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Fox Island Laboratory

Shoreline Change Evaluation

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Sequim, Washington

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Prepared for
ManTech Advanced Systems International, Inc.,
for Naval Surface Warfare Center,
Carderock Division,
Detachment Bremerton, Washington

Battelle, Pacific Northwest Division
of Battelle Memorial Institute

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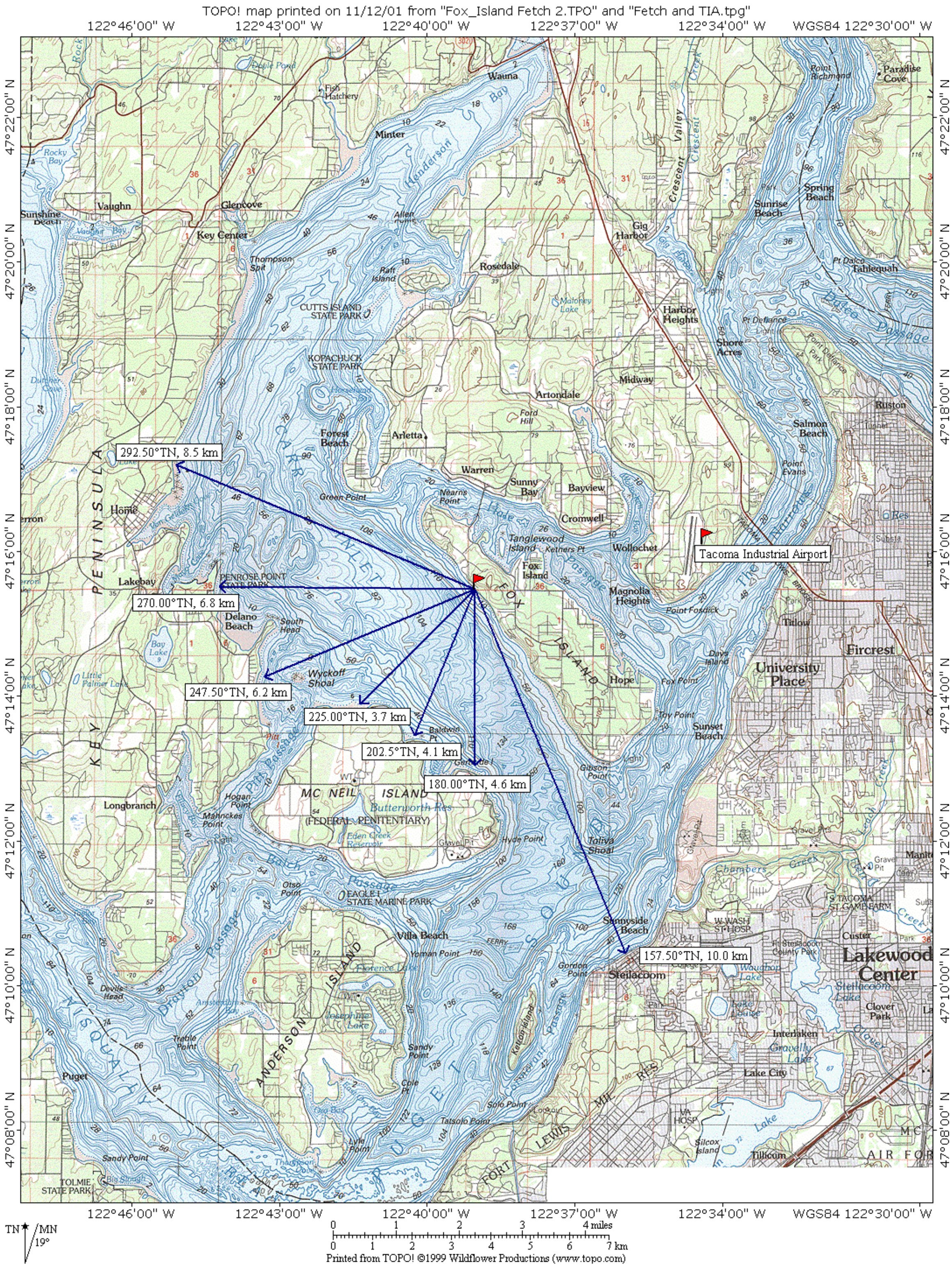

Figure 1. Location of the Fox Island Laboratory on Carr Inlet in South Puget Sound. Arrows indicated the direction and fetch distances for waves arriving at the site. The Tacoma Industrial Airport is located about 3.25 miles ENE of the laboratory.

Figure 2. Fox Island Laboratory and pier facility at low tide. Photo was taken from the M241 barge and shows the laboratory building, log debris on both sides of the pier and riprap bulkhead in front of the building.

Figure 3. North side of FIL pier showing low tide beach with mooring dolphins and riprap structure in front of house. Additional structures can be seen along the beach.

Figure 4. Deteriorating boat ramp and riprap bulkhead along the beach north of the FIL.

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EXECUTIVE SUMMARY

Foreword: The Battelle Marine Science Laboratory has conducted a series of studies at the Navy's Fox Island Laboratory (FIL), the objectives of which were to 1) evaluate the shoreline processes that have lead to the present configuration of the shoreline in the vicinity of the FIL; 2) evaluate the potential effect on the shoreline configuration of selected modification options that are being contemplated by FIL management; 3) survey the woody debris that has collected on the FIL shoreline and evaluate its habitat value; and 4) survey and map the nearshore vegetation and evaluate the potential effects of the modifications on the nature and extent of the eelgrass beds. The site was visited on May 1 and June 21, 2001, for reconnaissance and to take photographs of the FIL and adjacent beaches. A diving survey and more extensive beach reconnaissance was conducted on August 1, 2001. The dynamic beach processes were evaluated using techniques developed by the U.S. Army Engineer, Coastal and Hydraulics Laboratory, and through application of other procedures obtained in current engineering literature. In addition, the REF/DIF numerical model, which is commonly used to evaluate the combined effects of wave refraction and diffraction by structures, was used to demonstrate the sheltering effect of the offshore barge. Findings are summarized below for each element of the scope of work and are further documented in the body of the report and appendix.

Geologic, Geomorphic, and Oceanographic Factors Contributing to the Present Shoreline Configuration: The FIL is situated at the bottom of a hill and is flanked on both sides by steep terrain of glacial origin. The *Coastal Zone Atlas of Washington* (WDOE 1979) classifies the region immediately on either side of the laboratory as "unstable old slide;" whereas, the site of the laboratory itself and the hill immediately shoreward is classified as "stable." The sand and gravel, which comprises the beach sediment, is derived from the erosion of the island bluffs and uplands, as there are no substantial input of beach material from rivers or streams. The beach sediment is transported alongshore by the action of waves and currents. The waves are generated by local winds blowing across Carr Inlet and are relatively small except during the most severe storms, which tend to arrive from the southwesterly direction. The littoral currents are generated by tide, direct wind effect, and by momentum transport due to waves. Evaluation of wind conditions measured at the Tacoma Industrial Airport and at the FIL indicates that they generate waves that move sediment in both directions along the beach. The predominant wave direction, however, moves more sediment toward the north than toward the south. Net transport, using results from wind measurements at the FIL, indicate that the potential net transport was about 1,700 cuyds (1300 cubic meters) during 2000. Air photographs of the FIL taken by the Corps of Engineers between 1970 and 2000 were used to trace the build-up of the prominent gravel salient extending seaward under the pier in front of the laboratory. The salient has developed shoreward of a service barge that has been moored, long axis parallel to shore, at the end of the pier, which extends perpendicular to the shoreline. Though the size of the barge has changed over the years, the present 195-ft by 59-ft (59.4 m by 18 m) barge (designated the M241) is approximately 200 ft (61 m) from the riprap shoreline. The barge effectively serves as a breakwater that shelters the shoreward beach from wave attack. In addition, the bending of the waves around the barge by diffraction reduces the energy of the waves and current and allows sediment to build out from the beach. The pier also serves to reduce wave energy and traps woody debris that is transported along the nearshore by high water and waves. The debris serves to retain sediment by providing further shelter from direct wave attack. The equilibrium distance to which the salient will build from the mean shoreline depends on the length of the breakwater and its distance offshore. The calculation method is given below. Though the barge acts like a breakwater, it is not attached to the bottom, so the salient will not reach the barge and form a tombolo that would totally block longshore transport. Sediment trapped in the sheltered zone behind the barge does not reach adjacent beaches but the sediment is not trapped with 100 percent efficiency. Some of the material that is transported into the sheltered area is by-passed to adjacent beaches. We do not have estimates of the amount of by-passing. Longshore transport is not the only source of sand and gravel for beaches adjacent to the FIL material, however. Make-up feed for the Fox Island beach is derived from the feeder bluffs, which erode and supply the beach with additional sand and gravel. Measures taken by homeowners to stop this source of material, such as construction of bulkheads and revetments, also keep material from the beach.

Likely Effect of Installing a New 360 ft (109.7 m) Long Pontoon and Mooring It 40 ft (12.2 m) Farther Offshore: The proposed new pontoon barge would be 165 ft (50.3 m) longer than and about the same width as the M241. Present plans call for mooring it 40 ft (12.2 m) farther offshore and extending the pier and catwalk to accommodate the additional distance. This configuration would greatly increase the sheltered zone shoreward of the barge and would increase the alongshore dimensions of the salient. Under these conditions, it is possible that a double salient would form. The additional material retained behind the larger barge would be prevented from reaching adjacent beaches until equilibrium is attained. This option has potential to exacerbate the alleged erosion on adjacent beaches by retaining more of the littoral transport of sediments in the lee of the barge. Moving the barge offshore would likely have a beneficial effect on the recovery of eelgrass beds, since the foreshore is very steep. The present beds are not extensive and do not appear in water depth greater than -15 ft (-4.6 m) mean lower low water (MLLW). The typical zone for eelgrass growth in this portion of Puget Sound is from about +3 ft. to –15 ft (MLLW) (+1 m to –5 m). (Williams, et al, 2001). Mooring a barge farther offshore would decrease the shading of shallow water and could allow greater propagation of eelgrass.

Likely Effect of Replacing Existing Dolphins and Retaining Present Barge Configuration: The dolphins are composed of wooden pile clusters used to position the barges. Six such clusters of between 7 and 19 piles are in water depths from about 0 to -22 ft (0 to -6.7 m) MLLW. Details of method, locations, and materials contemplated for the replacement dolphins are not available. Removal and replacement of clusters with concrete piles would have no effect on the development of the shoreline salient. Other effects could be associated with removing the piles, however, such as remobilization of contaminants (e.g., creosote) and local, probably temporary damage to the eelgrass in the removal and replacement processes.

Likely Effect of Detached Fixed Breakwater: The specific effects of a detached fixed breakwater on the coastal evolution of the FIL site depend on the design details, specifically the dimensions of the breakwater, depth of construction, and distance offshore. Implementation of this option would have the following disadvantages:

- It would be extremely more difficult and time consuming to obtain the required permits for construction.
- The bottom-founded structure would likely protect the shoreline in the same manner as the present barge configuration. It would have the additional effect of allowing a tombolo to form. A Tombolo is a causeway-like accretion that connects the shoreline to the structure and which would totally block longshore transport to adjacent beaches.
- The option would be expensive, because the bottom slope is steep and the nearshore water depth is quite deep. The stability of the structure would present engineering difficulties.

Likely Effect of a Fixed Pier with a Dogleg: The installation of a fixed pier with a dogleg would replace the present mooring system and would allow a permanent platform against which to moor the M241 barge. The effect of this option depends on the specific design, but it would not remove the barge from the nearshore, so the breakwater function of the barge would not be decreased. In addition, the pier would likely have the effect of accumulating sediment because of the sheltering effect of the pilings. This would depend on the pile density, size of individual pilings, and the layout of the structure. The structure would also tend to accumulate large woody debris (LWD), because it would act like a filter for large objects floating along the nearshore zone.

Likely Effect of Removal of Beach Debris: A great amount of LWD has accumulated on the upper portion of the FIL beach on both sides of the pier. The debris pile is more extensive at the FIL than at adjacent beaches, because the longshore transport of the floating material is blocked by the pier pilings, and the offshore breakwater is effective in locally reducing the longshore current. The debris provides habitat for a variety of plants and animals and is generally valued as a component of natural shorelines in Puget Sound. A preliminary survey of the LWD indicates that there are no known endangered or listed species that presently inhabit or depend on the debris at the FIL site. The Corps of Engineers generally encourages coastal property owners to allow the LWD to remain on the beach, because it provides a measure of shore protection from wave erosion (Barger, personal communication, 2001). In this location, it may also contribute to the retention of beach material and exacerbate the loss of down-beach drift. Though removal of the LWD would eliminate an additional factor causing sediment retention to the local beach, the sediment would not likely be remobilized to adjacent beaches by natural means since the breakwater and pier still reduce the longshore energy. Thus, local LWD accumulation is a symptom of altered shoreline processes due to the pier and breakwater structures; the relative benefits of its removal would be negligible and short-lived because the pier and breakwater will continue to trap LWD and retain sediments.

Effect of Removal of All Facilities: The final modification option is the removal of all Naval facilities, including the pier, barges, dolphins, laboratory, and bulkhead. Under this option, the existing salient would likely erode and eventually flatten along the adjacent beaches until the shoreline assumed an orientation similar to that prior to the construction of the FIL. Without the protection and sediment retention effects afforded by the facilities, waves and longshore transport would remove the protruding shoreline. Without the structure present, local wave refraction would serve to increase the wave height at the salient, and sediment would be removed until a new equilibrium shoreline is attained. Since most sediment transport takes place during storms the time required to remove the salient would depend on the frequency, intensity, and duration of these events. The gross transport (e.g., transport in both directions along the beach) would tend to remove the material, so it is likely that equilibrium would be reached in a matter of 2 to 5 years.

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1.0 INTRODUCTION

1.1 Site Location

The Navy Fox Island Laboratory (FIL) is located on Fox Island in the southern end of Puget Sound, about 6 miles SSW of Gig Harbor and west of Tacoma. The island is bounded by Hale Passage to the northeast and by Carr Inlet to the southwest. The Naval Acoustic Range was established on Carr Inlet in the vicinity of Fox Island in 1953. In 1968, land was acquired from local residents, and the FIL onshore facility was built on the southwest shore of the island facing Carr Inlet (Figure1). The general orientation of the shoreline at the site is approximately 140° to 320° relative to true north.

1.2 Laboratory Facilities

The Fox Island Laboratory (FIL) is situated at the water's edge at the base of a steep slope. The upland area owned by the laboratory is 150 ft (45.7 m) wide at the water and extends inland 450 ft (137.2 m), with an area of 1.10 acres. The southern portion of the facility includes an area near the former bluff line that has been leveled and filled. The laboratory building is on a level platform of fill that is protected from wave erosion by riprap (Figure 2). The access road leading to the site merges into a pile-supported pier that extends from the high water shoreline across the beach for 184 ft (56.1 m). Pilings supporting the pier are spaced 20 ft (6.1 m) apart along the 15-ft (4.6 m)-wide roadway. At the termination of the pier, a 30-ft (9.1 m) catwalk or brow leads to the moored barge (YFN-912, 110 ft. long x 34 ft. wide), which serves as an on-water machine shop and work area for conducting maintenance on small boats, assembling mechanical in-water systems, and storing mooring and rigging gear. Outboard of the YFN-912 are two 60 ft long x 30 ft side barges breasted along side as camels. Outboard of these two barges is the M241 (200 ft long x 55 ft wide), which provides laboratory and service facilities for experiments conducted by the FIL. Allowing for overlap at each end of the catwalk, the distance from the historical shoreline to the inboard side of the M241 barge is about 283 ft (86.3 m). The width of the M241 is about 55 ft. (16.8 m) so the distance from the historical shoreline to the outboard side of the M241 is about 338 ft. (103 m). The M241 barge is attached to anchors and mooring dolphins. Total distance from the shoreward side of the YFN-912 barge to the shoreward end of the pier, which formed the pre-construction, high water shoreline, is about 214 ft (65.2 m). These descriptions apply to the configuration of the barges in Jun 2001 and to a contemplated arrangement using the pontoon barge. Various other barges and layouts have been used over the years to meet various operational requirements.

Tides at the Fox Island site are semi-diurnal (e.g., two high and two low tides per lunar day) with a diurnal inequality (e.g., the elevations of successive tides are usually not equal). Based on a station at Arletta, across Hale Passage at the north end of the island, the maximum observed tidal range (e.g., difference between the highest and lowest observed tidal elevations) is about 15 ft (4.6 m). Mean high water is 12.4 ft (3.8 m). Unless otherwise indicated, elevations in this report are referred to Mean Lower Low Water (MLLW). In spite of the large tidal range, nearshore tidally generated currents at the laboratory are reported to be small (McReady, Personal Communication).

Early photographs of the site (e.g., 1970) show the shoreline along the FIL was relatively straight. Over the years, the beach has accumulated sediment, and a salient or cusp has developed by the accretion, extending the shoreline under the pier. In addition, woody debris has accumulated on both sides of the pier (Figure 2). The salient has formed a wedge of coarse sediment under the pier and extends toward the barge sufficiently that the corner of the barge grounds at extreme low water.

2.0 PROJECT DESCRIPTION

The Navy presently intends to continue using the FIL and has acquired a pontoon barge to be used as a permanent mooring platform for the M241 and other vessels used by the laboratory. This barge will allow the M241 to be moved into Carr Inlet as needed for experiments while maintaining the mooring system. The proposed 360- by 60-ft (109.7- by 18.3 m) pontoon barge would be moored to new or existing dolphins but positioned about 40 ft (12.2 m) farther offshore. As part of the reconfiguration of the floating laboratory facilities, the Navy has requested an evaluation of the environmental processes that have led to the present shoreline salient development and a review of the potential impacts to the shoreline configuration from the following scenarios:

- Placement of a 360 ft x 60 ft pontoon barge parallel to shore with access from the present pier over a 70 ft catwalk. The M241 barge would be moored outboard of the pontoon barge and the 912 barge and one 60 ft long service barge would be placed on either side of the catwalk, on the shoreward side of the pontoon;
- Replacement of the current mooring system with new dolphins and retention of the present configuration;
- Installation of a detached fixed breakwater seaward of the present barge and replacement of the present mooring system;
- Installation of a fixed pier with a dogleg to replace the present mooring system;

- Removal of the beach debris, with no other change to the physical configuration; and
- Removal of all Naval facilities, including the pier, barges, building, and retaining wall.

The Navy also has requested an evaluation of the habitat value of the woody debris around and under the present pier facility, as well as an evaluation of the offshore vegetation. The vegetation of particular concern is eelgrass, which is considered important habitat for juvenile salmon and prey species upon which they feed. The evaluation will consider the likely impacts of the above scenarios on the biological habitat.

3.0 ENVIRONMENTAL SETTING

3.1 Beach Description

The FIL beach consists of coarse sand and gravel with a slope of approximately 1 to 10. The bathymetry in the region is steeply sloping and reaches depths of 50 ft (15.2 m) within a short distance of shore. A slight indentation in the shoreline provides deeper water closer to shore at the FIL site than along adjacent beaches. The availability of such depth was part of the appeal of the site for the Navy, as deep water is desired for many of the experiments, and infrastructure can be located close by. Beach material consisting of sand and gravel is supplied to the shore by erosion of the bluffs composed of glacial till. In the project area, the till is underlain by the Lawton Clay, a dense, dark gray to green clay deposited in glacial lakes during the advance of the Puget Lobe of the Vashon Stade, between 15,000 and 13,000 years ago. Exposures of the Lawton Clay eroded by waves at present sea level produce oddly shaped clay concretions. Such an outcrop is found several hundred feet north of the FIL on what is locally known as "Clay Baby Beach."

The beach immediately north of the FIL does not have a shore protection structure on it; however, for about a mile (1.6 km) toward the north, there are extensive structures consisting of riprap bulkheads, as well as several concrete boat ramps that are built along the shoreline (Figures 3 and 4). The beach to the south of the laboratory consists of coarse sand and gravel. The shoreline has fewer structures than that to the north. An isolated bulkhead has been constructed on the beachfront about ¼ mile (0.4 km) south of the FIL.

3.2 Wind and Wave Conditions

The site is open to waves generated by winds blowing across Carr Inlet from the SSE to the WNW and is protected from waves from all other directions (Figure 1). The distribution of wave heights was determined by hindcast from wind measurements at nearby airports and was compared with wave heights estimated from winds measured at the FIL. These wave conditions were then used to calculate the direction and net annual sediment transport using several methods of calculation. Details of the methods are provided in Appendix A.

The wind conditions at the Tacoma Industrial Airport (TIA) were obtained for the two complete years (1999 and 2000) for which data were available. The airport is located ENE of the FIL at Point Fosdick on the west side of Tacoma Narrows at an elevation of about 300 ft (91.4 m). The percentage of distribution of speed and direction is given in Table 1. Winds were recorded hourly and are reported in miles per hour (mph).

Table 1. Distribution of Wind Speed (mph) and Direction for Winds Measured at Tacoma Industrial Airport During 1999 and 2000

	Speed Category (MPH)						
DIR	**0-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**All Speeds**
N[(a)]	20.8	6.8	2.4	0.5	0.0	0.0	30.5
NNE	2.5	4.4	0.5	0.0	0.0	0.0	7.4
NE	1.3	1.4	0.0	0.0	0.0	0.0	2.6
ENE	0.7	0.4	0.0	0.0	0.0	0.0	1.1
E	0.4	0.1	0.0	0.0	0.0	0.0	0.6
ESE	0.7	0.2	0.0	0.0	0.0	0.0	0.9
SE	1.1	0.5	0.0	0.0	0.0	0.0	1.7
SSE	1.4	2.1	0.2	0.0	0.0	0.0	3.7
S	2.8	9.1	4.4	2.0	0.7	0.2	19.2
SSW	1.6	6.0	3.5	0.9	0.1	0.0	12.1
SW	1.7	4.2	1.8	0.5	0.1	0.0	8.3
WSW	1.6	2.6	0.4	0.1	0.0	0.0	4.6
W	1.7	2.3	0.1	0.0	0.0	0.0	4.1
WNW	0.7	0.4	0.0	0.0	0.0	0.0	1.1
NW	0.6	0.1	0.0	0.0	0.0	0.0	0.8
NNW	0.8	0.4	0.0	0.0	0.0	0.0	1.2
ALL	40.4	41.1	13.3	3.9	1.0	0.2	100.0

(a) Periods of zero velocity are included with the N direction.

Information is not available on the duration of the measurement period or the elevation of the anemometer. The data represent 88% of the expected recordings during the 2-year period. Winds from the north are over-represented, because periods of calm appear to have been included in that class. When all speeds are considered, the strongest and most frequent winds occur from the south (e.g., 19.2%, 10.2 mph average speed), with winds from the SSW occurring second most frequently.

Winds were also recorded at the FIL using an anemometer on the M241 barge. The sensor was approximately 32.8 ft (10 m) above the water surface and recorded winds every 10 minutes. The period of measurement (2000) represents 88.6% data return. Percentage of distribution by speed and direction is given in Table 2. By direction, the most frequent and strongest winds are from the SSW (11.0%), followed by winds from the south. The third most frequent are from the ENE. Because ENE is the offshore direction at the site, thermal effects of the local land-sea temperature difference could be driving these winds. Because they blow in the offshore direction and are in the lowest speed category, they would have no effect on the local wave conditions. By speed, the winds correspond closely to those of Tacoma. Conditions at both sites are relatively mild, with wind speeds less than 10 mph more than 80% of the time.

Table 2. Distribution of Wind Speed (mph) and Direction for Winds Measured at Fox Island Laboratory During 2000

	Speed Category (MPH)								
DIR	**0**	**1-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**Z**	**All Speeds**
N	0.73	0.42	0.10	0.00	0.00	0.00	0.00	0.00	1.24
NNE	0.66	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.89
NE	2.91	3.16	0.03	0.00	0.00	0.00	0.00	0.00	6.10
ENE	6.02	9.50	0.06	0.00	0.00	0.00	0.00	0.00	15.59
E	2.50	2.35	0.04	0.00	0.00	0.00	0.00	0.00	4.88
ESE	0.94	0.58	0.04	0.00	0.00	0.00	0.00	0.00	1.57
SE	1.39	1.03	0.20	0.01	0.00	0.00	0.00	0.00	2.63
SSE	2.38	2.73	1.47	0.10	0.01	0.00	0.00	0.00	6.70
S	2.10	3.42	4.11	1.87	0.35	0.07	0.03	0.00	11.96
SSW	1.28	3.09	5.60	3.13	0.43	0.10	0.03	0.00	13.67
SW	0.63	1.47	1.55	0.60	0.05	0.01	0.00	0.00	4.30
WSW	0.57	1.12	0.85	0.32	0.07	0.02	0.00	0.00	2.95
W	5.22	2.37	2.49	0.88	0.21	0.06	0.01	0.00	11.23
WNW	1.02	2.09	1.86	0.37	0.12	0.02	0.00	0.00	5.48
NW	1.28	2.58	2.34	0.24	0.02	0.00	0.00	0.00	6.46
NNW	1.13	1.67	1.40	0.15	0.01	0.00	0.00	0.00	4.36
% total obs.	30.75	37.80	22.15	7.67	1.26	0.29	0.08	0.00	100.00
Z[(a)]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.41	11.41

(a) Z indicates periods of no data.

Waves were calculated for each fetch direction from SSE to WNW, using the method of the *Shore Protection Manual* (SPM) (USACE 1984). Several methods of wave hindcast calculation were evaluated before this method was chosen, including both graphical and formulaic procedure in the more recent update of the SPM, the *Coastal Engineering Manual* (Resio 1996). It was found that the graphical methods of the latter provided unrealistically small waves and short periods. The formulaic method has incomplete instructions on the determination of the friction velocity, U_*. In addition, the method recommended for calculating wave period is clearly in error. Dr. Ed Thompson of the Coastal Hydraulics Laboratory, one of the authors of the chapter, confirmed this observation and indicated that the formula would be corrected in a later version of the document.

The method selected for the calculation of wave conditions was that of the SPM (1984) in which the formulas for fetch limited conditions were used for significant height and peak period. Details of the calculation and results are given in Appendix A. The method consists of:

- Obtain the wind conditions for the direction of interest;
- Correct the winds as necessary for height of measurement, over-water or over-land conditions, averaging interval, if known, and stability of the boundary layer;
- Use the adjusted wind and fetch to calculate significant wave height and peak period.

3.3 Longshore Sediment Transport

The calculation of sediment transport based on winds measured at TIA and the FIL was made using methods from the SPM (USACE 1984), combined with techniques from a recent US Army Corps of Engineers Engineering Manual (USACE 1992b) and was confirmed by calculations using the Automated Coastal Engineering System (ACES 1.07e) (Leenknecht et al. 1992). The ACES is an interactive computer-based design and analysis system for a variety of coastal engineering applications. It was publicly available at no charge until recent years and is still available through a vendor. The system has been widely used by the Corps of Engineers and others in the design and evaluation of coastal processes. Since it is based on the procedures in the SPM, it is expected that it would give comparable results to the formulaic technique. Details of the calculation procedure and results of intermediate steps are given in Appendix A. The results are summarized in the Table 3 below.

Table 3. Summary of Potential Longshore Transport Rate Based on Winds Measured at the Tacoma Industrial Airport and at Fox Island Laboratory.

	Tacoma Industrial Airport		**Fox Island Laboratory**	
	ACES 1.07e	**SPM**	**ACES 1.07e**	**SPM**
Gross Transport toward North, m/yr	13,747	13,100	5,688	5,428
Gross Transport toward South, m/yr	-2,198	-1,658	-4,199	-3,929
Net Transport, m/yr[(a)]	11,549	11,442	1,301	1,499

(a) Net annual transport is predicted to be toward the north, to the right when facing seaward at the FIL beach.

The difference in potential longshore transport volume calculations based on the TIA and FIL winds are a result of the higher percentage of measured winds blowing toward the north at TIA. These are summarized in Table 4. The largest percentage difference is apparent in winds from the southerly direction, which is recorded 16.4% of the time at TIA and only 6.4% of the time at the FIL. It is also apparent from the TIA data that measured winds causing northerly transport occur much more frequently (ratio 3.6:1) than those recorded at FIL (ratio 1.5:1). Because the predicted sediment transport is related to the square of the wave height, the ratio of northerly to southerly transport volume, calculated from the TIA winds, is much higher (ratio 6.3:1).

Wave transport directions and velocities are also estimated in the *Coastal Zone Atlas of Washington* (WDOE 1979), though no details of the calculation method are provided other than Corps of Engineer procedures. Winds were those from McChord Air Force Base about 15 miles to the SW of the FIL. Net transport was estimated to be toward the south at 2500 cu yd (1911.5 cubic meters)/6 mo during the half-year from May through October, and 5000 cu yd (3823 cubic meters)/6 mo toward the north during the half-year from November through April.

Table 4. Comparison of Percentage of Wind Directions, Recorded at Tacoma Industrial Airport (TIA) and Fox Island Laboratory (FIL), Producing Northerly and Southerly Transport at the FIL.

Wind Direction	Percentage of Observations	
	Tacoma Industrial Airport	Fox Island Laboratory
SSE	2.1	1.6
S	16.4	6.4
SSW	10.5	9.3
SW	6.6	2.2
Total % from South, Northerly Transport	35.6	19.5
WSW	4.7	2.4
W	4.1	6.0
WNW	1.1	4.5
Total % from North, Southerly Transport	9.9	12.9

3.4 Which Transport Prediction Is Correct?

The answer to this question is an unsatisfying, “all” and “none.” The transport predictions are based on measured winds and the hindcast of waves resulting from those winds. The two methods of predicting the transport applied for this report provided consistent results for each wind data set. The transport estimates in the Environmental Atlas are close to those that result from using the FIL winds. Winds measured near the site of interest (e.g., FIL winds) are preferred for the prediction, because fewer assumptions are required to correct the winds for overwater conditions, thus reducing a potential source of error. The FIL winds, however, represent only a single year of observation (i.e., 2000), which could not be compared directly with the TIA winds, which provided 2 years of observation (1999 and 2000). Neither data set is long enough to establish ‘average’ conditions. The sediment transport relationships used for the calculation are based on experiments conducted at field sites and in laboratories and relate to sand-sized material, e.g., grain diameter less than 2 mm, and there are few studies that provide guidance for coarse material. The grain size on the FIL beach was not measured using a sieve but was observed to vary widely from sandy-silt near MLLW to gravel (D> 2 mm to 64 mm) and pebbles in the upper part of the beach and the salient. The transport rate of coarse-grained gravel observed along the FIL and adjacent shorelines would not be well predicted by these relationships.

The result of the wind and wave analysis, based on the existing data, is that net transport is toward the north along the FIL beach. The wave climate would be considered to be mild since waves are locally generated and are fetch limited. Wind velocities measured at both the FIL and TIA are less than 10 mph between about80% and 90% of the time (81.5 % based on TIA and 90.7 % based on FIL).

The conclusion regarding northerly transport is disputed by one source (Schwartz et al. 1991), which concluded transport was toward the south along this section of coastline. Evidence cited in this document is based on observations of the accumulation of sediment and debris on the sides of bulkhead offsets and boat ramps, which indicates southerly net drift along the FIL beach. The results of calculations using the annual wind measurements clearly indicate net northerly transport. Results from the *Coastal Zone Atlas of Washington* (WDOE 1979), however, show southerly transport during the spring and summer and northerly transport in the fall and winter. The accumulation noted by Schwartz et al. (1991) might have been influenced by the timing of the observation.

4.0 EVOLUTION OF THE FIL BEACH

4.1 Introduction

The Fox Island shoreline was relatively straight prior to the establishment of the FIL. The Army Corps of Engineers has taken air photographs of the island shoreline annually. A series of these photos, taken every other year from 1970, the year after the pier was constructed, through 2000 is shown in Figure 5(a-d). These photos show that between the 1970 and the 1986 photos, the beach shape changed very little in spite of the presence of a barge moored at the end of the pier. In the 1988 photo, a longer barge replaced the relatively small one and, subsequent photos show the formation of a prominent salient or cusp extending seaward under the pier. The exact timing of the shoreline change cannot be established, as photos for this study were obtained only every other year.

Because the photos were taken at various stages of the tide and with no vertical control, it is not possible to make detailed measurements of beach width to estimate transport volumes from the photos. It is apparent, however, that the salient is nearly symmetrical under the pier and that the barge position since 1988 is off-center slightly toward the south. Several mooring arrangements, which include the main barge and other smaller vessels or barges, were also used during the period from 1970 to 2000. These arrangements included smaller barges moored to the main barge (M241), as well as along the pier. The 1990 and 1992 photos show what appears to be a longer barge at the end of the pier that is not present in the other photos. The salient is also particularly prominent in these two photos, because they were apparently taken at low tide.

4.2 Processes Leading to the Salient

The salient or cusp that has formed at the FIL pier is a result of the protection from wave energy afforded by the barge and, to a certain extent, by the pilings of the pier. The LWD observed on both sides of the pier may also help retain sediment, because the debris further reduces wave energy. The barge acts as an effective floating breakwater that protects the shoreline in the lee of the structure by reducing wave energy by reflection directly from the structure and by diffraction or bending of wave energy in the geometric shadow of the barrier. The reduction in wave energy in the breakwater's shadow reduces entrainment and transport of sediment by wave action in this region. Sand transported from the nearby region by a predominant longshore current or circulation will tend to be deposited in the lee of the structure where the energy is too low to move the particles in either suspension or as bed load. A cuspate spit may develop and, in the case of bottom-founded structures, may eventually connect to the breakwater. Such a connected feature is called a 'tombolo' and totally blocks the littoral transport.

The placement of the breakwater causes the shoreline to adjust to the new conditions and seek an equilibrium configuration. If the waves arriving at the seaward side of the breakwater are essentially parallel to the original shoreline, energy passing around the ends of the breakwater will transport sand from the edges into the shadow zone. The process will continue until the shoreline is essentially parallel to the diffracted wave crests and net longshore transport is again zero. In this case, the cuspate shoreline will have a symmetrical shape since equal amounts of energy enter from each end of the breakwater. If waves are not normal to the structure, the cuspate spit that results from the oblique wave attack can be expected to be asymmetric, with its shape dependent on the structure length, distance from shore, nearshore bathymetry, and wave conditions. The longshore current generated by the oblique wave attack can be expected to slow or stop behind the breakwater. The breakwater's length and distance from shore are critical in determining its effect on longshore currents and sediment transport (USACE 1992a).

There is limited engineering experience with prototype-detached breakwaters in the United States. A survey of the engineering literature (USACE 1992a) indicates that a tombolo (i.e., a causeway-like accretion spit that connects the shoreline to a bottom-founded breakwater) would likely form if the length of the breakwater is twice as long as the distance from the average shoreline: $l/y_B \geq 2$, where l is the breakwater length and y_B is the distance of the breakwater offshore from the average shoreline. In the case of the FIL barge, a tombolo would not be formed because the barge is not founded on the bottom. A salient would be expected to form when $l/y_B \leq 1$ to about 0.4. There would be no effect to the shoreline if $l/y_B \leq 0.17$ to about 0.5. The zones overlap somewhat because of the differing conditions reported in the literature (see e.g., USACE 1992a, Table 4-2).

Based on relatively small-scale experiments, Dean and Dalrymple (2001) indicate that if the breakwater is located a distance offshore greater than 6 times its length, it will have no effect on the shoreline. They also provide a relationship for estimating the offshore amplitude of the salient based on breakwater length and its distance offshore.

$$\frac{y_s}{y_B} = 1 - 0.678\left(\frac{y_B}{l}\right)^{0.215}$$ Equation 1. (Dean and Dalrymple 2001, Eq.12.9)

where y_s is the distance the salient extends offshore from the average shoreline.

The potential salient distance has been calculated using equation 1 for the present barge configuration and for the configuration of the pontoon barge. The growth of the salient was assumed to project from the historical mean tide water line, which was located relative to the historical high water line at the shoreward end of the pier by assuming a 1V to10H slope and a maximum tide level of 15 ft. Using the mean tidal range of 12 ft, the reference shoreline was 60 ft shoreward of this historical mean tide water line. Accounting for the remaining pier, the catwalk and the barge widths, distance from this hypothetical mean tide line to the seaward edge of the M241 is 248 ft and the resulting salient is predicted to extend seaward 72 ft (rounding up). The seaward side of the pontoon barge was used to calculate the salient for the proposed configuration. This was selected rather than the seaward side of the M241 (moored outboard of the pontoon) because the pontoon provides the primary blocking of the waves. With the extended catwalk, distance to the seaward side of the pontoon is 224 ft and the predicted salient distance is 87 ft.

The following points should be made concerning this calculation:

- Equation 1 is based on limited field observations and small-scale laboratory experiments. It should not be considered as design information but rather as an indication of relative conditions.
- Equation 1 provides an estimate of the seaward extent of the salient but not the longshore extent. Though the configuration using the pontoon barge predicts only an increase of 15 ft in the salient, considerably more sand may be trapped in the protected area because of the additional barge length. Under some conditions, multiple salients have been observed but these are not predicted by equation 1.

5.0 APPLICATION OF REFRACTION-DIFFRACTION NUMERICAL MODEL

The combined refraction and diffraction numerical model, REFDIF (version 2.5) was applied to an idealized configuration of the FIL barge and shoreline to demonstrate the extent of the shadow zone behind the barge (Kirby and Dalrymple 1994). The model was run for four simulations: two geometries, the existing barge, and a larger pontoon barge placed 40 ft (12.2 m) farther offshore; and two wave conditions, waves normal to the barge and waves arriving 20 degrees to the south of normal.
The computational grid was developed in 1.64 ft (0.5-m) increments in each along-shore and cross-shore direction. The computation domain was 1,640.4 x 1,640.4 ft (500 x 500 m) with 1001 x 1001 cells. Simulations were made on a UNIX workstation and the graphics were developed on a windows-based PC using Generic Mapping Tools (GMT) software. The model was set up and tested on a standard data file to ensure correct configuration and proper operation. Distance measurements for the configurations tested were entered to the nearest half-meter.

The bathymetry of the FIL shoreline was idealized to a constant slope along shore and a flat bottom farther offshore. Shoreward, the bottom uniformly rises to the east at a rate of 0.909 ft/ft (0.277 m/m) (estimated from drawings supplied by the FIL staff) until it is above the high-water line. The high water line (shoreward boundary of the model) was assumed to be the shoreward end of the FIL pier. The bathymetry was taken as uniform in the along-shore direction.

The first case to be run was the present geometry, e.g., 184 ft pier, 30 ft catwalk on to the 912 barge, with the M241 barge separated from the 912 by 30 ft wide service barges. An additional 5 ft was used as fender space between the barges. Though the pier is also shown in figures 6 through 9, the effects of the pier itself were not included in the simulation. The bathymetry under the footprint of the barge was set to zero, effectively treating the barge as an island. This is justified since the barge is wide relative to the incident wavelengths and totally blocks the incident waves. The footprint of the M241 was set to 200 ft (61 m) long and 55 ft (16.8 m) wide. The seaward edge of the M241 was set at 338 ft (103 m) from the high water shoreline. The wave conditions were a 1-m-high wave of a 3-sec period. Unit height was selected to conveniently scale the waves in the lee of the barge. The selected wave period used for the simulation was in the upper (longer wave length) end of those calculated to occur at the site (see Appendix A). One run was made with waves arriving normal to the barge (e.g., crests parallel to the long axis of the barge) and another run with waves arriving from a direction 20 degrees south of normal to simulate the predominant wind and wave direction. The results are displayed in Figures 6 and 7, and each shows a large shadow zone shoreward of the barge. The 20-degree case shows the centroid of the shadow zone displaced from the center of the barge in the down-wave direction. Assuming the salient would form about the centroid, this result corresponds to the displacement seen in the air photographs.

The second geometry run was modified by the addition of a 360- by 60-ft (109.7- by 18.3-m) pontoon barge placed with its shoreward side approximately 40 ft (12.2 m) farther offshore than the previous condition (e.g., catwalk extended to 7 ft span from the end of the existing pier), and with the M241 barge moored seaward of the pontoon. The 912 and a 60 ft service barge are placed inboard (shoreward) of the pontoon on either side of the catwalk. The bathymetry under the footprint of the barge and pontoon was again set to zero, effectively treating the barge and pontoon as a single island. Wave condition and directions were the same as the previous case. The results (Figures 8 and 9) show that the shadow zone in the lee of the combined mooring is larger than that of the M241 alone, implying that a larger potential salient would be formed.

6.0 EVALUATION OF UPPER BEACH LARGE WOOD DEBRIS

6.1 Large Woody Debris Survey Methods

A visual survey of the plant and animal species associated with a significant accumulation of driftwood on the upper beach area was conducted on August 1, 2001, to evaluate the present habitat value of the debris and estimate how these habitats might change under the proposed options. A list of living plant species was compiled during this survey and area coverage was estimated using aerial photos. Additional literature surveys were used to derive an estimate of LWD habitat value and functions.

6.2 Plant Species Associated with Upper Beach Woody Debris

The qualitative survey revealed at least 11 driftwood-associated plant species in upper beach habitats (Table 5); whereas, no birds or mammals were observed in this habitat at the time of the midday survey. Most of these plant species are herbaceous, although several shrubs and trees have also recruited to the area (Figure 10). In general, many of the observed plant species are typical of frequently disturbed coastal habitats, beaches, or emergent saline wetlands. These species provide a number of functional attributes to coastal habitats. For example, along sloping shorelines and dunes, plant root systems assist in soil reinforcement, anchoring, weight surcharge, and particle binding. Both red alder and beach pea have root-associated nitrogen fixing bacteria that enrich soils. Many species, including madrone, red

Table 5. Plant Species Associated with Woody Debris and Drift Logs in Upper Beach and Backshore Habitats

Form	Exotic	Common Name	Scientific Name
Tree		Douglas Fir	*Pseudotsuga menziesii*
		Madrone	*Arbutus menziesii*
		Red Alder	*Alnus rubra*
Shrub		Red elderberry	*Sambucus racemosa ssp. pubens*
	*	Himalayan Blackberry	*Rubus procerus*
Herb	*	Curly dock	*Rumex crispus*
		Saltbush	*Atriplex patula*
		Gumweed	*Grindelia integrifolia*
		Plantain	*Plantago maritime juncoides*
	*	Canada Thistle	*Cirsium arvense*
	*	Beach pea	*Lathyrus japonicus*

elderberry, blackberry, plantain, and saltbush, have fruit or vegetation that is commonly consumed by birds (including waterfowl) and mammals. Small shrubs and trees provide thickets that function as refuge and buffer habitat for a variety of small birds and mammals; larger trees provide perch, nesting, and roosting habitat for raptors, herons, and other birds of prey.

6.3 Habitat Value of Woody Debris

Woody debris and driftwood accumulate in upper beach and backshore habitats through transport at extreme high tides and during winter storms (Maser and Sedell 1994). Woody debris may buffer the shore from increased storm wave erosion, and in sheltered beaches may help to trap and stabilize beach sediment, encouraging the growth of plants that aid in beach stabilization and accretion.

Using aerial photos, the area of driftwood accumulation in front of and directly adjacent to the FIL has been estimated at a total of 7800^2 ft (724.6^2 m). The area of accumulation north of the pier encompasses an area of approximately 6000^2 ft (557.4^2 m) and supports a well-developed plant community. South of the pier and directly in front of the laboratory building, approximately 1800^2 ft (167.2^2 m) of upper beach habitat is densely covered in driftwood of a variety of sizes (Figures 10 through 13).

Large woody debris provides a number of potential benefits to shorelines in Puget Sound, and as a result, is becoming increasingly valued as a component that maintains natural shoreline processes and functions. As noted in a recent state of the knowledge white paper on shoreline modifications (Williams and Thom 2001):

> Large woody debris (LWD) (stumps, drift logs, tree root masses) is a natural component of Pacific Northwest shorelines and beaches and can function to trap sediment and absorb wave energy (Zelo and Shipman 2000, Macdonald et al. 1994). Drift logs form semi-permanent stockpiles which trap beach sediment and promote the establishment of vegetation on beaches with large berms (Downing 1983). Natural protection of shore bluffs may be provided by drift logs in this manner along many undeveloped beaches in Puget Sound. Some beach protection and shoreline restoration efforts utilize LWD to harness these functions and provide a natural alternative to conventional manmade structures. Installation of LWD involves anchoring the material with steel cables to imbedded earth anchors (typically precast concrete blocks or screw anchors). Under extreme conditions, however, anchored wood may become unstable and cause damage to property. … No systematic study has examined the use of wood in restoration or erosion

control projects on marine shorelines, or the expected benefits these natural shoreline components accrue as habitat to nearshore species (Zelo and Shipman 2000).

Unfortunately, LWD in upper beach and backshore areas has not been well studied for its ecological functions (Williams et al. 2001). It is thought to provide a variety of microhabitats for invertebrates and birds, and also supports a unique assemblage of vegetation tolerant of wind, salt spray, and shifting substrate. Large driftwood offers shelter and shade, allowing colonizing plants to begin growing in the moist sand along its protecting edge (Maser and Sedell 1994). Biological decay of wood material is also a source of organic detritus, the principal energy source for estuarine and shallow-water marine food webs. Large driftwood may be used as a protected perch by water birds, and may also be used by small mammals (e.g., spotted skunks) as preferred sites under which to construct dens (Maser and Sedell 1994).

Washington State once permitted cutting and removal of beached drift logs by licensed operators (Terich and Milne 1977). Currently, no formal state management policy appears to be in place regarding preservation of LWD along shorelines, although it is generally considered a valued habitat resource. Some local jurisdictions might have adopted some language in their master programs to limit removal and burning while encouraging use of LWD as ‘soft’ erosion protection. The inherent value of LWD is high, and activities to actively remove or alter this habitat would likely be perceived as detrimental to natural shoreline processes and functions.

7.0 SURVEY OF AQUATIC VEGETATION

7.1 Overview

SCUBA-equipped divers conducted a survey of the aquatic vegetation in the vicinity of the FIL pier and barge on August 1, 2001, to assess the extent of eelgrass (*Zostera marina*) and other vegetation. The qualitative monitoring was designed to verify presence or absence of eelgrass within the vicinity of the proposed project area and the pier and to provide a baseline that could be used to assess changes that could occur due to later modifications to the facility. The dive team followed the preliminary eelgrass habitat survey guidelines established by the Washington Department of Fish and Wildlife (WDFW, 1996). Along-shore transects were surveyed every 32.8 ft (10 m) perpendicular to the shoreline and extending 328 ft (100 m) on each side of the FIL pier (Figure 14). Divers recorded the time and depth for changes in the substrate, presence of eelgrass and its density, macroalgae, and estimated the density of geoduck clams (*Panopea abrupta*). Divers swam each transect out to a depth of approximately -20 ft (-6.1 m) MLLW or to the deeper edge of eelgrass habitat, whichever came second.

7.2 Map Results

The eelgrass survey was completed during the course of a single day, and a baseline map of eelgrass distribution at the Fox Island Laboratory was prepared (Figure 14). The extent of eelgrass was classified as 'sparse,' (a small patch of fewer than 10 shoots), 'moderate' (a medium-sized patch of more than 10 shoots), or 'dense' (a large patch or bed). The survey revealed that eelgrass was present throughout the study area, ranging from sparse patches near the pier and progressing to dense patches and contiguous eelgrass beds near the outer edges of the survey area.

The bathymetry in the area was atypical in that at about -10 ft (-3.05 m) MLLW, the bottom started to rapidly descend, resulting in the lower depth limit of eelgrass on or very near this steep drop off throughout most of the study area. Eelgrass was sparse at the deeper limit and was not found at depths greater than about -15 ft (-4.6 m) MLLW.

The substrate of the nearshore was fairly typical of Puget Sound in that the higher intertidal zone was mostly gravel and cobble progressing to an increasingly greater proportion of fine sand and silt material at lower elevations (Figures 15 and 16). The divers recorded several species of fishes and macroinvertebrates during the survey (Table 6), which were typical of soft-bottom habitats in Puget Sound (Dethier 1990).

Table 6. Fish and Macroinvertebrates Observed During SCUBA Surveys

Common Name	Scientific Name
Fishes	
Shiner surfperch	*Cymatogaster aggregata*
Striped surfperch	*Embiotoca lateralis*
Staghorn sculpin	*Leptocottus armatus*
Penpoint gunnel	*Pholis laeta*
Unidentified flatfish	*Bothidae or Pleuronectidae*
Macroinvertebrates	
Graceful crab	*Cancer gracilis*
Red rock crab	*Cancer productus*
Hermit crab	*Pagurus spp. or Elassochirus sp.*
Sunflower sea star	*Pycnopodia spp.*
Geoduck	*Panopea abrupta*
Moon Snail	*Polinices lewisii*
Rough Piddock	*Ziphaea pilsbryi*
Cockle	*Clinocardium* spp.

This survey verified that eelgrass is present in the immediate vicinity of the Fox Island Laboratory. Before pier construction and the ensuing salient formation, historic eelgrass distribution was most likely a continuous band of patchy-to-dense beds throughout the nearshore landscape. Shoreward of the existing pier, eelgrass loss was likely exacerbated as a result of boating activity, barge shading, and vessel grounding during low tides. Though eelgrass was not extensive, this is not unusual for the South Puget Sound Region. A recent survey of the region by the Washington Department of Natural Resources indicates that green algae is the most prominent intertidal vegetation and that eelgrass is present over about 2% to 5% of the shoreline length (Bailey et al. 1998).

Relative to the proposed actions, an extension of the pier and prohibition of barge or boat grounding in habitats immediately shoreward of the barge facilities would reduce disturbance to the shallow, nearshore marine habitats, and would allow natural propagation and reestablishment of eelgrass beds. This action would most likely reestablish connectivity of eelgrass beds while minimizing the influence (e.g., shading and physical disturbances) of over water structures in the project area.

8.0 CONCLUSIONS

We have conducted an evaluation of the environmental factors that have led to the present configuration of the shoreline at the Navy's Fox Island Laboratory (FIL) and have predicted the effect on the shoreline of changes to the arrangement of nearshore facilities that are being considered. The evaluation included:

- Reviewing historical photographs of the site from 1970 through 2000;
- Evaluating the development of the observed salient based on engineering considerations and numerical model simulation using the REF/DIF combined refraction and diffraction model;
- Analyzing wind records from measurements taken at the Tacoma Industrial Airport (TIA) and the FIL;
- Estimating wave height, period, and direction based on measured winds at the TIA and FIL and on the fetch distance to the site;
- Calculating the potential net sediment transport direction and rate along the FIL shoreline;
- Surveying the extent of nearshore aquatic vegetation and evaluating possible effects on vegetation for potential alterations in the laboratory facilities; and
- Evaluating the extent and effects of the large woody debris (LWD) that has accumulated adjacent to the FIL pier.

Wave conditions hindcast from wind records from both the TIA and the FIL indicate net littoral transport of beach material is toward the north. The potential rate of transport is about 1,500 m^3/yr (1,962 cy/yr) based on one complete year (2000) of measured winds at the FIL. Though two years (1999 and 2000) of measured winds are available from the TIA, they are not representative of the over-water winds that generate wave at the FIL. Differences in elevation (the TIA is at about 300 ft elevation), exposure to different directions, over-land versus over-water velocity, and stability of the boundary layer are all cited as factors that modify local winds (SPM, 1984). Winds measured at the FIL required fewer corrections for use in wave hindcast so were preferred over measurements made at the TIA in spite of the shorter measurement period.

The protected area behind the several barges moored at the end of the FIL pier trapped sand and gravel from longshore transport and developed the salient, which extends seaward from the FIL shoreline. The barges act similar to a floating breakwater. Such effects are noted in the coastal engineering literature and the area of wave protection or shadow zone shoreward of the barge is clearly shown by the numerical model results. Though all of the barge configurations and sizes were not modeled, the essential elements were sufficiently represented to show the breakwater effect. Placement of a longer barge, 40 ft farther offshore will increase the length of the protected shoreline and will trap more material in littoral transport. The redistribution of the salient along the shoreline by mechanical means would return the sediments to the littoral drift but this step would need to be undertaken periodically since the salient would re-accumulate if the present barge remains in place or if the pontoon barge is used as proposed.

Though all of the material in longshore transport is not retained in the salient, material that is trapped does not move to adjacent beaches. The development of the salient may, therefore, have exacerbated erosion by retaining sand and gravel that would otherwise have been transported to the adjacent beaches. Other sources of natural nourishment to those beaches have been cut off, as well, by the placement of structures, such as bulkheads and revetments. These structures limit erosion of the feeder bluffs, which naturally supply sand and gravel to the beach.

The LWD provides habitat for shore plants and animals and also traps and retains sediments. Removal of the debris may allow additional sediments to move longshore, though no estimates are available of the additional volume of transport. However, this solution only addresses the symptoms of the problem and would need to be revisited periodically. Local shoreline processes would continue to accumulate drift logs (LWD) and trap sediment within the sheltered area of the barge and against the legs of the pier.

Based on this study, we make the following recommendation:

- Continue monitoring winds at the FIL in order to obtain a long term record from which to hindcast the wave climate;

- Determine the volume of sediment in the existing salient by taking beach profile measurements; and

- Conduct regular periodic beach profile measurements at the FIL and adjacent beaches to monitor the changes after reconfiguration of the facilities.

- Conduct quantitative eelgrass surveys and georeferenced habitat mapping to determine baseline density and patch configuration. This information will be used to estimate changes (expected expansion) of eelgrass populations post-construction.
- Complete a comprehensive design analysis before extensive modifications to the in-water facilities of the FIL are undertaken.

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APPENDIX A

CALCULATION METHODS FOR LONGSHORE SEDIMENT TRANSPORT

CALCULATION USING THE SPM AND EM 1110-2-1502

The longshore sediment transport rate at the Fox Island Laboratory was calculated using several methods. The following documents the details of the methods used and the assumptions in selecting the parameters.

U.S. Army Engineer, *Coastal Littoral Transport*, Engineer Manual No. 1110-2-1502, 20 August 1992. Chapter 6, Sediment Transport Processes.

The potential sediment transport rate for each wind direction was calculated using the wind data from both the Tacoma Industrial Airport (1999 and 2000) and from wind data collected at the Fox Island Laboratory (2000). The results of the wave and transport calculations, based on these wind distribution are summarized in Tables 3 and 4. The results of each column are:

Wind Speed and Direction – Wind speed in miles per hour were recorded at both of the sites (TIA and FIL). Data were sorted into bins of 5 mph increments. Directions were tabulated into 16 cardinal compass directions. Directions follow the meteorological convention of indicating the direction from which the wind is blowing. The TIA wind tabulation apparently lumped all of the zero wind velocities into the N direction, thus over representing that direction. It was assumed that the winds in the other bins had a velocity greater than zero. Wind speed was converted to meters per second (m/s) assuming that all of the winds occurred at the top of the range. This provides conservative results and should over estimate the potential transport rate.

Wind directions used in the calculation included only those that produced a component of drift up (northward) or down (southward) the island. Thus, wind from SSE, S, SSW and SW were considered to produce positive transport, i.e., by convention positive is to the right when looking off shore and negative is to the left. Winds from WSW, W, and WNW were considered to produce negative transport. The wind direction relative to the average shoreline orientation (140-320 degrees true) was used as the wave direction and provided the deep-water wave angle.

Fetch Distance – The fetch distance for each direction was measured from the FIL to the upwind shoreline using the direction feature in the TOPO! *Interactive Maps for the Puget Sound Region.*

Fetch Limited Wave Height in Deep Water – The spectral wave height was calculated from:

$$\frac{gH_{mo}}{U_A^2} = 1.6x10^{-3}\left(\frac{gF}{U_A^2}\right)^{1/2}$$ Equation 1 (Eq. 3-33, SPM, 1984)

where:

H_{mo} = the zeroth moment wave height, corresponding to the significant wave height, m

g = the acceleration of gravity, taken as 9.8 m/s^2,

U_A = the adjusted windspeed (see below), m/s, and

F = the fetch distance, m.

Wind Adjustment – A wind adjustment was applied to the TIA wind measurements using the procedures in the SPM. Measured winds were converted to adjusted wind using:

$$U_A = 0.71U_{10}^{1.23} \text{ m/s}$$ Equation 2 (Eq. 3-28a, SPM, 1984)

Since the wind velocities (U) were made over land, they were multiplied by 1.2 to adjust for the difference in boundary layer conditions between land and water. The measurement height was assumed to be 10 meters, no adjustment was made for boundary layer stability, and no adjustment was made for wind speed duration. Equation 3-28a then becomes;

$$U_A = 0.71(Ux1.2)^{1.23} \text{ m/s}$$ Equation 3

Substituting Equation 3 into Equation 1 gives, for fetch-limited wave height;

$$H_{mo} = 4.54x10^{-4}U^{1.23}F^{1/2} \text{ m}$$ Equation 4

in which units are meters and the wind speed is measured at the land site (e.g., TIA).

Wave Period – Wave peak spectral period (T_M) calculated using;

$$\frac{gT_m}{U_A} = 0.2857\left(\frac{gF}{U_A^2}\right)^{1/3}$$ Equation 5 (Eq. 3-34, SPM, 1984)

Making the above substitutions for wind speed gives;

$$T_m = 6.0x10^{-2}U^{0.41}F^{1/3} \text{ seconds}$$ Equation 6

Deep Water Wave Length – The deep-water wave length (L_o) was calculated using the deep approximation to the linear wave dispersion relationship ($L_o = 1.56T^2$ m). This is justified since the calculated maximum wave period was 3.29 sec, and most waves were shorter and the water depth over nearly the entire distance is less than $L_o/2$.

Water Depth at Breaking – Though the breaker height could be calculated in several ways, the approximate depth at breaking was calculated using ($d = 1.25H$) (Dean and Dalrymple, 1984). The relative wave height (d/L_o) was calculated using the deepwater wave length since little shoaling occurs prior to breaking in the steep foreshore bathymetry near the FIL.

Wave Shoaling and Breaker Angle – Though the foreshore is steep, the waves do shoal and the breaker angle to the shoreline is modified from the direction of the wind and the wave angle in deep water. These adjustments were made using the procedures in the Corps of Engineers, EM 1110-2-1502, *Coastal Littoral Transport* (CLT, 1992). Monochromatic wave height and direction were corrected for refraction and shoaling using Figure 3-18 (CLT 1992).

Potential Transport Rate – The longshore potential sediment transport rate was calculated using the energy flux method reviewed in CLT, 1992. The daily potential transport depends on the breaking wave height and angle;

$$Q_l = \left(5.1x10^3\right)H_{bs}^{5/2}\sin\left(2\alpha_b\right)$$ Equation 7 (Eq. 6-7b, CLT,1992)

where Q_l is the potential transport rate in m^3/day and H and α are the breaker height (m) and angle respectively. The transport rate is considered to be 'potential' since it depends on the availability of sand size material. The rate has been empirically correlated with data from quartz density sand beaches with median grain size (D_{50}) in a relatively narrow range of 0.2 to 1.0 mm. The sediment transport results from gravel beaches are very limited (Hattori and Suzuki, 1979; Komar, 1988) so the calculated transport rate can be used only as a guide.

The transport rate for each wind speed-direction and fetch distance category was multiplied by the annual percent of time for that occurrence, and was added, in order to get the gross transport to the left or the right of the FIL. Transport to the right, facing offshore, is normally taken as positive and that to the left is negative. Net transport was determined to be in the northerly direction based on calculations using the TIA or FIL winds though the net rates are considerably different.

The results of the littoral transport calculations using TIA and FIL winds are provided in Tables A1 and A2 respectively.

CALCULATION USING ACES

As check on the calculation procedure, the longshore sediment transport was also computed using the Littoral Processes procedure in the ACES 1.07e software CERC, 1992). These routines use the energy flux method to calculate transport for selected conditions of offshore wave angle and deepwater wave height. The program was allowed to automatically calculate and apply the refraction and shoaling coefficients.

An adjustment was made to the empirical coefficient, K, normally set at 0.39 for computation dealing with sand sized sediment. Several studies have indicated that, the value of K should be reduced for larger grain sizes and Hattori and Suzuki (1979) suggested a value of $K \approx 0.2$ for $D_{50} = 2cm$ (CLT, 1992). A value of $K \approx 0.211$ was selected for these runs and results were quite close to those calculated using the SPM and EM methods.

The results of the sediment transport calculations using ACES 1.07e are given in Table A3 and A4 for winds measured at TIA and FIL respectively.

Longshore sediment transport Fox Island using Tacoma winds
Transport Calculated using procedure from EM 1110-2-1502
Wave Height and Period Calculated using SPM

Wind from SSE: 157.5 deg. T.
Fetch Distance: 9.9 km
Deep Water Wave Angle: 72.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, Lo, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.12	1.79	5.01	0.15	0.0304	0.70	0.0853	18.00	6.37	2.8	0.00
6-10	4.47	0.29	2.38	8.83	0.36	0.0403	0.6600	0.1881	22.00	54.39	2.1	417.20
11-15	6.71	0.47	2.81	12.33	0.59	0.0476	0.6500	0.3054	23.00	189.06	0.2	138.11
												555.31

Wind from S: 180 deg. T.
Fetch Distance: 4.6 km
Deep Water Wave Angle: 50.00

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, Fig. II-2-23 CEM	Wave Period, T sec. Fig. II-2-24 CEM	Deep Water Wave Length, Lo, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.08	1.39	3.01	0.10	0.0345	0.98	0.0814	12.00	3.92	2.8	0.00
6-10	4.47	0.19	1.84	5.30	0.24	0.0458	0.9300	0.1807	16.00	37.52	9.1	1246.97
11-15	6.71	0.32	2.18	7.39	0.40	0.0541	0.9000	0.2882	20.00	146.20	4.4	2349.63

16-20	8.94	0.46	2.45	9.36	0.57	0.0609	0.8900	0.4057	22.00	371.30	2	2712.32
21-25	11.18	0.60	2.68	11.24	0.75	0.0667	0.8700	0.5221	22.50	710.15	0.7	1815.69
26-30	13.41	0.75	2.89	13.05	0.94	0.0719	0.8500	0.6379	25.00	1269.86	0.2	927.63
												9052.24

Wind from SSW: 202.5 deg. T

Fetch Distance: 4.1 km

Deep Water Wave Angle: 24.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, Fig. II-2-23 CEM	Wave Period, T sec. Fig. II-2-24 CEM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.08	1.34	2.79	0.10	0.0352	1.15	0.09		0.00	1.6	0.00
6-10	4.47	0.18	1.77	4.91	0.23	0.0467	1.10	0.20	10.00	31.91	6	699.22
11-15	6.71	0.30	2.10	6.85	0.38	0.0552	1.05	0.32	11.00	108.48	3.5	1386.83
16-20	8.94	0.43	2.36	8.67	0.54	0.0621	1.02	0.44	12.00	264.74	0.9	870.27
21-25	11.18	0.57	2.58	10.41	0.71	0.0680	1.00	0.57	12.50	520.66	0.1	190.17
												3146.49

Wind from SW: 225 deg. T.

Fetch Distance: 3.7 km

Deep Water Wave Angle: 5.00

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, Fig. II-2-23 CEM	Wave Period, T sec. Fig. II-2-24 CEM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport

0-5	2.24	0.07	1.29	2.60	0.09	0.0358	1.20	0.09		0.00	1.7	0.00
6-10	4.47	0.17	1.71	4.58	0.22	0.0475	1.15	0.20	2.00	6.40	4.2	98.13
11-15	6.71	0.29	2.02	6.40	0.36	0.0561	1.11	0.32	2.00	20.42	1.8	134.23
16-20	8.94	0.41	2.28	8.09	0.51	0.0631	1.07	0.44	2.00	45.01	0.5	82.20
21-25	11.18	0.54	2.50	9.72	0.67	0.0692	1.05	0.57	2.00	85.40	0.1	31.19
												345.75

Wind from WSW: 247.5 deg. T.

Fetch Distance: 6.2 km

Deep Water Wave Angle: -17.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, Fig. II-2-23 CEM	Wave Period, T sec. Fig. II-2-24 CEM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.10	1.53	3.67	0.12	0.0328	1.19	0.11	-7.00	-5.50	1.6	-32.17
6-10	4.47	0.23	2.04	6.47	0.28	0.0436	1.12	0.25	-7.50	-42.35	2.6	-402.21
11-15	6.71	0.37	2.40	9.02	0.46	0.0515	1.08	0.40	-8.00	-143.62	0.4	-209.83
16-20	8.94	0.53	2.71	11.42	0.66	0.0579	1.07	0.57	-8.00	-339.09	0.1	-123.85
												-768.06

Wind from W: 270 deg. T.

Fetch Distance: 6.8 km

Deep Water Wave Angle: -40.00

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, Fig. II-2-23 CEM	Wave Period, T sec. Fig. II-2-24 CEM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport

0-5	2.24	0.10	1.58	3.90	0.13	0.0323	1.08	0.11	-16.00	-10.62	1.7	-65.94
6-10	4.47	0.24	2.10	6.88	0.30	0.0429	1.02	0.24	-15.00	-72.69	2.3	-610.64
11-15	6.71	0.39	2.48	9.60	0.49	0.0507	1.00	0.39	-16.00	-255.67	0.1	-93.38
												-769.96

Wind from WNW: . 292.5 deg. T

Fetch Distance: :8.5 km

Deep Water Wave Angle: -62.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, Fig. II-2-23 CEM	Wave Period, T sec. Fig. II-2-24 CEM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.11	1.70	4.53	0.14	0.0312	0.85	0.10	-17.50	-8.35	0.7	-21.34
6-10	4.47	0.26	2.26	7.98	0.33	0.0414	0.80	0.21	-20.00	-67.29	0.4	-98.31
												-119.65

Transport to Right (North) 13099.78
Transport to Left (South) -1657.67

Net Transport (North) 11442.11

Table A1. Calculation of longshore sediment transport using winds measured at the Tacoma Industrial Airport for the years 1999 and 2000 and the method of the Shore Protection Manual (SPM, 1984).

Longshore sediment transport Fox Island, based on FIL winds for 2000

Transport Calculated using procedure from EM 1110-2-1502

Wave Height and Period Calculated using SPM Procedure

Wind from SSE: 157.5 deg. T.

Fetch Distance: 9.9 km

Deep Water Wave Angle: 72.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, Lo, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.12	1.79	5.01	0.15	0.0304	0.70	0.0853	18.00	6.37	2.73	0.00
6-10	4.47	0.29	2.38	8.83	0.36	0.0403	0.6600	0.1881	22.00	54.39	1.47	292.04
11-15	6.71	0.47	2.81	12.33	0.59	0.0476	0.6500	0.3054	23.00	189.06	0.1	69.05
16-20	8.94	0.67	3.16	15.60	0.84	0.0536	0.6300	0.4213	25.00	449.96	0.01	16.43
												377.53

Wind from S: 180 deg. T.

Fetch Distance: 4.6 km

Deep Water Wave Angle: 50.00

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, Lo, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.08	1.39	3.01	0.10	0.0345	0.98	0.0814	12.00	3.92	3.42	0.00
6-10	4.47	0.19	1.84	5.30	0.24	0.0458	0.9300	0.1807	16.00	37.52	4.11	563.19
11-15	6.71	0.32	2.18	7.39	0.40	0.0541	0.9000	0.2882	20.00	146.20	1.87	998.59
16-20	8.94	0.46	2.45	9.36	0.57	0.0609	0.8900	0.4057	22.00	371.30	0.35	474.66

21-25	11.18	0.60	2.68	11.24	0.75	0.0667	0.8700	0.5221	22.50	710.15	0.07	181.57
26-30	13.41	0.75	2.89	13.05	0.94	0.0719	0.8500	0.6379	25.00	1269.86	0.03	139.15
												2357.15

Wind from SSW: 202.5 deg. T

Fetch Distance: 4.1 km

Deep Water Wave Angle: 24.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.08	1.34	2.79	0.10	0.0352	1.15	0.09		0.00	3.09	0.00
6-10	4.47	0.18	1.77	4.91	0.23	0.0467	1.10	0.20	10.00	31.91	5.6	652.61
11-15	6.71	0.30	2.10	6.85	0.38	0.0552	1.05	0.32	11.00	108.48	3.13	1240.22
16-20	8.94	0.43	2.36	8.67	0.54	0.0621	1.02	0.44	12.00	264.74	0.43	415.79
21-25	11.18	0.57	2.58	10.41	0.71	0.0680	1.00	0.57	12.50	520.66	0.1	190.17
26-30	13.41	0.71	2.78	12.08	0.89	0.0733	1.01	0.72	12.50	933.77	0.03	102.32
												2601.11

Wind from SW: 225 deg. T.

Fetch Distance: 3.7 km

Deep Water Wave Angle: 5.00

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.07	1.29	2.60	0.09	0.0358	1.20	0.09		0.00	1.47	0.00
6-10	4.47	0.17	1.71	4.58	0.22	0.0475	1.15	0.20	2.00	6.40	1.55	36.21
11-15	6.71	0.29	2.02	6.40	0.36	0.0561	1.11	0.32	2.00	20.42	0.6	44.74
16-20	8.94	0.41	2.28	8.09	0.51	0.0631	1.07	0.44	2.00	45.01	0.05	8.22

21-25	11.18	0.54	2.50	9.72	0.67	0.0692	1.05	0.57	2.00	85.40	0.01	3.12
												92.29

Wind from WSW: 247.5 deg. T.

Fetch Distance: 6.2 km

Deep Water Wave Angle: -17.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.10	1.53	3.67	0.12	0.0328	1.19	0.11	-7.00	-5.50	1.12	-22.52
6-10	4.47	0.23	2.04	6.47	0.28	0.0436	1.12	0.25	-7.50	-42.35	0.85	-131.49
11-15	6.71	0.37	2.40	9.02	0.46	0.0515	1.08	0.40	-8.00	-143.62	0.32	-167.87
16-20	8.94	0.53	2.71	11.42	0.66	0.0579	1.07	0.57	-8.00	-339.09	0.07	-86.70
21-25	11.18	0.70	2.96	13.71	0.87	0.0635	1.05	0.73	-9.00	-721.22	0.02	-52.69
												-461.26

Wind from W: 270 deg. T.

Fetch Distance: 6.8 km

Deep Water Wave Angle: -40.00

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.10	1.58	3.90	0.13	0.0323	1.08	0.11	-16.00	-10.62	2.37	-91.92
6-10	4.47	0.24	2.10	6.88	0.30	0.0429	1.02	0.24	-15.00	-72.69	2.49	-661.08

11-15	6.71	0.39	2.48	9.60	0.49	0.0507	1.00	0.39	-16.00	-255.67	0.88	-821.78
16-20	8.94	0.55	2.79	12.14	0.69	0.0571	0.975	0.54	-16.00	-579.94	0.21	-444.83
21-25	11.18	0.73	3.06	14.58	0.91	0.0625	0.95	0.69	-17.50	-1169.93	0.06	-256.39
26-30	13.41	0.91	3.29	16.93	1.14	0.0674	0.094	0.09	-18.00	-6.46	0.01	-0.24
												-2276.24

Wind from WNW: 292.5 deg. T.
Fetch Distance: 8.5 km
Deep Water Wave Angle: -62.50

Wind Speed, mph	Wind Speed, m/s	Wave Height, Hs, meters, SPM	Wave Period, T sec. SPM	Deep Water Wave Length, meters	Approximate depth at breaking, d=1.25*H, m (Dalrymple, 1984), p.115	Relative depth, d/L	Combined Refraction and Shoaling Coefficient, Fig. 3.18 EM 1110-2-1502	Corrected Wave Height	Wave Angle at Breaking, Fig. 3.18 EM 1110-2-1502	Transport Rate, cubic meters/day	Annual Percent Occurrence	Annual Net Transport
0-5	2.24	0.11	1.70	4.53	0.14	0.0312	0.85	0.10	-17.50	-8.35	2.09	-63.73
6-10	4.47	0.26	2.26	7.98	0.33	0.0414	0.80	0.21	-20.00	-67.29	1.86	-457.12
11-15	6.71	0.44	2.67	11.14	0.54	0.0489	0.79	0.34	-22.00	-245.72	0.37	-332.08
16-20	8.94	0.62	3.01	14.09	0.77	0.0550	0.77	0.48	-23.00	-576.72	0.12	-252.77
21-25	11.18	0.82	3.29	16.92	1.02	0.0602	0.76	0.62	-25.00	-1182.18	0.02	-86.36
												-1192.06

Transport to Right (North) 5428.09
Transport to Left (South) -3929.55

Net Transport (North) 1498.53

Table A2. Results of longshore transport calculation using winds measured at Fox Island Laboratory for the years 2000 and applying the method of the SPM (1984).

Fox Island Net Longshore Transport using **Tacoma** Winds for 1999 and 2000. Wave Calculated from ACES 1.07e, K=0.211

Wind Direction	Deepwater Wave Height, Hso meters	Deepwater Wave Angle Relative to Fox Island	Annual Tranport Rate, cubic meters/yr Based on ACES 1.07e	Daily Transport rate, cubic meters/da	Annual Percent Occurrence	Annual Net Transport, cubic meters /yr	
SSE	0.12	72.5	2342	6	2.8	66	
	0.29	72.5	21262	58	2.1	447	
	0.47	72.5	71099	195	0.2	142	
							654
SSE	0.08	50	0	0	2.8	0	
	0.19	50	15337	42	9.1	1396	
	0.32	50	56459	155	4.4	2484	
	0.46	50	139879	383	2	2798	
	0.6	50	271792	744	0.7	1903	
	0.75	50	474801	1300	0.2	950	
							9530
SSW	0.08	24.5	0	0	1.6	0	
	0.18	24.5	11200	31	6	672	
	0.3	24.5	40163	110	3.5	1406	
	0.43	24.5	98786	270	0.9	889	
	0.57	24.5	199854	547	0.1	200	
							3167
SW	0.07	5	0	0	1.7	0	
	0.17	5	2285	6	4.2	96	
	0.29	5	8684	24	1.8	156	
	0.41	5	20640	57	0.5	103	
	0.54	5	41090	112	0.1	41	
							397
WSW	0.1	17.5	1981	5	1.6	32	
	0.23	17.5	15895	44	2.6	413	
	0.37	17.5	52172	143	0.4	209	
	0.53	17.5	128123	351	0.1	128	
							-782
W	0.1	40	3220	9	1.7	55	
	0.24	40	28736	79	2.3	661	
	0.39	40	96731	265	0.1	97	
	0.55	40	228461	625	0.21	480	
							-1292

WNW	0.11	62.5	2995	8	0.7	21	
	0.26	62.5	25727	70	0.4	103	
							-124

Transport to North	13747
Transport to South	-2198
Net Transport (North)	11549

Table 3A. Longshore sediment transport using TIA winds for 1999 and 2000 and ACES 1.07e computation program.

Fox Island Net Longshore Transport using FIL Winds for 2000 and Wave Calculated from ACES 1.07e

Wind Direction	Deepwater Wave Height, Hso meters	Deepwater Wave Angle Relative to Fox Island	Annual Tranport Rate, cubic meters/yr Based on ACES 1.07e	Daily Transport rate, cubic meters/da	Annual Percent Occurrence	Annual Net Transport, cubic meters /yr	Total Transport
SSE	0.12	72.5	2342	6	2.73	64	
	0.29	72.5	21262	58	1.47	313	
	0.47	72.5	71099	195	0.1	71	
	0.67	72.5	172506	472	0.01	17	
							465
SSE	0.08	50	0	0	3.42	0	
	0.19	50	15337	42	4.11	630	
	0.32	50	56459	155	1.87	1056	
	0.46	50	139879	383	0.35	490	
	0.6	50	271792	744	0.07	190	
	0.75	50	474801	1300	0.03	142	
							2508
SSW	0.08	24.5	0	0	3.09	0	
	0.18	24.5	11200	31	5.6	627	
	0.3	24.5	40163	110	3.13	1257	
	0.43	24.5	98786	270	0.43	425	
	0.57	24.5	199854	547	0.1	200	
	0.71	24.5	346076	948	0.03	104	
							2613
SW	0.07	5	0	0	1.47	0	
	0.17	5	2285	6	1.55	35	
	0.29	5	8684	24	0.6	52	
	0.41	5	20640	57	0.05	10	
	0.54	5	41090	112	0.01	4	
							102
WSW	0.1	17.5	1981	5	1.12	22	
	0.23	17.5	15895	44	0.85	135	
	0.37	17.5	52172	143	0.32	167	
	0.53	17.5	128123	351	0.07	90	
	0.7	17.5	256851	703	0.02	51	
							-465
W	0.1	40	3220	9	2.37	76	
	0.24	40	28736	79	2.49	716	
	0.39	40	96731	265	0.88	851	
	0.55	40	228461	625	0.21	480	
	0.73	40	463674	1269	0.06	278	
	0.91	40	804468	2203	0.01	80	

							-2481
WNW	0.11	62.5	2995	8	2.09	63	
	0.26	62.5	25727	70	1.86	479	
	0.44	62.5	95849	262	0.37	355	
	0.62	62.5	225910	619	0.12	271	
	0.8	62.5	427249	1170	0.02	85	
							-1252

Transport to North	5688
Transport to South	-4199
Net Transport (North)	1301

Table A4. Calculation of longshore transport using FIL winds for 2000 and the ACES 1.07e calculation procedure.

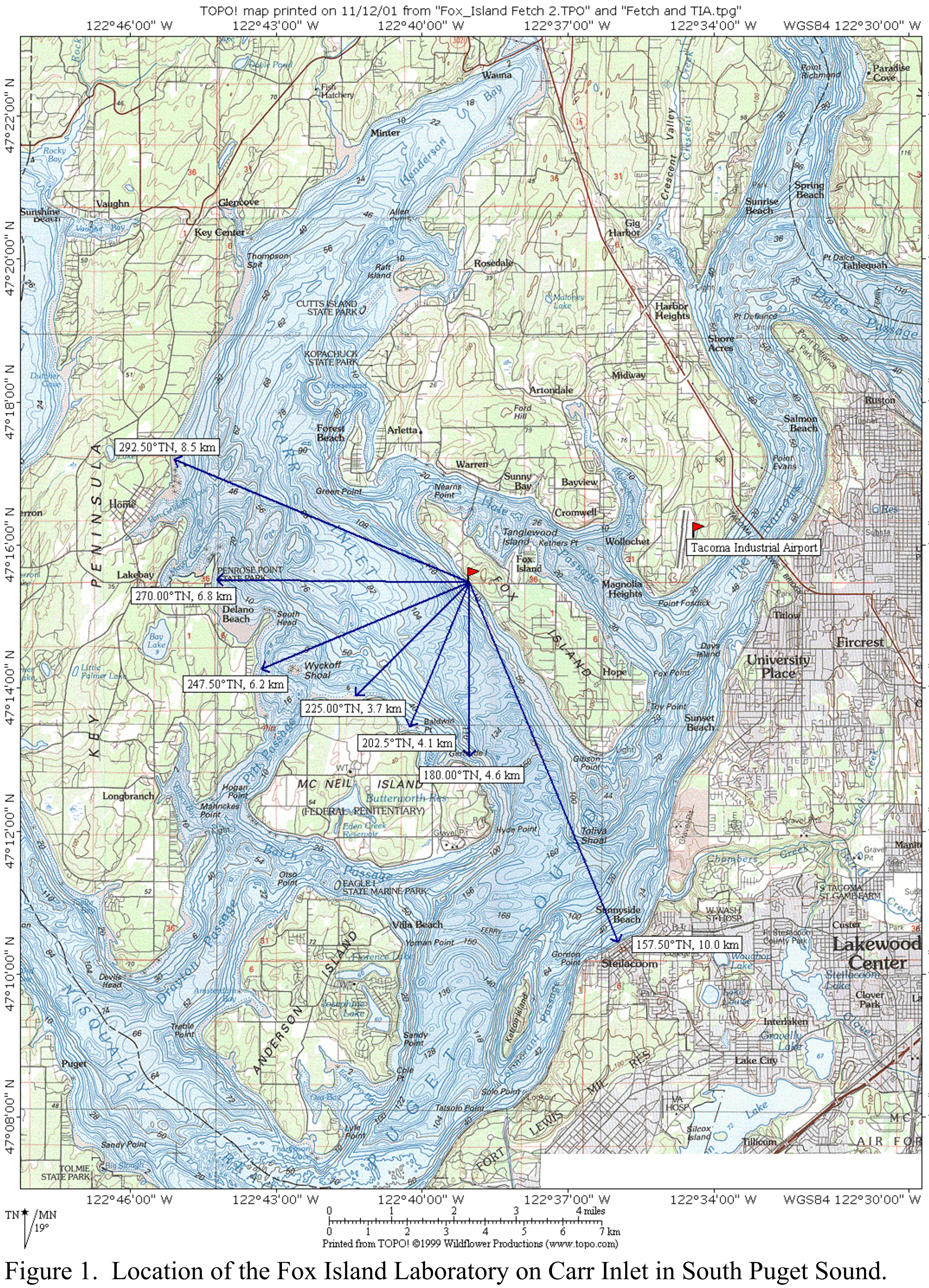

Figure 1. Location of the Fox Island Laboratory on Carr Inlet in South Puget Sound. Arrows indicated the direction and fetch distances for waves arriving at the site. The Tacoma Industrial Airport is located about 3.25 miles ENE of the laboratory.

Figure 2. Fox Island Laboratory and pier facility at low tide. Photo was taken from the M241 barge and shows the laboratory building, log debris on both sides of the pier and riprap bulkhead in front of the building.

Figure 3. North side of FIL pier showing low tide beach with mooring dolphins and riprap structure in front of house. Additional structures can be seen along the beach.

Figure 4. Deteriorating boat ramp and riprap bulkhead along the beach north of the FIL.

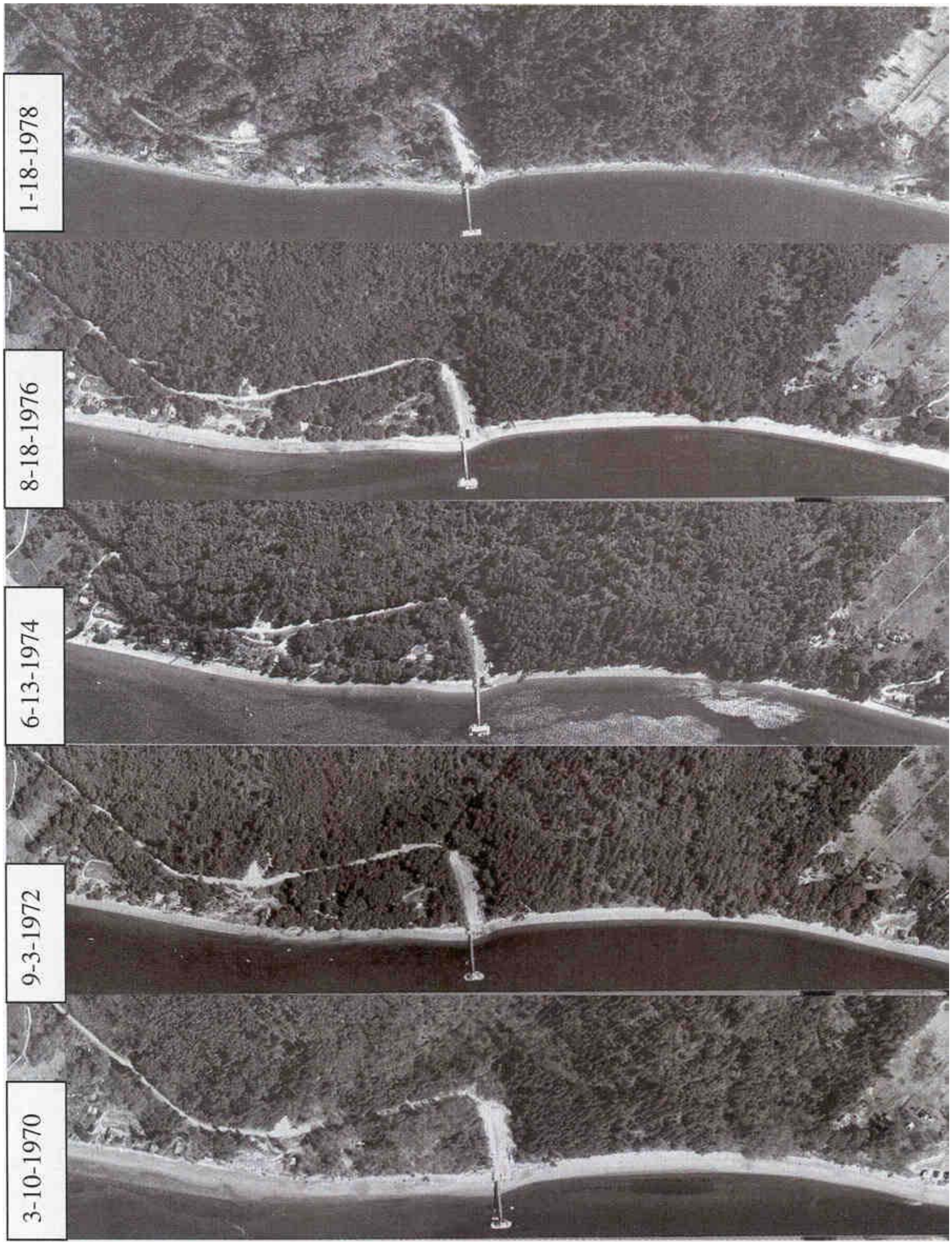

Figure 5a. Aerial photographs of Fox Island Laboratory and shoreline from 1970 to 1978.

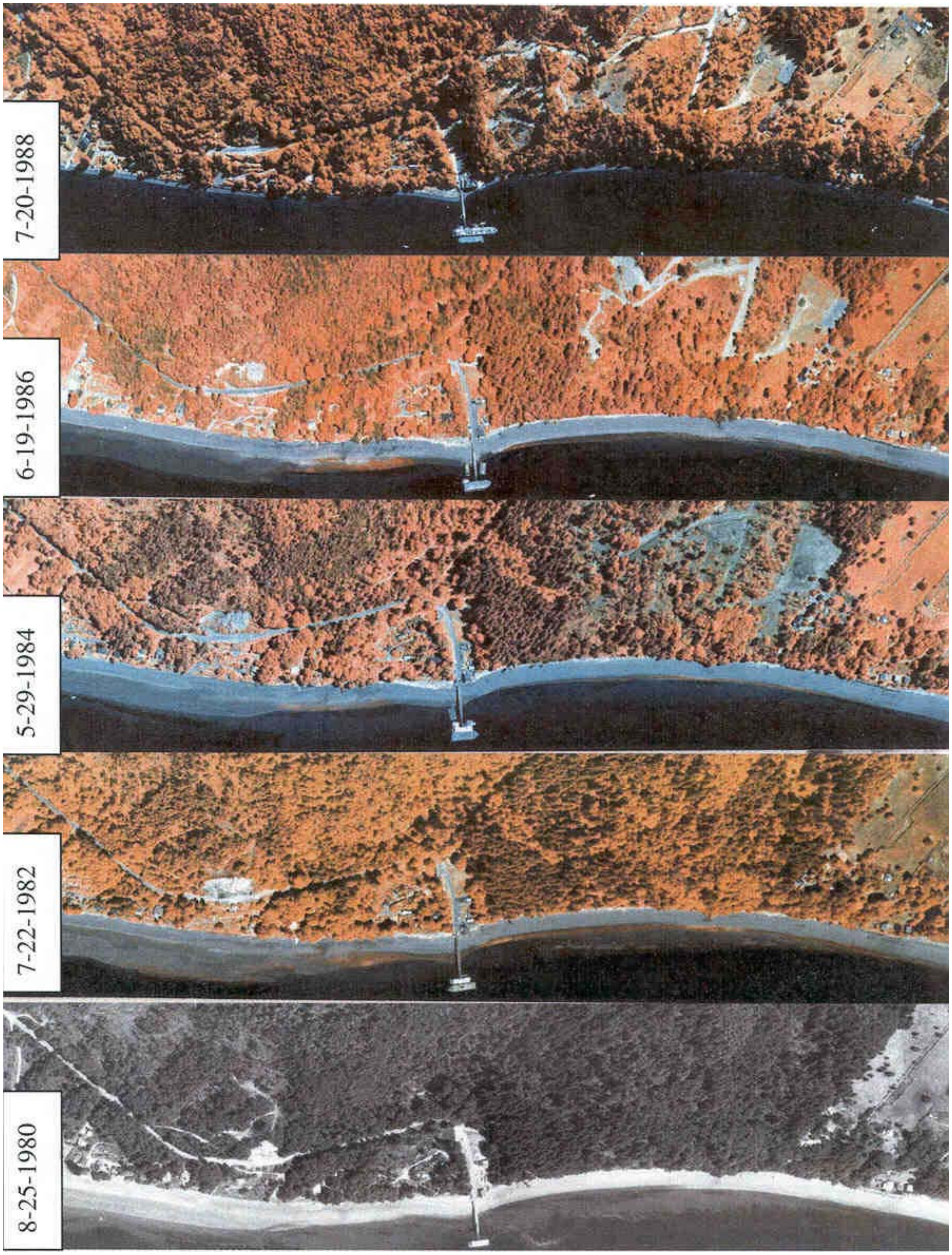

Figure 5b. Aerial photographs of Fox Island Laboratory and shoreline from 1980 to 1988.

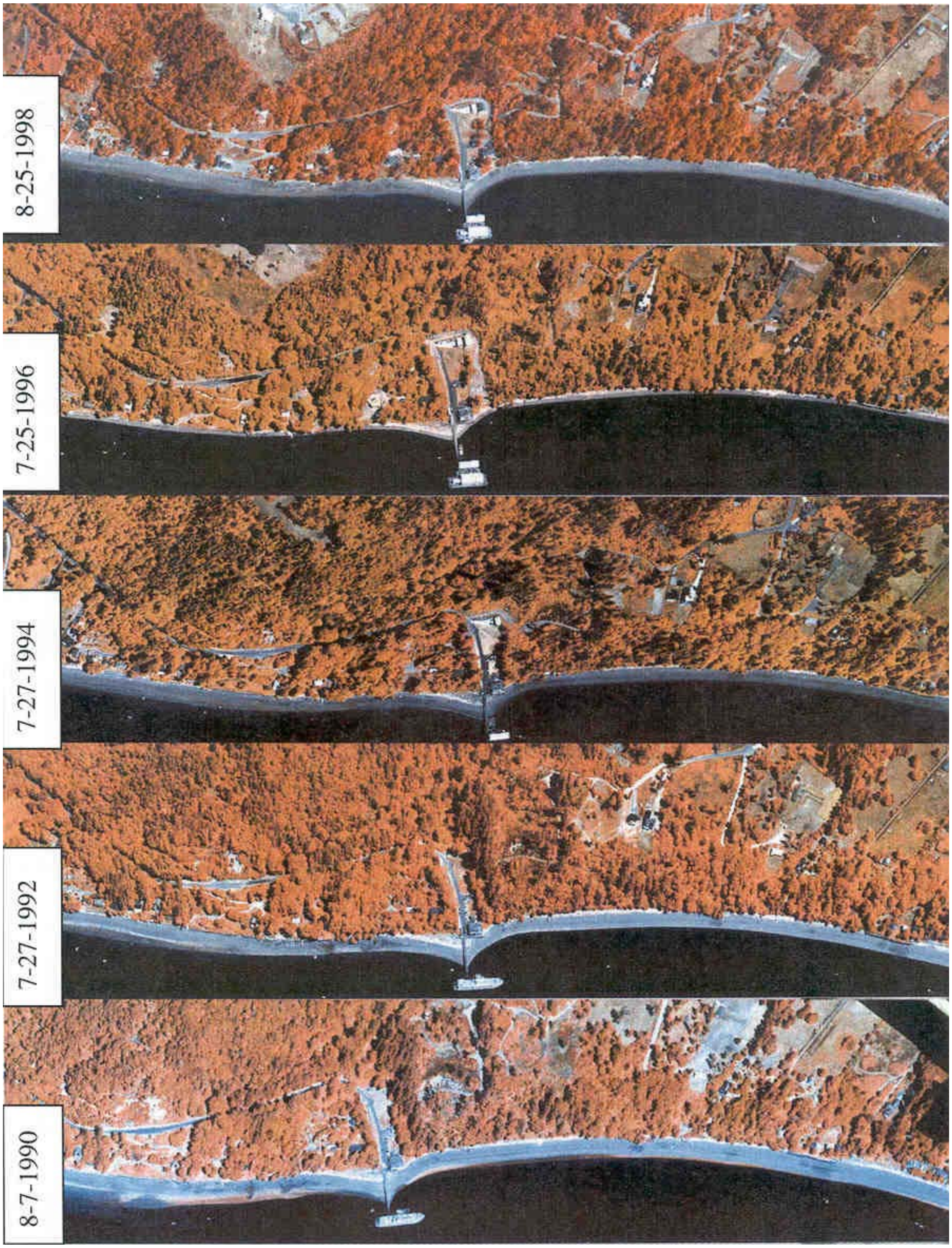

Figure 5c. Aerial photographs of Fox Island Laboratory and shoreline from 1990 to 1998.

Figure 5d. Aerial photograph of Fox Island Laboratory and shoreline in 2000.

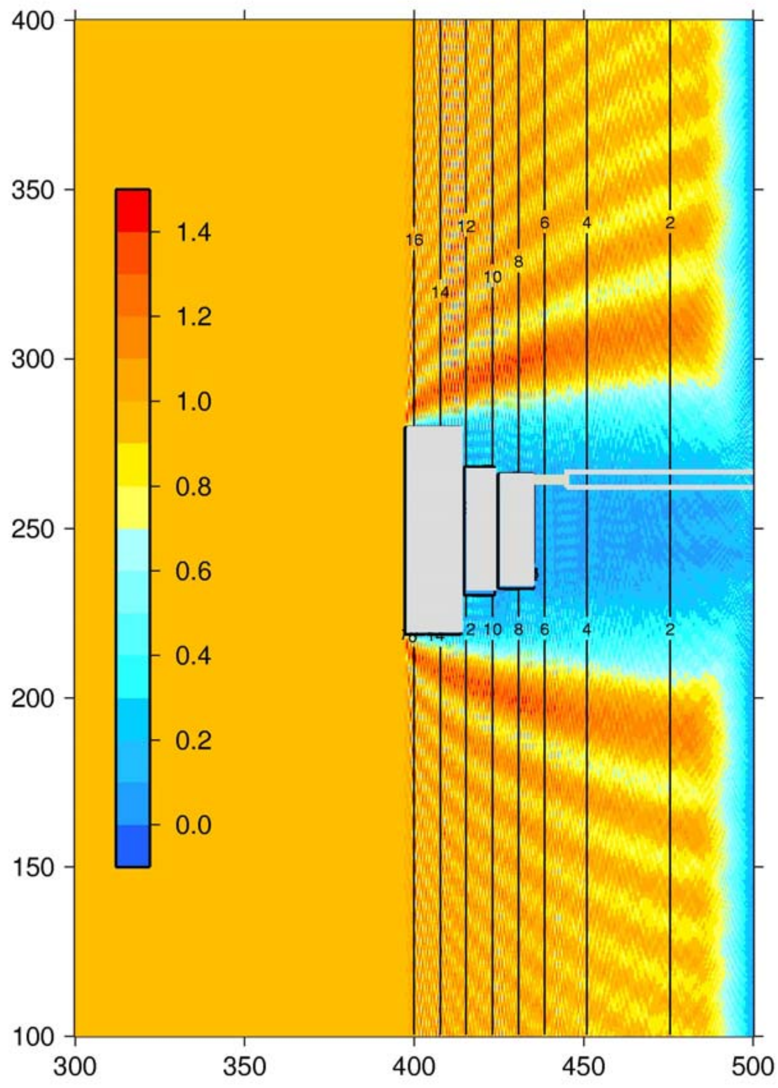

Figure 6. Normalized wave heights for existing configuration (M241 Barge with waves from the left, normal to the barge, 3-second wave period). Position and depths are in meters.

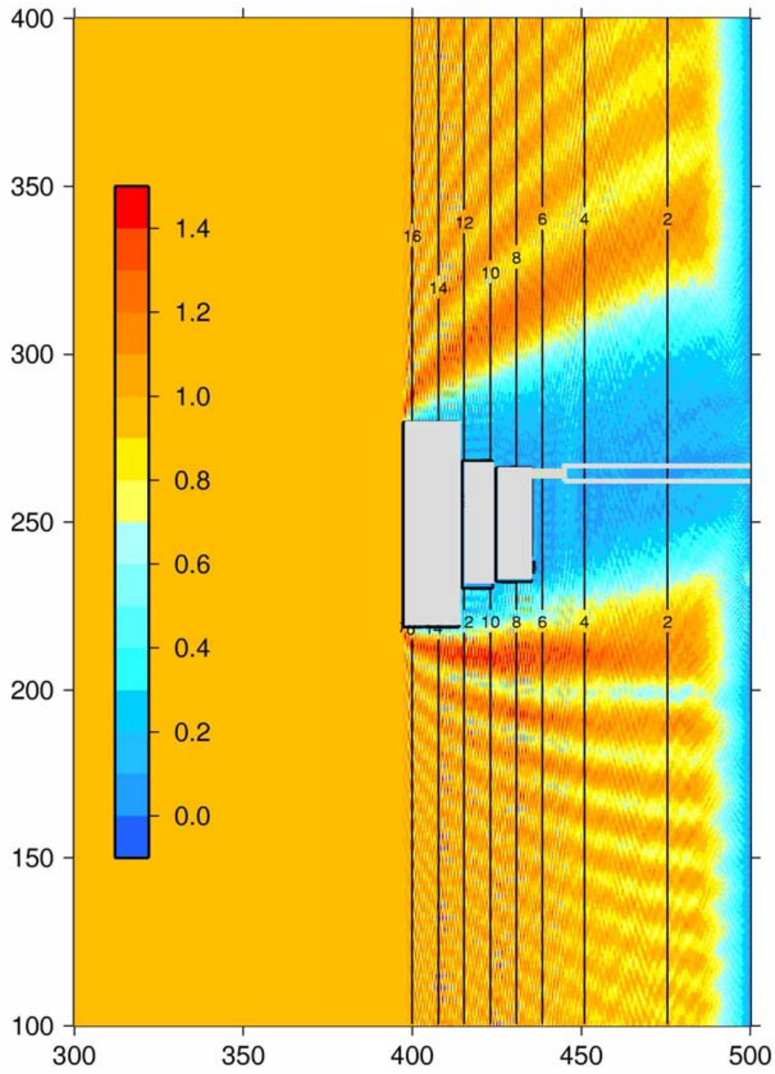

Figure 7. Normalized wave heights for existing configuration (M241 Barge with waves from 20 degrees south of normal, 3-second wave period). Position and depths are in meters.

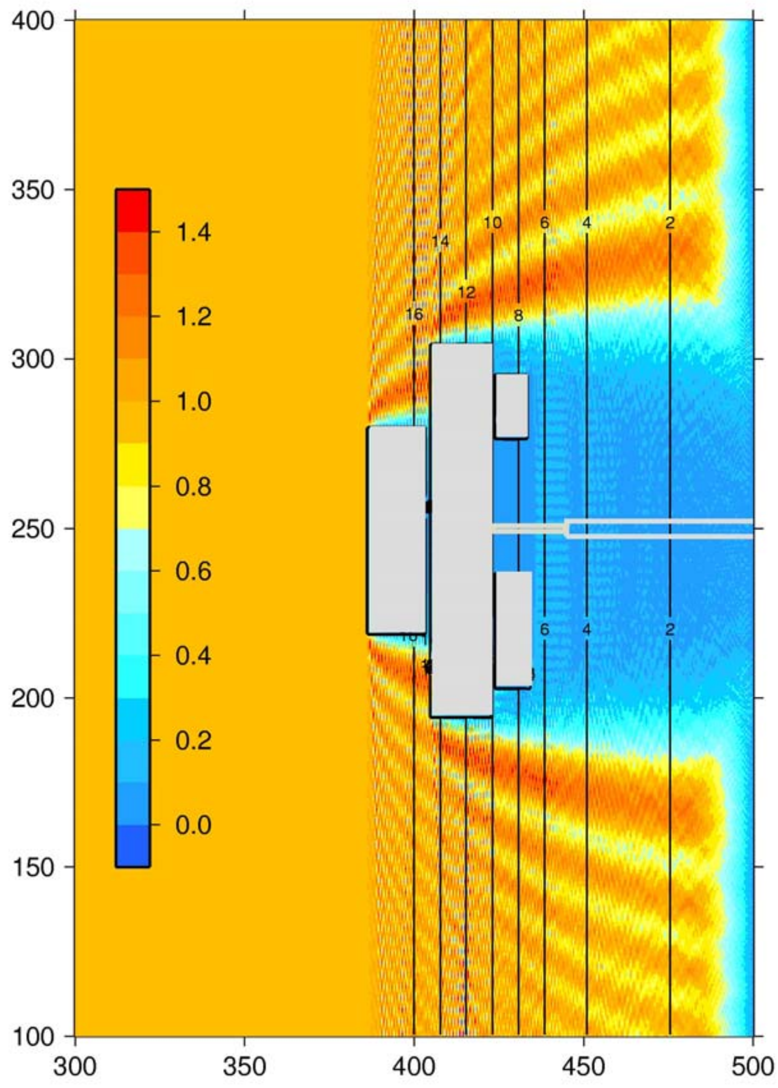

Figure 8. Normalized wave heights for proposed pontoon barge (M241 Barge and pontoon with normally directed 3-second waves). Position and depths are in meters.

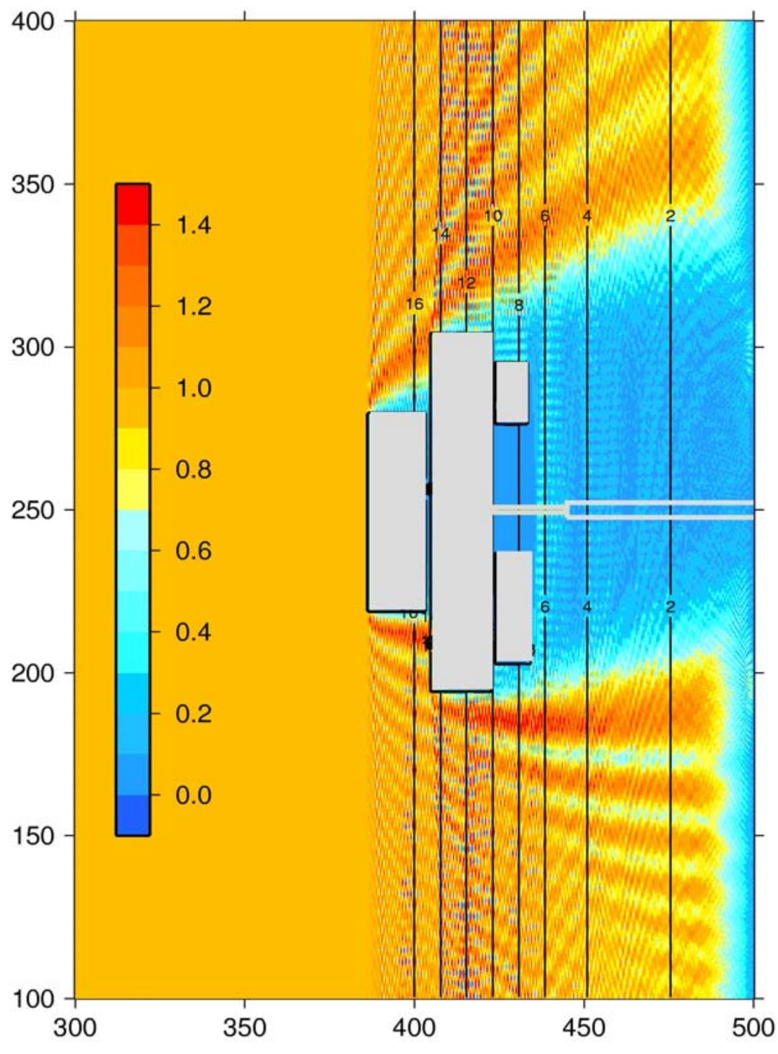

Figure 9. Normalized wave heights for proposed pontoon barge (M241 Barge and pontoon with 20 degrees northward of east directed 3-second waves). Position and depths are in meters.


Figures 10 and 11. Driftwood accumulation and riparian vegetation associated with upper beach and backshore habitat to north (photo left) and south (photo right) of FIL, as seen during near-high tide.


Figures 12 and 13. Driftwood associated with upper beach habitat to north (photo left) and immediately in front of (photo right) FIL facilities, as seen during near-mid tide.


Figure 15. Shoreline south of FIL pier during near-low tide.


Figure 16. Shoreline north of FIL pier during near-low tide.