Hawaii National Marine Renewable Energy Center (HINMREC)

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Task 3: Wave Resource Model, Wave Field Measurements and Data Analysis

Wave Energy Resources for Representative Sites Around the Hawaiian Islands

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Foreword

This report provides wave energy resource information required to select coastal segments for specific wave-energy-conversion (WEC) technology and to initiate engineering design incorporating production estimates and the wave loading that devices must survive during their life cycle. As the design progresses beyond the preliminary stages, site specific wave resource measurements will be required.

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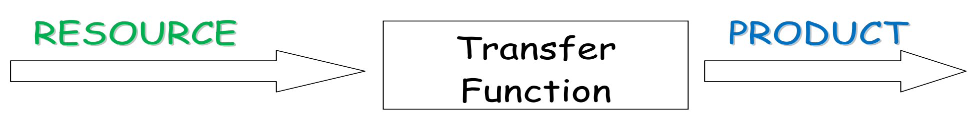
Summary

This report provides wave resource information required to select coastal segments (e.g., see Table 1 and Figure 1) for specific wave-energy-conversion (WEC) technology and to initiate engineering design incorporating production estimates and the wave loading that devices must survive during their life cycle. As the design progresses beyond the preliminary stages, site specific wave resource measurements will be required.

The wave power flux (P_o), through a vertical plane of unit width perpendicular to the wave propagation direction is used to represent the resource. As illustrated in the flow diagram below, the spectral parameters (e.g., Hs, Te) are used to quantify estimates of P_o (kW/m). Designers use their proprietary transfer function (wave power matrix) to estimate daily, monthly and annual electricity production for specific sites. In addition, they incorporate the extreme events into their survivability design.

Discussion of the proprietary transfer functions, required to determine electricity production with specific devices, is beyond the scope of this report.

Wave Energy Conversion



RESOURCE	Transfer Function	PRODUCT
$P_{O(kW/m)}=f(H_s;T_e;\theta)$	Proprietary	kWh
Ocean Area	not 24/7	

Background: Wave Power Conversion

This report was conceived to provide information about wave power resources in a format that would be useable to designers and project developers, and not as a primer on the nascent wave power conversion field. Currently, there are only two operating devices transmitting electricity to distribution lines (i.e., utility interconnected): the 500 kW shore based oscillating-water-column (OWC) Limpet in Islay, Scotland; and, the 40 kW OPT heaving buoy off Kaneohe Bay, Oahu.

There are numerous wave energy conversion (WEC) concepts discussed in the literature. These range from simple sketches to reports of at-sea tests. Some are shoreline based[1] others seabed mounted or moored in depths of < 70 m. According to their directional characteristics they can be classified as point absorbers, terminators and attenuators. Point absorbers have dimensions that are small relative to ocean wave lengths and are usually axis-symmetric[2]. The principal axis of terminators is aligned perpendicular to the direction of wave propagation and in the case of attenuators[3], parallel to the direction of propagation. These have dimensions in the order of the wave lengths.

WECs currently applicable in the state of Hawaii can be categorized under two operating principles: OWC; and, wave-activated, The OWC devices use wave action to expand and compress air above a water column, to rotate an air turbine-generator (e.g., the Oceanlinx project, planned for installation off Pauwela, Maui by 2012, sized at < 2.7 MW). The wave-activated devices oscillate due to wave action relative to a fixed part of the device and use a hydraulic system to turn a motor-generator; or a linear generator which generates electricity by moving a magnetic assembly within a coil; or direct rack and pinion mechanical coupling.

Licensing and Permitting

The proposed location determines the various agencies and regulations that apply. In general, one must consider the Federal Energy Regulatory Commission (FERC), the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEM), formerly Minerals Management Service (MMS) of the Department of the Interior (DOI), the Army Corps of Engineers, the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce (DOC), the US Coast Guard and various state, county and city agencies. In addition to the licenses and permits that must be secured from different agencies, the project must comply with several other applicable laws.

Independent of location, licensing of WEC devices is the responsibility of FERC. In Hawaii, the State Government has jurisdiction up to 3 nautical miles (nm) offshore. The Federal Government has jurisdiction in the Outer-Continental-Shelf (OCS) extending between the outer limits of State waters and the inner boundary of international waters, which begins approximately 200 nm offshore. BOEM defines the OCS as including submerged lands, subsoil, and seabed.

For wave energy projects to be located on the OCS, BOEM will issue *leases, easements, and rights-of-way* and will conduct any necessary environmental reviews including those under the National Environmental Policy Act (NEPA). FERC has exclusive jurisdiction to issue *licenses* and exemptions

[1] The 500 kW OWC Limpet (Land Installed Marine Powered Energy Transformer) has been operational since 2000.
[2] The 40 kW OPT heaving buoy currently under testing in Kaneohe Bay, Oahu, State of Hawaii.
[3] The 3rd generation Pelamis (~ 500 kW) is scheduled for deployment at the European Marine Energy Center (EMEC) in 2010.

for the *construction and operation* of wave energy projects and will conduct any necessary analyses, including those under NEPA, related to those actions. FERC, however, will not issue a license or exemption until the applicant has first obtained a lease, easement, or right-of-way from BOEM. Moreover, BOEM and FERC can choose to become a cooperating agency in the preparation of any environmental document required under either process. This does not preclude other DOI agencies (*e.g.*, U.S. Fish and Wildlife Service, the National Park Service, and the Bureau of Indian Affairs) from intervening. This situation could lead to the requirement of two distinct (although similar in content) Environmental Impact Statements (EIS): one for BOEM and subsequently another for FERC.

For wave energy projects located in State Waters, BOEM has no jurisdiction, licenses would still be issued by FERC and all other requirements would be under state, county and city rules.

Challenges and Barriers

WEC systems are in the pre-commercial phase with several experimental projects having already demonstrated ability to convert wave energy into electrical energy but lacking the operational records required to proceeding into commercialization. Adequately sized pilot or pre-commercial projects must be implemented to obtain these long-term operational records. In addition, validation of the performance and survivability of specific WECs under harsh ocean conditions is required to gain commercial acceptance.

There are some WEC designs with appropriate operational records although they are only cost competitive under limited conditions. A validated concept is given by, for example, incorporating the OWC LIMPET into new breakwaters. Currently, this concept is not practical in Hawaii because no new breakwaters are planned.

Major challenges can be summarized as follows:

- We are not aware of any first generation WEC system that would be cost competitive in Hawaii;
- How to overcome the lack of consistent funding that is required for industry to proceed from concept design to the required pre-commercial demonstration phase;
- How to streamline the burdensome, although necessary, process of obtaining licenses and permits including the necessary Environmental Impact Statement (EIS). The process is project specific, expensive and requiring about 3-years for commercial projects;
- How to evolve into a situation represented by a one-stop-shop where industry can process all documentation stipulated for licensing & permitting under federal, state, city and county regulations avoiding duplicity, contradictory requirements and interdepartmental jurisdictional disputes.

Perhaps a lesson can be learned from the successful commercialization of wind energy that was due to consistent government funding of pilot or pre-commercial projects that led to appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark and Spain. In this context, by commercialization we mean that equipment can be financed under terms that yield cost competitive electricity. This of course depends on site specific conditions.

Presently, for example, in Hawaii cost competitiveness requires electricity produced for less than about 0.12 $/kWh if the resource is intermittent and, therefore, not dispatchable.

Wave Power Resources: Previous Work

The useful references available at the onset of this project were:

1) ***"Ocean Wave Energy: Current Status and Future Perspectives"*** Cruz J. (2008) Editor. Published by Springer-Verlag, 423 pages.

Although not Hawaii specific, this book provides the most comprehensive reference for all aspects of wave energy conversion.

2) ***"Wave Energy Resources and Economic Assessment for the State of Hawaii"*** prepared by George Hagerman (June 1992) for the Dpt. of Business, Economic Development and Tourism of the State of Hawaii.

The main conclusion can be stated as follows: *"Except for Oahu, where electricity demand is comparable to 2/3 of the resource base, wave energy can be withdrawn at very low levels and still make a reasonable contribution to energy needs in the State of Hawaii".* This is a seminal report and remains the main reference for estimates of the wave resource as well as the identification of the coastal segments exposed to the relatively highest resource. Unfortunately, the author did not address siting issues and resource seasonal variability.

In the seminal report, the average wave power fluxes (kW/m) along coastal segments (Table 1) in the islands of Kauai, Oahu, Molokai, Maui and Hawaii (Big Island) were estimated using ocean data available as of 1991. Results are summarized below in Figure 1. Hagerman estimated that annual averages of wave power flux along the 80 m depth ranged from 10 to 15 kW/m. However, because the island shelves are so narrow, even this outer shelf depth contour can be closely sheltered by adjacent headlands or peninsulas, which is the case at Kailua, Oahu, and in the vicinity of Hilo. At these locations, wave power density along the 80 m depth contour ranges from 7 to 9 kW/m. Refraction and shoaling, however, significantly reduce wave power densities in shallow water. For example, along the 5 m depth contour, they were assumed to be roughly 20% lower than along the 80 m contour (Figure 1).

3) ***"EPRI Survey and Characterization of Potential Offshore Wave Energy Sites in Hawaii".*** E21 EPRI WP 003 HI, June 2004. This is one of several useful reports prepared by EPRI and available at http://oceanenergy.epri.com/

The information about WEC devices provided in this report remains current. The wave power resources discussed are from the 1992 Hagerman Report. The main conclusion is: *"In an annual basis, WEC devices could generate more than 30% of the electricity presently consumed in the State."* Unfortunately, although the estimate is theoretically correct, this report does not address siting and seasonal variability issues.

Coastal Segment	Description	Length
KAUAI-1	Nahili Pt. to Makaha Pt.	12 km
KAUAI-2	Makaha Pt. to Haena	18 km
KAUAI-3	Haena to Kepuhi Pt.	23 km
KAUAI-4	Kepuhi Pt. to Kahala Pt.	12 km
	Kauai Subtotal	*65 km*
OAHU-1	Kaena Pt. to Kaiaka Pt.	18 km
OAHU-2	Kaiaka Pt. to 4 km SW of Kahuku Pt.	17 km
OAHU-3	Kahuku Pt. vicinity	8 km
OAHU-4	4 km SE of Kahuku Pt. to Pyramid Rock	34 km
OAHU-5	Pyramid Rock to Moku Manu Island	4 km
OAHU-6	Moku Manu Island to Makapuu Pt.	20 km
	Oahu Subtotal	*101 km*
MOLOKAI-1	Ilio Pt. to 6 km SW of Kahiu Pt.	26 km
MOLOKAI-2	West coast of Kalaupapa Peninsula	6 km
MOLOKAI-3	East coast of Kalaupapa Peninsula	6 km
MOLOKAI-4	6 km SE of Kahiu Pt. to Lamaloa Head	20 km
	Molokai Subtotal	*58 km*
MAUI-1	Nakalele Pt. to Kahului	18 km
MAUI-2	Kahului to Opana Pt.	20 km
MAUI-3	Opana Pt. to Pukaulua Pt.	34 km
	Maui Subtotal	*72 km*
HAWAII-1	Upolu Pt. to Kukuihaele	33 km
HAWAII-2	Kukuihaele to Laupahoehoe Pt.	36 km
HAWAII-3	Laupahoehoe Pt. to Pepeekeo Pt.	23 km
HAWAII-4	Pepeekeo Pt. to Hilo Bay	12 km
HAWAII-5	Hilo Bay to Leleiwi Pt.	8 km
HAWAII-6	Leleiwi Pt. to 3 km NW of Kaloli Pt.	12 km
HAWAII-7	3 km NW of Kaloli Pt. to Cape Kumukahi	16 km
	Hawaii Subtotal	*140km*
	State Total	**436 km**

Table 1 - Coastal Segments Exposed to Predominant Wave Climates (Hagerman, 1992)

Wave Farms: Siting, Ocean Area Requirements

A wave farm would consist of arrays of WEC devices spaced such that interactions between components are minimized. For example, about 7 km^2 of ocean area would be required[4] for 100 x 1 MW or 200 x 0.5 MW WECs arranged into a 100 MW wave farm. For comparison consider that a 100 MW offshore wind farm would require about 12 km^2.

Multiplying the average wave power flux along the 80 m depth contour (Figure 1) by the length of each coastal segment (Table 1) and by the number of hours in a year, and summing the results for all segments, gives an estimate of the annual wave energy resource for a particular island. Estimated wave energy resources (GWh/year) from the 1992 Hagerman report are given in Table 2.

Given the Hawaiian wave resource and efficiencies achieved with viable WEC devices, we assume an all encompassing global capacity factor[5] of about 15%. As tabulated in the third column of Table 2, this factor is used to estimate the amount of electricity that could be generated in an annual basis. The cumulative name plate (MW) and the ocean area that would be required to accommodate the arrays are given in the fourth column. It must be emphasized that this analysis ignores seasonal resource variability and assumes that all coastal segments are utilized. This is not feasible because of conflicting ocean uses and because some of these segments would be off limits for the installation of WECs.

As indicated in Table 2, the 2007 electricity demand in the islands of Hawaii, Kauai and Molokai could have been generated with WEC farms somehow deployed in all coastal segments. In the case of Maui the analysis indicates as much as 90% and for Oahu less than 17%. This is done on an annual basis without matching the resource to the demand assuming that all electricity generated can be used when produced or somehow stored for later use. As shown in later sections of this report, the resource seasonal variability is such (e.g., see Figures 6 and 10) that during winter months electricity generation could be as much as six to seven times more than in the summer months.

Given the limited availability of unpopulated coastlines, siting of WEC devices would be challenging. In addition, WECs are currently designed to operate in waters shallower than about 70 m and because of the relatively narrow insular shelf surrounding the islands, wave farms would have to be deployed within 1 to 3 kilometers from the shoreline in full public view.

In summary, the issues of resource seasonal variability, siting considerations and the corresponding nearshore ocean area requirements pose a daunting challenge to the implementation of wave farms in the state of Hawaii.

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[4] Say 11 km (6.7 miles) along the coastline x 0.6 km (0.4 miles) away from coastline or other equivalent rectangular area.

[5] Number of hours per year, expressed as % of 8760 hours, which a WEC array operates at the rated power capacity (name plate).

Average Wave Power (kW/m) Along Selected Coastal Segments and Potential Constraints

	Coastal Segment	5 m Water Depth	80 m Water Depth
KAUAI	KA-1	6	9
	KA-2	10	13
	KA-3	12	15
	KA-4	9	12
OAHU	OA-1	10	11
	OA-2	8	12
	OA-3	12	14.5
	OA-4	8	11
	OA-5	10	12
	OA-6	7	9
MOLOKAI	MO-1	12	14
	MO-2	8	10.5
	MO-3	8	11
	MO-4	12	14
MAUI	MA-1	9	12
	MA-2	10.5	13.5
	MA-3	10.5	13.5
HAWAII	HA-1	9	10
	HA-2	11	13
	HA-3	10	12.5
	HA-4	5	7
	HA-5	6.5	8
	HA-6	6	8
	HA-7	10	11

Data Sources:
Hagerman (1992)
Kauai Coastal Resource Atlas, USACE (1984)

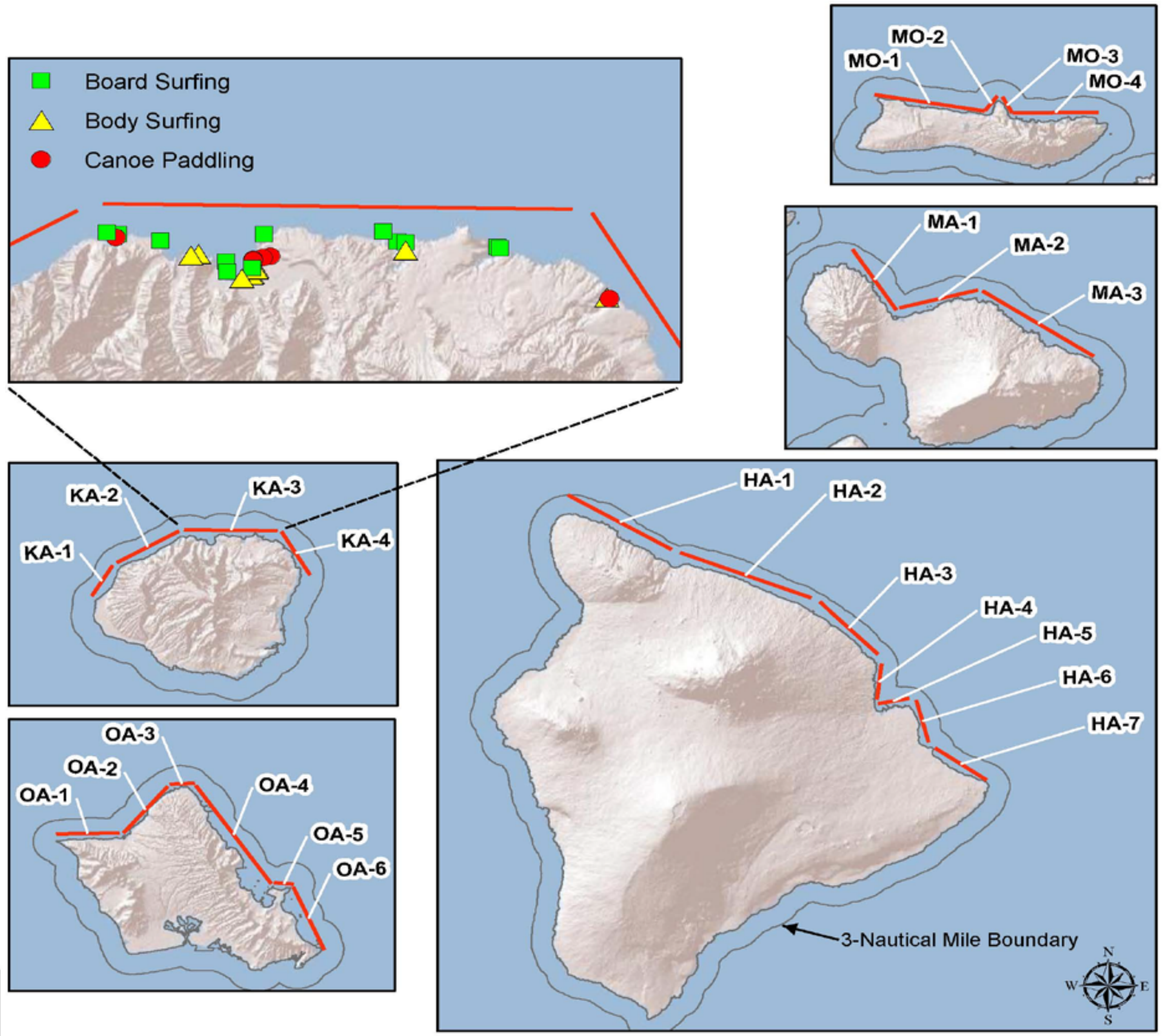

Figure 1.- Wave Power Flux (kW/m) along coastline segments identified in the George Hagerman 1992 Report

Island	Wave Energy Resource (GWh/year)	Extractable Energy with a Wave-to-Electricity Converter (GWh/year) CF:15%	Required Wave Farm Name Plate (MW) / Wave Farm Ocean Area Requirement (km^2)	2007 Electricity Consumption (GWh/year)	Potential Wave Energy Contribution to Electricity Consumption
Hawaii	12,900	1,940	1476 MW/103 km^2	1,259	150%
Maui	8,200	1,230	936/66	1,385	90%
Oahu	9,600	1,440	1096/77	8,293	17%
Kauai	7,200	1,080	822/58	266	400%
Molokai	6,800	1,020	776/54	39	2,600%
Totals		6,710		11,242	60%

Table 2 - Theoretical Wave Power Contribution for the Generation of Electricity

Offshore Wave Power Resources: Update

Wave power resources off the state of Hawaii consist of three main climate patterns: north swell; south swell; and, wind waves (Figure 2). The Hawaiian Islands are exposed to swells from distant storms as well as seas generated by trade winds. The island chain creates a localized weather system that modifies the wave energy resources from the far field. UH researchers working for the Hawaii National Marine Renewable Energy Center (http://hinmrec.hnei.hawaii.edu/) implemented a nested computational grid across the major Hawaiian Islands in the global WaveWatch3 (WW3) model and utilize the Weather Research Forecast (WRF) model to provide high-resolution mesoscale wind forcing. The resulting winds and deep water ocean waves estimated in this fashion compare favorably with satellite and buoy measurements.

The validated model reveals that under deep water conditions (> 150 m depths), in the winter months northwest swells have relatively large amounts of wave power of upwards of 60 kW/m (power per wave-crest unit length). However, in the summer months the wave power flux (also referred to as wave power density) due to northwest swells is less than 10% of the winter values. South swells, prevalent in the summer months, have lower power levels of < 15 kW/m. The wind waves are the most consistent throughout the year and yield offshore power levels in the range of 5-25 kW/m. Significant seasonal variations are present at all island sites between winter and summer months.

The consistency of the wave climate and the proximity to shore play an important role in the selection of optimal locations for deployment of wave energy devices. While the north and south facing shores would capture swell energy, the most favorable sites are in areas exposed to the direction of the wind waves (Figure 2). This indicates the soundness of the selection of coastal segments shown in Figure 1 from the Hagerman 1992 report.

This deep water model, however, is not applicable to shallow water conditions (e.g., water depths < 100 m) and the wave energy conversion (WEC) devices, under development, are to be installed in depths of at most 70 m such that the wave resource must be evaluated for shallow water conditions as is done in the following Section.

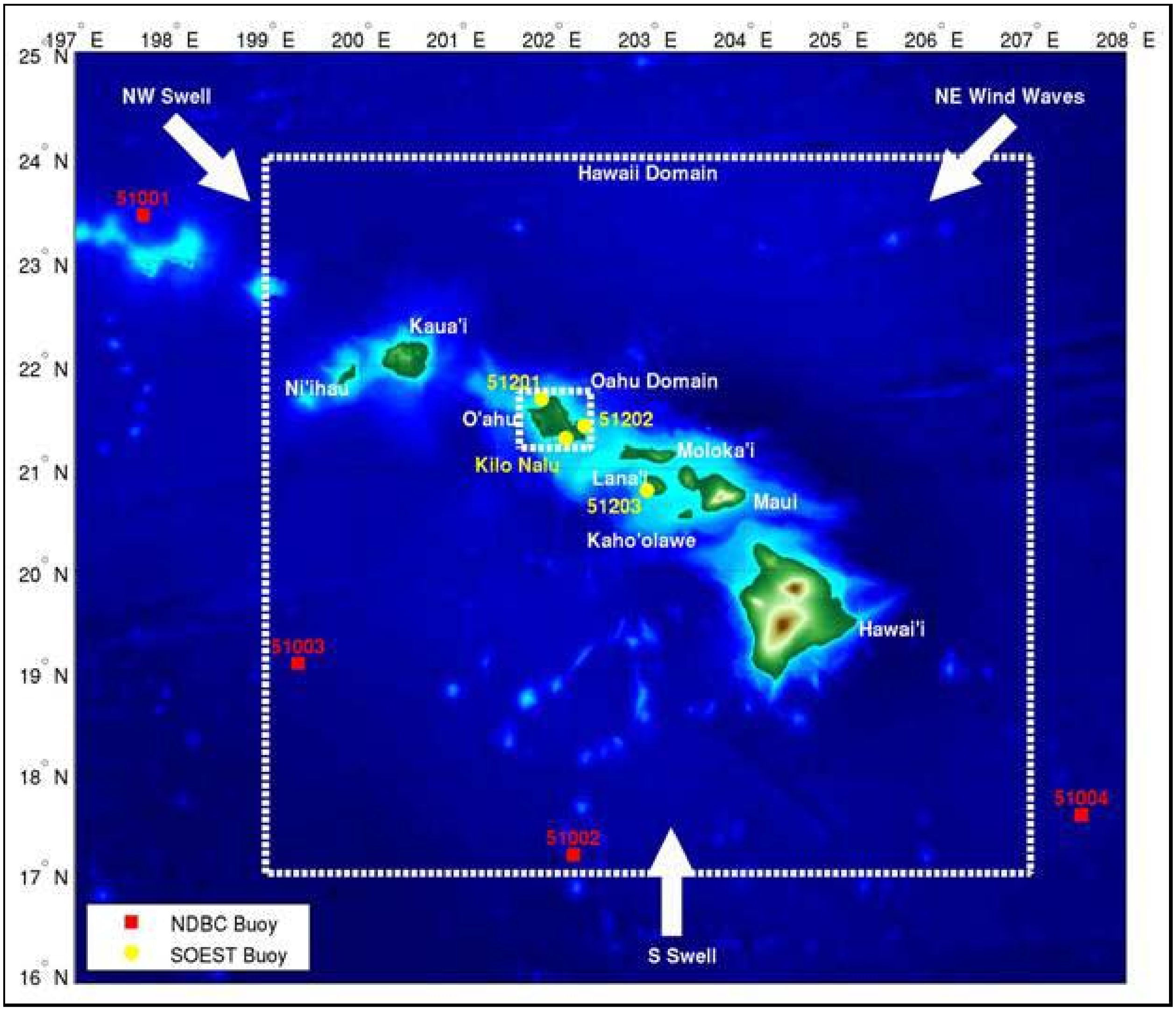

Figure 2 - Hawaii Wave Power Climate Patterns

Shallow Water Wave Power Resources: Update

To estimate the shallow water resource, the SWAN model was used with spectral wave data hindcasted from WW3 to obtain ten years (January 2000-December 2009) of the parametric wave data required by designers of WEC devices. This project, considered five representative sites (see Figures 3 and 4): (i and ii) North Beach in Kaneohe at two water depths (the OPT site); (iii) Pauwela in Maui (the Oceanlinx site); (iv) shallow water site off South Point (Big Island); and (v) shallow water site in the Alenuihaha Channel off Upolo Airport (Big Island). The model was evaluated using archival data available from the stations listed below (Appendix A).

Station	Location	Lat. (N)	Long. (W)	Water Depth (m)	Data Availability	System
51201	Waimea Bay	21.673	158.116	198	Sep 2004-Current	Waverider Buoy recording wave parameters and water temperature.
51202	Mokapu Pt.	21.417	157.668	100	"	"

For reference, the water depth and latitude and longitude coordinates of each site are presented in Table 3. We selected the Latitude and Longitude and the bathymetry is from LiDAR data with a resolution of ~ 4m.

These five locations were chosen to be in water depths of less than about 70 m to coincide with the upper limit of WEC devices currently under design by reputable developers. The Kaneohe site coincides with the location of the OPT 40 kW WEC device ("heaving buoy") currently installed and undergoing testing. We selected the Kaneohe II site as a possible location for an additional WEC in deeper waters (58 m vs. 27 m). The Pauwela site (73 m depth) was selected from within the area specified in the Preliminary Permit awarded to Oceanlinx by FERC. Oceanlinx is currently completing the design of a ~ 2.7 MW system based in the OWC concept. The other two sites off the Big Island were deemed to be interesting because of their exposure to trade wind waves (Upolo at 47 m) and both trade wind waves and southern swell (South Pt. at 40 m).

The wave power flux (P_o), through a vertical plane of unit width perpendicular to the wave propagation direction is used to represent the resource. Daily, monthly and annual averaged P_o (kW/m) over the ten year period are presented herein.

Site	Location	Latitude (N)	Longitude (W)	Water Depth (m)
Kaneohe	Kaneohe, Oahu	21.465	157.752	27
Kaneohe II	Kaneohe, Oahu	21.472	157.747	58
Pauwela	Pauwela, Maui	20.958	156.322	73
Upolu	Upolu, Hawaii	20.275	155.863	47
South Point	South Point, Hawaii	18.910	155.681	40

Table 3 - Location of Sites Selected for SWAN Analysis

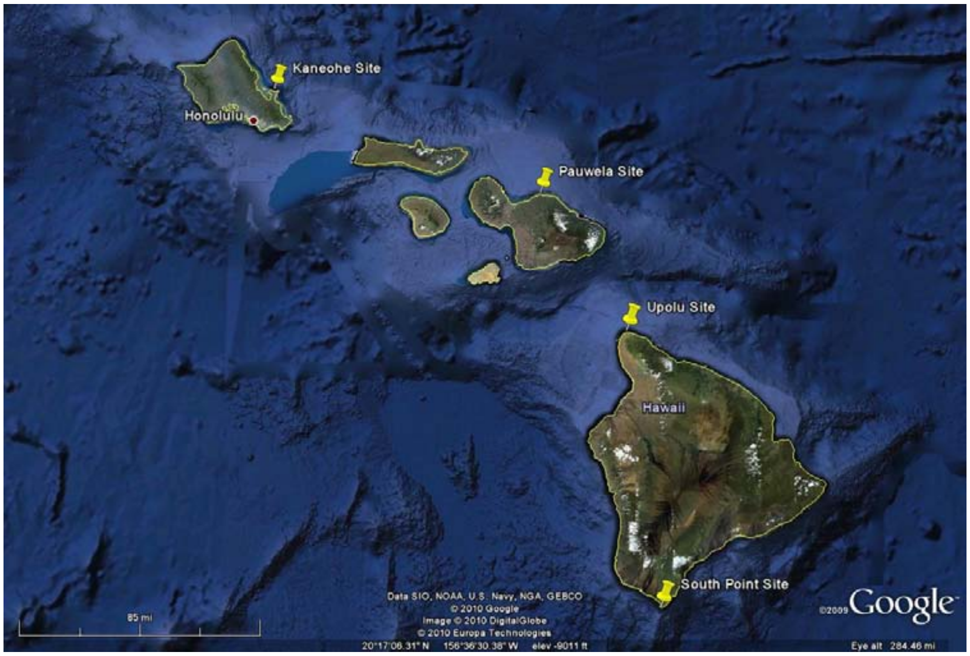

Figure 3 - Location of Representative Sites Selected for SWAN Modeling

Figure 4 - Location of Kaneohe Sites

The wave power flux for each site was estimated as described below (Eq. 1). Monthly and annual averaged estimates over the ten year period are given in Tables 4 and 5. All monthly averages are plotted in Figure 5 along with values derived from NOAA/NDBO Buoy 51202 (Mokapu). These show that the site selected by Oceanlinx in Pauwela represents a relatively high resource. The graphical representation in Figure 5 is indicative of the relatively high seasonal resource variability with summer months showing power levels of 1/7 the winter values in Pauwela and 1/3 in Kaneohe. In the case of the sites exposed to southern swell (see South Pt. and Mokapu) the seasonal difference is less pronounced.

The averaged daily and monthly values are shown in Figures 6 through 15. Significant seasonal variations between winter and summer months are clearly shown. The average monthly wave power flux between May and September show similar values for the Upolu and Kaneohe sites (~ 5-7 kW/m), and slightly higher values at the Pauwela (~ 6-9 kW/m) and South Point (~13 kW/m) sites. Between October-April, significantly higher values (~ 17-43 kW/m) are shown at the Pauwela site. The daily variability is also pronounced indicating relatively large swings that would be expected in the power output from any WEC device.

$$P_o = \rho g \int_{\omega=0}^{\omega=\infty} Cg(\omega,h) \left(\int_{\theta=0}^{\theta=2\pi} S(\omega,\theta,h)\, d\theta \right) d\omega \quad \text{(W/m)} \qquad (1)$$

where,

- $S(\omega,\theta,h)$ = site specific wave spectrum
- θ = wave direction
- ω = wave frequency
- h = water depth
- Cg = site specific group speed
- g = gravitational acceleration, ~ 9.81 m/s^2
- ρ = density of sea water, ~ 1025 kg/m^3

P_o can be expressed as:

$$P_o = c_G E_{tot} = \frac{\rho g^2}{64\pi} \mathrm{T_e} H_s^2 \quad (\textit{Watts/m}) \qquad (2)$$

indicating that, P_o is proportional to the wave period and to the square of the wave height.

The Energy-Period, T_e, and the significant wave height are defined as:

$$H_s = 4\sqrt{\iint (S(\omega,\theta,h)\, d\omega d\theta} \qquad (3)$$

$$T_e = 2\pi \left(\frac{\iint \{(S(\omega,\theta,h)/\omega) \tanh(kh)[1+2kh/\sinh(2kh)]\} d\omega d\theta}{\iint S(\omega,\theta,h)\, d\omega d\theta} \right) \qquad (4)$$

It must be noted that P_o, as properly defined above, applies to any water depth. The approximation for deep water conditions (not applicable herein) is found to be used incorrectly throughout the open literature even when discussing shallow water waves.

	Power Flux (kW/m)											
Site	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Kaneohe	15.5	13.1	13.2	11.1	5.9	4.9	4.8	5.0	6.3	9.7	16.2	16.6
Kaneohe II	15.7	13.1	13.0	10.9	5.8	4.8	4.6	4.8	6.2	9.7	16.3	17.1
Pauwela	41.8	33.0	26.1	18.1	8.8	6.4	5.9	6.4	8.9	16.6	30.4	43.3
Upolu	15.2	12.8	13.2	11.3	6.5	6.0	6.1	6.6	6.8	9.6	14.9	15.6
South Point	17.0	15.3	14.2	14.2	12.7	13.1	12.7	12.5	12.4	11.8	12.8	15.5
Mokapu Buoy	22.2	20.2	16.7	16.7	12.2	10.2	10.7	10.2	8.7	12.7	20.7	21.7

Table 4 - Monthly Average Wave Power Flux

Site	Power Flux (kW/m)
Kaneohe (27 m)	10.2
Kaneohe II (58 m)	10.2
Pauwela (73 m)	20.5
Upolu (47 m)	10.4
South Pt. (40 m)	13.7
Mokapu Buoy (100 m)	15.2

Table 5 - Annual Average Wave Power Flux

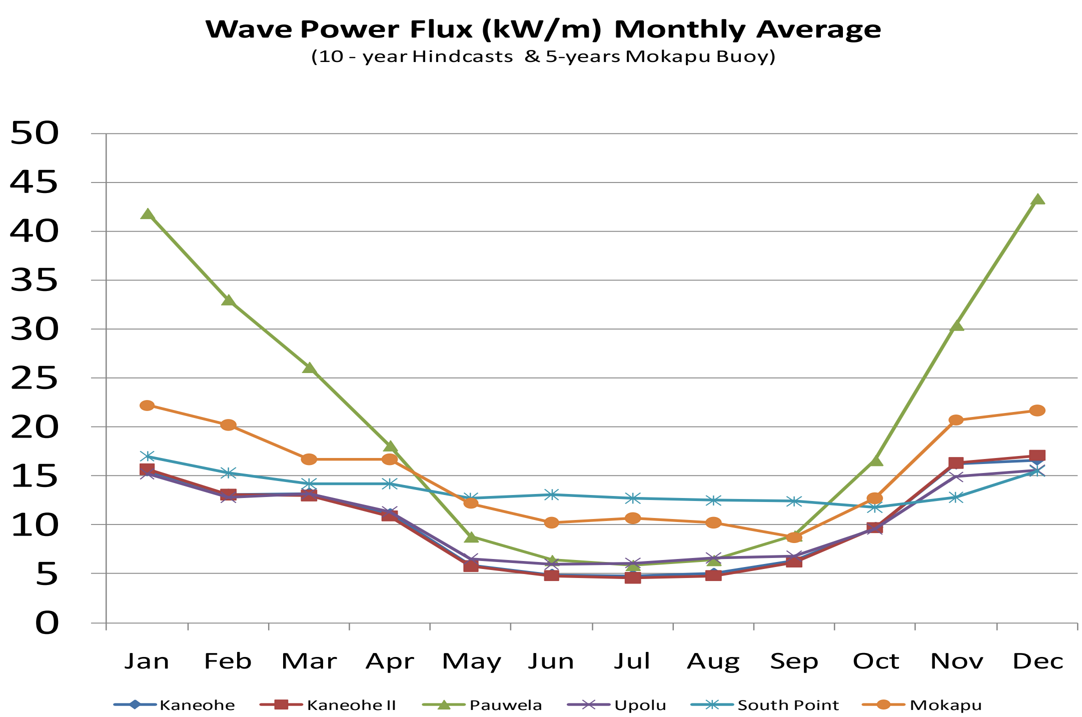

Figure 5 - Monthly Average of Wave Power Flux at all Sites

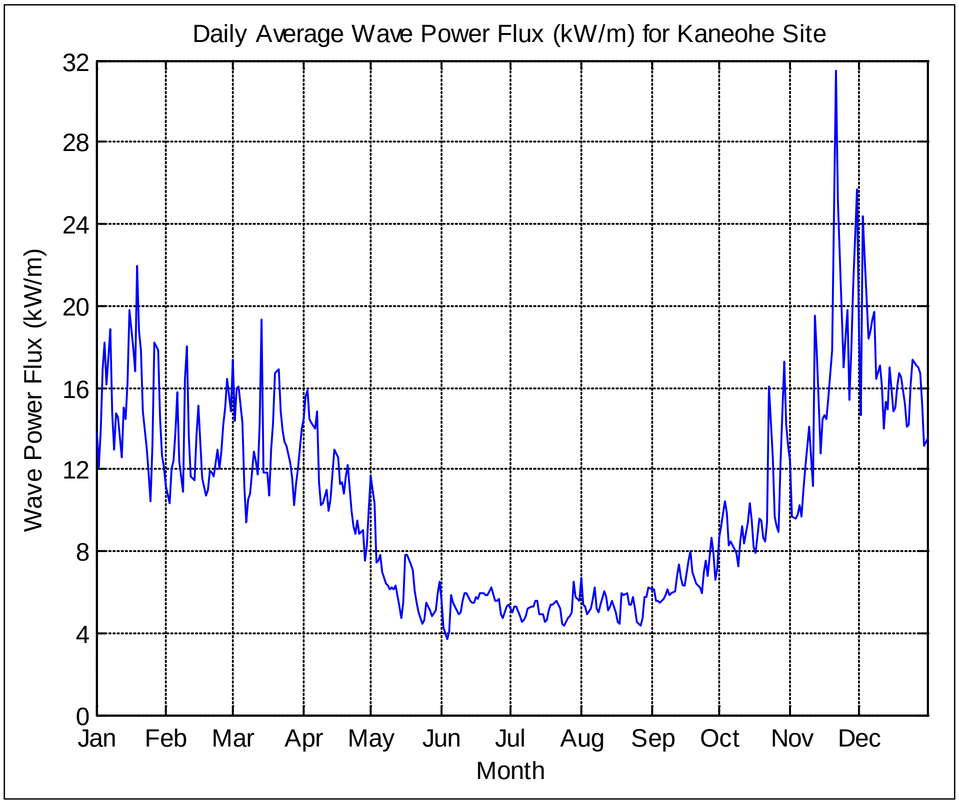

Figure 6 – Daily Average Wave Power Flux for Kaneohe Site (27 m)

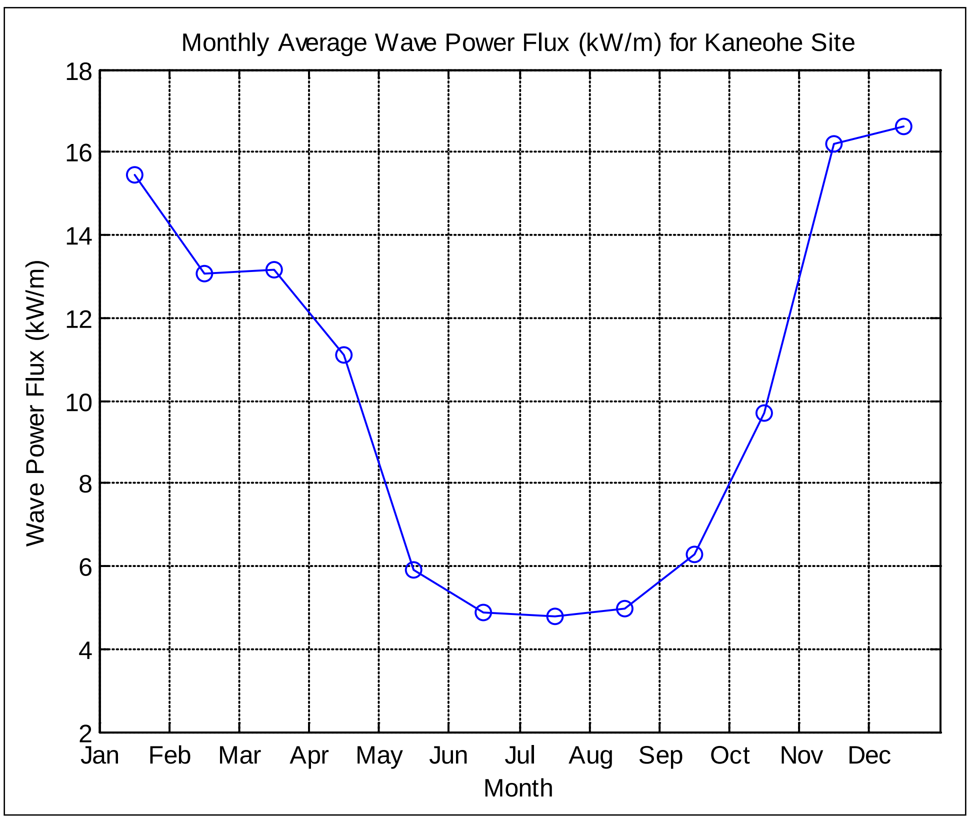

Figure 7 – Monthly Average Wave Power Flux for Kaneohe Site (27 m)

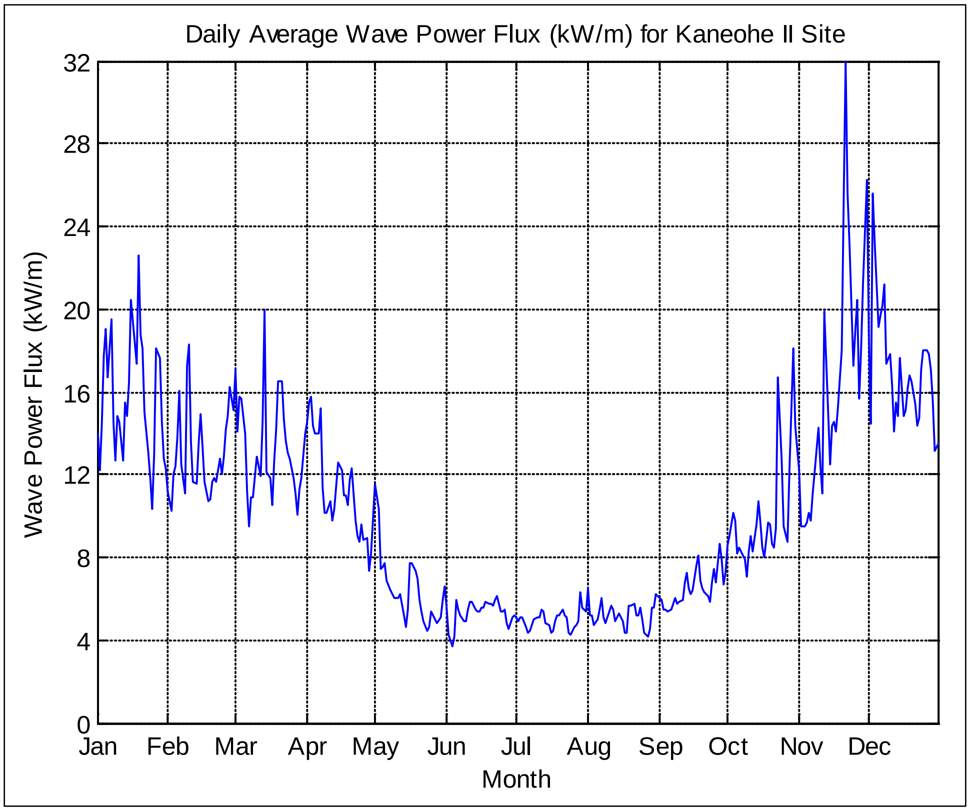

Figure 8 – Daily Average Wave Power Flux for Kaneohe II Site (58 m)

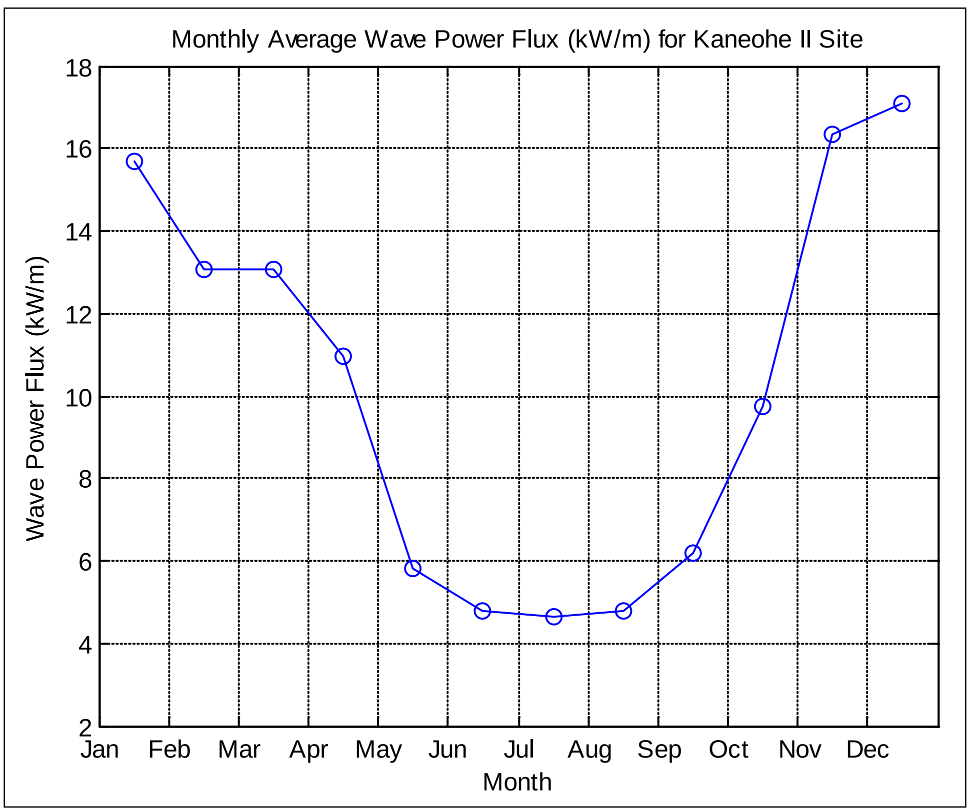

Figure 9 – Monthly Average Wave Power Flux for Kaneohe II Site (58 m)

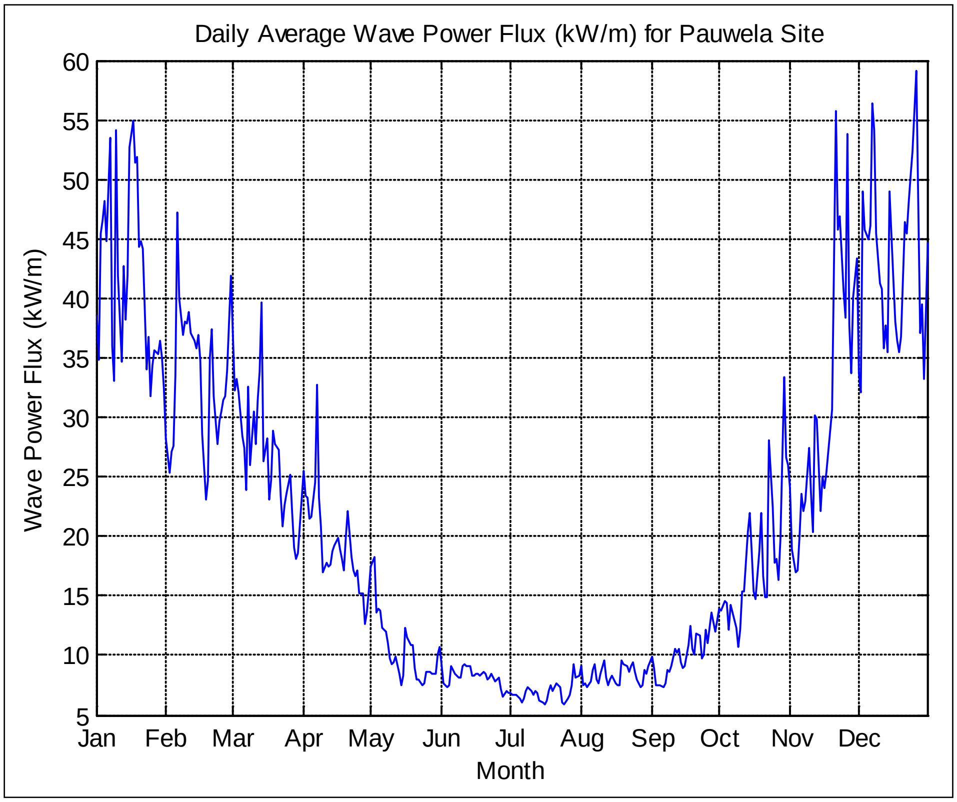

Figure 10 – Daily Average Wave Power Flux for Pauwela Site (73 m)

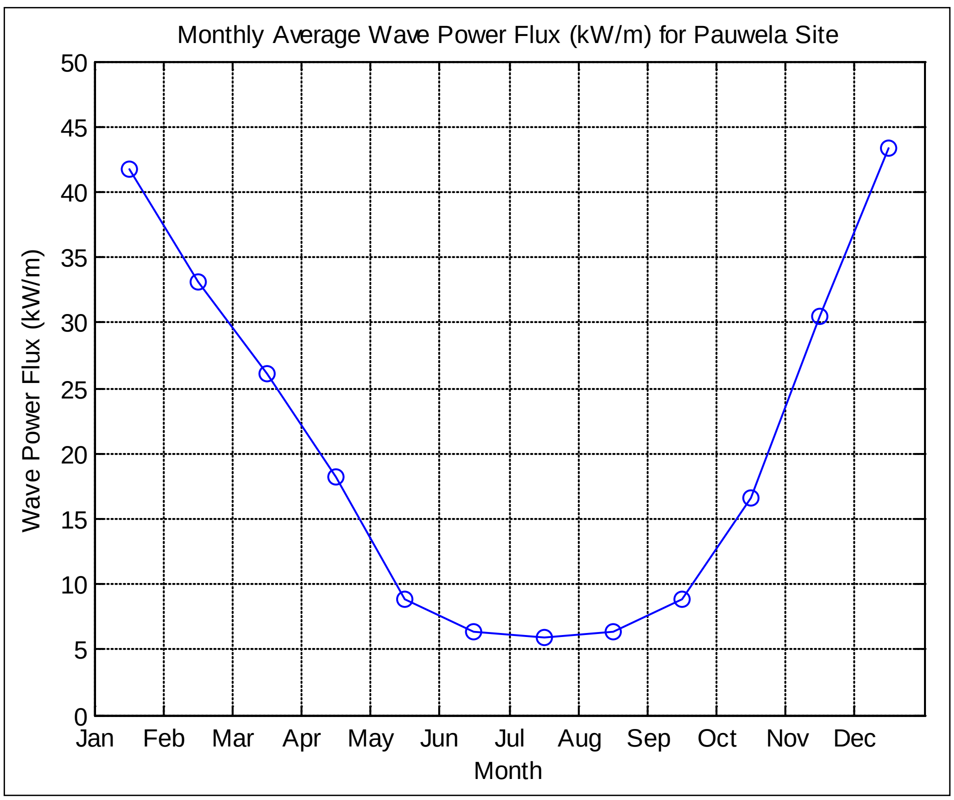

Figure 11 – Monthly Average Wave Power Flux for Pauwela Site (73 m)

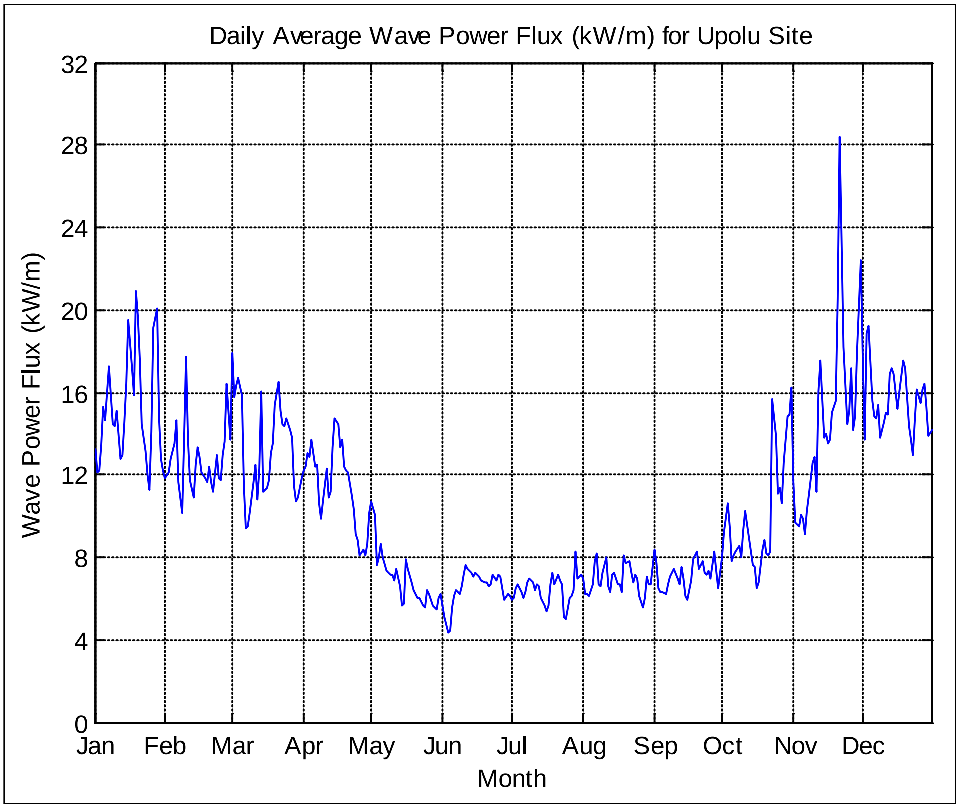

Figure 12 – Daily Average Wave Power Flux for Upolu Site (47 m)

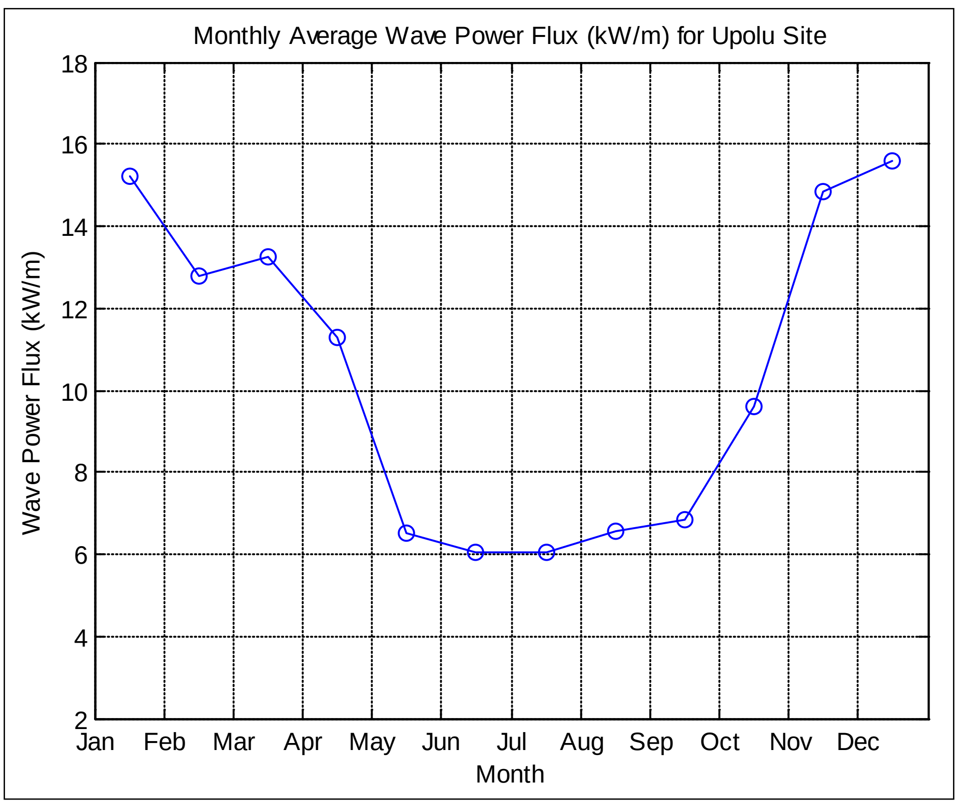

Figure 13 – Monthly Average Wave Power Flux for Upolu Site (47 m)

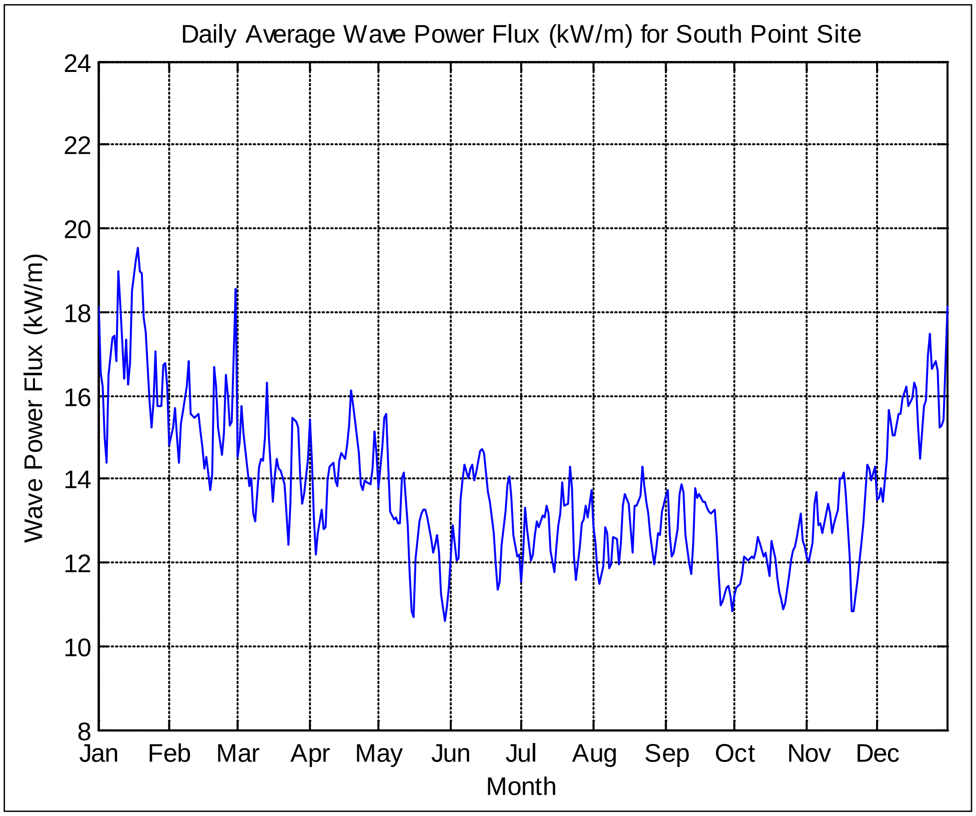

Figure 14 – Daily Average Wave Power Flux for South Point Site (40 m)

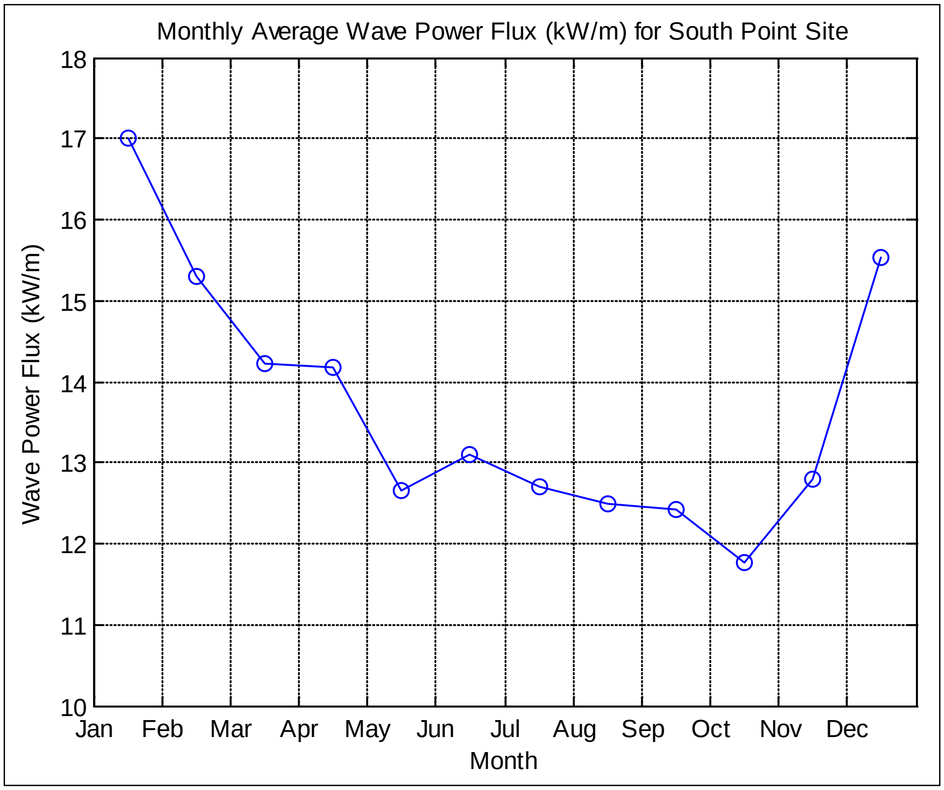

Figure 15 – Monthly Average Wave Power Flux for South Point Site (40 m)

Comparing annual average estimates obtained herein (Table 5) with the 1992 estimates (Figure 1) indicates that, with the exception of the Pauwela site, the original estimates are useable for initial evaluation. However, monthly and daily estimates, as presented in this report, are required to proceed beyond a simple site evaluation.

Site	**Annual Average (Table 5)**	**Coastal Segment (Fig. 1)**	**Annual Average**
Kaneohe (27 m)	10.2 kW/m		
Kaneohe II (56 m)	10.2 kW/m	OA-5 (80 m)	12.0 kW/m
Pauwela (73 m)	20.5 kW/m	MA-3 (80 m)	13.5 kW/m
Upolu (47 m)	10.4 kW/m	HA-1 (80 m)	10.0 kW/m
South Pt. (40 m)	13.7 kW/m		

References

1) SWAN Team, 2006: SWAN User Manual: SWAN Cycle III version 40.51, Delft University of Technology, 137 pgs.

2) http://www.ndbc.noaa.gov/station_history.php?station=51202

Appendix A

SWAN Calibration

Archival data available for the NOAA/NDBC Buoy 51201 and Buoy 51202 includes estimates of significant wave height (Hs) for the period September 2004 to December 2009. Buoy location and water depth are given in Table A1. To assess the accuracy of parameters obtained with SWAN over the same period, scatter plots of computed and measured Hs were obtained as shown in Figure A1 and Figure A2 at both locations.

While analysis based on all available buoy data indicates that SWAN appears to underpredict Hs at the shallower buoy site (Mokapu Pt.), the correlation value at both locations is 0.9. Scatter plots were also derived for the more energetic period of November-April, and the May - October period (Figure A3 through Figure A6) with results indicating that SWAN underpredicts Hs values (≤ 1 m) during the energetic period. The correlation values are included in the Figures. NOAA/NDBC reports an accuracy of ± 0.2 m in their estimates of wave height.

It must be noted that the wave power flux, as defined by equation 1, can be expressed as

$$P_o = c_G E_{tot} = \frac{\rho g^2}{64\pi} \mathrm{T_e} H_s^2 \quad (\mathit{Watts/m}) \tag{2}$$

such that, the wave power flux is proportional to the wave period and to the square of the wave height.

The Energy-Period, T_e , and the significant wave height are defined as:

$$H_s = 4\sqrt{\iint (S(\omega,\theta,h) d\omega d\theta} \tag{3}$$

$$T_e = 2\pi\left(\frac{\iint \{(S(\omega,\theta,h)/\omega)\tanh(kh)[1+2kh/\sinh(2kh)]\} d\omega d\theta}{\iint S(\omega,\theta,h) d\omega d\theta}\right) \tag{4}$$

Station	Location	Latitude (N)	Longitude (W)	Water Depth (m)	Data Availability
51201	Waimea Bay	21.673	158.116	198	Sep 2004-Dec 2009
51202	Mokapu Point	21.417	157.668	100	Sep 2004-Dec 2009

Table A1 - NOAA/NDBC Buoy Locations

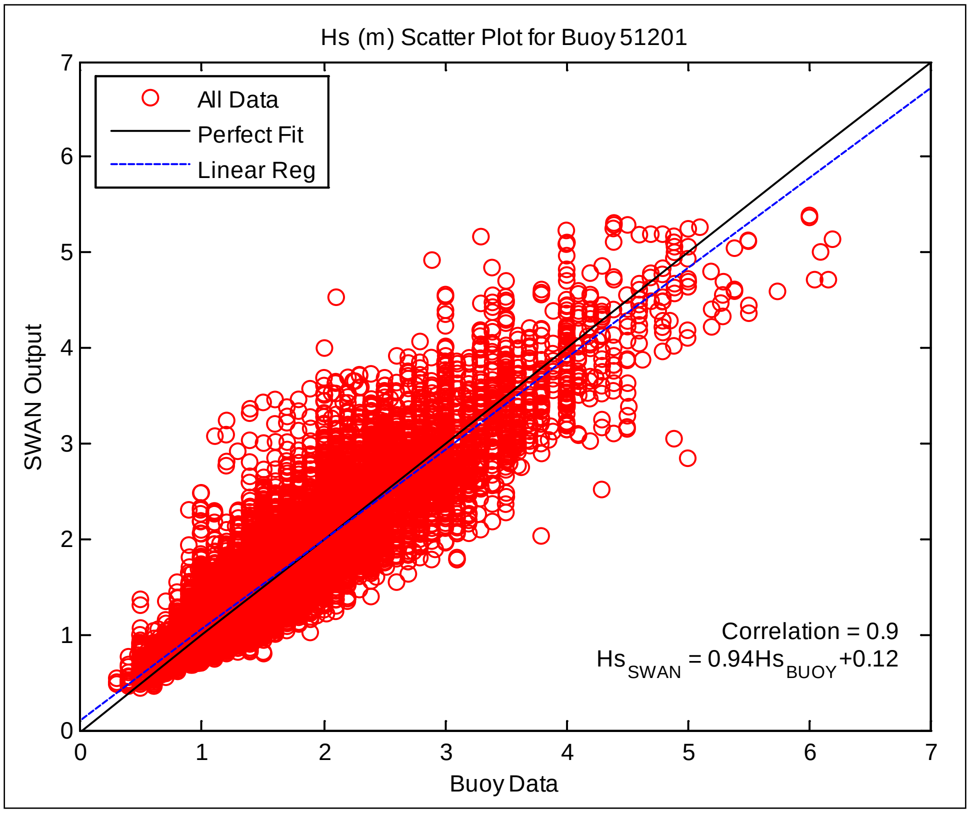

Figure A1 - Hs Scatter Plot for Buoy 51201 (198 m)

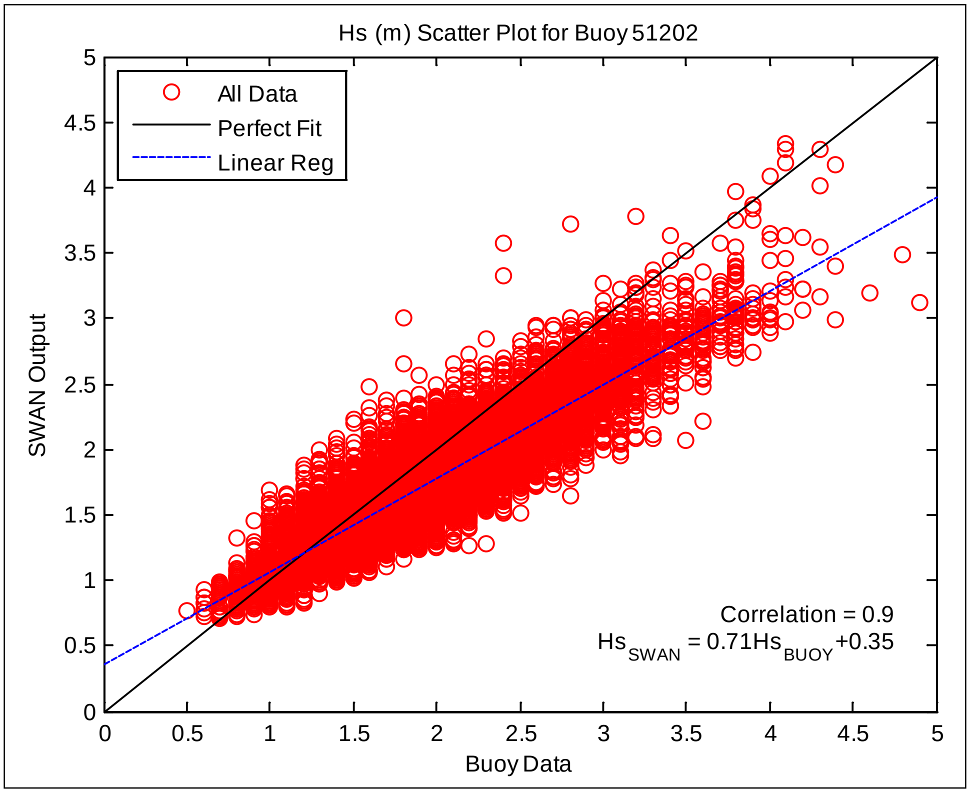

Figure A2 - Hs Scatter Plot for Buoy 51202 (100 m)

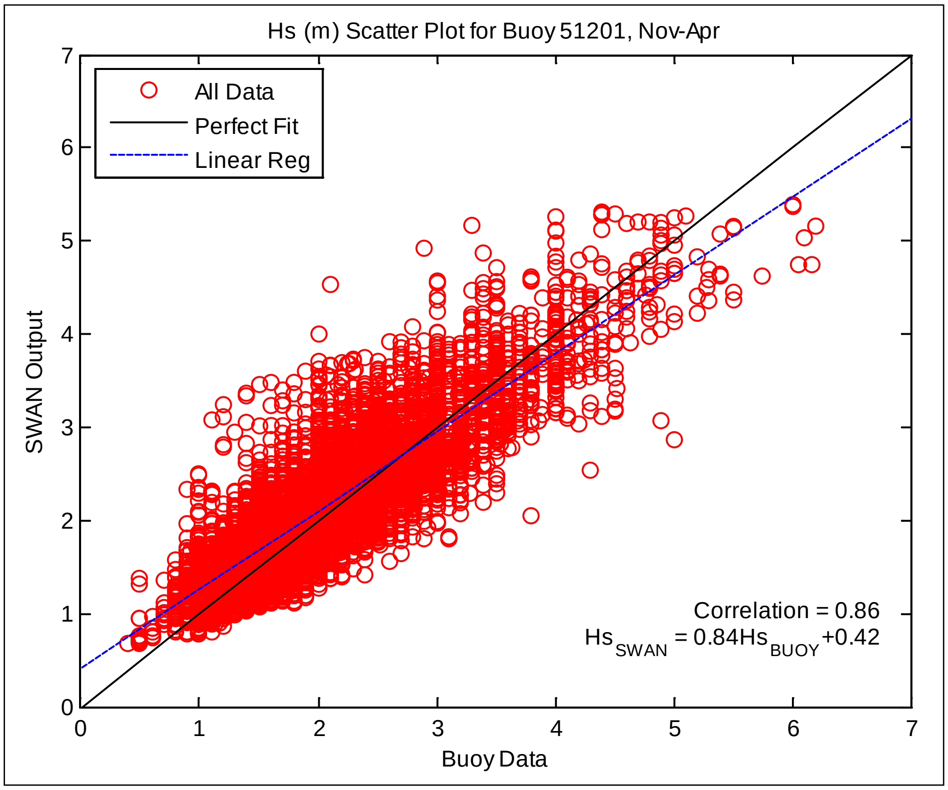

Figure A3 - Hs Scatter Plot for Buoy 51201(198 m), November – April

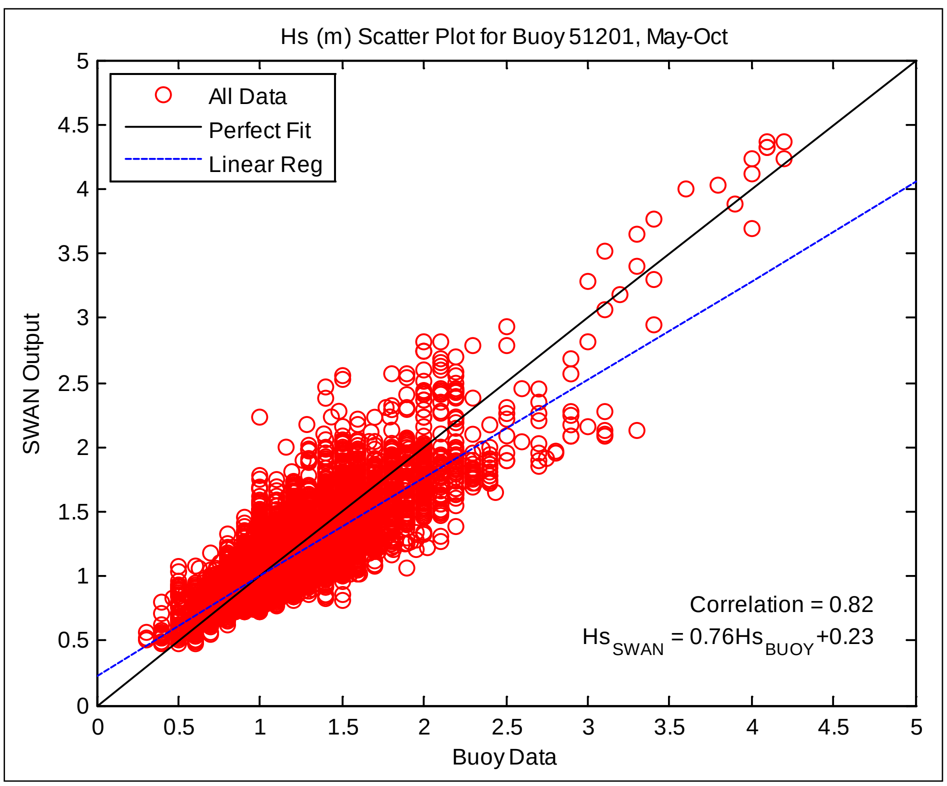

Figure A4 - Hs Scatter Plot for Buoy 51201 (198 m), May-October

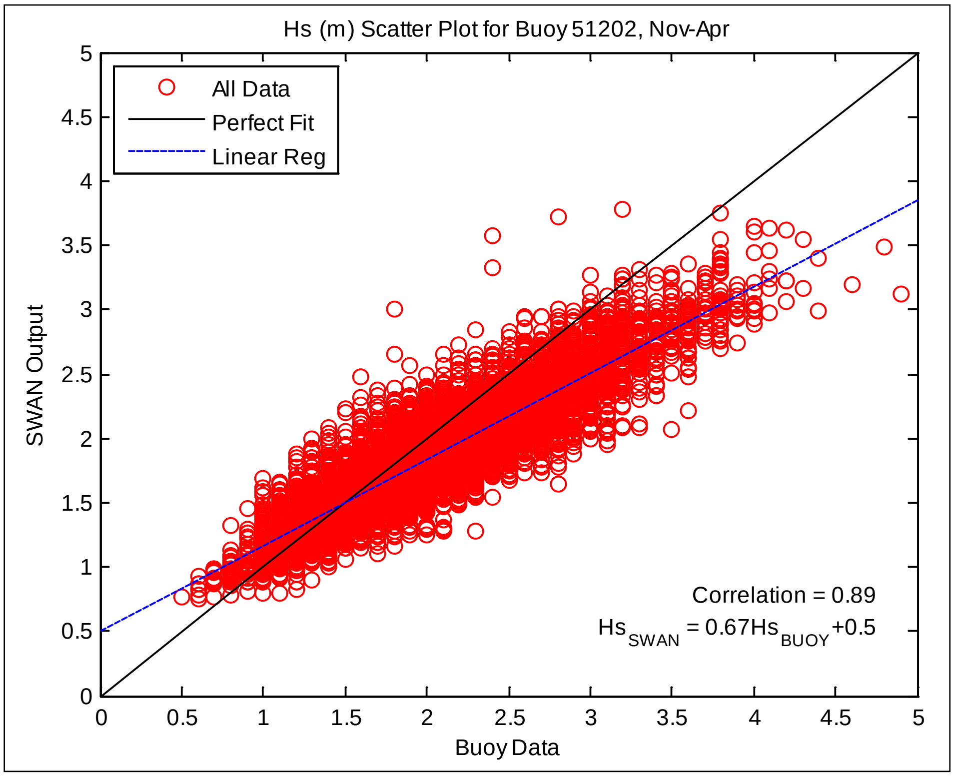

Figure A5 - Hs Scatter Plot for Buoy 51202 (100 m), November-April

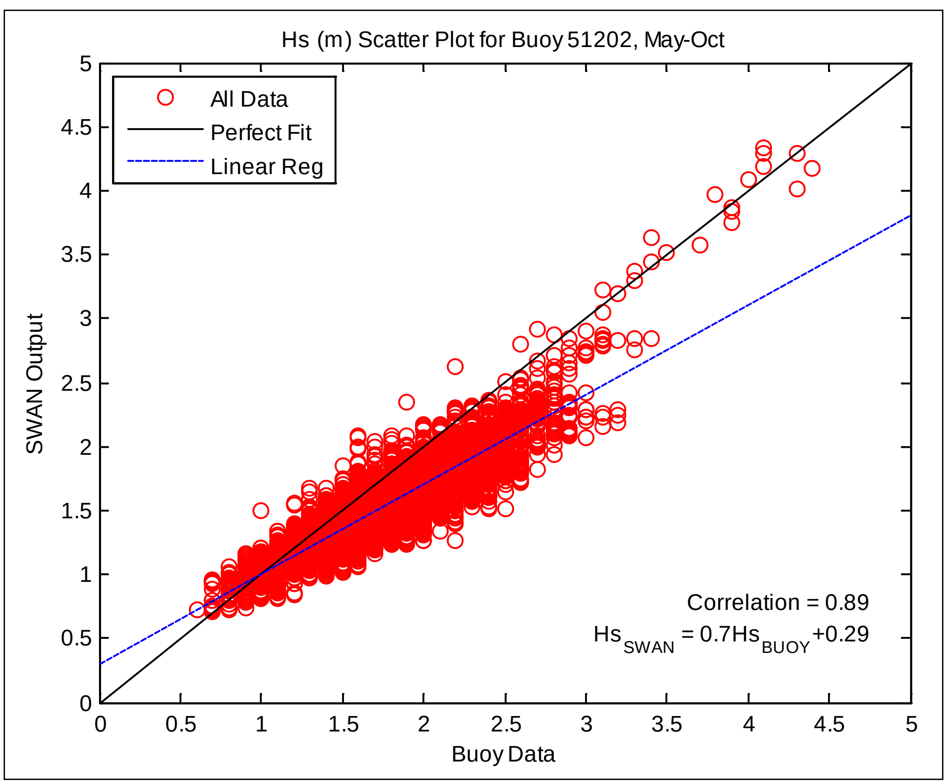

Figure A6 - Hs Scatter Plot for Buoy 51202 (100 m), May-October