Assessment of the US Wave Energy Resource using In Situ Data

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1.0 Abstract

By using measured data collected by buoys deployed along the coast of the United States by the National Data Buoy Center (NDBC) the average annual wave power at discrete points along the coastline can be calculated. Traditionally the raw wave power potential has been calculated using a peak period technique. A more accurate spectral method for predicting the wave power potential using In situ measurements has been investigated similar to the method used to produce the Portuguese ONDATLAS (Pontes). Speaking only about the annual average power potential can be erroneous since there are large seasonal fluctuations in the available wave power. Probability distributions of the measured wave power allow for this variability to be better investigated.

2.0 Methodology

The National Oceanic and Atmospheric Administration maintains a network of wave measurement buoys along the coast of the United States through NDBC. Real time data from these buoys is made available via the NDBC website (NOAA). In addition, historical data on the significant wave height and peak period along with the wave spectrum are logged every twenty minutes. This historical data has been used to conduct an investigation of the wave power potential along the coast of the United States.

2.1 Peak Period Method

The energy of a progressive water wave can be defined using linear wave theory and is proportional to the wave height squared. The wave energy is the sum of the potential energy of the water particle relative to the still water line and the kinetic energy due to the water particle velocity. The linear wave energy per wave per unit width is proportional to the wave height squared and can be expressed as:

$$E = \frac{1}{8}\rho g H^2 \qquad (1)$$

where:

E = Linear Wave Energy

ρ = Water Density

g = Gravitational Constant

The energy in a linear wave is transmitted at the group velocity of the wave. The group velocity in deep water is half the wave celerity and can be defined as:

$$C_g = \frac{C}{2} \tag{2}$$

where:

C_g = Group Velocity

C = Wave Celerity

In deep water the wave celerity simplifies to:

$$C = \frac{g}{\omega} \tag{3}$$

where:

g = Gravitational Constant

ω = The Wave Frequency

Finally the wave energy flux, or wave power, can be determined by taking the product of the wave energy and the group velocity:

$$E_{flux} = \frac{g}{2\omega}\frac{1}{8}\rho g H^2 \tag{4}$$

In order to calculate the average wave energy flux based on the significant wave height and peak period the following equation can be used:

$$E_{Flux} = \frac{1}{8}\rho g {H_{RMS}}^2 C_g \tag{5}$$

$$C_g = \frac{gT_P}{4\pi} \tag{6}$$

where:

T_P = Peak Period

The RMS wave height can be determined from the significant wave height by the relation:

$$H_{RMS} = \frac{H_{1/3}}{\sqrt{2}} \tag{7}$$

where:

$H_{1/3}$ = Significant Wave Height

The NDBC reports the average historical significant wave height and peak period for a ten year period from 1991-2001. This data was used to calculate the average wave power for each of the 21 stations analyzed.

Since the data for the peak period method is readily available and the calculation method very simple the wave power potential can be calculated quickly and with a small amount of data.

2.2 Spectral Method

A real seaway contains waves of many frequencies, not just a single monochromatic wave train. These stochastic seas can be represented by a wave energy spectrum. As can be seen in figure 1, the wave energy spectrum, $S(\omega)$, is the probability distribution of energy density over a range of frequencies.

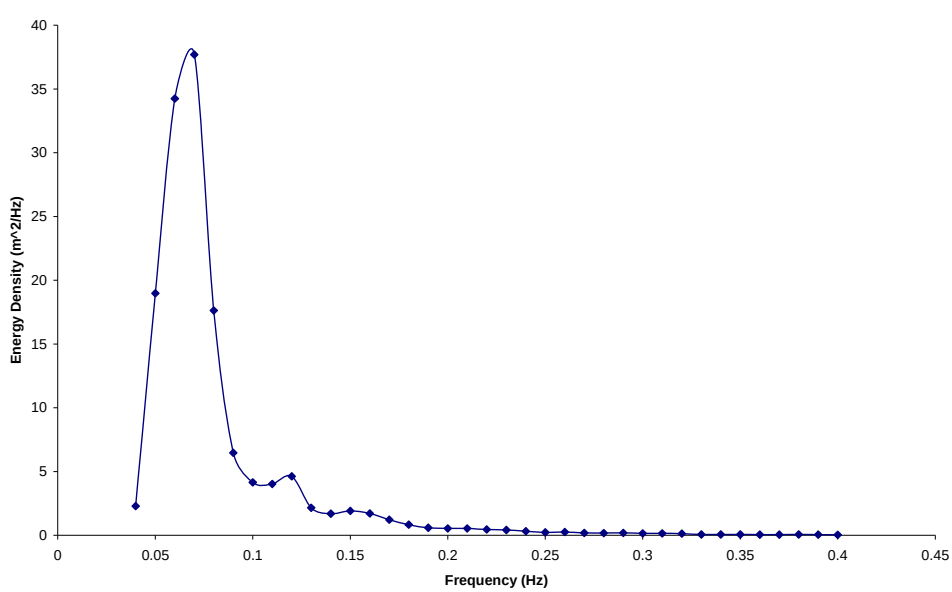


Figure 1: Wave energy spectrum 1/1/2004 NDBC Station 46050 - STONEWALL BANKS - 20NM West of Newport, OR

In order to determine the total wave energy of the entire spectrum the energy density is integrated over the range of frequencies:

$$E = \int S(\omega) d\omega \tag{8}$$

The wave energy flux can again be defined as the product of the wave energy and the deep water group velocity. These leads to the following equation for wave energy flux, analogous to equation 5:

$$E_{Flux} = \int \frac{1}{2}\frac{g}{\omega}\rho g S(\omega) d\omega \tag{9}$$

The NDBC records the wave spectrum every twenty minutes using 50 discrete frequency bins range from 0 to .5 Hz. These spectra are posted on the NDBC website and can be numerically integrated to determine the average wave energy flux for each 20 minute period:

$$E_{Flux} = \sum_1^N \frac{1}{2}\frac{g}{\omega_i}\rho g S(\omega_i)\Delta\omega \tag{10}$$

For the spectra used from the NDBC N is 50 and $\Delta\omega$ is .01 Hz. Once the wave energy flux has been determined for each 20 minute period the results can be averaged over the entire year to find the average wave energy flux. Five years of data wave used to generate a long terms average for each NDBC station.

This spectral method requires integration and the use of a substantially larger data set. It is much more computationally intensive than the peak period method. Since the method takes into account the distribution of the wave energy over a range of frequencies instead of assuming the energy to be transmitted at a single peak frequency it should yield more accurate results.

2.3 Wave Power Statistics

The average wave power is only a single statistic that can describe the overall distribution of different power levels at a given location. A probability density function of the wave power

levels can be generated from the wave energy fluxes calculated using the spectral method in order to analyze the distribution of these events.

The wave power data was sorted into 1 kW/m bins and the probability of each power level determined based on the five years of data for each station. Power levels greater than 189 kW/m were excluded from the probability density function. The higher power levels corresponding to significant wave heights of 7 meters and greater were deemed too large to make wave energy extraction feasible.

PDFs of wave power have been generated for the 10 west coast stations and the most probable and median power levels determined. The total wave energy production can then be assessed and comparisons made between stations and with the calculated statistics.

3.0 Results

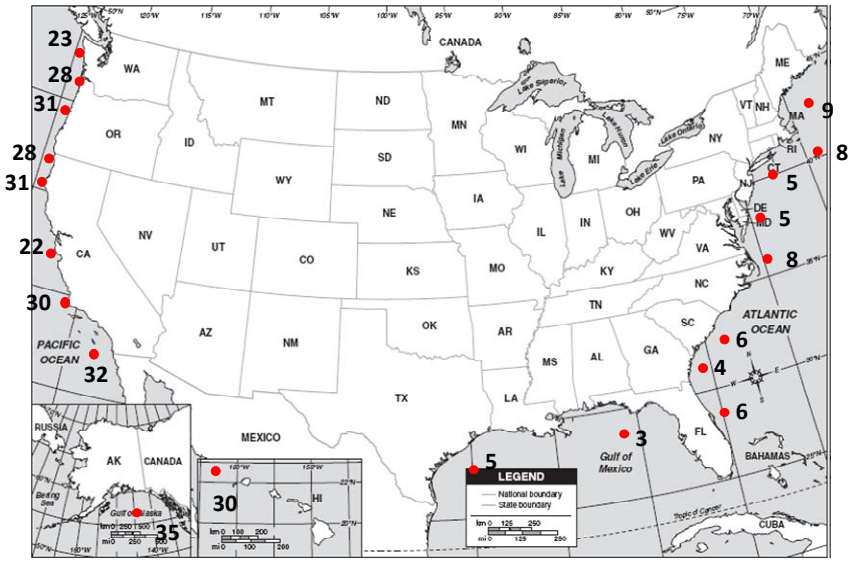
3.1 US Wave Energy Potential

The average annual wave power levels calculated using the peak period and spectral methods are included in Table 1. The wave power levels calculated using the peak period method range from 3 kW/m off the coast of Florida to 35 kW/m in the Bay of Alaska. The power levels calculated using the spectral method range from 3 kW/m to 30 kW/m with the spectral averages generally between 15 and 30 percent lower than those calculated using the peak period method.

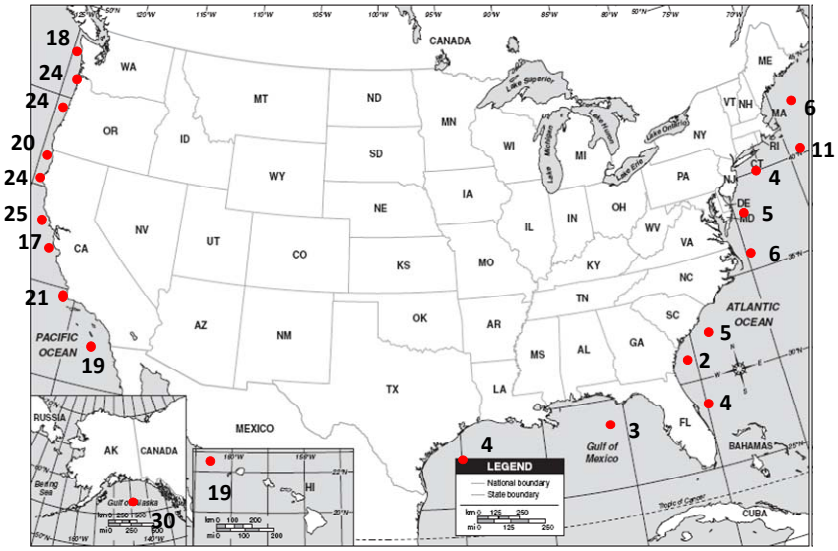
Table 1: Wave Power Statistics for the Coast of the United States

Location Name	Wave Power				
	Spectral Average	Peak Period Average	% Difference	Most Probable (Spectral)	Median (Spectral)
non-dim	kW/m	kW/m	non-dim	kW/m	kW/m
Station 46001 - GULF OF AK 88NM South of Kodiak, AK	30	35	14.29%	4	16
Station 46022 - EEL RIVER - 17NM West-Southwest of Eureka, CA	24	31	22.58%	4	16
Station 46014 - PT ARENA - 19NM North of Point Arena, CA	25	32	21.88%	5	15
Station 46028 - CAPE SAN MARTIN - 55NM West Northwest of Morro Bay, CA	21	30	30.00%	8	14
Station 46027 - ST GEORGES - 8NM West Northwest of Crescent City, CA	20	28	28.57%	5	14
Station 46047 - TANNER BANKS - 121NM West of San Diego, CA	19	32	40.63%	8	14
Station 51001 - NW HAWAII 170 NM West Northwest of Kauai Island	19	30	36.67%	8	13
Station 46029 - COL RIVER BAR - 78NM South Southwest of Aberdeen, WA	24	28	14.29%	4	12
Station 46050 - STONEWALL BANKS - 20NM West of Newport, OR	24	31	22.58%	2	11
Station 46041 - CAPE ELIZABETH- 45NM Northwest of Aberdeen, WA	18	23	21.74%	3	11
Station 46012 - HALF MOON BAY - 24NM South Southwest of San Francisco, CA	17	22	22.73%	4	11
Station 44008 - NANTUCKET 54NM Southeast of Nantucket	11	8	-37.50%	2	5
Station 44014 - VIRGINIA BEACH 64 NM East of Virginia Beach, VA	6	8	25.00%	2	3
Station 41009 - CANAVERAL 20 NM East of Cape Canaveral, FL	4	6	33.33%	1	2
Station 41008 - GRAYS REEF - 40 NM Southeast of Savannah, GA	2	4	50.00%	1	1
Station 44005 - GULF OF MAINE 78 NM EAST OF PORTSMOUTH,NH	6	9	33.33%		
Station 41004 - EDISTO - 41 NM Southeast of Charleston, SC	5	6	16.67%		
Station 44009 - DELAWARE BAY 26 NM Southeast of Cape May, NJ	5	5	0.00%		
Station 42019 - Freeport, TX 60 NM South of Freeport, TX	4	5	20.00%		
Station 44025 - LONG ISLAND 33 NM South of Islip, NY	4	5	20.00%		
Station 42039 - PENSACOLA - 115NM East Southeast of Pensacola, FL	3	3	0.00%		

Figures 2a and 2b illustrate the distribution of wave power along the US coast using the peak period and spectral data respectively. Both methods show a clear trend of higher power on the west coast of the United States than the east and gulf coasts. The trend of higher wave power levels in the North and lower in the South generally seen on maps of global wave power distribution is not evident on the west coast of the United States. While the highest wave power corresponds to the farthest North station power levels between Washington and Southern California do not show a trend toward higher power levels in the North.



a)



b)

Figure 2 Annual Average Wave Power using a) the Peak Period Method and b) the Spectral Method

3.2 Probability Distributions of Wave Power

A typical probability density function of the wave power level can be seen in figure 3. The PDFs for the other 9 stations have been included in the appendix. The PDF has been normalized by the average power in order to give a better understanding of the distribution of power as it relates to the mean annual wave power. It is clear that the most probable wave power level is well below the mean. This is true for all 10 of the stations investigated as shown in table 2.4. While there are a large number of events with power levels less than the mean the relatively fat tail of the distribution skews the average to be much higher than the mode of the distribution. The median wave power level is also well below the mean as illustrated by the cumulative density function (figure 4) .

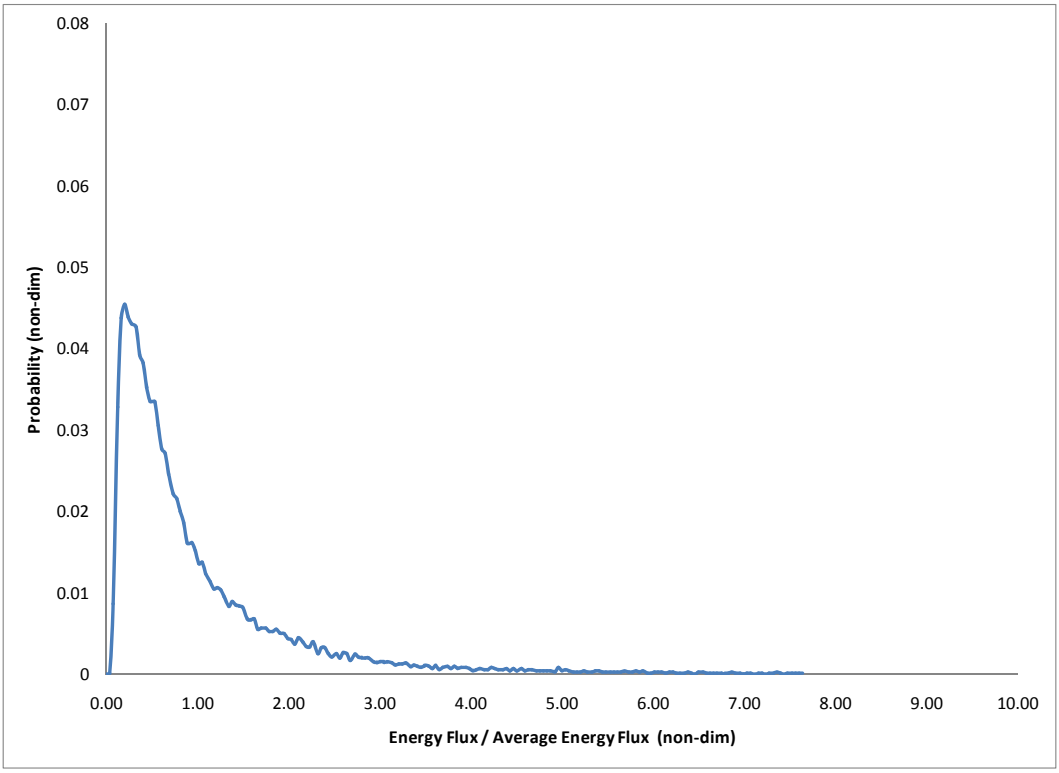


Figure 3 Probability Density Function of Wave Power for NDBC Station 46014
19 NM North of Point Arena California

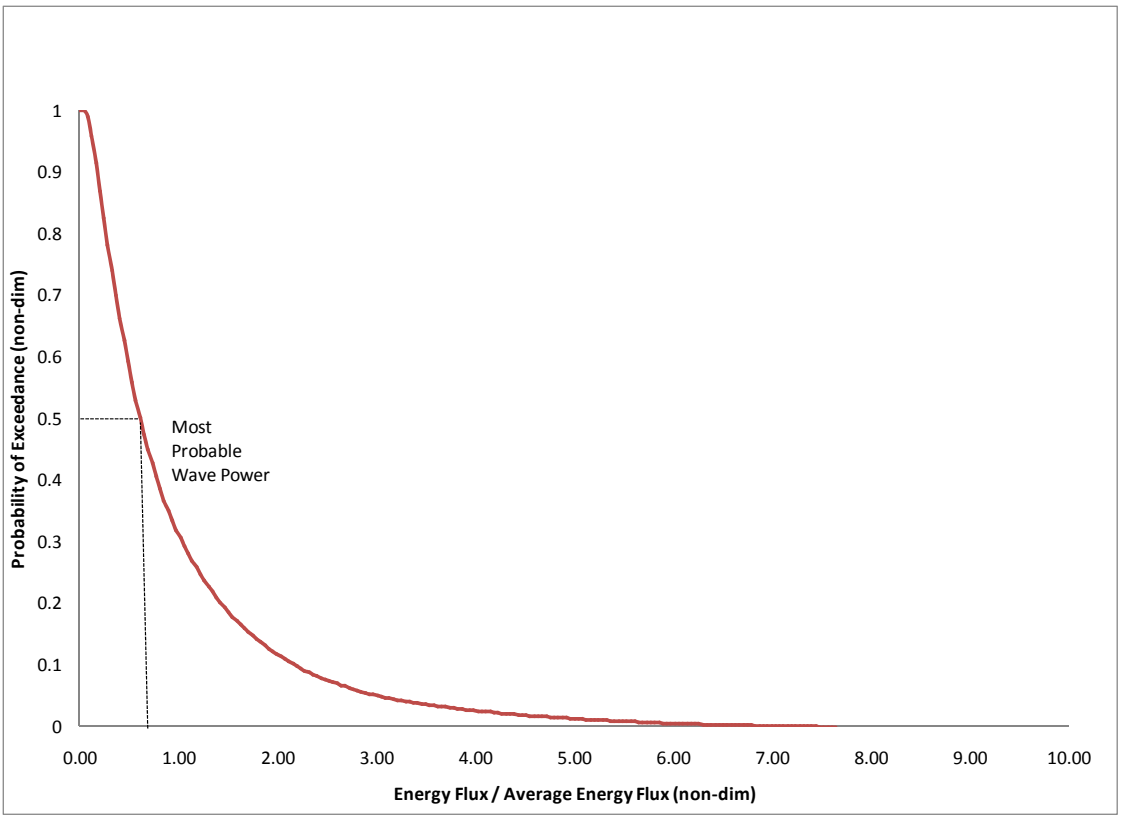


Figure 4 Cumulative Density Function of Wave Power for NDBC Station 46014
19 NM North of Point Arena California

The wave power PDF can also be used to determine the total annual energy available for each of the measurement stations investigated. In addition the distribution of this energy with respect to the wave power bins can also be determined. This distribution of energy over the power spectrum can be seen in Figure 5. As illustrated in the figure the median wave power level corresponds to the highest energy bin for all the stations investigated. The distributions for the other nine stations have been included in the appendix.

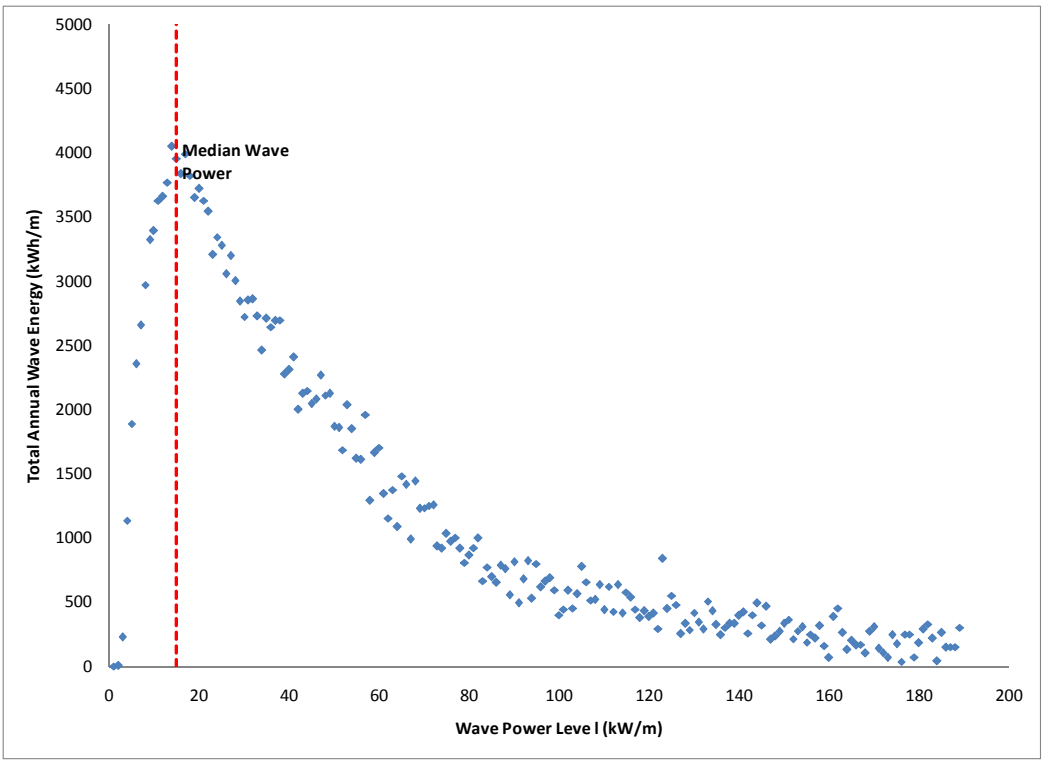


Figure 5 Distribution of Wave Energy over the Power Spectrum

4.0 Discussion and Concluding Remarks

A comparison of the wave power levels calculated using the peak period method and the spectral method show that the peak period method over predicts the annual average wave power for all the stations but one. This indicates that the peak period approach represents a non conservative method for calculating the available wave power. The peak period method is attractive, however, given its relative simplicity and the small amount of data need for the power calculations. Figure 6 provides a plot of the wave power calculated using the peak period approach versus the power calculated using the spectral approach. As can be seen in the figure a linear trend line can be drawn through the data with and R^2 value of .943. This indicates that a correlation coefficient may be added to equation 5 to improve the peak period method:

$$E_{Flux} = E_L \frac{1}{8} \rho g {H_{RMS}}^2 C_g \qquad (11)$$

where:

E_L = .75

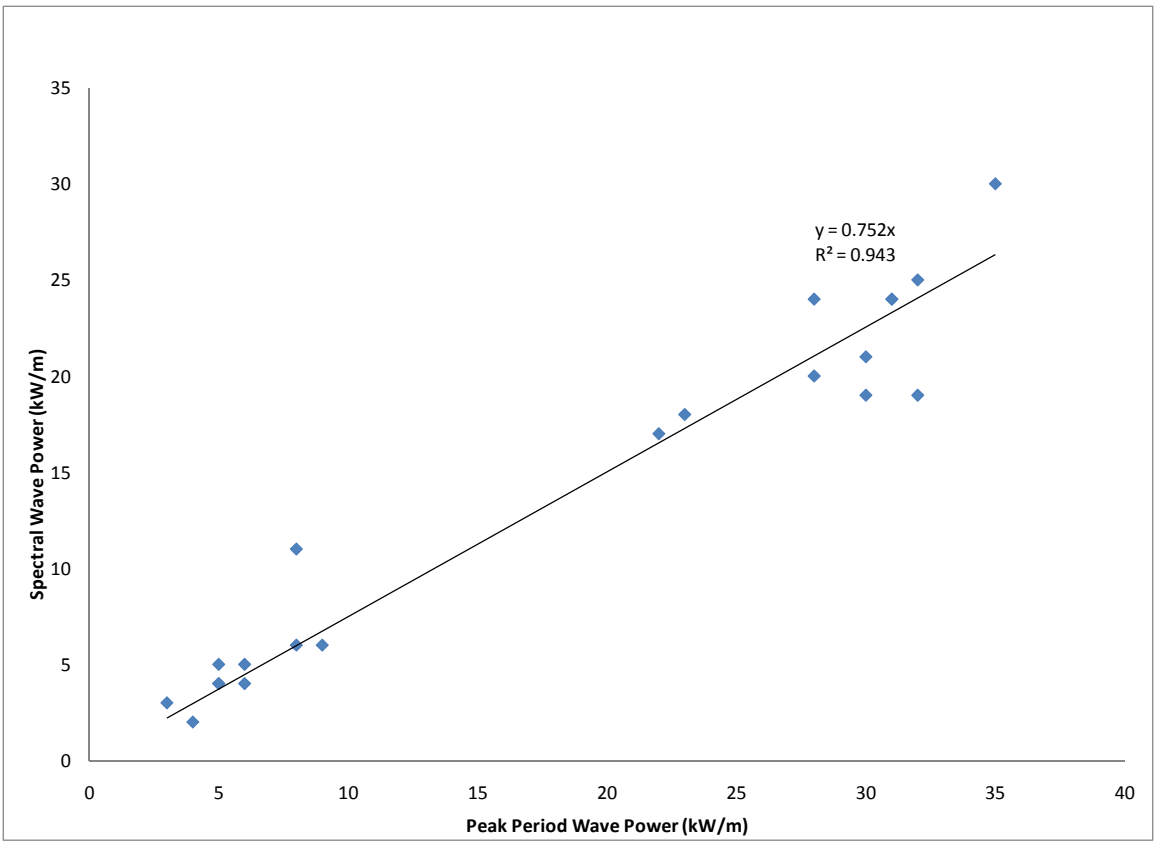


Figure 6 Relation between Power Calculated using Peak Period and Spectral Method

Analysis of the distribution of wave power levels and the total annual energy produced shows that the most probable power and median power levels are well below the annual average. This indicates that the annual average power may not be the best value to be used in preliminary power calculations. Since the median power level represents the power bin producing the largest amount of energy per year it might be more appropriate to use this median power level to compare the relative merits of potential sites for wave energy conversion. This median power level might also be appropriate for preliminary power calculations since it is the power level that has the greatest potential for energy production.

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NOAA. National Data Buoy Center. 6 June 2008 <http://www.ndbc.noaa.gov/>.