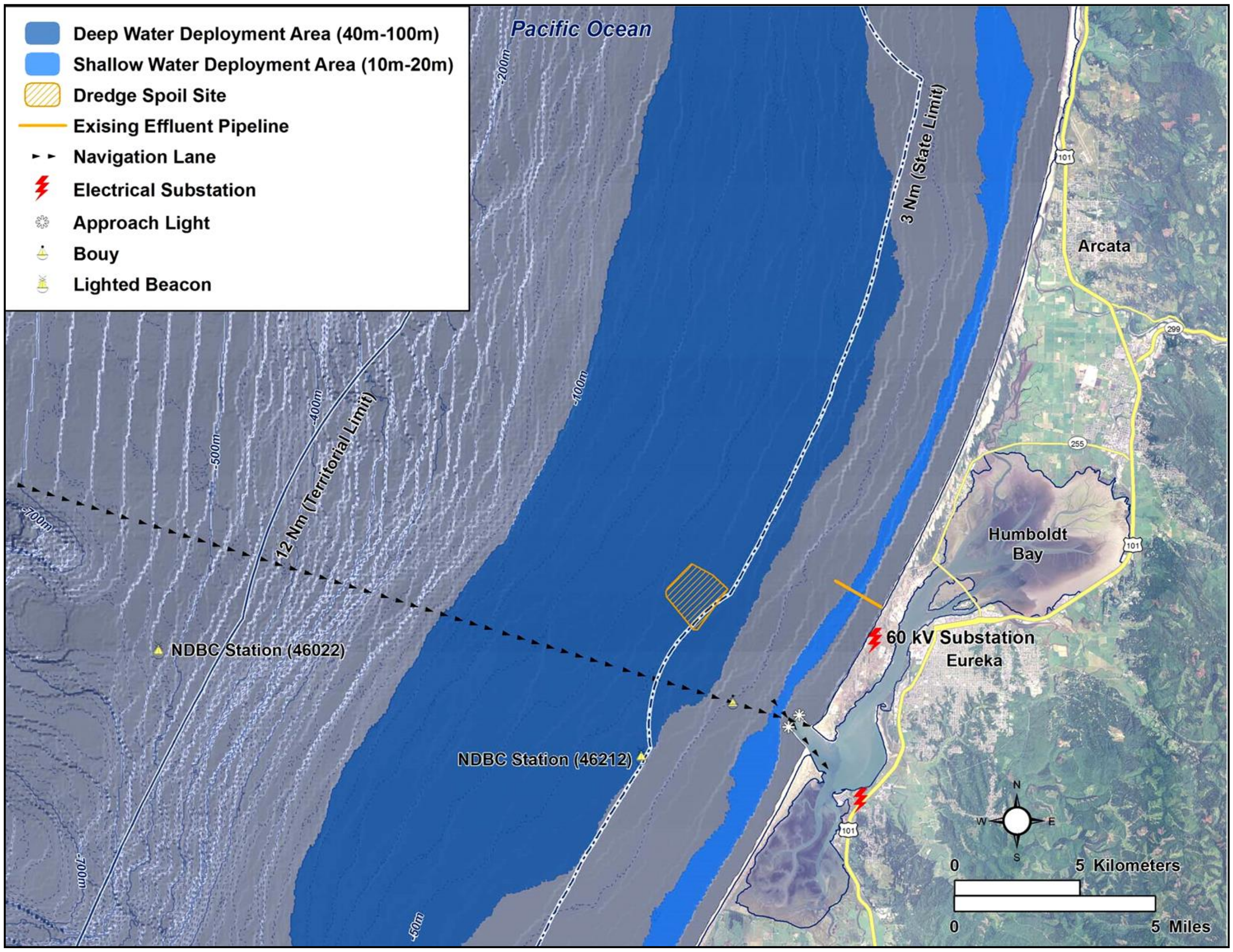
The cost of electricity from a particular technology can depend heavily on operational aspects at sea. These are affected by the type of mooring system required, operational considerations and port-side infrastructure. While device operational requirements can not be affected by siting choice, the mooring system and port-side infrastructure is site-dependent. As such they play an important role as a site-specific impact on the cost of electricity. In order to provide baseline information for mooring and infrastructure design considerations, some background material on the deployment site is provided in this document. The site of interest on the northern California coast is off shore from Humboldt Bay, as shown in the illustration below. The site is presently being developed by Pacific Gas & Electric (PG&E) for the development of the WaveConnect project. WaveConnect is a facility that is designed to demonstrate and test early adopter commercial wave power technologies. The project has been funded by the Department of Energy (DoE) and the California Public Utilities Commission, and has been granted a preliminary permit from FERC. While the project study site is closely co-located with the PG&E site, no conclusions from this study should be drawn for the PG&E process.



The area chosen for this site is slightly north and directly off shore from the Humboldt Bay deep water channel, where port facilities are available to stage installation and operation activities. A 60KV substation, just north of the bay inlet, was chosen for connection to the grid.

Grid Interconnection Options

Approximately 5 miles north of the Humboldt Bay inlet, there is a 60kV substation in very close proximity to the coastline. This station will serve as the interconnection point to the local electrical grid. An existing outfall location is shown in orange in the following figure, which could be used to accommodate the proposed electrical subsea cable. This easement may eliminates the need to directionally drill to shore to accommodate the power cable landing. However, as details of specific sites are clarified, use of existing outfalls, particularly an outfall that is still in service, is more complex and may not be a viable alternative.



Port Facilities

The port nearest to the area is located in the Humboldt Bay. This is the only deep-water port on California's North Coast and has excellent facilities for the operation of wave farms. There are multiple piers within the bay, making it a good site from which to launch installation and operation activities. The following illustration shows a nautical chart of the area of interest.

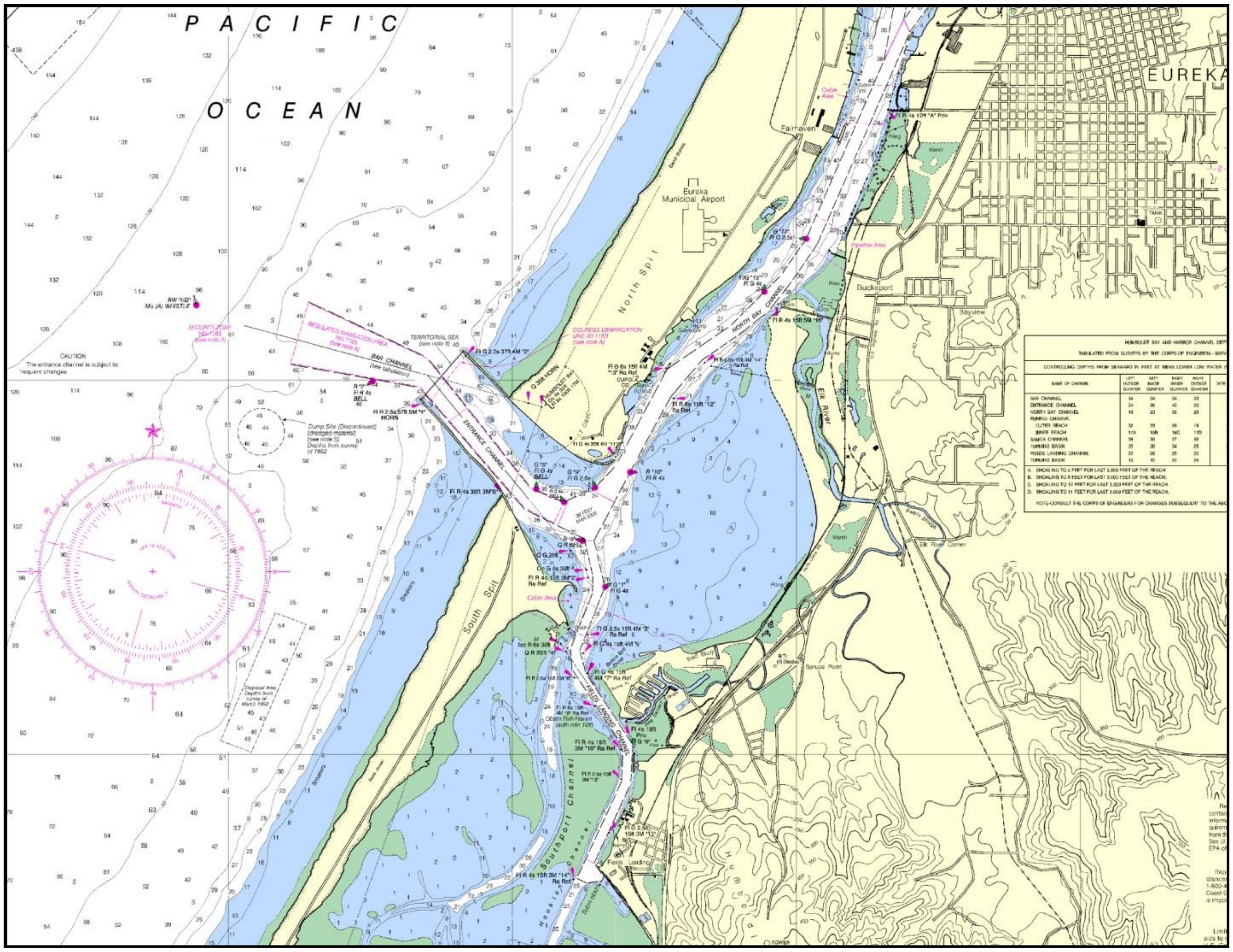


Figure 3 - NOAA Nautical Chart (Humboldt Bay)

Bathymetry

As shown in the following figure, the deployment site features a gently sloping seabed without many irregularities (such as canyons) that could disturb the local wave field. It is therefore likely that the wave-field is homogeneous over the deployment area of interest. Deep-water deployment sites are located approximately along the 70m contour line, which is located about 3Nm from shore. Water depths suitable for the Aquamarine Oyster are much closer to shore at a distance of less than 1000 yards. Shallow water and deep water deployment areas are identified in the following illustration.

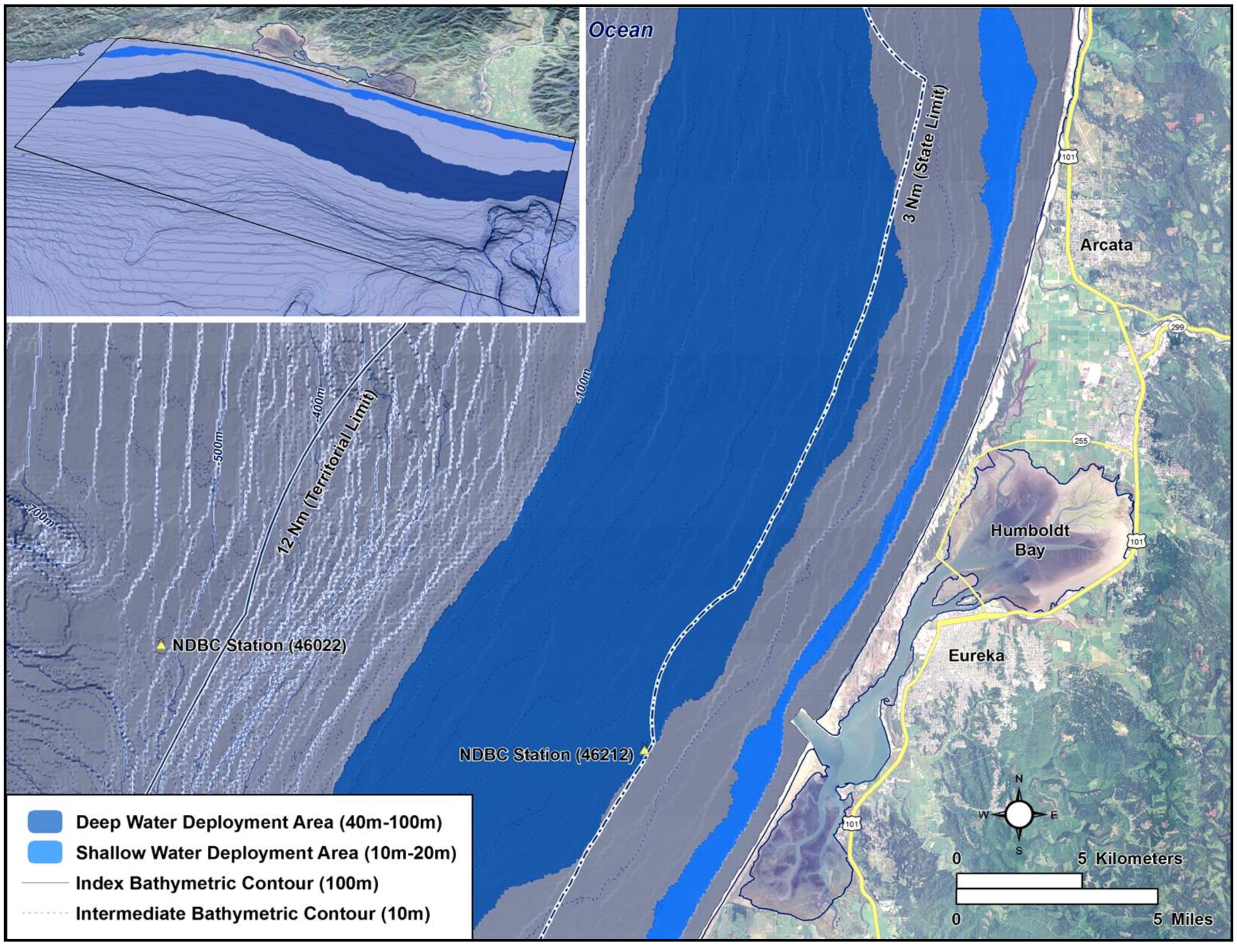


Figure 4 - Local site Bathymetry Plan and perspective showing the water depth in meters

Seabed Composition

Most of the seabed in the near shore region of the Humboldt site consists of soft sediments (sand and clay). There are rocky areas near Trinidad Head to the north, but these may be readily avoided. Sediments within the proposed cable route and deployment area are well suited for subsea cable burial and anchoring.

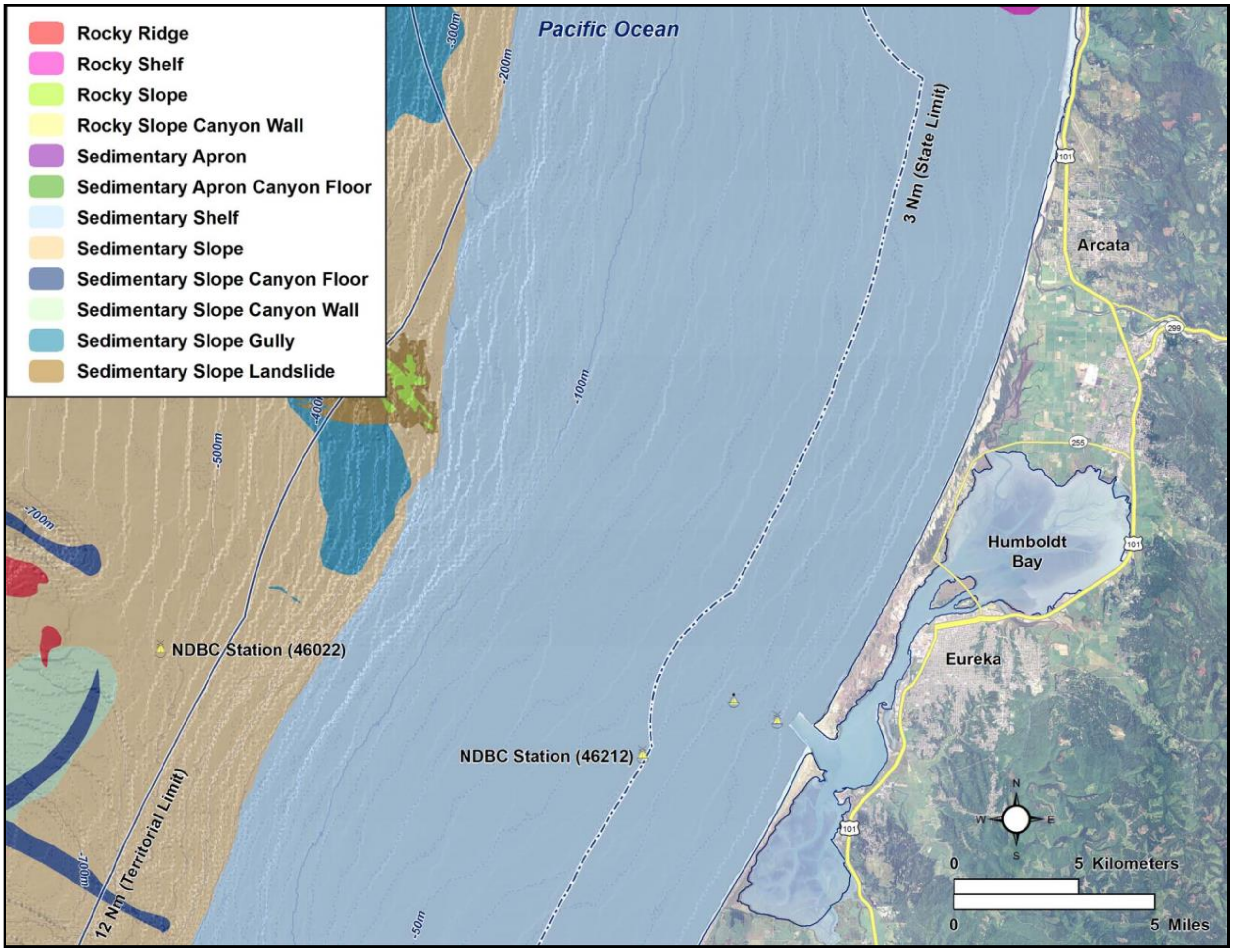


Figure 5 - Seabed Classification

Conclusions

References