Boat wakes and their influence on erosion in the Atlantic Intracoastal Waterway, North Carolina

Citation for this Report

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Boat wakes and their influence on erosion in the Atlantic Intracoastal Waterway, North Carolina

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ABSTRACT

Boat wakes in the Atlantic Intracoastal Waterway (AIWW) of North Carolina occur in environments not normally subjected to (wind) wave events, making sections of AIWW potentially vulnerable to extreme wave events generated by boat wakes. The Snow's Cut area that links the Cape Fear River to the AIWW is an area identified by the Wilmington District of the U.S. Army Corps of Engineers as having significant erosion issues; it was hypothesized that this erosion could be being exacerbated by boat wakes. We compared the boat wakes for six combinations of boat length and speed with the top 5% wind events. We also computed the benthic shear stress associated with boat wakes and whether sediment would move (erode) under those conditions. Finally, we compared the transit time across Snow's Cut for each speed. We focused on two size classes of V-hulled boats (7 and 16m) representative of AIWW traffic and on three boat speeds (3, 10 and 20 knots). We found that at 10 knots when the boat was plowing and not yet on plane, boat wake height and potential erosion was greatest. Wakes and forecast erosion were slightly mitigated at higher, planing speeds. Vessel speeds greater than 7 knots were forecast to generate wakes and sediment movement zones greatly exceeding that arising from natural wind events. We posit that vessels larger than 7m in length transiting Snow's Cut (and likely many other fetch-restricted areas of the AIWW) frequently generate wakes of heights that result in sediment movement over large extents of the AIWW nearshore area, substantially in exceedance of natural wind wave events. If the speed, particularly of large V-hulled vessels (here represented by the 16m length class), were reduced to pre-plowing levels (~ 7 knots down from 20), transit times for Snow's Cut would be increased approximately 10 minutes but based on our simulations would likely substantially reduce the creation of erosion-generating boat wakes. It is likely that boat wakes significantly exceed wind wave background for much of the AIWW and similar analyses may be useful in identifying management options.

KEYWORDS: Waves, wind waves, boat wakes, vessel speed, erosion, Atlantic Intracoastal Waterway, WEMo, BoMo, wave heights, Snow's Cut.

1. INTRODUCTION

Vessel or boat wakes have been recognized as a significant management issue in the coastal waters of the United States. (National Research Council 2007). However, the absence of a geographically accurate means of predicting boat wakes has limited manager's abilities to evaluate their effect on coastal shorelines, property, maritime safety and maintenance dredging frequency. Boat wakes are generally, but non-specifically, associated with shoreline erosion and boating safety yet we lack a quantitative basis for determining to what level boat wakes should be managed to constitute effective mitigation of impacts. Here, we describe a novel application of new forecasting tools that will provide a quantitative assessment of boat wake scenarios and seafloor erosion to inform mitigation strategies.

At the request of the Wilmington District of the U.S. Army Corps of Engineers we applied these tools to Snow's Cut, a small section of the Atlantic Intracoastal Waterway (AIWW) that passes through North Carolina and links the Cape Fear River to the lagoonal portion of the AIWW where maintenance dredging issues (and presumably costs) have emerged as a significant management concern. We asked what the boat wake levels could be in this area of the AIWW in comparison to wind waves and whether boat wakes could be a cause of erosion and thus, increased dredging.

2. METHODS

Applied Models

We applied two forecasting tools. First was a Wave Exposure Model (**WEMo**[1]; Malhotra and Fonseca 2007) that we created for assessment of wind wave conditions (significant wave height, wave energy, and shear stress at the seafloor) at discrete study points. Second was a prototype boat wake model (**BoMo**) that will produce the same output but as the result of boat wakes generated by the passage of a boat where the user selects the boat hull type, length, speed and sailing line in a geographic information system (GIS). Our approach was as follows:

- Run **WEMo** to create a baseline of wind-generated wave height, wave energy and sediment movement (at the seafloor) conditions arising from ambient conditions.
- Compare the wind wave parameters here with that of nearby open water bodies (i.e., New River Estuary, NRE) to provide a context for this site.
- Compare the wind wave parameters here with the AIWW wake history profile to estimate exceedance from vessel waves.
- Run **BoMo** for 2 different hull types at 3 different speeds each and see where the performance of these vessels exceed the wind wave parameters.
- Examine all the **BoMo** runs for erosion 'hot spots'; this includes mapping out sediment movement forecasts.

WEMo: The **W**ave **E**xposure **Mo**del (**WEMo**) is a freely distributed GIS tool for hindcasting or forecasting wave heights, wave energy and seafloor sediment erosion for sites in estuarine and closed water bodies in response to local wind generated waves (~ 50 km). Field validation trials

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[1]Wave Exposure Model (**WEMo**) http://www.csc.noaa.gov/digitalcoast/tools/wemo/index.html (last accessed Feb. 8, 2012).

reveal that **WEMo's** results agree well with observed conditions indicating that **WEMo** can be an effective tool in predicting local wave energy in closed estuarine environments.

BoMo: **BoMo** is a forecasting tool to predict wave heights generated by boats hulls of various shapes and sizes at various speeds. **BoMo** also predicts the resulting seafloor erosion zones created by these boat wakes. **BoMo's** architecture is implemented as two distinct modules: a wake generator (WG) module to generate the boat wakes and a wave propagator (WP) module to propagate the generated wake on to the shoreline.

The WG module employs an artificial neural network based on field-collected data and then verified against different models for different hull types, most prominent of those are Sorensen model (Sorenson 1967) for displacement hulls, and a modified U.S. Army Corps of Engineers model for planing hulls. The WG module also employs non-linear regression models we created from field experiments conducted on recreational boats of various hull shapes and sizes at different depths. The WG module utilizes the appropriate model based on the parameters (hull characteristics, sailing speed and depth) selected by the user.

The WP module propagates the wake generated by WG module over the water onto the shoreline. The WP module utilizes extended fully non-linear Boussinesq models (Nwogu 1993, Chen et al. 2000) as it is the most suitable model for non-linear wave propagation from relatively deep to shallow water. Boussinesq equations include the effects of weak dispersion and nonlinearity and allow accurate nearshore simulation of wave transformation processes including refraction, diffraction and shoaling (Kirby 1997).

The wave heights and wave periods derived from WG module are further used in determination of shear stress, critical shear stress and sediment erosion zones using the Estimated Spectral Analysis (ESA) method (Wiberg and Sherwood 2008).

Some examples of how **BoMo** may be used include:

- Evaluate the effects of boat wakes on marine habitat and help in selecting the site for restoration work.
- Evaluate the effectiveness of artificial barriers (seawall, sandbars and shoals) on habitat and ecological functions due to boat wake impact.
- Effect of seagrass beds on reducing the boat wake impact due to bottom friction.
- Impact of boat wake on unprotected shoreline erosion.

Context: Boat wakes in the AIWW

To understand the boat wake issue in the AIWW a pressure transducer array was established along an unregulated speed portion of the AIWW starting in January 2010 (77° 18' 37.99"W, 34° 33' 3.26"N; approximately 80km north along the coast from Snow's Cut) as part of a DCERP[2] research program. This array remains in place and will continue to collect data during most of 2011. The pressure transducer array functions as an integrated wave recorder and consists of four RBR loggers XR 620D and one RBR logger XR 620 attached to a piling installed at the edge of the AIWW. Each logger collects pressure data continuously over the year at 6Hz (6 reading per second) to resolve the individual wave and identifying the transient (short duration, high frequency) of boat wakes. The loggers were programmed to start and stop sequentially with minimum time

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[2] Defense Coastal/Estuarine Research Program   https://dcerp.rti.org/ (last accessed Feb. 8, 2012).

overlap meaning that collectively, the array of 5 loggers provides a continuous record for approximately 3 weeks. At this interval, the loggers are downloaded, memory cleared, batteries replenished and redeployed by NOAA CCFHR researchers. The loggers undergo calibration procedures every time before deployment to check for drift and data quality. A more detailed description of these data and their processing can be found in Appendix I.

Figure 1 shows a comparison of the cumulative frequency distribution of ~16 months (February 2010 – June 2011; inclusive) of AIWW boat wakes with wind wave conditions of a nearby water body[3]. This preliminary comparison reveals that the median and 95th percentile of wind waves is larger than those of the boat wake universe but the top few percent of wave events are much larger for boat wakes. However, the relative distribution of wind wave versus boat wakes in the estuary will determine impacts; areas subjected to frequent large wind waves will likely prove resilient to most boat wakes. However, boat wakes measured here occur in the AIWW where fetches are limited and wave heights rarely exceed 0.15m (not shown), meaning that for the sheltered reaches of the AIWW over half of the boat wakes would be exceedance events. The consequences of boat wakes in the sheltered portions of the AIWW are manifested in our observations of large marsh peat fragments tossed onto the marsh surface in the presence of boat wakes. We suspect that the frequency of these extreme event boat wakes is sufficient to cause substantial shoreline erosion. Given that un-modified shorelines in the NRE exposed to wind wave heights of ~ 0.35 m are eroding from year to year, it is not surprising that larger waves from vessels would be responsible for similar levels of shoreline erosion that we have documented along the AIWW.

Snow's Cut Wind Waves
A 100 x 100 ft (30.48 x 30.48 m) array of grid points was created that encompassed the entire Snow's Cut area (Figure 2) yielding a resolution of wave parameters at the 26900 ft² (2500 m²) extent. **WEMo** was run for each grid point, using the top 5% of wind events over the last three years taken from the National Data Buoy Location Station NOXN7 – North Carolina Reserve, NC (34°9'20" N 77°51'3" W**).** Bathymetric data in the area was coarse, therefore the Wilmington District conducted a new, detailed, shore-to-shore bathymetric survey of the area which was merged with Coastal Relief Model bathymetry to create a seamless topography within which **WEMo** and **BoMo** could be applied (Figure 3).

Snow's Cut Boat Wake Simulation
For the **BoMo** simulation the bathymetry was generated as grid cells of 1.5 by 7 ft (across channel and down channel, respectively to provide a necessary minima of sample points for the model's requirement) yielding a resolution of wave parameters at 10.5 ft² (0.98 m²) resolution. Due to resource limitations, we simulated vessel traffic moving north only. We selected vessel sizes and speeds based on an associated, ongoing study (see footnote 2, above) where vessels were automatically filmed and wake size recorded in a nearby (~80 km north of Snow's Cut) non-speed regulated portion the AIWW (within Marine Corps Base Camp Lejeune) during the spring of 2009 when vessels were migrating north through the AIWW for the season. These data were previously used as training, validation and test data to create artificial neural network models (Figure 4) for V-hulled vessels only as these produce the majority of boat wakes in the AIWW (data not shown). Figure 5 shows a frequency histogram of V-hull vessels detected during three, one-week

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[3] New River Estuary (NRE). **WEMo**-derived significant wave heights produced by the top 5% of wind speeds over the most recent three-year period for a grid of 2000 points on 500m centers encompassing the entire NRE.

surveillance session passing the array between April and May 2008. The mean hull length was 13 m (median 12.8 m). The hull lengths of ~7 m and ~16 m represent the bounding conditions for the 25th and 75th percentiles, respectively which we chose as our test case vessels; note that these do not represent the largest vessels observed and thus extreme wake waves were not simulated. We chose six test combinations; two vessel sizes representing large vessels and the more frequent smaller vessels as well as three vessel speeds each representing Slow (3 knots, making headway), Plowing (here, 10 knots and 25% percentile of V-hull observed speed; not shown) and Planing speeds (here, 20 knots and 50% percentile) (Table 1).

Table 1. Description of input parameters for **BoMo** runs. Wave heights and periods are derived from previous modeling efforts (see Figure 4).

Length (m)	Draft (m)	Beam (m)	Vessel displacement Tonnes (1000kg)	Speed Description	Speed (kts)	Speed (m/s)	Wave height (m)	Wave period (s)	Vessel description
7	0.38	2.6	2	Planing	20	10.3	0.177	1.8	23' center console runabout
				Plowing	10	4.63	0.24	1.9	
				Slow	3	1.54	0.07	1.6	
16.4	1.28	5.26	34	Planing	20	10.3	0.29	2.2	54' yacht
				Plowing	10	4.63	0.38	2.3	
				Slow	3	1.54	0.09	1.8	

Comparative Analyses – wind waves vs. boat wakes

We compared the boat wakes for each combination of the six combinations of boat length and speed with the top 5% wind events at each sample point. From the wave height and wave period estimates, we also computed the benthic shear stress associated with a given wave at each sample point. Based on an assumption of fine sand throughout the area (0.015 mm average grain diameter) we also computed whether sediment on the seafloor would move and potentially erode (erosion here is considered to be when sediment is moved from its original position) under those conditions. Finally, we compared the transit time across Snow's Cut for each speed with the difference among wind waves and boat wakes. Transit time provides a preliminary basis for assessing costs imposed on vessel traffic in an attempt to mitigate wave heights, energy and sediment shear stress above ambient (wind wave) conditions caused by boat wakes.

3. RESULTS

Transit Times

We computed the difference in time it would take to transit the 2 mile section of Snow's Cut for the different vessel speeds simulated in this study (Table 2).

Table 2. Time to travel 2 miles at different vessel speeds.

KNOTS	MPH	TRANSIT TIME	INCREASED TIME (min)	X INCREASE
20	23.0	5.2	--	--
10	11.5	10.4	5.2	2.0

7	8.1	14.9	9.7	2.9
3	3.5	34.8	23.2	6.7

Boat wake heights vs. wind waves

Wave height forecasts provide the first step in determining where sediment movement and erosion may occur. Such forecasts also provide a basis for assessing where mariner safety may be at risk. The boat wake X speed models (Figure 4) reveal a rapid increase in boat wake size over that of local wind conditions above speeds of ~ 7 knots.

Wind Waves: Wind waves in Snow's Cut can occasionally develop to ~ a third of a meter (~ 1 foot) under normal conditions (top 5% of wind events, excluding extra-tropical storms) given the long fetch susceptible to ENE and WSW winds (bottom panel, Figures 6 & 7). Boaters may experience slightly larger, steep waves when tidal currents are running against a strong wind.

7m vessel waves: The top three panels of Figure 6 show the results of the **BoMo** simulation for wave heights using 7 m vessels for each of the three speeds and in comparison to wind waves. At slow speed, boat wake heights were within the range of local wind conditions, indicating no substantial addition of energy to the system beyond that of ambient conditions. At plowing speeds, wave heights have begun to match or slightly exceed that of top wind events. At planing speeds, wave heights have diminished to within the range of wind events revealing the comparatively (to plowing) lower displacement of the hull for vessels of this size when on plane

16m vessel waves: The top three panels of Figure 7 show the results of the **BoMo** simulation for wave heights using 16 m vessels for each of the three speeds and in comparison to wind waves. As with the 7 m vessel, at slow speed, boat wake heights were within the range of local wind conditions, indicating no substantial addition of energy to the system beyond that of ambient conditions. However, at plowing speed, wave heights frequently reached 0.5 m which greatly exceeds the wave heights for local wind events, and, were focused on the south side of Snow's Cut as well as around a constriction approximately 1500 feet from the west end of Snow's Cut. At planing speeds, wave heights frequently reached 0.3 m which were substantially greater than the ambient wind wave heights and were broadly distributed throughout Snow's Cut. Even on plane, vessels of this size do not rise sufficiently onto the water surface to displace less water than as seen for the 7 m vessels; vessel speeds would have to be considerably greater to lift the bulk of the vessel onto the water surface; such speeds have not been observed in our video reconnaissance of the AIWW (see above: ***Context: Boat wakes in the AIWW***). However, at planing speeds, wakes were diminished as compared with plowing speed conditions.

Boat wake erosion zones vs. wind waves

Although wave heights describe energy distribution at the water surface, sediment movement only occurs if waves enter sufficiently shallow water to transfer energy to the seafloor. Here, we computed whether sediments were likely to move and potentially erode from the seafloor based on the various combinations of vessel size and speed as compared to wind events over the Snow's Cut area. Given that most of the channel margins are composed of sand at the angle of repose, waves did not cause erosion until very close to shore, giving the appearance in the figures of this being shoreline erosion; all erosion forecasts here are for areas of submerged seafloor only.

Wind wave erosion: The bottom panels of Figures 8 and 9 (identical) shows where sediment movement should occur as the result of wind waves. Many of the locations occur on shallow

subtidal shoals near the shore and give some appearance of coinciding with irregularities in the channel margins. These features may focus wave energy and thus are particularly vulnerable 'hot spots' for erosion potential.

7 m vessel erosion: At slow speeds for this vessel size, no significant additional erosion was forecast (Figure 8). Once the vessel reaching plowing speed, large but narrow extents of the shoreline and nearshore shoals became susceptible to erosion, particularly on the south side of Snow's Cut. These areas occurred throughout the areas forecast for wind waves, but expanded and joined those zones. However, once this size vessel reaching planing speed, erosion on the north side of Snow's Cut virtually ceased and both the extent and width of the erosion zone on the south side of Snow's Cut was also measurably diminished. The west end of Snow's Cut and the southern shoreline of Snow's Cut were consistent 'hot spots' for potential sediment erosion.

16 m vessel erosion: Even at slow speeds, some erosion was forecast to occur on the south side of Snow's Cut, but the area was largely within a zone already forecast for wind wave erosion (Figure 9). When this vessel size reaching plowing speed, most of the shoreline and shoals within Snow's Cut were within erosion zones; the west end of Snow's Cut and long sections of the south side of Snow's Cut were particularly vulnerable. At planing speed, the erosion zones forecast for the plowing speed was generally diminished but mostly by a slight reduction in the width of the zones in the direction of the channel; linear extent of the erosion zones along Snow's Cut did not diminish substantially. The west end of Snow's Cut and the southern shoreline of Snow's Cut were again consistent 'hot spots' for potential sediment erosion and these zones became noticeably wider and longer under wakes from this vessel size.

4. CONCLUSIONS

Boat wakes in the AIWW along the North Carolina coast produce wave heights that rival those of wind waves in nearby water bodies (New River Estuary; NRE) and exceed that forecast for Snow's Cut. In a stretch of the AIWW approximately 80 km north of Snow's Cut that does not have vessel speed regulation; we estimate that ~50% of boat wake heights exceed the largest wind-generated waves.

At Snow's Cut, both simulated V-hulled vessels generated the greatest wake heights and largest sediment movement zones at plowing speeds. V-hulled vessels of ~7 and 16 m length represent the 25th and 75th percentile of boat traffic in the AIWW based on surveillance at Marine Corps Base Camp Lejeune. Vessels of the 7 m size class generate wakes that only slightly exceed the heights of the top 5% of natural wind waves, but do so over a more expansive area resulting in a measurable extension of the sediment movement and presumably, erosion zone. V-hulled vessels of the 16 m size class generated wakes and sediment movement zones greatly exceeding that forecast to arise from natural wind events. The trench-like nature of Snow's Cut ensures that waves reach nearshore or shoreline locations with little reduction in height. Concentration of energy in these narrow bands along the shoreline would seem to create the potential for bank under-cutting and even collapse which would add more sediment to the waterway.

Several factors should be considered to create a more comprehensive examination of the hydrology of the waterway. As mentioned previously, we did not simulate south-moving traffic due to resource limitations; this simulation could reveal some new 'hot spots' but could only increase, not negate, any of the erosion forecasts already provided. We did not perform simulations at higher

vessel speeds that could generate greater wakes given that our highest speed was the median value for V-hull boats in the waterway. We also did not consider tidal currents in our assessment. One of the principal roles that tidal currents could play however would be to increase or decrease the wave energy at which sediment motion initiates. Thus, aside from re-distributing sediment in the waterway and contributing to the formation of shoal features, tidal currents could contribute to near-shore liberation of sediment. A comprehensive energy budget of the waterway that examines the comparative contribution of the comparatively few, but extreme wake waves generated by the largest vessels should be considered; extreme events are well-known agents in exceeding living habitat and shoreline stability limits.   Finally, the influence of very large but slow-moving vessels such as barges that have substantial displacement as compared with the volume of the waterway should be studied; these vessels generate what is effectively a very long period wave with high erosive capacity and fast moving currents along the edges of the shore. Their rare appearance in the waterway may also constitute an extreme event.

Nonetheless, even with the limited examination of vessels and speeds conducted in this rather preliminary study, measurable boat wake wave impacts were forecast. We posit that the larger size vessels transiting Snow's Cut (and likely other extensive fetch-restricted areas of the AIWW) frequently generate wakes of heights that result in sediment movement in nearshore area that are substantially in exceedance of natural wind wave events. If the speed, particularly of large V-hulled vessels, were reduced to pre-plowing levels (~ 7 knots from 20 knots) vessel wakes are generated that are sufficiently small so as to not transform into sediment-eroding waves as they encounter shallow water at the margins of the waterway) transit times for Snow's Cut would be increased approximately 10 minutes. These longer transit times (and smaller wakes) would likely substantially reduce the creation of erosion-generating boat wakes. It is likely that boat wakes significantly exceed wind wave background for much of the sheltered portions of the AIWW and similar analyses may be useful in identifying management options.

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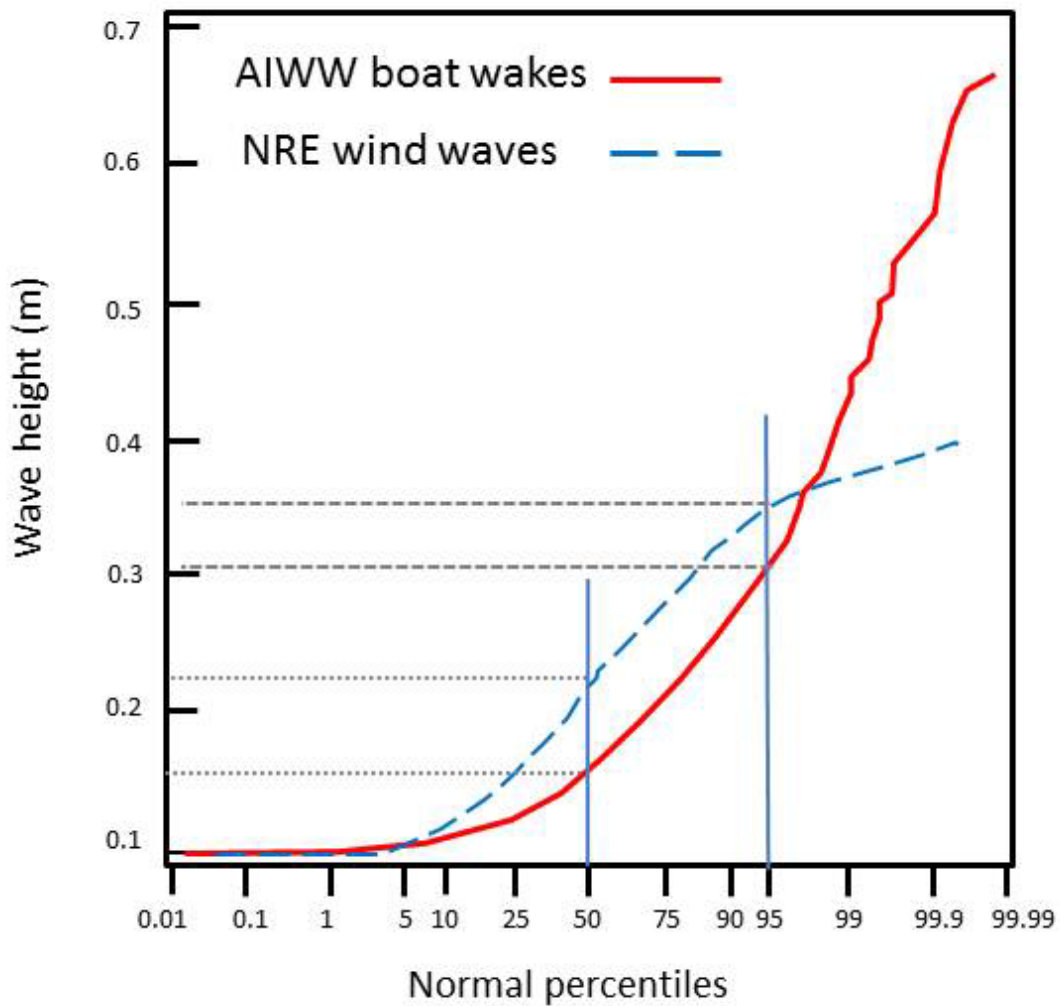
FIGURES

Figure 1. Cumulative frequency of natural wind waves from the New River Estuary and boat wakes in the AIWW; Note: Data are only for waves > 0.10m. Boat wake data are for February 2010 – June 2011 (inclusive); wind wave data are for top 5% wind events 2007-2010.
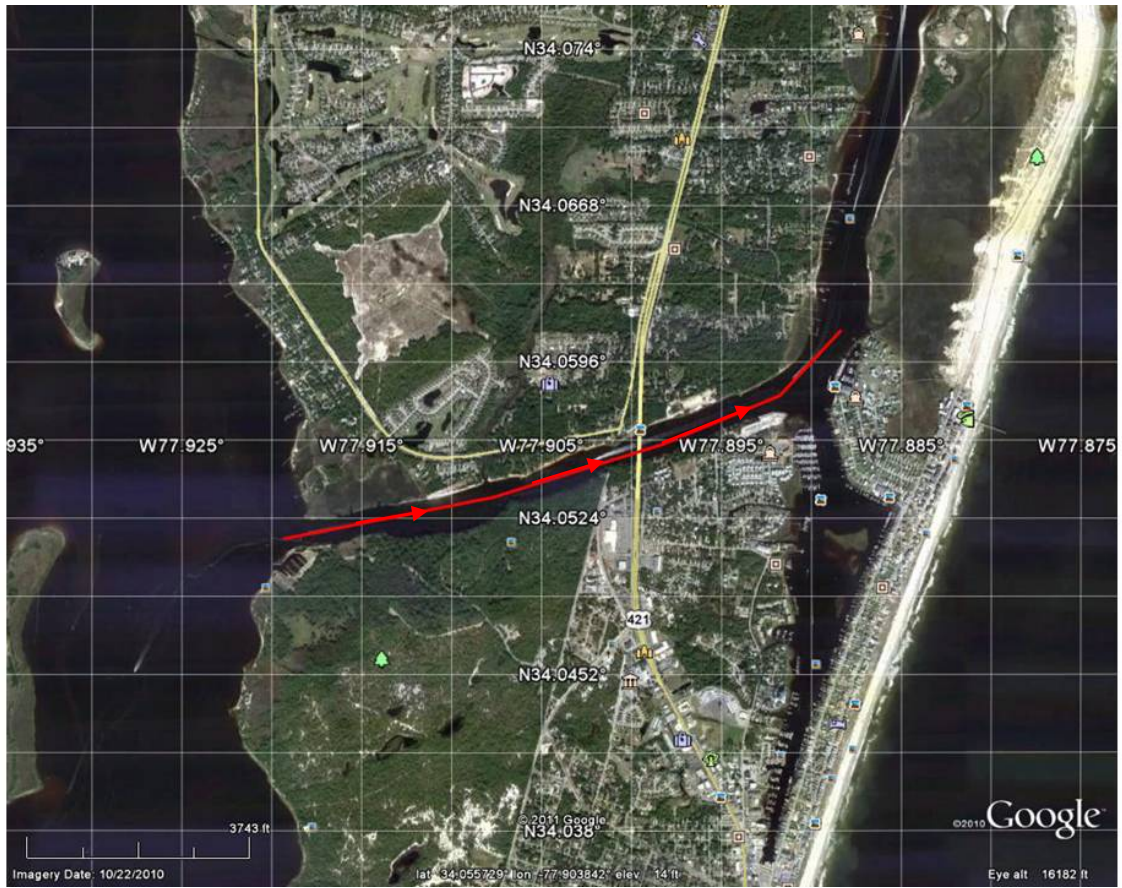
Figure 2. Google Earth image of Snow's Cut, North Carolina. Red line is the 2 mile distance used for calculation of transit times (Table 2).
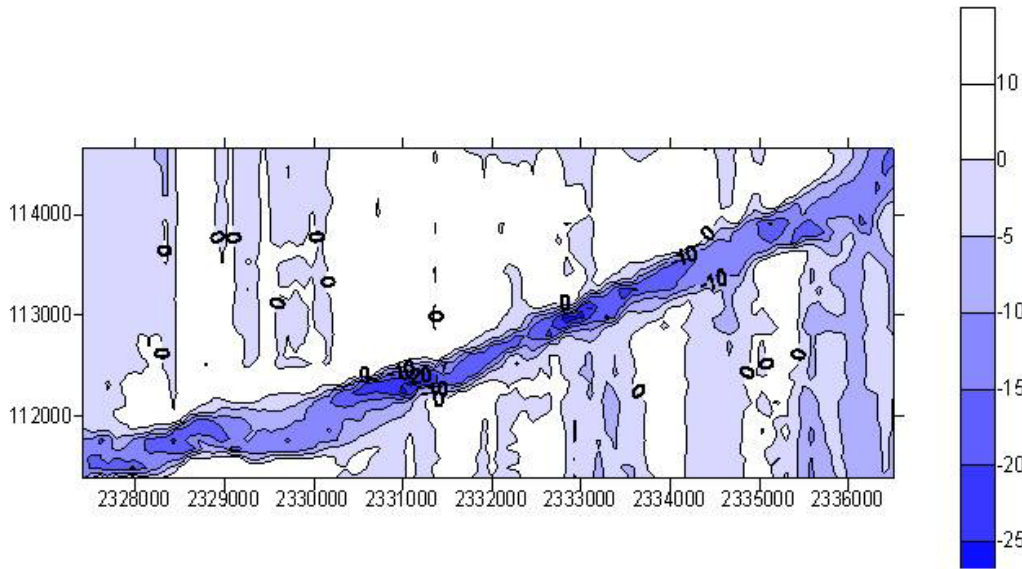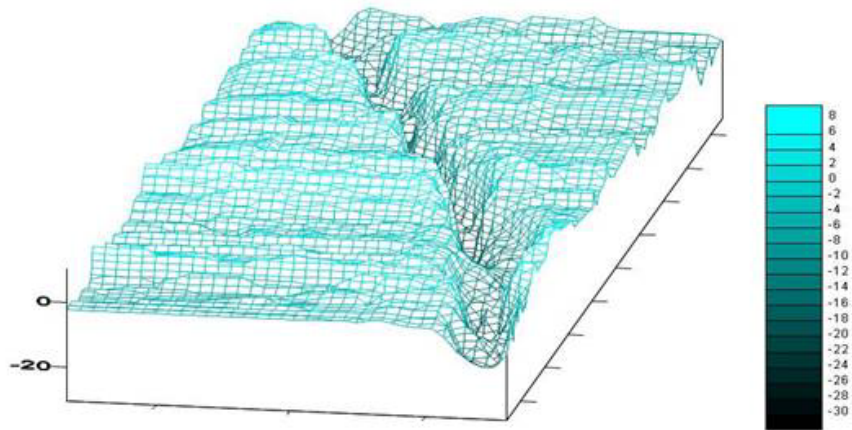
Figure 3. Top: 3-dimensional rendition of Snow's Cut. Bottom: plan view of bottom contour map of Snow's Cut. All elevations in feet (State Plane Coordinate System).
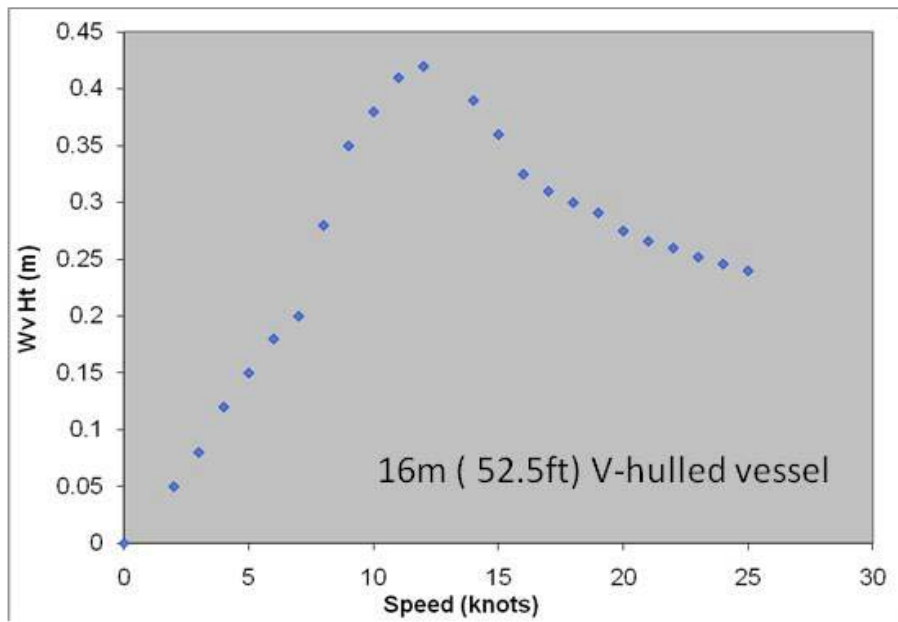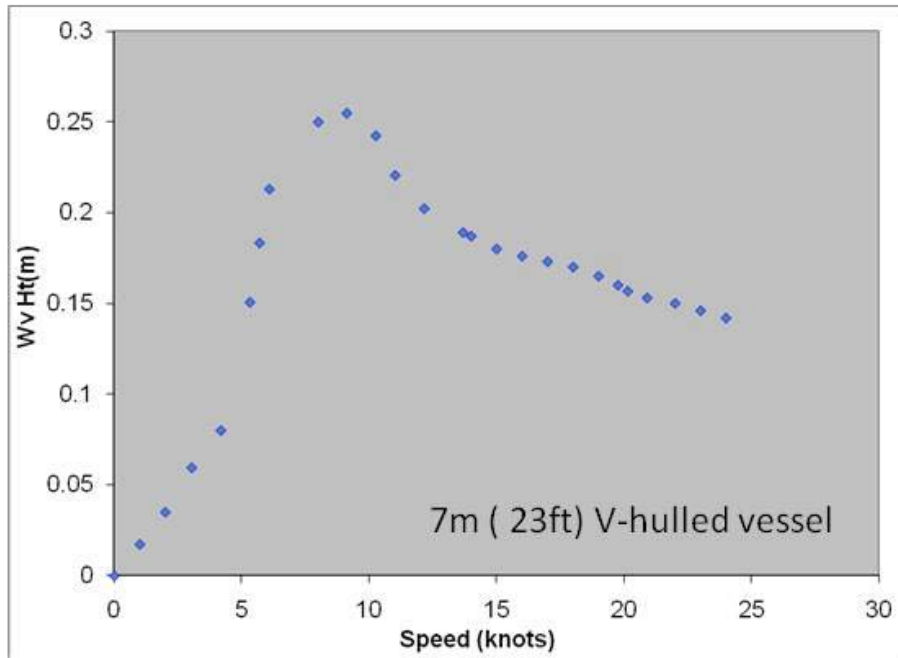
Figure 4. Boat wake wave heights as a function of boat speed. Top: 7m hull. Bottom: 16m hull. Note difference in vertical scales among panels.
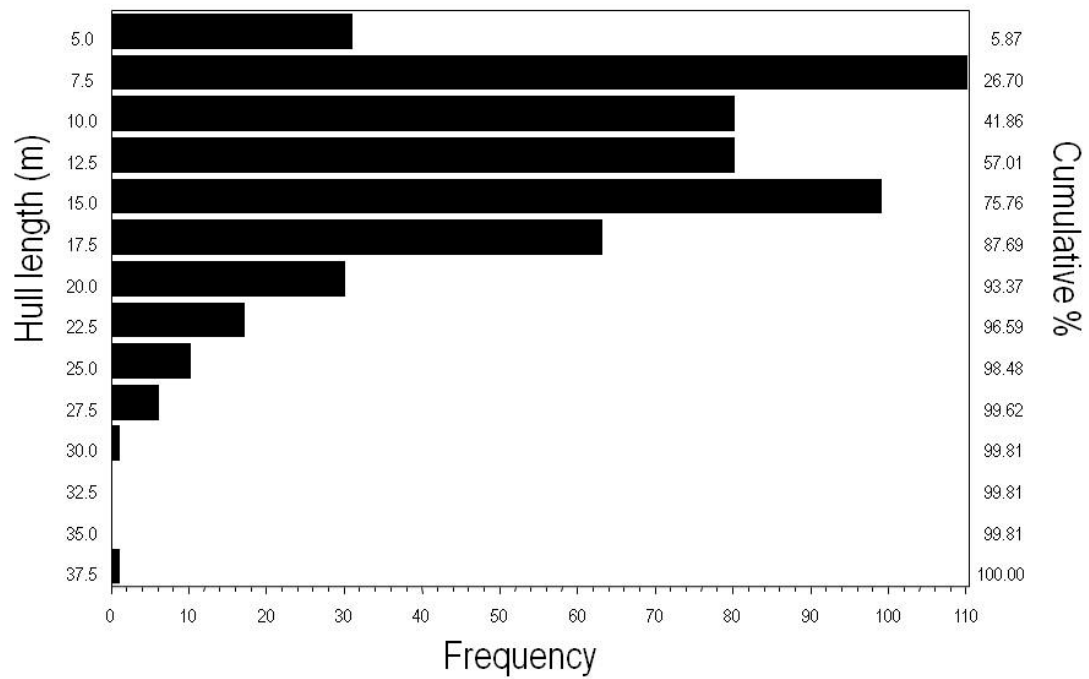
Figure 5.   Frequency distribution of V-hull boats transiting the AIWW in the vicinity of Snow's Cut.
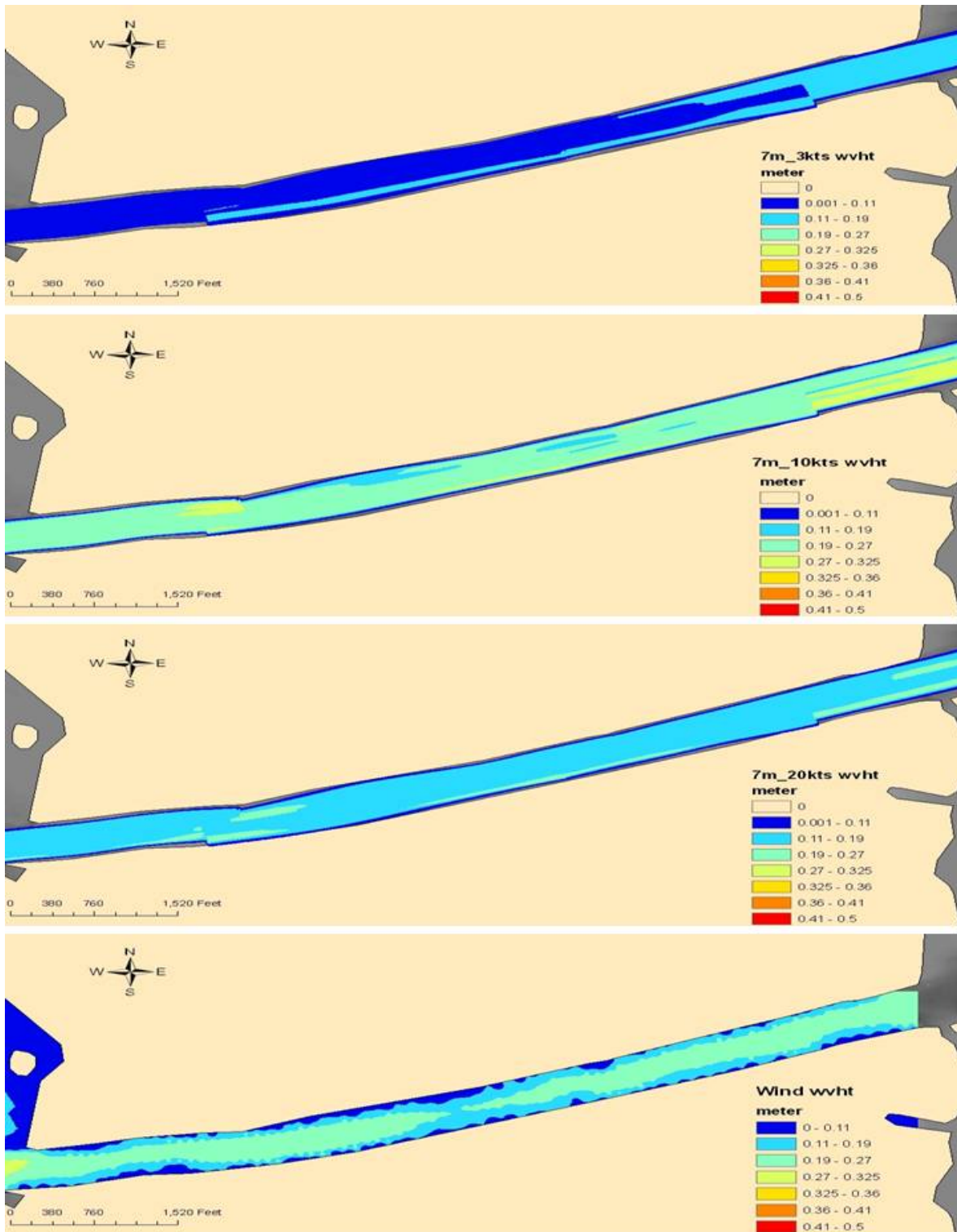
Figure 6. Wave height (m) map of Snow's Cut showing boat wakes (top 3) for a 7 m (23 ft) vessel at speeds of 3 knots (slow), 10 knots (plowing) and 20 knots (planing). Bottom plate shows wind wave distribution for the top 5% of wind events in this area over a three year period.
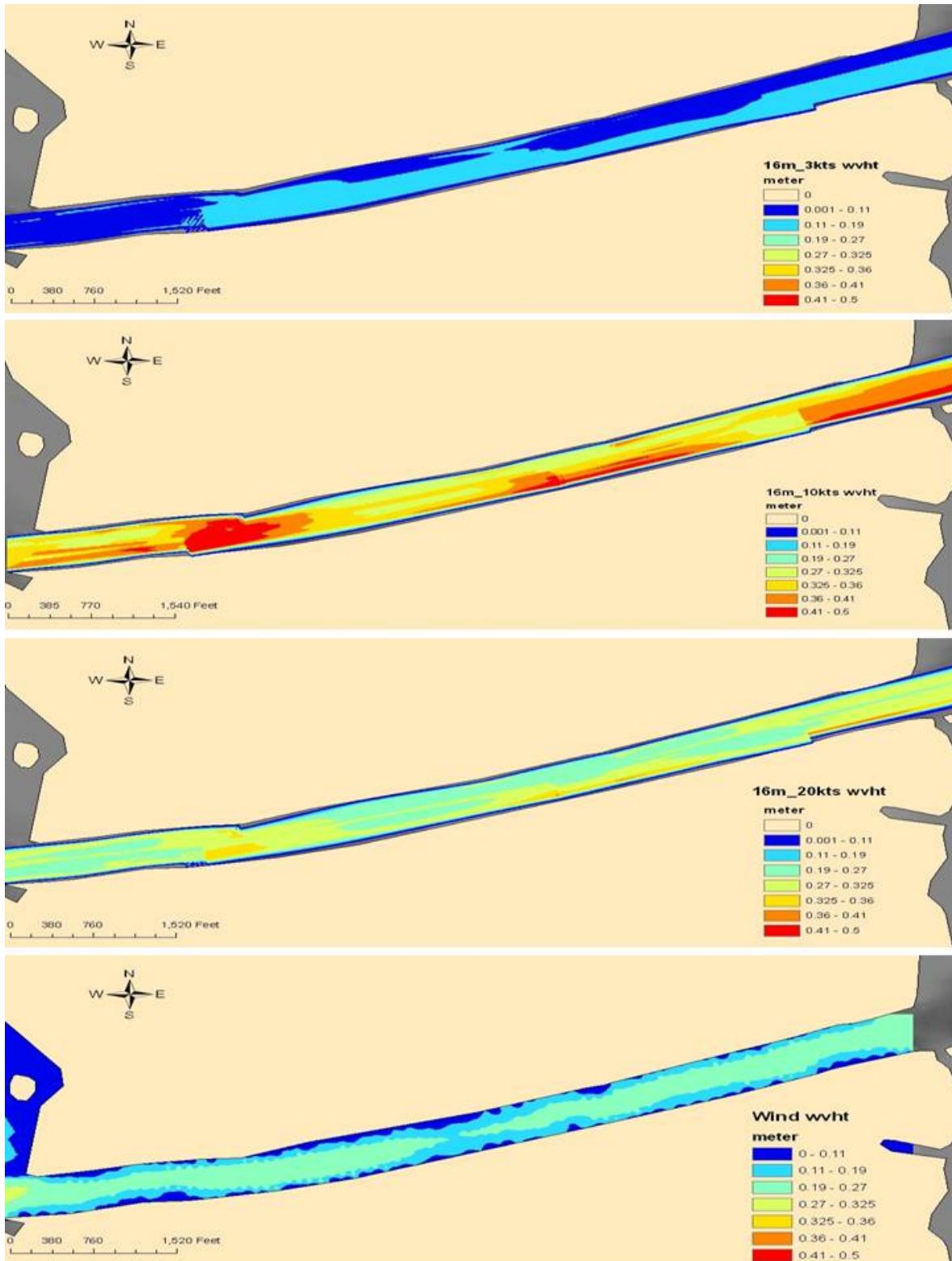
Figure 7. Wave height (m) map of Snow's Cut showing boat wakes (top 3) for a 16 m (52.5 ft) vessel at speeds of 3 knots (slow), 10 knots (plowing) and 20 knots (planing). Bottom plate shows wind wave distribution for the top 5% of wind events in this area over a three year period (same as Figure 6).
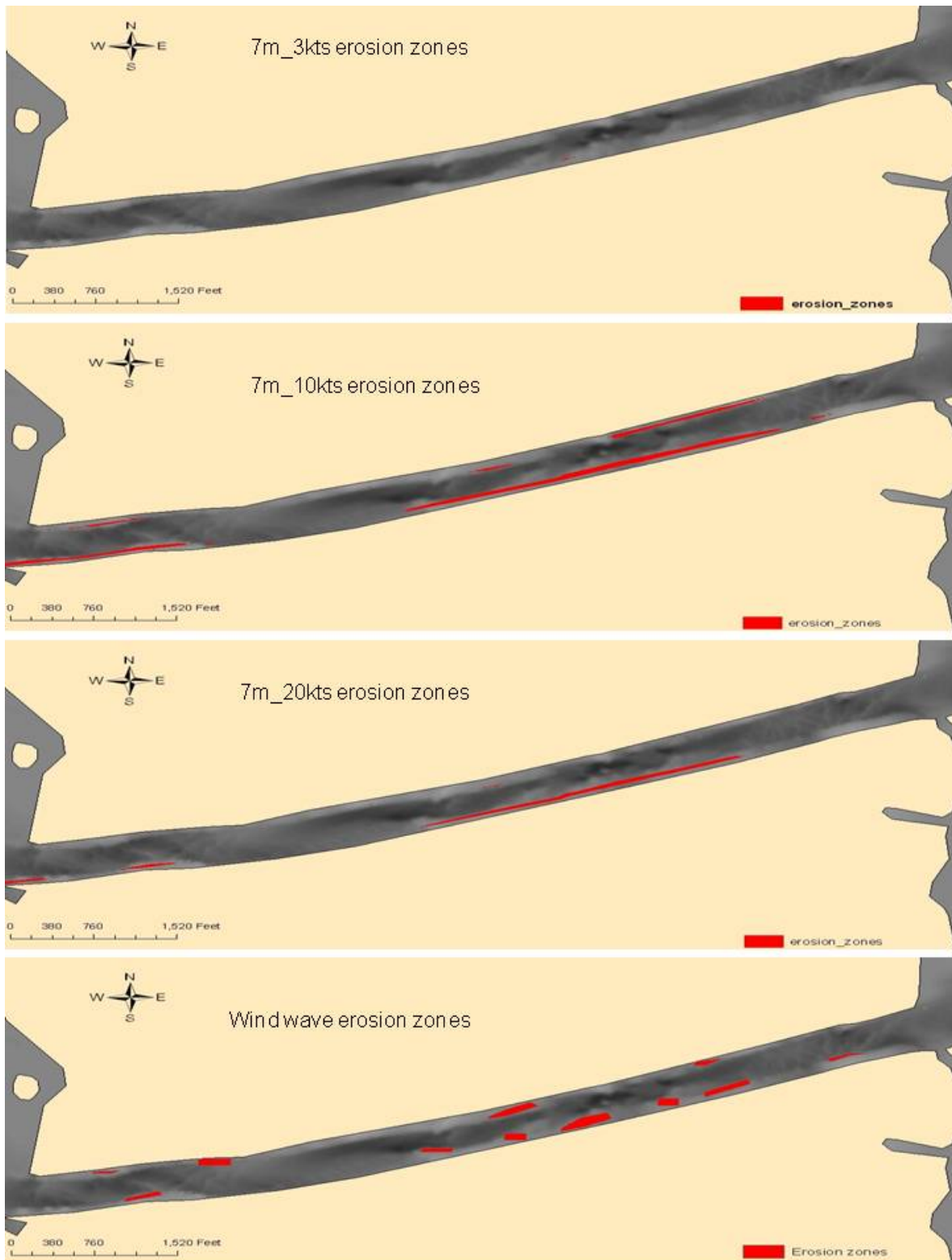
Figure 8. Sediment erosion zone (red) map of Snow's Cut showing boat wakes (top 3) for a 17 m (23 ft) vessel at speeds of 3 knots (slow), 10 knots (plowing) and 20 knots (planing). Bottom plate shows wind wave driven sediment erosion for the top 5% of wind events in this area over a three year period.
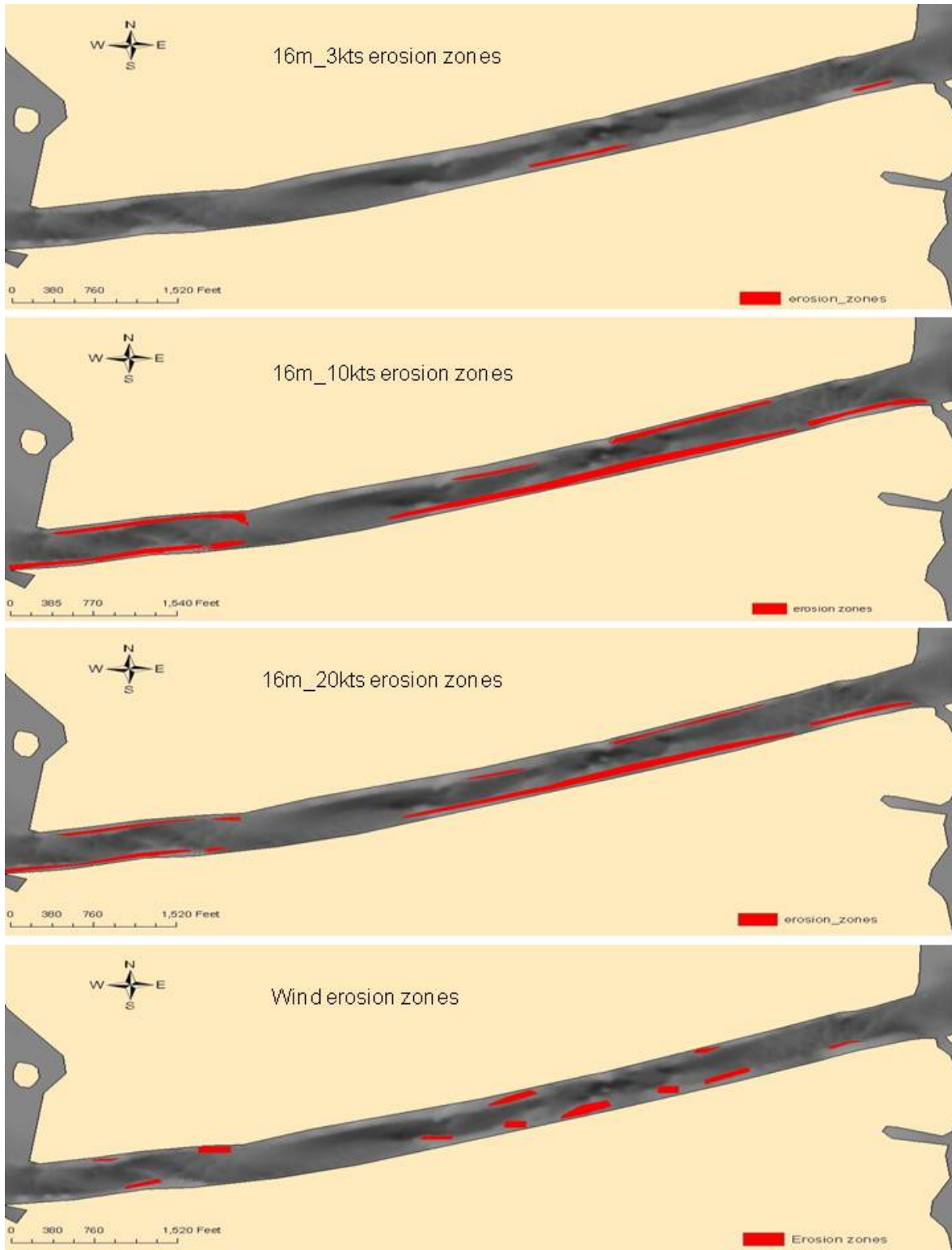
Figure 9. Sediment erosion zone (red) map of Snow's Cut showing boat wakes (top 3) for a 16 m (52.5 ft) vessel at speeds of 3 knots (slow), 10 knots (plowing) and 20 knots (planing). Bottom plate shows wind wave driven sediment erosion for the top 5% of wind events in this area over a three year period (same as Figure 8).

APPENDIX I

Boat wake capture on the AIWW
During three week periods, the five loggers collect almost 500 MB of pressure data making it a very large dataset for a whole year with more than 5 million records. The processing of the dataset was accomplished using SAS[©]. The data processing was divided into three phases: transformation, extraction and loading.

The *Transformation phase* involved taking raw data from the logger and converting into the SAS dataset. The converted SAS dataset was created in a standard SAS format and all outlier and unwanted data were removed. Unwanted data were temperature time series data and header statements collected by the loggers as well as very small (< 5 cm) wind ripple waves. Outliers were introduced while retrieving and installing the loggers (which artificially changed water pressure) as well as rare, extremely low, wind-driven tides; these were removed during visual inspection of each retrieved data file.
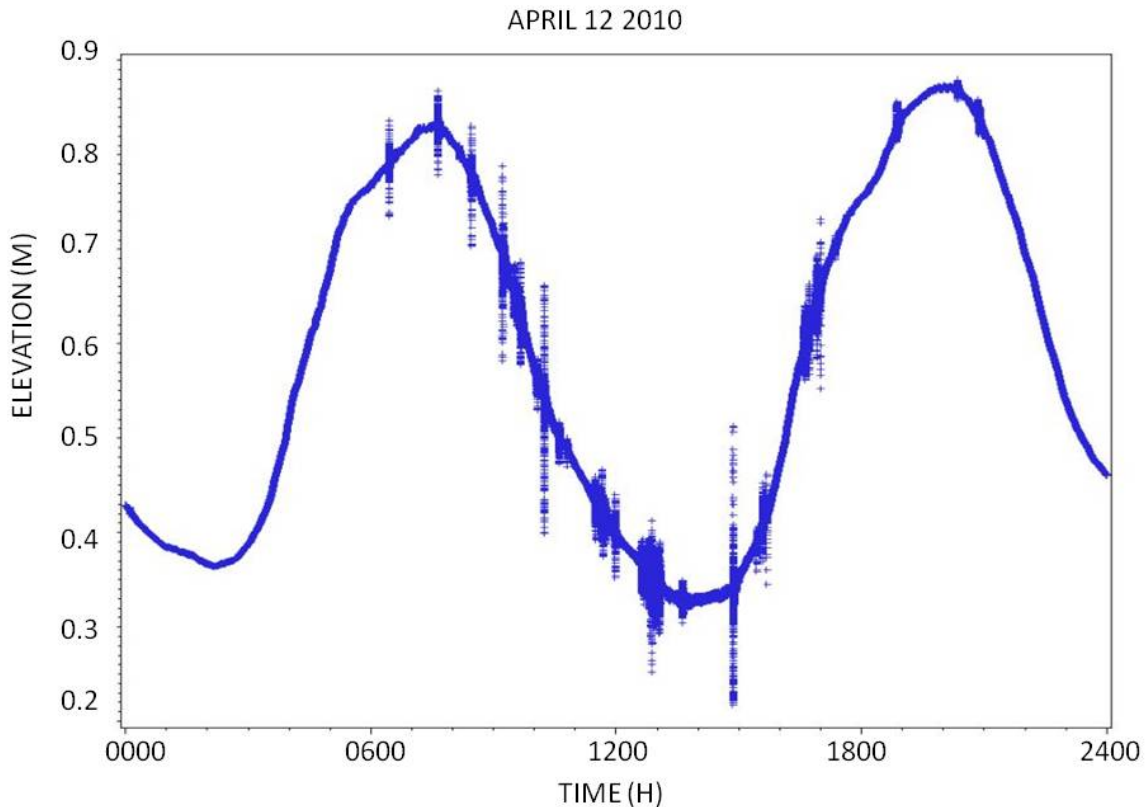

Figure A1. Surface elevation data at AIWW site including boat wake and tidal signals (data excerpt shown here for April 12, 2010).

The *Extraction phase* involved using algorithms to extract boat wakes from the raw pressure data. The first step involved converting pressure data to depth (summing the water level and the elevation of the sensor above the seafloor) using standard equations from linear wave theory that incorporate both static pressure and kinematic velocity of the propagating wave. These depth data include signals of boat wakes, tide, a wide range of wind generated waves and minor tidal current-induced changes in pressure at the sensor surface (**Figure A1**).

Because a boat wake has a characteristic, transient wave signature (i.e., the wave signature does not have the duration of a wind-generated wave train), it can be distinguished from the background noise or other wave signals by running the loggers at these high frequencies. This characteristic was exploited to design a high pass filter for extracting boat wakes from the background noise. The high pass filter was designed and built using SAS. These boat wake signatures extracted using the high pass filter (**Figure A2**) consisted of series of elevation data recorded by the loggers but still contained external noise (i.e., the tidal cycle signal over which the boat wakes are superimposed). To isolate the boat wakes, tidal effects were removed by applying a 5 second moving average window (boat wakes have wave periods less than 5 seconds), thus normalizing all the remaining signals to a common elevation basis. In addition, the signal noise from very small waves (±5 cm) were also removed (**Figure A3**).
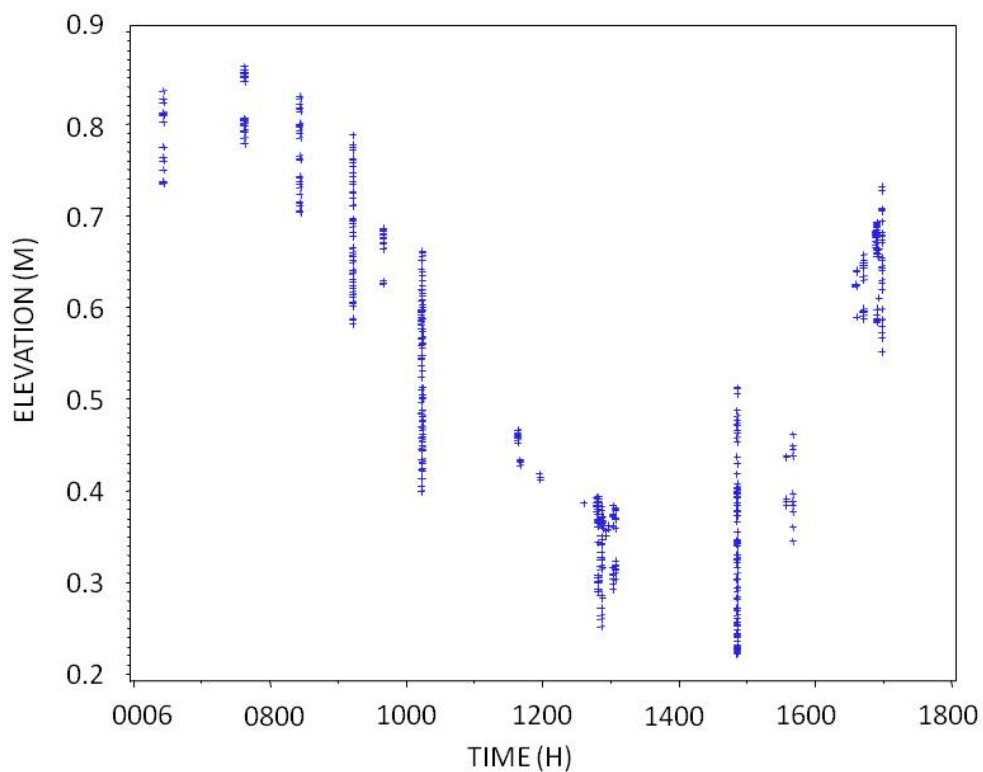

Figure A2. Boat wake signatures extracted after running high pass filter (data excerpt shown here for April 12, 2010).
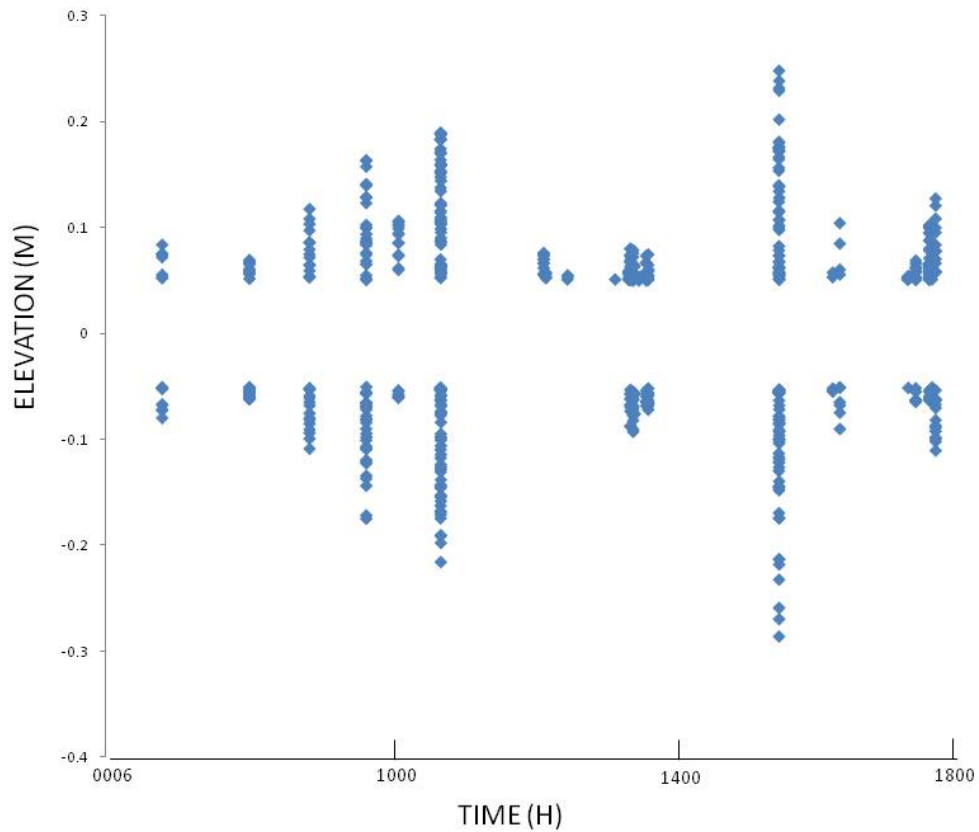
Figure A3. Boat wake signatures extracted after removing the tidal signal and above the ±5 cm threshold value (data excerpt shown here for April 12, 2010).

The final step of the extraction process was to calculate the maximum wave height of individual boat wakes. An algorithm was written in SAS to isolate individual boat wakes by comparing the difference in wave height among sequential records and applying a Boolean test that changed the value in a companion data field if the time between a 5 cm change in water level among sequential records exceeded 10 seconds. Once the water level records were thus uniquely named as individual waves, we computed the minimum and maximum of each individual wave signature; the difference of maximum and minimum provided the boat wake height (**Figure A4**). For illustration purposes, the time scale represented by red box in Figure 4 was expanded in **Figure A5**. These data in **Figure A5** represented a series of three individual boat wakes that occurred at 16:00 hrs on April 12, 2010.
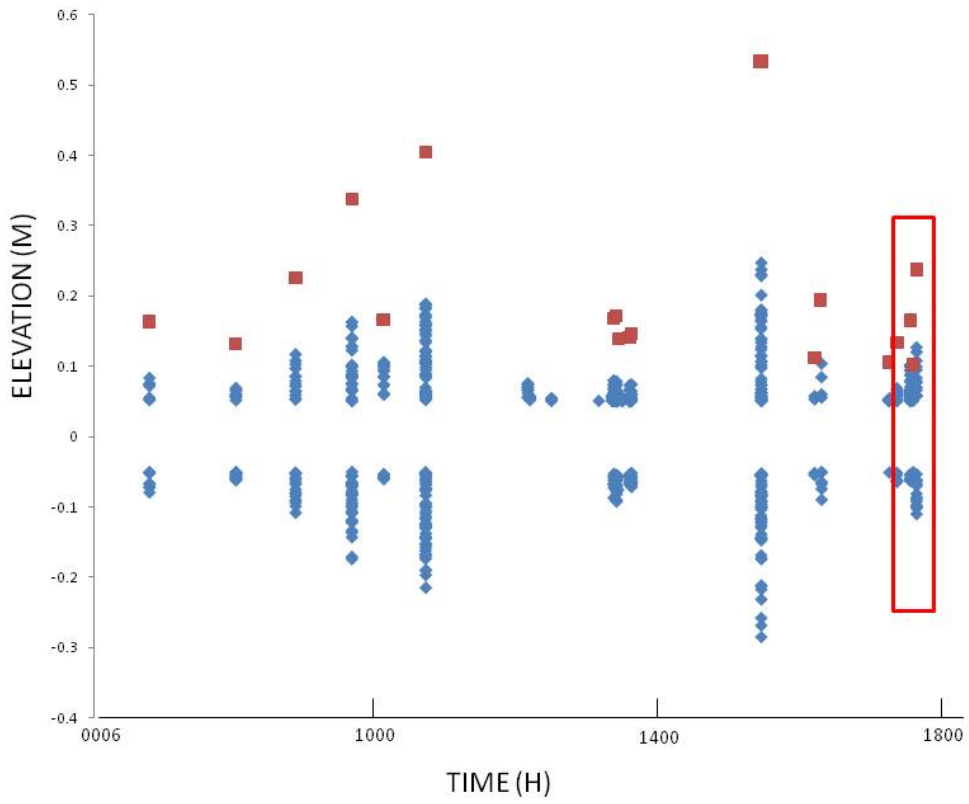
Figure A4. Boat wake signatures extracted (blue diamonds) overlaid with boat wake wave heights (red squares) (data excerpt shown here for April 12, 2010**).**
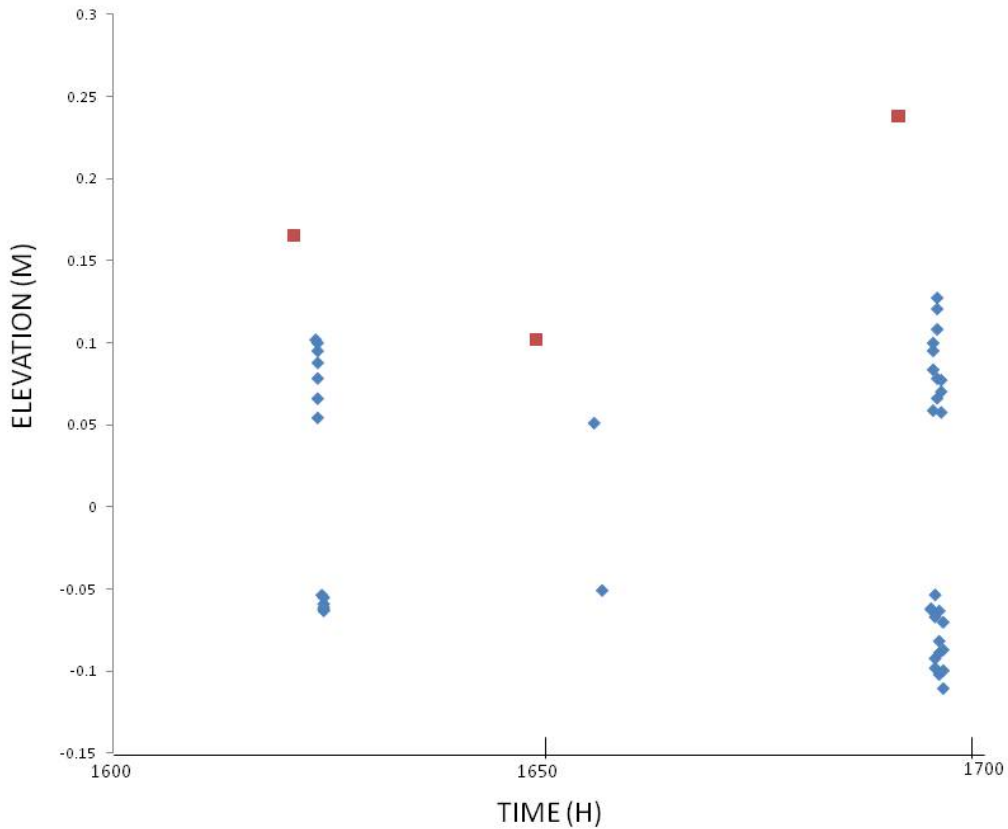
Figure A5. Boat wake signatures extracted (blue diamonds) overlaid with boat wake wave heights (red squares) for zoomed in for a one hour window (data excerpt shown here for April 12, 2010).

The *Loading phase* included putting the raw and processed data into a database. An open source database PostgreSQL DBMS was chosen for ease and cost effectiveness after approval by NOAA Information Technology. All data was transferred from SAS to PostgreSQL using SAS scripts. Ten GB of data were loaded into the database for efficient access in this standard format.

We have also conducted additional, periodic surveys of boat wakes by placing an automated camera that recorded the passage of vessels; from these video clips we obtained vessel size, speed and hull type in synchrony with a wave sensor that recorded vessel-generated wakes. These surveys were conducted as previously reported and at the same location as the wave sensor array..

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