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memorandum

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from Joel Darnell, PE, Pablo Quiroga

subject Preliminary Shoreline Wave Analysis at Greenbank Marsh

INTRODUCTION

This memo summarizes ESA's preliminary wave analysis performed for the Greenbank Marsh project located on Whidbey Island near Greenbank, Washington. ESA understands that Element Solutions is currently supporting the Whidbey Island Conservation District (WICD) in the development of conceptual designs for the project, which focuses on replacing a deteriorating stormwater outfall and dike system to provide potentially improved flood protection and the opportunity for ecological restoration. To assist Element Solutions and WICD with project feasibility, ESA developed an estimate of annual wave power at the site by performing a preliminary-level desktop analysis and modeling of site specific conditions according to the scope of work outlined below:

- Participate in a one-hour kickoff phone call and a one-hour review call prior to completion.
- Process available wind data at Cama Beach State Park (2003-2005), develop representative wind statistics from these data, and generate wave modeling input.
- Perform numerical modeling of wind waves in Saratoga Passage & Holmes Harbor to develop an initial understanding of the wave climate affecting the site and generate a time series offshore wave conditions.
- Transform the offshore times series to one (1) mutually agreed nearshore location and compute annual wave power at that location for use by Element Solutions and WICD.
- Provide a brief Technical Memorandum deliverable summarizing the methodology and estimated annual wave power at the agreed location. Iterations or changes to location would require additional scope and budget.

Given the budget and schedule limitations, ESA relied on readily available public data and limited duration wind data for this analysis. Further refinement is recommended in a future phase of work should the project proceed to more detailed level of study and/or design.

METHODOLOGY & RESULTS

Wind Analysis

Winds in Puget Sound are generated by the interaction of atmospheric forcing and the region's topography, resulting in local patterns on the order of three miles (Overland and Walter, 1983). Wind patterns within central Saratoga Passage and Holmes Harbor are generally understood to follow along the topography of Whidbey and Camano Islands. ESA reviewed regional wind data at nearby NAS Whidbey, Cama Beach State Park, and Everett Paine Field. Based on this limited review, the wind record at Cama Beach State Park (2002-2005) was selected due to its proximity (3.3 miles to the northwest) and directional distribution that aligns with the shorelines and topography of Saratoga Passage and Holmes Harbor. Extension of the limited duration wind record by comparative analysis of wind records at long term stations such as Everett Paine Field or Seattle West Point may allow for extension of the wind record in future phases of work, but was beyond the scope of this analysis.

Cama Beach State Park wind data range from October 22, 2002 to May 25, 2005. The data were collected at 10-meters above MLLW and consist of 15-minute averaged data reported every 15 minutes (Finlayson 2006). The wind record consists of 16.4 percent missing data. The 15-minute data were sampled hourly and adjusted to 1-hour intervals to better represent the wave-generation timescale over the site's fetches. The wind speed record was also adjusted slightly to account for sensor height. Both of these adjustments were made according to USACE (2002). The annual distribution of wind speed and direction for the adjusted Cama Beach State Park data is shown in Figure 1, where direction is reported in the typical meteorological convention (direction wind is blowing from). Winds are most common from the south-southwest and north sectors, consistent with wind patterns at stations throughout Puget Sound. Winds from the south exhibit more variability in direction and also include the highest wind speeds. A seasonal distribution of winds is provided in Figure 2, exhibiting a typical pattern of south-dominated winds during winter, north winds in summer, and mixed winds from north and south during other seasons.

Wave Model Setup and Verification

ESA applied the Simulating WAves Nearshore model (SWAN) to simulate wind wave conditions in Saratoga Passage and Holmes Harbor. SWAN is an industry standard two-dimensional wave model which employs third-generation wave processes (Deltares 2014). The relevant wave processes which are included in the SWAN model include wave growth and propagation, refraction, shoaling, and breaking. Saratoga Passage and Holmes Harbor were discretized to a 50-meter grid and elevation (depth) assigned to each grid from NOAA's 1/3 Arc Second Port Townsend Digital Elevation Model (DEM). Figure 3 provides a visualization of the SWAN model grid bathymetry. The wave model parameters were set to represent wave generation, wave-wave interactions, dissipation, bed friction, breaking, and the wave spectrum's spatial and frequency discretization typical of enclosed bays.

Wave measurements are not available at the project site, therefore wave data collected at Cama Beach State Park and documented by Finlayson (2006) were used to verify the SWAN model results for wind cases from the dominant north and south fetches. Figure 4 shows the location of the SWAN output offshore of the project site and the model/wave measurements at Cama Beach State Park. Two extreme wind events from north and south, and one moderate wind event from the south were evaluated to verify and calibrate the SWAN model. Figure 5 illustrates the simulated wave field for the south moderate event for wind blowing at 20.3 mph from 180 degrees. Model verification results are summarized in Table 1, comparing significant wave height (Hs) and peak period (Tp). Though the model slightly over predicts wave height and period for the more extreme events, model results are generally consistent with wave observations and considered reliable for the purpose of this study.

Table 1. Wave Model Verification

Event		Measured Wind		Wave Measurement		Wave Model	
		Speed (mph)	Direction (deg)	Hs (ft)	Tp (s)	Hs (ft)	Tp (s)
South	18/NOV/2002 18:00	30.0	180	1.5	3.0	1.9	3.0
North	4/MAR/2004 16:00	26.2	315	2.0	2.7	2.0	3.7
South Moderate	30/JAN/2003 00:00	20.3	180	1.0	2.1	1.2	2.5

Wave Power Hindcast

The verified wave model was configured to simulate wave heights for the range of wind speeds and directions observed at Cama Beach State Park. Wind speeds were discretized in 5 mph intervals and wind direction into 16 cardinal directions for consistency with the measured wind data. A total of 68 wind speed and direction combination runs were simulated in SWAN. Changes to water level and tidal currents were ignored due to the very deep water in the model domain and offshore of the project. For each model run, the simulated significant wave height, mean direction, and peak period was extracted offshore of the project site in 82 ft of water (see Figure 4) and results tabulated into lookup tables. A one-hour interval wave hindcast time series was then generated from the wind time series (October, 2002 to May 2005) using corresponding SWAN model wave height, period, and direction from the lookup table. ESA has applied this approach on similar project in the past to evaluate inlet stability at restoration sites (ESA-PWA 2012, ESA 2015).

Offshore wave power, P (in units of ft-lbf/s/ft of crest length), can be conceptually calculated as follows:

$$P = \frac{\gamma g H^2 T}{32\pi}$$

Where γ is the unit weight of sea water (64.1 lbf/ft^3), g is the acceleration of gravity (32.2 ft/s^2), H is the root-mean-square (rms) wave height (ft), and T is wave period. For each hour of the wave hindcast time series, wave power was computed per the equation above and an offshore wave power time series was generated (Figure 6). Missing wind data, accounting for 16.4 percent of the time series, were accounted for by adding the mean hourly wave power for the overall period of record for each missing hour of data. Wave power results are summarized in Table 2. Per Table 2 below, the mean annual wave power offshore of the project site is estimated to be 6.0x10^8 ft-lbf/yr/ft. ESA's experience with similar sites with longer periods of record indicates wave power may vary on an annual basis by about ±30 percent.

Table 2. Annual wave power offshore of Greenbank Marsh

Year	Wave Power (ft-lbf/yr/ft)
2003	6.3x10^8
2004	5.7x10^8
Mean	6.0x10^8

DISCUSSION

The wave analysis presented above is consistent with nearby observations and produced similar wave power results when compared to other efforts by ESA at similar exposed shorelines in Puget Sound. The preliminary results summarized above are considered conservative and suitable for feasibility level analysis.

Conceptually, tidal inlets whose openings are stable maintain a balance between wave-driven processes that tend to close or relocate the channel and tide-driven processes that tend to scour and maintain it. As such, inlet stability is often assessed by comparing these opposing processes relative to reference sites (Johnson 1973, ESA 2013, ESA 2015). Previous studies provide relatively little insight into the performance of mixed sand-gravel beaches (see Battalio et al., 2007) in this regard so comparison of local wave power and tidal prism relationships at nearby reference lagoons on Saratoga Passage with similar sediment grain size would be useful to ground truth inlet stability. Other factors beyond the scope of this memo that should be considered in future phases of work might include:

- **Extension of the Wind and Wave Hindcast.** Comparative wind analysis at other longer term wind stations could provide a way to extend the record of wave hindcast and related analyses at the project site. A longer record would provide a more reliable picture of annual wave power for more detailed project analysis.
- **Nearshore Wave Power and Sediment Transport Rates.** Offshore wave power can be transformed to the nearshore and range of sediment transport rates computed for a given grain size distribution.
- **Sediment Transport versus Tidal Prism.** Bruun and Gerritsen (1960) classify the stability of an inlet by evaluating the ratio of spring tidal prism to total annual littoral drift. This ratio, often called the Bruun ratio, characterizes the capacity of tidal flows to scour sediment entrained by the inlet from the littoral drift.
- **Tidal Inlet Geometry versus Tidal Prism.** Hydraulic geometry relationships between the tidal prism and the cross-sectional area of the inlet channel have been verified with a large amount of empirical evidence (O'Brien, 1931; Jarrett, 1976; Townsend, 2005). Hughes (2002) extended the relationship for smaller inlets. The limited research on tidal inlets on mixed or coarse-grained beaches suggests that inlet geometry is somewhat tied to the sediment size (e.g. Webb et al., 1991). Reference channels at nearby lagoons may provide valuable insight on channel morphology and design.
- **Inlet Morphology.** As geomorphic features linked to the inlet, flood and ebb shoals are relevant factors in the inlet's sediment budget and long-term morphology. Constraints to natural migration of the inlet relative to the longshore sediment transport direction should be considered.
- **Episodic Closure.** Large storm events could close the inlet by overwhelming it with sediment before tidal forces can be mobilized to scour away deposited materials. Episodic maintenance requirements of the inlet could be evaluated using estimates of sediment transport or observations from nearby channels/shoreline structures.

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FIGURES

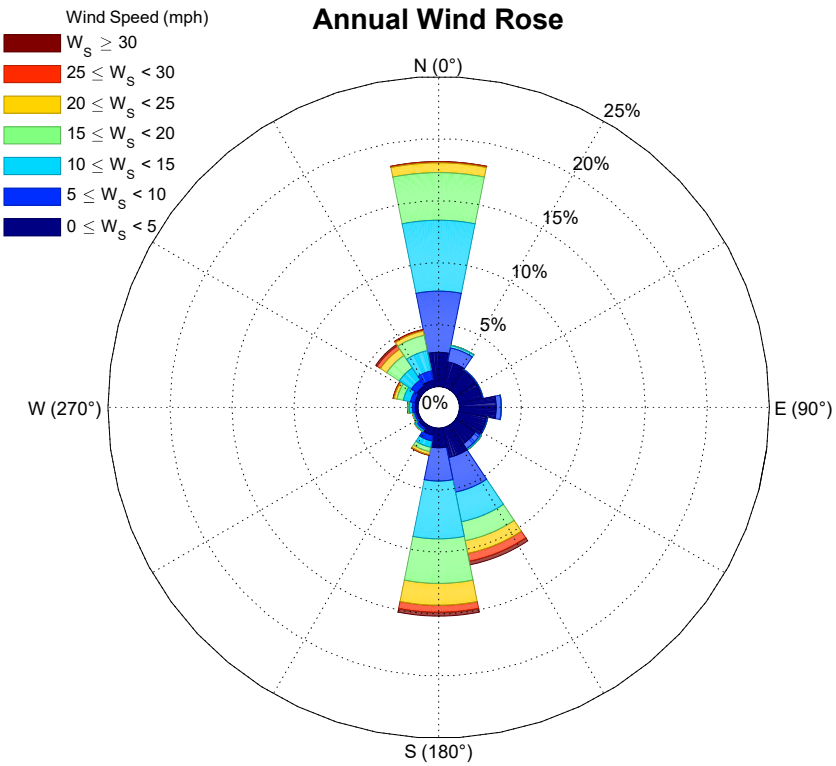

Figure 1. Cama Beach State Park Annual Wind Rose

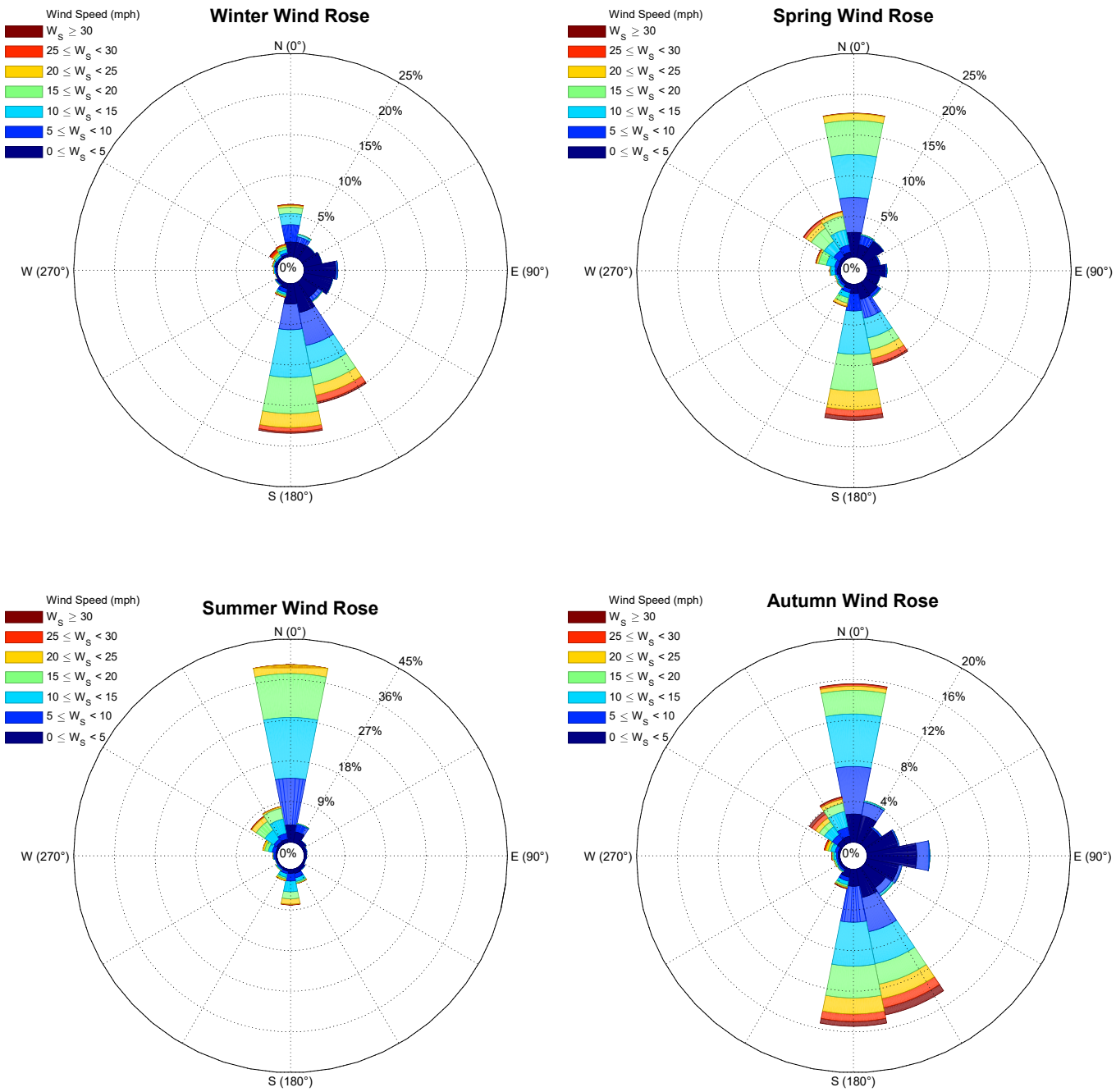

Figure 2. Cama Beach State Park Seasonal Wind Roses

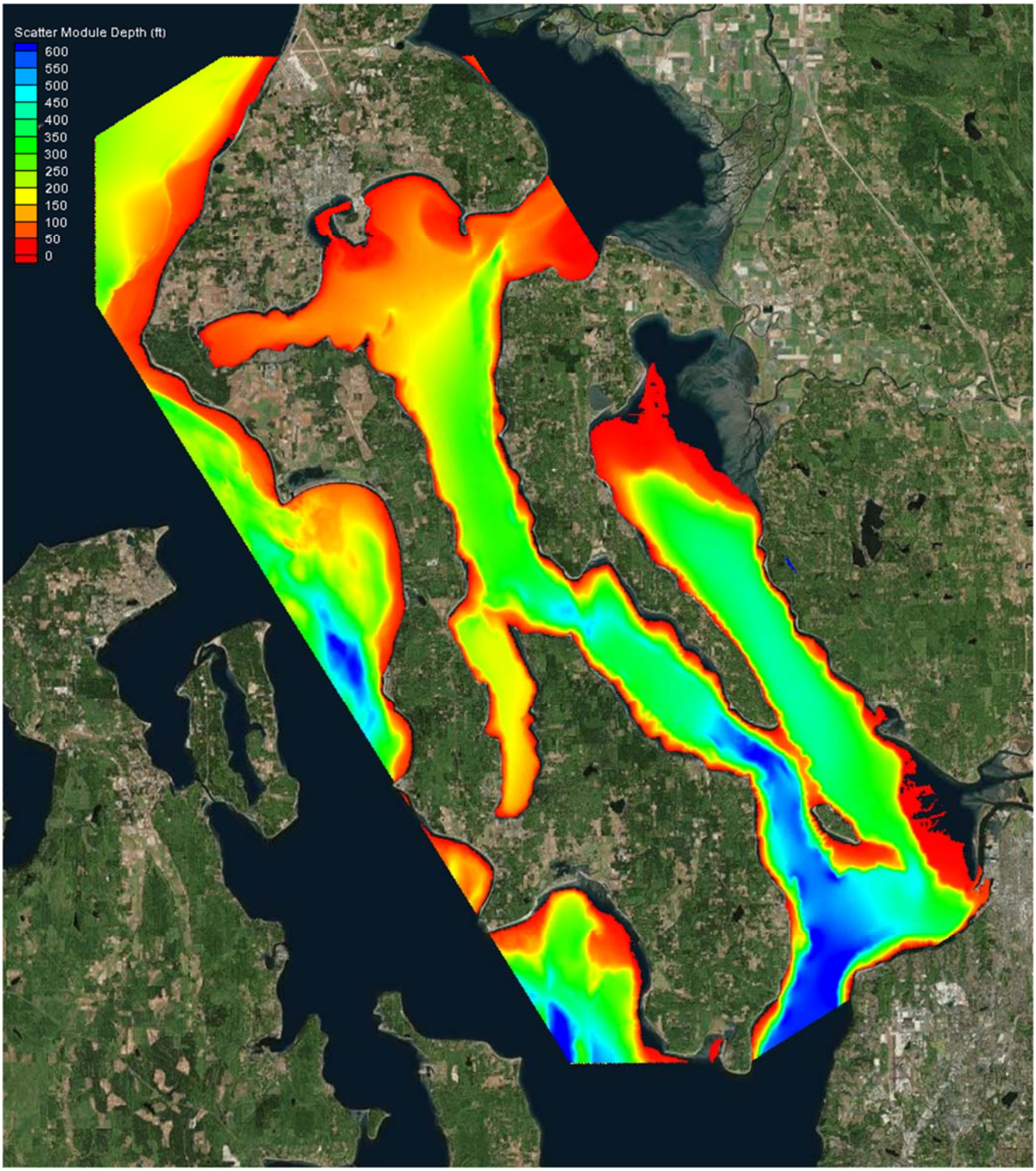

Figure 3. Wave Model Domain Bathymetry

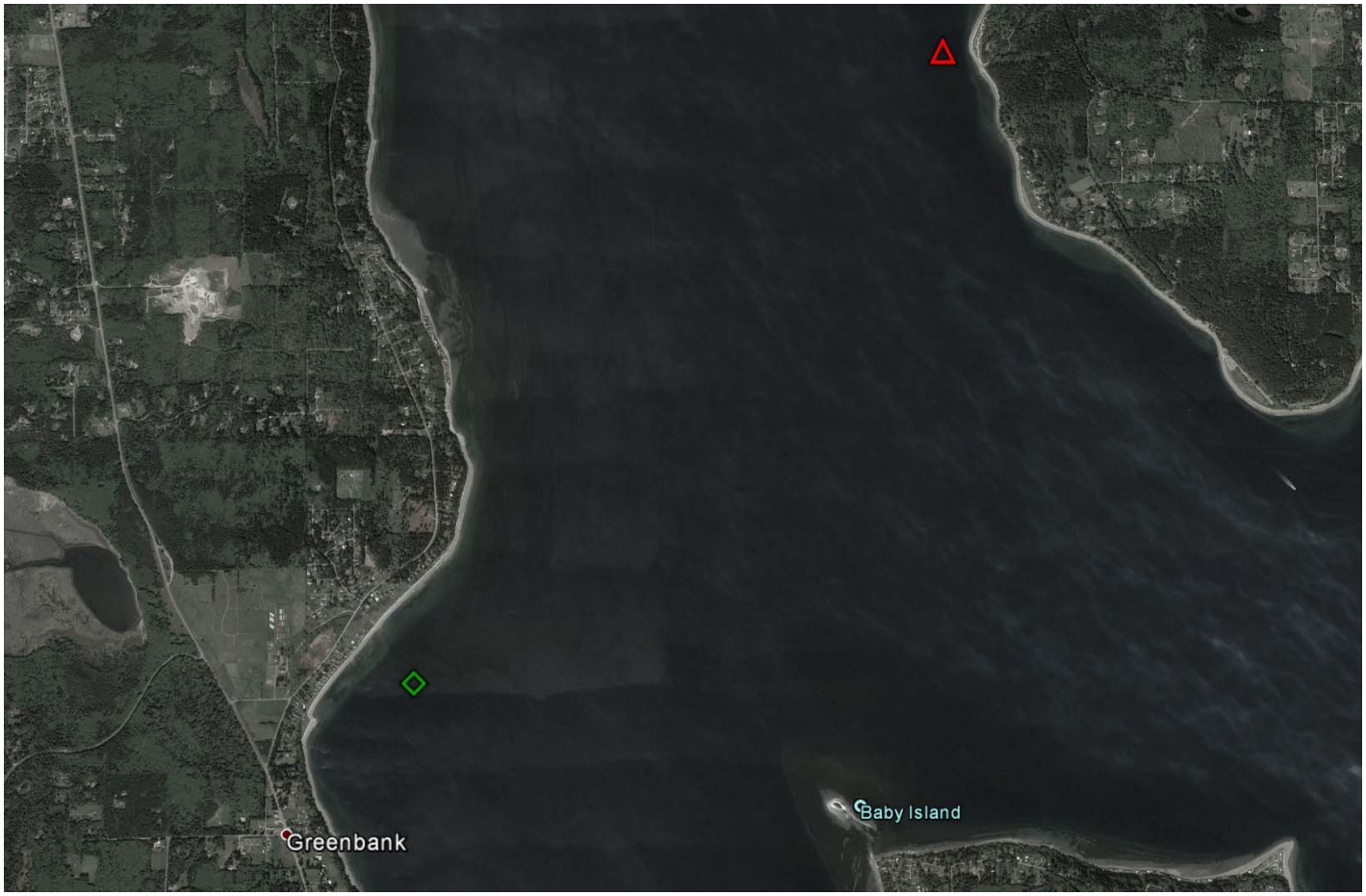

Figure 4. Wave Output Locations. ◇ Offshore Site △ Wave measurements.

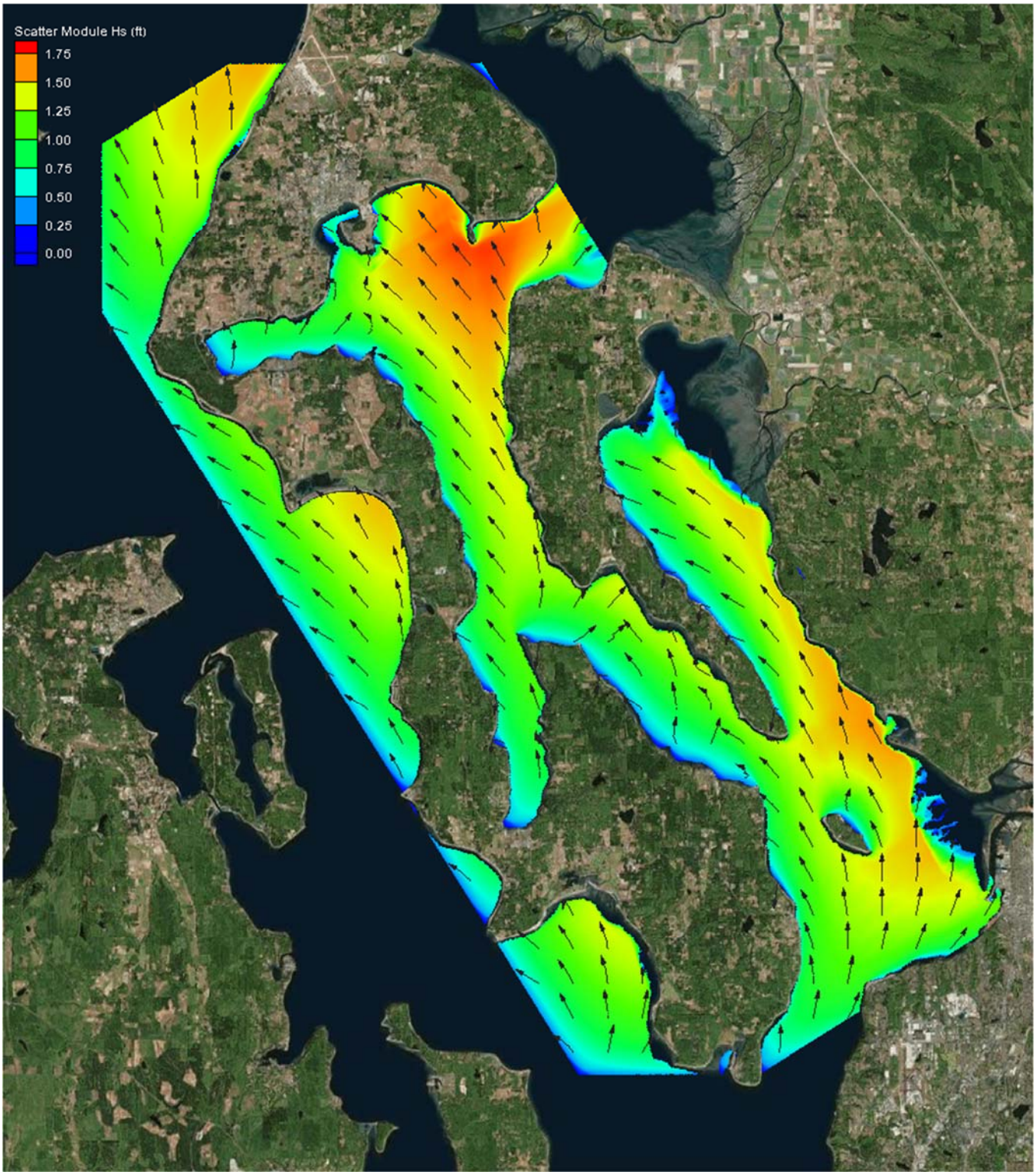

Figure 5. Examples Wave Model Result for Moderate South Wind Case

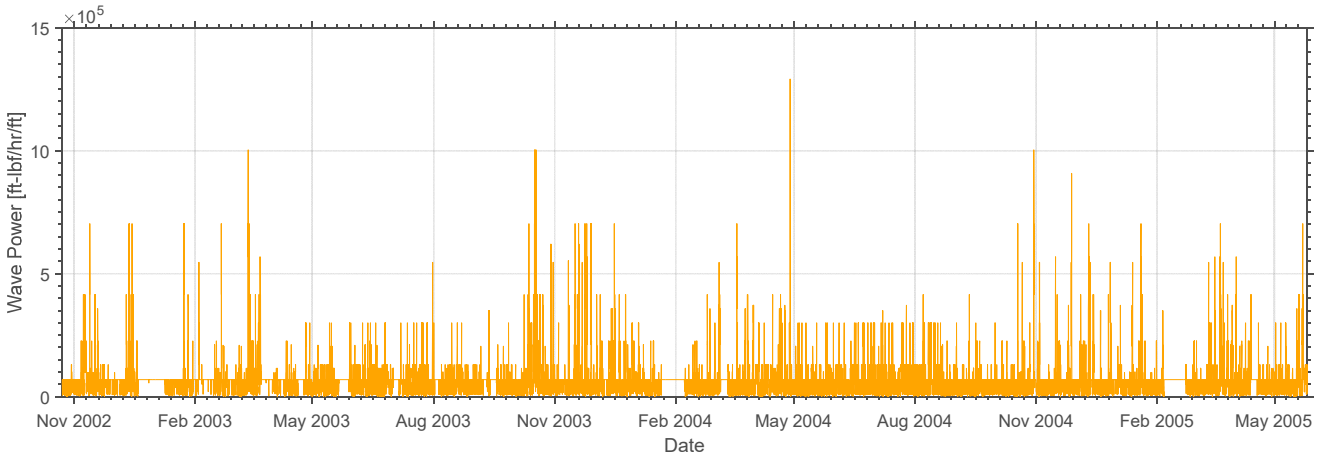

Figure 6. Hourly Wave Power Time Series (October 2002- May 2005)