Carry Bay Causeway, Lake Champlain
A Wave Modeling and Beach Stability Study

Prepared For

Vermont Department of Fish & Wildlife

Prepared By
BINKERD ENVIRONMENTAL

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Mr. Lawrence Becker, State Geologist - thank you for accompanying me on a day well spent walking along beaches in North Hero and Alburgh. I hope you enjoy the virtual tour of the beach.

To all property owners in North Hero and Alburgh, I extend a very heart-felt thank you. It was my pleasure to work on this project and present to you this report. Thank you for your cordial hospitality during my site visits, and for your emails, letters, pictures, historical insights, and your patience.

[Notes: Many of the figures and charts in this report rely on color to present data. If this report is viewed in black and white, this information will be compromised. Contact information: info@binkerd.com http://www.binkerd.com/carrybay/]

[Cover Picture - Waves approach the east shore of Carry Bay, November 17, 2008 - Upon entering shallow water the wave crest peaks up, breaks and entrains air creating white water, and closest to shore, the final swash of the wave up the beach.]

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A	Eroded cross-sectional area of the slope's profile	m^2 (m – meter)
D	Diameter of rock	m
D_{n50}	Equivalent cube length of median rock	m
g	acceleration due to gravity - 9.81 m/s^2	m/s^2 (s – seconds)
H	Wave height, crest to trough	m
H_b	Breaking wave height	m
H_s	Significant wave height	m
h	water depth	m
h_b	local water depth at wave breaking	m
L	Wavelength	m
L_{om}	Deepwater wavelength	m
N_z	Number of waves	
n	number of observations	
P	Notational permeability	
S	Damage level, relative eroded area $S = A / (D_{n50})^2$	
s	Local wave steepness, $s = H / L$	
s_m	Wave steepness (design), $s_m = H_s / L_{om}$	
T	Wave Period	s
W_{50}	50% value of the mass distribution curve	kg (kilogram)
α	Beach (or structure) slope angle	degrees
Δ	Relative buoyant density, $(\rho_s / \rho_w) - 1$	
ξ_m	Surf similarity parameter, $\xi_m = \tan \alpha / s_m^{0.5}$	
ρ	Mass density	kg/m^3
ρ_s	Mass density of rock	kg/m^3
ρ_w	Mass density of water	kg/m^3
γ_b	breaker index, $\gamma_b = H_b / h_b$	

Abstract

Background – Lake Champlain is one of the most beautiful lakes in the world, but the water quality of the lake has been degraded by human activities, including the construction of causeways. One such causeway, built in 1899 by the Rutland Railroad, extends from Pelots Point, North Hero to Point of the Tongue, Alburgh. A group of residents from North Hero theorized that removal of this causeway would improve water quality. A hydrodynamic study completed in 2004 by ***BINKERD ENVIRONMENTAL*** concluded that an improvement in water quality would occur if even 1/3rd of the causeway were removed. However, with a portion of the causeway removed, waves would enter Carry Bay from the west and could cause damage to beaches and property.

Objectives – The purpose of this project was to describe changes and quantify impacts, especially with regard to waves and beach stability, due to waves entering Carry Bay from La Motte Passage.

Methods – Waves were modeled using a computer program called SWAN (*Simulating Waves Near Shore*) for present conditions (causeway in-place) and two possible future configurations of the north-section of the causeway. With predicted wave characteristics and geological shore data, beach stability was evaluated using two independent methods: (1) weight of rock was calculated using formulas developed for design of shore structures, and compared with weight of rock on beaches; and, (2) by comparing Carry Bay beach characteristics with another beach in Lake Champlain that has characteristics that mimic future conditions.

Results – The return level for wind speeds for various return periods were determined for eight sectors. The return level for a 100 year return period, west wind was 52 mph. Winds and frequency from four sectors (N, NW, W and SW) were >30 mph, 18 days/yr; >35 mph, 5.6 days/yr; >40 mph, 1.5 days/yr; >45 mph, 0.4 days/yr; and, >50 mph, 0.1 days/yr. Common shore types are rocky beaches that either terminate, or do not terminate, at bedrock banks. Boulders, cobbles and gravel on beaches are from adjacent bedrock and glacial till. Toe of bedrock banks varied from 99 – 100 ft MSL. Lake elevations are expected to exceed 99 ft MSL twenty-four days/yr, and 100 ft MSL seven days/yr. *SWAN* was applied to model the Carry Bay study area and used to predict wave characteristics for present and future conditions. The model predicted wave characteristics for eight wind directions (southwest counterclockwise to north), and seven wind speeds (10 mph increments from 10 to 70 mph). For example, with the causeway in-place, wave heights near Blockhouse Point and 100 meters from shore, for SW winds of 30, 40, 50 and 60 mph were predicted to be 0.4, 0.55, 0.7 and 0.85 meters, respectively. For these same conditions, but with the north section of the causeway removed, wave heights were 0.5, 0.65, 0.85 and 1.05 meters. Wave heights and increases in wave heights decrease closer to shore. Lake levels greater than 99 ft MSL concurrent with winds >30 mph from N, NW, W and SW, were estimated to occur 1.2 days per year.

Conclusions – An evaluation of existing beach armor compared with design requirements for stability of rock covered embankments, concludes that beaches are stable for existing conditions, and would remain stable for conditions expected after removal of the north section of the causeway. The rate of bedrock recession would not increase due to the relatively small increase in wave energy and the infrequent simultaneous occurrence of high water and high winds. Also, bedrock bank recession is related to stability of the foreshore and, since beaches adjacent to bedrock remain stable, the rate of bedrock weathering and erosion would not change in the future. In general, a 10 mph increase in wind speed was equivalent to removal of 1/3rd of the causeway, e.g. wave conditions observed now at Blockhouse Point with winds of 50 mph, would be observed at 40 mph with 1/3rd of the causeway removed.

1.0 INTRODUCTION

The Carry Bay causeway extends about eight tenths of a mile from Pelots Point, North Hero to Point of the Tongue, Alburgh, and was constructed in 1899 as part of the "Champlain Island Extension" by the Rutland Railroad.[1,2,3] The Rutland Railroad operated the Champlain Island Extension from 1901 to 1961. In 1961 the Rutland Railroad applied to the Interstate Commerce Commission (ICC) for total abandonment of the Champlain Island Extension. The ICC approved the request for abandonment in 1962. The following year, the State of Vermont purchased sections of the abandoned railroad line, including the section between Pelots Point and Point of the Tongue.

Water quality has deteriorated throughout Lake Champlain, but even more in Alburgh Passage, Carry Bay, and Pelots Bay since these regions receive discharge from Missisquoi Bay, and the natural flow was changed by causeway construction.

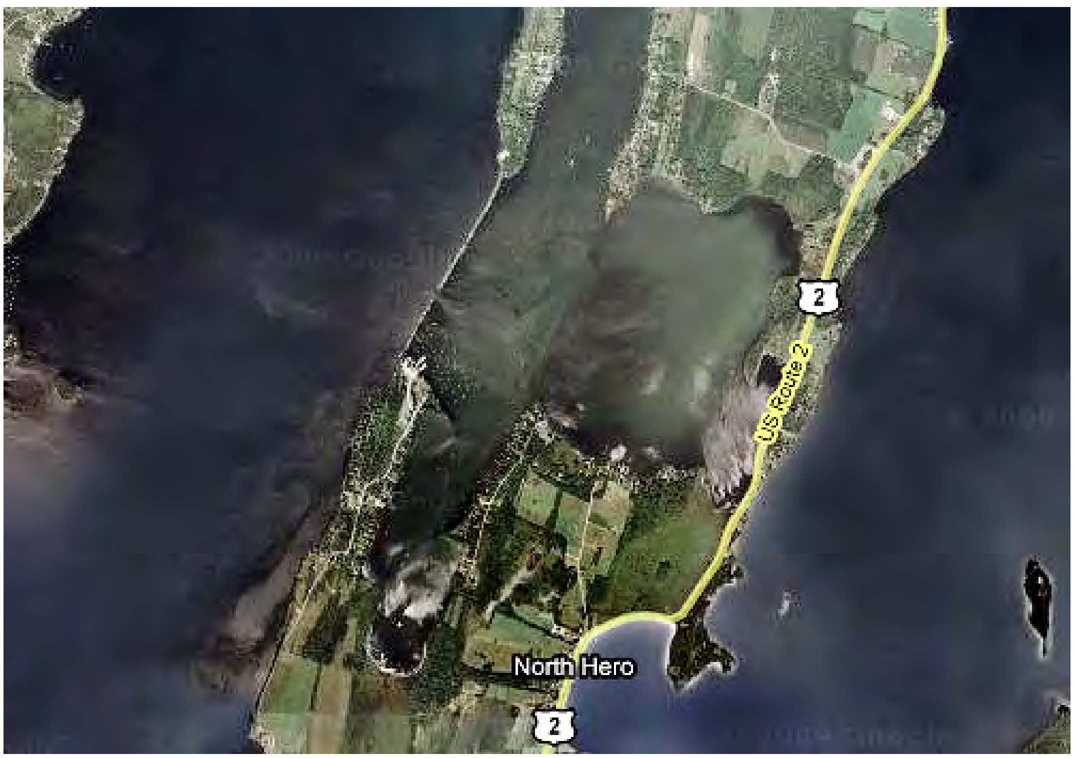

Figure 1.1 Aerial photograph of study area from Google, July 20, 2003.

[1] Rutland Railroad Association
[2] The Island Line, Burlington to Alburgh
[3] Causeways built as part of the Champlain Island Extension are: (1) Carry Bay causeway extending 4,345 feet; (2) a causeway from Colchester to South Hero extending 3.16 miles and separating Mallets Bay from the main lake; and, (3) a causeway 0.4 miles long extending from Grand Isle to North Hero at the west entrance to the Gut.

The aerial photograph in Figure 1.1 was taken on July 20, 2003, and the green color of the surface of the water is, most likely, algae.

In 2003 a group of residents in North Hero formed the "Northern Lake Champlain Restoration Committee" and promoted a bill in the Vermont legislature to fund a study to determine if removal of the causeway would improve water quality east of the causeway. In 2004 a study was completed that demonstrated water quality would improve by increasing exchange of water east of the causeway in Alburgh Passage, Carry Bay, and Pelots Bay with water west of the causeway in La Motte Passage.[4]

The increase in water quality predicted in the 2004 ***BINKERD ENVIRONMENTAL*** study supports causeway removal, but other environmental impacts must be considered. For example, the causeway is essentially a breakwater and prevents waves from entering Carry Bay from La Motte Passage. If a portion of the causeway were removed, waves from La Motte Passage would enter Carry Bay unimpeded and possibly cause damage to beaches, bedrock, and property. The purpose of this report is to describe changes and quantify impacts, especially with regard to waves, beach stability, and bedrock recession that would occur due to larger waves entering Carry Bay.

1.1 Overview of Analysis Method

The analysis begins with predictions of wind wave characteristics with the causeway in-place (present condition) and with portions of the north section of the causeway removed (future conditions). Waves are predicted using a mathematical model called SWAN, *Simulating Waves Near Shore*, written by Delft Hydraulics Laboratory.[5] Site data required to apply this model to Lake Champlain were lake topography, lake water elevation, wind velocity, and geometry of the causeway. Three different configurations of the causeway were simulated: (1) existing geometry (in-place); (2) 1,150 feet of the north section of the causeway removed (no-north); and (3) 1,450 feet of the north section of the causeway removed (littoral-zone). The length of the causeway removed in the simulation for no-north configuration equals the length of the middle section. The littoral-zone configuration provides a larger opening and extends closer to shore.

The previous study on water quality investigated removal of the middle section; this study considers removal of the north section. Removal of either section would provide similar water quality results, but removal of the north section would help restore connectivity of the littoral zone[6] at Point of the Tongue.

[4] "*Carry Bay Causeway, A Field Study and Hydrodynamic Model,*" January 2004, by *BINKERD ENVIRONMENTAL*.
[5] WL | Delft Hydraulics
[6] Definition of littoral zone in the Coastal Engineering Manual, Appendix A, Glossary of Coastal Terminology "…an indefinite zone extending seaward from the shoreline to just beyond the breaker zone." Definition of littoral

The next task was to evaluate beach stability. Beaches[7] in the study area are covered with gravel, cobbles, and boulders similar to rock covered embankments. Revetment (rock on an embankment) protects against erosion by wave action or currents. Rocks on beaches serve the same purpose. The task is to evaluate beach stability for sea states predicted with the causeway removed. Using descriptions of the beach and wave information from SWAN, beach stability was evaluated using formulas developed by Van der Meer.[8,9] Van der Meer's formulas have been extensively tested and are included in the U.S. Army, *Coastal Engineering Manual*[10] for design of embankments, dikes, breakwaters, berm breakwaters and other shoreline structures.

The method chosen to evaluate beach stability at Carry Bay was similar to a method described by Nurmohamed, et al.,[11] which was used to investigate dike stability. Dikes with a single layer of stone were built in the Netherlands between the years 1820 and 1910 and have survived many years, but the question was – How stable are they? His approach was to obtain descriptions of the slope and weight of rocks on dikes, and wave information from SWAN, and then evaluate dike stability using design formulas developed by Van der Meer - the same procedure used in this evaluation.

Unal, 1998, also used Van der Meer's formulas for investigation of gravel movement on beach slopes.[12] Stability of gravel beaches with slopes up to 1:25 were analyzed by Sistermans, 1993[13] who also used van der Meer's formulas. Sistermans made the point that design criteria for breakwaters and other human made structures often require statically stable structures, which allow no (or very little) displacement of rock at design conditions, whereas, gravel beaches are dynamically stable and reshaping of the beach face

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zone by the Minnesota Department of Natural Resources specifically for lakes is "…that portion of the lake that is less than 15 feet in depth. The littoral zone is where the majority of the aquatic plants are found and is a primary area used by young fish. This part of the lake also provides the essential spawning habitat for most warm water fishes (e.g. bass, walleye, and panfish)."

7 A shore of unconsolidated material such as sand, cobbles and gravel, is usually called a "beach." Coastal Engineering Manual, Appendix A, Glossary of Coastal Terminology.

8 Van der Meer, 1988. Rock slopes and gravel beaches under wave attack. Doctoral thesis, Delft University of Technology, Also Delft Hydraulics Publication no. 396.

9 Van der Meer, J. W., 1987. Stability of breakwater armour layers – design formulae. *Coastal Engineering*, 11, page 234, equation (24).

10 U.S. Army Corps of Engineers, EM 1110-2-1100, revised 1 Jun 06. Coastal Engineering Manual. Part VI, equation VI-5-68).

11 Nurmohamed, N., G. J. Steendam and J. W. Van der Meer. Weight and stability assessment of single layers of orderly placed or pitched natural rock. ASCE, ICCE 2006, San Diego.

12 Unal, N. Erdem and M. Bayazit, 1998. Incipient motion of coarse particles on a slope by regular or irregular waves. *Journal of Waterway, Port, Coastal, and Engineering.* Vol. 124, No. 1, Technical Note No. 14411.

13 Sistermans, P. G. J., 1993. Stability of rock beaches. Delft University of Technology, Hydraulic and Geotechnical Engineering Division, Master Thesis.

does not result in "failure." Dynamic stability permits reshaping of the seaward face as long as there is no loss of material from the system. Sistermans also evaluated beaches with much gentler slopes of 1:25 compared with of slopes of 1:1 to 1:6 investigated by van der Meer and concluded that, for gently slopes, wave attack is reduced and the stability of rock due to gravity forces increases.[14]

Further, a study by Marcel van Gent (1995)[15] applied van der Meer's formulas, finite element mathematical modeling, and scaled hydraulic physical models to study shaping and reshaping of rocks on the seaward face of dynamically stable berm breakwaters. Van Gent proposed an extension of his work on engineered structures to include gravel beaches "…This same procedure could be adapted to model the reshaping process for structures or beaches that contain large immovable components….Examples include gravel beaches fronting seawalls…" Instead of building massive structures that depend on gravitational forces to resist the power of waves,[16] an alternative design for shore protection copies nature's design for gravel and cobble beaches with bedrock banks, like those found near Carry Bay.

The second method to evaluate stability of Carry Bay beaches for future conditions was based on a well-established hydrodynamic analysis technique that utilizes physical hydraulic models. The physical hydraulic model used in this analysis, however, was not a typical scale model found in the laboratory, but Lake Champlain itself - a full-scale physical model. This method compares Carry Bay beach characteristics with characteristics of a stable beach in Lake Champlain that has been exposed, for a long time, to wind and wave conditions that mimic future wave conditions at Carry Bay.

1.2 Overview of Report

After a brief description of the purpose of this report, **Chapter 1 –Introduction** presents the overall analysis approach, which is, to predict the sea state for present and future conditions and determine if existing beach armor provides adequate protection.

The analysis of wind waves and beach stability require descriptions of meteorological, geological, and hydrological site characteristics. Each of these descriptions is contained in a separate chapter. Meteorological data are analyzed and design wind speeds and directions are selected in **Chapter 2 – Meteorological Characteristics**. Selection of design wind speeds is based on an analysis of the

[14] *ibid*., page 28.
[15] Van Gent, Marcel R. A., 1995. Wave interaction with berm breakwaters. *Journal of Waterway, Port, Coastal, and Engineering.* Vol. 124, No. 1, Technical Note No. 14411.
[16] Sveinbjornsson, P. I., 2008. Stability of Icelandic type berm breakwaters. Delft University of Technology. Master of Science Thesis.

frequency of return of a wind event of a certain magnitude. This meteorological analysis utilized 59 years of daily maximum wind observations from the Burlington International Airport.

A geological description of the study area is presented in **Chapter 3 – Geological Characteristics** featuring a virtual tour of the shore. Geological features and processes are discussed using specific examples depicted in photographs. Quantitative measurements of beach slope and rock characteristics are also presented in Chapter 3.

Chapter 4 - Hydrological Characteristics begins with a section on lake water levels with emphasis on return frequency of selected lake elevations. A hundred year database is utilized in this analysis. With meteorological information and lake level data, wave characteristics are calculated using a mathematical model. Chapter 4 contains a section on model application to Carry Bay. Results include predictions of sea states[17] for four different wind directions (north, northwest, west, and southwest), three design wind speeds (30, 50 & 70 miles per hour), and three causeway configurations (in-place, no-north, and littoral-zone).

Estimates of wave impacts are presented in **Chapter 5 – Analysis of Meteorological, Geological and Hydrological Data** using techniques documented in the U. S. Army Corps of Engineers "*Costal Engineering Manual.*" The report ends with **Chapter 6 – Conclusions and Recommendations**.

[17] Sea state is a description of the sea (lake) surface with regard to wave action. Coastal Engineering Manual, Appendix A, Glossary of Coastal Terminology.

2.0 METEOROLOGICAL CHARACTERISTICS

2.1 Measurement Conventions

Wind is a vector quantity and is described by speed and direction. Wind direction is reported as the direction that the wind is blowing from relative to true north. Wind direction is measured in degrees or grouped into one of sixteen sectors. Using the letters N, E, S and W to represent north, east, south and west, respectively, these sectors are N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW. Dividing the degrees in a circle (360 degrees) by sixteen results in arcs of 22.5 degrees. Winds blowing from 11.25 degrees either clockwise or counterclockwise from true north are grouped in the N sector; those from 11.25 degrees clockwise to 22.5 degrees clockwise would fall in the NNE sector, and so on around the circle. Winds are also often grouped into eight 45-degree sectors: N, NE, E, SE, S, SW, W, and NW. The speed component of the wind vector is commonly measured in units of miles (statue miles) per hour or nautical miles per hour (knots).[18]

2.2 Data and Analyses

Figure 2.1 shows a "wind rose" based on wind data collected at Colchester Reef from 1996 to 2006. The orientation of the causeway is also shown in Figure 2.1. This wind rose was developed by the National Weather Service[19] based on data collected by the Vermont Monitoring Cooperative.[20] This plot is divided into sixteen sectors.

Based on orientation of the axis of the causeway, winds from the S and SSW would *not* cross the causeway from east to west. For these wind conditions, waves in Carry Bay would be unaffected with the north section of the causeway removed. Winds from these two sectors, S and SSW, occur about 35% of the time. Likewise winds from the SSE, SE, ESE, E, ENE, and NE would generate waves that would move from Carry Bay west, toward Isle La Motte, and would not impact waves east of the causeway. Winds blow from the north slightly less than 10% of the time, and from each of all other sectors, except S and SSW, less than 10% of the time. Winds are calm (zero or close to it) 5.5% of the time.

[18] A nautical mile is 1852 meters or 6076.115 feet. A statute mile is 5280 feet.
[19] Personal communication with Burlington office of the National Weather Service
[20] Vermont Monitoring Cooperative

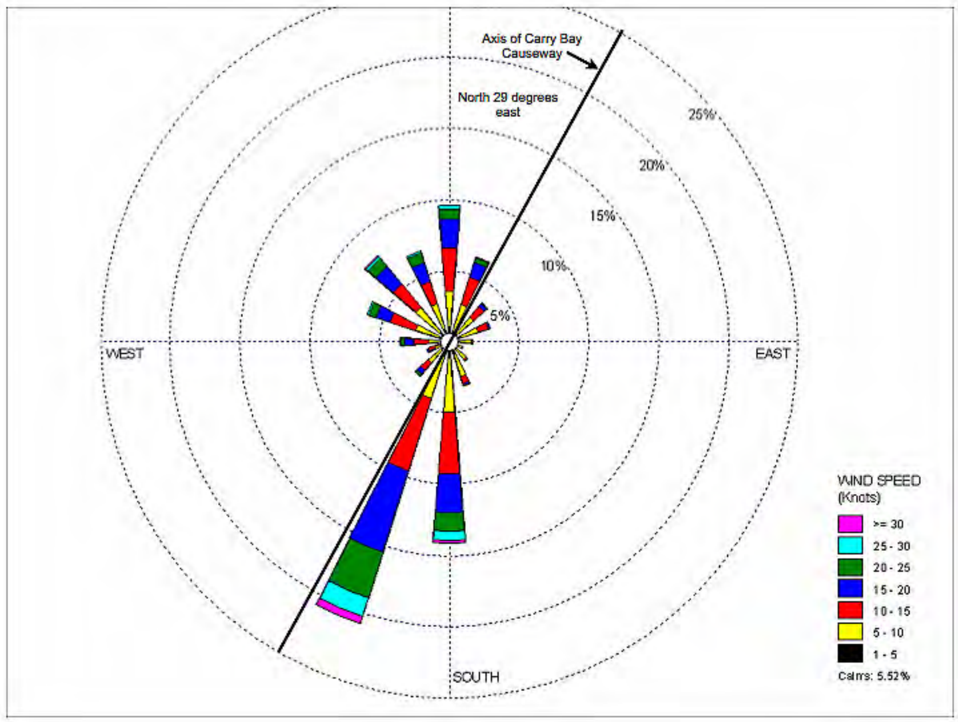

Figure 2.1. Wind Rose prepared by National Weather Service, Colchester Reef, 1996-2006.

The colors in the wind rose (Figure 2.1) represent various ranges in wind speed measured in knots. The maximum range in wind speed includes all wind speeds greater than 30 knots (34.5 mph). This wind rose displays the most frequently observed wind directions, but provides little information concerning infrequent, potentially high impact wind events at speeds greater than 30 knots. To obtain more detailed wind information for higher speeds, other data records need to be investigated.

There are three major weather stations near the study area: Clinton County Airport, New York (#94733/PBL)[21], Burlington International Airport (#14742), and Colchester Reef. All have their pros and cons for selection as a database to use in this study. The Clinton County Airport station is closest to the study area. The Colchester Reef station is also close to the study area but has the shortest database of all stations. The Burlington Airport station is located somewhat further away from the study area, but has the longest period of record dating to 1948 and was selected for this analysis.

Weather observations at the Burlington International Airport are recorded at least once each hour and more frequently when weather conditions are changing rapidly. Wind data records are saved in an

[21] Clinton Country Airport meteorological weather station is inactive. Plattsburg International Airport, New York (#64776/PBG) weather station began operation in July 2007.

“Hourly Observation Table” which contains observations for sustained wind speed (mph), wind direction to the nearest 10 degrees, and wind gust speed (mph). Maximum daily wind speed for each of eight sectors was determined daily from January 1, 1948, through August 8, 2007. This resulted in a database of 21,770 daily records. The highest maximum daily wind speeds for the top forty days are listed in Table 1. Each day has an entry for each of the eight sectors, but only one sector contains the maximum daily wind speed.

Table 1. Forty days with highest recorded wind speeds in mph. Burlington International Airport Weather Station #14742/BTV, 1948-2007.

Date	N	NE	E	SE	S	SW	W	NW
7/19/91	0	7	40	5	**60**	13	0	0
7/23/78	15	3	0	0	24	0	12	**58**
6/26/02	0	**56**	9	6	20	32	0	**56**
7/9/07	**56**	5	7	7	31	0	0	0
2/22/88	0	0	0	51	**54**	0	0	0
2/13/90	0	0	0	49	**54**	10	0	0
5/10/90	0	6	5	36	**54**	21	15	0
11/11/95	0	0	0	45	**54**	0	0	0
12/31/04	0	0	0	0	**54**	0	0	0
6/20/06	30	39	0	39	18	10	0	**54**
1/3/76	0	0	0	0	**53**	0	9	5
9/29/05	0	0	0	21	**53**	30	41	22
4/23/07	0	0	0	0	30	24	**53**	0
2/15/76	0	5	5	8	**52**	0	0	0
6/22/81	0	10	8	25	**52**	35	17	0
9/23/89	29	0	0	33	**52**	17	29	0
2/27/90	0	0	0	24	**52**	0	0	0
2/17/06	0	0	0	0	41	**52**	45	35
1/30/82	0	0	12	15	**51**	0	0	0
5/13/88	0	0	0	7	47	5	**51**	0
2/15/95	0	6	6	18	**51**	0	0	0
10/21/95	0	0	33	**51**	0	0	0	30
11/29/05	0	0	0	41	**51**	17	0	0
12/6/06	0	0	3	0	**51**	0	0	0
3/22/07	0	0	0	0	**51**	0	0	0
10/16/54	14	9	0	3	**49**	23	0	0
10/7/78	0	0	0	0	15	12	**49**	21
11/11/82	0	0	8	32	**49**	0	0	0
1/26/89	12	0	0	46	**49**	0	0	15
1/15/95	0	0	0	7	**49**	0	0	0
4/26/96	22	0	7	0	31	0	**49**	0
11/14/03	0	0	0	0	0	0	44	**49**
11/5/04	0	0	0	0	32	10	**49**	40
1/2/05	44	0	0	0	**49**	0	0	0
4/19/75	0	0	0	0	**48**	39	28	0
3/5/76	0	0	0	14	37	**48**	0	0
12/17/78	0	0	0	18	22	0	**48**	35
3/29/79	6	0	0	0	**48**	9	0	3
1/17/96	0	0	0	7	**48**	8	0	0
9/17/99	46	0	0	0	0	0	0	48

Thirteen wind ranges were selected from zero to 60 mph and the number of days that had its maximum wind speed in each range was counted for each wind directions N, NW, W and SW, as shown in Figure 2, columns 2, 4, 6, and 8, respectively. For example, considering just north winds, 8801 days of 21,770 days had maximum daily north wind speeds less than one mph, 1669 days had maximum daily north wind speed greater than one mph but less than 5 mph, and so on.

As seen in this table, eight days out of 21,770 had wind speeds from the north greater than 40 mph, twenty-six days had wind speeds from the northwest greater than 40 mph, forty days had wind speeds from the west greater than 40 mph, and fifteen days had wind speeds from the southwest greater than 40 mph; for a total of eighty-nine days with winds greater than 40 mph. So, for winds that create waves that could travel from west to east through an opening in the causeway, 89 days of 21,770 days had winds greater than 40 mph (about 4/10^{ths} of 1 percent). Also, 335 days of 21,770 days had winds greater than 35 mph (1.5%); and 1,065 days of 21,770 days had winds greater than 30 mph (4.9%). Column 3 in Table 2 lists the percent of days per year that wind speed would be *within* a certain speed.

Table 2. Number of days wind speed recorded within each speed range for each of four sectors. Burlington International Airport Weather Station #14742/BTV, 1948-2007.

Wind Speed RANGE, mph	Number of days maximum wind speed from NORTH within RANGE in 21770 days	NORTH Wind, percent of days per year	Number of days maximum wind speed from NORTH-WEST within RANGE in 21770 days	NORTH-WEST Wind, percent of days per year	Number of days maximum wind speed from WEST within RANGE in 21770 days	WEST Wind, percent of days per year	Number of days maximum wind speed from SOUTH-WEST within RANGE in 21770 days	SOUTH-WEST Wind, percent of days per year
W <1	8801	40.4	8864	40.7	12032	55.3	11172	51.3
1< W <5	1669	7.7	1198	5.5	1726	7.9	1704	7.8
5< W <10	4908	22.5	4442	20.4	3958	18.2	4822	22.1
10< W <15	3413	15.7	3343	15.4	1756	8.1	2152	9.9
15< W <20	1655	7.6	1767	8.1	817	3.8	1073	4.9
20< W <25	902	4.1	1157	5.3	764	3.5	552	2.5
25< W <30	287	1.3	565	2.6	352	1.6	161	0.7
30< W <35	100	0.5	309	1.4	239	1.1	82	0.4
35< W <40	27	0.1	99	0.5	83	0.4	37	0.2
40< W <45	6	0.03	18	0.08	31	0.1	11	0.05
45< W <50	1	0.005	5	0.02	7	0.03	3	0.01
50< W <55	0	0	1	0.005	2	0.01	1	0.005
55< W <60	1	0.005	2	0.009	0	0	0	0

Weather Source, LLC[22] was contracted by ***BINKERD ENVIRONMENTAL*** to analyze the Burlington International Airport weather database to determine the return level (maximum sustained wind speed) for return periods of 10, 25, 50 and 100-year wind events. Data used by Weather Source were daily maximum-recorded wind speeds for each of eight sectors N, NE, E, SE, S, SW, W and NW. The return levels for four of eight wind sectors are listed in Table 3. For example, in the NW sector it is expected that a return level of 53 mph would occur every 50 years.

[22] Weather Source LLC, Amesbury, MA

Table 3. Return period for N, NW, W, and SW sectors.

DIRECTION, True	Return Period, years	Return Level 95% LowBound mph	Return Level mph	Return Level 95% HighBound mph
North	**2**	36	**37**	38
North	**5**	39	**40**	42
North	**10**	41	**43**	46
North	**25**	44	**46**	51
North	**50**	46	**48**	54
North	**100**	47	**51**	57
NorthWest	**2**	40	**41**	42
NorthWest	**5**	43	**45**	47
NorthWest	**10**	45	**47**	50
NorthWest	**25**	48	**51**	55
NorthWest	**50**	50	**53**	59
NorthWest	**100**	52	**56**	62
West	**2**	41	**42**	43
West	**5**	44	**45**	46
West	**10**	46	**47**	49
West	**25**	48	**49**	52
West	**50**	49	**51**	54
West	**100**	50	**52**	57
SouthWest	**2**	37	**38**	40
SouthWest	**5**	40	**42**	44
SouthWest	**10**	42	**44**	47
SouthWest	**25**	44	**47**	50
SouthWest	**50**	45	**49**	53
SouthWest	**100**	46	**50**	55

2.3 Review – Meteorological Information

- The axis of the causeway is 29^{o} east of true north. The orientation of the causeway determines which winds create waves that could enter Carry Bay from La Motte Passage through existing or proposed passages in the causeway.

- Of sixteen wind sectors, winds from the south-southwest occur 21% of the time; and, winds from the south occur 14% of the time. Winds from these directions do not produce waves that will enter Carry Bay from La Motte Passage through passages in the causeway.
- Of eight wind sectors, winds from the north, northwest, west and southwest create waves that could travel from the west toward the east through openings in the Carry Bay causeway; winds from the south, southeast, east and northeast will not.
- For all winds which create waves that could travel from La Motte Passage through an opening in the causeway, 4/10^{ths} of 1 percent of the number of days per year will have winds greater than 40 mph; 1.5% of the days per year will have winds greater than 35 mph; and 4.9% of the days per year will have winds greater than 30 mph.
- The highest wind speed recorded at the Burlington International Airport from 1948 to 2007 was 60 mph from the south on July 19, 1991.
- It was predicted that the return level for a 100 year return period for north winds is 51 mph; for northwest winds - 56 mph; for west winds - 52 mph; and, for southwest winds - 50 mph.

3.0 GEOLOGICAL CHARACTERISTICS

3.1 Bedrock Map

A map of bedrock near Carry Bay is found at the Vermont Geological Survey web page,[23] Figure 3.1 shows bedrock surrounding Carry Bay. Maps depicting geological cross-sections west to east through Pelots Bay indicate that bedrock extends under the lake. Bedrock shoreward of the beach is often covered with a consolidated layer of glacier till, and with a thin layer of topsoil above the till layer.

Figure 3.1. Vermont Geological Survey, Special Bulletin Series Maps of Champlain Islands.

There are two distinct bedrock types surrounding Carry Bay and both are shale - a fine-grained sedimentary rock typically derived from mud. The dark-orange and orange colored areas in Figure 3.1 represents *Iberville Shale* described as dark gray to black in color, splintery fracturing, and non-calcareous. The second bedrock type, colored dark-gray and light gray in Figure 3.1, is *Stony Point Shale* described as black, fissile, carbonaceous, and calcareous shale.

[23] Vermont Geological Society, Special Bulletin Series Maps On Line

3.2 Classification of Rocks

There are several standards for rock classifications. The one used in this report is from C. K. Wentworth, "A scale of grade and class terms for clastic[24] sediments,[25] " J. Geology 30:377–392 (1922).[26]

Clay range in diameter from 0.00049 millimeters (mm) to 0.0039 mm.

Silt particles range in diameter from 0.0039 mm to 0.0625 mm.

Sand particles range in diameter from 0.0625 mm (about one-twelfth (1/12) of an inch) to 2 mm (0.079 inches). Within this size range sand is divided into fine, medium, and coarse.

Gravel is any loose rock that is larger than 2 mm (0.079 inches) and no more than 64 mm (about 2.5 inches). Gravel is called granular from 2-4 mm (1/12 inch to 0.157 inch) with different classifications of pebbles (small, medium, large, and very large) for rock greater than 4 mm and less than 64 mm (0.157 inches to 2.5 inches).

Cobble is any loose rock that is larger than 64 mm and no more than 256 mm (about 10.1 inches) and is divided into two classifications of small and large cobbles.

Boulder is any loose rock that is larger than 256 mm (about 10.1 inches) in its largest dimension.

3.3 Shoreline Profiles

Nine shoreline profiles were measured on July 22, 2007 at locations identified in Figure 3.1. Each transect was about 60 feet long and perpendicular to the edge of water. At two transects, North Hero Marina and Pelots Bay, the shoreward end of the beach slope did not end in a steep bank. At seven transects there was a steep bedrock bank at the shoreward end. The elevation of the toe of the bedrock bank at these locations is listed in Table 4. The slope of the beach, i.e., from the toe of a bank, if present, toward the lake, is about 1:10, or 1 foot vertical for every 10 feet horizontal.

[24] Definition: Clastic rocks are composed of fragments, or clasts, of pre-existing rock.

[25] Definition: Sediment is any particulate matter that can be transported by fluid flow and which eventually is deposited as a layer of solid particles on the bed or bottom of a body of water or other liquid.

[26] U.S. Army Corps of Engineers, 2002. Coastal Engineering Manual. Part III, Chapter 1, page 8.

Table 4. Toe of bank elevations.

Transect Location	Elevation of Toe of Bank, ft MSL
East Shore Alburg Passage - Upper	99.9
Blockhouse Point	99.3
East Shore Carry Bay - Upper	100.3
East Shore Carry Bay - Middle	100.1
Carrying Point	100.1
South Shore Carry Bay - West	99.3
East Shore Pelots Bay	-
North Hero Marina	-
West Shore Alburg Passage - Lower	98.9

3.4 Beach Description and Shoreline Map

Rocks found along the shore are from weathering[27] and erosion of local bedrock and glacier till. Weathering activity fractures and loosens bedrock and glacier till by physical and chemical processes. Erosion processes transport weathered rock to the beach. The most effective natural physical weathering process in the study area environment is, most likely, repeated freeze-thaw action. Freeze-thaw cycles weaken and break bedrock along joints into angular pieces. Fragmented and angulated rocks erode as individual pieces, or as larger slides. At times of high lake levels, loose rocks are washed off the bank by waves and end up on the beach. Over time, angulated rocks become smaller and smoother by grinding and rubbing. As rocks become smaller, waves and currents can more easily transport and sort rocks both on-shore/off-shore and longshore (parallel to the shore). Fine particles, originally in till, are transported away from the beach and removed from the system. Gravel, cobbles and boulders remain on the beach and, in some places, dominate beach materials. At other locations gravel and cobble size rocks from

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[27] Definition: “weathering” - decomposition of rocks through direct contact with the earth’s atmosphere. Weathering occurs *in situ*, with no movement, as opposed to erosion, that involves movement of rocks by water, gravity, and other forces.

bedrock are more numerous. In most location there is a mix of gravel, cobble and boulder size rock from both sources - bedrock and glacier till.

The upward "swash" of the wave pushes gravel size rocks up the beach face. Rocks are deposited as the wave loses momentum. Water seeps between the rocks and returns to the lake and some water flows back down the beach face, but not with sufficient momentum to drag gravel size rock with it. As more and more gravel is transported up the face and deposited, the beach face grows higher and steeper. Gravel is also moved longshore and is accumulated next to natural and human made jetties.

Ridges are formed as the lake level rises and falls throughout the year. When the lake level rises rapidly, gravel may not be pushed ahead by the leading edge of water and gravel size rocks would be submerged. Submerged gravel size rocks are then moved about in the surf zone. Wave action tops off the gravel ridges and fill-in troughs. As lake level falls, waves move gravel up the beach face as before and form ridges. Lake levels may rise and fall at any time during the year so these processes play out continuously, and in various ways. Beaches that reshape without net loss of materials are dynamically stable. Dynamically stable berm breakwaters are similar to beaches in this respect since they are designed to permit movement of rock and reshaping of the structure.[28]

In addition to rock beaches, there are five separate marsh areas along the shoreline. Marshes are located between Savage Point and Graveyard Point, between Green Point and Route 2,[29] just north of camps and cottages that border Route 2, and in the northeast area of Carry Bay. The marsh area identified in Figure 3.2 as "the pit" was excavated in 1939 for fill for Route 2. A beaver dam controls water level in the pit; water level in all other marshes change with lake level.

From a review of maps and field inspections the shoreline can be described as one of three types: (1) marsh; (2) rock covered beach that terminate at bedrock banks; or (3) rock covered beach that do not terminate at bedrock banks. Locations of these geological types are depicted in Figure 3.2. Deviations from these three major shoreline types are: (1) on the east shore of Alburgh Passage about 100 feet of shoreline is described as "rock & sand on slope;" (2) along the east shore of Carry Bay a section is described as "low land, rocks with some sand on slope;" and, (3) "riprap" near the Carrying Place.

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[28] Sistermans, P. G. J., 1993. Stability of rock beaches. Delft University of Technology, Hydraulic and Geotechnical Engineering Division, Master Thesis.
[29] This marsh extends south to City Bay in the Inland Sea of Lake Champlain and east of the center of North Hero. A causeway, constructed for Route 2 extends across the southern boarder of this marsh and separates this marsh and City Bay.

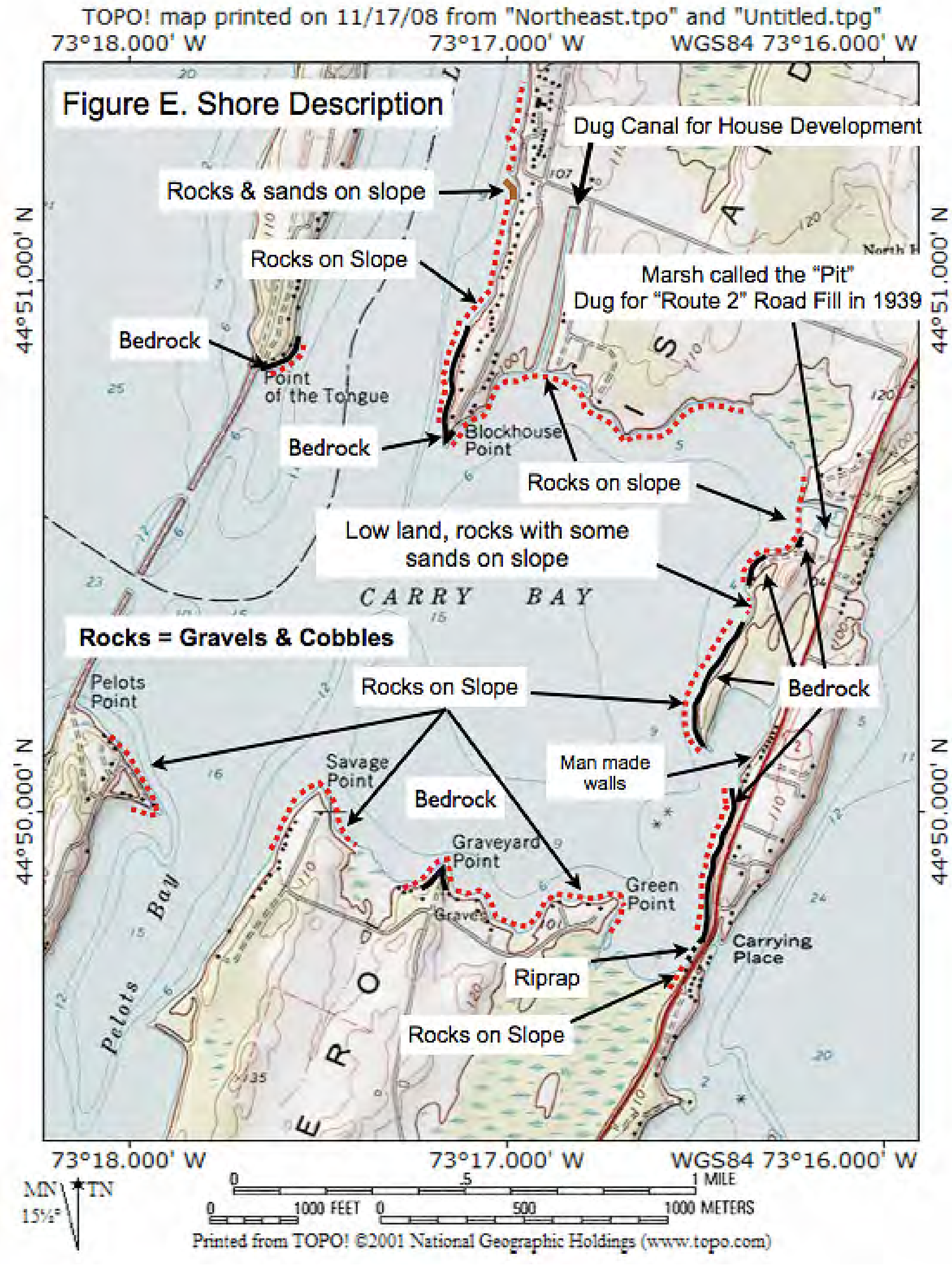


Figure 3.2 Map of study area with shoreline geological characteristics.

3.5 Geological Shore Features; A Virtual Field Trip

Pictures illustrating geological shoreline features are presented in Photographs 1-19. These pictures were taken at locations shown in Figure 3.3.

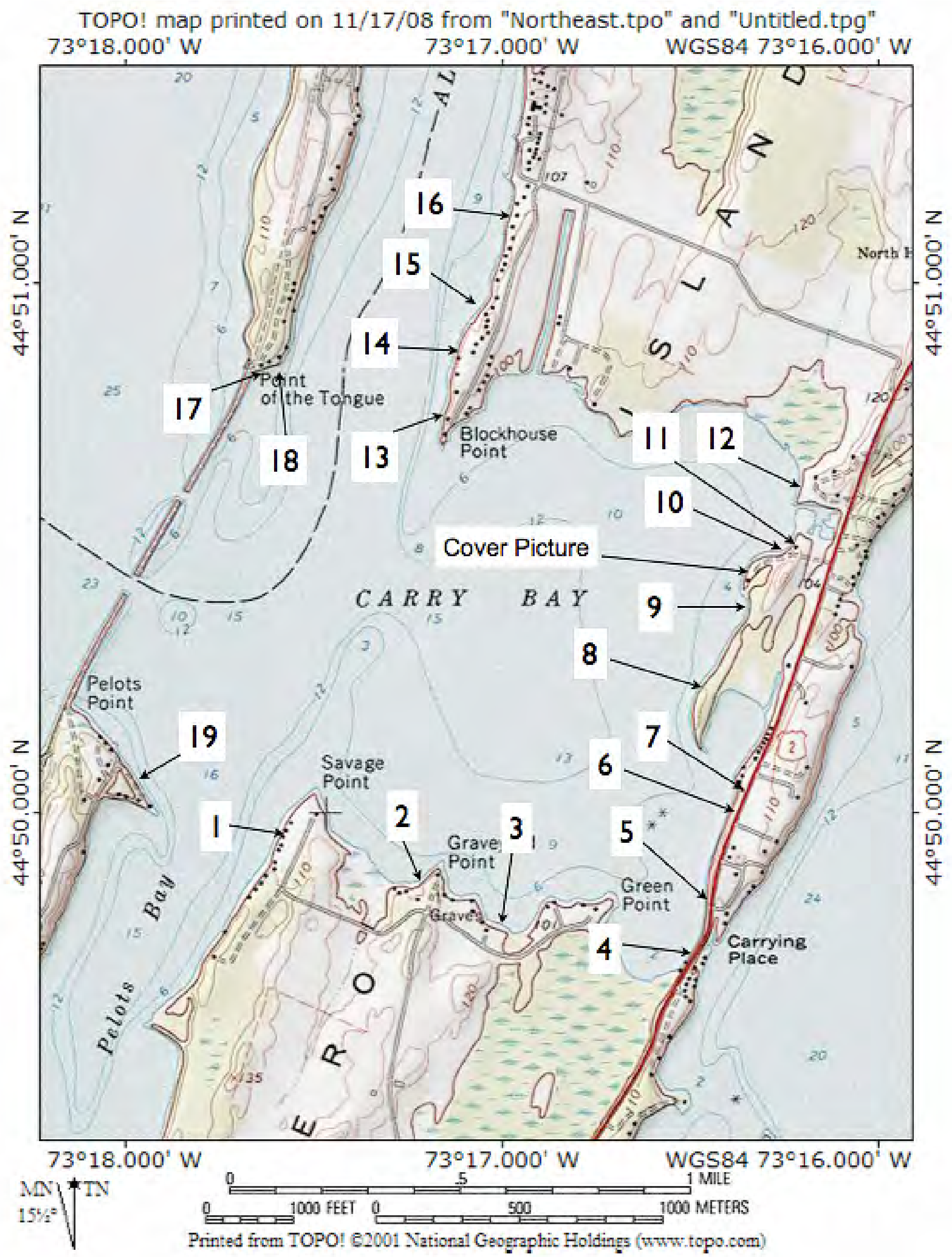
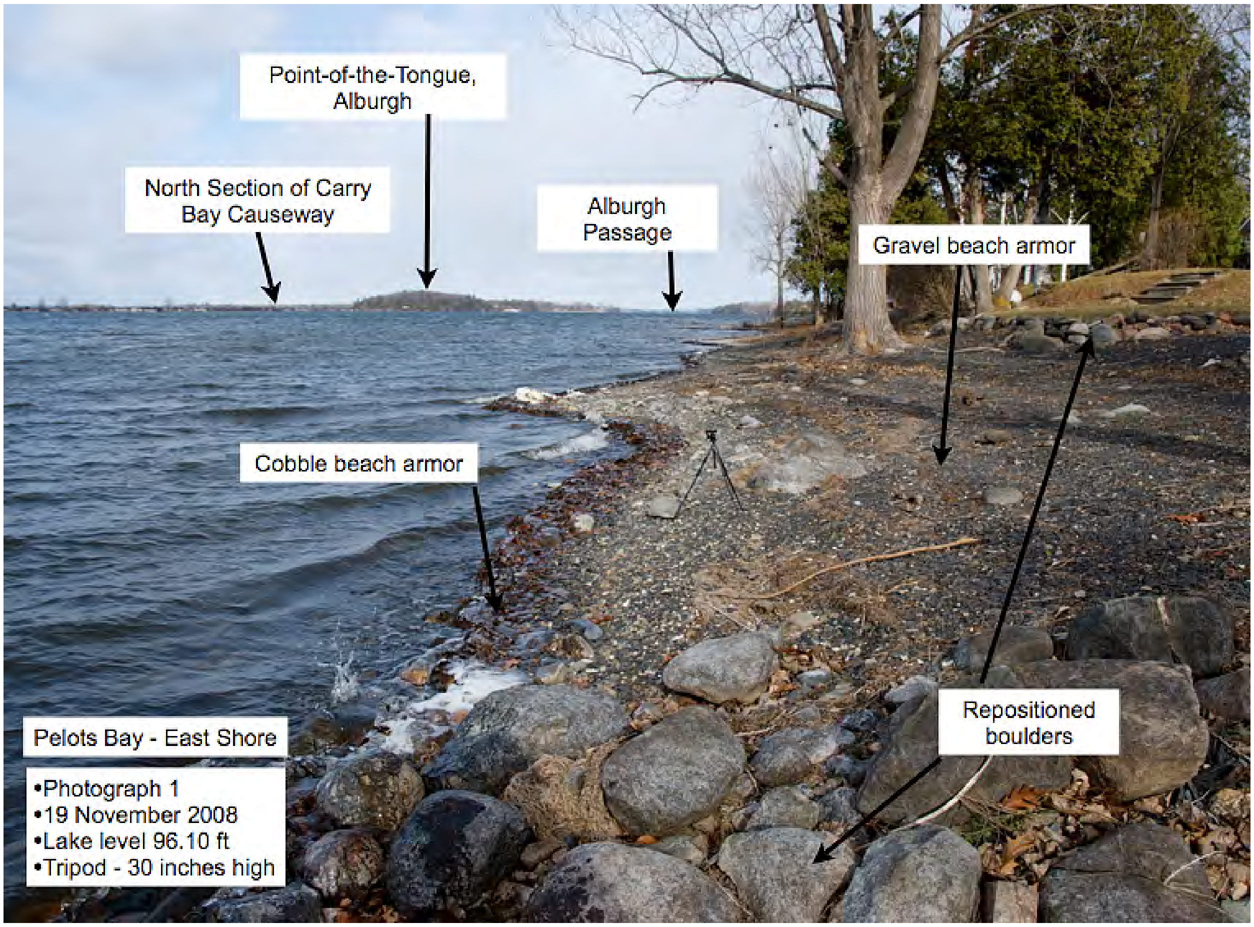
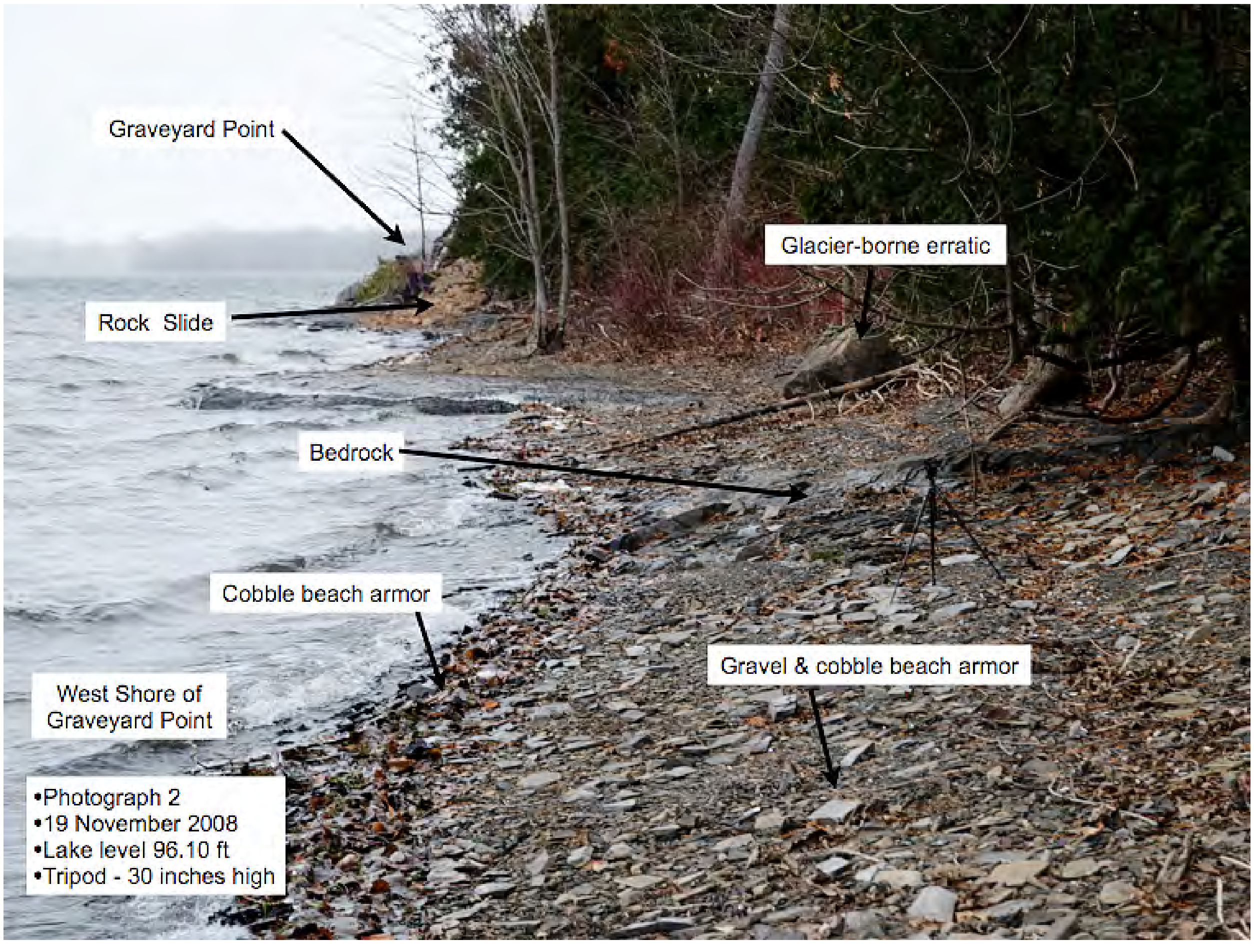


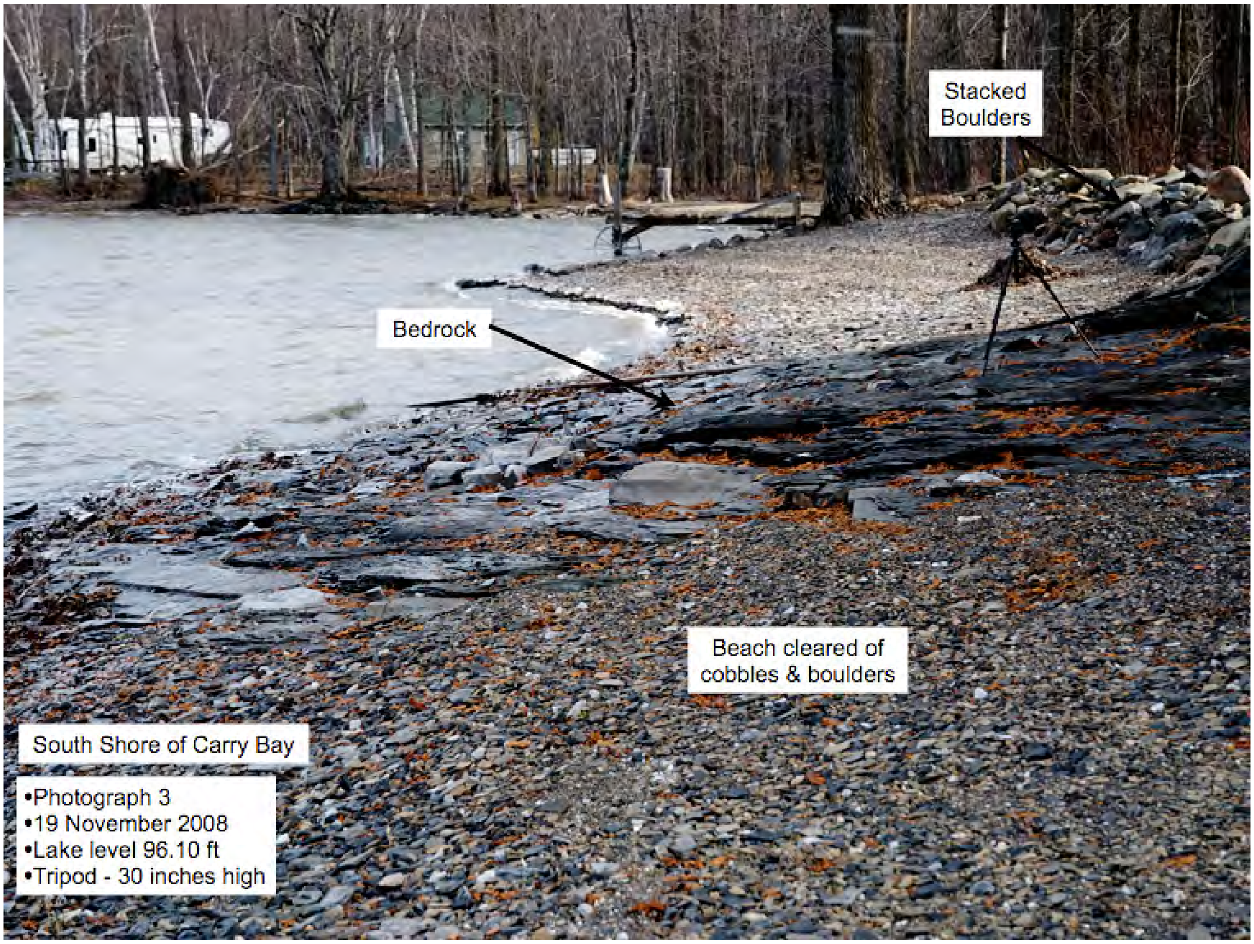
Figure 3.3 Locations of Photographs 1-19 and Cover Photograph.



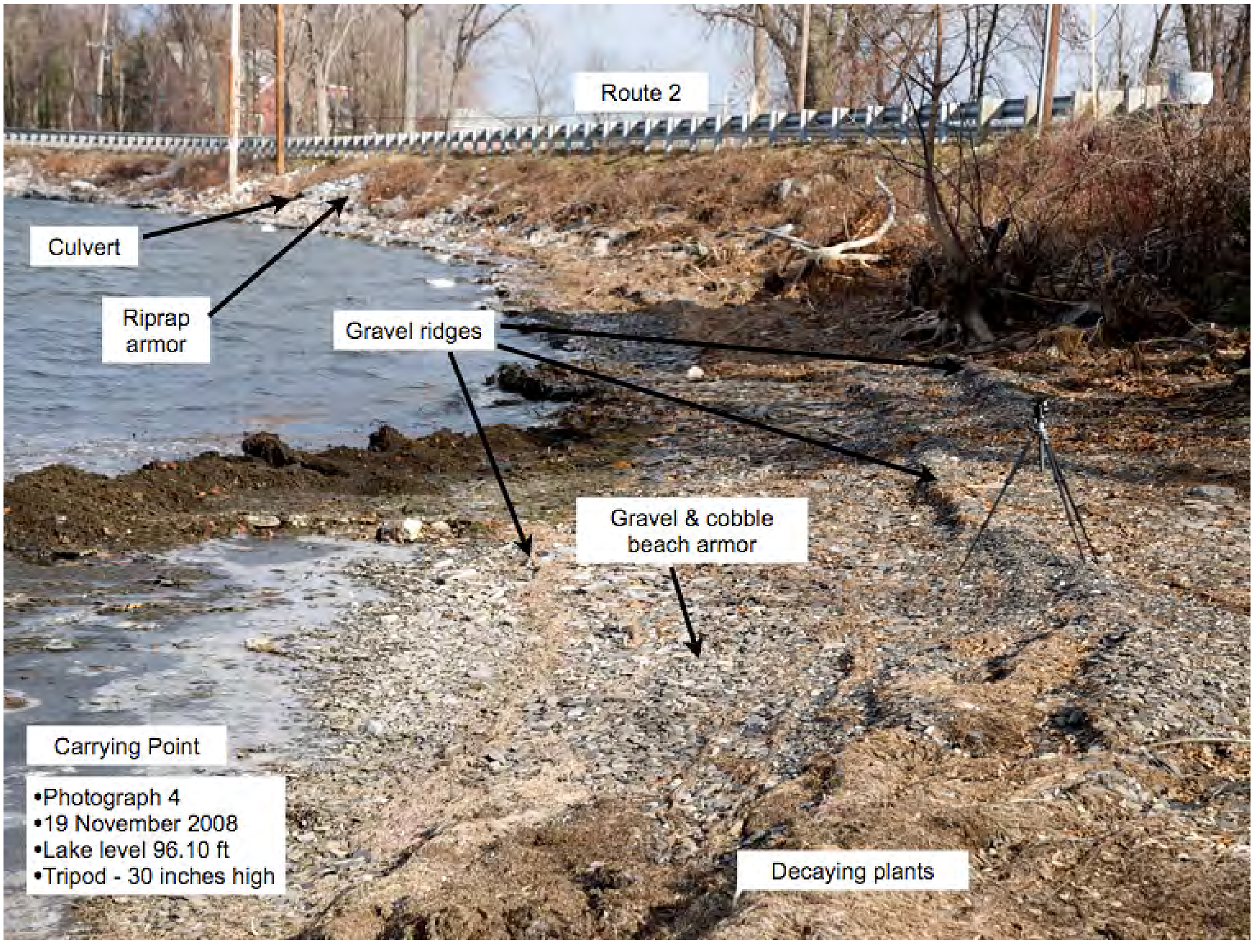
Photograph 1 - This picture was taken looking north along the west shore of Pelots Bay and south of Savage Point. Boulders were moved and grouped together to construct walls and groins. The beach slope extends landward and ends at the base of the stairs seen in the upper right where permanent vegetation begins. Cobbles dominant from the edge of water and offshore (foreshore) while gravel are more plentiful landward (backshore).



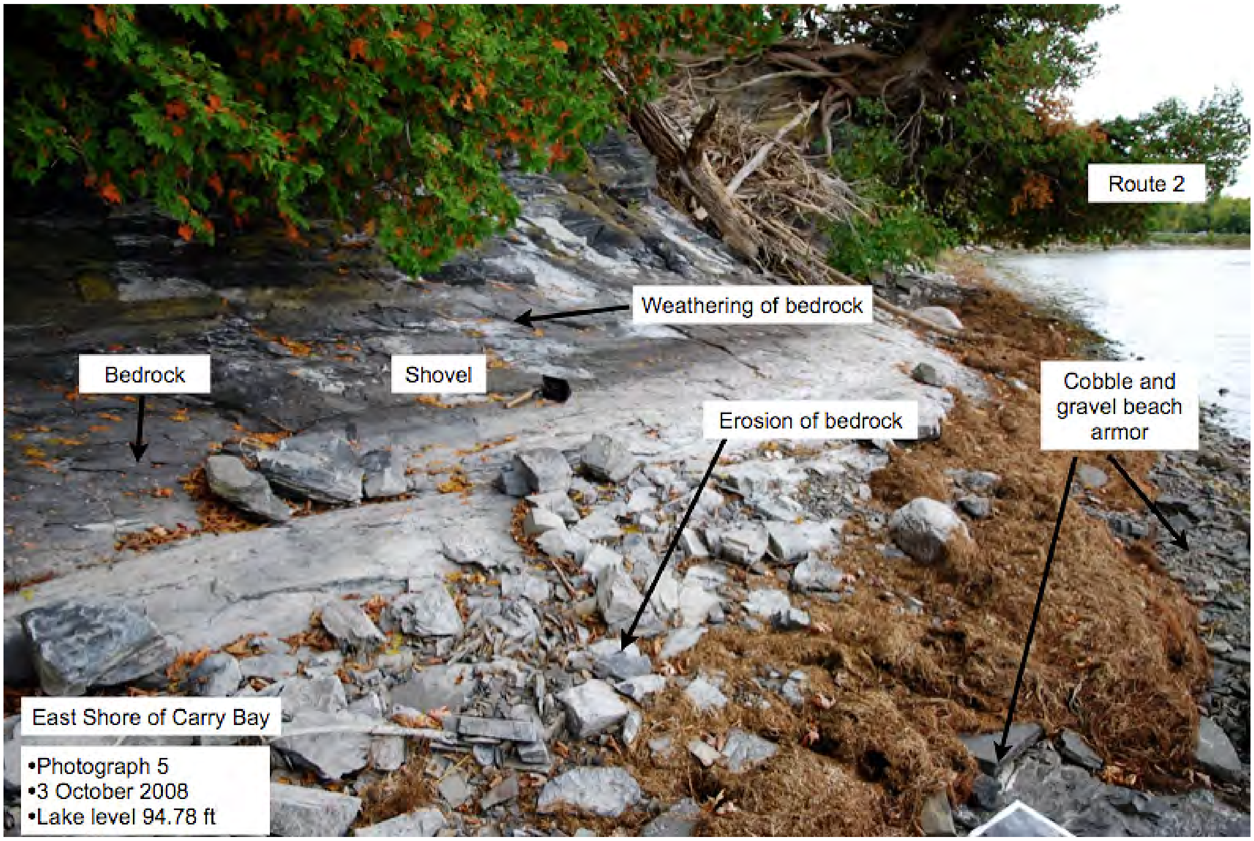
Photograph 2 – This picture depicts the west shore of Graveyard Point looking north. A more natural shore appears in this photograph than in Photograph 1. Cobbles mixed with gravel are above the water line. Cobbles with much less gravel are at the edge of water and lakeward. A recent landslide illustrates erosion of the bank and one source of beach material.



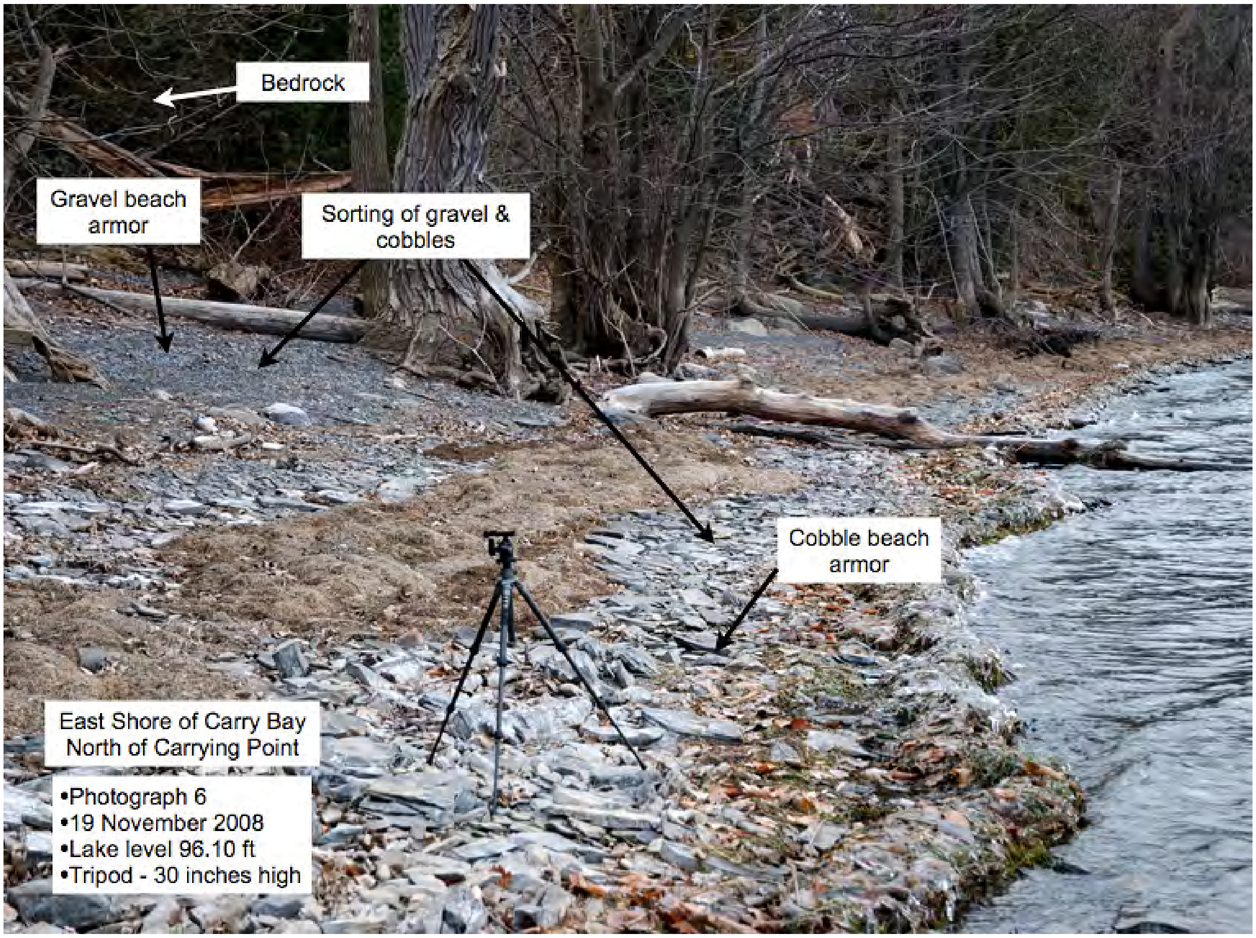
Photograph 3 – Photograph 3 was taken on the south shore of Carry Bay looking west. Most likely the boulders stacked in the upper right of this picture were once on the beach. Also, there are no cobbles on the beach. Bedrock outcropping is evident on the beach face.



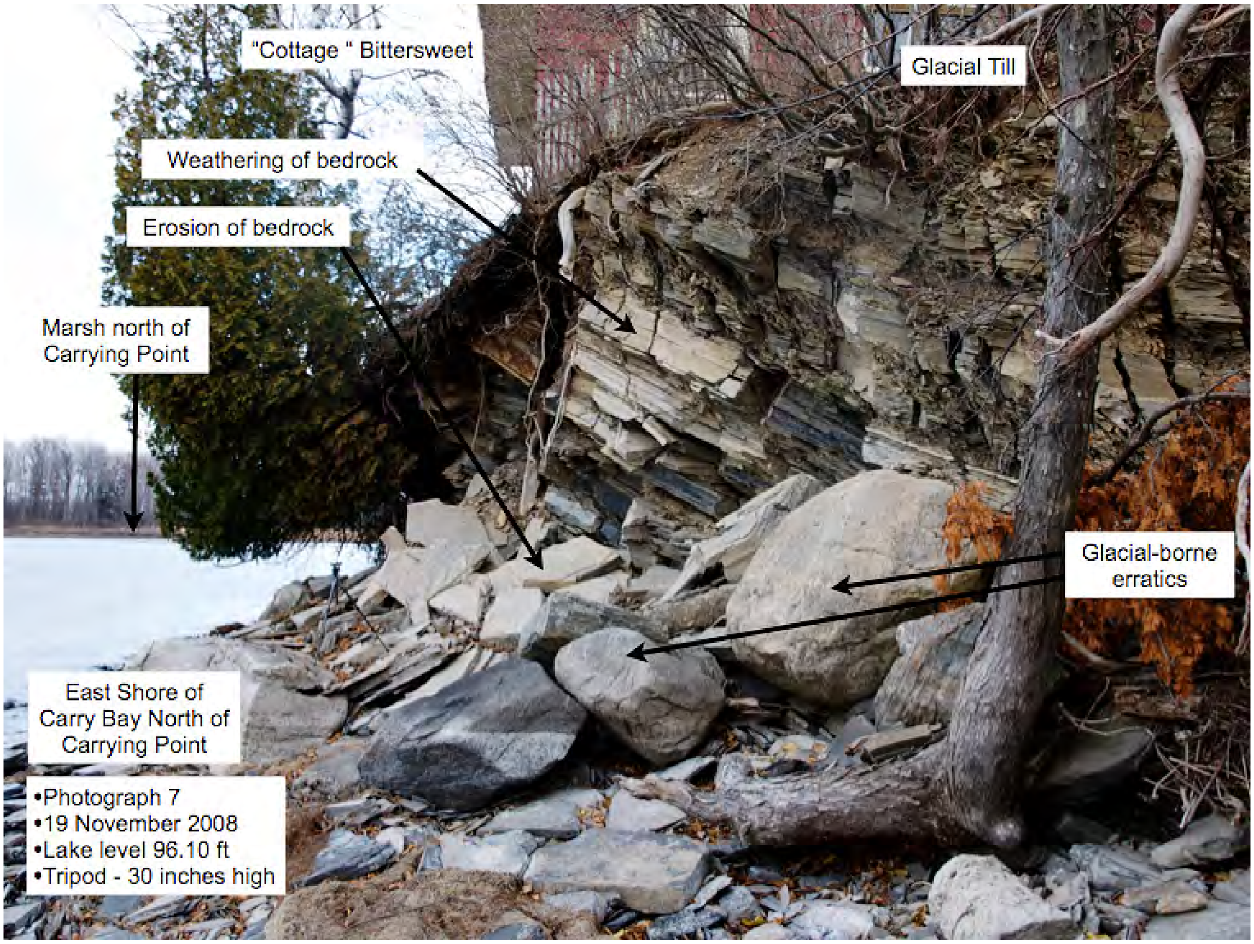
Photograph 4 - This picture was taken looking north close to the “Carrying Point.” This area has been greatly modified and a steep riprap bank extends along the shore. A culvert provides very little exchange of water between Carry Bay and the Inland Sea. Gravel ridges appear along the shore where wave action piled gravel size rocks in rows parallel with the edge of water. A large amount of decaying plants were along the shore.



Photograph 5 - This picture depicts a section of the east shore of Carry Bay, north of the Carrying Point and looking southeast. This beach appears natural since access to this location is protected by a steep bank and lack of roadside parking. Also, there are no houses along this stretch of shore. Numerous cobble size rocks on the beach were weathered and eroded from the adjacent bedrock bank. Some cobble size rocks at this location were glacier-borne. Cobbles and decaying vegetation line the shore.

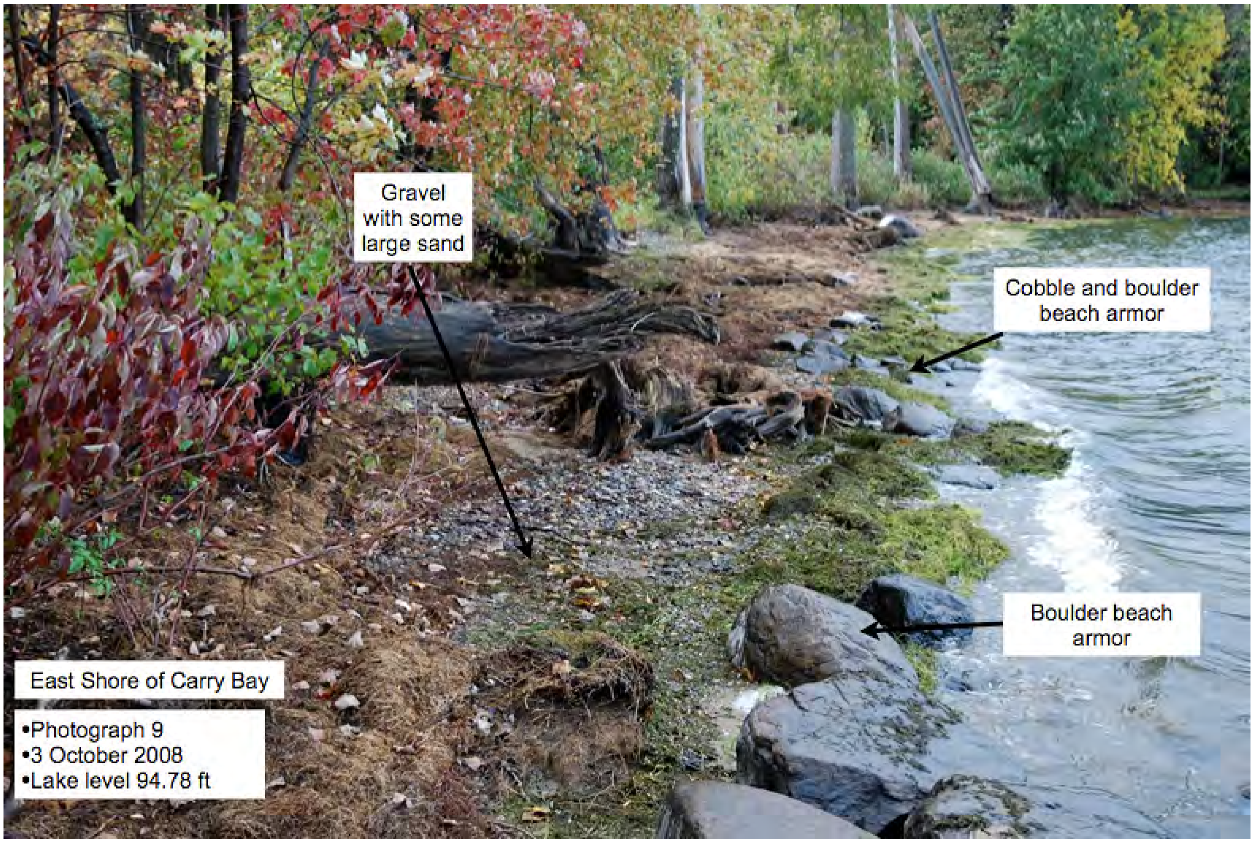


Photograph 6 – This picture depicts a section of the east shore of Carry Bay, north of Photograph 5, and looking south. This section of beach appears natural even though it is next to Route 2. Sorting of rock is evident with gravel further from, and cobbles closer to, the edge of water.

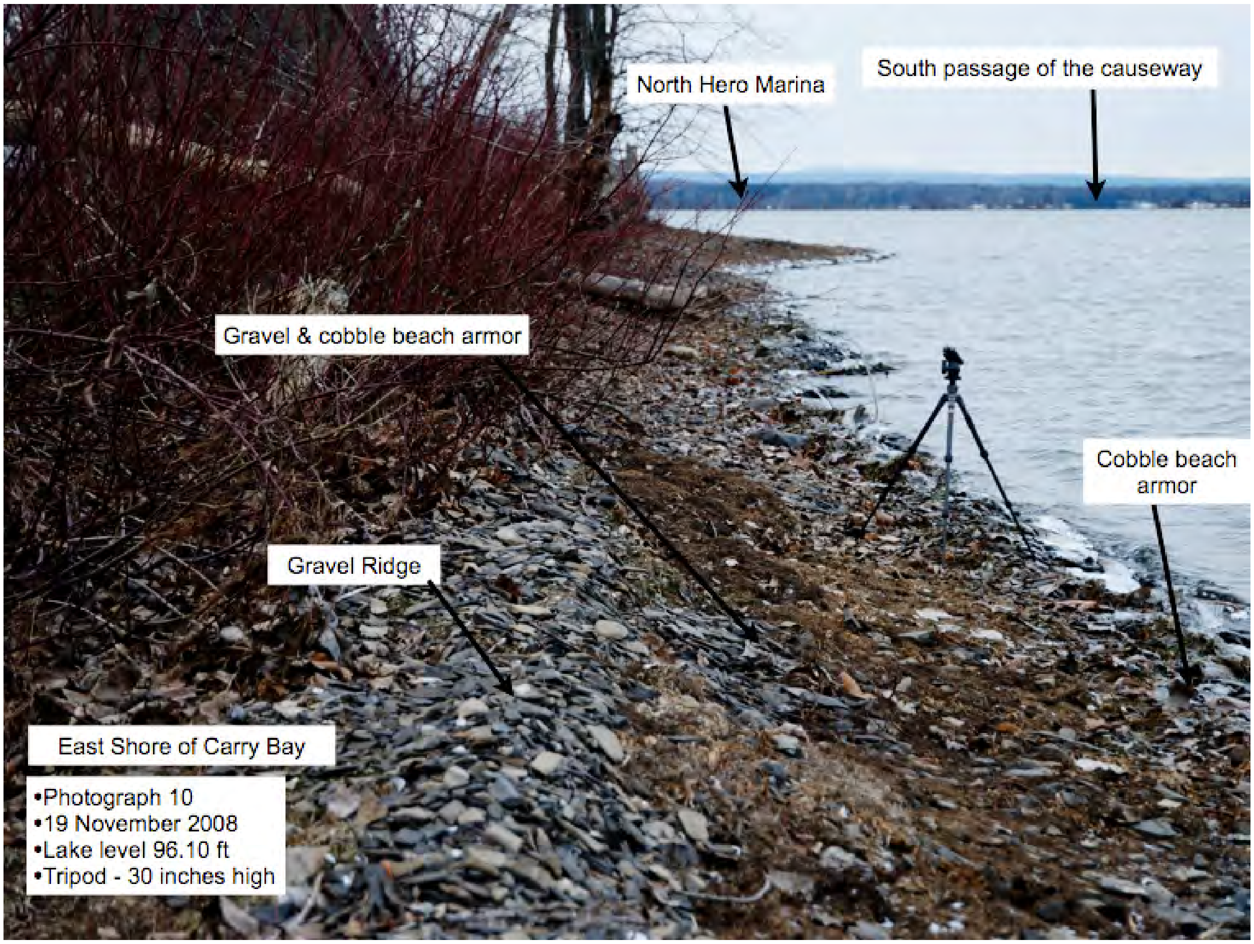


Photograph 7 - Photograph 7 was taken looking north and is only a short distance north of the location show in Photograph 6. The erosion evident in this picture was accelerated by human activity due to the construction of a cottage next to the edge of the bank. This location is protected by waves from the north and northwest, and waves most likely played a minor role in this erosion.

Photograph 8 - This picture was taken during the survey of beach slopes on July 22, 2007. The instrument on the tripod is a laser level. The beach is armored with boulders with cobbles.

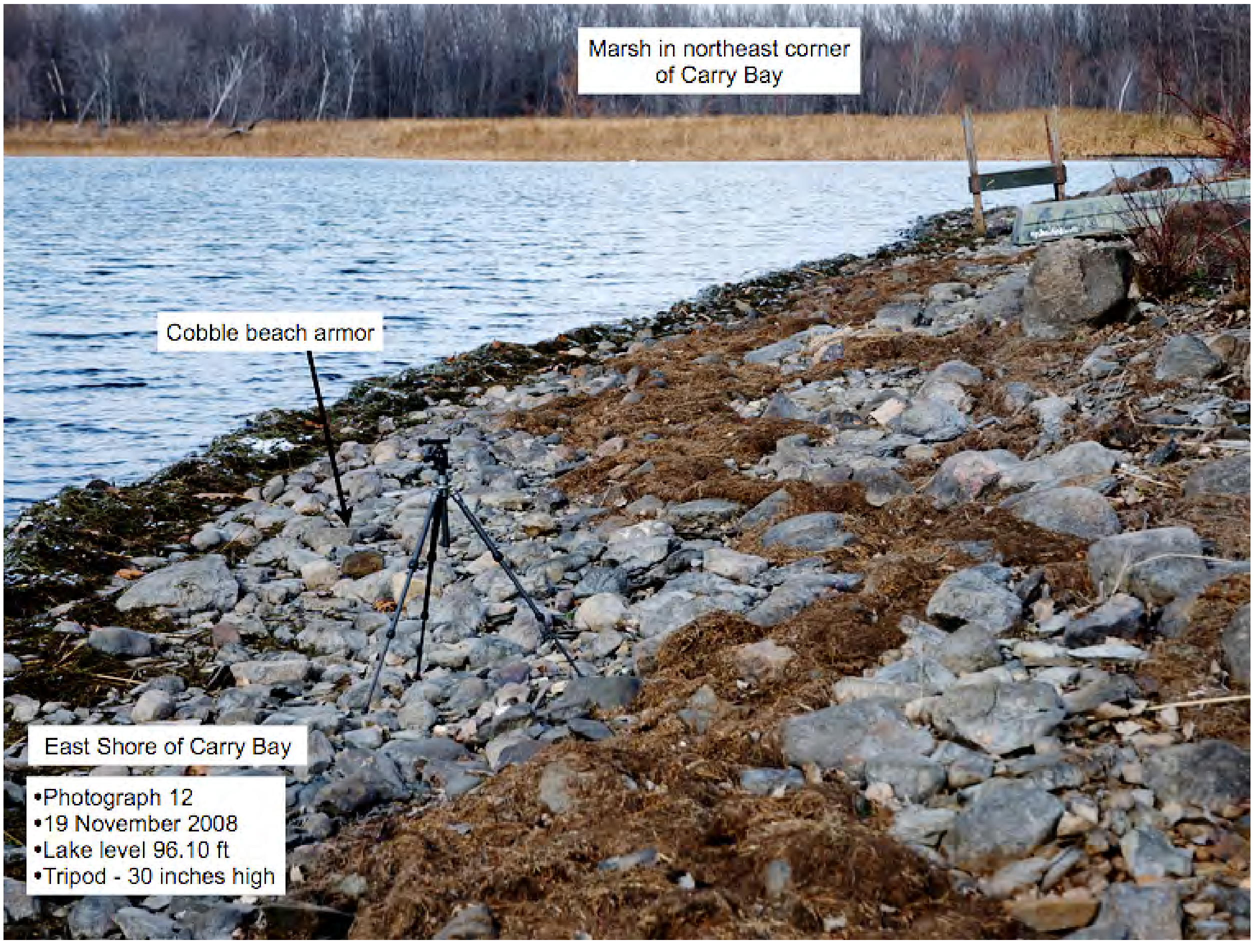


Photograph 9 - Photograph 9, taken on October 3, 2008, also depicts boulders along the edge of water, but this section of beach is not boarded by a bedrock bank as seen in Photograph 8. Sections of this beach have deposits of sand, which is rare for beaches in the study area. The low elevation of the backshore appears to flood at higher lake levels.

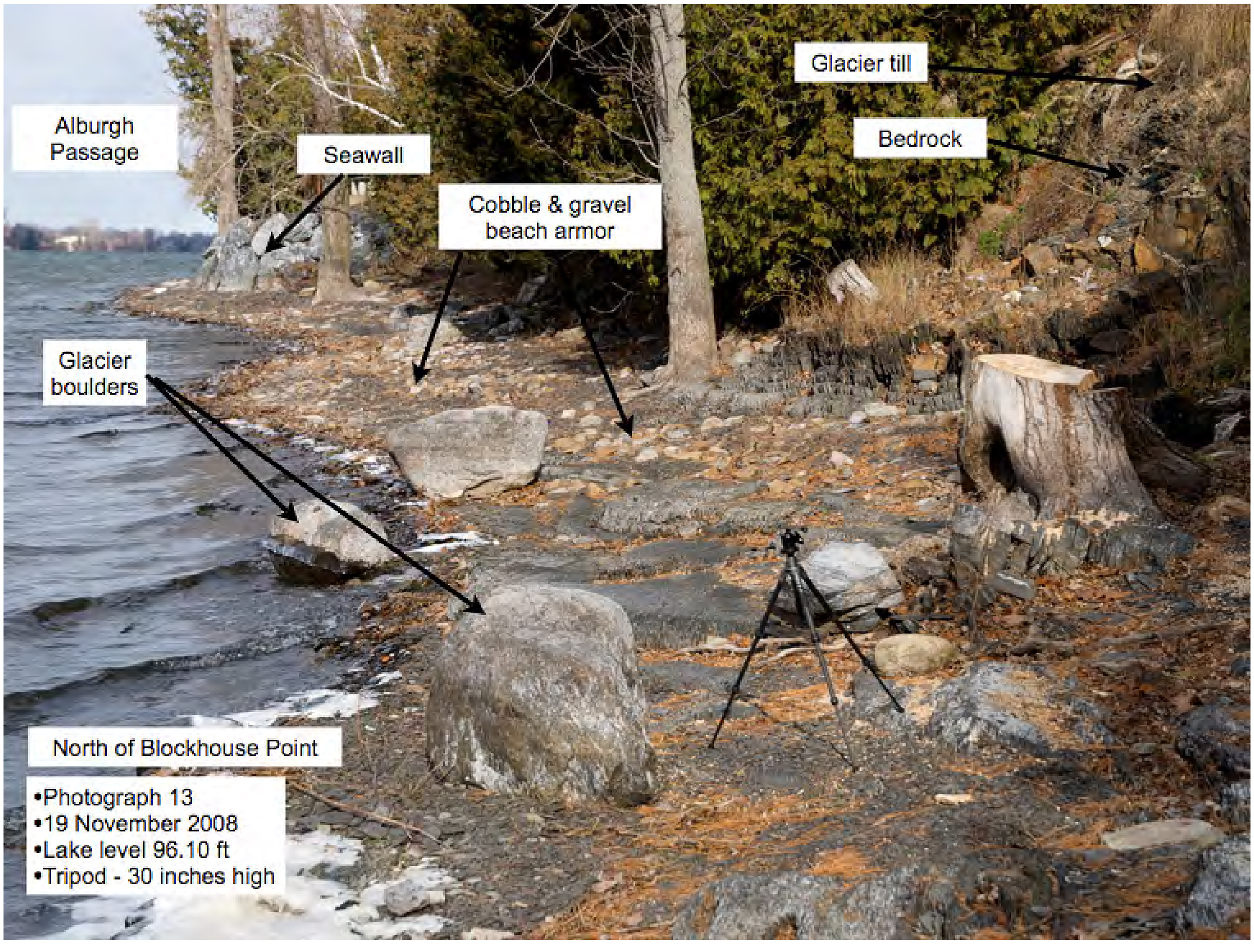


Photograph 10 - This particular shore extends west to east and faces north. This picture was taken looking west. A well-established ridge of gravel is parallel with the edge of water. Rocks are sorted due to wave action with gravel piled higher on the beach. Cobbles are more numerous near the edge of water.

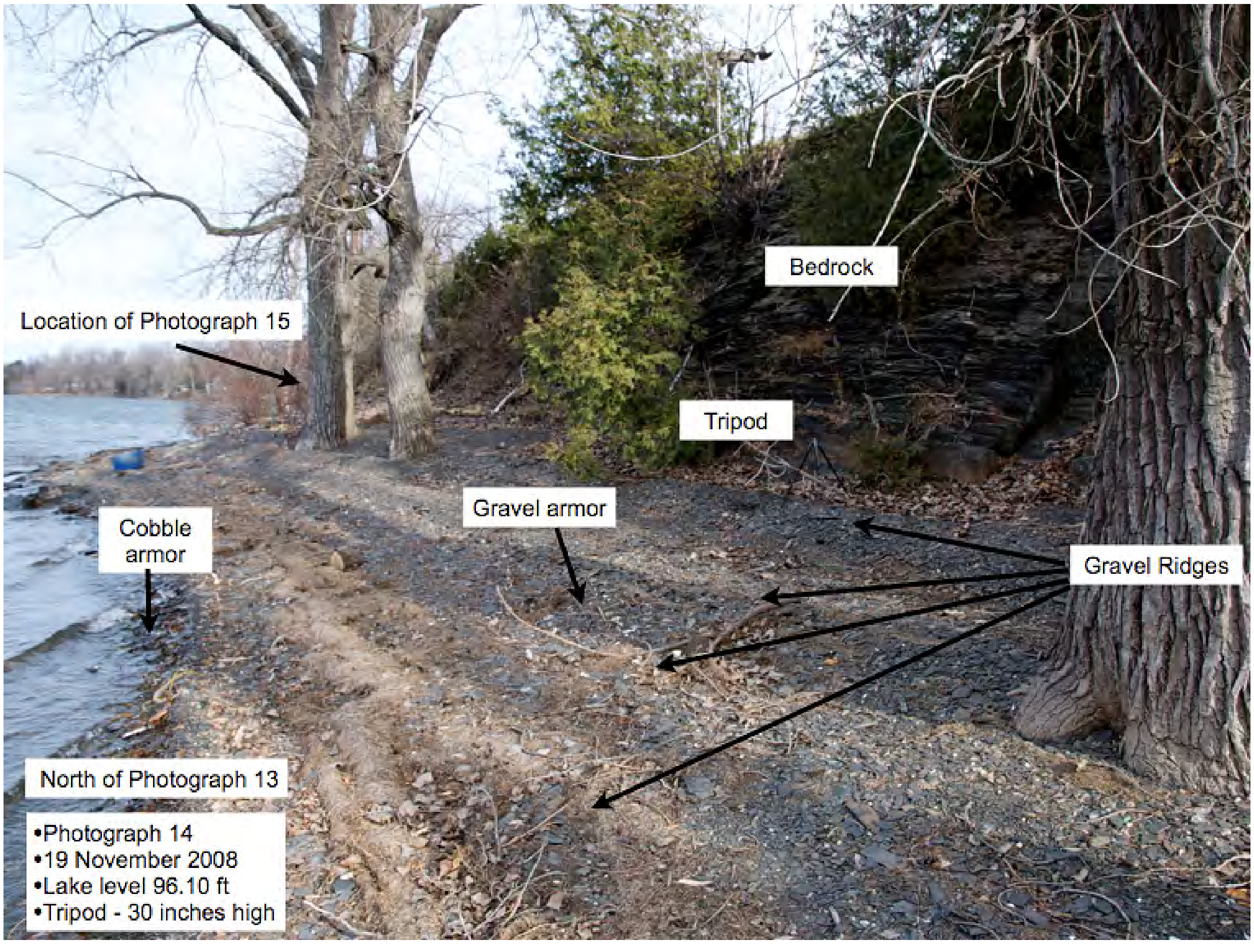
Photograph 11 - Photograph 11 was taken a short distance north of the location show in Photograph 10. This beach extends north/south and abuts the beach shore in Photograph 10 at nearly a right angle. This section of beach has few gravel size rocks in spite of the bedrock bank to the right and bedrock slabs along the shore. Gravel rocks may have been moved to the beach seen in Photograph 10. Glacier-borne erratics are plentiful.



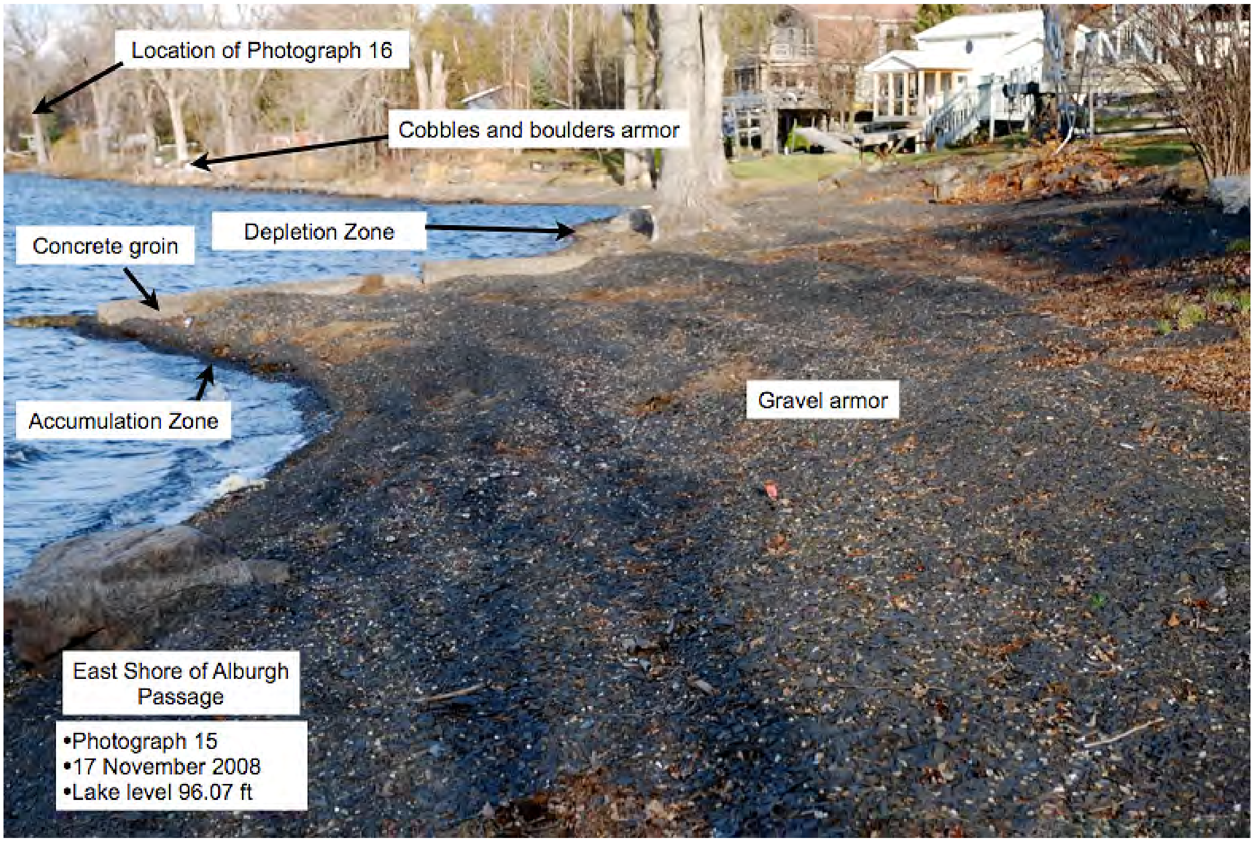
Photograph 12 - This beach is predominately covered with cobbles and boulders. This beach faces west along the east shore of Carry Bay and is north of Photograph 11. The mean weight of six cobbles from this beach was 7.0 pounds. A marsh in the northeast corner of Carry Bay is seen in this picture.



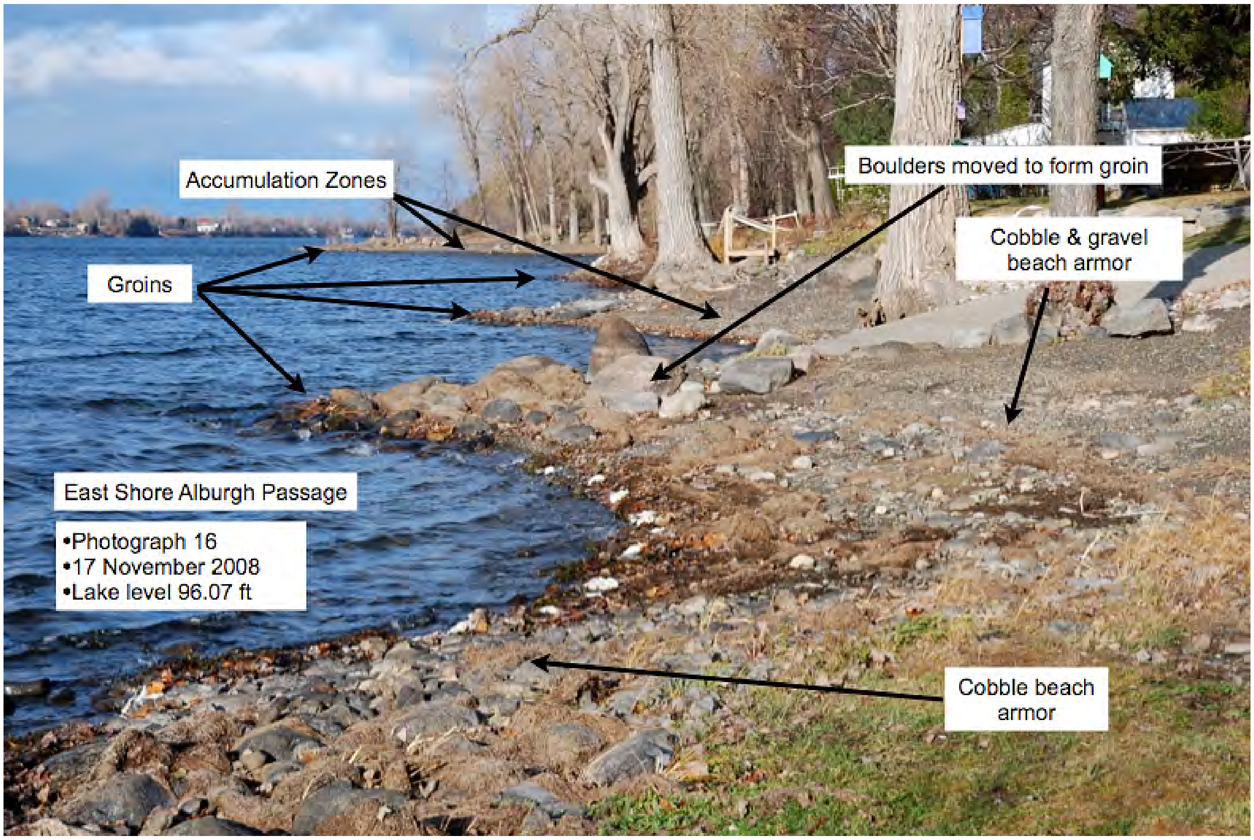
Photograph 13 - This picture was taken looking north and shows the east shore of Alburgh Passage not too far north of Blockhouse Point. Gravel, cobbles and boulders are all present on top of bedrock with a bedrock bank to the right. The seawall is the only human made seawall along this shore.



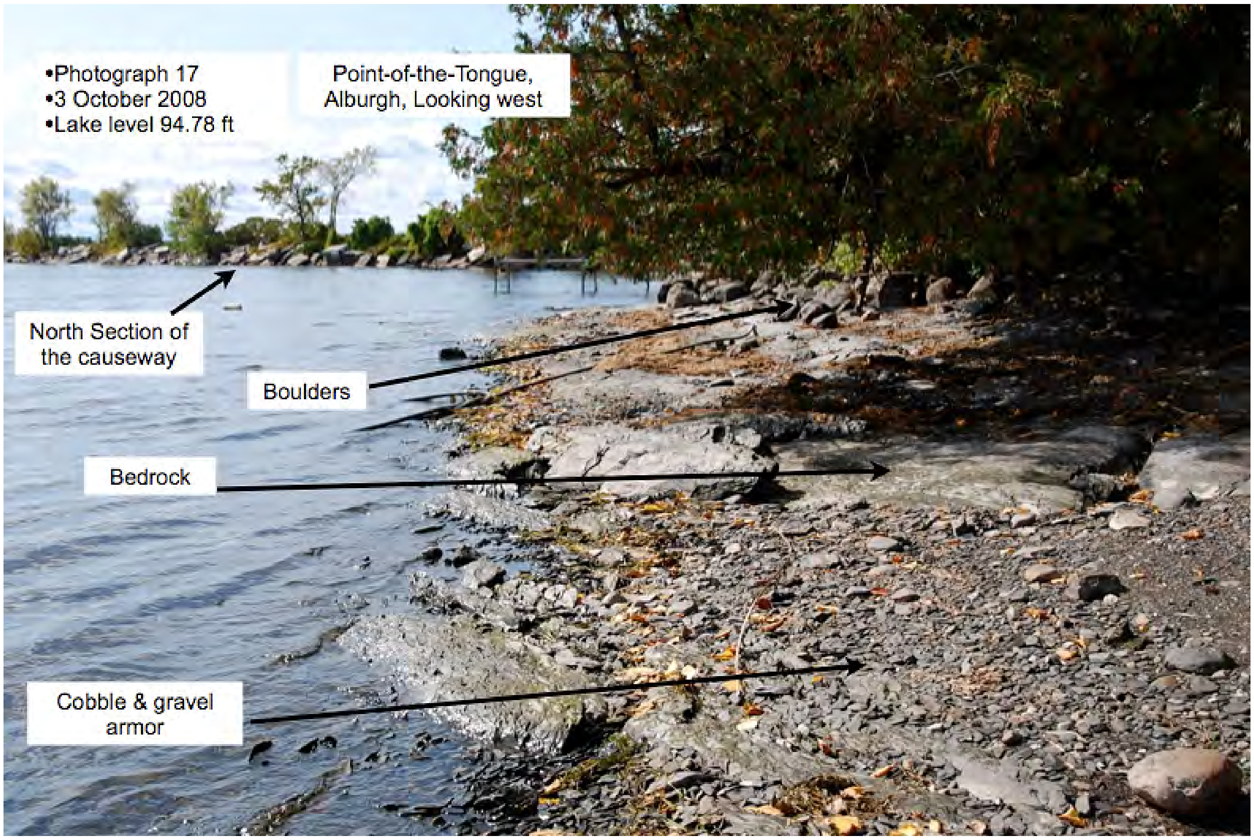
Photograph 14 - This picture shows the east shore of Alburgh Passage north of the location of Photograph 13. The bedrock bank is quite high at this location. The quantity of gravel is due to transport of materials north from the point of Blockhouse Point and local production. Terracing of gravel is well established with many ridges seen parallel with the edge of water. This photograph was taken in November following a period of steadily falling lake water elevations. Well-defined ridges and terracing are evidence of wave action at lower and lower water elevations.



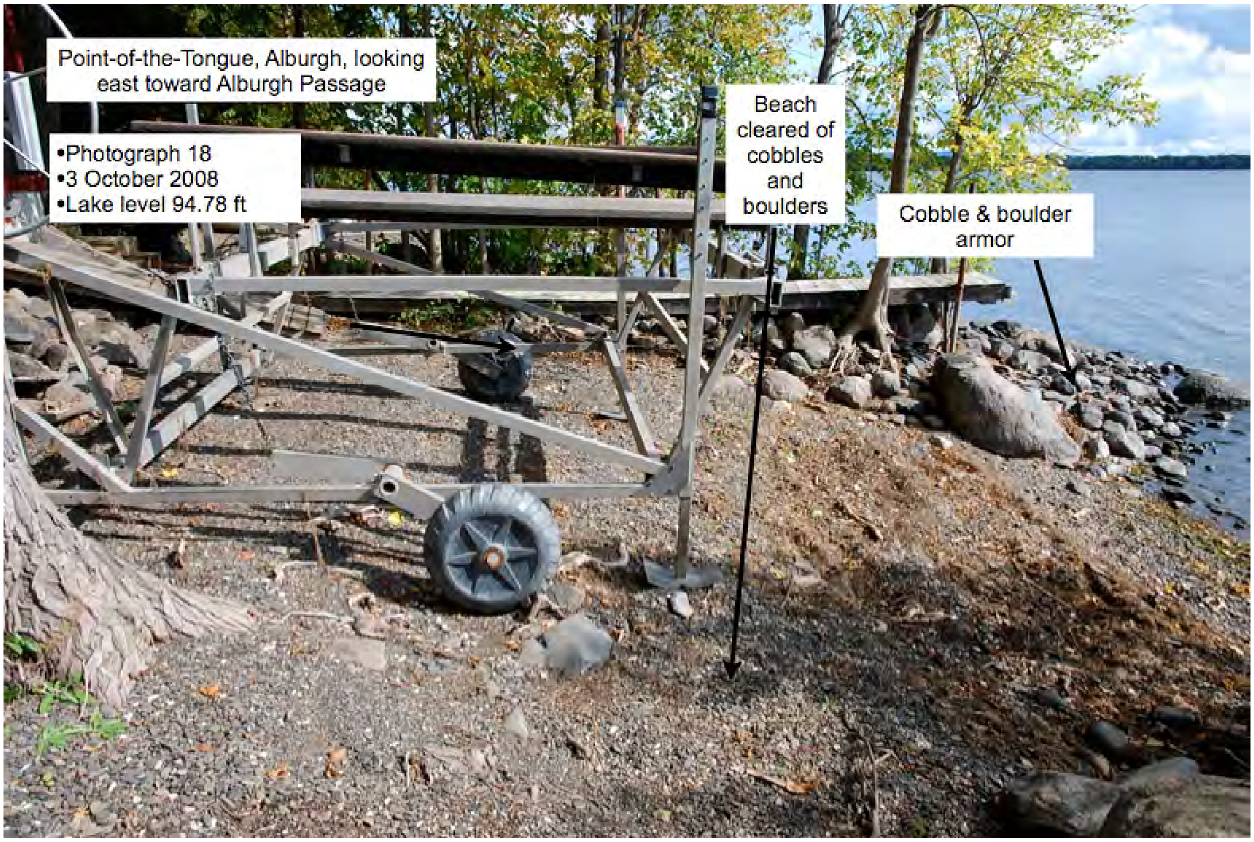
Photograph 15 - Photograph 15 depicts the east shore of Alburgh Passage looking north. The groin, which is made of concrete in addition to boulders, traps gravel. Further north more cobbles and less gravel are evident. The mean weight of eight cobbles selected from the beach north of the groin was 4.8 pounds.



Photograph 16 - This picture was taken along the east shore of Alburgh Passage and is looking north. The mean weight of thirteen cobbles selected from this beach was 4.3 pounds. Several groins are evident in this picture most likely due to human activity.



Photograph 17 - This picture was taken at Point of the Tongue, Alburgh, facing west. A dock extends into the water just east of the causeway. Bedrock outcrops are seen along the shore and a bedrock bank covered with glacier till is to the right. Again, cobbles mixed with gravel provide beach armor.



Photograph 18 - This picture was also taken at Point of the Tongue looking east toward Alburgh Passage. This section of beach has been cleared of cobbles and boulders.

Photograph 19 - This picture shows a cobble and gravel covered beach just east of the North Hero Marina. This is the last picture and it completes a full circle around the study area.

3.6 Review – Geological Information

- Rocks found along the shore were either derived from local bedrock or transported to this area by glaciers.
- Weathering processes act on exposed bedrock and the glacier till layer. Erosion processes deposit fractured and angulated pieces of bedrock and glacial till on the beach. Small sand, silts and smaller particles in consolidated glacier till are transported away the shore as suspended load and are lost from the beach forever; gravel, cobbles and boulders remain and provide armor for beach stability.
- Many long stretches of beach appear undisturbed by human activity. Undisturbed beaches are in difficult to access places and usually not adjacent to houses.
- Fragmented and angulated rocks fall from bedrock onto the beach as individual pieces or as larger slides. Loose rocks are washed off bedrock banks by waves and end up on the beach. Over many years, angulated rocks become smaller and smoother by grinding and rubbing.
- As rocks become smaller waves and currents can more easily transport them. Waves sort rocks both on-shore/off-shore and longshore by bed load transport processes.
- Marshes are located between Savage Point and Graveyard Point, between Green Point and Route 2, north of the Carrying Place near Route 2, and in the northeast corner of Carry Bay.
- The shoreline can be described as one of three types: (1) marsh; (2) rock covered sloping shoreline that terminate at bedrock banks; and (3) rock covered sloping shoreline that continue inland and do not terminate at bedrock banks.
- Many long stretches of beach are undisturbed by human activity. These beaches are usually in hard to reach places and where houses are not nearby. Beaches near roads and in front of houses display more human activity.
- Results of human activities observed along the shore were structures close to the edge of banks, boulders re-arranged or removed from the beach, gravel and cobbles removed from the beach, imported sand on the beach, raked gravel, boat access ramps and walkways cut through bedrock, and seawalls and groins constructed alongshore or into the lake. Many of these activities contribute to a lowering of beach stability.

4.0 HYDROLOGICAL CHARACTERISTICS

4.1 Lake Champlain Water Elevations

Lake Champlain surface water elevations have been measured and recorded since 1907 providing a 100-years of daily data.[30] The following plot, obtained from the United States Geological Survey website, displays daily data for a ten-year period. The "median daily elevation statistic" plotted in this figure was based on a static 73-year database. National Weather Service Flood Stage is defined at 100.0 ft MSL.

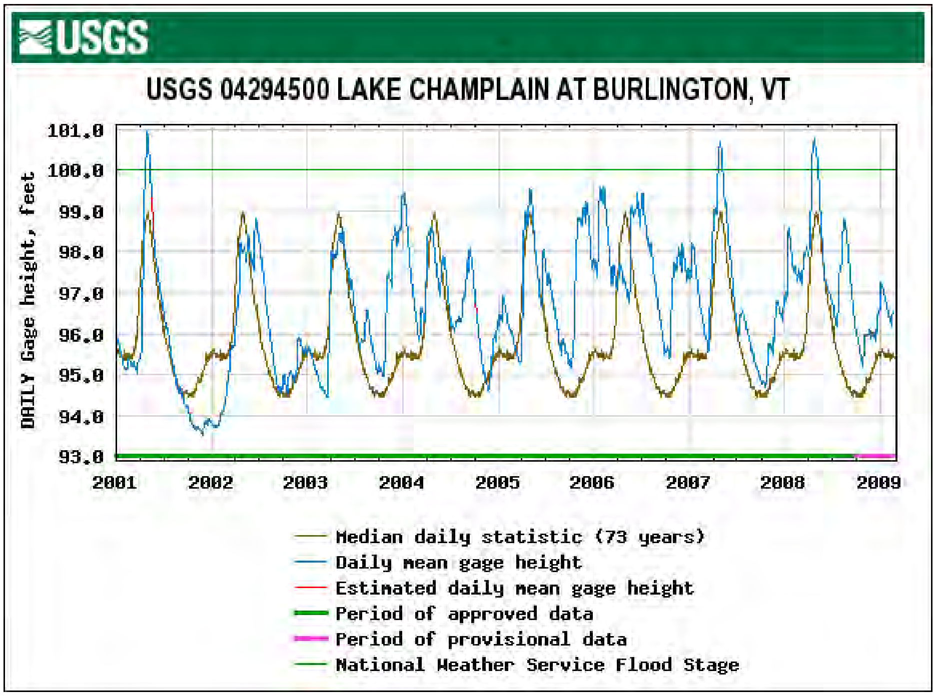


Figure 4.1. Lake Champlain Water Elevation, 2001 to 2008.

Lowest water elevations typically occur in the summer, followed by a small increase in the fall and early winter, a large increase during spring runoff, and then a return to summer lows. During some years the "median daily statistic" provides an accurate forecast but, as seen by recent data, the deviation between observed water levels and the historical average can be quite large.

Mean daily elevations (32,383 data records) for the 100-year period of record were used to compute the numbers of day's lake levels are expected to exceed a selected level. Mean daily water level data were sorted from lowest recorded elevation (92.61 feet, MSL on December 4, 1908) to highest (101.84 feet,

[30] USGS 04294500 Lake Champlain at Burlington, Vermont

MSL on April 4, 1993). The number of days exceeding each ½ foot increment from 92.5 to 102 feet was obtained from this distribution and converted to expected days per year lake levels are greater than a selected ½ foot increment, Table 6. Since 92.61 feet was the lowest elevation recorded, all 365 days per year are expected to be above this level. Likewise elevations are not expected to exceed 102.0 feet since the highest elevation recorded is 101.84 feet. Of special interest for this study is the number of days expected per year to exceed 99 to100 feet MSL per year since at these elevations a sloping beach profile changes to a steep bedrock bank for much of the study area. As indicated in Table 6, lake level is expected to be greater than 99.0 feet twenty-four days per year, and lake level is expected to be greater than 100 feet MSL seven days per year. It is most likely that these days will occur in April and May.

Table 6. Lake elevations and expectations. Based on daily data from 1907 to 2007 (n=32383)

Lake Elevation, feet MSL	Expected Days Greater than corresponding lake elevation per year
92.5	365
93.0	364
93.5	357
94.0	330
94.5	294
95.0	246
95.5	200
96.0	154
96.5	120
97.0	96
97.5	72
98.0	52
98.5	37
99.0	24
99.5	14
100.0	7
100.5	3.5
101.0	1.3
101.5	0.2
102.0	0

4.2 Brief Description of Wind Waves

The picture on the cover depicts waves approaching the east shore of Carry Bay. This picture was taken on November 17, 2008 while a west wind was blowing at 15-20 miles per hour. Each wave crest in this picture is at a different stage of the process described in the following paragraphs. The wave crest on the far left had a rounded profile showing little interaction with the bottom, while the adjacent wave crest has peaked up, but has not broken. Next, the wave breaks and entrains air creating a considerable amount of white water. Closest to shore is the final swash of the wave up the beach.

Wind waves are classified as “deepwater waves,” “intermediate-water waves,” and “shallow-water waves” depending on the ratio of water depth and wavelength (*h/L*), which is called “relative depth.”[31] Waves with wavelengths greater than twice the depth are deepwater waves. The height of a deepwater wave is limited only by wind speed, the amount of time the wind blows, and the extent of open water over which the wind blows, which is called “fetch.” Water depth has no impact on deepwater waves since orbital particle motion is essentially zero at depths greater than ½ the wavelength. When relative depth is greater than ½, orbital particle motion interacts with the bottom and impacts wave properties. Intermediate-wave speed and length are dependent on both water depth (*h*) and wave period (*T*). At a relative depth less than 0.05 (1/20) wave speed is dependent only on depth and these are shallow water waves.[32]

At the upwind end of the fetch waves begin as ripples. Wave size increases as energy is transferred from wind to waves. With distance downwind, waves become larger and ripples turn to chop. When the ratio of wave height to wavelength (*H/L),* called wave steepness, reaches 1/7th the wave whitecaps and breaks. Energy is lost due to turbulence, but some energy is transferred to other waves, which, in deep water, reform with longer wavelengths. Waves with longer wavelengths can support larger wave heights. Eventually, the speed of the wave equals the speed of the wind and energy transfer ceases. At this point wind waves are fully developed and, even with longer fetch and more time, waves will not get any larger. As wind diminishes waves previously formed by wind form swells, which can travel long distances in oceans. Swells are uncommon in lake environments since waves in lakes are generated by local winds and dissipate against shores soon after the wind stops.

Deepwater waves traveling into shoaling water will eventually travel over water depths less than ½ their wavelength and feel the bottom. If the wave crest approaches bottom contours at an angle, the portion of

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[31] Ippen, A.T., 1966. *Estuary and Coastline Hydrodynamics*, page 25, published by McGraw-Hill.
[32] Bascom, W., 1980. *Waves and Beaches*, page 33, published by Doubleday.

the wave in the shallowest water will slow down relative to the portion of the wave crest in deeper water. This differential wave speed will bend the wave crest and it will tend to become parallel with bottom contours. The bending of a wave crest to align parallel with bottom contours is called "refraction." The wave crest may become completely aligned with the shoreline but, if it doesn't, it will break at the shoreline at an oblique angle and generated forces both perpendicular and parallel to the shoreline.

In addition to possible refraction as waves approach shore, wavelength decreases and wave steepness increases. At a wave steepness ratio of about 1/7th the wave will break (just as waves do in deepwater). Upon entering shallow water the wave crest "peaks up" (see cover photograph) contributing to steepness ratio. When the wave height is about 1 – 1.5 times the water depth, the wave breaks.[33] The ratio of breaking wave height (H_b) to local water depth (h_b) is called the breaker index (γ_b). Waves in shallow water may break due to steepness ratio, as in deepwater, or due to interactions with the bottom. The breaking wave loses energy, but may reform at a lesser height until it again travels over water depths of 1 – 1.5 times its new height and breaks again. This process may repeat several times. Finally, the wave ends with a swash up the beach face. Water sinks into beach material (sand, gravel, cobbles) and some runs back down the beach face. Gravel beaches are, in general, more stable than sand beaches because the gravel's permeability prevents the backwash of waves from eroding the beach.

Waves breaking on a sloping beach are classified as spilling, plunging, collapsing and surging.[34] Waves of relatively low steepness ratios that travel over flat slopes break by continuously spilling foam down the face of the wave until the wave is dissipated. With a relative increase in steepness and slope, a wave will peak, curl forward and plunge. At an even higher wave steepness and slope, the wave will peak and curl forward but, before the crest plunges, the base of the wave will surge up the beach face.

As the lake water level increases the edge of water moves further up the slope but, if the slope is constant, waves demonstrate similar characteristics relative to distance from the edge of water. If lake level increases sufficiently, the entire slope could be submerged and lake water level may rise above the toe of a natural bedrock bank. Waves will break and loss energy as they travel across the sloping beach profile as before, and any remaining energy would dissipate by breaking against the bedrock bank or be reflected back towards the lake.

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[33] Battjes, J. A., 1974. Computation of set-up, longshore currents, run-up and overtopping due to wind generated waves. Doctoral Thesis, Delft University of Technology, The Netherlands, Figure 2.6, page 21.
[34] *ibid.*, Figure 3.4, page 17.

4.3 Wave Model Application to Carry Bay, Lake Champlain

4.3.1 Domain

The area depicted in Figure 1 (located following Section 6) represents the model domain in Vermont Plane Coordinate System[35] in meters. The model domain extends 12.5 miles from Long Point, New York in the south to Stephenson Point, Vermont at the northern end of Alburgh Passage. The model domain extends three miles from Holcomb Point in Isle La Motte eastward to the east shore of Carry Bay in North Hero. The domain includes Pelots Bay, Carry Bay and Alburgh Passage.

All lines radiating from the causeway intercept land features and result in maximum fetch except in the south-southwest direction. For this wind direction boundary conditions were examined to ensure that maximum waves were realized in the area of interest.

4.3.2 Model Depths

Lake water depths were obtained from National Oceanic and Atmospheric Administration (NOAA) charts of Lake Champlain, Figures 1 and 2. The plane of reference in these figures is 99.5 feet mean sea level (MSL) referenced to the National Vertical Geodetic Datum of 1929. Additional soundings were obtained near the causeway using Global Positioning System (GPS) and a weighted cloth measuring tape.

4.3.3 Model Grids

Once the shoreline features (x and y coordinates) and depths of water (z coordinate) were obtained a three-dimensional digital representation of physical space was created. This space was divided into computational cells. Each cell was described by quadrangles with inside angles as close to 90 degrees as possible, and a depth value referenced to 99.5 feet MSL. Figures 3 and 4 depict the model grid.

An enlargement of the plan view of cells representing the computational grid near Carry Bay is depicted in the upper portion of Figure 4. This grid represents the causeway in-place. The causeways' north and south sections form extensions of the land boundary and contain no grids. The middle section is also depicted by an absence of grids. To create this representation of causeway in-place, it was necessary to start with a master grid containing cells within the outline of the entire causeway. Cells were removed to depict the south, middle and north sections of the causeway. Cells were replaced to represent sections of the causeway removed.

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[35] The Vermont Coordinate System, Chapter 17, Vermont Statutes Online.

Note that grid cells near the shore are smaller than those further offshore. Relatively small grid size at these locations was designed to increase resolution and provide sufficient detail for modeling wave characteristics in shallow water near shore.

The grid cell configuration shown in Figure 4 is called “no-north,” and even though 1,150 feet of causeway is removed, about 480 feet of the north section of the causeway remains. In Figure 47 the “littoral-zone” configuration is depicted with an additional 300 feet of the north section of the causeway removed, leaving 180 feet of rock fill extending from shore.

Three distinct computational grids were used in the simulations: in-place, no-north, and littoral-zone. All grids were created from one master grid representing the entire modeled area depicted in Figure 3. Using this approach, parameters of interest could be calculated for each grid and results for individual cells could be compared.

4.3.4 Model Wind Speed & Direction

Of the sixteen sectors only those from NNE to SSW were selected for model analysis. All nine sectors, NNE, N, NNW, NW, WNW, W, WSW, SW, and SSW, were modeled using seven different wind speeds ranging from 10 to 70 mph in 10 mph increments.

4.3.5 Model Time Duration

Passages of low-pressure systems, that create the highest wind events, are usually relatively rapid. Inspection of wind data indicates that maximum wind speeds occur for considerably less than 24 hours. Simulation model time duration was set at 24 hours to ensure stable and maximum-modeled wave conditions.

4.3.6 Model Reference Elevation

A high water 99.5 feet MSL was selected to produce nearly maximum wave heights for offshore.[36]
As the lake level increases the edge of water moves further up the slope, but if the slope is steady, waves approaching the shore experience the same sequence of changes, just at different locations. Therefore, the lake level in the simulation was held constant at 99.5 MSL.

4.3.7 Model Output Wave Parameters

The *SWAN* model predicts a wave spectrum of different size wave heights and frequencies within a sea state and, from these spectrums, significant wave heights are calculated. Significant wave height is the average of the highest one-third of all predicted wave heights.[37]

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[36] Fourteen days per year are expected to have water levels greater than 99.5 feet MSL, see Section 4.1.

Other common wave characteristics are wavelength (distance from wave crest to wave crest) and wave period (duration of time between successive waves passing a fixed point) and wave energy. Wave energy is proportional to the square of the wave height and increases four fold with each doubling of wave height. Wave heights are reduced by bottom vegetation, which is abundant at Carry Bay, but this process was not simulated.[38]

4.3.8 Model Initial Conditions and Physical Parameters and Constants

The initial condition for each sea state was set at a zero wave height throughout the model domain. The model executed computations until the difference between consecutive sea state descriptions was negligible.

Physical constants are acceleration due to gravity (9.81 meters per square second) and density of water (1000 kg/cubic meters). Minimum water depth was set at the model default value of 0.05 meters (about 2 inches)

Wind was defined at an elevation of 10 meters (standard) and uniform throughout the model domain. Depth induced wave breaking was activated using the formulation by Battjes and Janssen (1978)[39] with default coefficients set at dissipation equal to 1.0 and breaker parameter equal to 0.73. Bottom friction was set using the formulation by Hasselmann et al., 1973.[40]

4.3.9 Example of Model Output

Wave characteristics were predicted for each cell in the model domain. As an example, significant wave heights are displayed in Figure 5 for wind from the northwest at 50 mph, and with the north section of the causeway removed. Colors correspond to ranges of significant wave heights. Even through results were always computed for the entire model domain, most model results in this report depict only the area near Carry Bay.

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[37] This parameter was developed when wave heights were measured by manual observations. Observers tended to measure only the larger waves and ignored smaller waves. Bascom, W., 1980. *Waves and Beaches*.

[38] Kobayashi, Nobuhisa, 1993. Wave attenuation by vegetation. *Journal of Waterway, Port, Coastal, and Engineering.* Vol. 119, No. 1, Paper No. 2413.

[39] Battjes, J.A. and J.P.F.M. Janssen, 1978. Energy loss and set-up due to breaking of random waves, Proc. 16th Int. Conf. Coastal Engineering, ASCE, 569-587

[40] Hasselmann, K., et. al., 1973. Measurements of wind-wave growth and swell (JONSWAP), Dtsch. Hydrogr. Z. Suppl., 12, A8

4.4 Wave Predictions - No-North & In-Place Configurations

4.4.1 Significant Wave Height

Significant wave height predictions are displayed in Figures 6 to 29. These twenty-four figures are arranged in four sets of six figures. The first six figures (Figures 6 to 11) display winds from the north for 30, 50, and 70 mph. The next six figures display results for northwest winds (Figures 12 to 17), followed by results from the west (Figures 18 to 23), and southwest directions (Figures 24 to 29).

Each set has three pairs of figures representing winds of 30, 50 and 70 mph. The first figure of each pair depicts significant wave height and the second figure of the pair depicts the difference in wave height, i.e., no-north minus in-place. Wave heights are contoured in 0.15-meter increments (about 6 inch intervals), and the difference in wave heights are contoured in increments of 0.05 meters (about 2 inch intervals).

Figures 6 and 7 depict significant wave height and the difference in significant wave height, respectively, for 30 mph west winds. The upper part of Figure 6 represents significant wave height predictions for the causeway in-place configuration and has a large area of very light blue color that represents wave heights ≥0.3 meters and <0.45 meters (greater than or equal to 0.3 meters and less than 0.45 meters). In the lower drawing, representing the no-north configuration, a large portion of the area that was very light blue in the upper drawing is now green. Green is the next higher wave height increment in the color legend indicating that predicted wave heights are ≥0.45 and <0.6 meters.

Figure 7 (the second figure of this pair) illustrates the difference in significant wave height for the same wind conditions depicted in Figure 6 (no-north minus causeway in-place). As seen in Figure 7, the change in wave height throughout most of the study area is represented by the two darkest shades of blue. The larger area on the darkest blue color represents wave height increases <0.05 meters (about 2 inches); the next lighter color of blue represents an increase of <0.10 meters (about 4 inches). The largest increases in significant wave heights are just east of the removed north section of the causeway in the former wind shadow. Figures 8 and 9, the second pair of the north wind set, represent conditions for 50 mph, and Figures 10 and 11 represent conditions for 70 mph.

Near shore characteristics, illustrated in Figure 8 and 10, show similarities between the upper (in-place) and lower (no-north) drawings. A thin strip of dark blue color near shore indicate that, despite offshore differences, predicted significant wave heights near shore are consistently <0.10 meters regardless of causeway configuration.

Figure 30 through Figure 33 depict enlargements of portions of the study area to better illustrate near shore significant wave height predictions. Figure 30 depicts the area near the north section of the causeway and from Point of the Tongue east to Blockhouse Point. In this enlargement, the portion of the north section of the causeway removed in the model is clearly illustrated (lower drawing). The entire north section is clearly illustrated in the upper drawing. The dark maroon color represents significant wave heights ≥1.20 and <1.35 meters (one color up from red). This dark maroon area, in the lower part of Figure 30, extends from the causeway nearly to Blockhouse Point.

Figure 31 presents another enlargement of the same area focusing on near shore conditions. Figures 32 and 33 depict two other areas of Carry Bay, near the Carrying Place and Savage Point, where, in spite of larger predicted significant wave height of offshore, waves near shore remain little changed.

4.4.2 Wave Energy

Figures 34 through 39 depict predicted wave energy in units of watts[41] per meter of wave crest. For a wave crest parallel to shore this equates to watts per meter of shoreline. Energy transport is a vector quantity described by magnitude and direction; therefore, energy transport is represented by an arrow (direction), and length and color of the arrow (magnitude). Figure 34 depicts energy transport and areas with yellow arrows represent wave transport energy less that 2,400 watts/meter. Wind was from the west and some arrows align with wind direction. More often, though, energy vectors do not align with the wind direction since waves crest tend to align parallel with bottom contours.

For conditions represented in Figure 34, energy transport is increasing from west to east as wave gains energy from wind. Wave energy is greater on the west side of the causeway and less on the east side since waves break and dissipate their energy while passing over shallower depths.

Figures 35 and 36 depict wave energy for the same wind conditions (70 mph west wind) with the causeway in-place and no-north, respectively. In Figure 35 the energy is clearly dissipated against the west face of the causeway. In the wind shadow east of the causeway waves have less energy. Further east in Carry Bay waves have started to regain energy from the wind. Then, wave energy is reduced as waves approach the shore and break. Blue vectors, denoting low energy transport values, appear near the shore for both causeway in-place and no-north configurations as shown in Figures 35 and 36, respectively.

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[41] One watt is equal to a force of 0.737 foot-pounds per second or 0.001341 horsepower. One horsepower equals 750 watts. In metric units, one watt is equal to one joule per second or one Newton meter per second.

Figure 37 is an enlargement of a relatively small area of Carry Bay located near the northeast corner. Energy transport decreases from 1,600 watts per meter (red arrow) offshore to between <200 watts/meter and <400 watts/meter (blue and dark blue arrows) near shore.

Figures 38, 39 and 40 depict a relatively small area between the causeway and Blockhouse Point that has been enlarged to reveal more detail. Wind from the west was modeled for wind speeds of 70 mph, 50 mph and 30 mph, as shown in Figures 38, 39 and 40, respectively

4.4.3 Wavelength and Wave Period

Figures 41, 42 and 43 describe wavelengths, and Figures 44, 45 and 46 describe wave period, for west winds of 30 mph, 50 mph, and 70 mph, respectively. Results of wavelength and wave period are used in the analysis of beach stability in Chapter 5.

4.5 Wave Predictions - Littoral-Zone Configuration

Figure 47 depicts bottom depths and the computational grid for the littoral-zone configuration and, for comparison, the no-north configuration. In the littoral-zone configuration the same 1,150 feet of causeway is removed as in the no-north configuration, plus an additional 300 feet of the north section, leaving 180 feet of causeway extending from shore. Removal of this additional 300 feet of causeway would reduce water depths at the southern end of the remaining north section by 4 to 5 feet. Figure 48 depicts the causeway from North Hero Marina to Point of the Tongue for the littoral-zone configuration.

There are two main areas of interest in this analysis: west shore of Blockhouse Point and east shore of Point of the Tongue close to the causeway. Figure 49 depicts the sea state at a high wind speed (70 mph) from the west for the littoral-zone and no-north configurations from the causeway to Blockhouse Point. The magnitude of the wave heights near Blockhouse Point remain about equal but the area affected increases. Most of this increase in area is in the north to south direction that coincides with the increase in width of the causeway opening. The sea state closer to shore remains similar along the west shore of Blockhouse Point and also along the east shore of Point of the Tongue.

Figure 50 depicts predictions significant wave heights for a southwest wind of 70 mph. Figures 51, 52 and 53 depict the change in sea state between the littoral-zone and no-north configurations, which is similar to the difference between the littoral zone and causeway in-place since both configurations produced a wind shadow east of the causeway.

Figure 51 depicts a large increase in wave heights just east of the portion of causeway that was removed. This area was in the wind shadow of the no-north configuration. Difference in wave heights decrease toward the north. Waves in the area offshore, but still in the wind shadow of the remaining causeway, could experience waves of about one foot for the highest winds of 70 mph. As winds decrease these changes would be less as shown in the bottom display in Figure 51 for a west wind of 50 mph. Figure 52 depicts the same wind speeds of 70 mph and 50 mph but from the southwest. More typical are wind speeds of 30 mph and 20 mph shown in Figure 53. East of the remaining 180 feet of the north section of the causeway for west winds of 20 - 30 mph, wave heights were predicted to be less that 1/2 foot offshore and decreasing towards the shore.

4.6 Review – Hydrographical Information

- Lake level is expected to be greater than 99.0 feet twenty-four days per year, and lake level is expected to be greater than 100 feet MSL seven days per year. It is most likely that these days will occur in April and May.
- Wave conditions with the causeway in-place (present conditions) and with the north section of the causeway removed (future conditions) were calculated using SWAN, *Simulating Waves Near Shore*, written by Delft Hydraulics Institute.
- Site data required for the model are lake topography, lake water elevation, wind velocity and geometry of the causeway. Three different configurations of the causeway were simulated: (1) existing geometry (in-place), (2) 1,150 feet of the north section of the causeway removed (no-north), and (3) 1,450 feet of the causeway removed (littoral-zone).
- The model domain extends 12.5 miles from Long Point, New York in the south to Stephenson Point, Vermont at the northern end of Alburgh Passage. The model domain extends three miles from Holcomb Point in Isle La Motte eastward to the east shore of Carry Bay in North Hero. The domain includes Pelots Bay, Carry Bay and Alburgh Passage.
- Winds from nine directions (NNE, N, NNW, NW, WNW, W, WSW, SW, and SSW) were modeled for seven different wind speeds ranging from 10 to 70 mph in 10 mph increments.
- Predictions of wave height, wave period, wavelength, and energy are presented for causeway in-place, and two configurations of portions of the north section of the causeway removed (no-north and littoral-zone). From the nine directions and seven wind speeds modeled, results presented in this report mainly represent N, NW, W and SW winds at 30, 50, and 70 mph.

5.0 ANALYSIS OF METEOROLOGICAL, GEOLOGICAL AND HYDROLOGICAL DATA

In this section predicted changes in wave characteristics are discussed relative to offshore and near shore regions. Offshore regions are lakeward of the toe of the sloping beach profile. Modeled wave heights and increases in wave heights are discussed in Section 5.1 for six locations in the offshore region.

Near shore regions, also called the “surf zone,” are shoreward of the toe of the sloping beach profile. At lake levels less than about 99 feet MSL near shore impacts are confined to the rocky beach. Suspended load and bed load transport processes are discussed in Section 5.2.1. Wave characteristics in the surf zone are presented in Section 5.2.2. Using formulas for the design of revetments and other shoreline structures, the stability of beaches are evaluated in Section 5.2.3. A second, independent analysis of beach stability using physical models is in Section 5.2.4.

Above a lake level of about 99 feet MSL, waves break on and are reflected away from bedrock banks. An analysis of bedrock recession is presented in Section 5.2.5.

5.1 Offshore Waves

Wave heights and the estimated change in wave heights are listed in Tables 6, 7, 8, and 9 for winds from the north, northwest, west and southwest, respectively. Wave heights listed in these tables were obtained from inspection of Figures 6 to 29. Locations selected were: three locations between the causeway and Blockhouse Point; at the center of Carry Bay; between Blockhouse Point and Savage Point; and, at the entrance to Pelots Bay.

With the causeway in-place and with winds from the west, the water surface is calm east of and adjacent to the causeway. However, as shown in Table 8 for a 50 mph west wind, at just 1/3rd of the distance from the causeway to Blockhouse Point wave heights *with the causeway in-place* have grown to between 0.45 meters and 0.6 meters from essentially zero. For these same conditions, at four of the other five locations predicted wave heights were >0.6 meters and <0.75 meters, and at the entrance to Pelots Cove wave height was > 0.45 meters and <0.6 meters. This illustrates the phenomena that waves rise rapidly in responds to wind, and achieve the highest increase in wave height in a relatively short distance.

From the causeway to Blockhouse Point, increases in significant wave heights exceeded all other regions in the study area. The highest increases in wave height would be just east of the causeway where waves were essentially zero for west winds with the causeway in-place. Tables 6 – 9 indicate that 1/3rd of the way to Block House Point, increases in wave height were >0.45 meters and <0.6 meters.

Figure 1 and 2 display water depths relative to a datum of 99.5 feet MSL. Because of deeper water in Isle La Motte Passage, waves build to longer wavelengths and support larger wave heights before reaching a steepness ratio of 1/7th and breaking. But, upon entering shallower water east of the causeway, wavelengths decrease, the steepness ratio increases, and, at a wavelength of about 1/7,th waves whitecap and break. The decrease in wave height as waves enter Carry Bay was shown in Figures 6 – 29. In addition, spreading of the wave crest after passing through the causeway results in a decrease in wave height.

In other impacted regions east of the causeway, but outside of the area between the causeway and Blockhouse Point, increases in wave height were generally less than 0.05 to 0.2 meters (less than 2 to 8 inches). The largest increase was 0.2 meters (about 8 inches) for a 70 mph wind - a wind this high is not expected even once in one hundred years. Relatively small increases in wave heights in these regions are related to the phenomena that waves rise rapidly in responds to winds and recover much of their height in a relatively short distance, consequently the difference between predicted wave heights before and after causeway removal was low in these areas.

Table 6. North Wind - Predicted wave height for causeway in-place and the change in wave height with removal of the north section (no-north configuration) for 30, 50 and 70 mph wind speeds.

Location	Predicted wave height in meters for IN-PLACE configuration			Predicted INCREASE in wave height in meters for NO-NORTH configuration		
	Wind Speed, miles per hour			Wind Speed, miles per hour		
	30	50	70	30	50	70
1/3 from center of north section to Blockhouse Pt.	>0.30 & <0.45	>0.45 & <0.6	>0.75 & <0.9	>0.10 & <0.15	>0.20 & <0.25	>0.40 & <0.45
2/3 from center of north section to Blockhouse Pt.	>0.30 & <0.45	>0.60 & <0.75	>0.75 & <0.9	<0.05	<0.05	<0.05
1/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.60 & <0.75	>0.75 & <0.9	<0.05	>0.05 & <0.1	>0.10 & <0.15
Center of Carry Bay	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	<0.05	>0.05 & <0.1	>0.05 & <0.1
2/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	>0.05 & <0.10	>0.10 & <0.15	>0.15 & <0.2
Center of entrance to Pelots Cove	>0.30 & <0.45	>0.75 & <0.9	>0.90 & <1.05	<0.05	<0.05	<0.05

Table 7. Northwest Wind - Predicted wave height for causeway in-place and the change in wave height with removal of the north section (no-north configuration) for 30, 50 and 70 mph wind speeds.

Location	Predicted wave height in meters for IN-PLACE configuration			Predicted INCREASE in wave height in meters for NO-NORTH configuration		
	Wind Speed, miles per hour			Wind Speed, miles per hour		
	30	50	70	30	50	70
1/3 from center of north section to Blockhouse Pt.	>0.15 & <0.3	>0.30 & <0.45	>0.60 & <0.75	>0.20 & <0.25	>0.40 & <0.45	>0.45 & <0.50
2/3 from center of north section to Blockhouse Pt.	>0.15 & <0.3	>0.45 & <0.6	>0.75 & <0.9	>0.10 & <0.15	>0.15 & <0.20	>0.20 & <0.25
1/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.45 & <0.6	>0.75 & <0.9	>0.10 & <0.15	>0.15 & <0.20	>0.20 & <0.25
Center of Carry Bay	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	>0.05 & <0.1	>0.10 & <0.15	>0.10 & <0.15
2/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	>0.10 & <0.15	>0.15 & <0.20	>0.15 & <0.20
Center of entrance to Pelots Cove	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	<0.05	<0.05	<0.05

Table 8. West Wind - Predicted wave height for causeway in-place and the change in wave height with removal of the north section (no-north configuration) for 30, 50 and 70 mph wind speeds.

Location	Predicted wave height in meters for IN-PLACE configuration			Predicted INCREASE in wave height in meters for NO-NORTH configuration		
	Wind Speed, miles per hour			Wind Speed, miles per hour		
	30	50	70	30	50	70
1/3 from center of north section to Blockhouse Pt.	>0.15 & <0.3	>0.45 & <0.60	>0.75 & <0.90	>0.20 & <0.25	>0.40 & <0.45	>0.55 & <0.60
2/3 from center of north section to Blockhouse Pt.	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	>0.10 & <0.15	>0.20 & <0.25	>0.25 & <0.30
1/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	>0.05 & <0.10	>0.05 & <0.10	>0.05 & <0.10
Center of Carry Bay	>0.30 & <0.45	>0.60 & <0.75	>1.05 & <1.20	<0.05	<0.05	<0.05
2/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.60 & <0.75	>0.75 & <0.90	<0.05	<0.05	>0.05 & <0.10
Center of entrance to Pelots Cove	>0.15 & <0.30	>0.45 & <0.60	>0.60 & <0.75	<0.05	<0.05	<0.05

Table 9. Southwest Wind - Predicted wave height for causeway in-place and the change in wave height with removal of the north section (no-north configuration) for 30, 50 and 70 mph wind speeds.

Location	Predicted wave height in meters for IN-PLACE configuration			Predicted INCREASE in wave height in meters for NO-NORTH configuration		
	Wind Speed, miles per hour			Wind Speed, miles per hour		
	30	50	70	30	50	70
1/3 from center of north section to Blockhouse Pt.	>0.30 & <0.45	>0.45 & <0.60	>0.90 & <1.05	>0.15 & <0.20	>0.30 & <0.35	>0.40 & <0.45
2/3 from center of north section to Blockhouse Pt.	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	>0.05 & <0.10	>0.10 & <0.15	<0.05
1/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	<0.05	<0.05	<0.05
Center of Carry Bay	>0.30 & <0.45	>0.60 & <0.75	>0.90 & <1.05	<0.05	<0.05	<0.05
2/3 from Blockhouse Point to Savage Point	>0.30 & <0.45	>0.45 & <0.60	>0.75 & <0.90	<0.05	<0.05	<0.05
Center of entrance to Pelots Cove	>0.15 & <0.30	>0.30 & <0.45	>0.60 & <0.75	<0.05	<0.05	<0.05

5.2 Near Shore Waves and Transport Mechanisms

5.2.1 General Discussion on Suspended and Bed Load Transport Processes Near Shore

Waves and currents produce water particle motion that act on materials such as silts, sands, gravel, cobbles and boulders. Materials are moved toward shore, away from shore, and along the shore in both directions. Materials can be transported as “suspended load” and/or “bed load.” Materials are transported as “suspended load” as long as they remain in suspension and a current is present. Bed load transport includes mechanisms such as rolling, sliding and saltation (a rapid vertical movement into the flow caused by various forces, being transported a short distance then settling). Transport of sand exhibit behavior associated with both suspended and bed load transport; gravel and cobbles are restricted to bed load transport.

When lake water level rises rapidly, gravel could be submerged. Submerged gravel would be moved about in the surf zone. As the lake level falls waves build gravel ridges (Photographs 4, 10 and 14). Gravel can be transported in both directions along the shore, with a net transport in the direction of the most dominant waves forces, creating accumulation and depletion zones (Photographs 15 and 16) near human made and natural groins. Since gravel is transported as bed load - a much slower process than transport of sand and silt by suspended load. Silts and sands, originally in glacial till, are transported away from the shore and lost from the beach forever. But smooth, rounded, flat rock of gravel size near their origin, as seen along the very end of Blockhouse Point, is evidence of slow net transport. Gravel distribution is dynamic and is reshaped by waves, while continually providing beach protection.

Cobbles are much less mobile than gravel and provide a static component to beach armor. Most cobbles observed along the shore and below water line were well packed and nestled together indicating little movement (Photograph 6). Cobbles rest on other cobbles and were often nestled with small gravel and coarse sand size particles providing additional stability (Photograph 2 and 5). A short distance offshore rocks are covered with zebra mussels, providing a virtual component of weight to rocks and, perhaps, more stability. At other locations cobbles are isolated and rest on loose gravel (Photograph 8 and 17). Some beaches are almost entirely composed of cobble (Photograph 12) and other beaches are mostly cobbles below and gravel above the edge of water (Photograph 10 and 14).

5.2.2 Significant Wave Heights Near Shore

Details of wave properties from model results were obtained at several locations throughout the study area at 10-meter intervals from the shoreline to 100 meters offshore (transects). Results from the following three locations were selected to provide near shore descriptions of waves: north of Blockhouse

Point along the east shore of Alburgh Passage; the east shore of Carry Bay; and, the south shore of Carry Bay. For these three locations significant wave height is tabulated at 1 m (3.28 feet), 10 meters (32.8 feet), 30 meters (98.4 feet) and 100 meters (328 feet) from the edge of water, in Tables 10, 11 and 12, respectively. Significant wave heights were tabulated in 10 mph increments from 20 mph to 70 mph for north, northwest, west and southwest winds. Also, wave energy dissipation is plotted for three locations from the shoreline to 40 meters offshore.

Wind speeds of 60 mph and 70 mph exceed the 100-year return period for winds in the study area. The return level for a return period of 100-years vary from 50 mph to 56 mph for winds from the north, northwest, west and southwest.

North of Blockhouse Point –Table 10

With or without the north section of the causeway, north winds had essentially the same impact on wave heights north of Blockhouse Point. For winds from the NW, W and SW wave heights increased with the causeway removed. At 100 meters from shore, southwest 70 mph winds develop the largest wave heights for both causeway configurations: 1.01 meters and 1.22 meters for causeway in place and no-north, respectively. West winds of 70 mph created the largest increase in wave heights at 100 meters from shore: 0.26 meters (from 0.88 meters to 1.14 meters).

Closer to shore, wave heights decrease as waves break in the surf zone. With the causeway in place and for 50 mph southwest winds, wave heights decreased from 0.69 meters at 100 meters from shore, to 0.48 meters at 10 meters from shore. At one meter from shore, lowest wave heights and the smallest increases in wave heights were predicted. Wave heights vary from 0.06 to 0.2 meters (2 to 8 inches) at 1 meter from shore for a low wind speed of 20 mph to extremely high wind speed of 70 mph, respectively.

For the Blockhouse Point location, predicted wave heights are plotted in Figure 5.1 for causeway in-place and no-north configurations. Data for no-north are plotted with dashed lines and data for causeway in-place use a solid line. Wave heights at one meter from shore were nearly the same for both configurations at all wind speeds. Predicted wave heights and the difference in wave heights increase with distance offshore and wind speed.

Energy dissipation is plotted in Figure 5.2 for the location north of Blockhouse Point. As seen in this figure, almost all of the wave energy was dissipated from the shoreline to 20 meters offshore. Energy dissipation is plotted for waves predicted with the causeway in-place and with the north section of the causeway removed. Energy dissipation for a 30 mph wind for causeway in-place almost coincides exactly with the energy dissipation curve for 20 mph wind for no-north causeway configuration. Similarly, the curves for in-place 40 mph wind coincides with the curve for 30 mph no-north configuration; and the 50 mph in-place curve nearly coincides with the 40 mph no-north curve. For higher wind speeds, this relationship does not hold and energy dissipation at 50 mph with the causeway removed have more energy and, therefore, more energy dissipation, than energy in waves created at 60 mph with the causeway in-place.

East Shore of Carry Bay – Table 11

Southwest winds, which caused the largest increases in wave heights near Blockhouse Point, show almost no difference in wave heights at 1, 10, 30 and 100 meters from shore with the north section of the causeway removed compared with the causeway in-place at the east shore of Carry Bay. The increase in wave height predicted with removal of the north section of the causeway were relatively small for all wind speeds and directions and locations up to 100 meters offshore, and do not exceed 0.1 meters (about 4 inches) at this location. Northwest winds at 70 mph show the largest wave heights for both causeway configurations, 0.98 meters for causeway in-place and 1.05 meters for no-north - an increase in height of 0.07 meters (2.8 inches). The largest increase in wave height of 0.09 meters is observed for a northwest wind speed of 50 mph at 100 meters from shore. For the east shore location, predicted wave heights are plotted in Figure 5.3 for causeway in-place and no-north configurations.

South Shore of Carry Bay – Table 12

Since the south shore of Carry Bay is shielded from southwest winds it is not surprising that changes in wave height for all modeled southwest wind speeds are less than 0.01 meters (less than ½ inch). Highest wave heights of 0.94 and 1.06 meters are predicted for a 70 mph northwest wind for causeway in-place and no-north configurations, respectively. This is an increase in wave height of 0.12 meters (less than 5 inches).

Table 10. Predicted significant wave height North of Blockhouse Point along the east shore of Alburgh Passage for causeway in-place and no-north configurations for various wind speeds and directions, x=437900, y=261000.

Wind direction & speed, mph	Predicted significant wave height in meters for IN-PLACE configuration				Predicted significant wave height in meters for NO-NORTH configuration			
	Distance Offshore, meters (Depth, meters)				Distance Offshore, meters (Depth, meters)			
	1(0.13)	10 (1.0)	30 (2.9)	100(5.7)	1(0.13)	10 (1.0)	30 (2.9)	100(5.7)
N 20	0.06	0.15	0.20	0.22	0.06	0.15	0.20	0.22
N 30	0.10	0.23	0.31	0.35	0.10	0.23	0.31	0.35
N 40	0.13	0.31	0.41	0.47	0.13	0.31	0.41	0.47
N 50	0.14	0.31	0.50	0.59	0.15	0.39	0.51	0.60
N 60	0.16	0.45	0.59	0.69	0.16	0.45	0.59	0.68
N 70	0.18	0.52	0.68	0.80	0.18	0.53	0.68	0.78
NW 20	0.07	0.16	0.18	0.18	0.08	0.17	0.19	0.19
NW 30	0.10	0.23	0.27	0.27	0.12	0.26	0.30	0.31
NW 40	0.13	0.31	0.38	0.39	0.14	0.37	0.43	0.44
NW 50	0.15	0.39	0.48	0.50	0.17	0.46	0.55	0.57
NW 60	0.17	0.47	0.58	0.62	0.19	0.56	0.69	0.73
NW 70	0.18	0.55	0.71	0.77	0.22	0.65	0.84	0.90
W 20	0.08	0.17	0.19	0.18	0.11	0.24	0.27	0.27
W 30	0.12	0.29	0.32	0.32	0.15	0.38	0.43	0.45
W 40	0.14	0.39	0.45	0.45	0.17	0.50	0.60	0.63
W 50	0.16	0.48	0.57	0.59	0.20	0.60	0.76	0.80
W 60	0.19	0.56	0.70	0.74	0.21	0.69	0.91	0.97
W 70	0.20	0.63	0.83	0.88	0.23	0.76	1.06	1.14
SW 20	0.09	0.19	0.22	0.24	0.11	0.24	0.27	0.30
SW 30	0.12	0.29	0.35	0.39	0.14	0.36	0.42	0.47
SW 40	0.15	0.39	0.46	0.54	0.17	0.49	0.58	0.66
SW 50	0.17	0.48	0.59	0.69	0.20	0.60	0.75	0.85
SW 60	0.19	0.57	0.72	0.85	0.21	0.69	0.91	1.04
SW 70	0.20	0.64	0.85	1.01	0.23	0.77	1.06	1.22

Table 11. Predicted significant wave height East Shore of Carry Bay for causeway in-place and no-north configurations for various wind speeds and directions, x=438700, y=259900.

Wind direction & speed, mph	Predicted significant wave height in meters for IN-PLACE configuration				Predicted significant wave height in meters for NO-NORTH configuration			
	Distance Offshore, meters (Depth, meters)				Distance Offshore, meters (Depth, meters)			
	1(0.15)	10 (0.9)	30 (2.9)	100(4.2)	1(0.15)	10 (0.9)	30 (2.9)	100(4.2)
N 20	0.08	0.15	0.19	0.20	0.09	0.17	0.20	0.22
N 30	0.11	0.23	0.29	0.32	0.12	0.26	0.32	0.36
N 40	0.13	0.30	0.39	0.44	0.16	0.34	0.44	0.49
N 50	0.17	0.37	0.50	0.57	0.18	0.41	0.56	0.63
N 60	0.17	0.43	0.61	0.70	0.18	0.44	0.68	0.76
N 70	0.18	0.45	0.73	0.84	0.19	0.48	0.79	0.90
NW 20	0.10	0.21	0.24	0.25	0.12	0.24	0.29	0.30
NW 30	0.14	0.31	0.39	0.40	0.16	0.35	0.44	0.47
NW 40	0.17	0.38	0.50	0.55	0.18	0.42	0.58	0.63
NW 50	0.19	0.45	0.64	0.70	0.18	0.47	0.72	0.79
NW 60	0.19	0.48	0.76	0.85	0.19	0.51	0.83	0.93
NW 70	0.20	0.53	0.86	0.98	0.20	0.55	0.91	1.05
W 20	0.10	0.22	0.25	0.26	0.11	0.23	0.27	0.27
W 30	0.14	0.31	0.38	0.40	0.15	0.33	0.40	0.43
W 40	0.17	0.38	0.47	0.54	0.18	0.41	0.54	0.57
W 50	0.19	0.45	0.57	0.67	0.19	0.47	0.66	0.72
W 60	0.20	0.50	0.64	0.82	0.20	0.52	0.70	0.86
W 70	0.20	0.53	0.73	0.95	0.20	0.54	0.88	1.00
SW 20	0.09	0.18	0.20	0.20	0.09	0.18	0.20	0.20
SW 30	0.12	0.27	0.32	0.32	0.13	0.27	0.32	0.33
SW 40	0.16	0.35	0.43	0.45	0.16	0.35	0.43	0.45
SW 50	0.18	0.41	0.55	0.58	0.17	0.41	0.55	0.59
SW 60	0.19	0.46	0.67	0.72	0.19	0.46	0.67	0.73
SW 70	0.19	0.49	0.78	0.87	0.19	0.49	0.79	0.87

Table 12. Predicted significant wave height South Shore of Carry Bay for causeway in-place and no-north configurations for various wind speeds and directions, x=438200, y=259200.

Wind direction & speed, mph	Predicted significant wave height in meters for IN-PLACE configuration				Predicted significant wave height in meters for NO-NORTH configuration			
	Distance Offshore, meters (Depth, meters)				Distance Offshore, meters (Depth, meters)			
	1 (0.14)	10 (0.9)	30 (2.0)	100 (3.8)	1 (0.14)	10 (0.9)	30 (2.0)	100 (3.8)
N 20	0.09	0.22	0.27	0.28	0.10	0.23	0.29	0.30
N 30	0.13	0.32	0.40	0.43	0.16	0.35	0.44	0.48
N 40	0.18	0.41	0.53	0.59	0.19	0.45	0.58	0.65
N 50	0.19	0.49	0.66	0.75	0.19	0.52	0.72	0.81
N 60	0.19	0.54	0.77	0.89	0.19	0.58	0.83	0.95
N 70	0.19	0.60	0.86	1.00	0.20	0.63	0.92	1.09
NW 20	0.09	0.21	0.24	0.26	0.11	0.24	0.29	0.30
NW 30	0.13	0.30	0.38	0.40	0.17	0.36	0.44	0.47
NW 40	0.18	0.41	0.51	0.55	0.19	0.46	0.59	0.64
NW 50	0.19	0.48	0.64	0.69	0.19	0.53	0.72	0.79
NW 60	0.20	0.55	0.76	0.82	0.20	0.59	0.84	0.93
NW 70	0.20	0.59	0.85	0.94	0.20	0.63	0.93	1.06
W 20	0.08	0.14	0.16	0.16	0.09	0.15	0.18	0.18
W 30	0.10	0.21	0.25	0.26	0.11	0.23	0.28	0.29
W 40	0.12	0.28	0.34	0.36	0.15	0.32	0.38	0.41
W 50	0.16	0.35	0.43	0.45	0.18	0.40	0.48	0.51
W 60	0.18	0.42	0.52	0.56	0.19	0.46	0.59	0.62
W 70	0.19	0.47	0.62	0.66	0.19	0.52	0.70	0.74
SW 20	0.03	0.04	0.05	0.05	0.04	0.05	0.05	0.05
SW 30	0.07	0.11	0.12	0.12	0.07	0.11	0.12	0.12
SW 40	0.09	0.15	0.18	0.21	0.09	0.15	0.18	0.21
SW 50	0.09	0.20	0.25	0.27	0.09	0.20	0.25	0.27
SW 60	0.10	0.25	0.31	0.34	0.11	0.26	0.31	0.34
SW 70	0.13	0.31	0.38	0.42	0.12	0.31	0.39	0.42

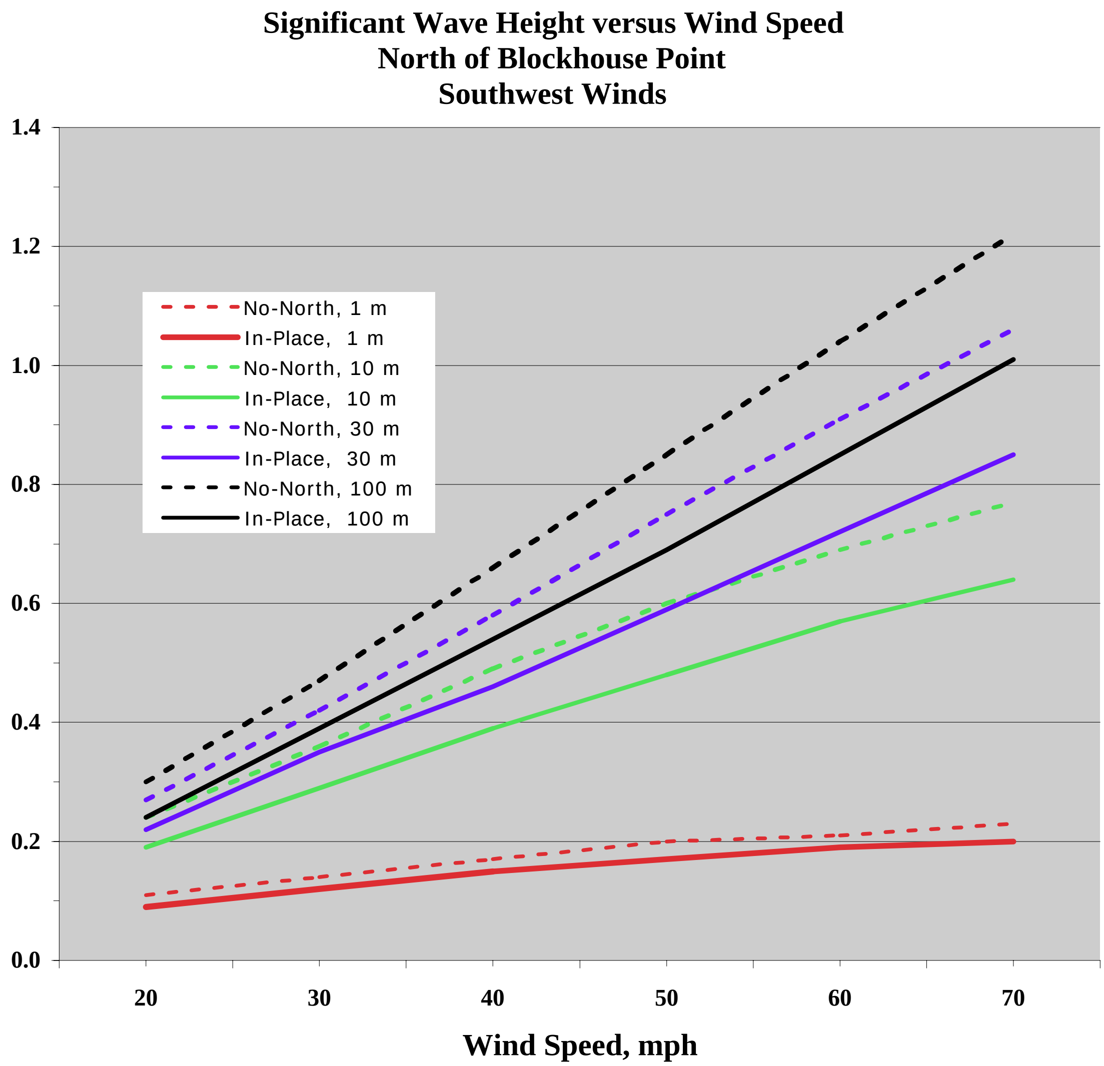

Figure 5.1 Predicted significant wave heights versus wind speed north of Blockhouse Point.

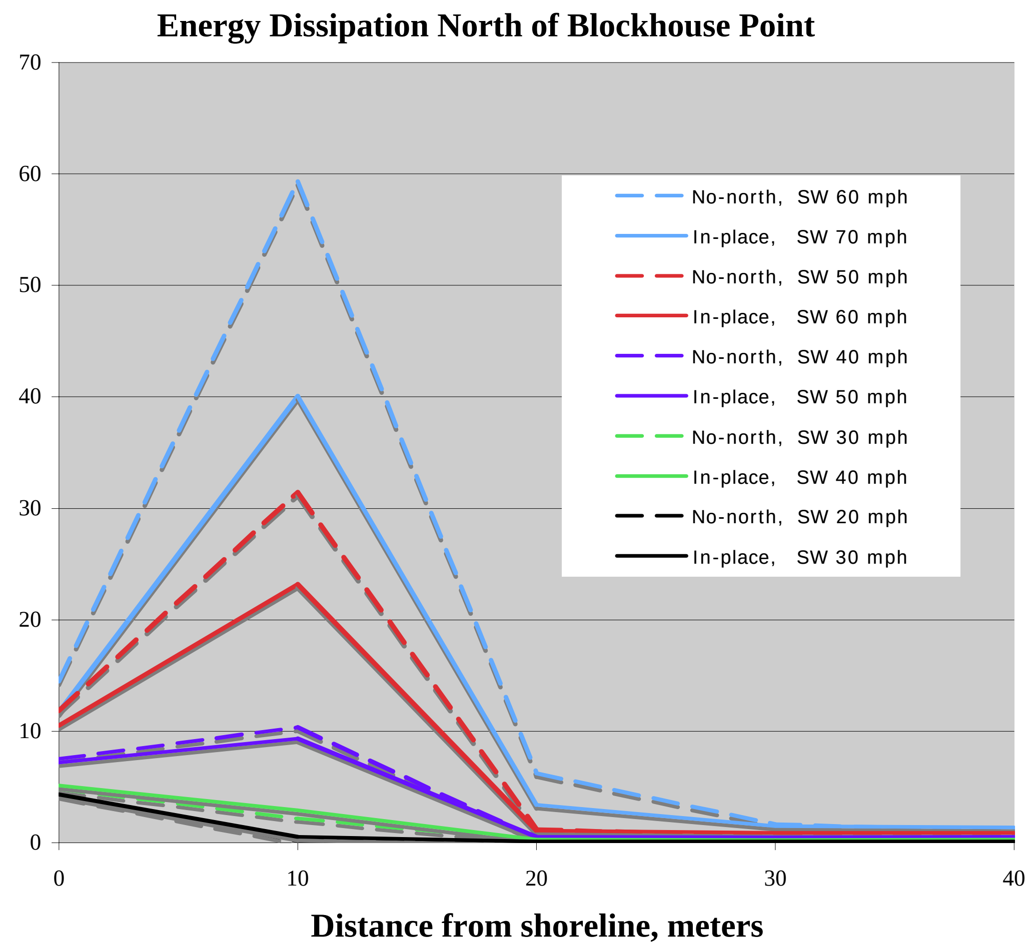

Figure 5.2 Energy dissipation versus distance from the shoreline, north of Blockhouse Point.

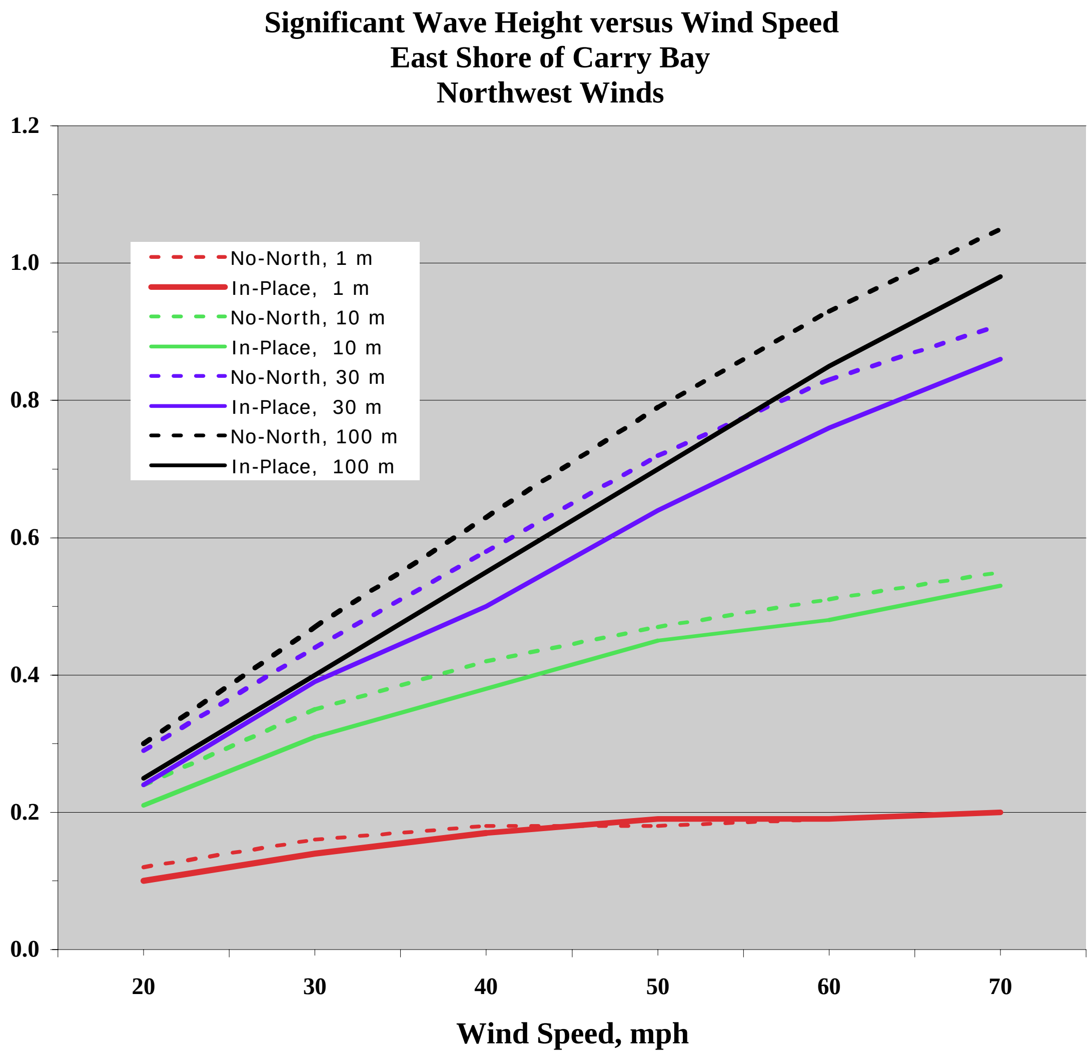

Figure 5.3 Predicted significant wave heights versus wind speed, east shore of Carry Bay.

5.2.3 Beach Stability – Design Formulas

Procedures in the U. S. Army Corps of Engineers, *Coastal Engineering Manual* (CEM) for design of sloped surfaces covered with two layers of randomly placed rock armor were used to evaluate stability of beaches. Specifically, rock size and weight calculated using design formulas developed by Van der Meer's were compared with weight of rocks on beaches in the study area.

Natural beaches have rocks that are nestled together forming tightly packed multiple layers. Gaps between cobbles are filled with smaller rocks providing increased stability. Natural rock beaches are assumed to be at least as stable as two layers of randomly placed rock of the same weight on which Van der Meers' stability equations are based.

The design equations by Van der Meer were: [42,43]

$$H_s / \Delta D_{n50} = 6.2\ S^{0.2}\ P^{0.18}\ N_z^{-0.1}\ \xi_m^{-0.5} \qquad (1)$$

where, ξ_m is the surf similarity parameter defined as

$$\xi_m = \tan\alpha / s_m^{\ 0.5} \qquad (2)$$

and,	H_s	Significant wave height (m)
	D_{n50}	Equivalent cube length of median rock (m)
	ρ_s	Mass density of rock (kg/m^3)
	ρ_w	Mass density of water (kg/m^3)
	Δ	Relative density $(\rho_s / \rho_w) - 1$
	S	Damage level, relative eroded area $S = A / (D_{n50})^2$
	A	Eroded cross-sectional area of the slope's profile (m^2)
	P	Notational permeability
	N_z	Number of waves
	α	Slope angle (degrees)
	s_m	Wave steepness, $s_m = H_s / L_{om}$
	L_{om}	Deepwater wavelength (m)
	g	acceleration due to gravity - 9.81 m/s^2

Equation (1) was used to solve for median rock diameter D_{n50}, which was converted to equivalent weight of rock using equation (3).

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[42] Van der Meer, J. W., 1987. Stability of breakwater armour layers – design formulae. *Coastal Engineering*, 11, page 234, equation (24).
[43] U.S. Army Corps of Engineers, EM 1110-2-1100, revised 1 Jun 06. Coastal Engineering Manual. Part VI, equation VI-5-68).

$W_{50} = \rho_s (D_{n50})^3$ (3)

where, W_{50} is the 50% value of the mass distribution curve (kg).

Parameters for application of the stability equation (1) to Carry Bay were:

- The slope of the beach was 1:10, tan α = 0.1 (see section 3.4);
- Significant wave height and mean wavelength at 30 meters from shore (toe of the beach slope) were obtained from modeled studies using SWAN (see section 5.2.2);
- Van der Meer provides damage level for the "no damage criteria."[44] Van der Meer investigated slopes from 1:1.5 up to 1:6 and selected values of S representing statically stable "no damage" conditions for each slope. At steep slopes, S was typically one (1) indicating that a single stone displaced represented the "no damage" criteria, $(D_{n50})^2 = A$. The "no damage criteria" can also be thought of as the "onset of damage." At a slope of 1:6, Van der Meer selected $S = 3$ for "no damage," and S = 17 to represent "failure." Van der Meer reasoned that the damage level representing "no damage" should increase with decreased slopes since there was more exposed rock in the surf zone. In this evaluation, $S = 3$ is used for "no damage" criteria even though the slope at Carry Bay was less than 1:6. A second damage level of S = 10 was also used, still less than Van der Meer's "failure" criteria for a steeper slope;
- The notational permeability selected was 0.5 as defined by Van der Meer for rock over a permeable base;[45]
- The number of waves selected was 7,500 based on the number of waves found by Van der Meer to cause maximum damage;[46] and,
- Density of stone, ρ_s, from measurements and typical values[47] was ρ_s is 2,650 kg/m^3 and ρ_w is 1,000 kg/m^3 for fresh water.

Significant waves heights north of Blockhouse Point were largest during southwest winds and were used to calculate weight of rock in Tables 13 and 14. Likewise, wind from the northwest produced the largest wave heights at the east and south shores of Carry Bay and these wave heights were used to calculate weight of armor required at these locations. Results of calculations displayed in Table 13 and 14 indicate that weight of rock armor at each of these locations were quite similar, however, with the north section of

[44] Van der Meer, J. W., 1987. Stability of breakwater armour layers – design formulas. *Coastal Engineering*, 11, page 228, Table 3.
[45] *ibid*., page 234, Figure 10.
[46] *ibid*., page 227, Figure 6.
[47] *ibid*., page 230.

the causeway removed, the heaviest armor to maintain a stable beach face was required at Blockhouse Point.

Table 13. Weight of rock armor for no damage criteria at three locations and various wind speeds and directions. Damage Criteria S=3.

Wind Speed, mph & Direction	Blockhouse Point, In-Place, Rock Weight Pounds	Blockhouse Point, No-North, Rock Weight Pounds
SW 20	0.11	0.19
SW 30	0.4	0.7
SW 40	0.8	1.7
SW 50	1.7	3.5
SW 60	2.9	6.2
SW 70	4.7	9.8
Wind Speed, mph & Direction	East Shore, In-Place, Rock Weight Pounds	East Shore, No-North, Rock Weight Pounds
NW 20	0.13	0.21
NW 30	0.4	0.7
NW 40	1.0	1.6
NW 50	2.0	2.9
NW 60	3.4	4.5
NW 70	4.9	6.2
Wind Speed, mph & Direction	South Shore, In-Place, Rock Weight Pounds	South Shore, No-North, Rock Weight Pounds
NW 20	0.14	0.22
NW 30	0.4	0.7
NW 40	1.0	1.7
NW 50	2.0	2.9
NW 60	3.2	4.6
NW 70	4.5	6.4

Table 14. Weight of rock armor for no damage criteria at three locations and various wind speeds and directions. Damage Criteria S=10.

Wind Speed, mph & Direction	Blockhouse Point, In-Place, Rock Weight Pounds	Blockhouse Point, No-North, Rock Weight Pounds
SW 20	0.05	0.09
SW 30	0.2	0.3
SW 40	0.4	0.8
SW 50	0.8	1.7
SW 60	1.4	3.0
SW 70	2.3	4.8
Wind Speed, mph & Direction	East Shore, In-Place, Rock Weight Pounds	East Shore, No-North, Rock Weight Pounds
NW 20	0.06	0.10
NW 30	0.2	0.3
NW 40	0.5	0.8
NW 50	1.0	1.4
NW 60	1.6	2.2
NW 70	2.4	3.0
Wind Speed, mph & Direction	South Shore, In-Place, Rock Weight Pounds	South Shore, No-North, Rock Weight Pounds
NW 20	0.07	0.11
NW 30	0.2	0.4
NW 40	0.5	0.8
NW 50	0.9	1.4
NW 60	1.6	2.2
NW 70	2.2	3.1

Figure 5.3 displays weight of rock armor for the “no damage” criteria listed in Table 13. There are six curves of weight of rock versus wind speed and they fall into two groups: (1) for the causeway in-place configuration (solid lines), and (2) for the no-north configuration (dashed lines). As an example from this graph, if the median weight of rock armor were *three* pounds, the beach would have “no damage” (as

defined by the damage criteria) for winds up to about 58 - 61 mph for the causeway in-place configuration, and up to 48- 51 mph for the no-north configuration. Essentially, to compensate for removal of 1/3rd of the causeway, a 10 mph decrease in wind speed was necessary to satisfy the "no damage" criteria. Similarly, if the median weight of rock armor were *two* pounds, the beach would have "no damage" (as defined by the damage criteria) for winds up to about 50 - 53 mph for the causeway in-place configuration, and up to 42 - 43 mph for the no-north configuration; a reduction of about 8 to 10 mph in wind speed was needed to satisfy the "no damage" (at these lower wind speeds) criteria for removal of 1/3rd of the causeway.

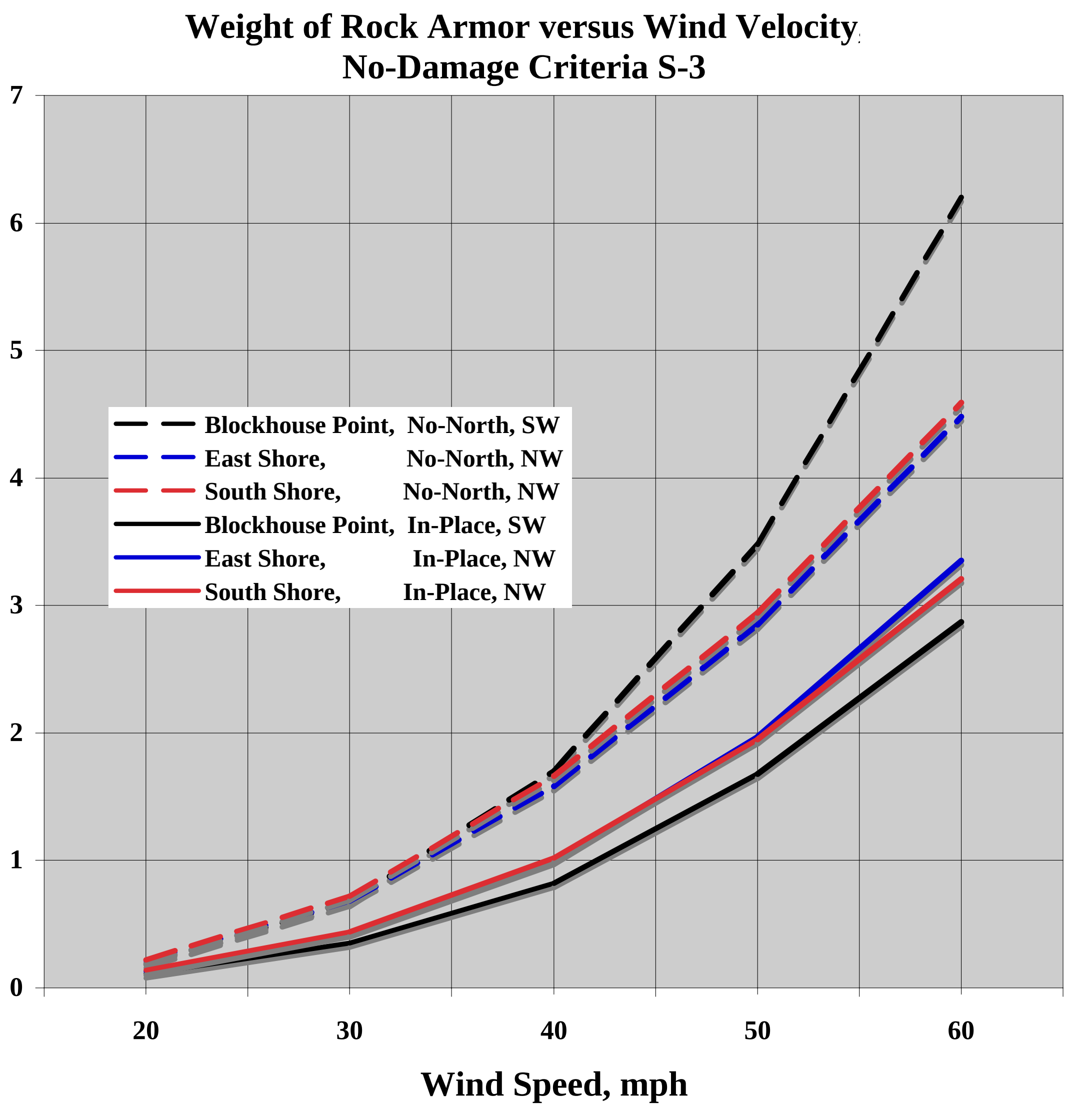

Figure 5.4 Calculated weight of rock armor versus wind speed, Carry Bay beaches.

As indicated in Section 3.3, the mean weight of cobbles gathered at two locations north of Blockhouse Point was 4.3 pounds (n=13) and 4.8 pounds (n=8). At the east shore of Carry Bay the mean weight of cobbles was 7.0 pounds (n=6). The average weight of all rocks from north of Blockhouse Point was 4.5 pounds (the median is assumed equal to the mean) and this weight of rock meets design requirements for "no-damage" up to wind speeds of 54 mph north of Blockhouse Point, and up to 60 miles per hour at the east and south shores of Carry Bay. The return level for a wind with a 100-year return period was calculated to be 50 – 56 mph (Table 2.3). This analysis indicates that beaches at Carry Bay have armor to withstand a 100-year storm with no damage (as defined by van der Meer's no damage stability criteria) for both in-place and no-north configurations.

5.2.4 Beach Stability – Physical Models

The second analysis of beach stability compares beaches at Carry Bay with another beach in Lake Champlain. Many rocky beaches along the shores of Lake Champlain are exposed to long distances of open water. In Charlotte a beach about 0.75 miles long that parallels Hills Point Road faces west, and is exposed to winds from the south counter-clockwise to the northeast. The fetch for the Charlotte beach for southwest and west wind is 5.7 and 3.3 miles, respectively. For comparison, the fetch from Isle La Motte to the Blockhouse Point and the east shore of Carry Bay are 1.7 and 2.9 miles, respectively. The slope of the Charlotte Beach is 1:10 - the same as the slope at Carry Bay.

The Charlotte beach is dynamically stable[48] (reshaping of the beach face occurs without loss of material) from Holmes Creek to about 0.75 miles north. At four locations along the Charlotte beach a two square foot area was selected and exposed rocks were collected and weighed. The mean weight of rocks in pounds (lbs) and number of rocks weighed (n) were 1.9 lbs (n=22), 2.3 lbs (n=17), 2.6 lbs (n=20), and 2.0 lbs (n=20). At this beach in Charlotte, mean weights of rocks are less and the fetch is greater for present and future Carry Bay beaches. Also, there are much deeper depths in the main lake offshore the Charlotte beach compared with depths in La Motte Passage, but upon passing over shoaling bottoms, waves at both locations are depth limited. Lower mean weight of rock for increased exposure at this dynamically stable Charlotte Beach compared with Carry Bay beaches, indicate that existing beach characteristics at Carry Bay will provide beach protection for wave conditions predicted with the causeway removed.

[48] Personal observation, 1978 - 2008.

5.2.4 Bedrock Recession

The sources of rocks found along the shore are from bedrock and glacier till. Weathering processes related to ground water, snow, ice, surface water, lake water, waves, vegetation, and human activity act on exposed bedrock and the glacier till layer. Erosion activity fractures and loosens bedrock and erodes the till.

Bedrock at Carry Bay weathers and erodes providing beach materials for protection but recedes in the process, therefore, - would bedrock recession increase after removal of 1/3rd of the causeway due to the change in the sea state? Kamphuis (1987) studied recession of glacier till bluffs along Lake Erie.[49] Kamphuis describes the mechanism of erosion for consolidated bluffs and concluded that it was *not the waves undercutting the bluff* that was the most important factor for bluff erosion, rather it was the *erosion of the foreshore* that controlled the recession. Kamphuis found that removal of material from the foreshore resulted in exposure of the toe of bank, leading to undercutting and bluff erosion. Had material from the bluff stayed on the beach, the toe of the bluff would have been protected and recession would have been reduced.

The beach at Carry Bay has been shown to be stable with the causeway in place and that it will remain stable with 1/3rd of the causeway removed. A stable beach implies that waves would not attack the toe of the bank. Other weathering and erosion processes (which provides new rock for beach protection) will continue independently of wave action.

Waves breaking on bedrock can cause weathering and erosion under certain conditions. Weathering of bedrock occurs because water from waves rush into and fill cracks and air is trapped and condenses and weakens the rock. When water retreats from the crack, energy stored in compressed air is suddenly released creating an explosion of expanding air.[50] It's possible that waves breaking on fractured bedrock surrounding Carry Bay could compress air in cracks and contribute to weathering and eventually erosion; however, for this to happen, high water and storm events producing high waves must coincide. The frequency of the simultaneous occurrence of high waves and high lake levels are estimated in this section.

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[49] Kamphuis, J. W. 1987. Recession rate of glacier till bluffs. *Journal of Waterway, Port, Coastal, and Engineering.* Vol. 113, No. 1, Paper No. 21196, page 1.
[50] Thunder hole in Acadia National Park is one (dramatic) example of this process.

Waves break on and reflect from bedrock banks when water levels are greater than 99 feet MSL. The probability of these two independent events occurring simultaneously is the product of the probability of one event occurring times the probability of the second event occurring. The probability that the lake level will exceed 99 feet MSL is 24 days per year; 24/365. These days are most likely to occur in April and May.

Waves enter Carry Bay any time wind blows from the SW, W, NW and N sectors. In 21,770 days that wind has been recorded at Burlington Airport, 1065 days had winds greater than 30 mph. The probability that the wind speed from these four sectors will exceed 30 mph is 1065/21,770, or about 18 days per year.

To estimate the probability of winds greater than 30 mph from any of these four sectors and water levels greater than 99 feet MSL, multiply the probabilities of these two events; therefore, the probability of water level above 99 feet and winds greater than 30 mph from the SW, W, NW and N, is 1.17 days per year.

5.3 Review - Analysis of Meteorological, Geological and Hydrological Information

- Changes in wave characteristics would be largest just east of the causeway since this area is presently in a wind shadow for SW and W winds. With the causeway removed, waves traveling from the SW and W would enter this region unimpeded and result in the largest increases in wave heights in the study area.
- Further east of the causeway, between the causeway and Blockhouse Point, increases in significant wave heights would exceed 0.5 meters.
- Near Blockhouse Point, largest significant wave heights predicted at 100 meters from shore were 1.01 and 1.22 meters for a 70 mph SW wind for causeway in-place and no-north configurations, respectively; an increase in wave height of 0.21 meters (8.3 inches).
- Near Blockhouse Point, largest significant wave heights predicted at 10 meters from shore were 0.64 and 0.77 meters for a 70 mph SW wind for causeway in-place and no-north configurations, respectively; an increase in wave height of 0.13 meters (5.1 inches).
- At the east shore of Carry Bay, largest significant wave heights predicted at 100 meters from shore were 0.98 and 1.05 meters for a 70 mph NW wind for causeway in-place and no-north configurations, respectively; an increase in wave height of 0.07 meters (2.8 inches).

- At the south shore of Carry Bay, largest significant wave heights predicted at 100 meters from shore were 1.00 and 1.09 meters for a 70 mph N wind for causeway in-place and no-north configurations, respectively; an increase in wave height of 0.09 meters (3.5 inches).
- Procedures in the U. S. Army Corps of Engineers, *Coastal Engineering Manual* (CEM) were used to evaluate stability of beaches in the study area. Specifically, measured rock size and weight were compared with of weight beach armor calculated using design formulae.
- With the causeway in-place, calculated weight of armor required was slightly higher at the east shore location.
- With the north section of the causeway removed, and for wind speed greater than 50 mph, the heaviest armor was required at Blockhouse Point.
- Comparison of beaches at Carry Bay with a dynamically stable beach in Charlotte, indicate that, even though the fetch is greater at Charlotte and offshore depths are deeper, median weights of rocks were less on the Charlotte Beach than weight of rocks measured at Carry Bay.
- Waves break on some bedrock banks when water levels are greater than 99 feet MSL. The probability of the simultaneous occurrence of winds greater than 30 mph from the N, NW, W and SW sectors and water levels greater than 99 feet MSL was calculated to be 1.17 days per year.
- Beaches at Carry bay have been shown to be stable with the causeway in place, and beaches will remain stable with 1/3rd of the causeway removed. A stable beach protects the bedrock bank from wave attack. Bedrock recession by non-lake related weathering and erosion processes would continue at natural rates.

6.0 CONCLUSIONS and RECOMMENDATIONS

Waves

Predicted wave characteristics were presented for all regions in the study area for present conditions (in-place) and proposed changes in causeway configurations (no-north and littoral-zone). Changes in waves characteristics in the study area varied from “none” to “significant.” From these results impacts can be determined based on the proposed activity and the change in wave characteristics. For example, near the North Hero Marina, predicted waves characteristics, for all wind conditions, with removal of the north section of the causeway were almost identical to predicted present conditions; therefore, there would be no impact at this location on any activity normally associated with a marina.

Waterfront property owners generally build docks and walkways within 30 meters from shore. In this region, and for all wind conditions, wave heights and the difference between predicted wave heights for present and future conditions decrease toward shore. Sometimes, depending on wind direction and location, there would be no difference in wave characteristics. When changes in wave characteristics were predicted, future wave characteristics were often observed to be about equal to predictions for present conditions, but at a 10 mph increase in wind speed, e.g., wave characteristics observed now at 50 mph would occur at 40 mph for future conditions.

Beach Stability

An evaluation of beaches in the study area concludes that beaches are dynamically stable for existing conditions and would remain dynamically stable with waves expected after removal of the north section of the causeway.

This conclusion is based on two analyses. First, weight of rocks on Carry Bay beaches was compared with weight of rocks calculated using formulas developed for design of statically stable rock covered shore structures. These formulas are conservative for the present application, i.e., calculated weight of rock armor would be higher than required, since it is only necessary that beaches in the study area be dynamically stable. Shaping and reshaping of rocks on the seaward face in response to changing environmental conditions distinguish dynamically stable beaches.

Factors used in design formula were predicted significant waves heights, mean wavelengths, beach slope, damage level, and number of storm waves. With the north section of the causeway removed, design formula[51] indicate that beaches would by statically stable for storms with wind speeds up to 53 mph at Blockhouse Point, and 60 mph at other locations. For a slightly higher damage level, but still well below slope failure criteria for static stability,[52] existing weight of rock exceeds calculated design weight of rock for future conditions up to wind speeds of about 68 - 70 mph.

The second analysis of beach stability was based on a well-established hydrodynamic analysis technique - physical hydraulic models. The physical model used was found in Lake Champlain, not in the laboratory, which has the advantage of being a full-scale physical model. A beach that mimics future conditions at Carry Bay was found in Charlotte. This Charlotte beach is dynamically stable, i.e., the beach face reshapes with changing conditions, but there is no loss of materials. Mean weight of rocks are less at the Charlotte beach compared with weight of rock on Carry Bay beaches, even though at Charlotte the fetch is longer and offshore depths are deeper. This supports the conclusion that Carry Bay beaches will remain dynamically stable with removal of the north section of the causeway.

Bedrock Recession

At lake levels greater than 99 feet MSL waves break on and reflect from bedrock. This occurs now and would continue with larger waves with the north section of the causeway removed. However, the increase in wave height near shore is expected to be small and the frequency of high water and high winds occurring simultaneously is low. Also, a stable beach protects the bedrock bank from wave attack and beaches at Carry bay have been shown to be dynamically stable with or without the causeway. Bedrock recession by non-lake related weathering and erosion processes would continue and remain the largest factor for bedrock recession.

Recommendations

Rocks provide armor for beach stability, but to do so, rocks must remain on the beach. The recommendation is to leave boulders, cobbles and gravel where they lie on the beach.

Bedrock and glacial-till are weathering naturally and much of the eroded material provides beneficial beach armor, but there is no need to accelerate this process by human activities.

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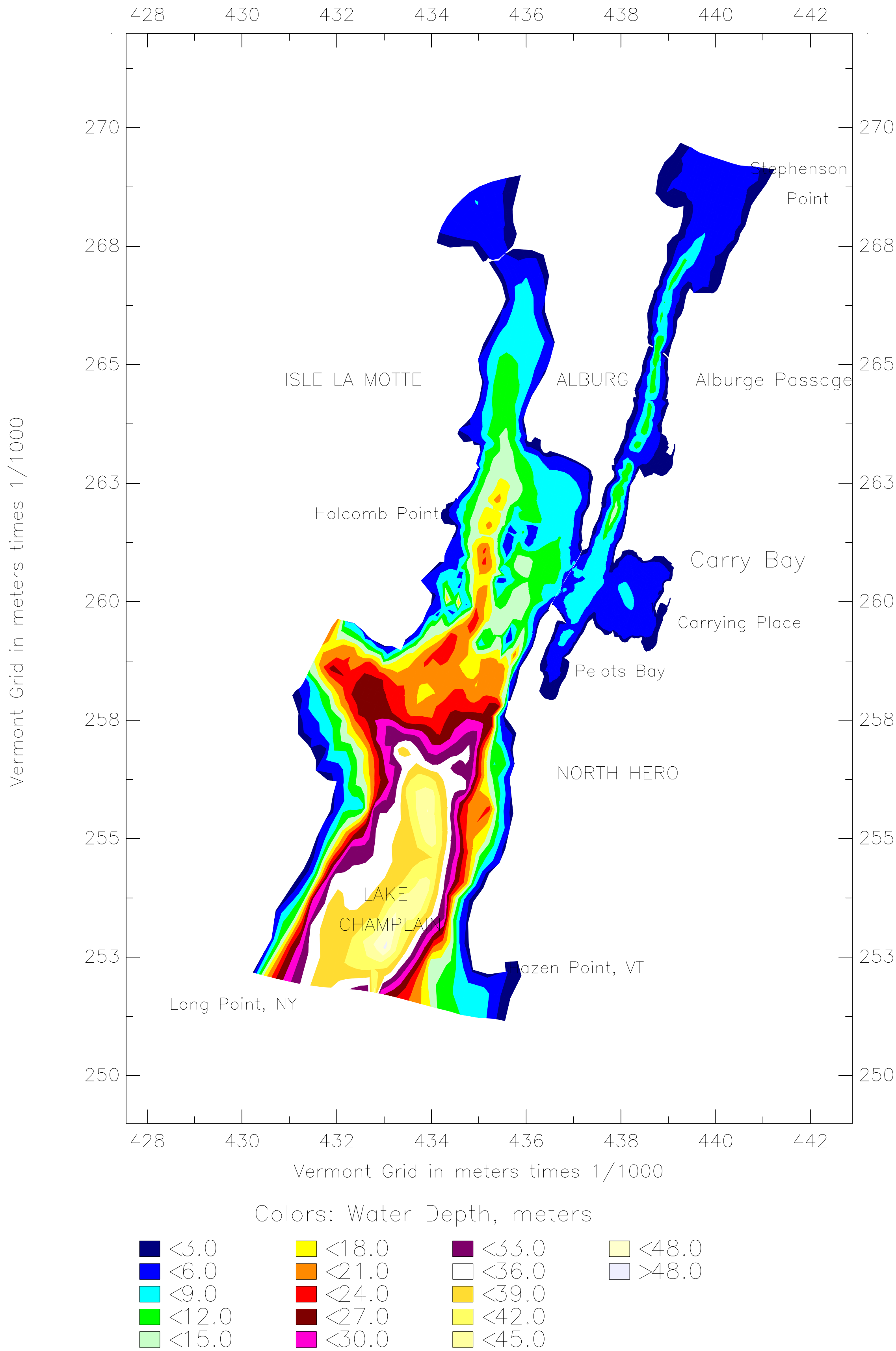
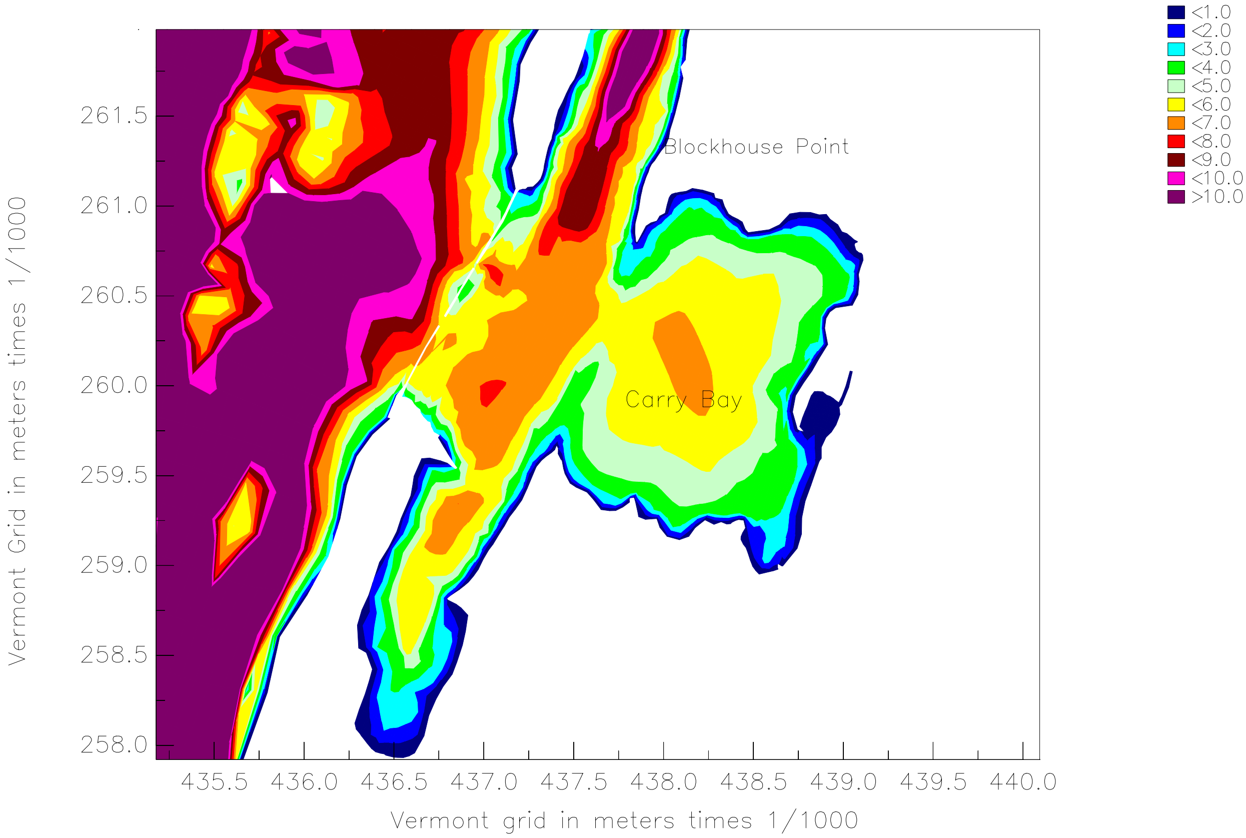
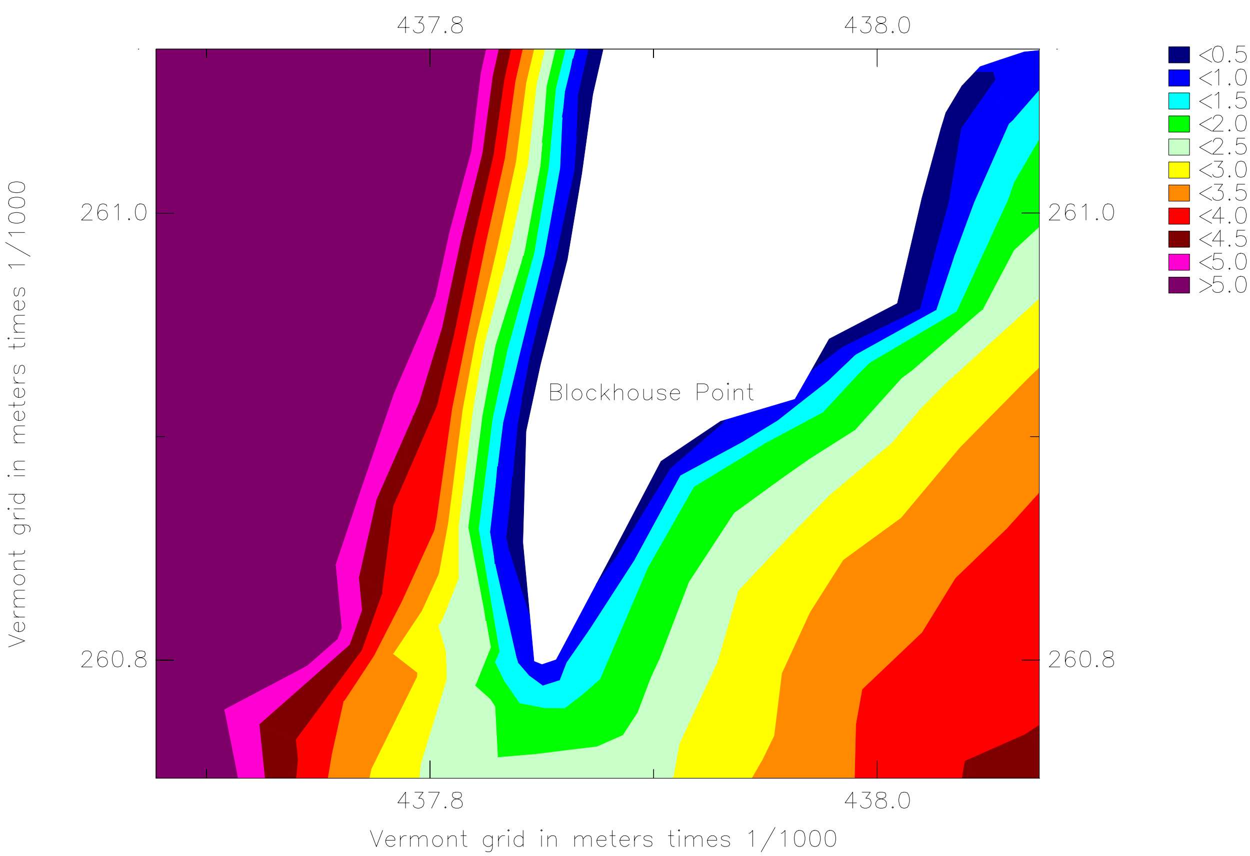
[51] Van der Meer, J. W., 1987. Stability of breakwater armour layers – design formulae. *Coastal Engineering*, 11, page 228, Table 3.
[52] *ibid*., page 228, Table 3.

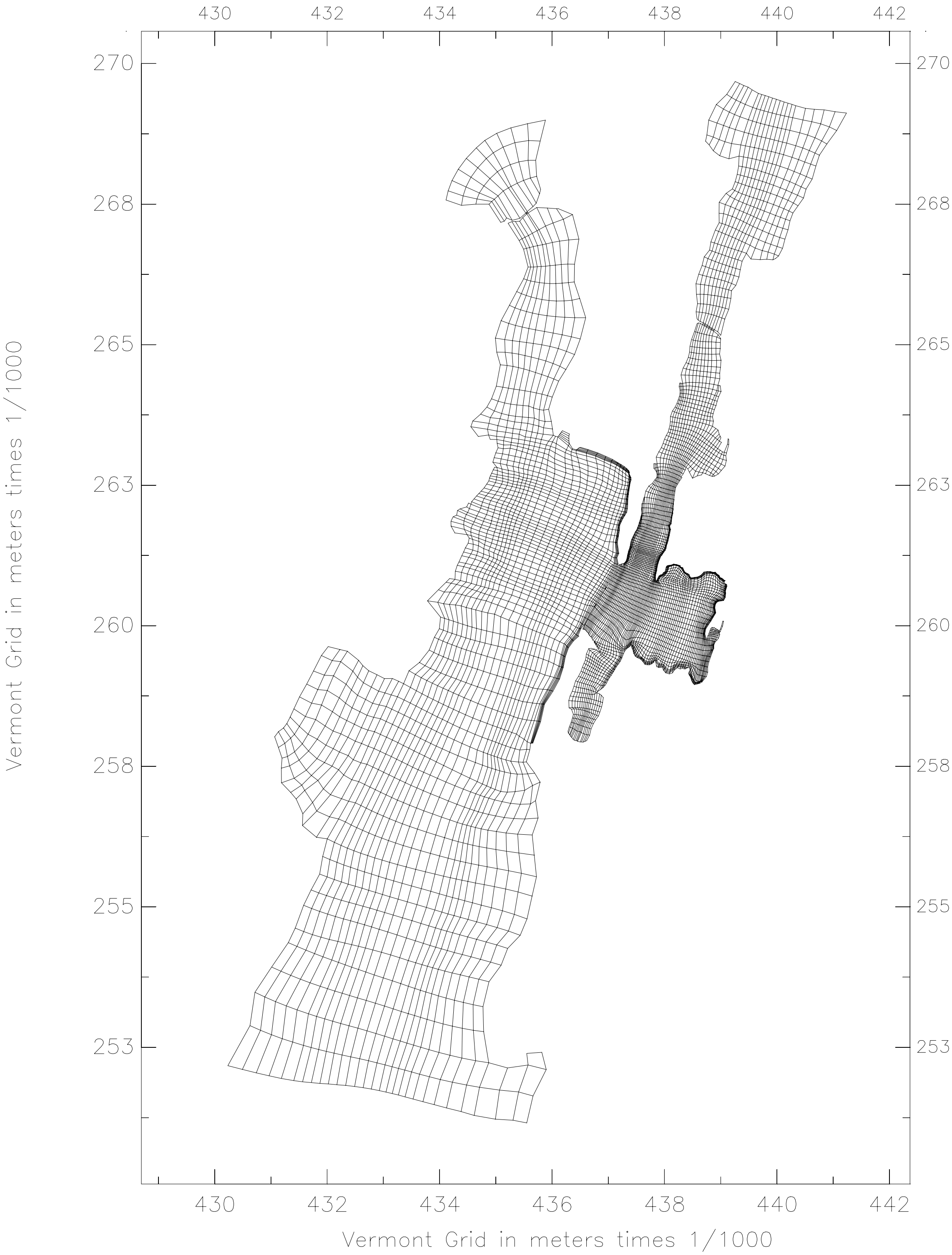


Plane of Reference – 99.5 feet above Mean Sea Level Long Pt., NY to Stephenson Pt., VT about 12.5 miles Holcomb Pt. to Carrying Place about 3 miles	Figure 1	Carry Bay Wave Study
	Model Extent & Model Depths	
Colors represent depths in meters – 3 meter intervals	Binkerd Environmental	December 2007





Plane of Reference – 99.5 feet above Mean Sea Level Upper Graph – Colors represent depths in meters at 1 METER intervals Lower Graph – Colors represent depths in meters at 0.5 METER intervals	Figure 2	Carry Bay Wave Study
	Depths at 1 m and 0.5 m contours	
Model Depths near Carry Bay & Blockhouse Point, meters	Binkerd Environmental	December 2007



This is the entire computational grid. Near Carry Bay the grid cell size decreases to obtain better resolution. There are about 8860 individual cells in the grid.

Figure 3

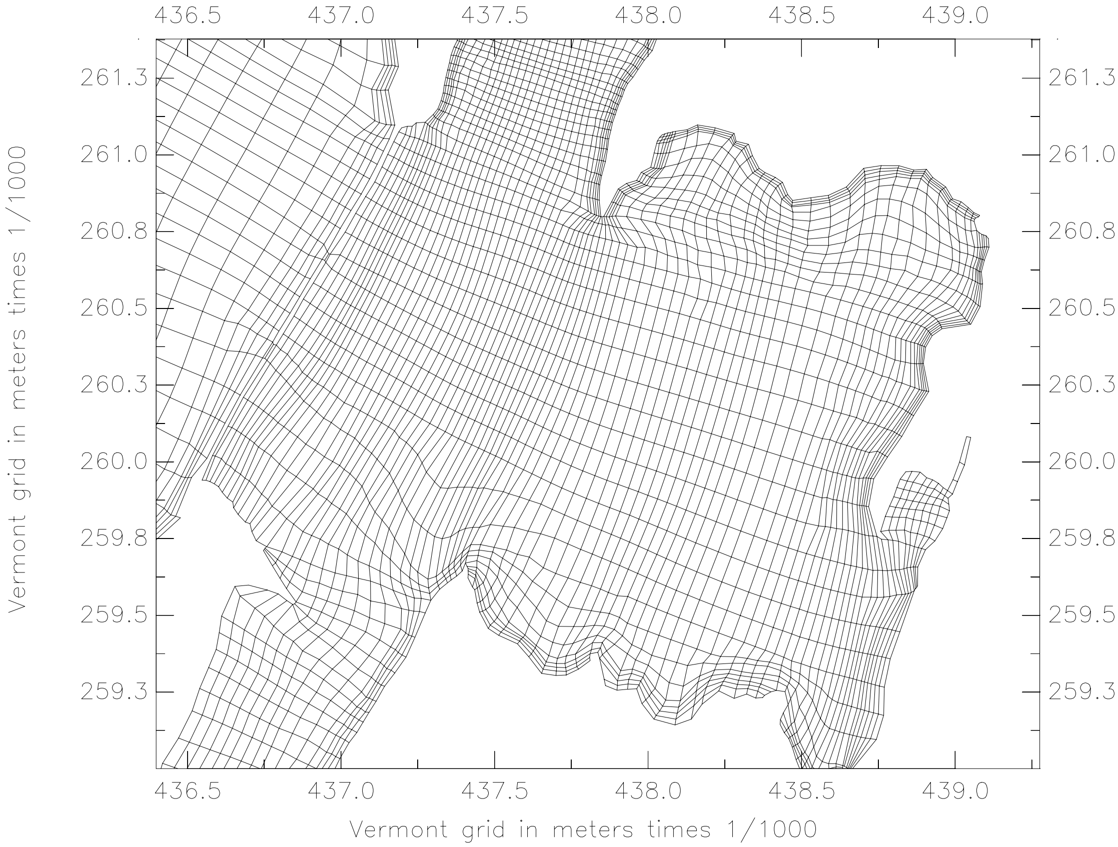
Carry Bay Wave Study

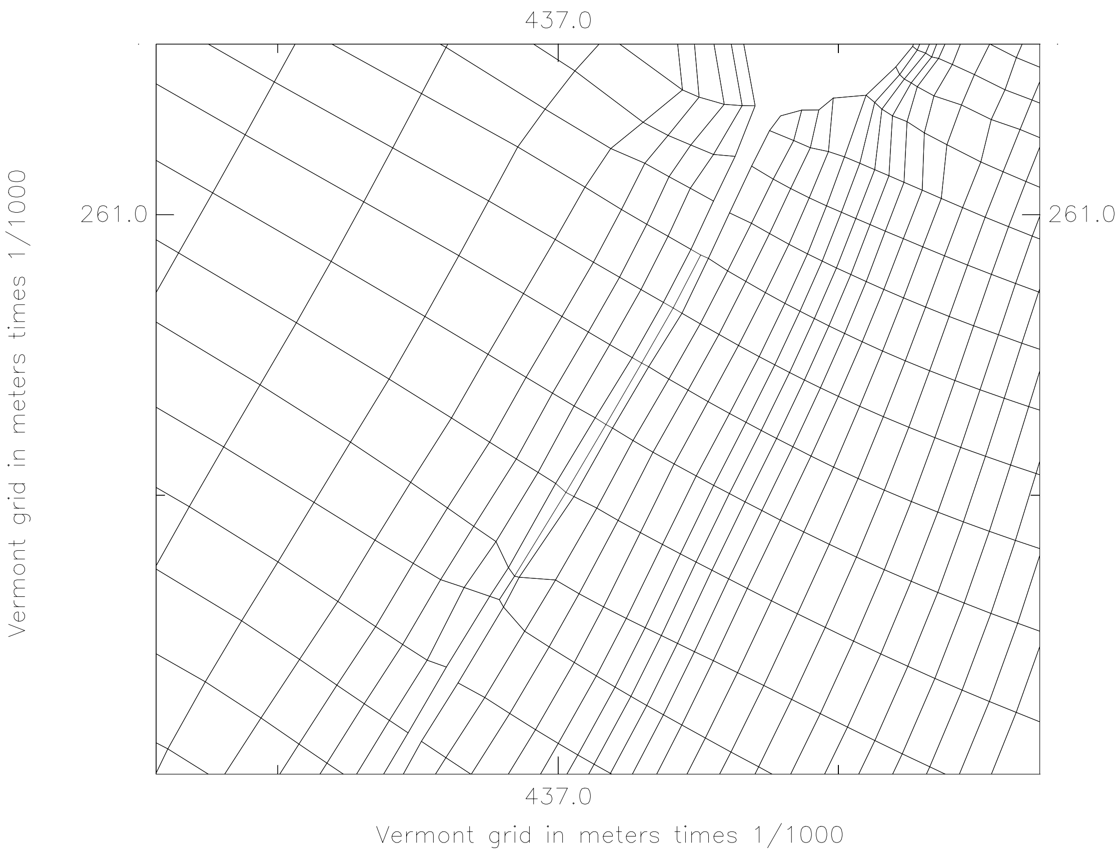
Model Grid

Computational Grid

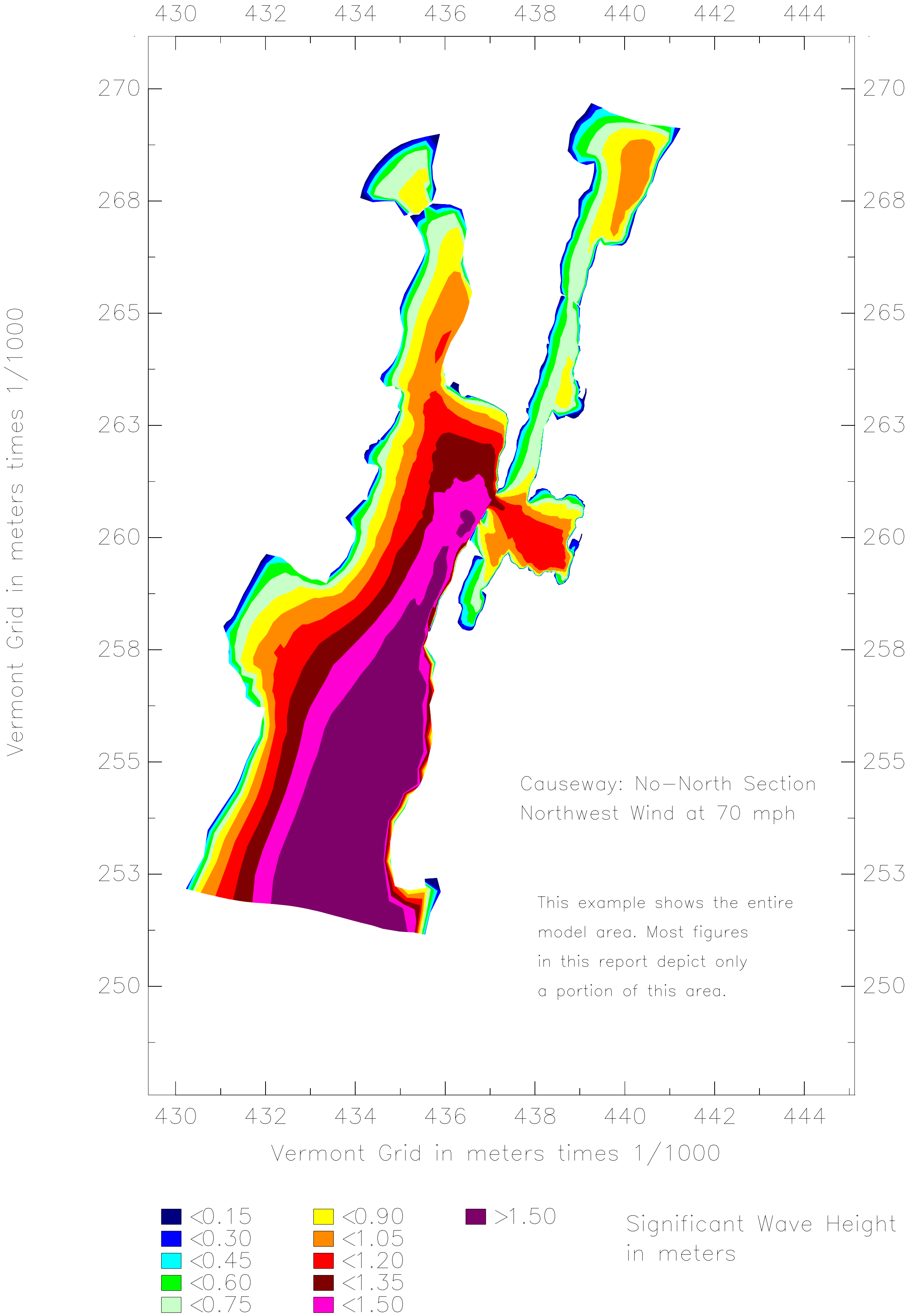
Binkerd Environmental

December 2007





Upper grid shows the details in Carry Bay and near the shore where the grids are smaller. The lower grid is near the north section of the causeway showing the section removed in the simulation of "no-north"	Figure 4	Carry Bay Wave Study
	Grids, Carry Bay & Causeway	
Comptational Grids, Carry Bay & Causeway North Section	Binkerd Environmental	December 2007



This is an example of model results for a 70 mph NW wind. In this case the colors represent different significant wave heights; e.g., the color yellow represents wave heights less than 0.9 meters but greater than 0.75 meters.

Figure 5

Carry Bay Wave Study

Example: Significant Wave Height

Wind from Northwest at 50 mph

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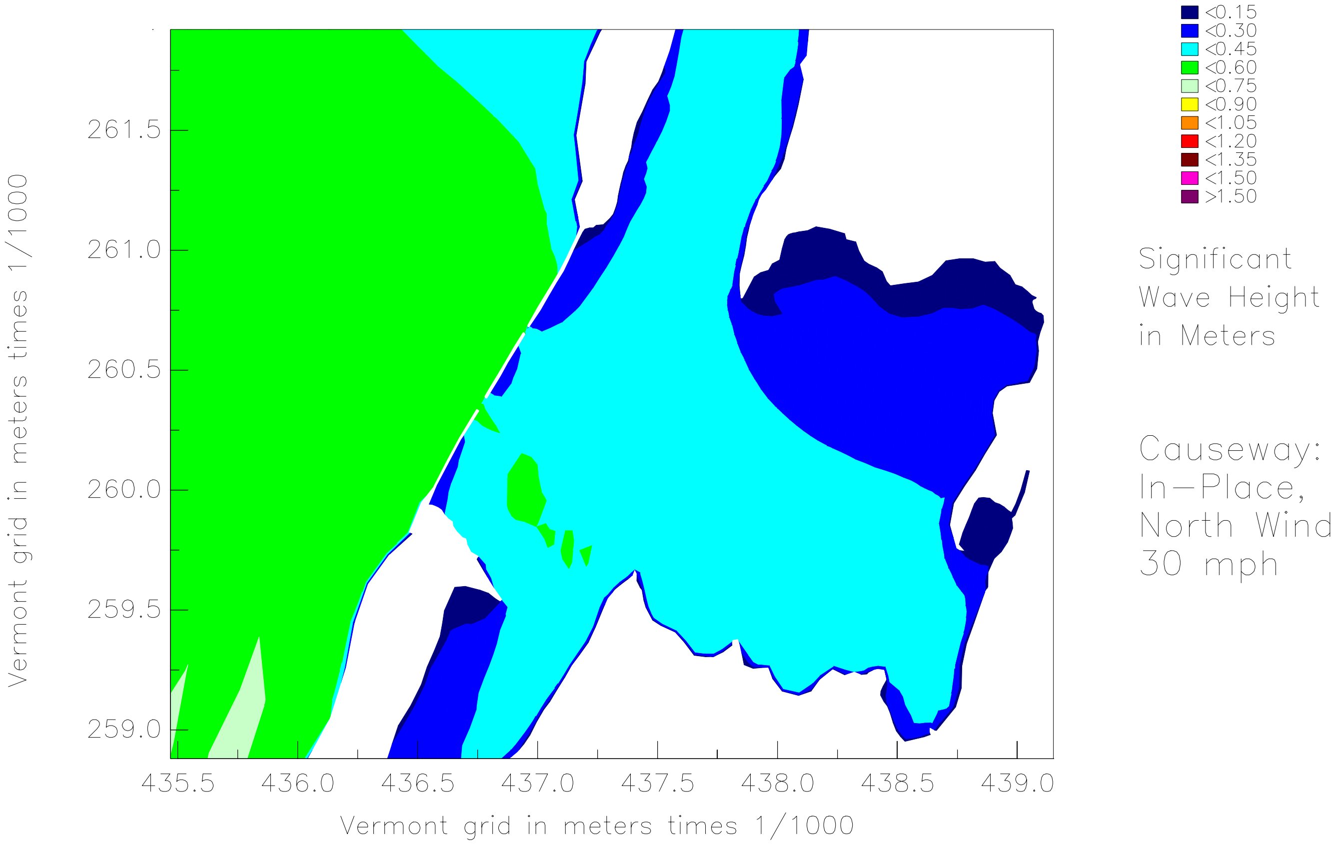
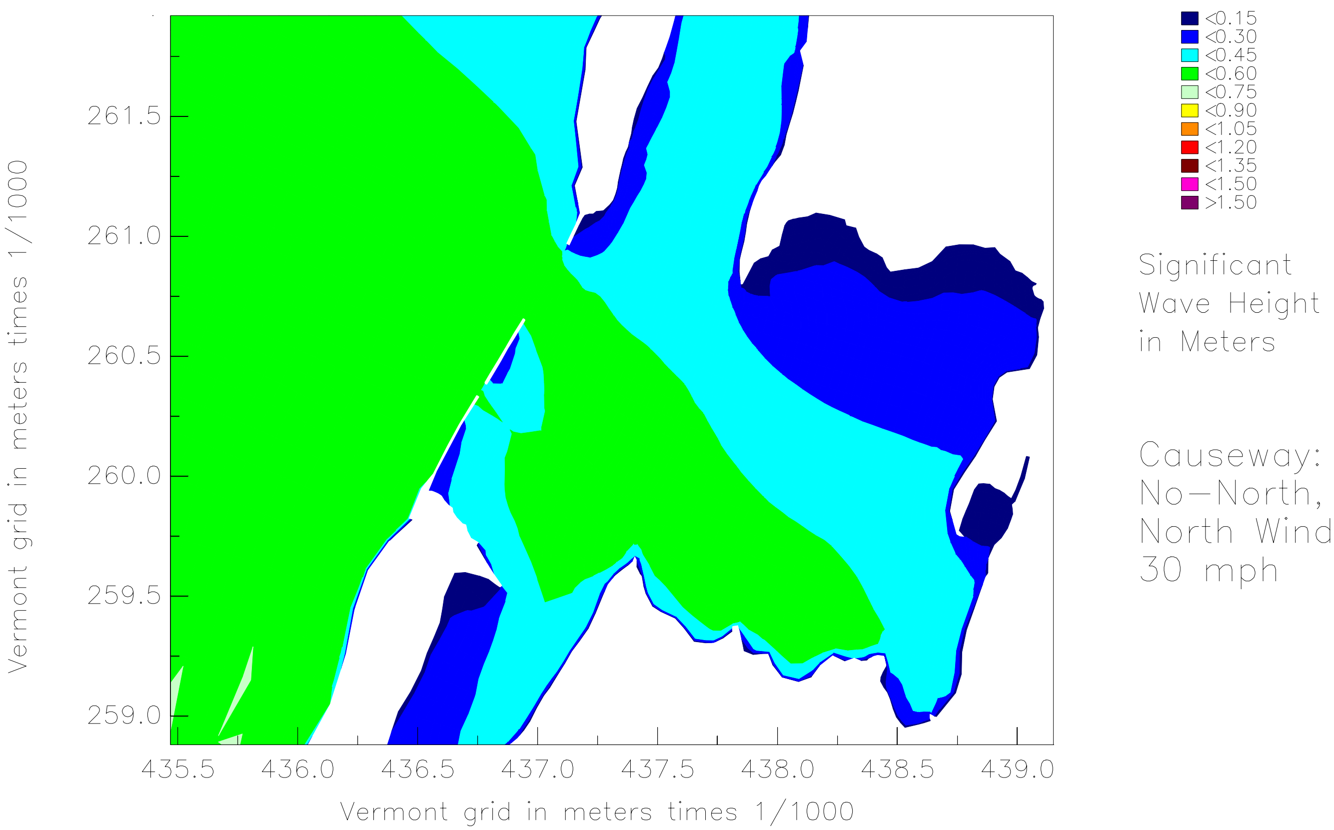
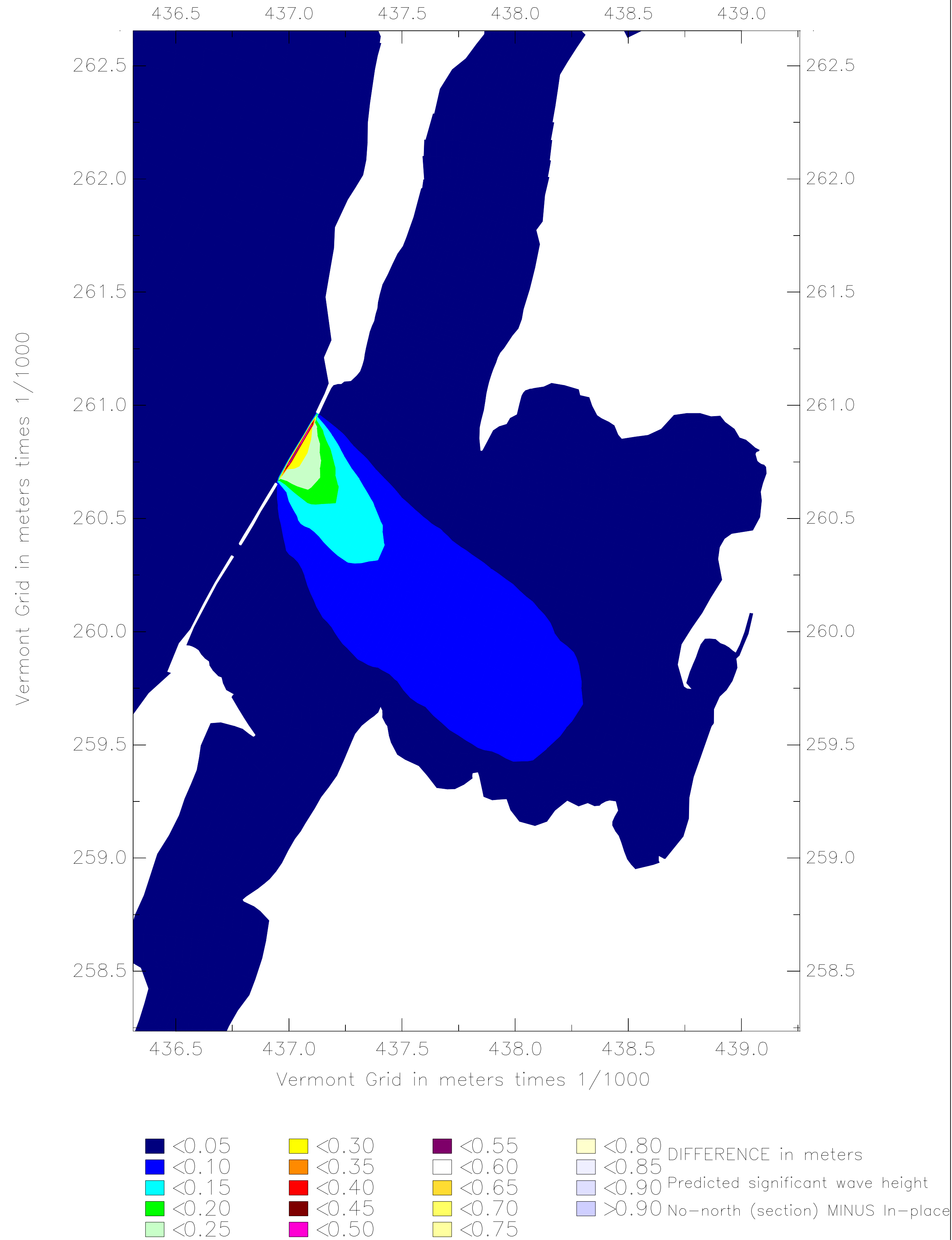
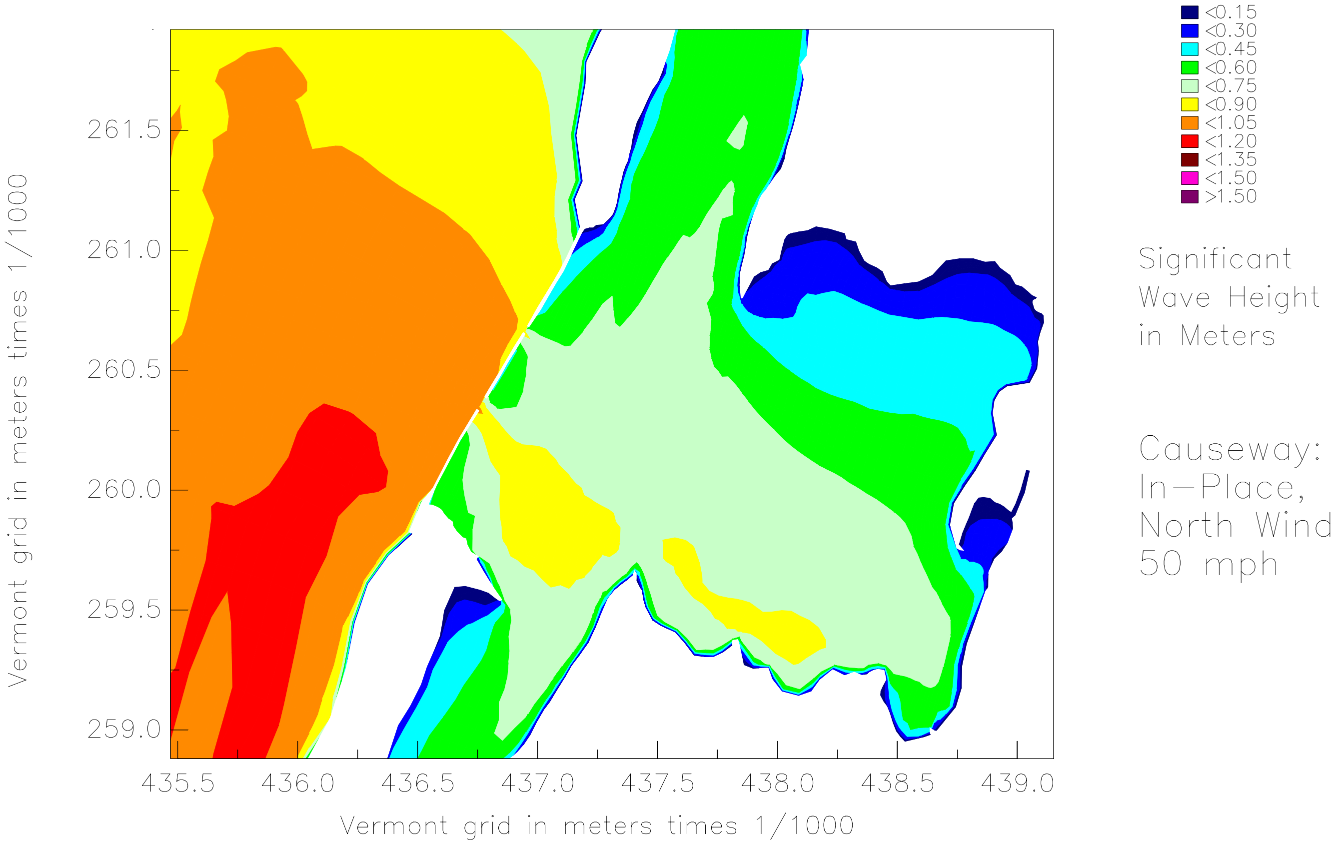


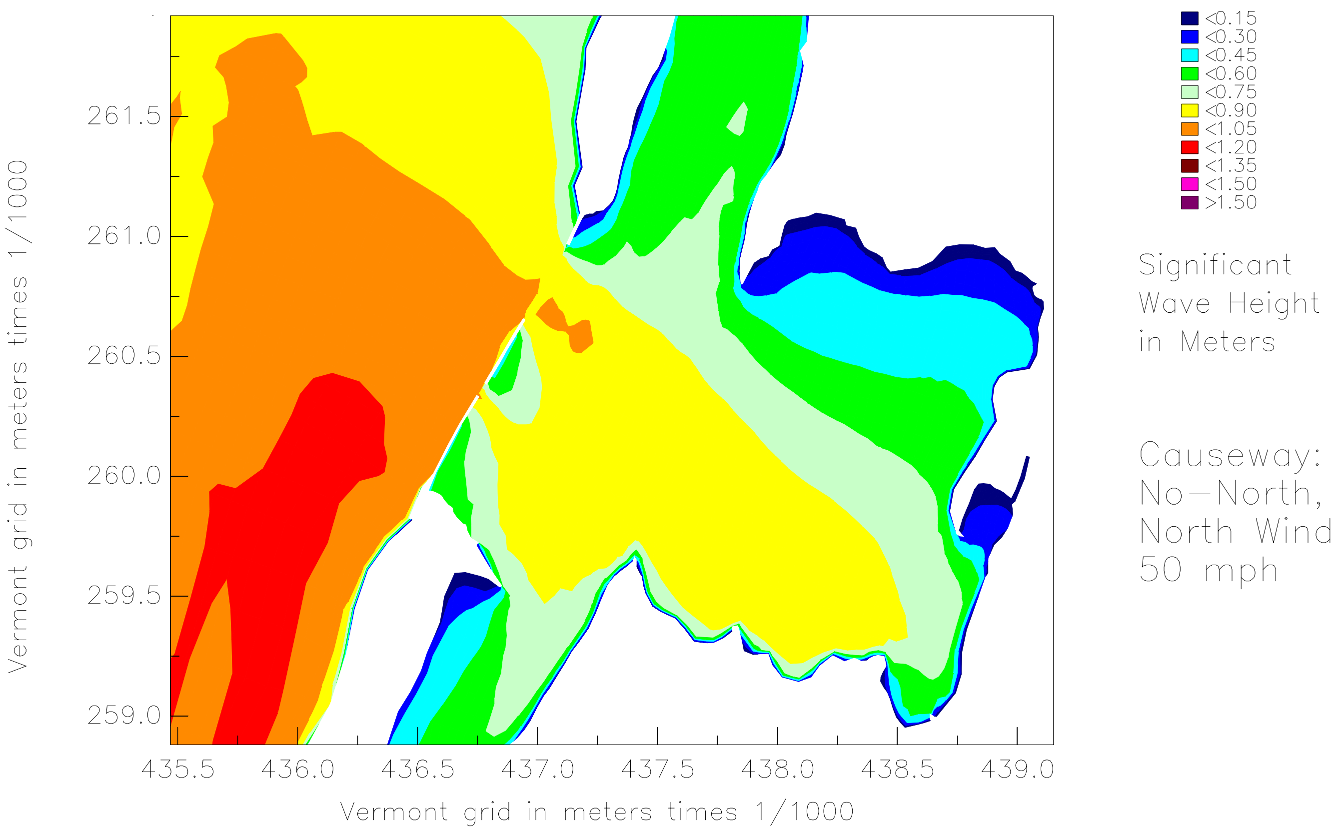


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 6	Carry Bay Wave Study
	Significant Wave Height	
Wind from North at 30 mph	Binkerd Environmental	December 2007

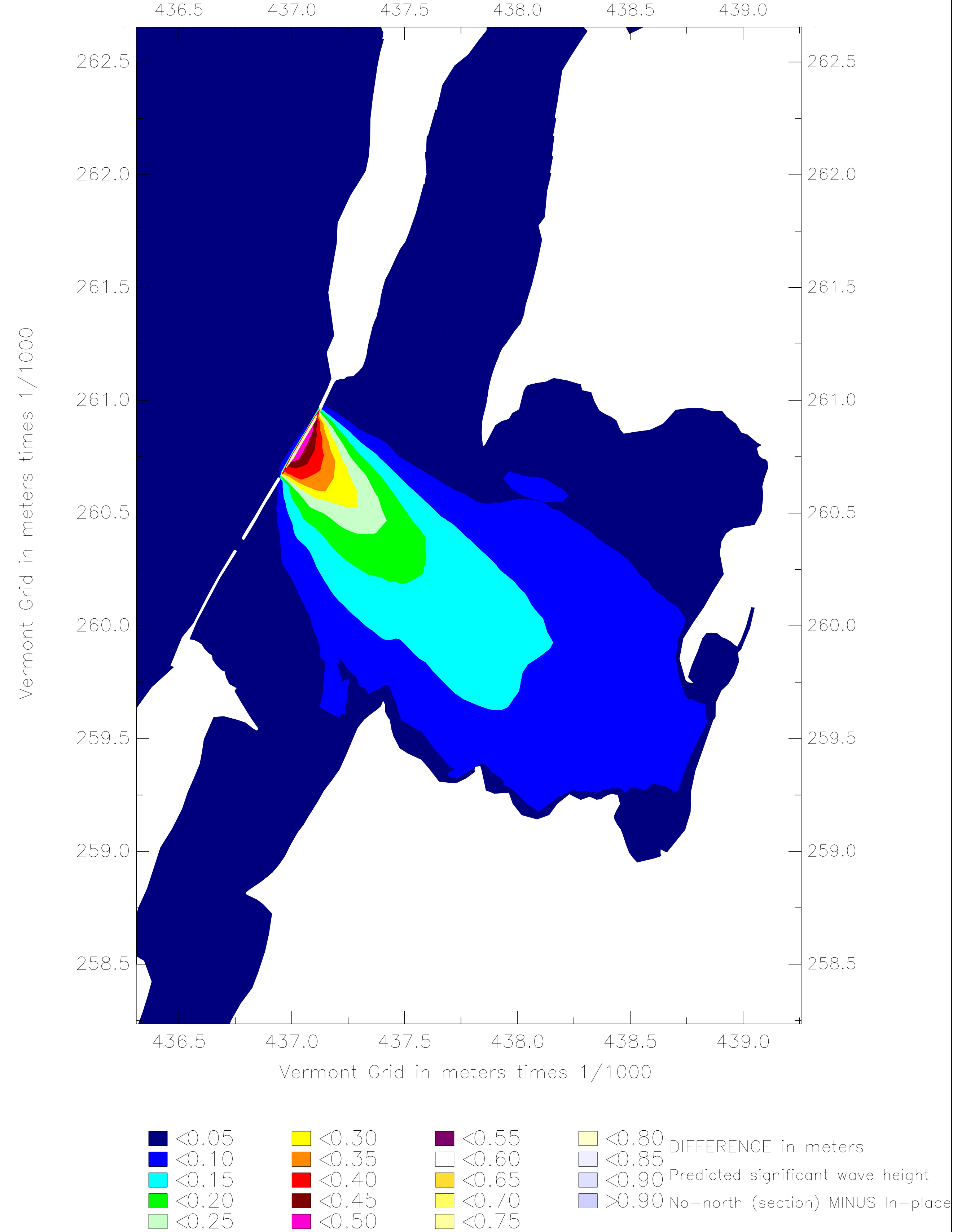


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 7	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from North at 30 mph	Binkerd Environmental	December 2007

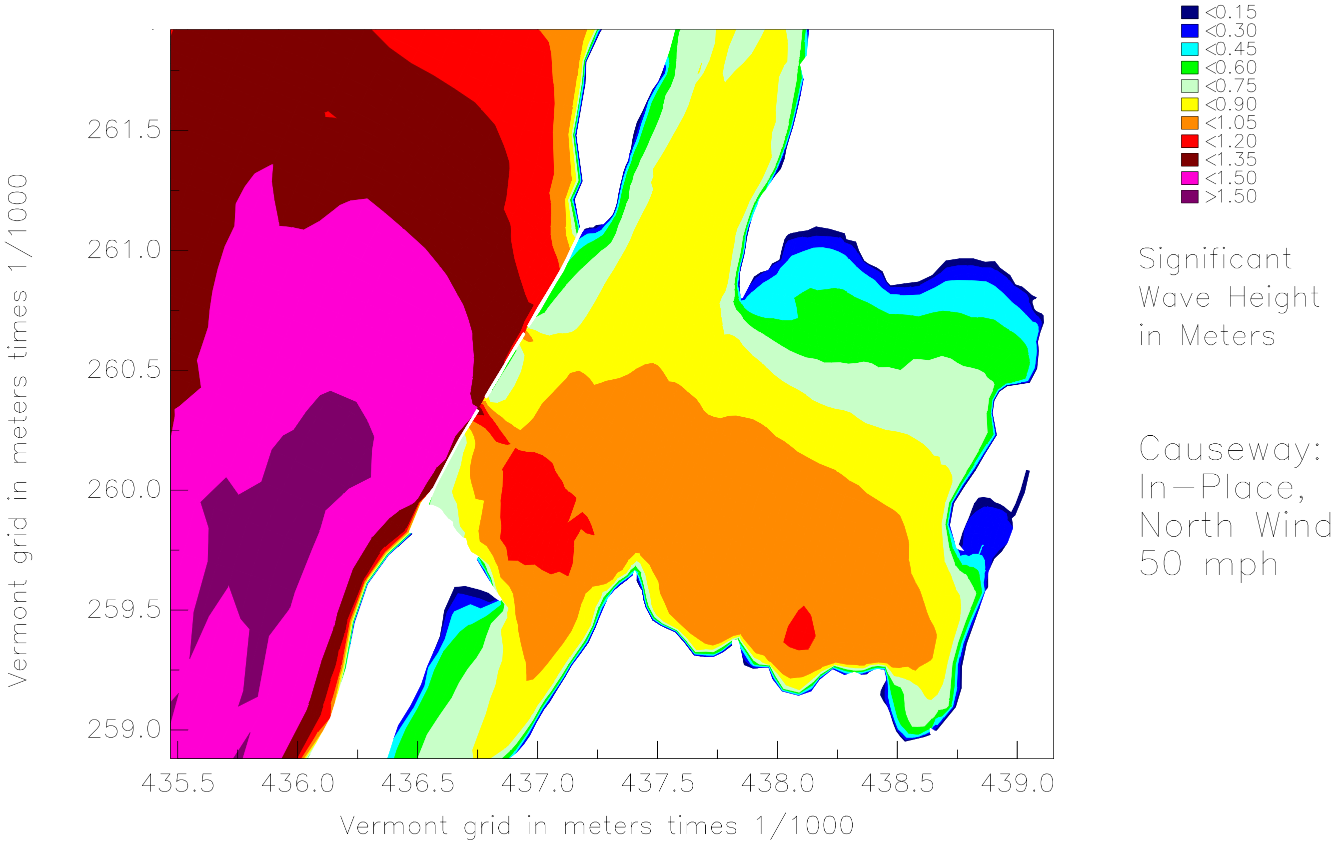




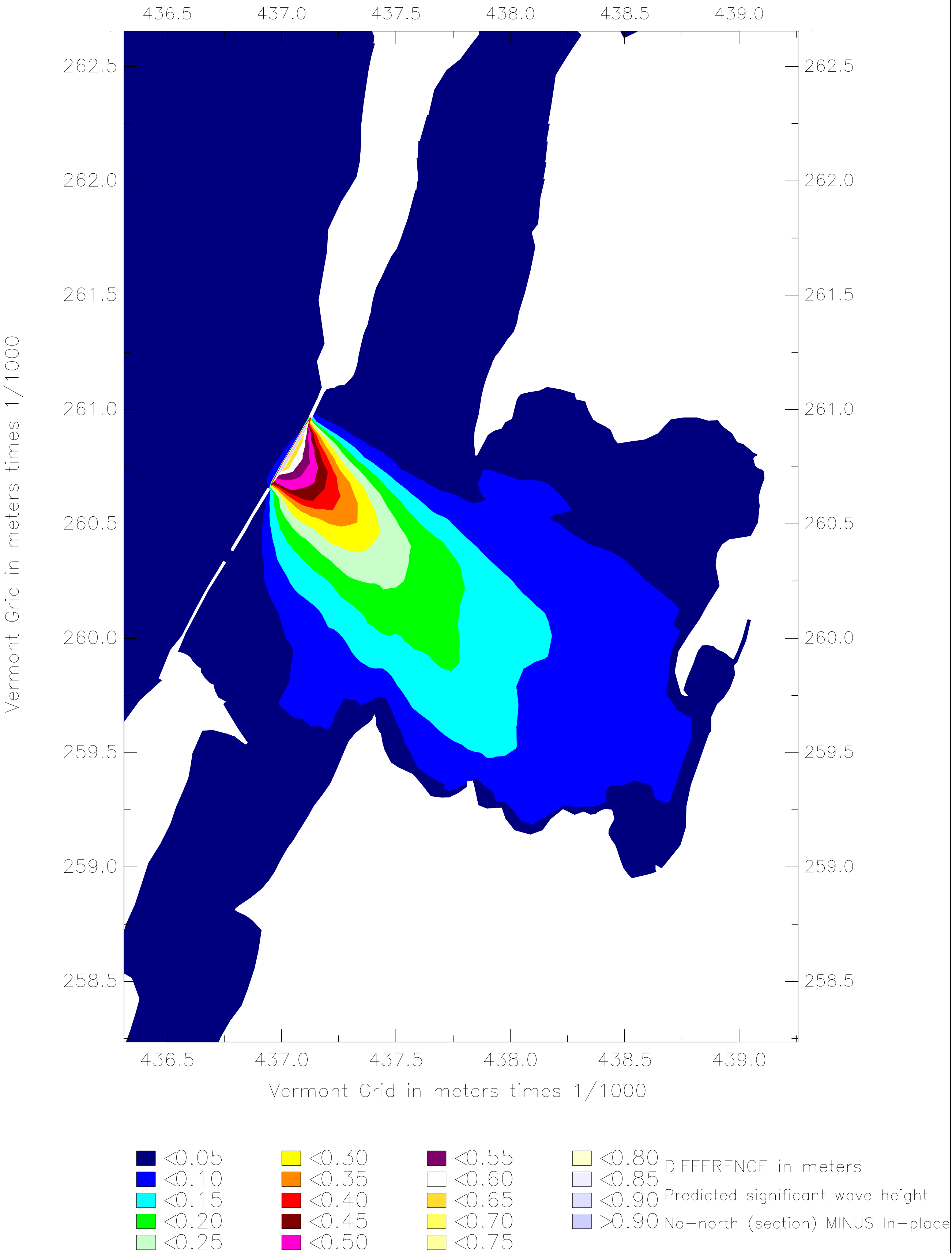
Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 8	Carry Bay Wave Syudy
	Significant Wave Height	
Wind from North at 50 mph	Binkerd Environmental	December 2007



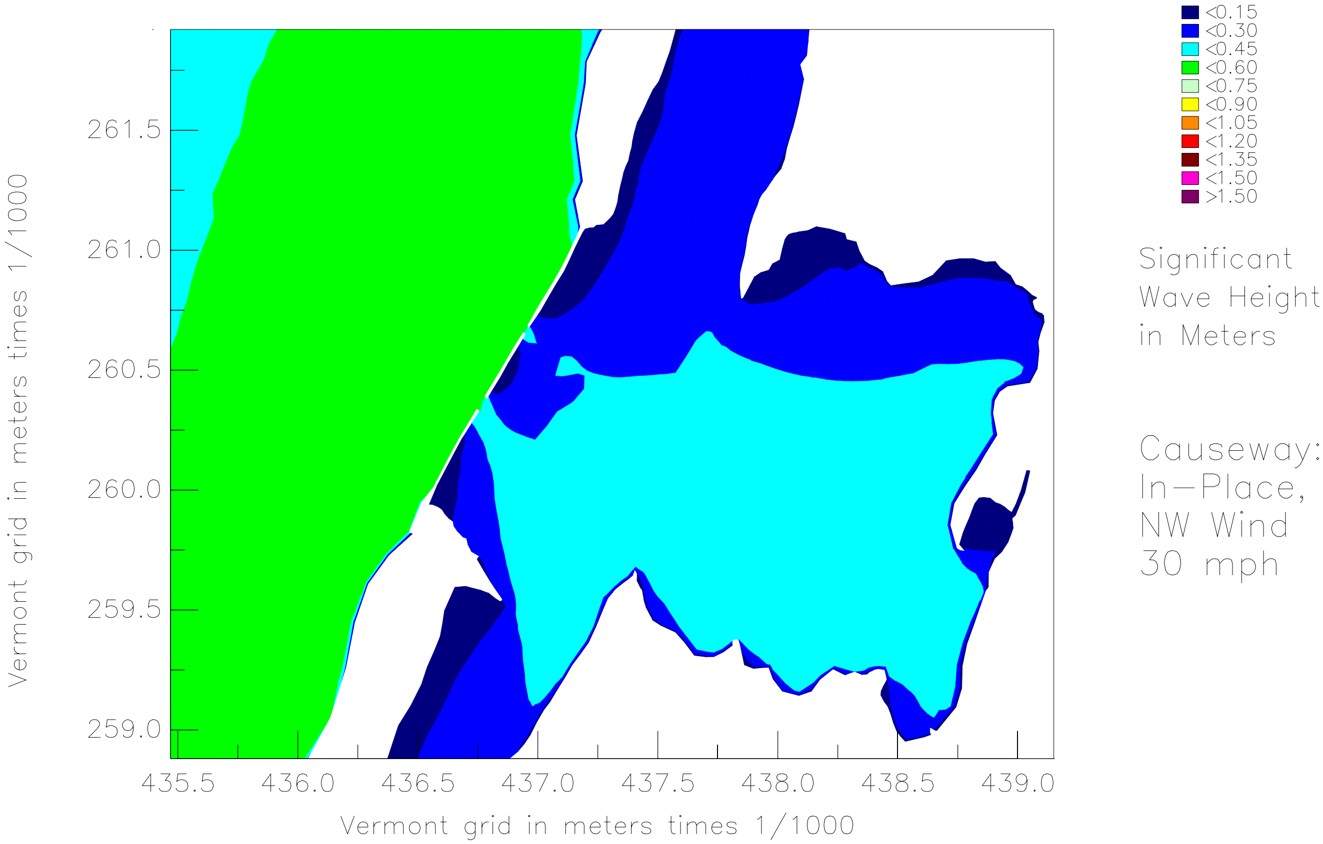
Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 9	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from North at 50 mph	Binkerd Environmental	December 2007

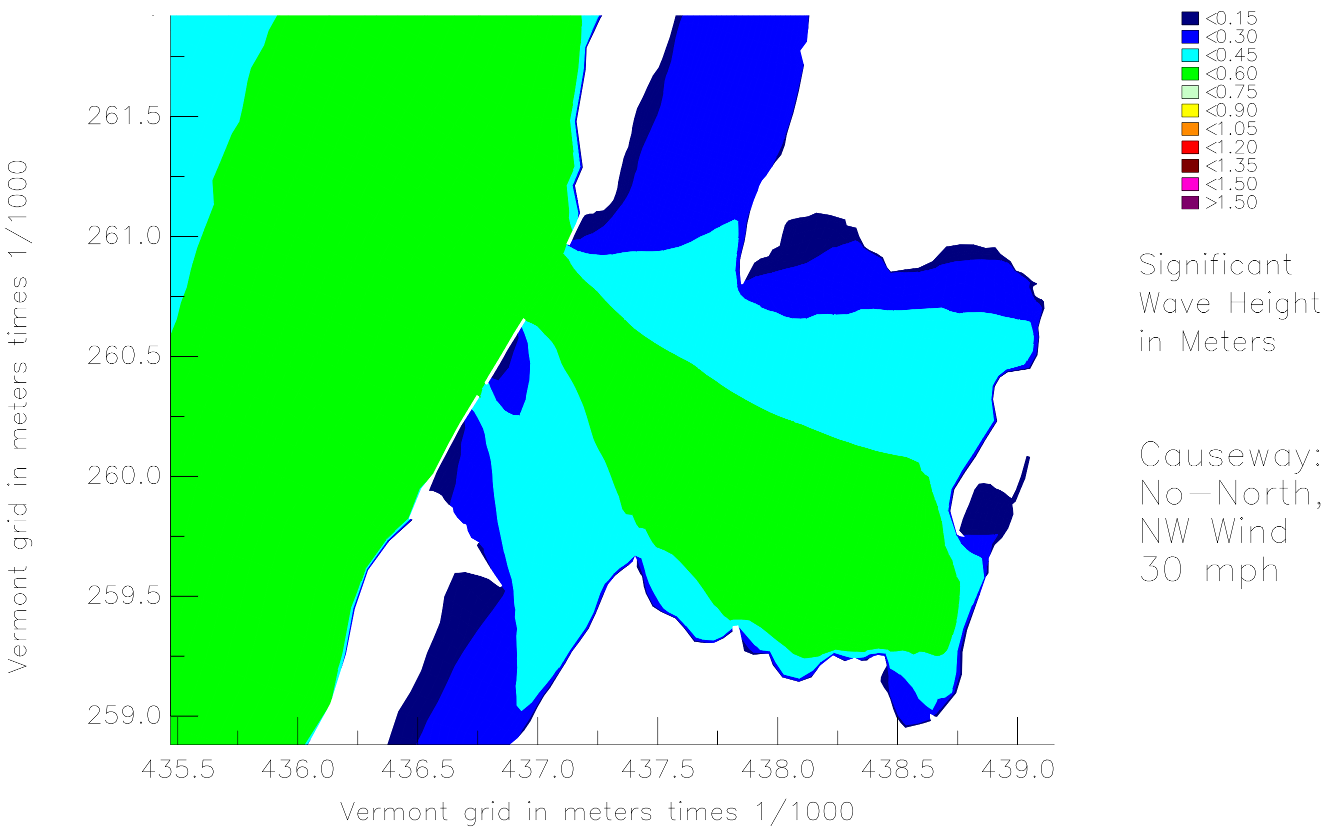


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 10	Carry Bay Wave Study
	Significant Wave Height	
Wind from North at 70 mph	inkerd Environmental	December 2007

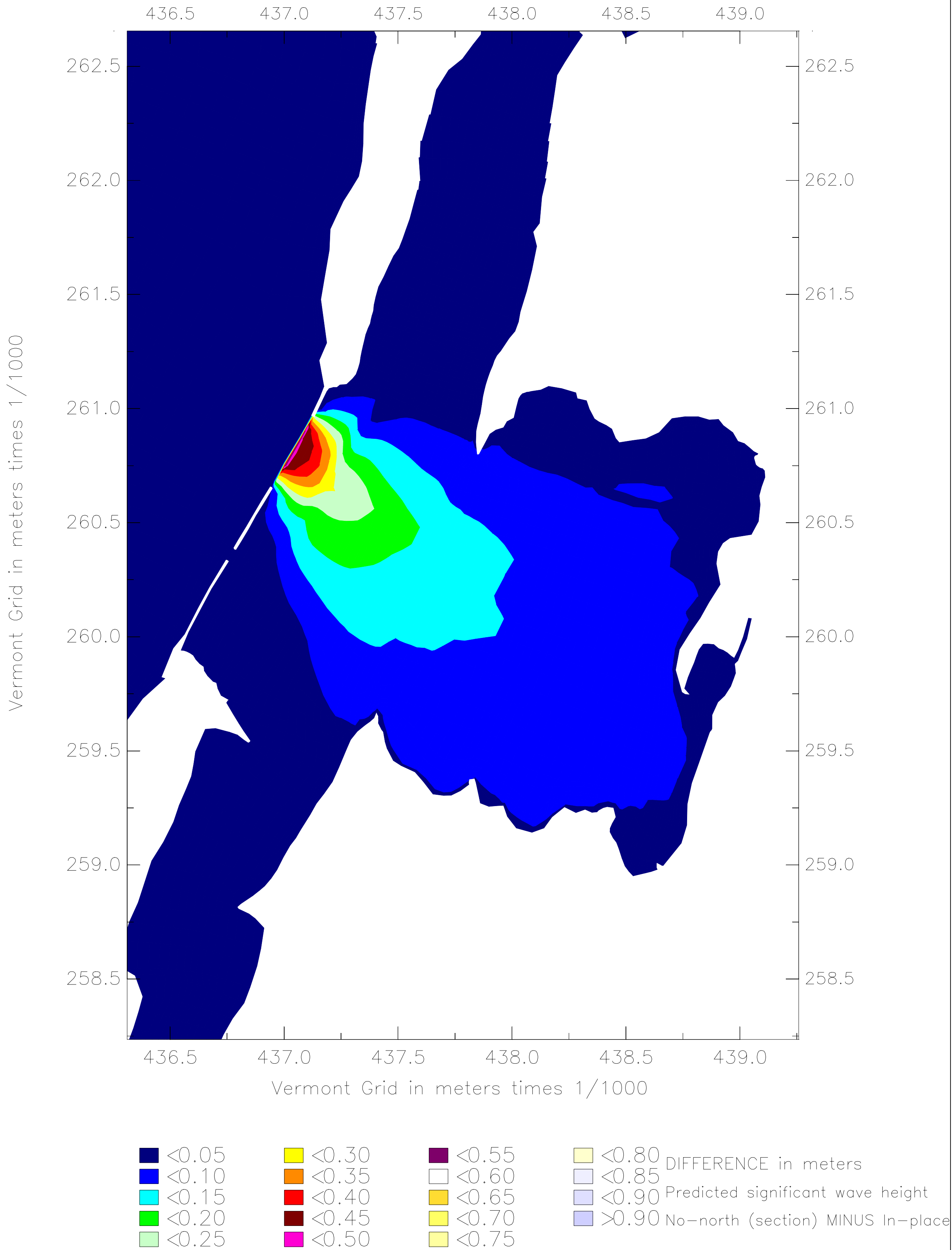


Colors represent DIFFERENCE in predicted significant wave heights in meters between no–north section and in–place causeway predictions.	Figure 11	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from North at 70 mph	Binkerd Environmental	December 2007

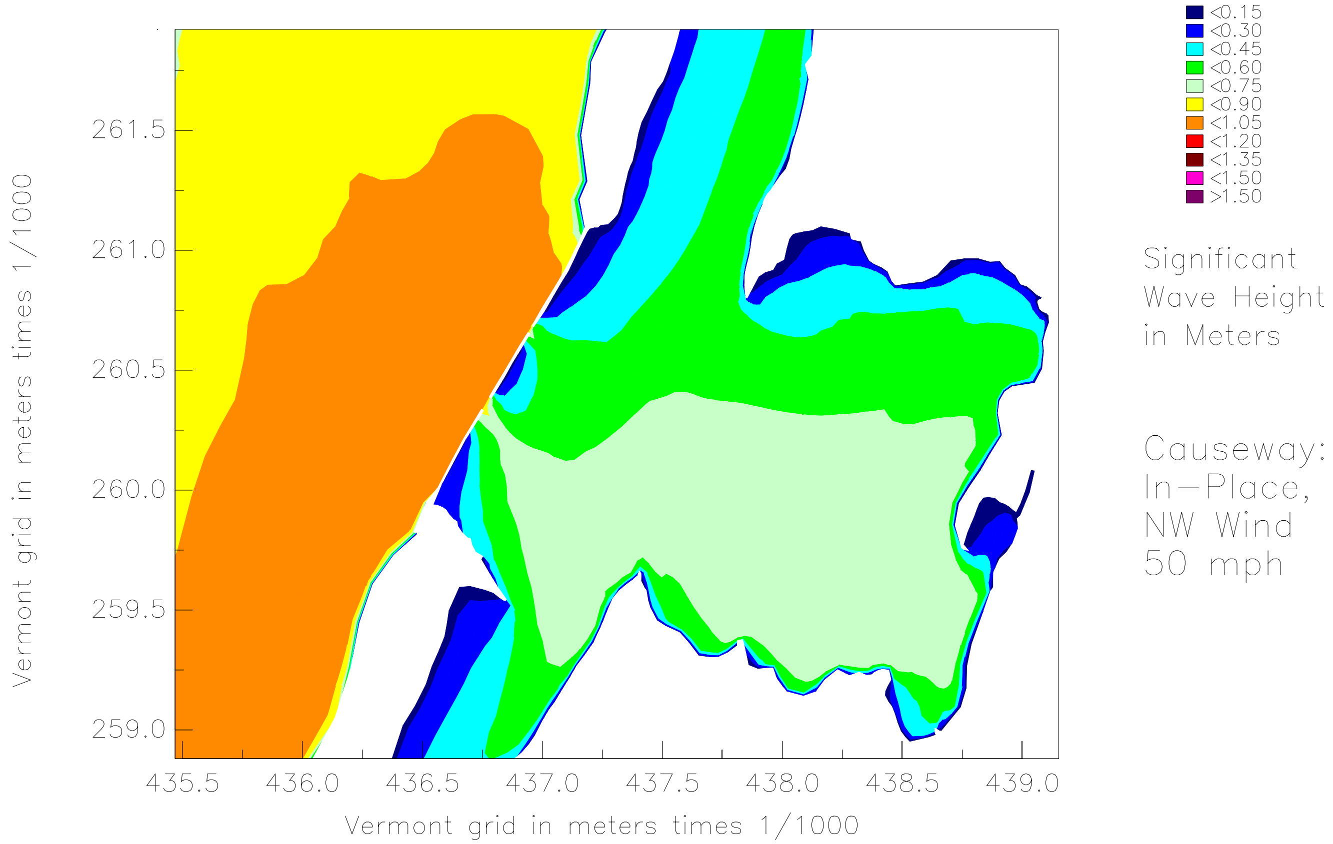


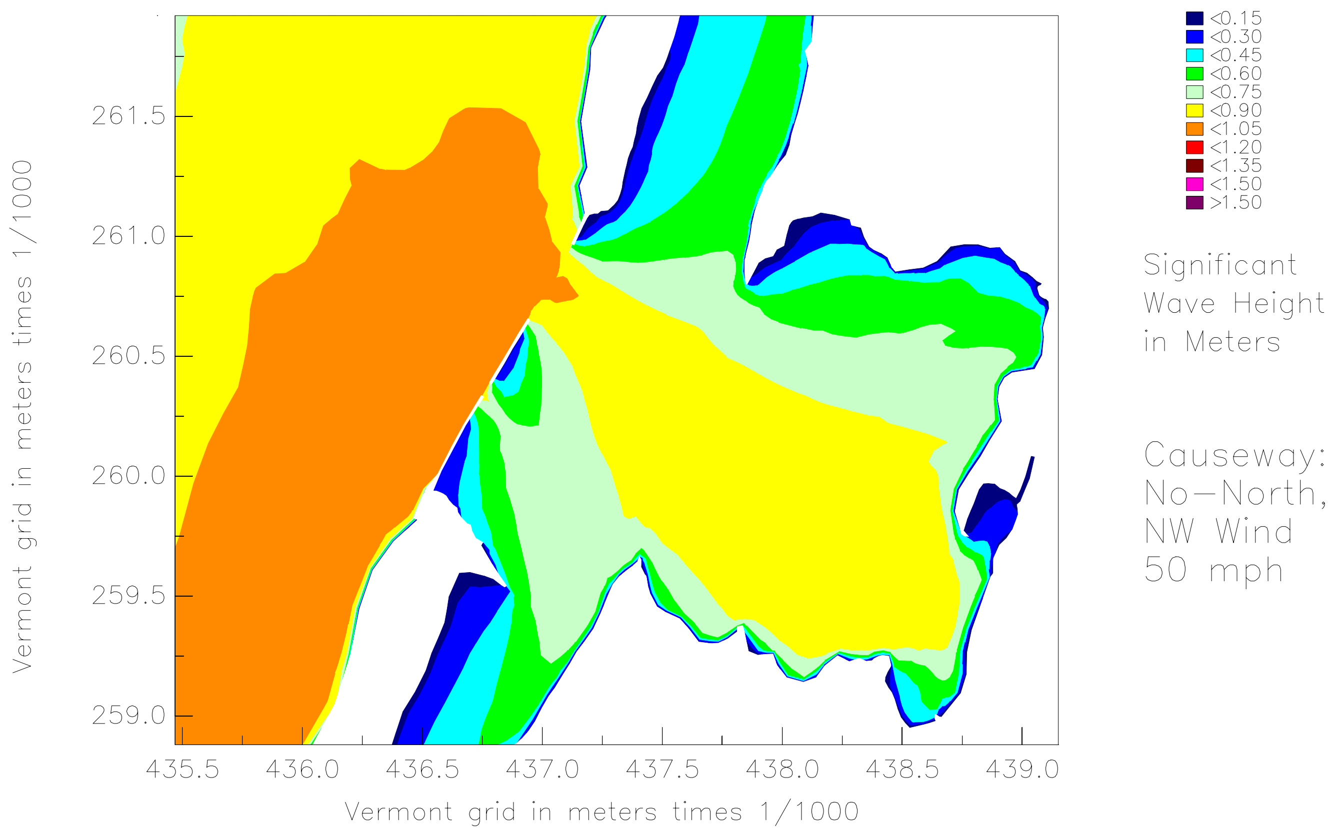


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 12	Carry Bay Wave Study
	Significant Wave Height	
Wind from Northwest at 30 mph	Binkerd Environmental	December 2007

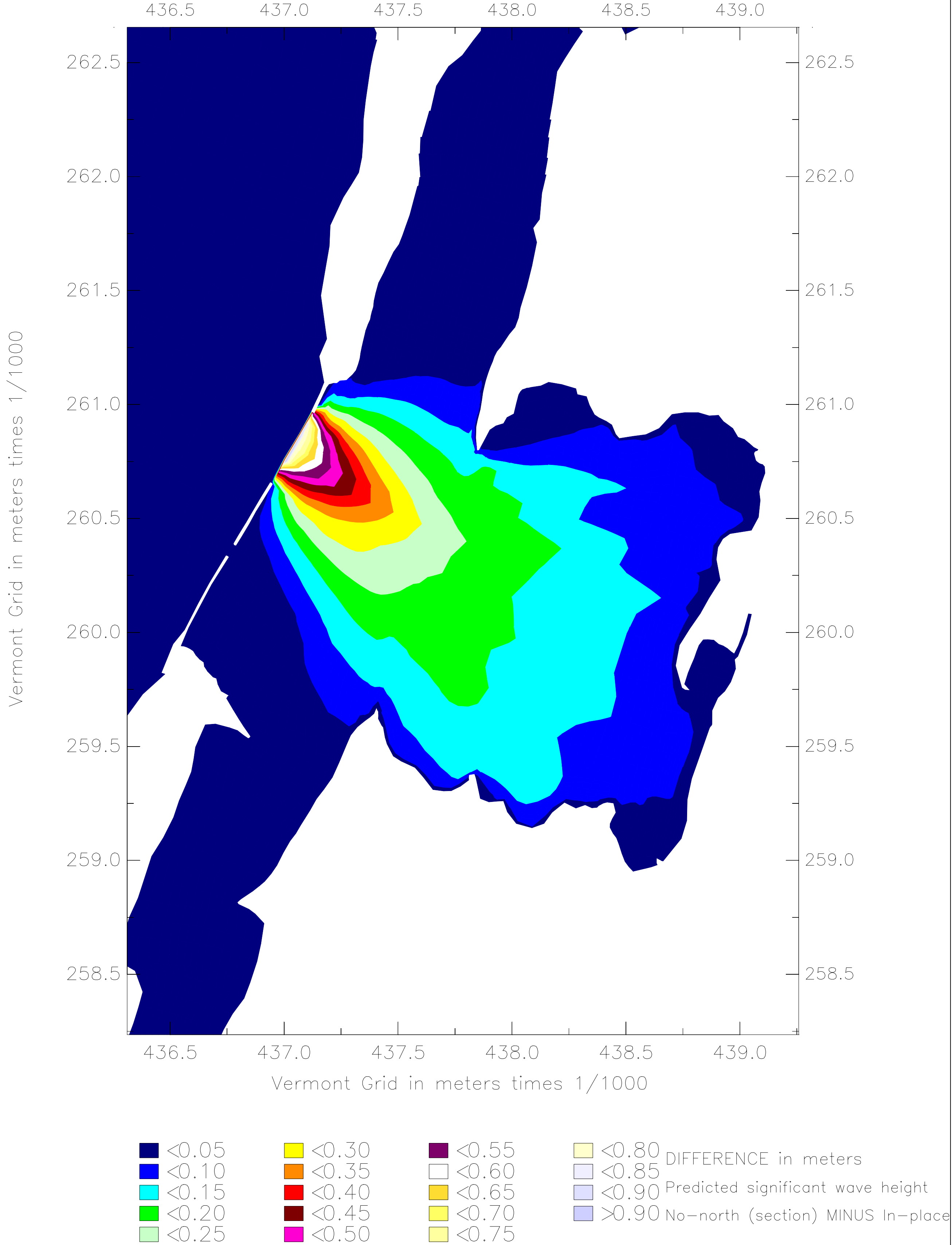


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 13	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from Northwest at 30 mph	Binkerd Environmental	December 2007

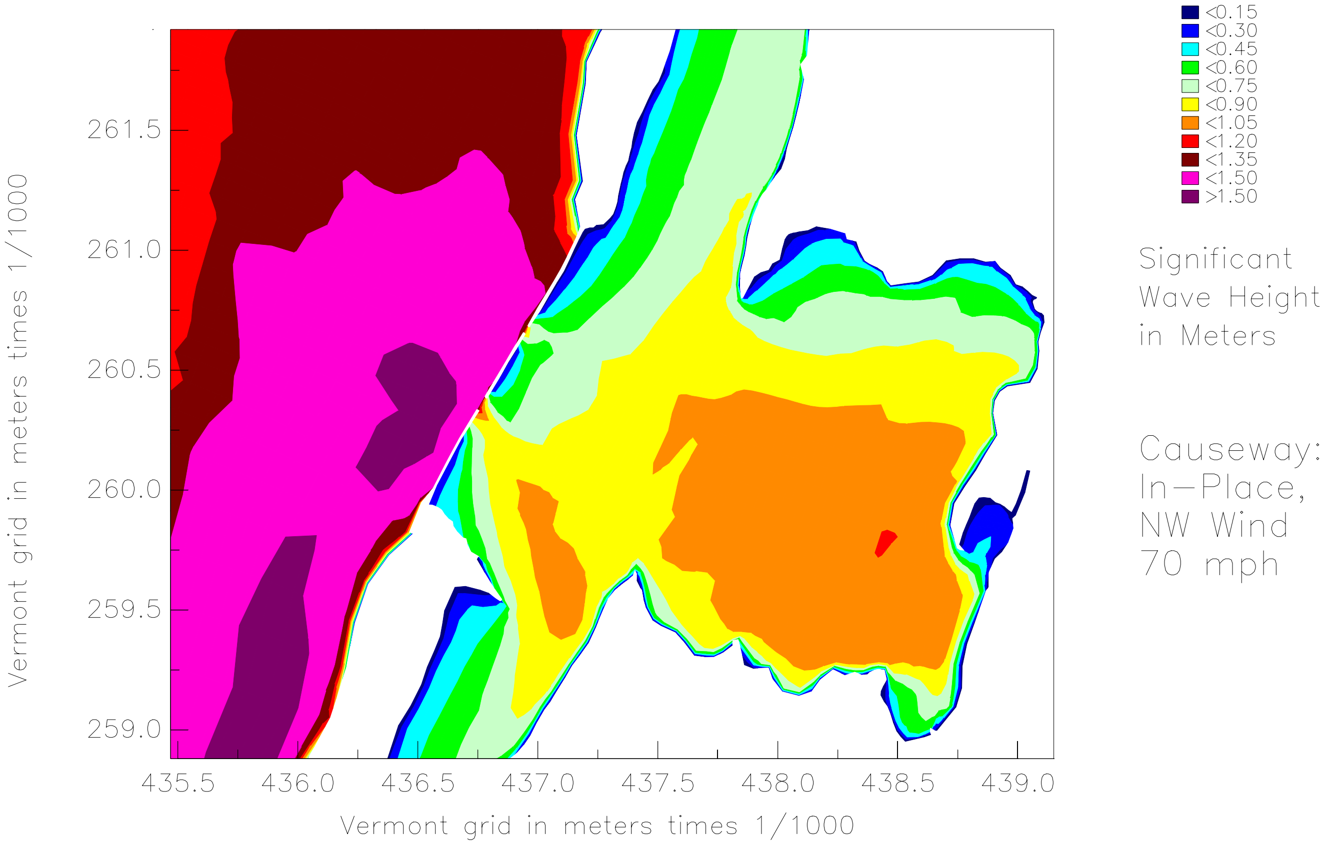


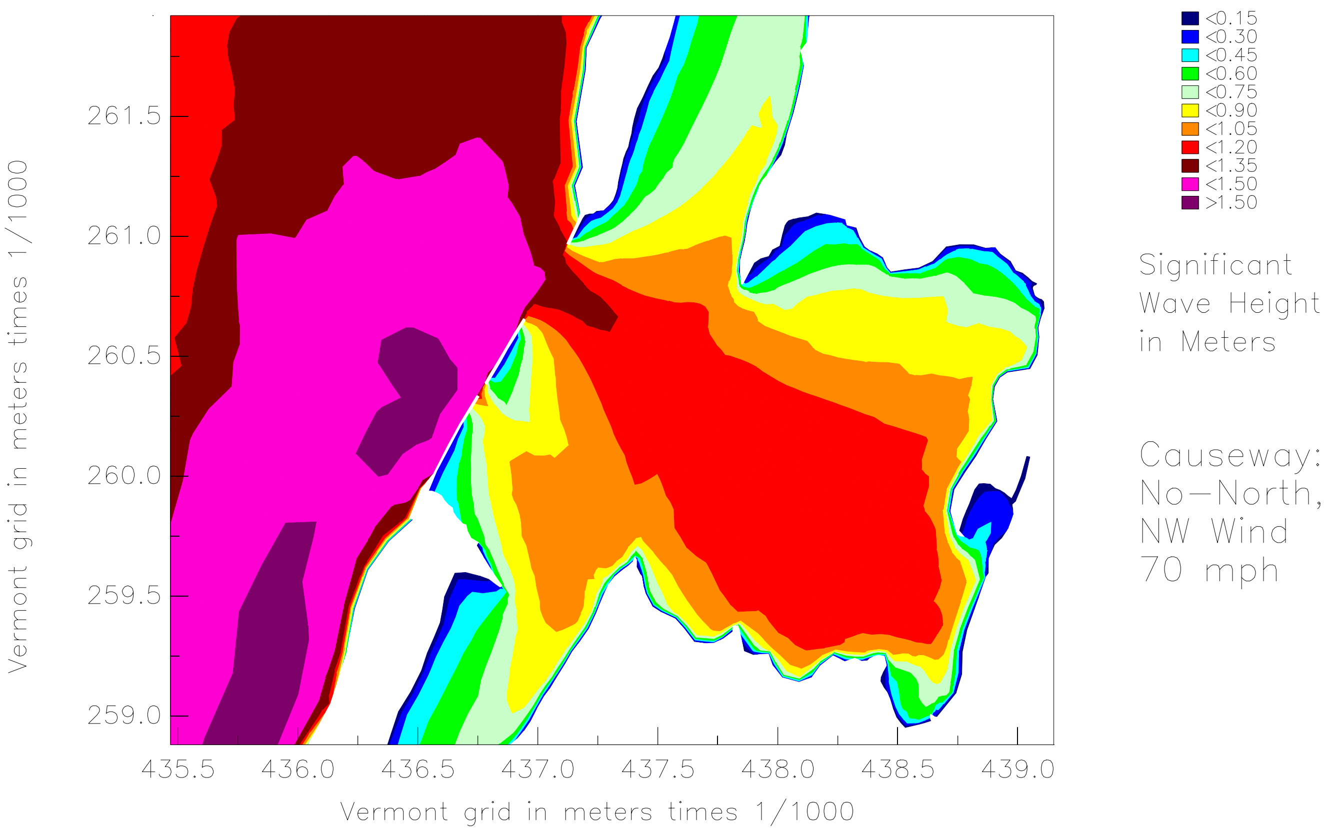


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 14	Carry Bay Wave
	Significant Wave Height	
Wind from Northwest at 50 mph	Binkerd Environmental	December 2007

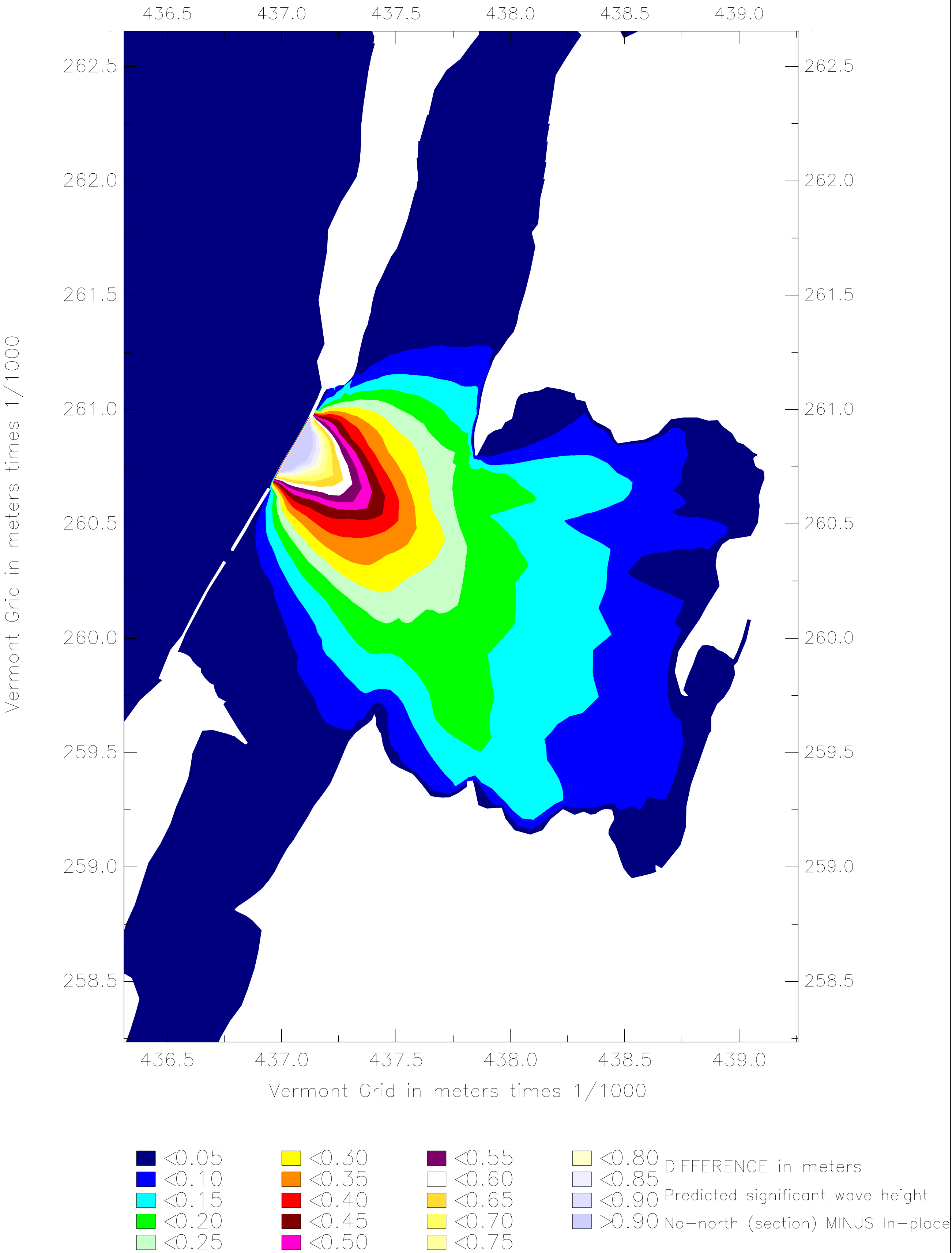


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 15	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from Northwest at 50 mph	Binkerd Environmental	December 2007





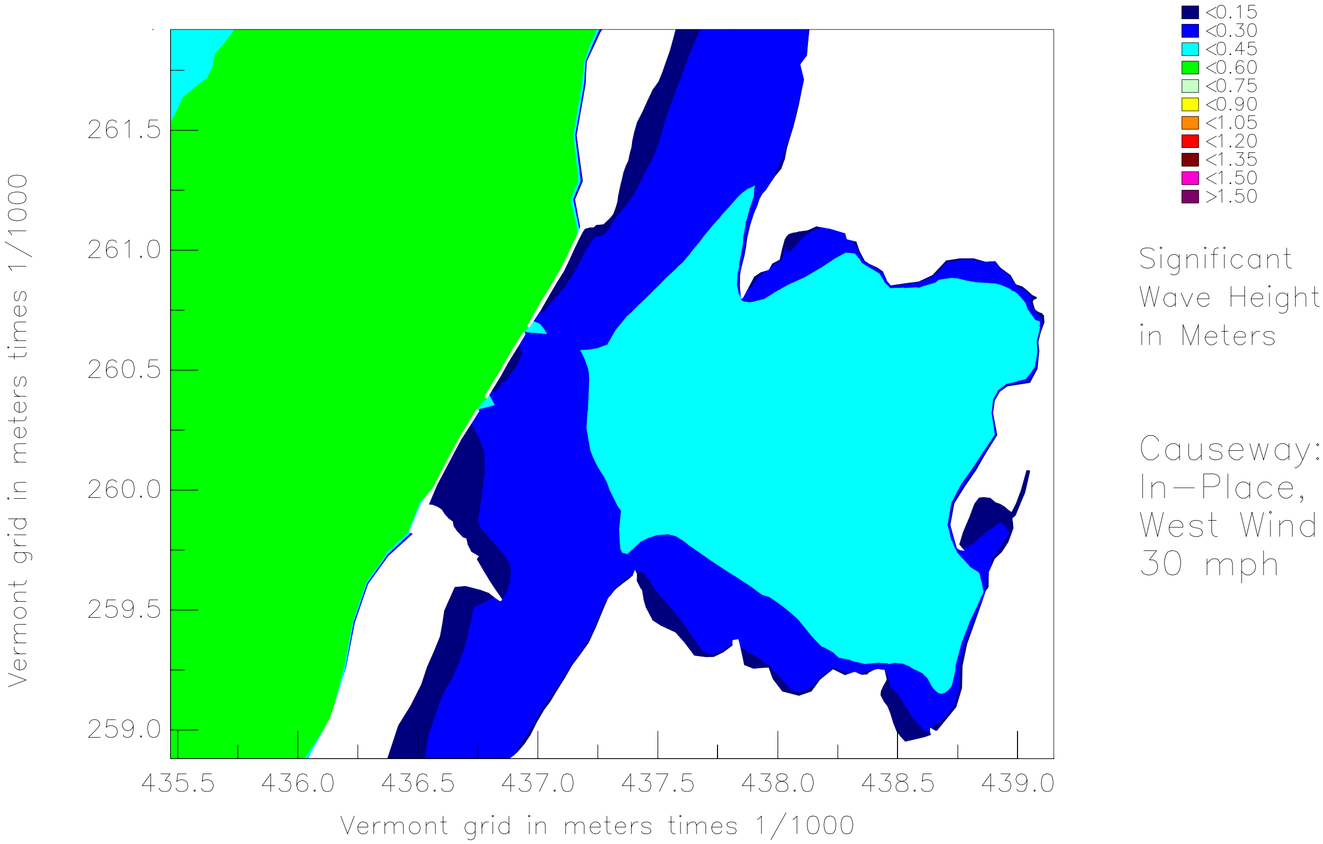
Top – Significant Wave Height (meters) – Causeway In-Place Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 16	Carry Bay Wave
	Significant Wave Height	
Wind from Northwest at 70 mph	Binkerd Environmental	December 2007

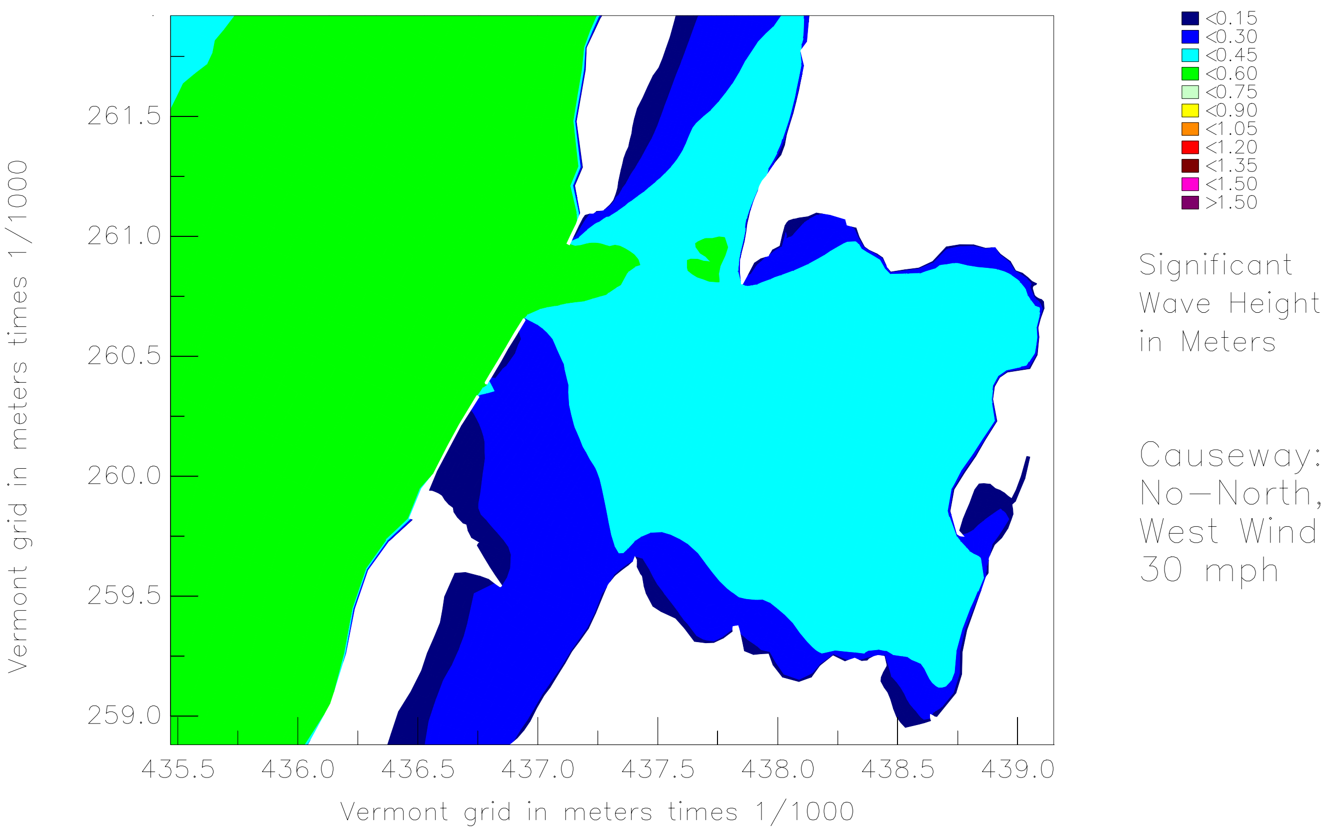


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.

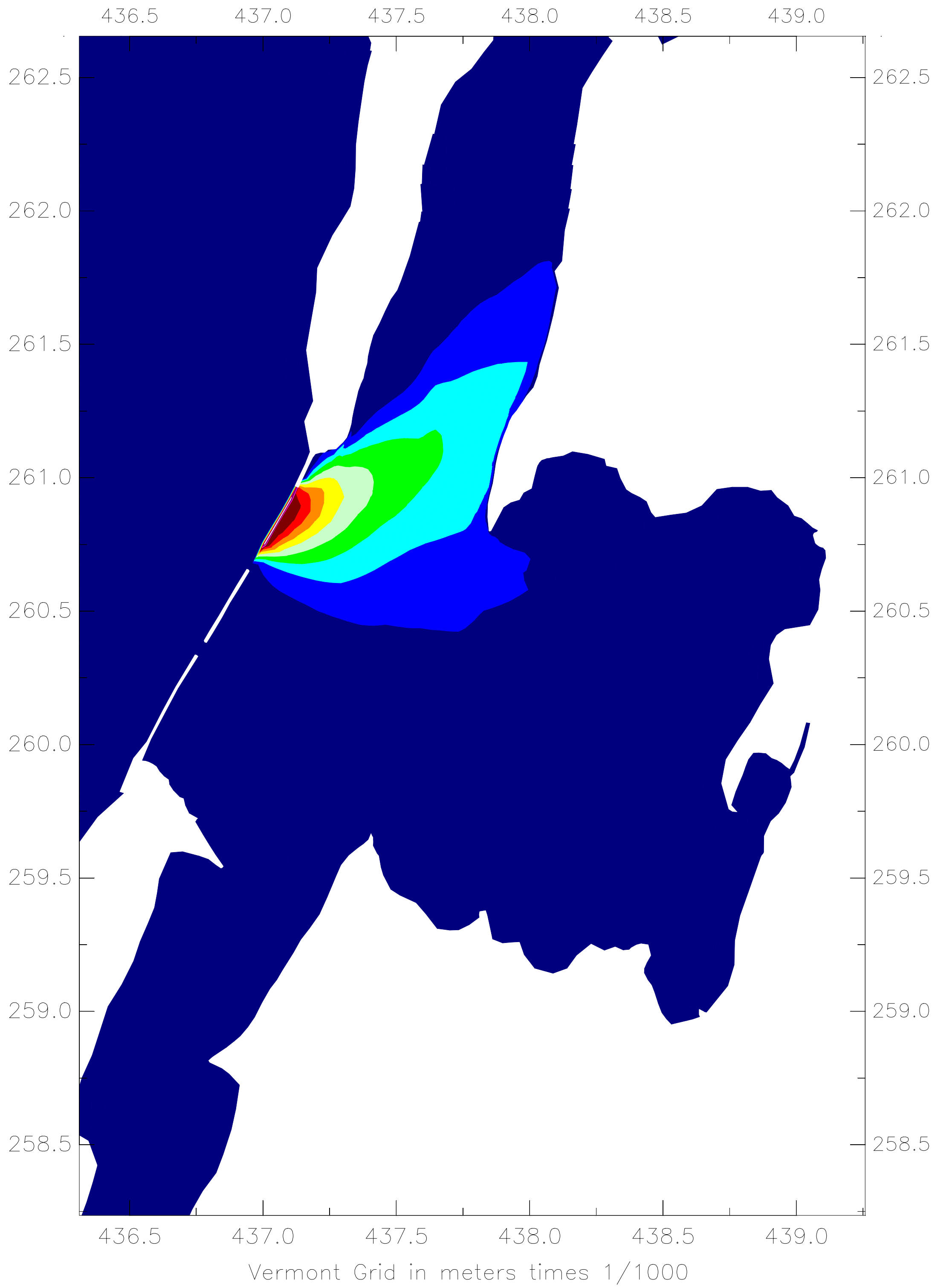
Wind from Northwest at 70 mph

Figure 17	Carry Bay Wave Study
Difference in predicted wave heights	
Binkerd Environmental	December 2007





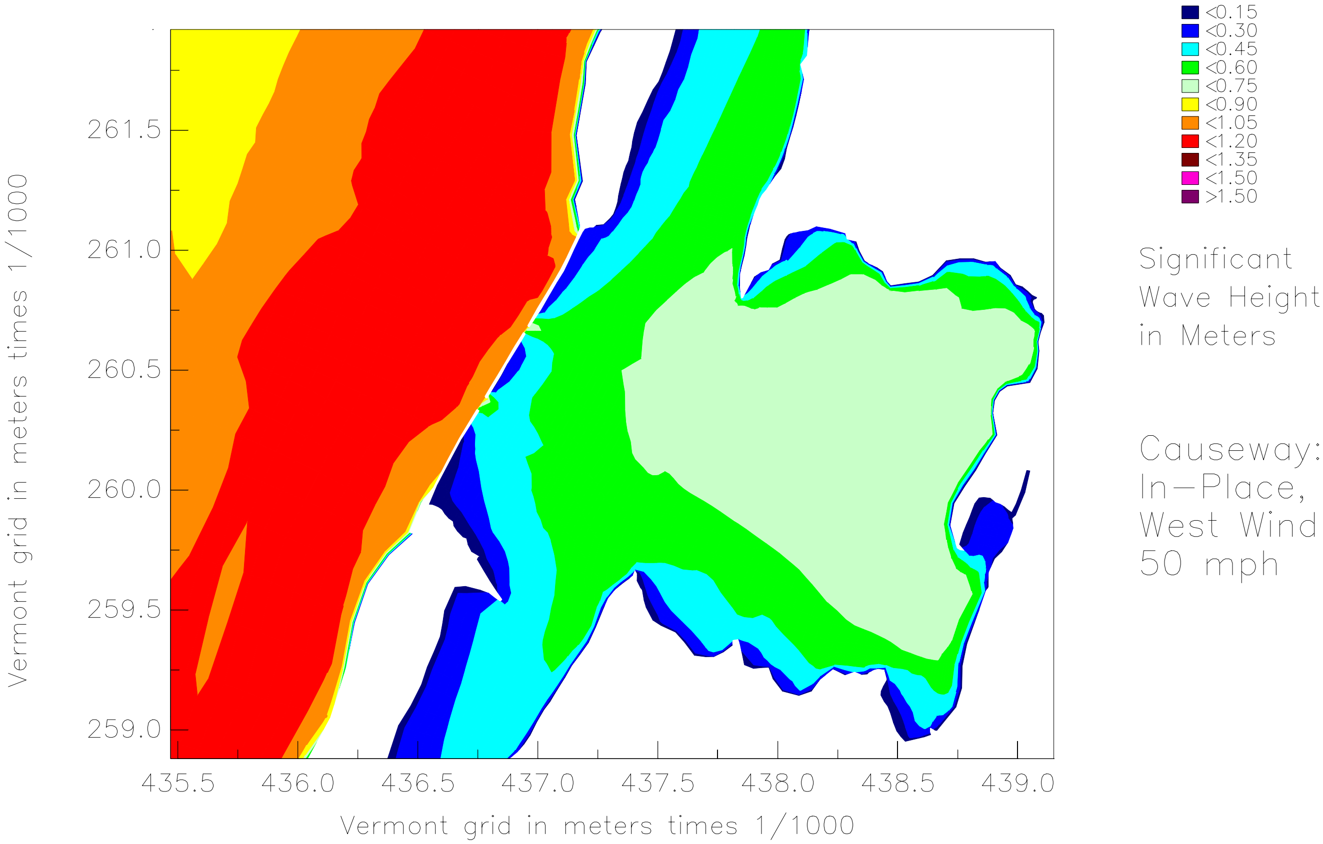
Top – Significant Wave Height (meters) – Causeway In-Place Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 18	Carry Bay Wave Study
	Significant Wave Height	
Wind from West at 30 mph	Binkerd Environmental	December 2007

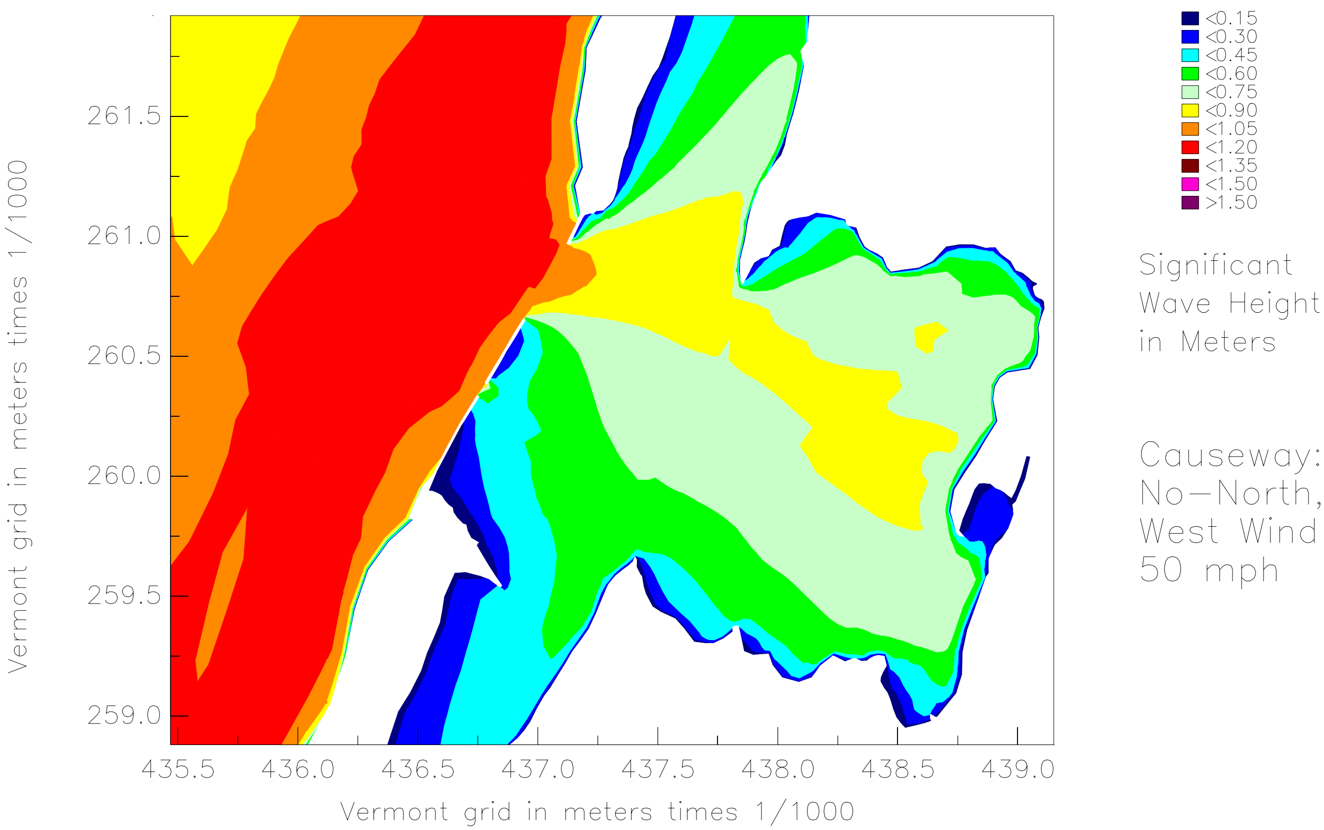


<0.05 <0.10 <0.15 <0.20 <0.25 <0.30 <0.35 <0.40 <0.45 <0.50 <0.55 <0.60 <0.65 <0.70 <0.75 <0.80 <0.85 <0.90 >0.90

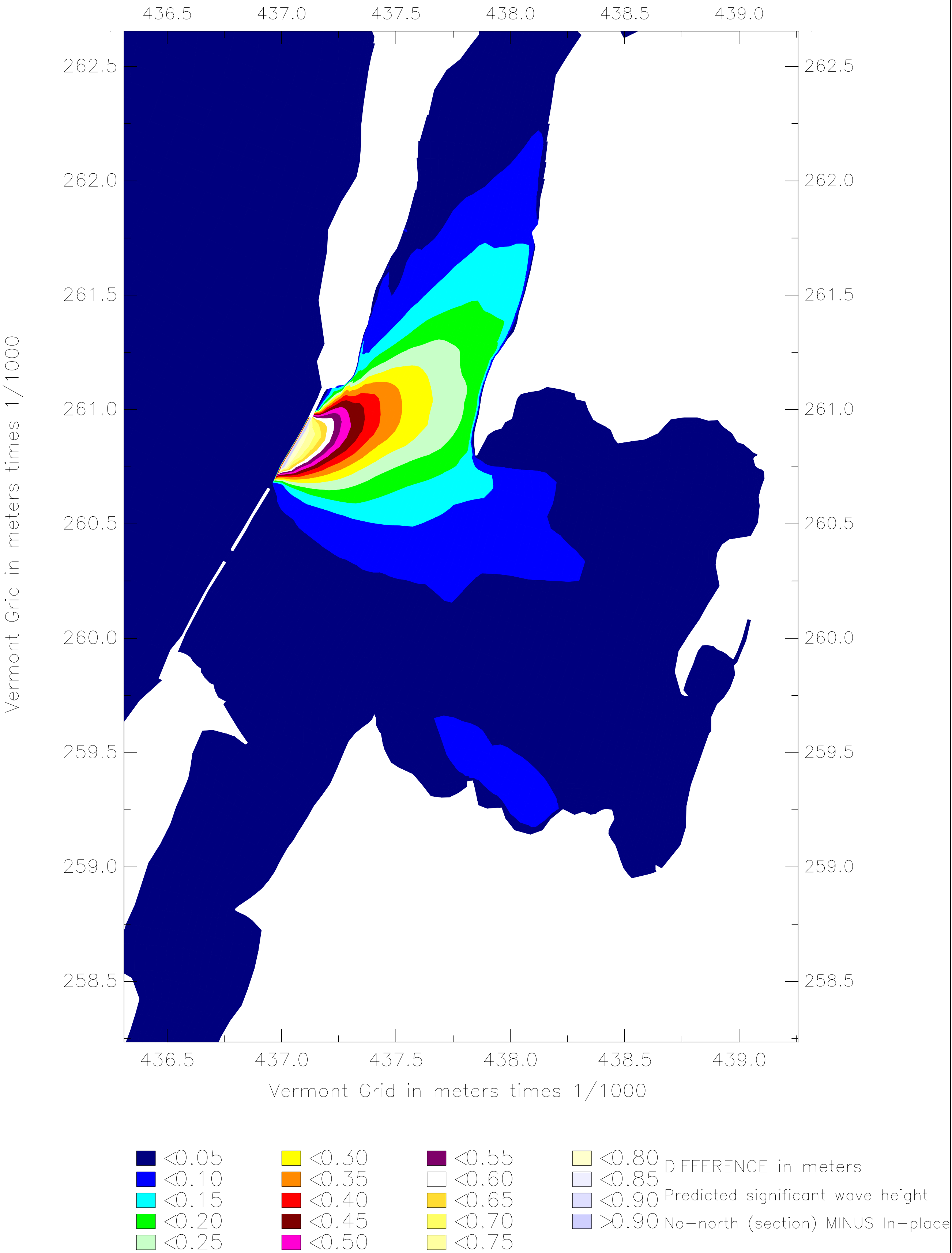
DIFFERENCE in meters
Predicted significant wave height
No-north (section) MINUS In-place

Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 19	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from West at 30 mph	Binkerd Environmental	December 2007

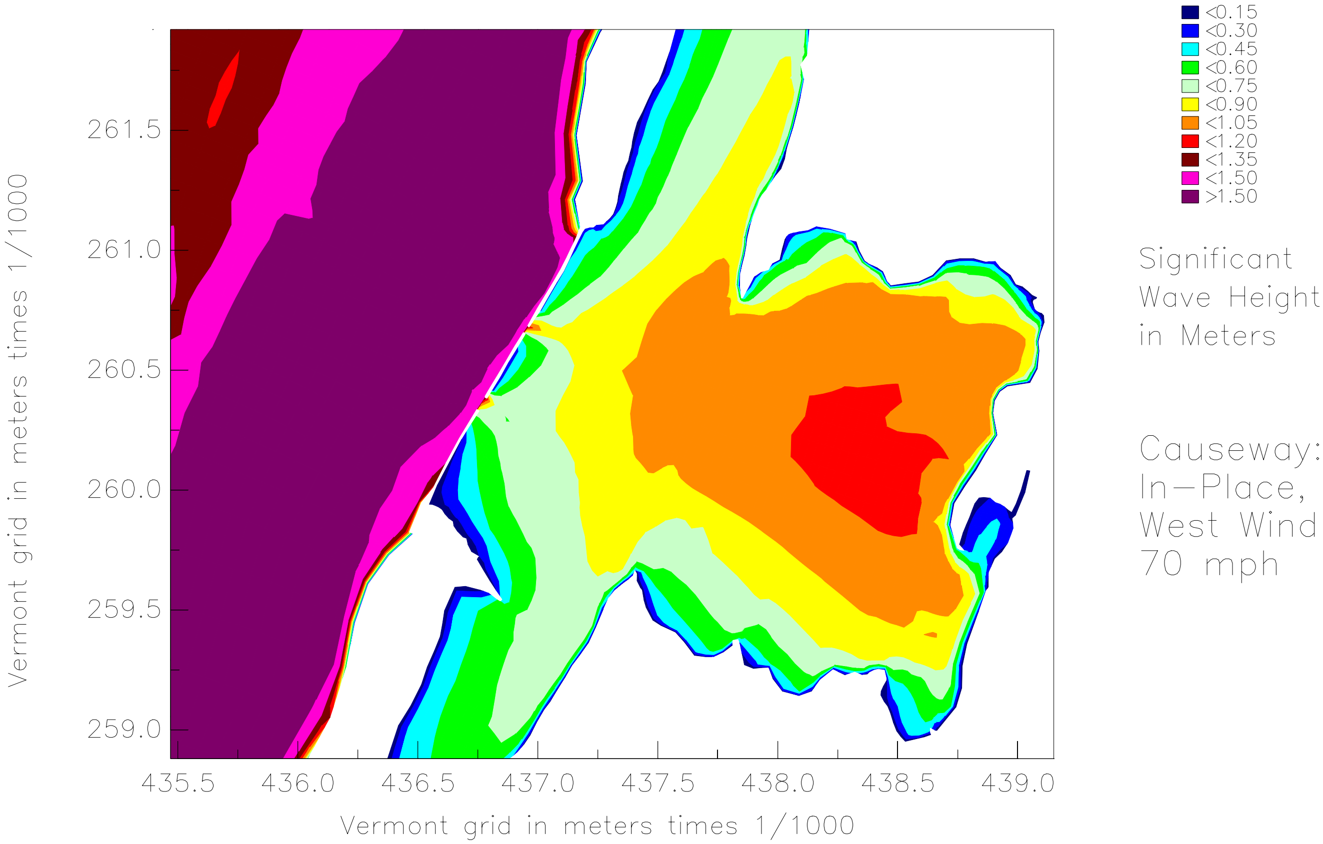


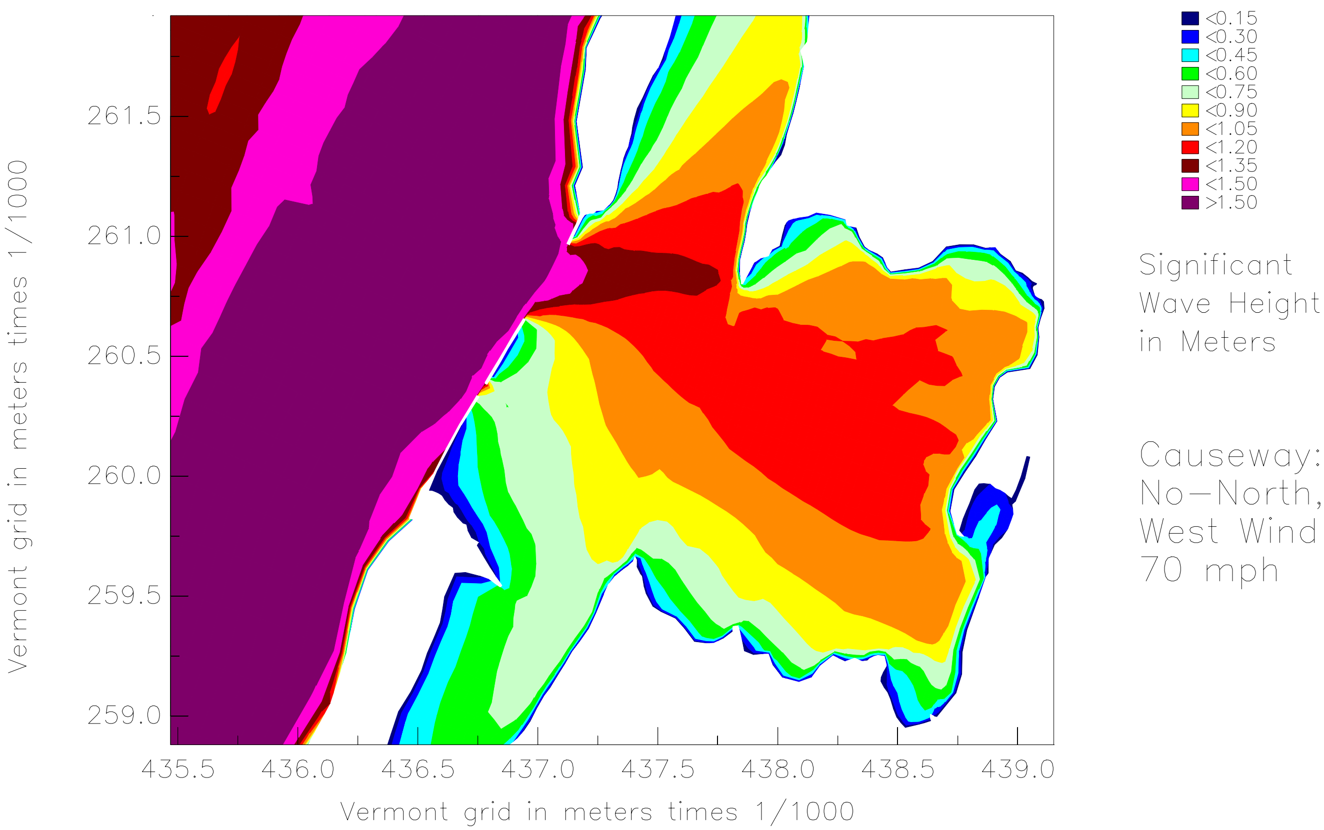


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 20	Carry Bay Wave Study
	Significant Wave Height	
Wind from West at 50 mph	Binkerd Environmental	December 2007

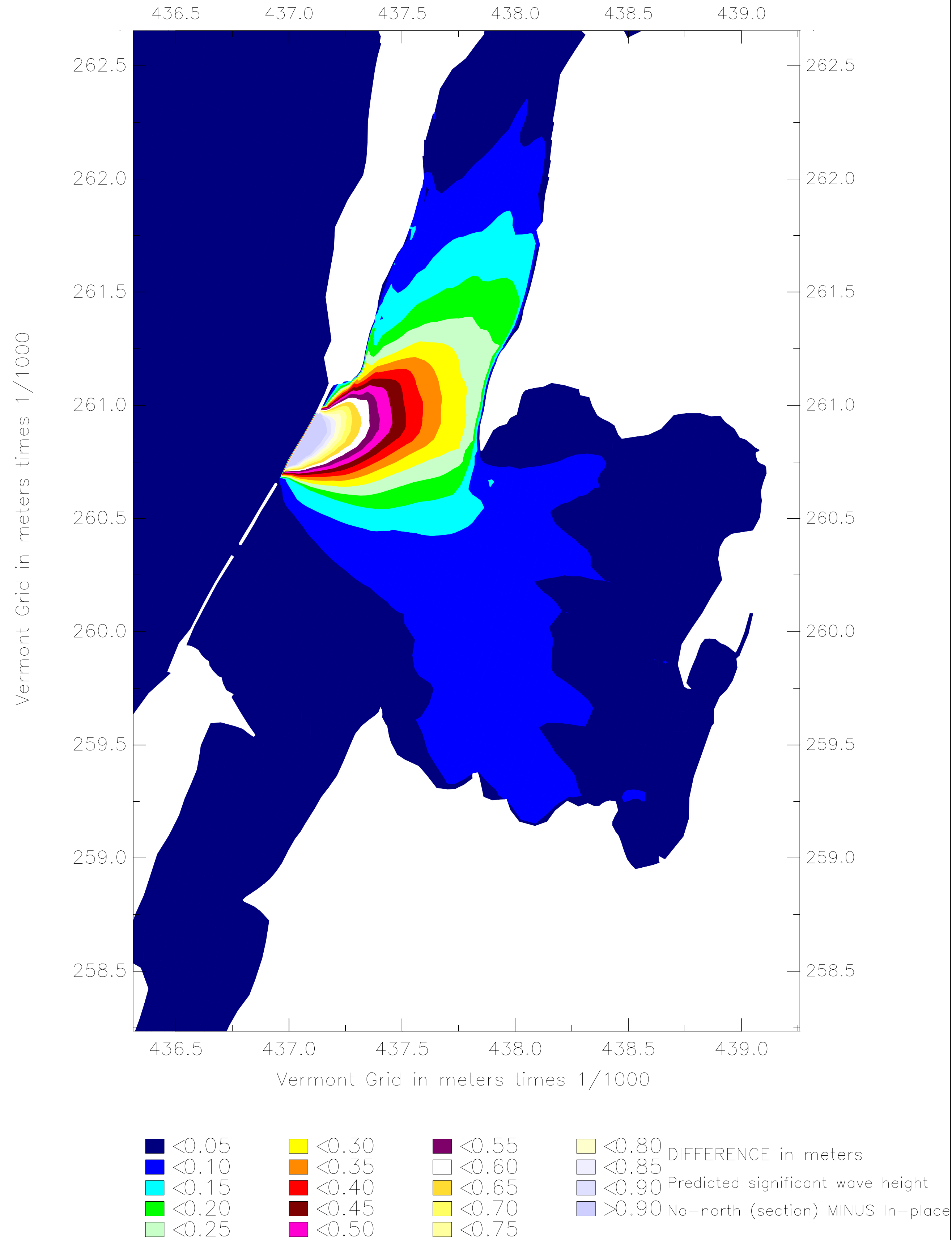


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 21	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from West at 50 mph	Binkerd Environmental	December 2007

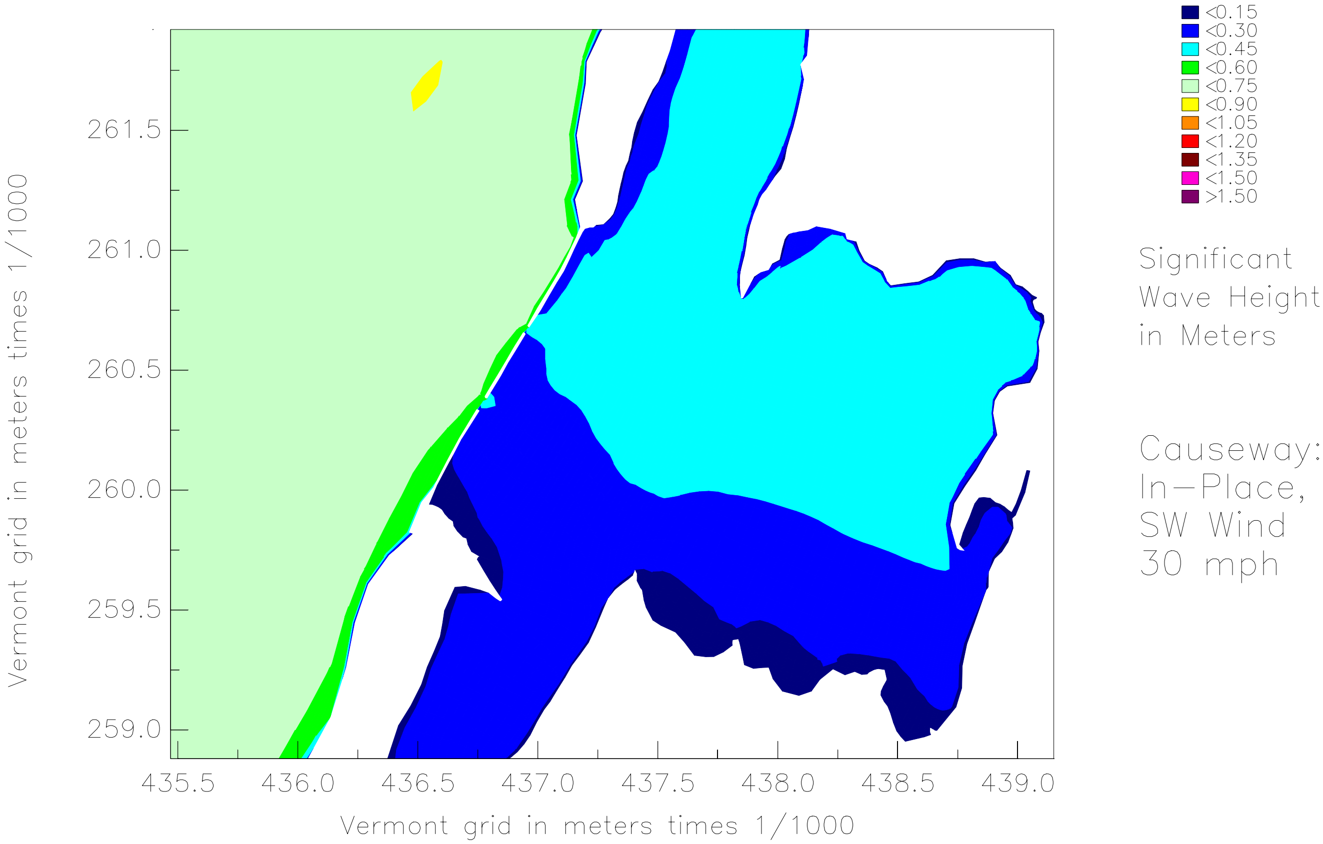


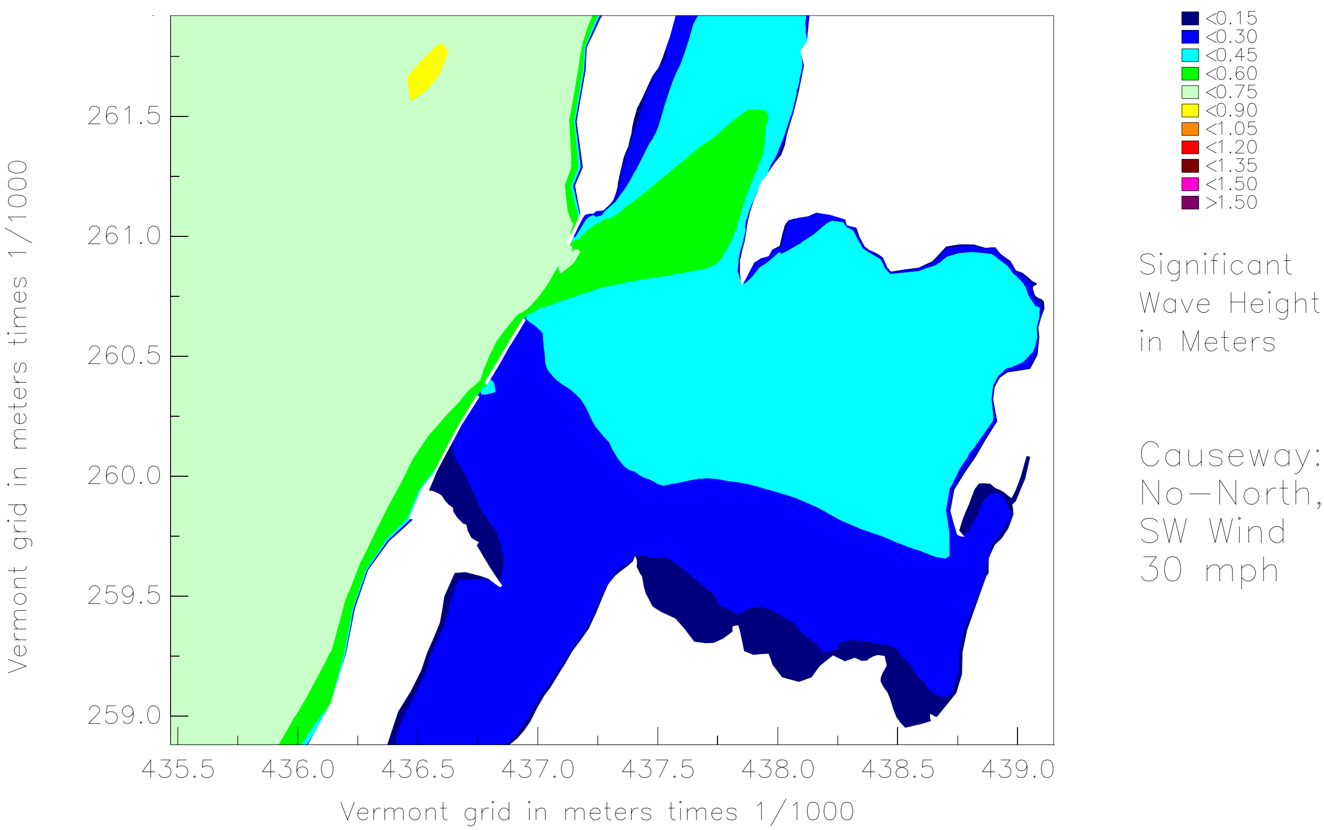


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 22	Carry Bay Wave Study
	Significant Wave Height	
Wind from West at 70 mph	Binkerd Environmental	December 2007

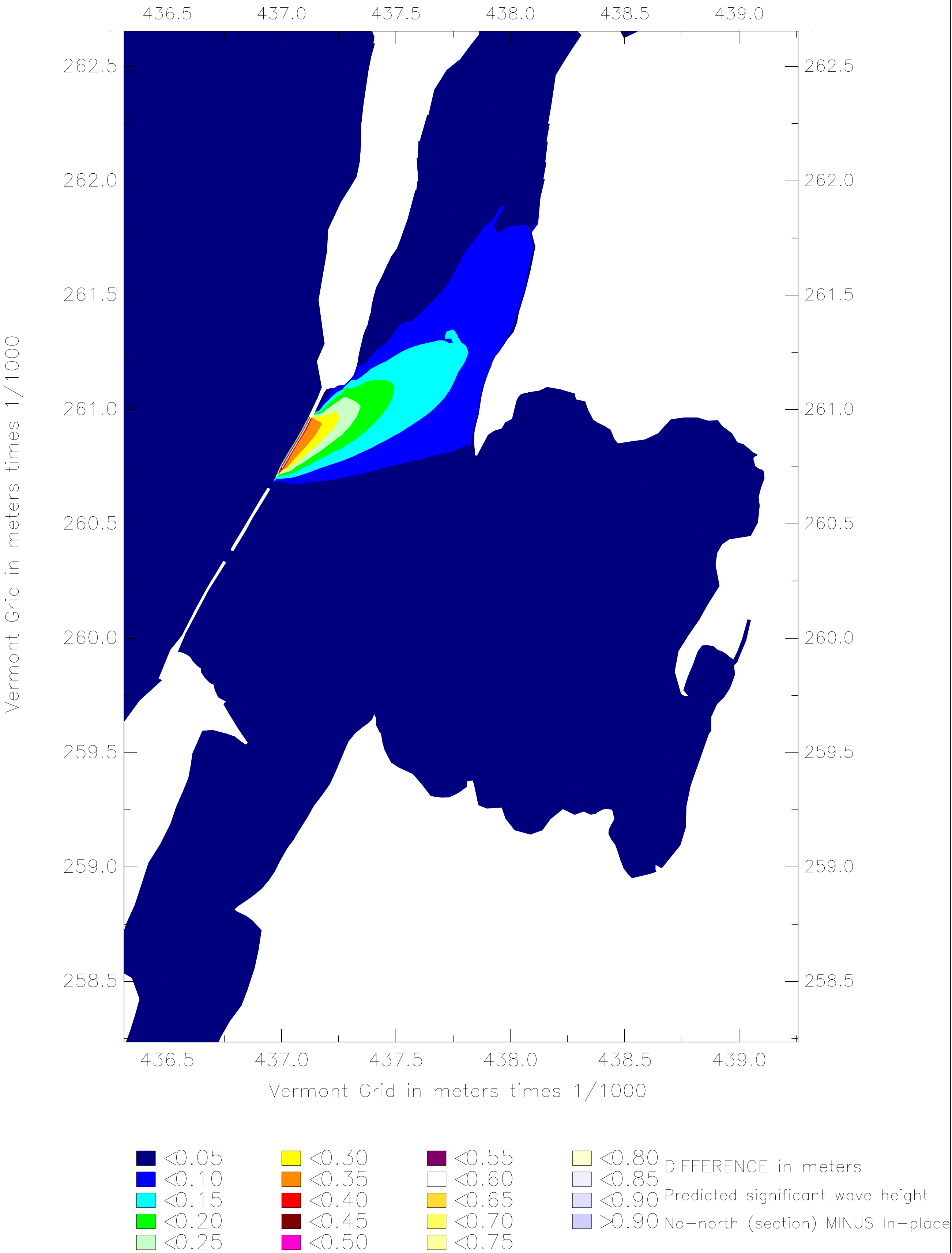


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 23	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from West at 70 mph	Binkerd Environmental	December 2007

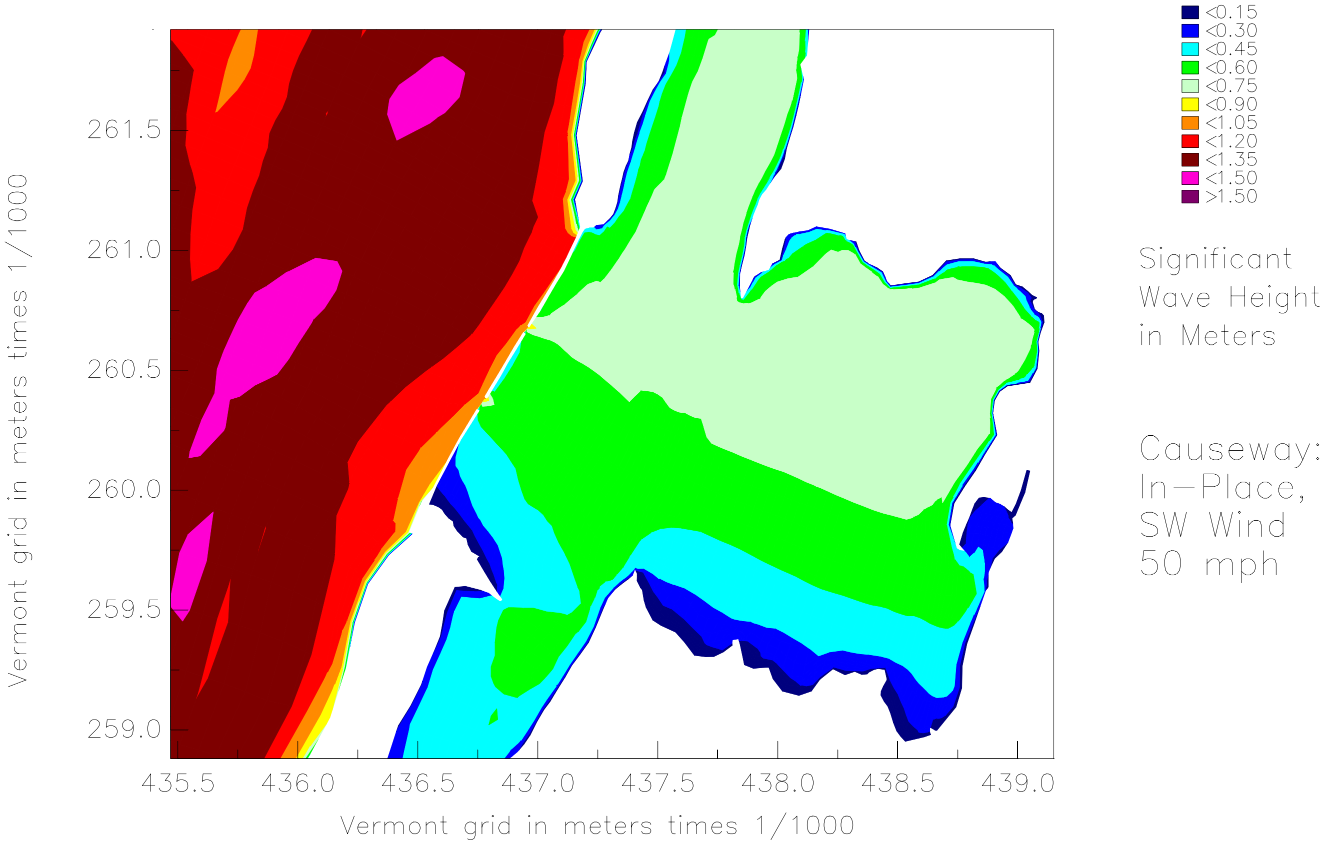


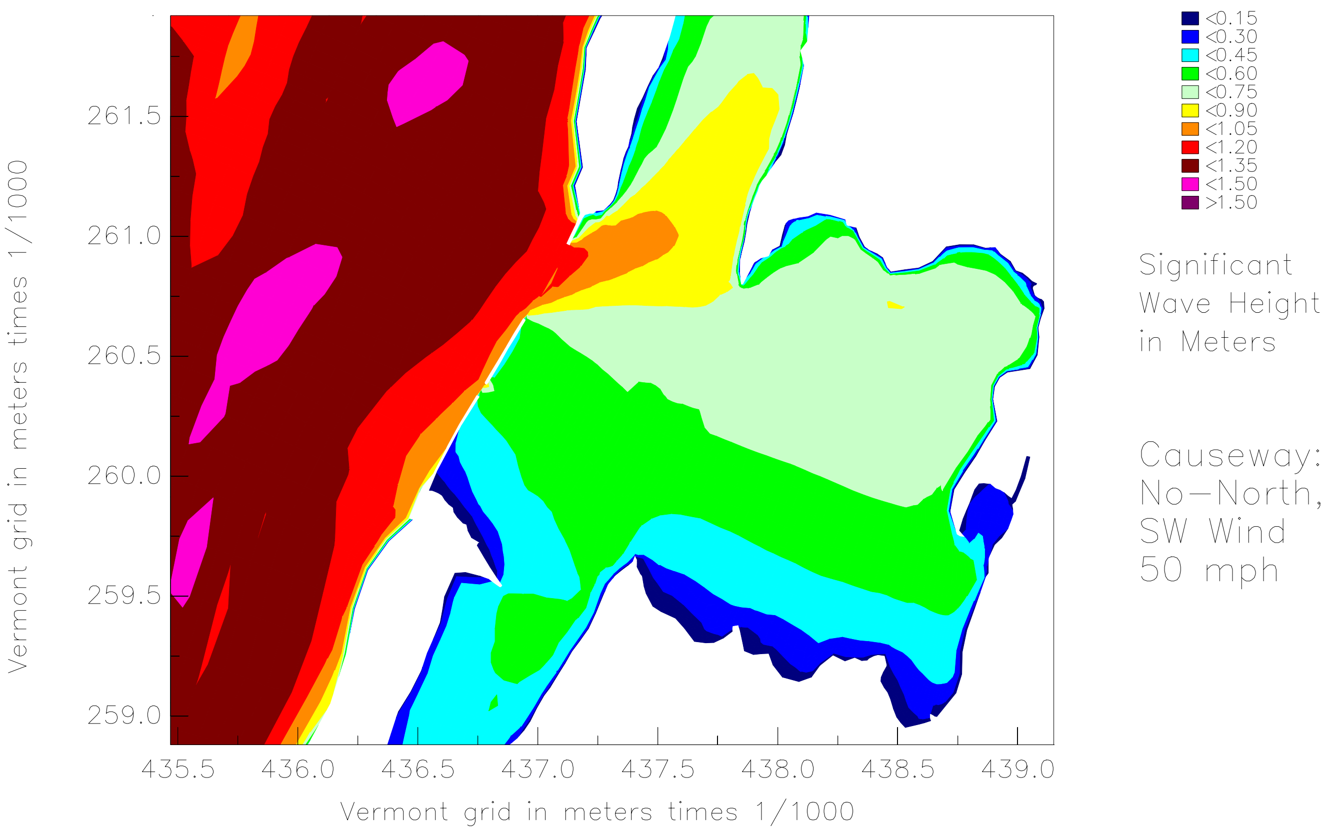


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 24	Carry Bay Wave Study
	Significant Wave Height	
Wind from Southwest at 30 mph	Binkerd Environmental	December 2007

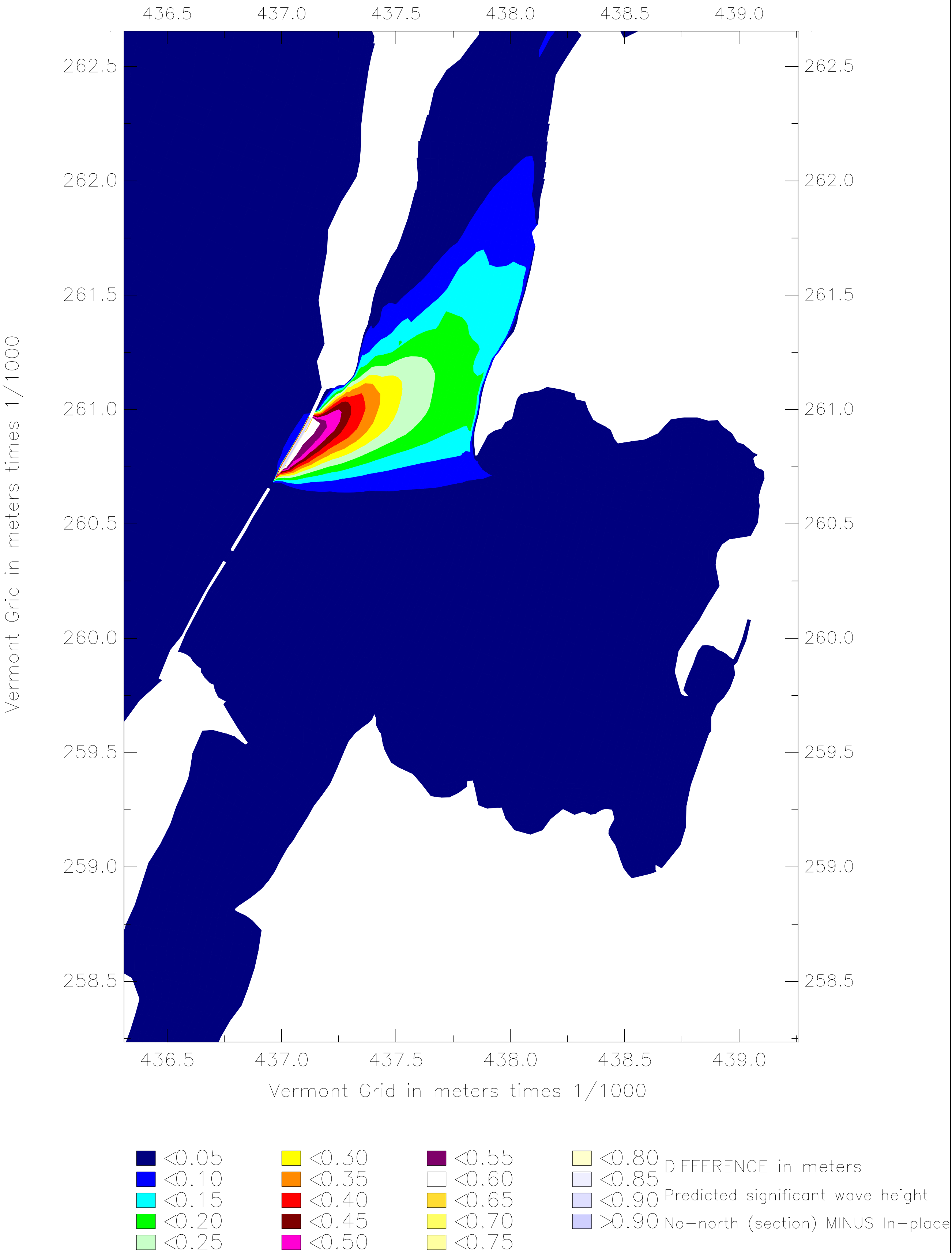


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 25	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from Southwest at 30 mph	Binkerd Environmental	December 2007

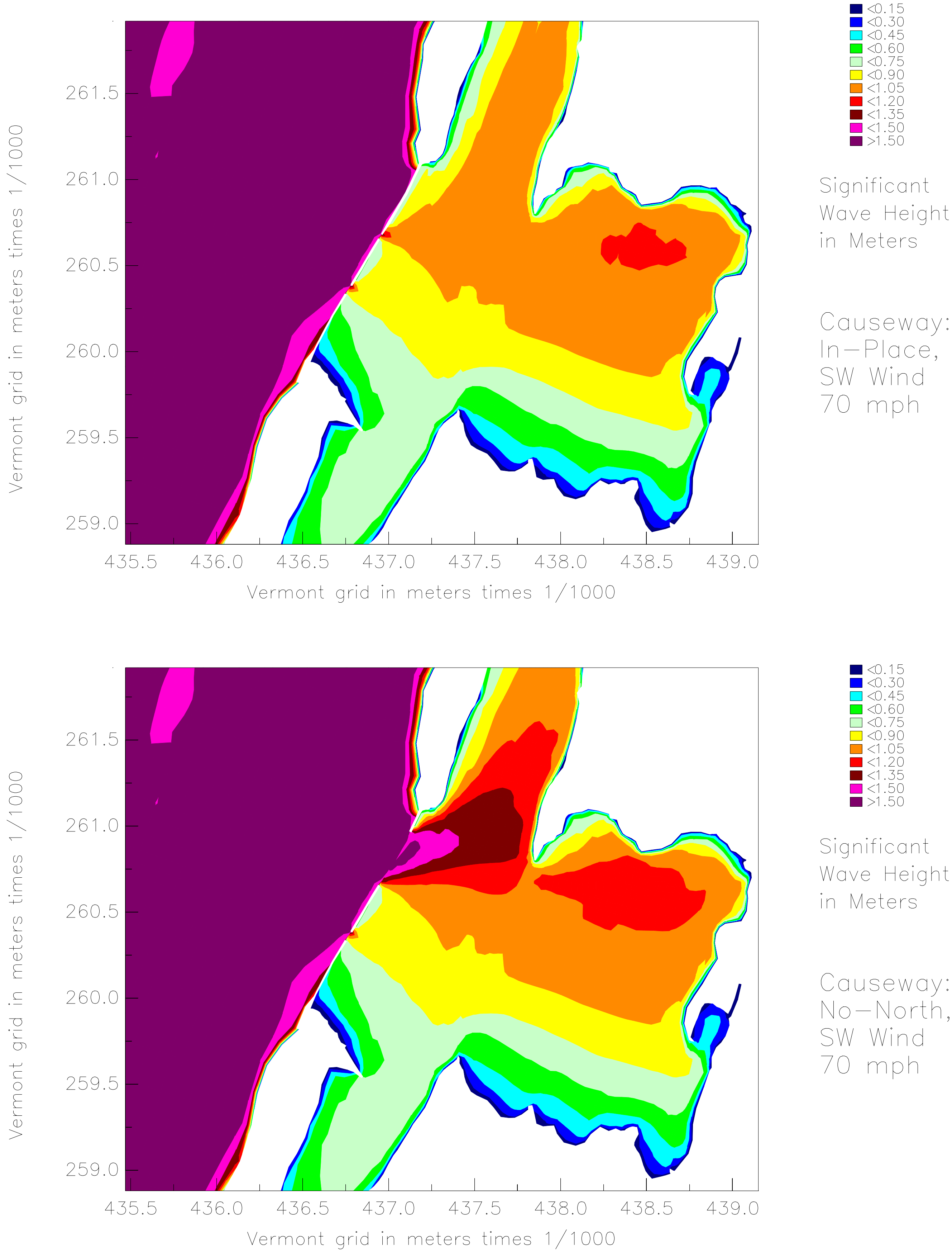




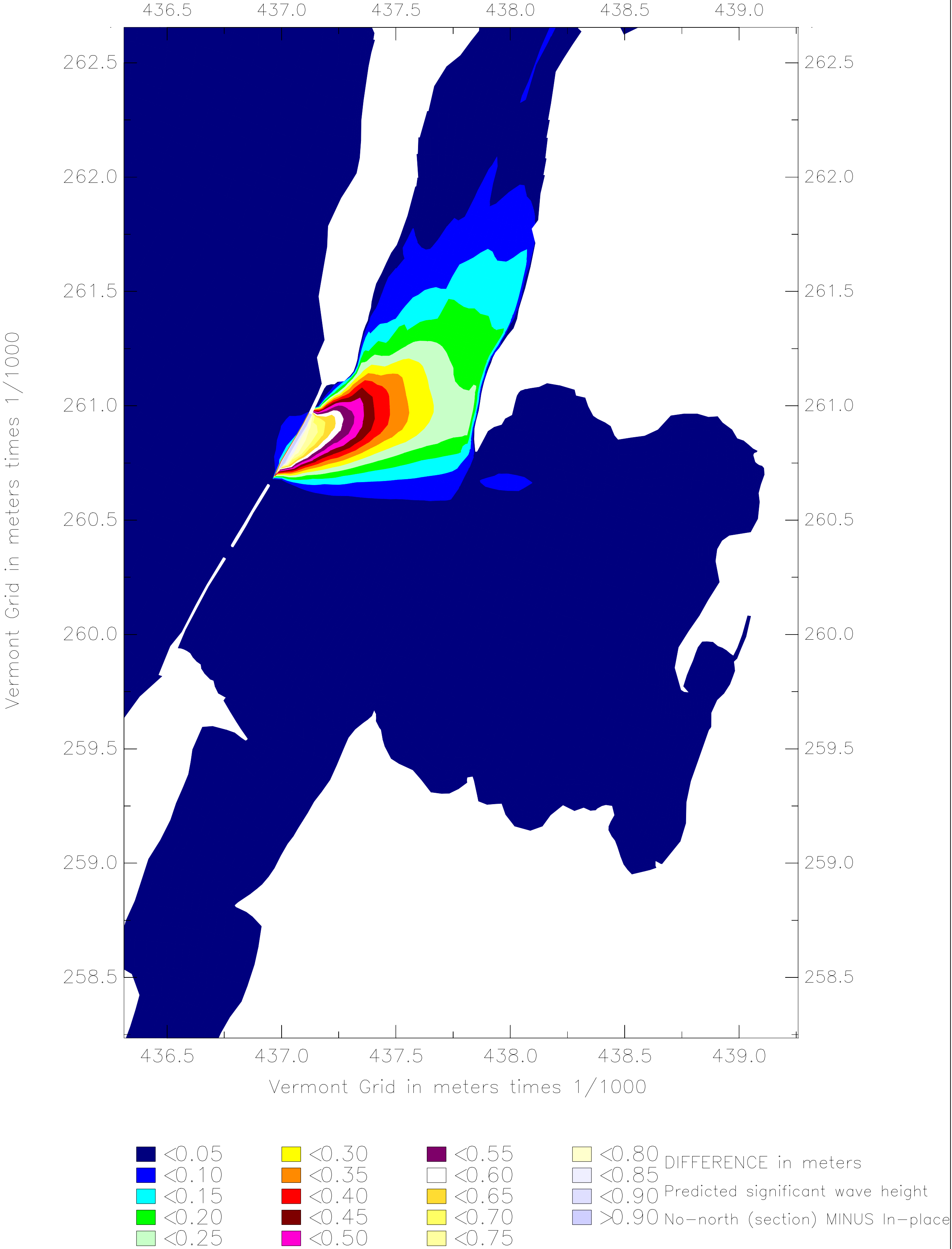
Top – Significant Wave Height (meters) – Causeway In-Place Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 26	Carry Bay Wave Study
	Significant Wave Height	
Wind from Southwest at 50 mph	Binkerd Environmental	December 2007



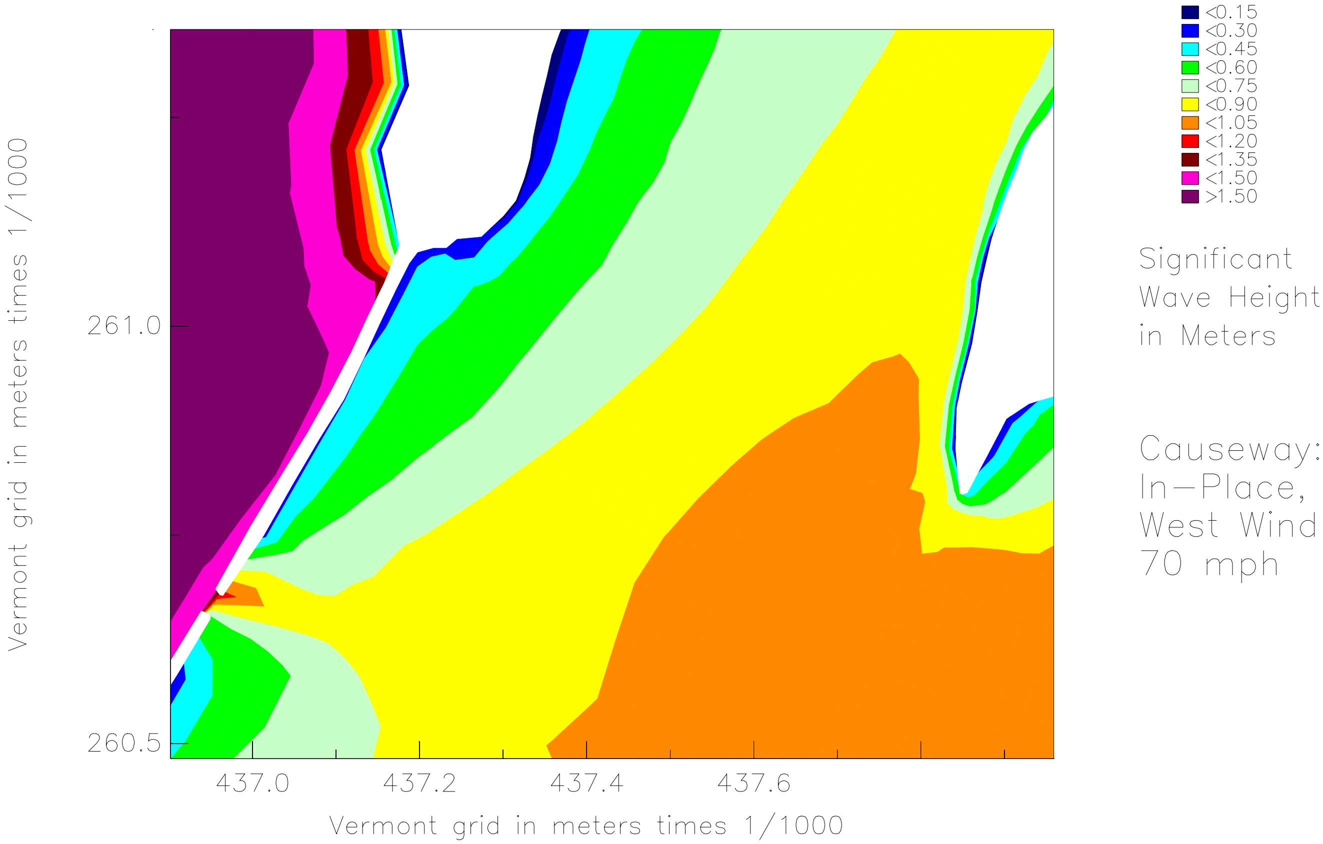
Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 27	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from Southwest at 50 mph	Binkerd Environmental	December 2007

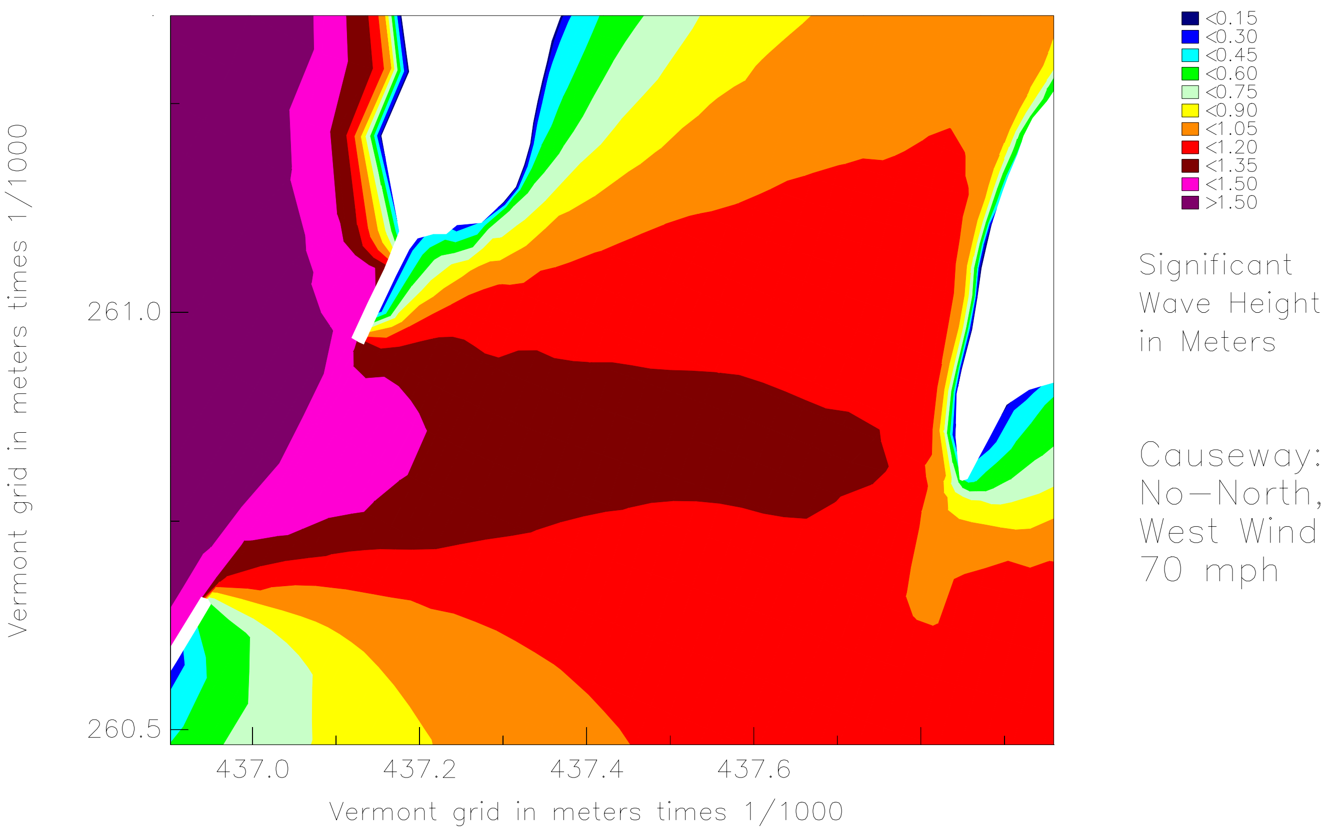


Top – Significant Wave Height (meters) – Causeway In-Place Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 28	Carry Bay Wave Study
	Significant Wave Height	
Wind from Southwest at 70 mph	Binkerd Environmental	December 2007

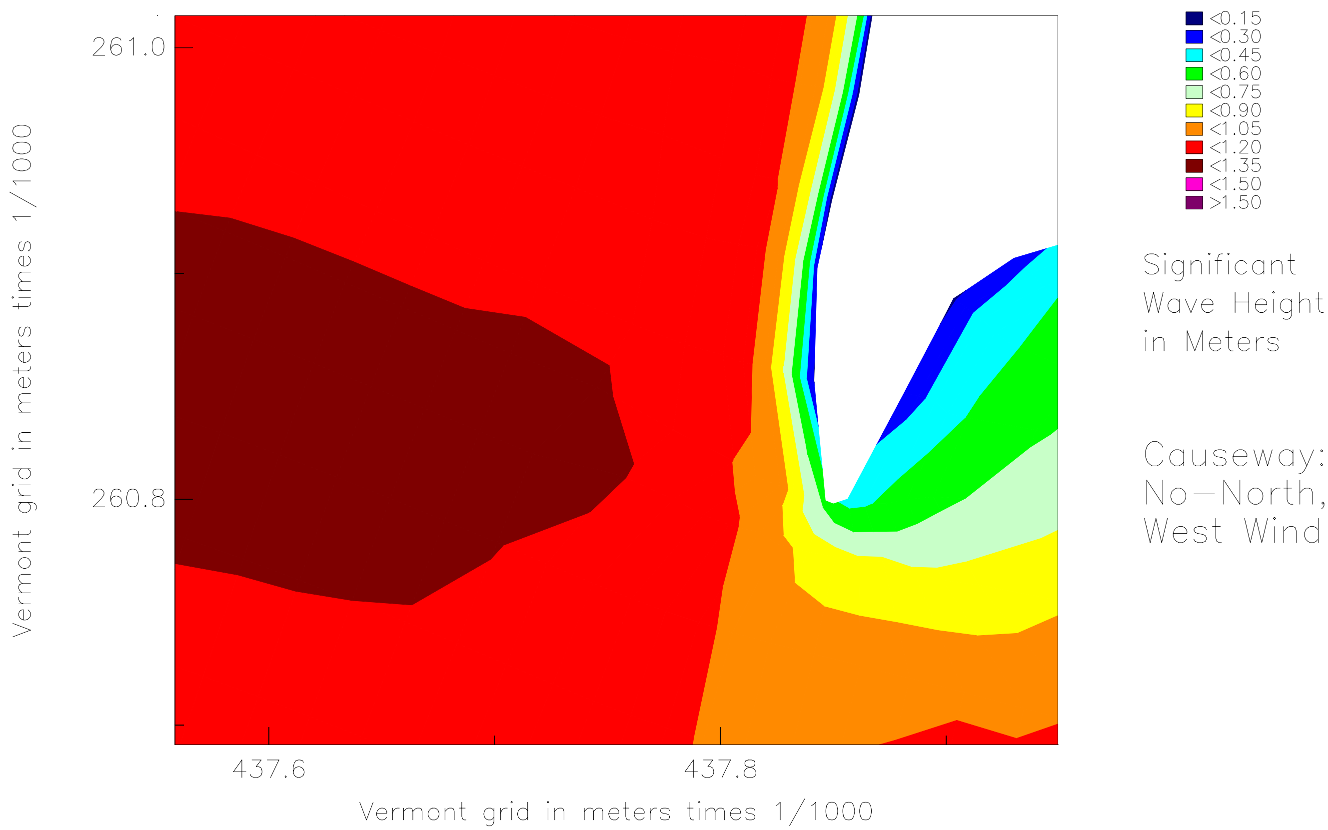


Colors represent DIFFERENCE in predicted significant wave heights in meters between no-north section and in-place causeway predictions.	Figure 29	Carry Bay Wave Study
	Difference in predicted wave heights	
Wind from Southwest at 70 mph	Binkerd Environmental	December 2007

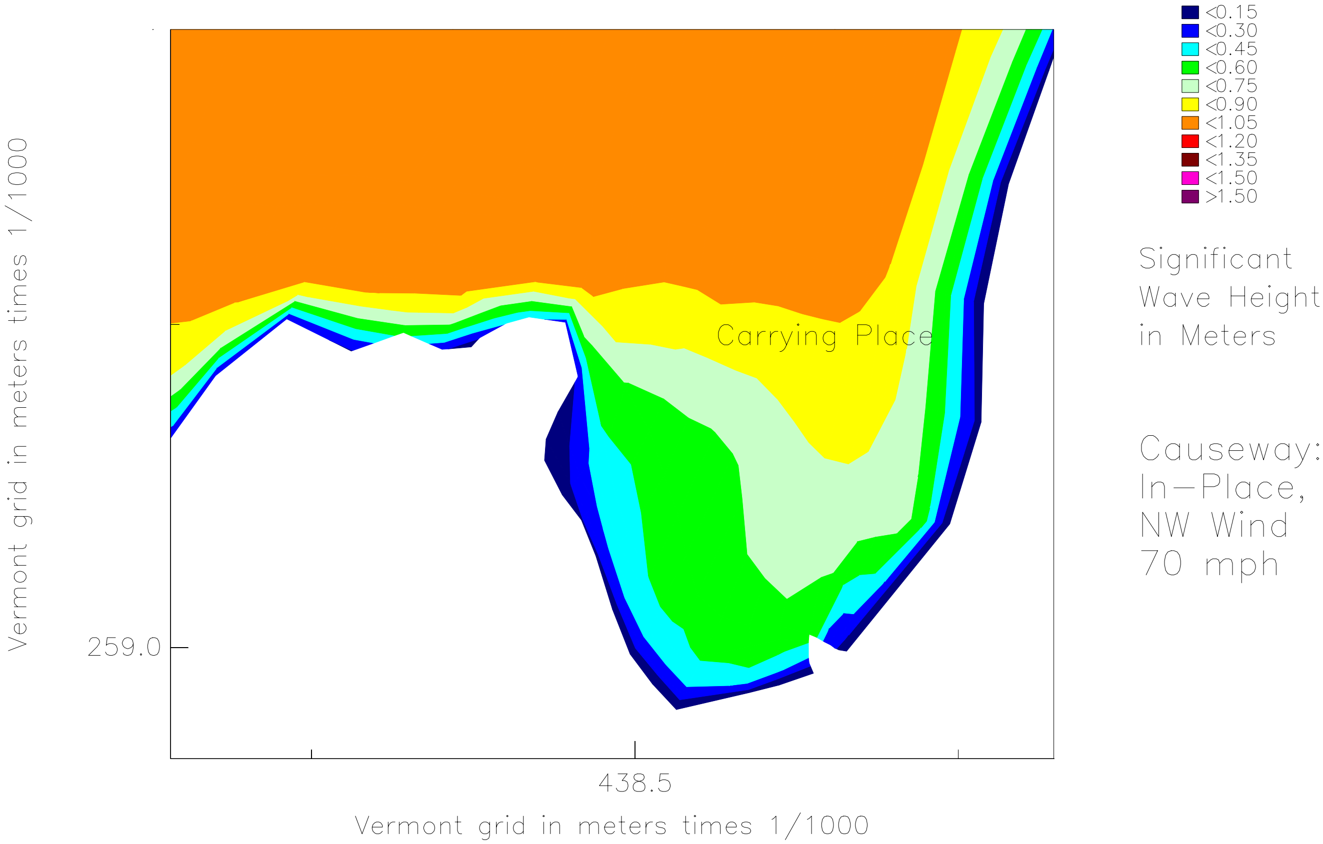


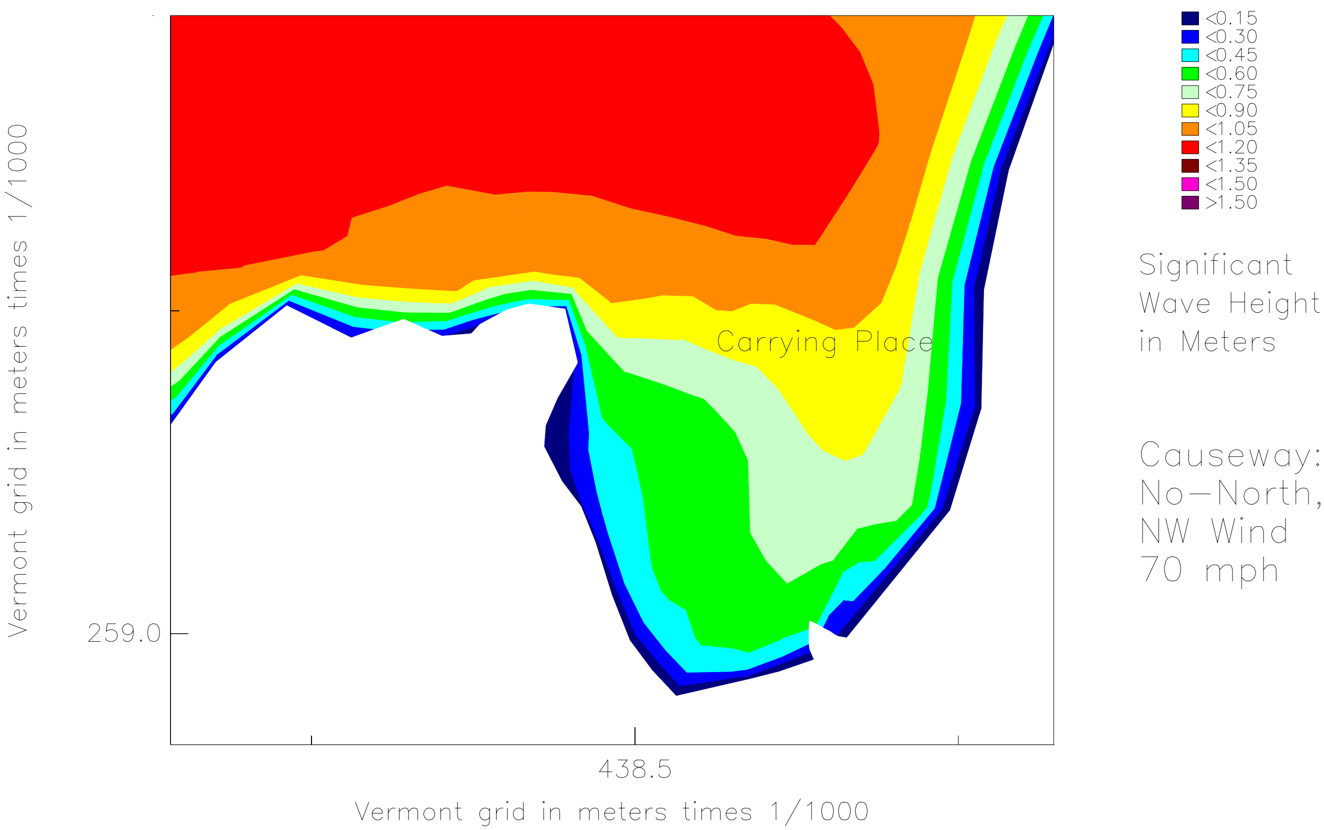


Top – Significant Wave Height (meters) – Causeway In-Place Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 30	Carry Bay Wave Study
	Significant Wave Height	
Causeway to Blockhouse Point – West Wind 70 mph	Binkerd Environmental	December 2007

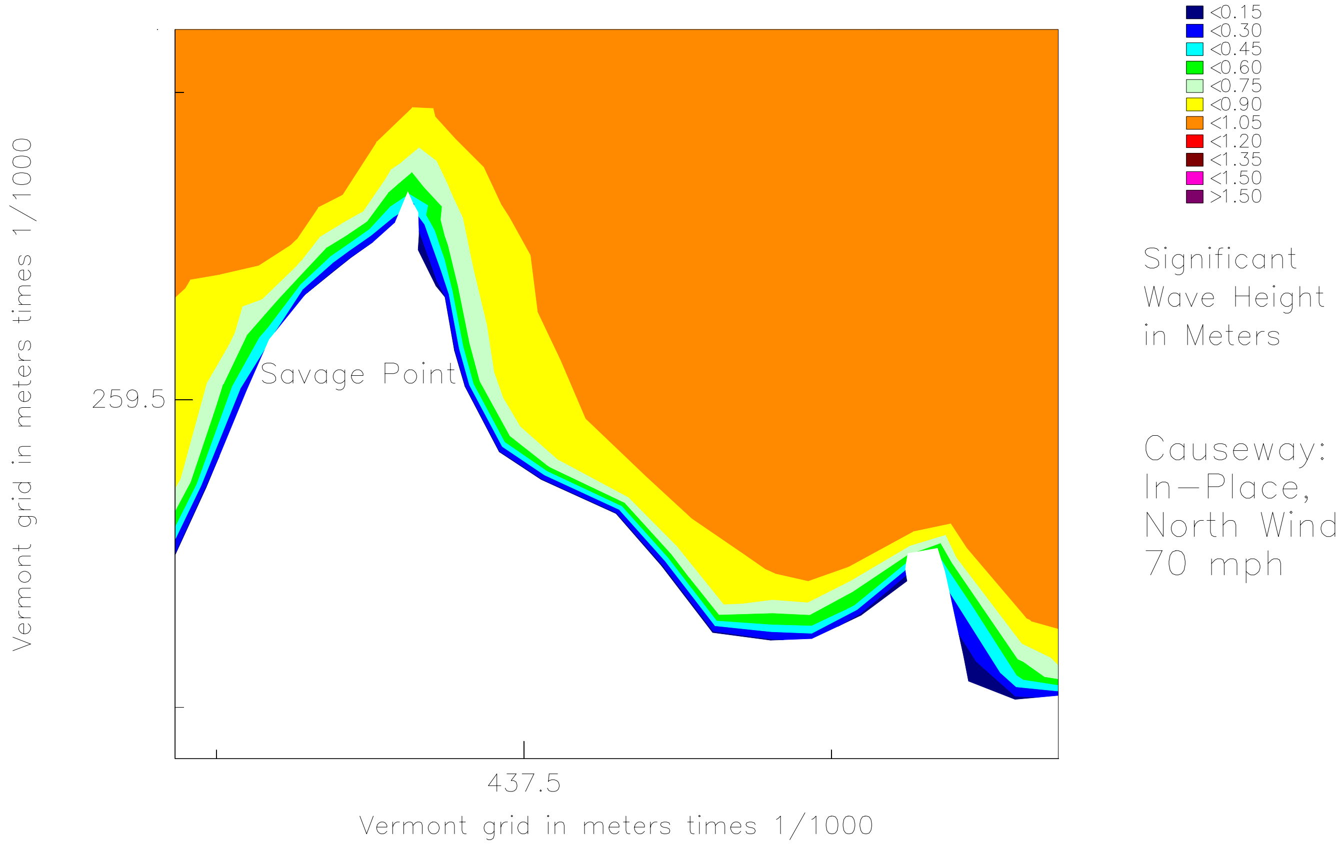


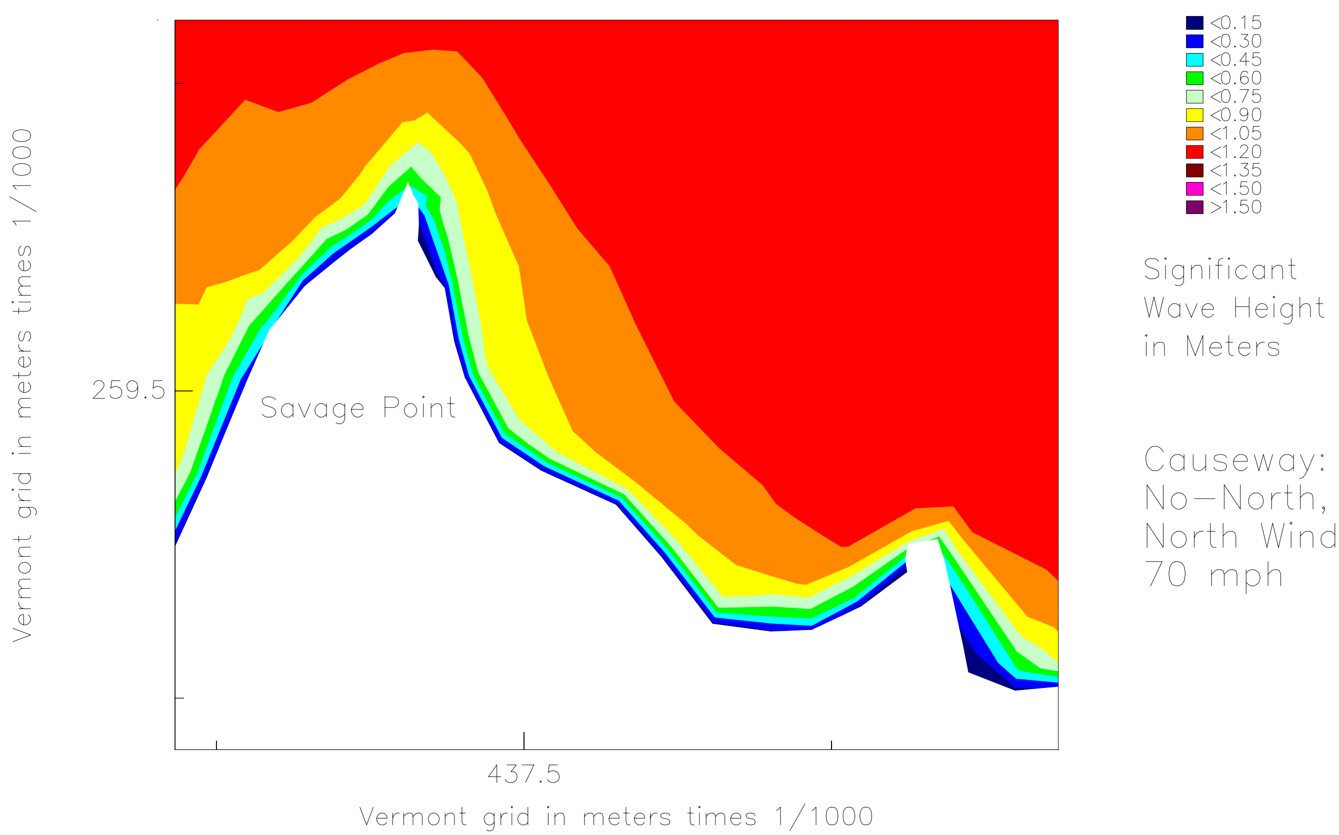
Top – Significant Wave Height (meters) – Causeway In-Place Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 31	Carry Bay Wave Study
	Significant Wave Height	
Close to Blockhouse Point – West Wind 70 mph	Binkerd Environmental	December 2007



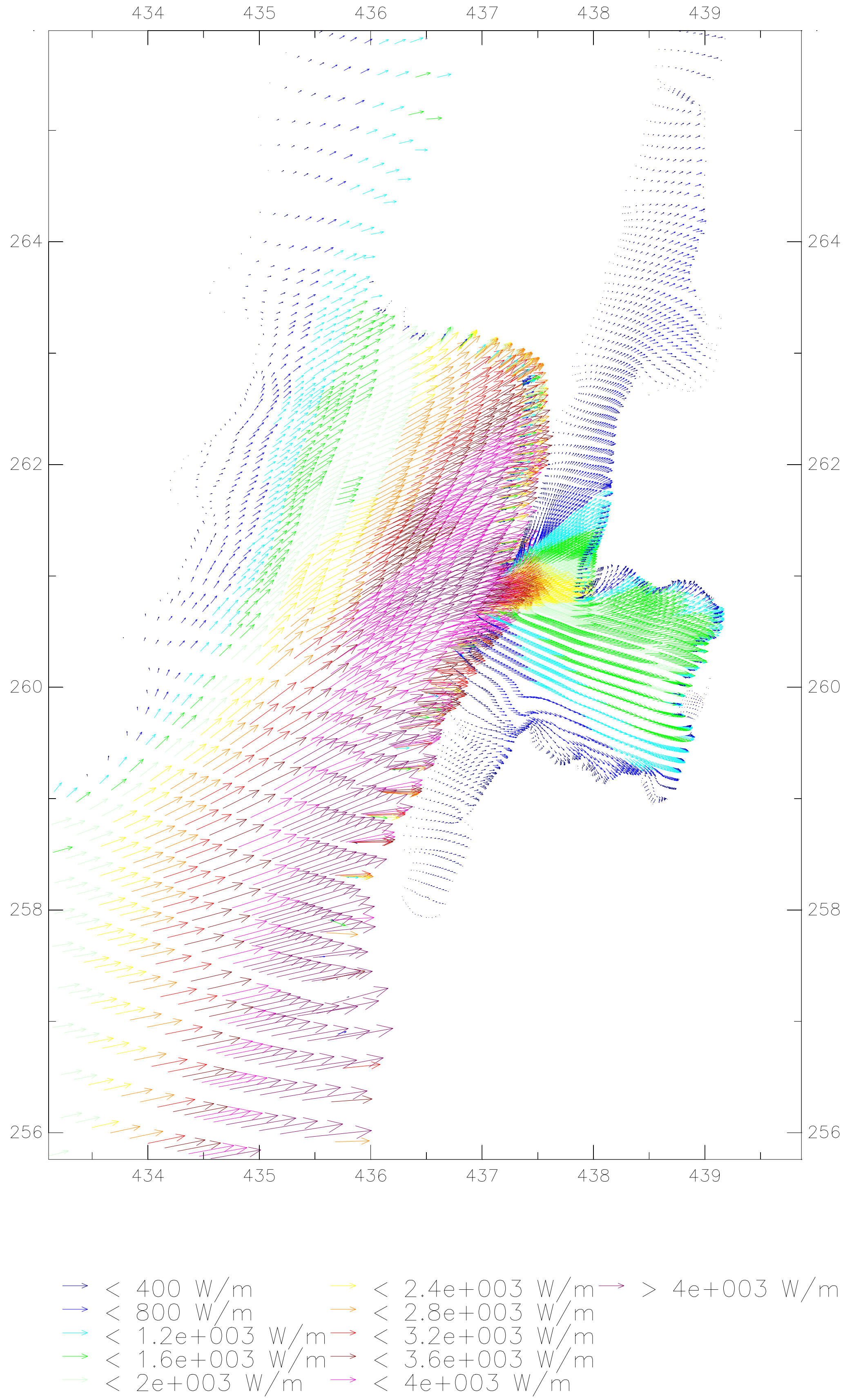


Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 32	Carry Bay Wave Study
	Significant Wave Height	
Southeast Area of Carry Bay – Wind NW 70 mph	Binkerd Environmental	December 2007





Top – Significant Wave Height (meters) – Causeway In–Place Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 33	Carry Bay Wave Study
	Significant Wave Height	
Near Savage Point – North Wind 70 mph	Binkerd Environmental	December 2007



Energy vectors ploted as different colors for various ranges of energy transport in Watts per meter of wave front.
North Section removed (No-North)

Figure 34

Carry Bay Wave Study

Energy Transport W/m, nn 70 W

Energy Tramsport in Watts/meter for 70 mph West Wind

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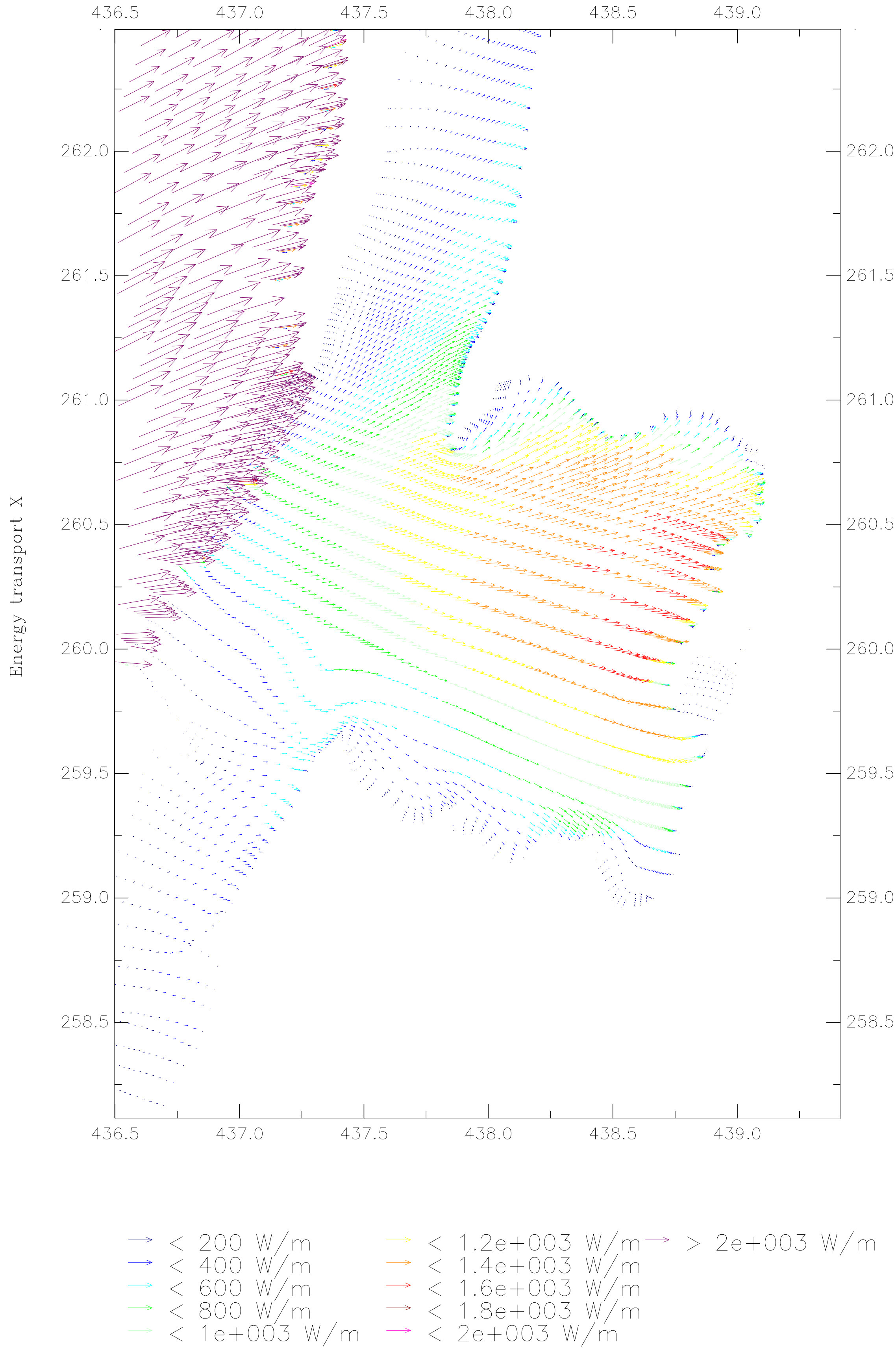
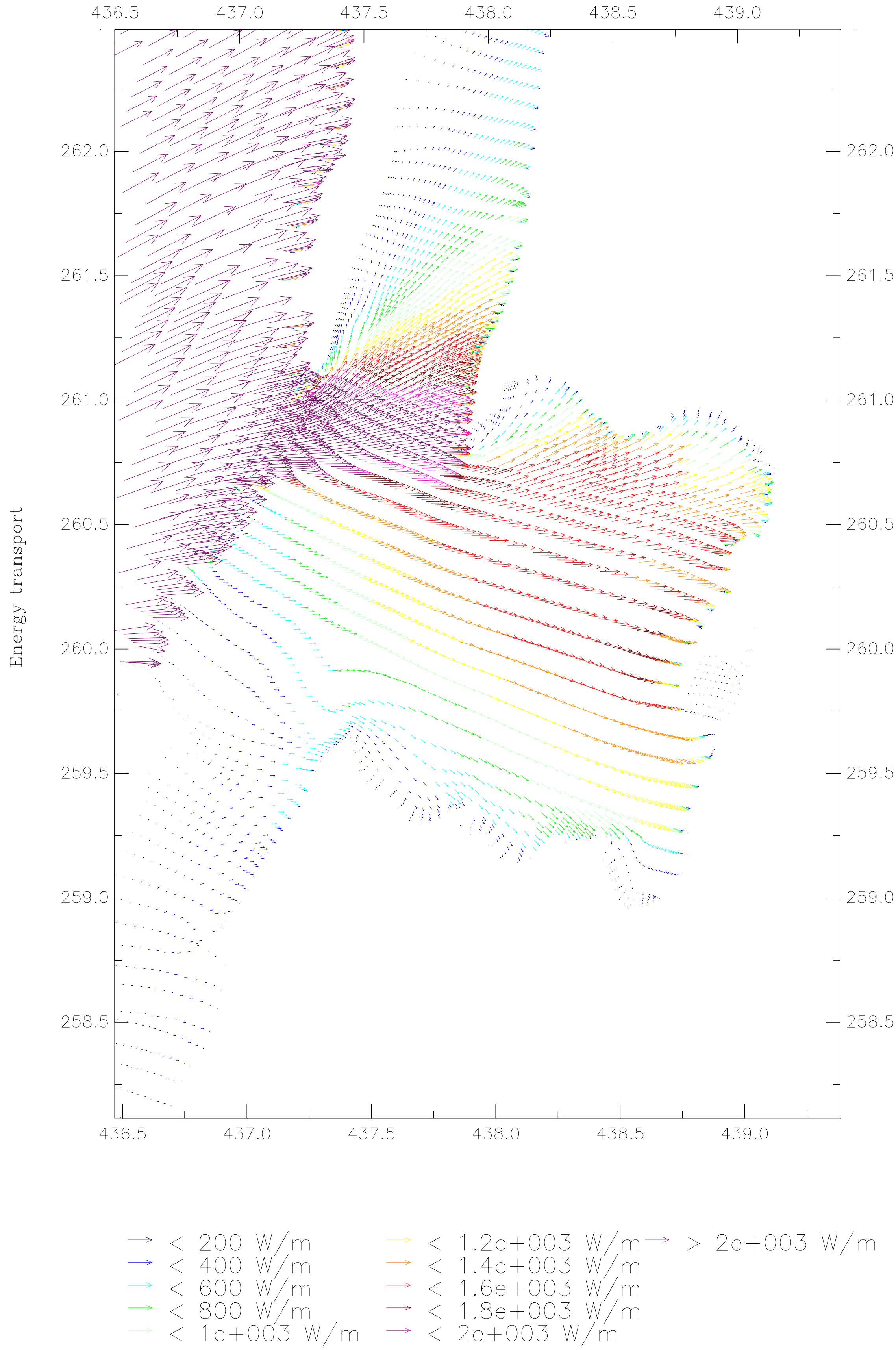
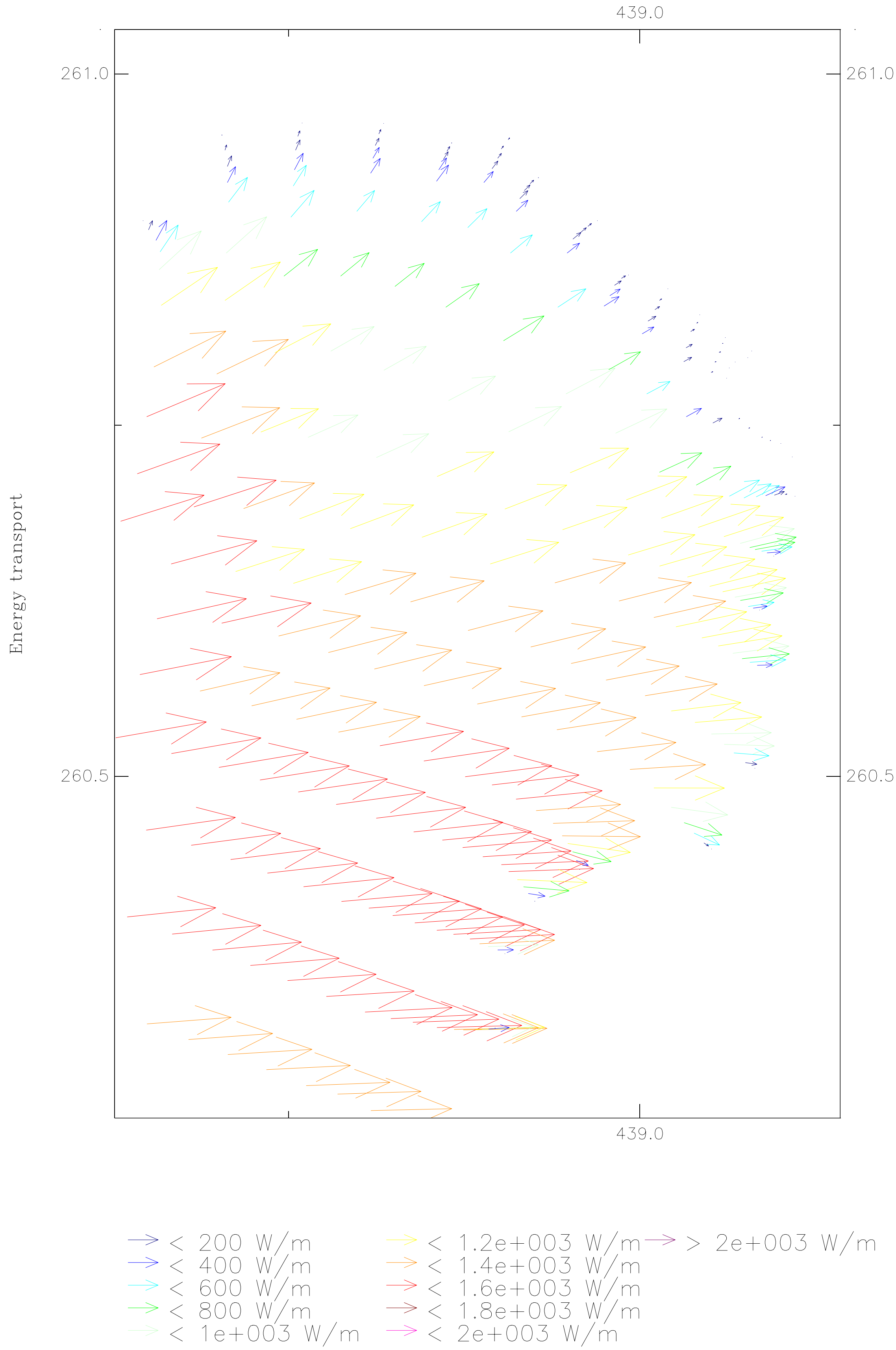
December 2007



Energy transport vectors for 70 mph west wind with causeway in–place. Compare with Figure 36 – north section removed.	Figure 35	Carry Bay Wave Study
	Energy Transport W/m	
Energy Transport in Watts/meter of wave front	Binkerd Environmental	December 2007



Energy transport vectors for 70 mph west wind with the north section of the causeway removed. Compare with Figure 35 – causeway in-place.	Figure 36	Carry Bay Wave Study
	Energy Transport W/m	
Energy Tramsport in Watts/meter of wave front	Binkerd Environmental	December 2007



Energy transport depicted in northeast corner of Carry Bay. This figure shows the loss of wave energy as a wave approaches the sloping bottom near shore (bottom slope 1:10)

Figure 37

Carry Bay Wave Study

Energy Transport W/m

Energy Tramsport in Watts/meter of wave front

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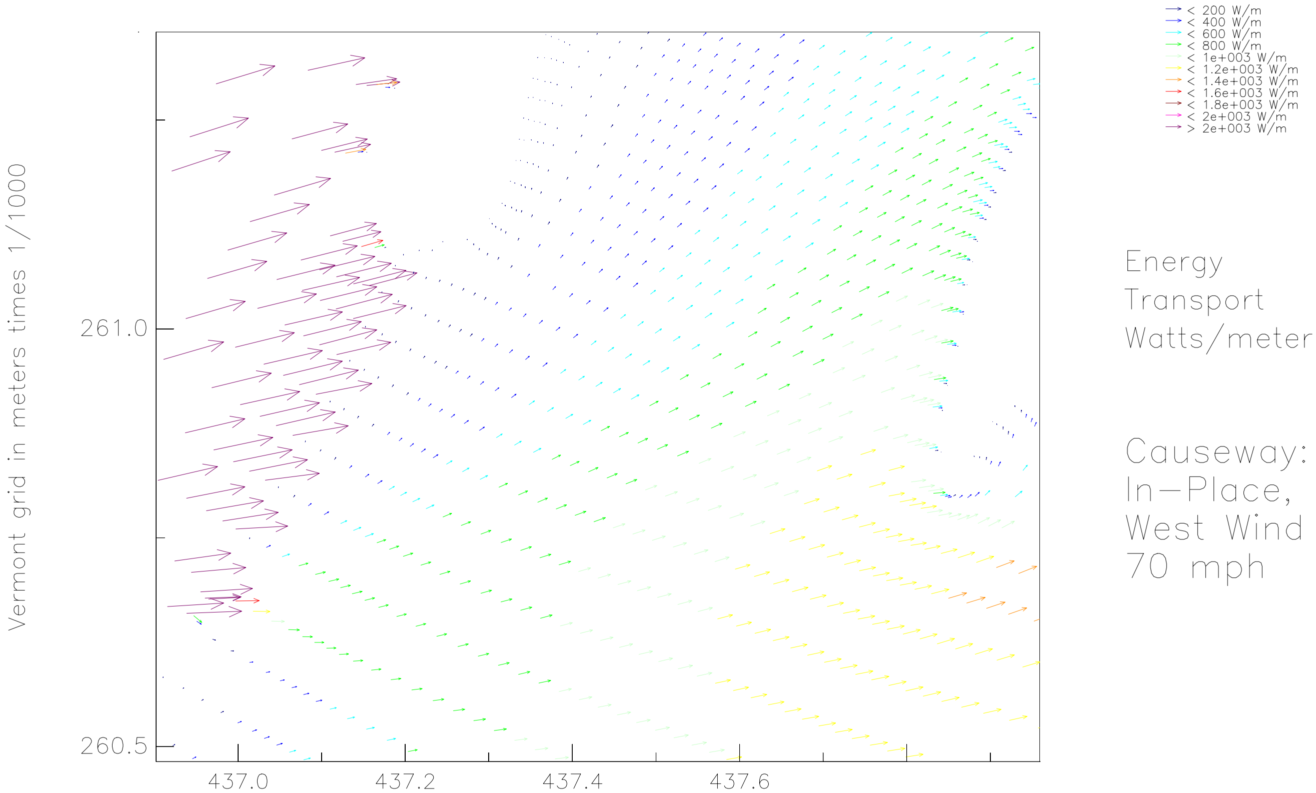
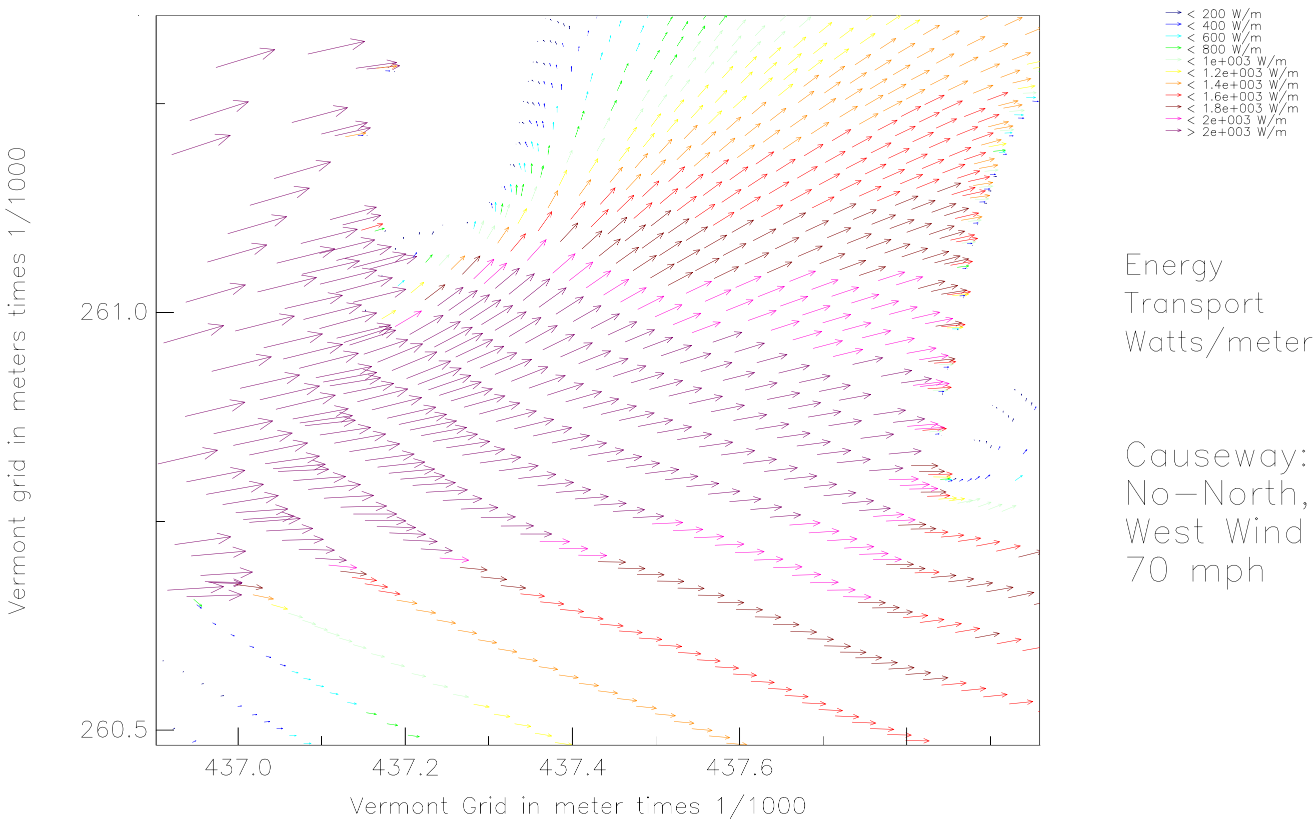
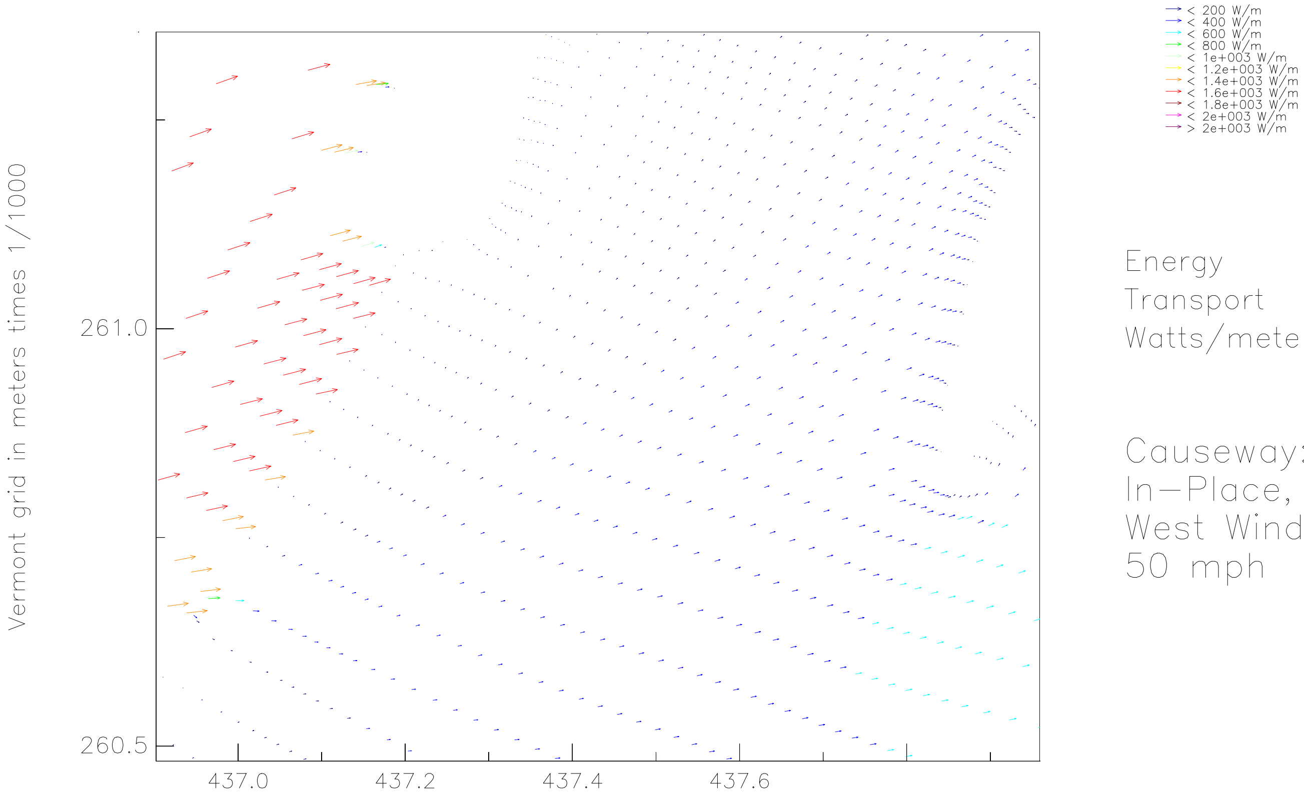
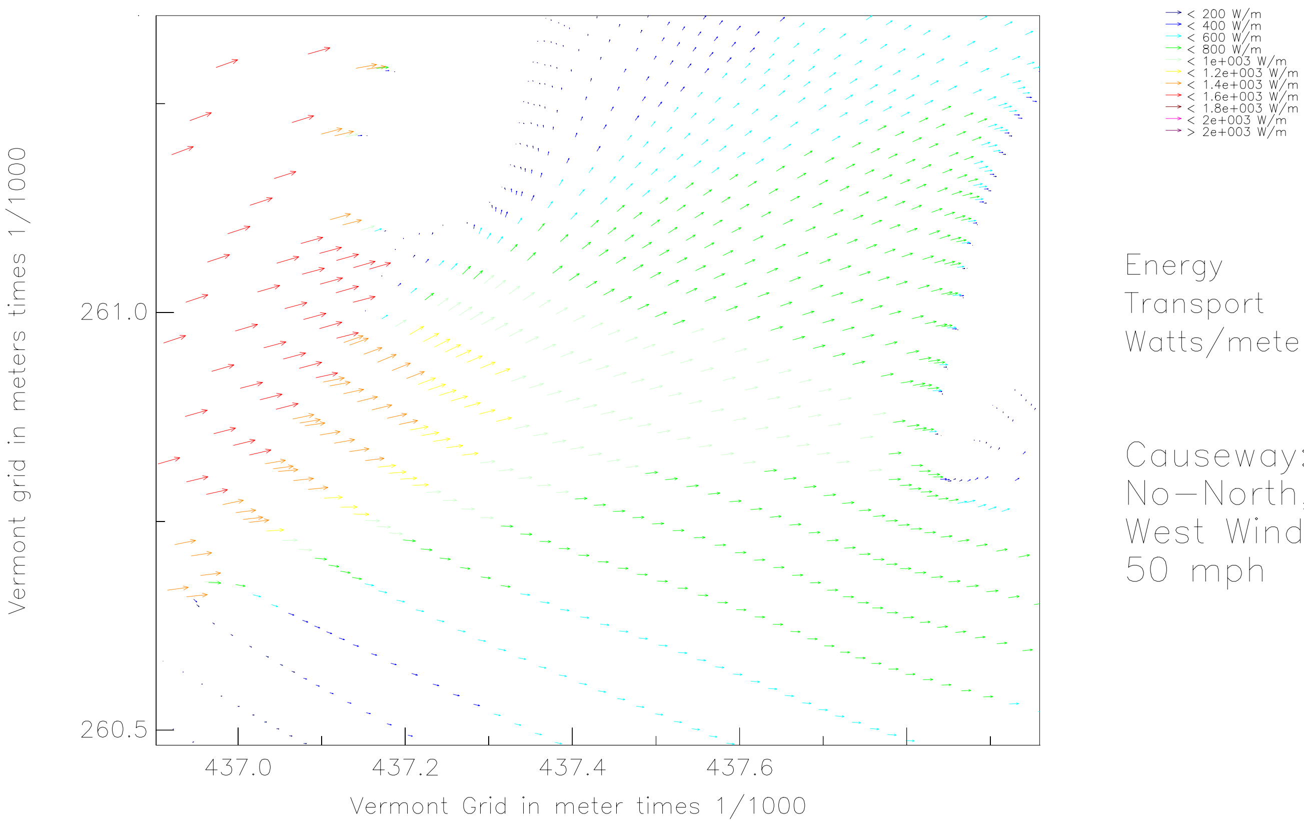


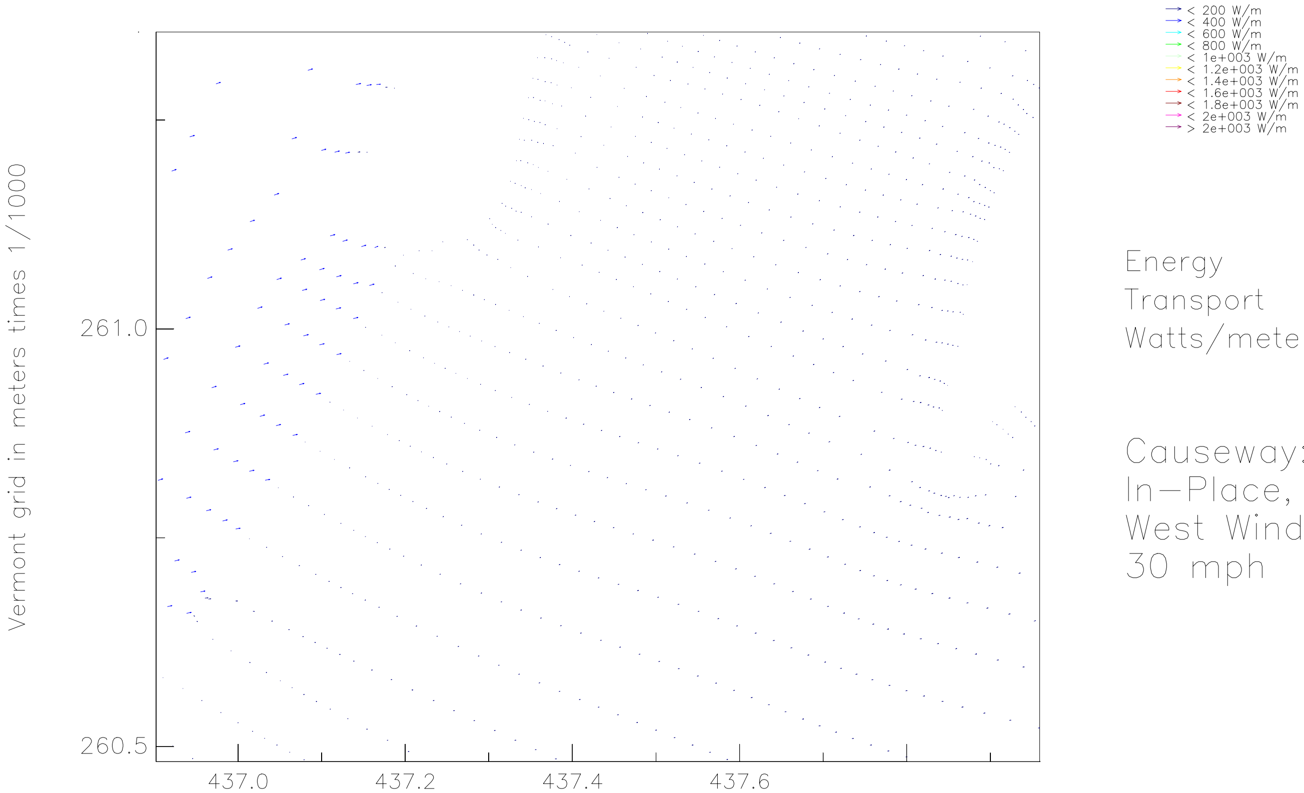


Top – Energy transport (W/m) – Causeway In-place Bottom – Energy Transport (W/m) – No-North Section Wind from the West at 70 mph	Figure 38	Carry Bay Wave Study
	Energy Transport W/m – 70 mph	
Energy Tramsport in Watts/meter of wave front	Binkerd Environmental	December 2007



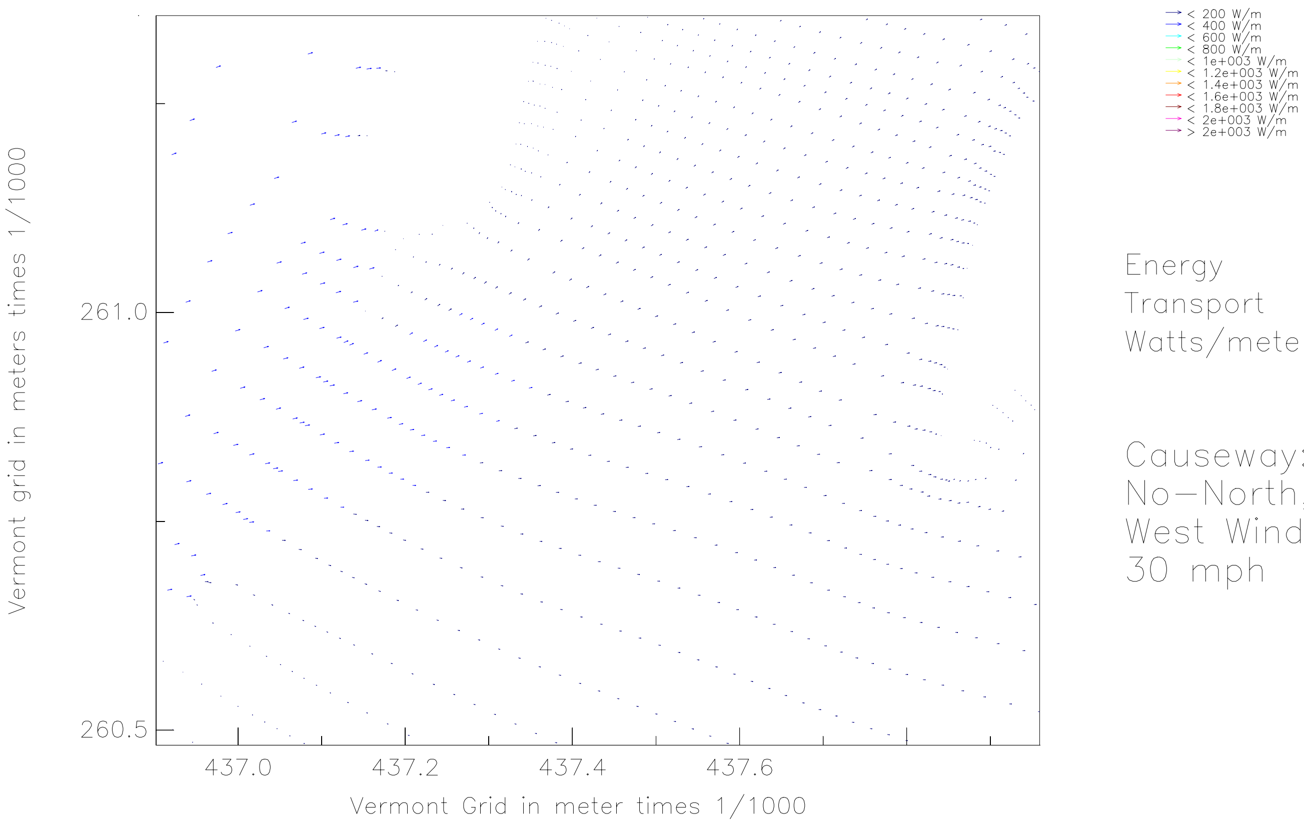


Top – Energy transport (W/m) – Causeway In–place Bottom – Energy Transport (W/m) – No–North Section Wind from the West at 50 mph	Figure 39	Carry Bay Wave Study
	Energy Transport W/m – 50 mph	
Energy Tramsport in Watts/meter of wave front	Binkerd Environmental	December 2007



Energy
Transport
Watts/meter

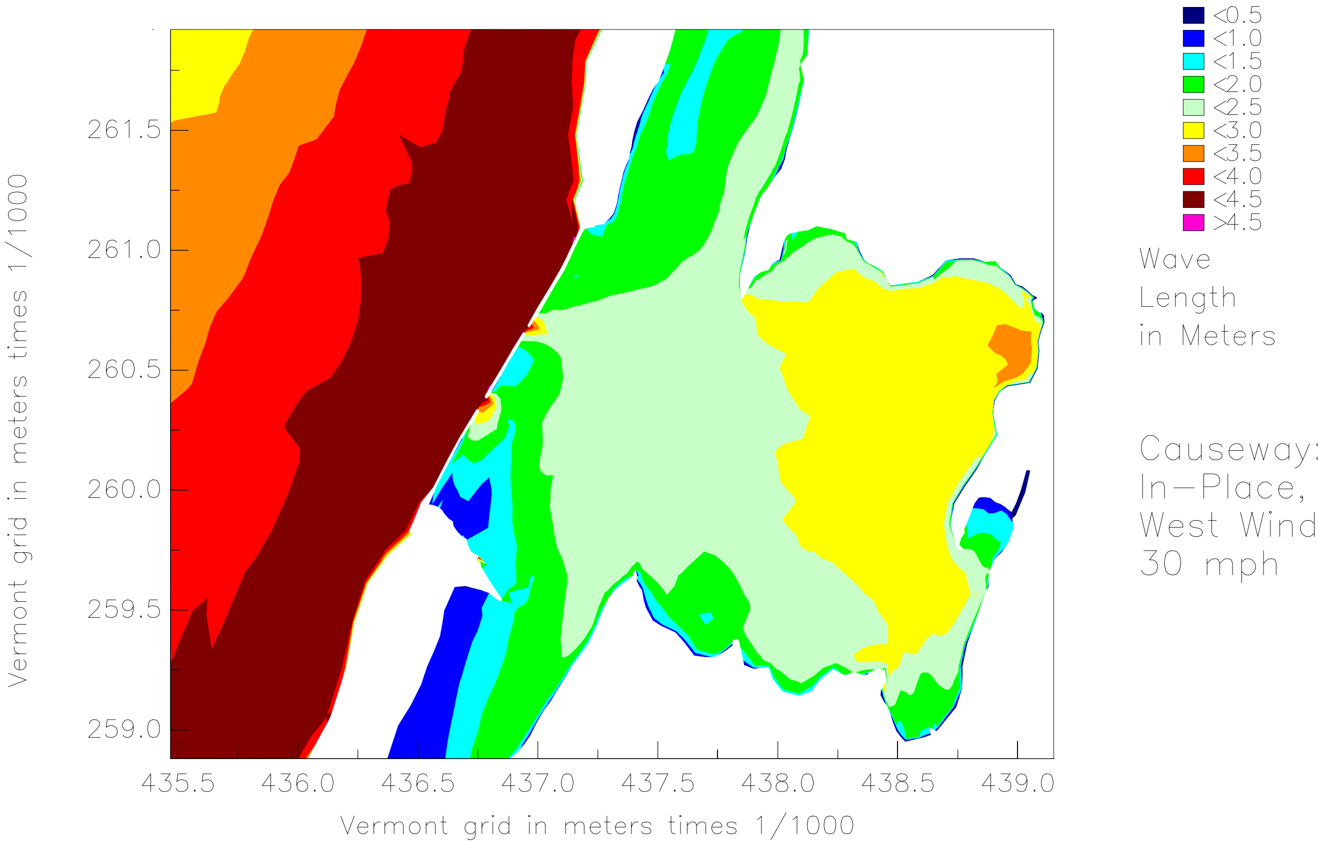
Causeway:
In–Place,
West Wind
30 mph

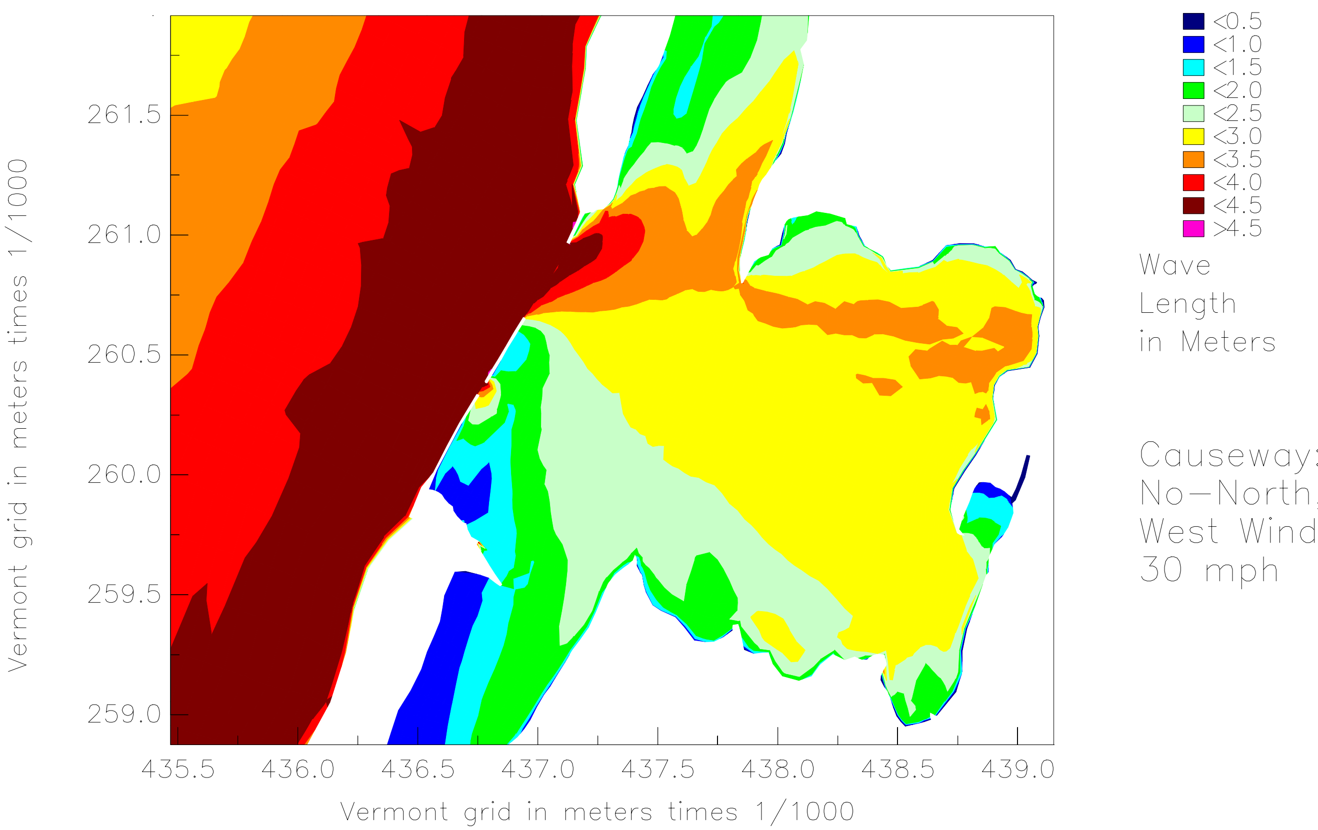


Energy
Transport
Watts/meter

Causeway:
No–North,
West Wind
30 mph

Top – Energy transport (W/m) – Causeway In–place Bottom – Energy Transport (W/m) – No–North Section Wind from the West at 30 mph	Figure 40	Carry Bay Wave Study
	Energy Transport W/m – 30 mph	
Energy Tramsport in Watts/meter of wave front	Binkerd Environmental	December 2007





Top – Wave Length (meters) – Causeway In–Place
Bottom – Wave Length (meters) – No–North Section
See color scale for wave length information

Figure 41

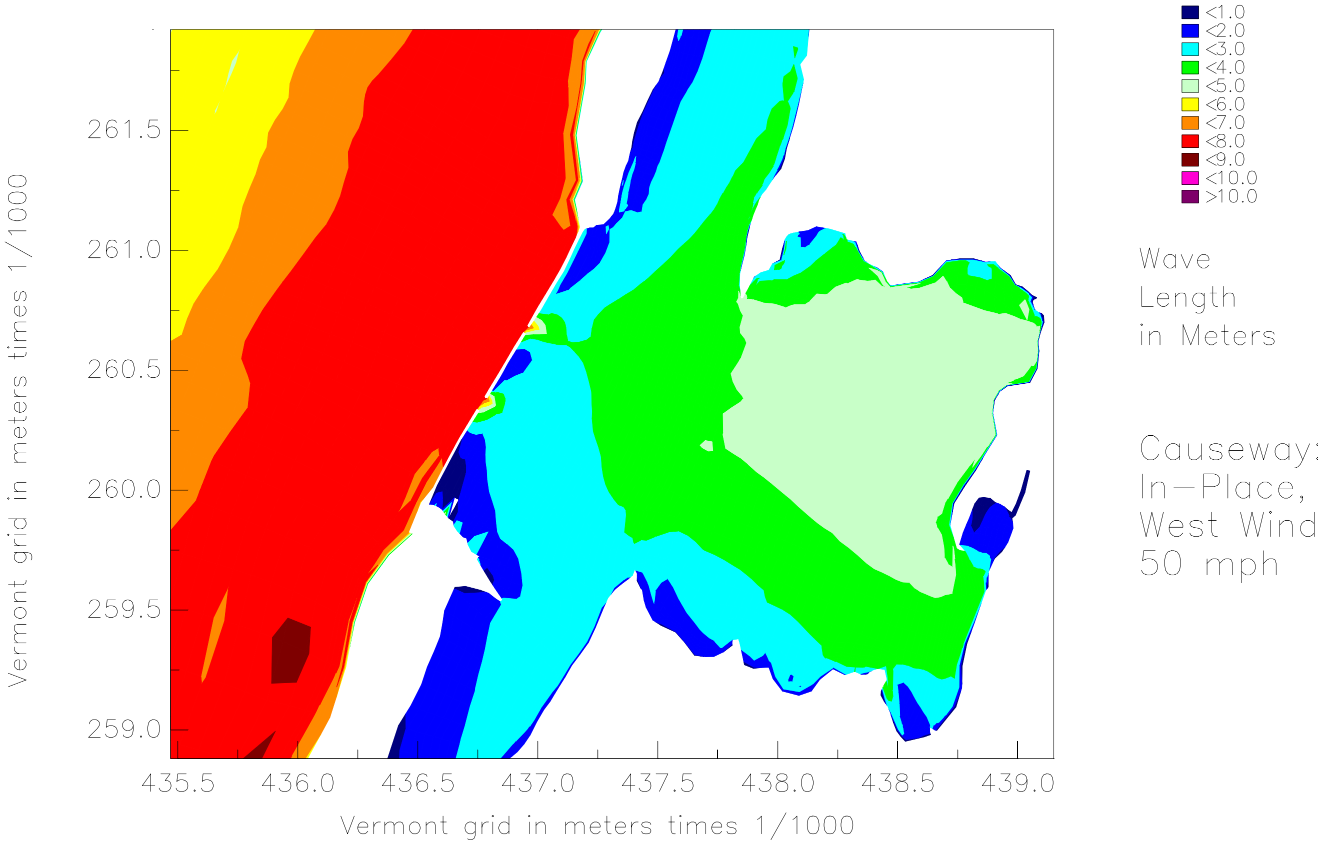
Carry Bay Wave Study

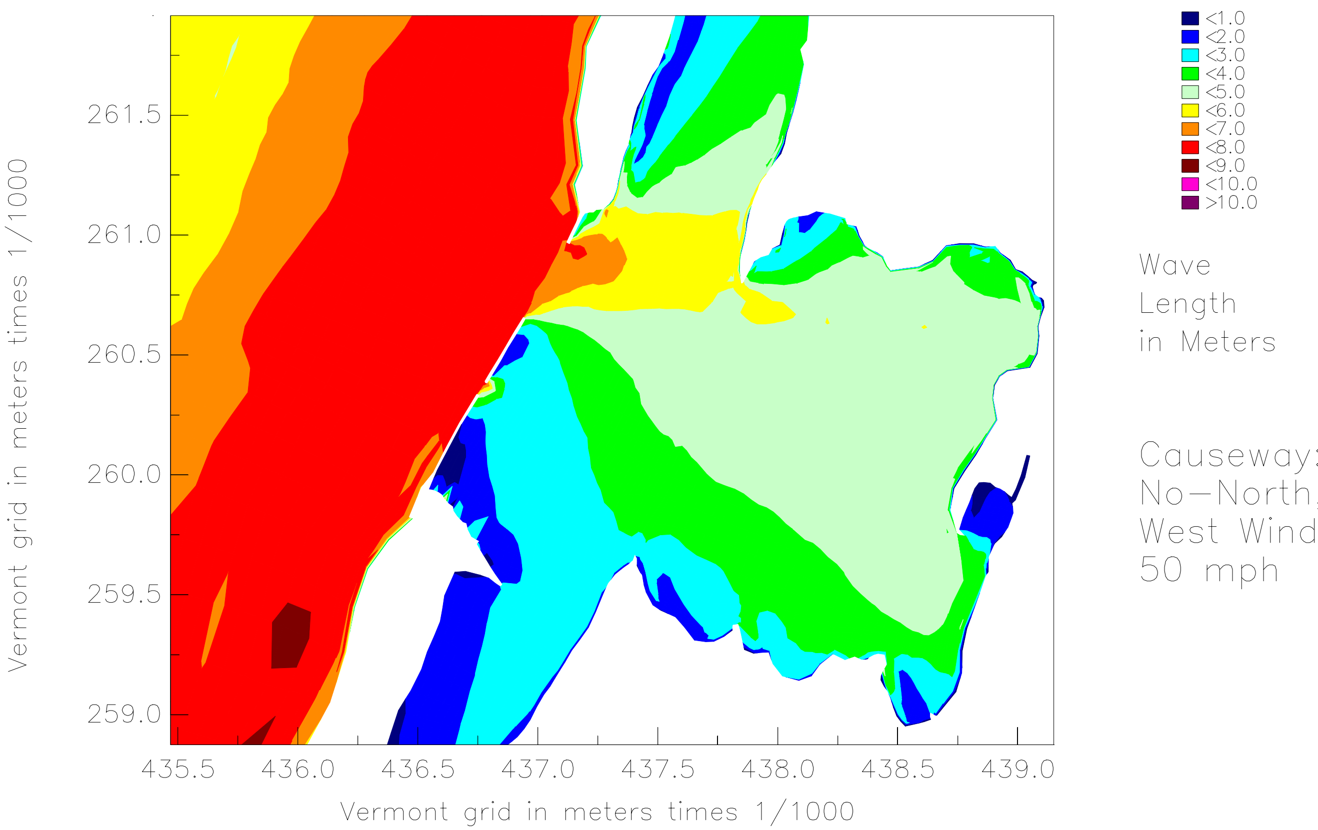
Wave Lenght, meters

Wind from West at 30 mph

Binkerd Environmental

December 2007





Top – Wave Length (meters) – Causeway In–Place
Bottom – Wave Length (meters) – No–North Section
See color scale for wave length information

Figure 42

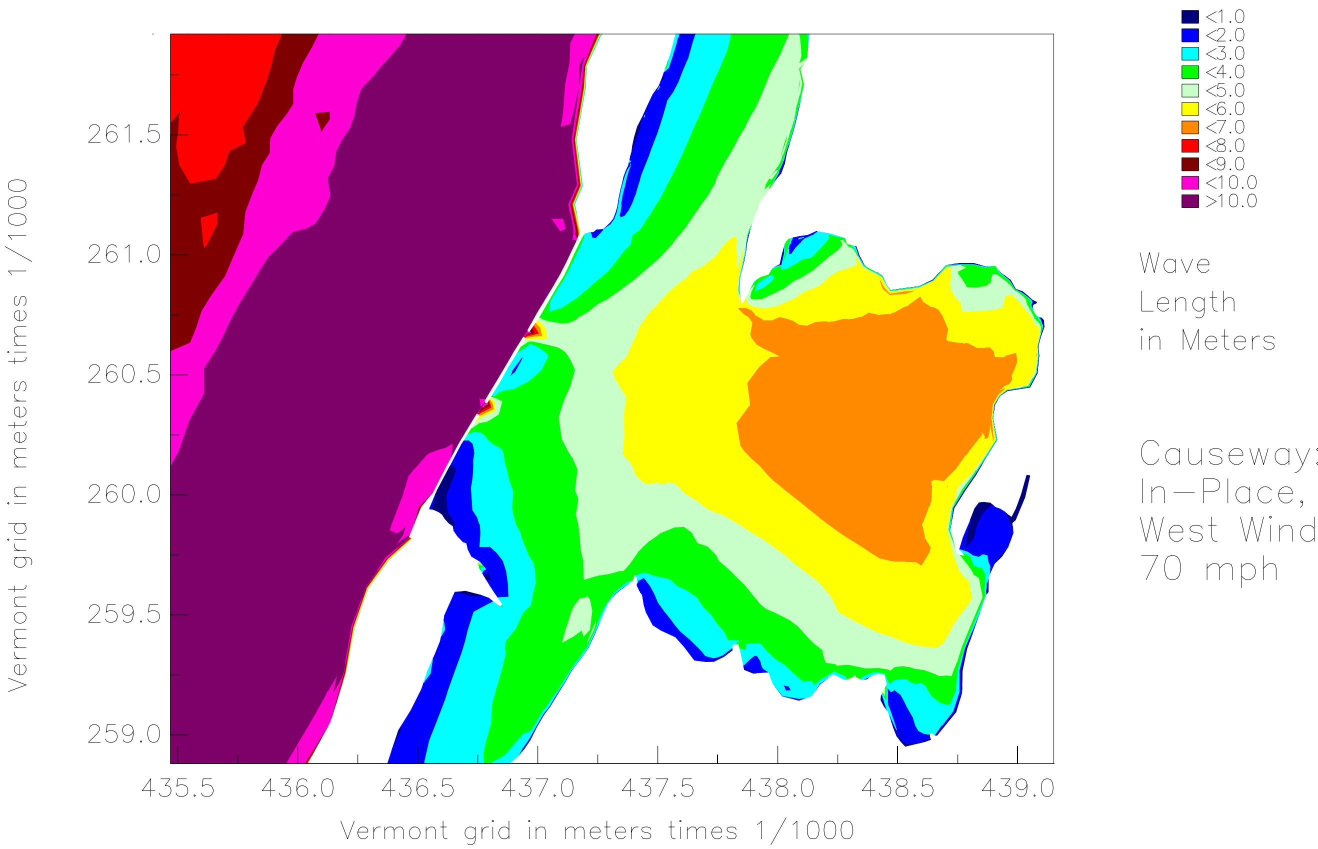
Carry Bay Wave Study

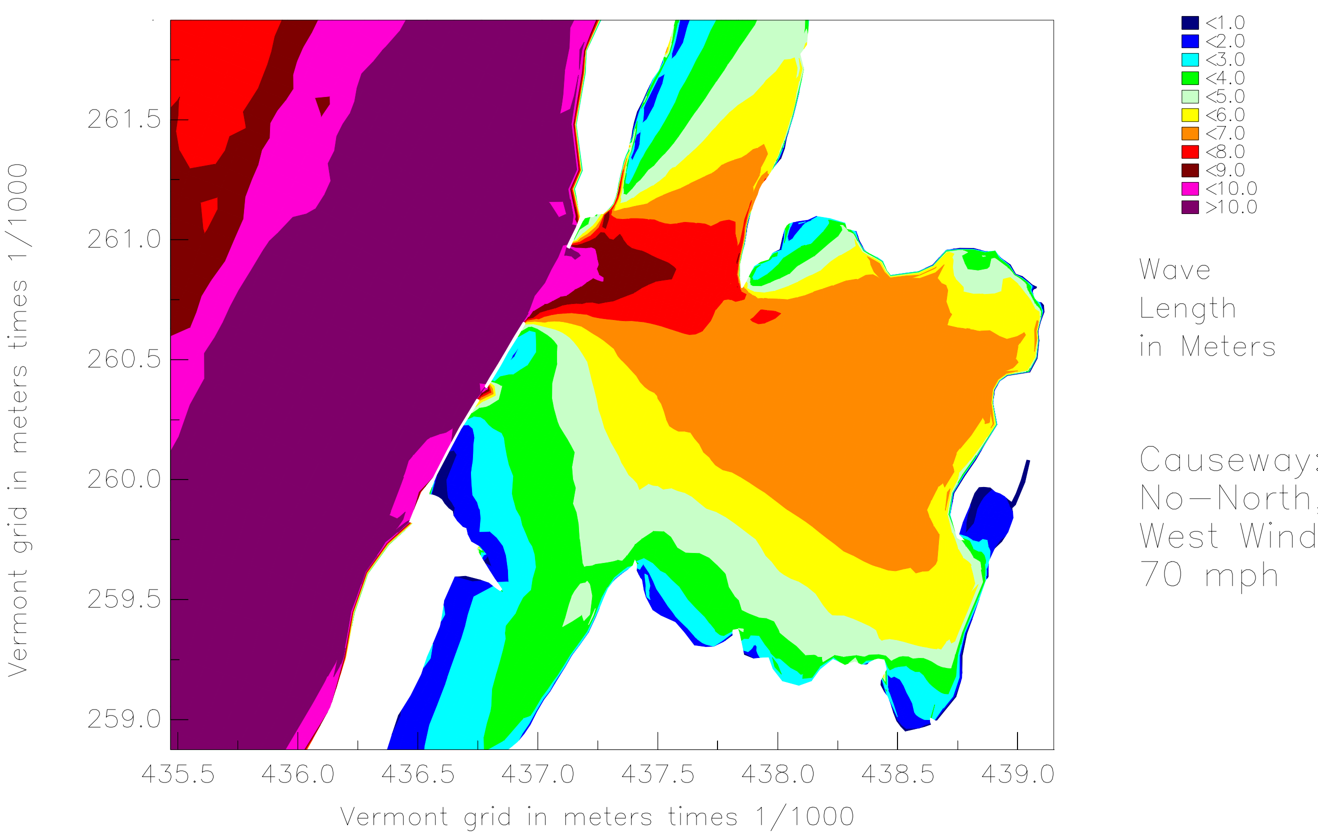
Wave Lenght, meters

Wind from West at 50 mph

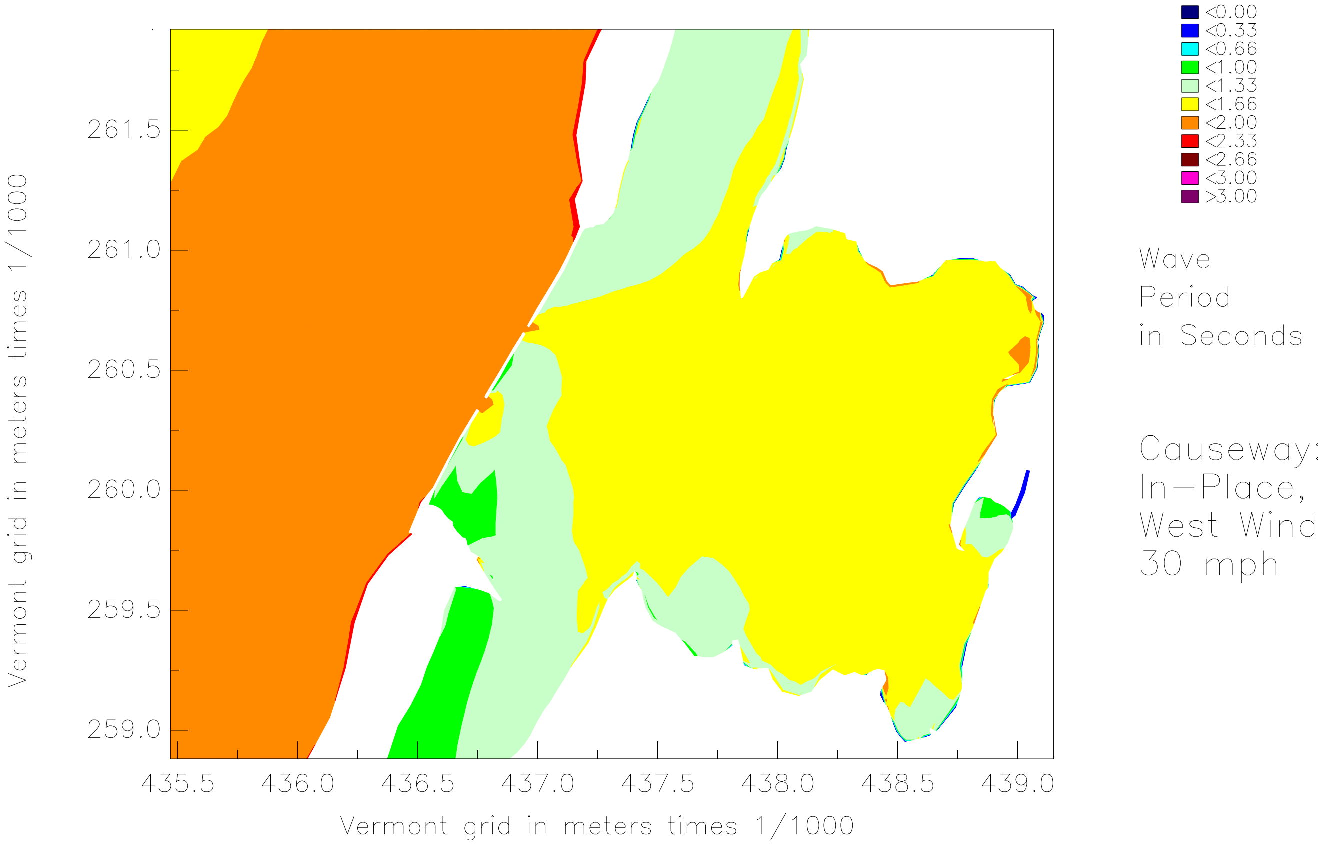
Binkerd Environmental

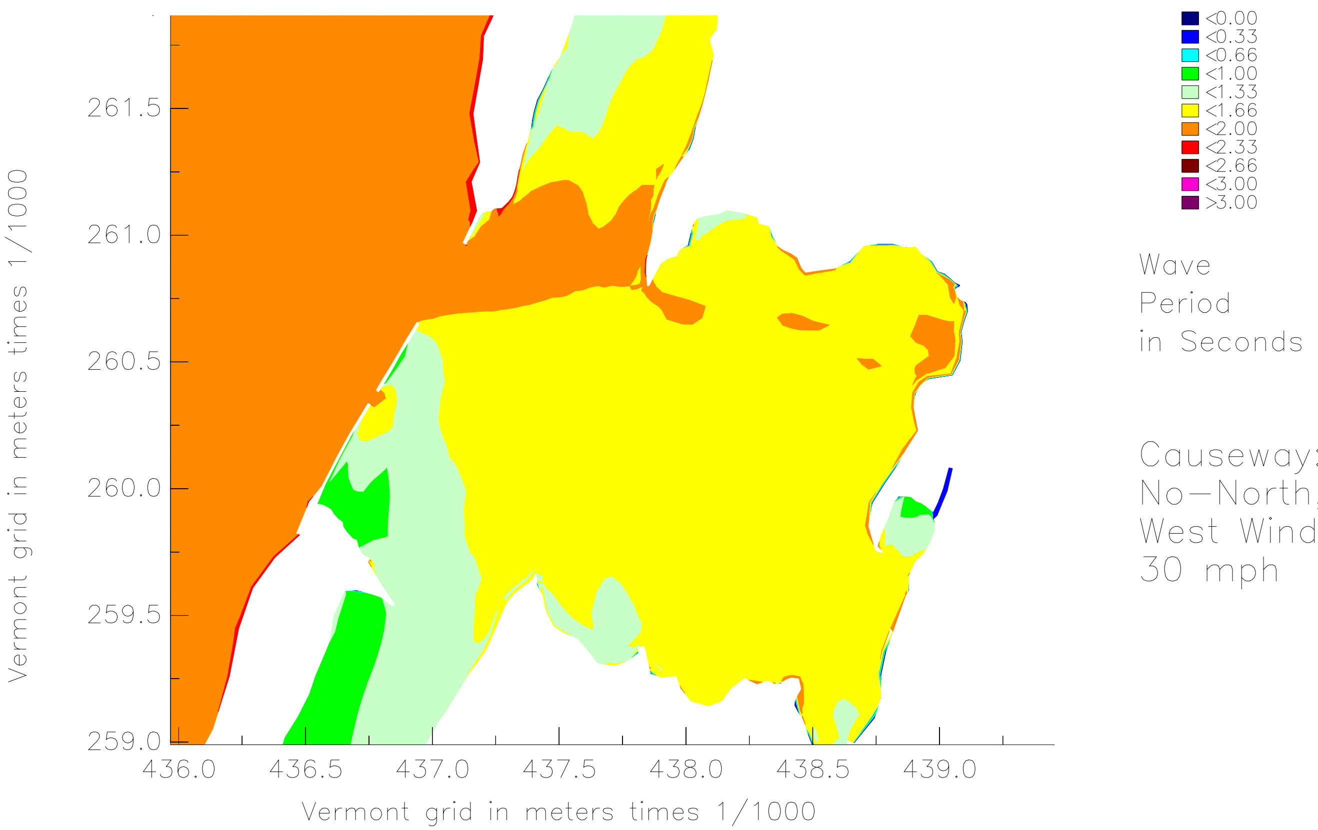
December 2007



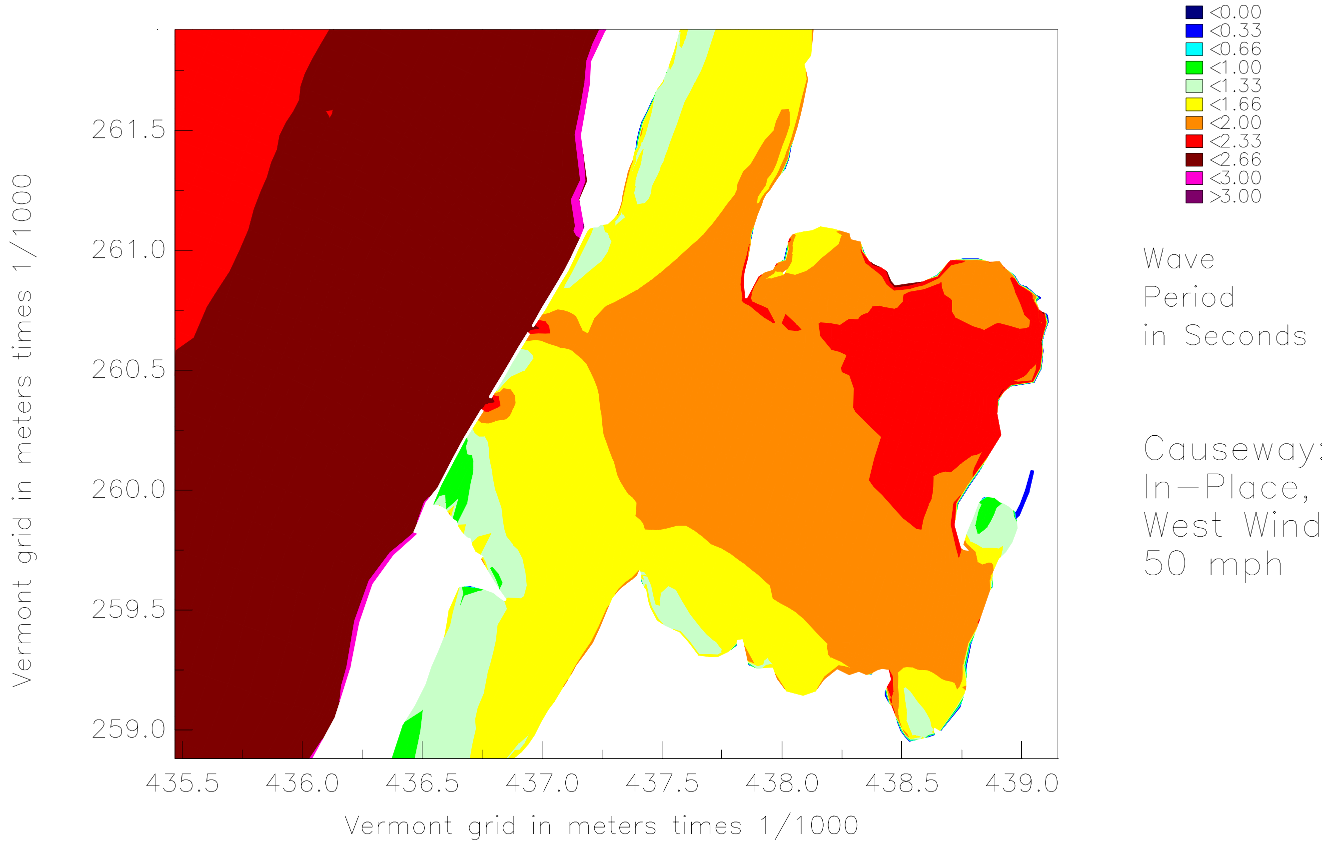


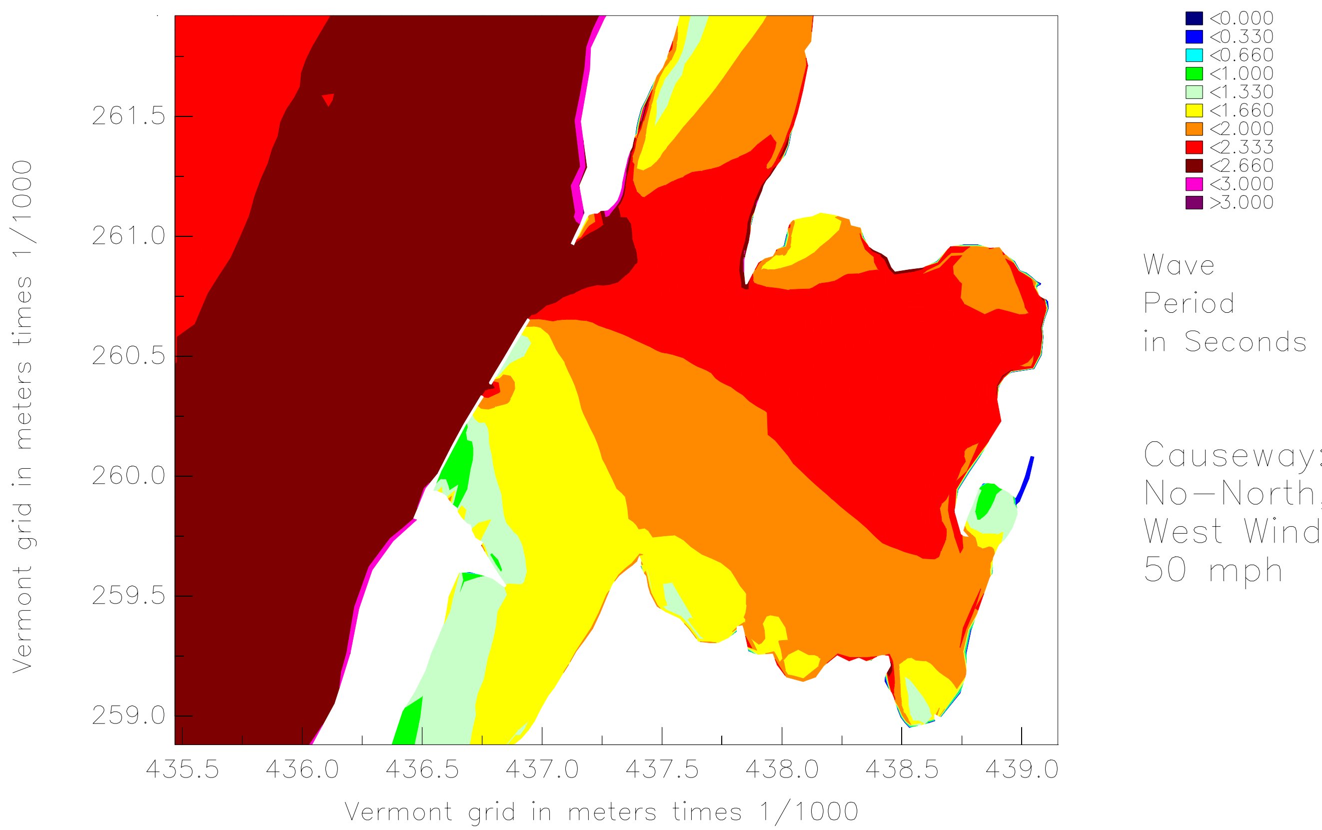
Top – Wave Length (meters) – Causeway In–Place Bottom – Wave Length (meters) – No–North Section See color scale for wave length information	Figure 43	Carry Bay Wave Study
	Wave Lenght, meters	
Wind from West at 70 mph	Binkerd Environmental	December 2007



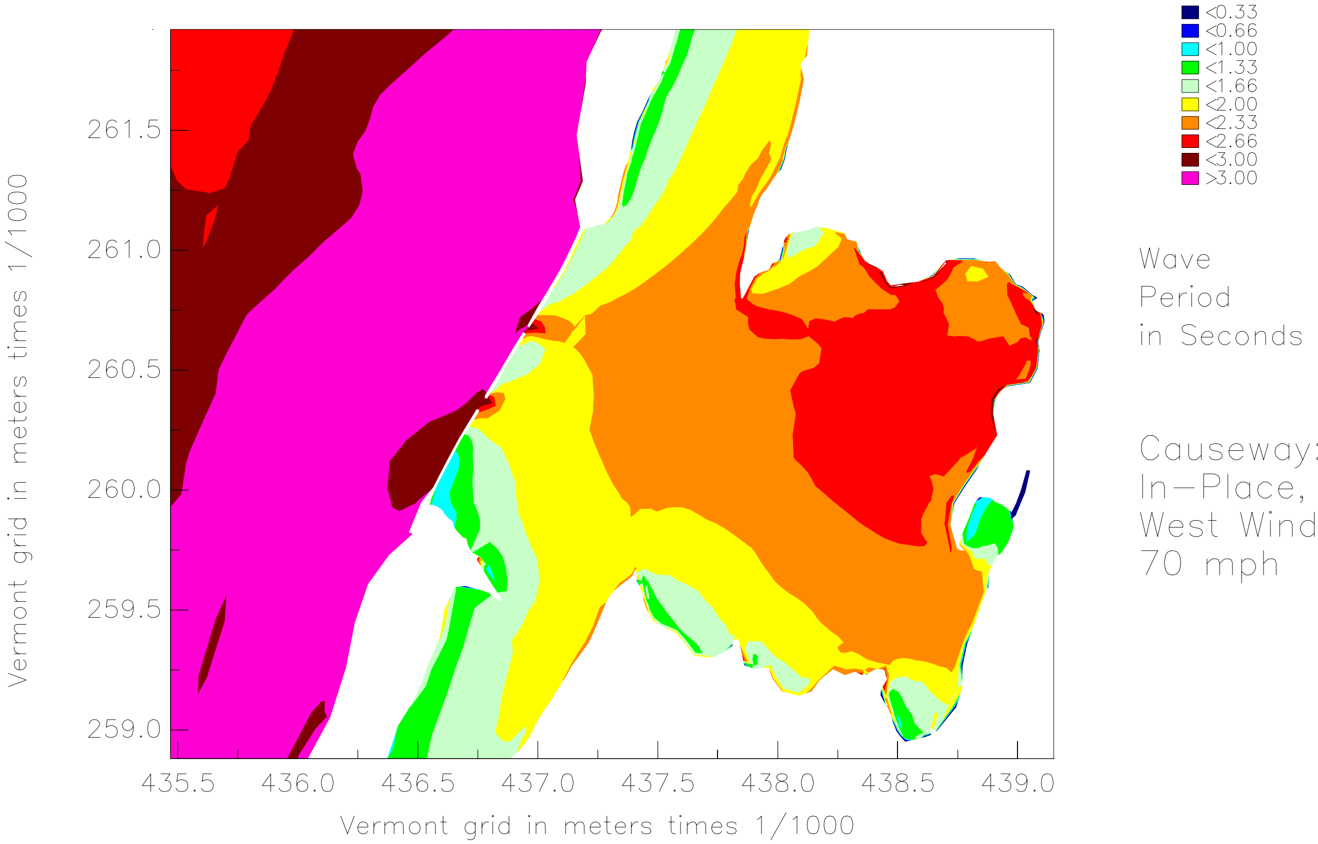


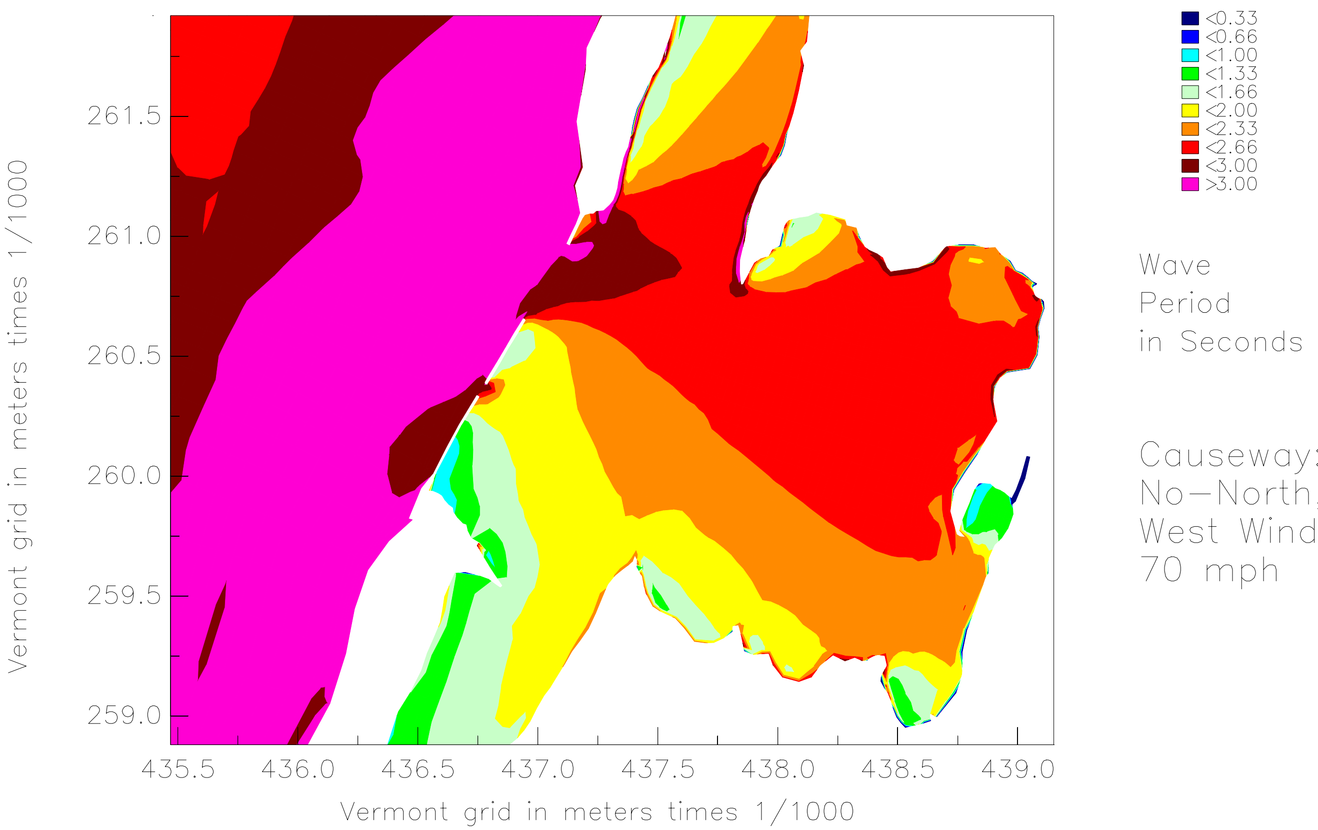
Top – Wave Period (seconds) – Causeway In–Place Bottom – Wave Period (seconds) – No–North Section See color scale for wave period information	Figure 44	Carry Bay Wave Study
	Wave Period, seconds	
Wind from West at 30 mph	Binkerd Environmental	December 2007



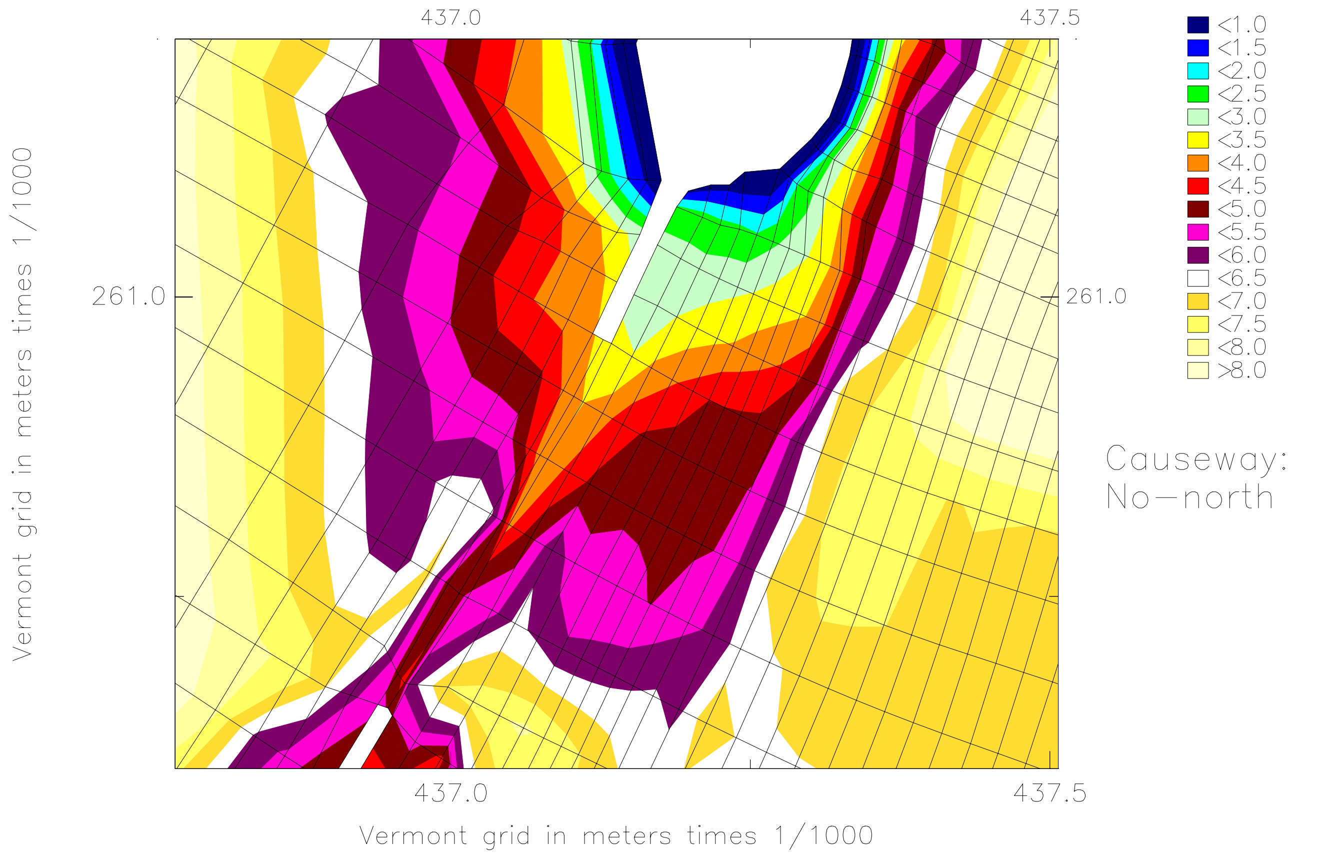


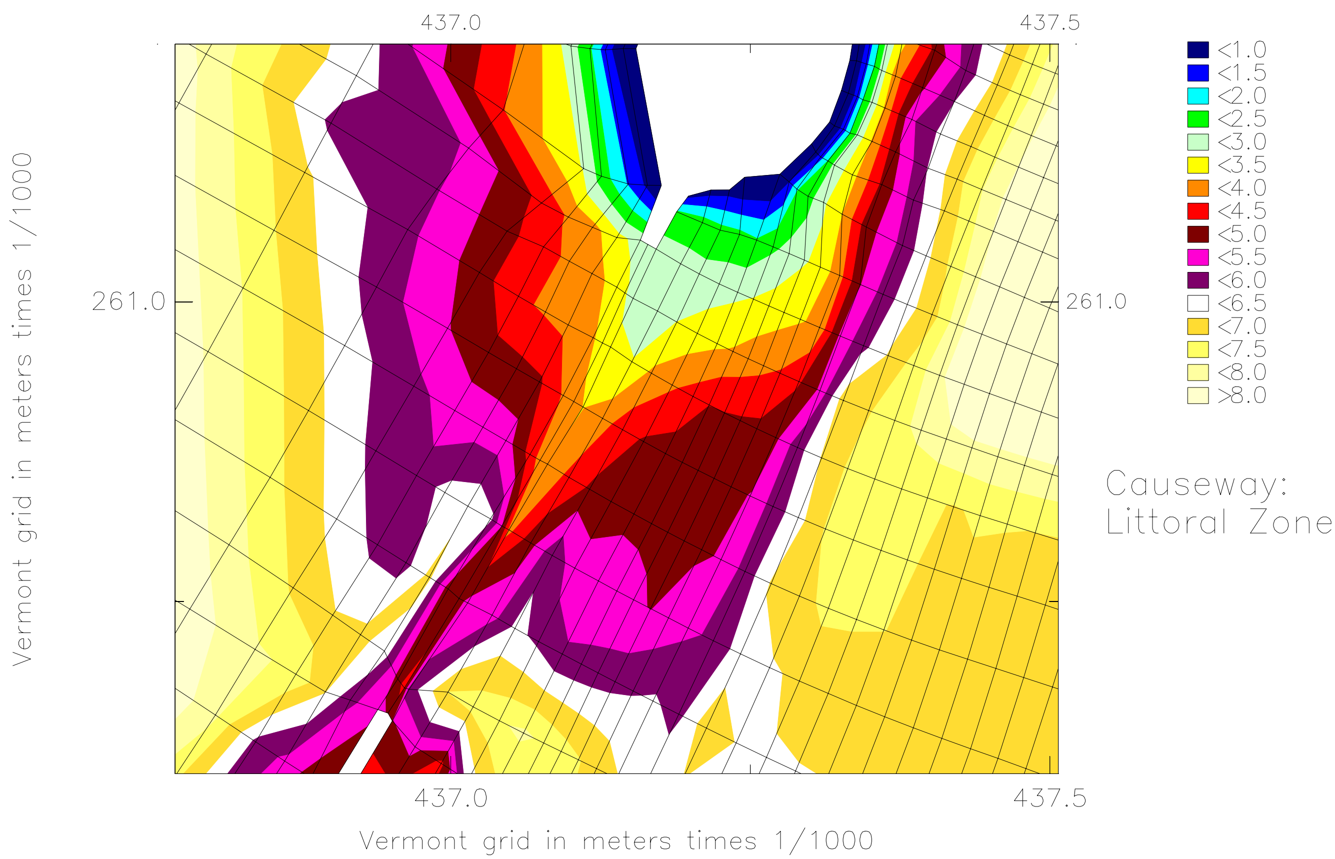
Top – Wave Period (seconds) – Causeway In–Place Bottom – Wave Period (seconds) – No–North Section See color scale for wave period information	Figure 45	Carry Bay Wave Study
	Wave Period, seconds	
Wind from West at 50 mph	Binkerd Environmental	December 2007



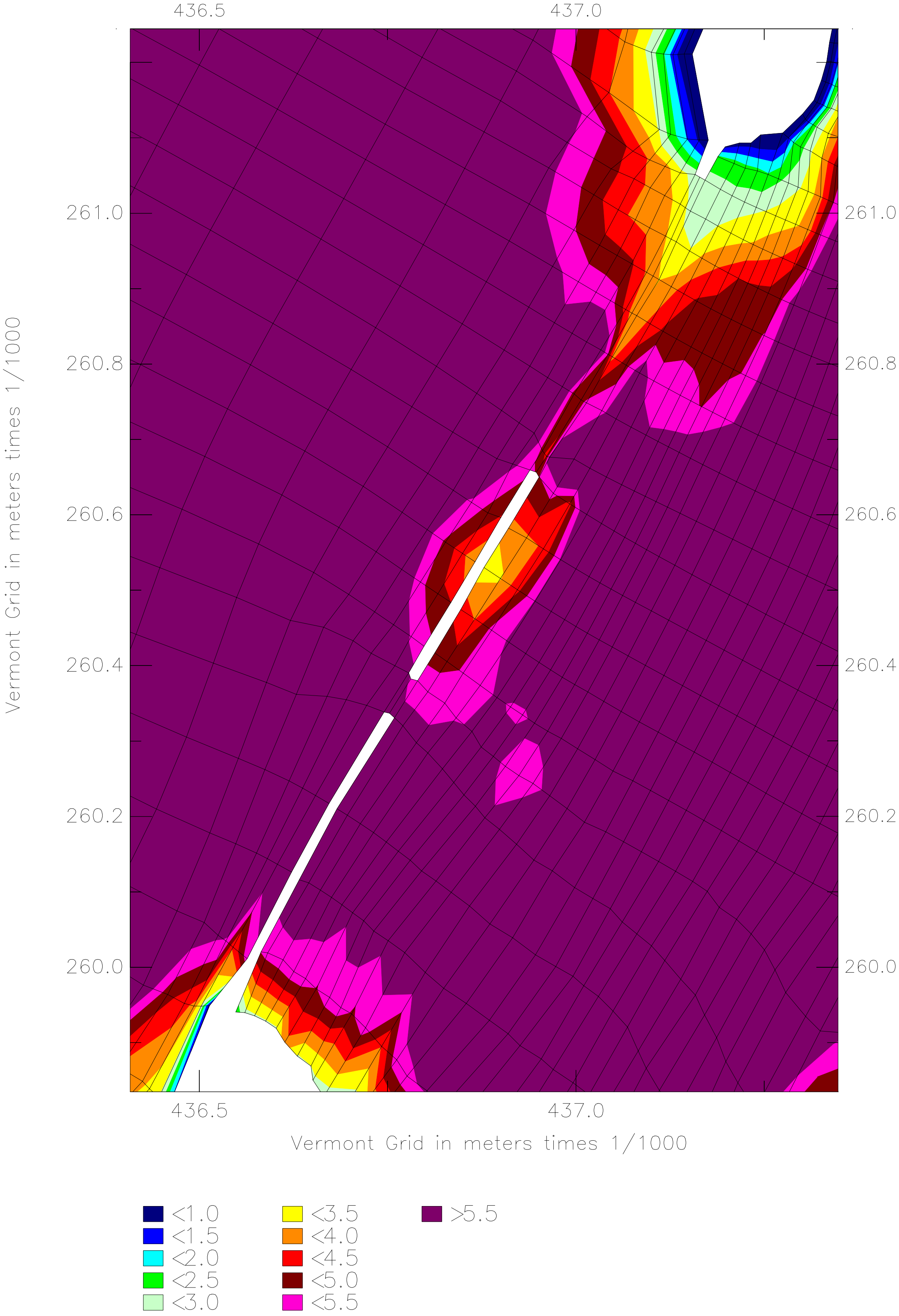


Top – Wave Period (seconds) – Causeway In–Place Bottom – Wave Period (seconds) – No–North Section See color scale for wave period information	Figure 46	Carry Bay Wave Study
	Wave Period, seconds	
Wind from West at 70 mph	Binkerd Environmental	December 2007

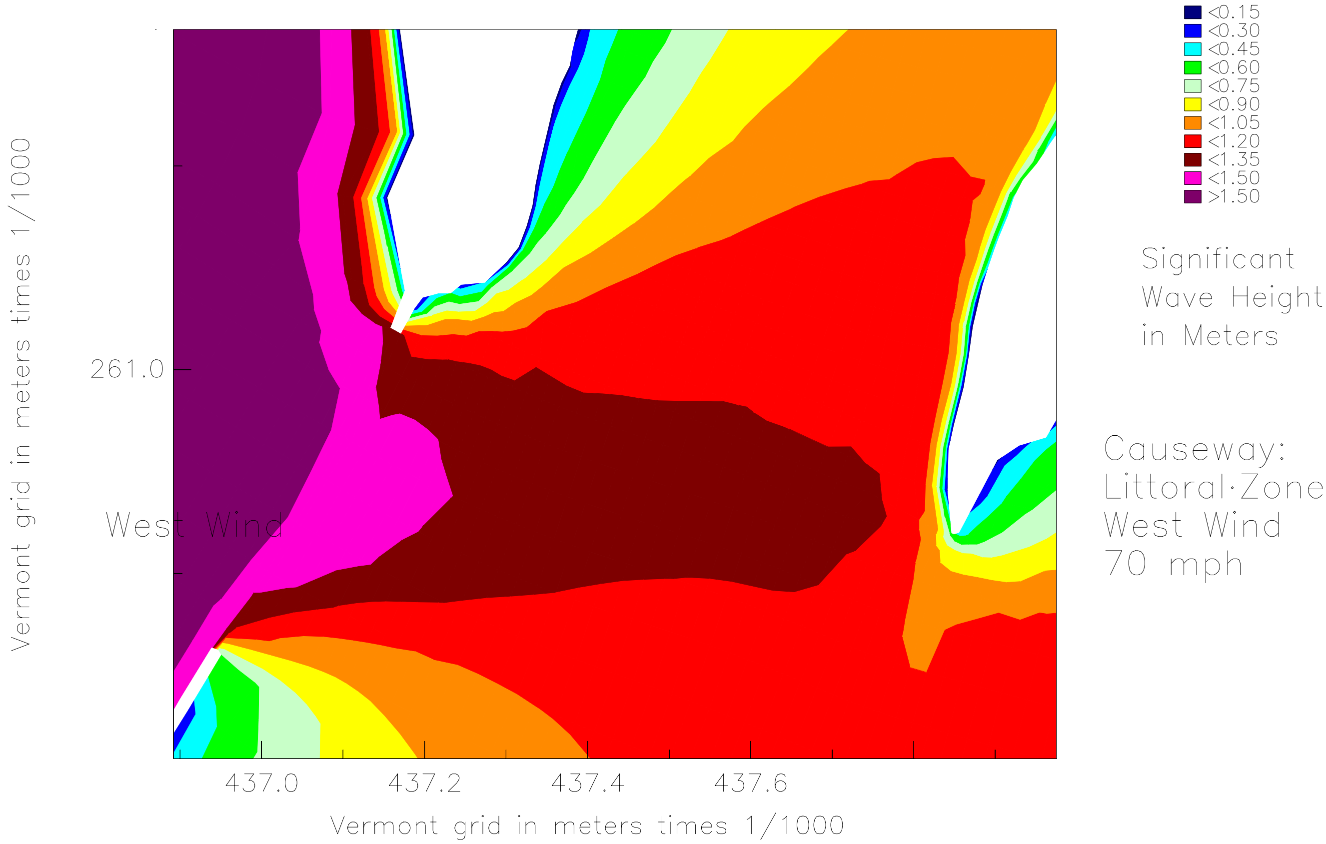


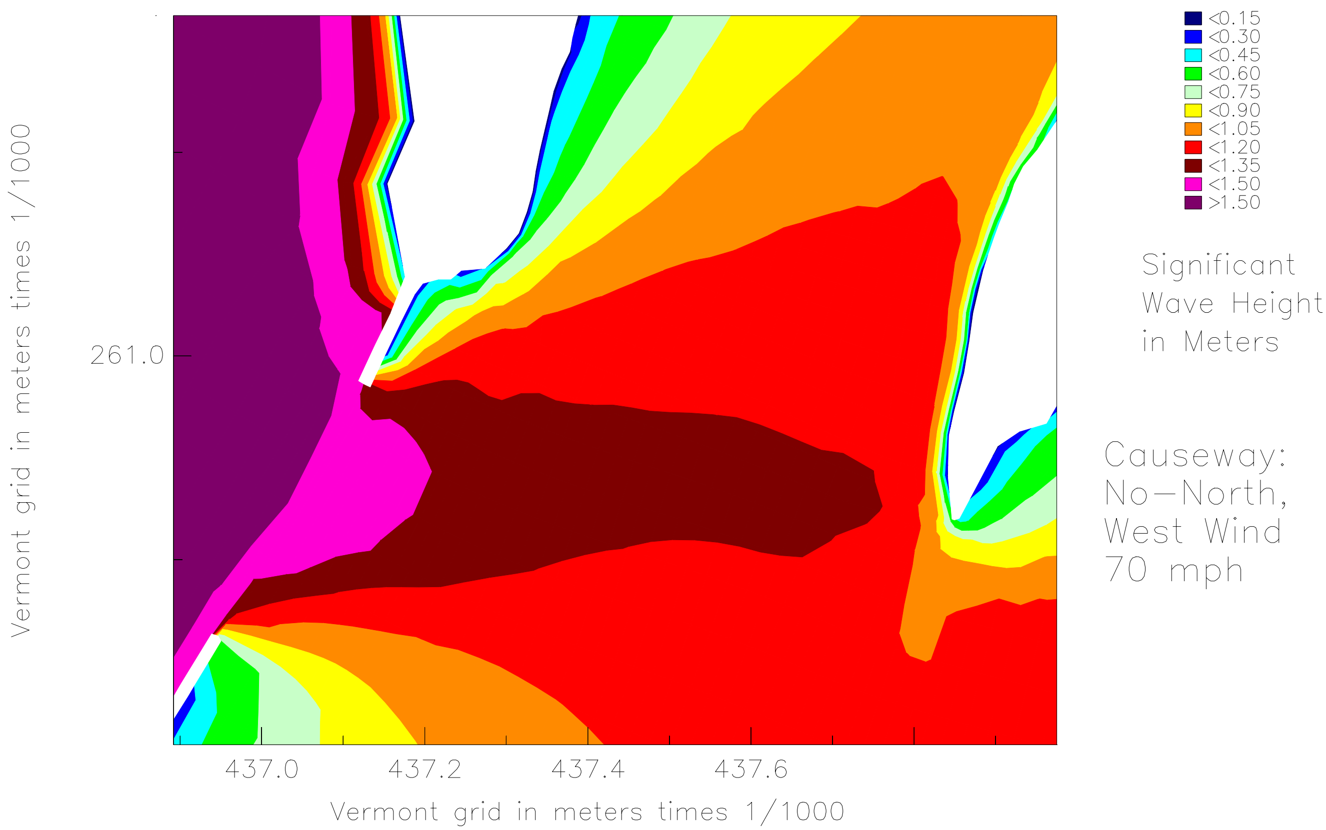


Top – Causeway configuration called "No-north" Bottom – Causeway configuration called "Littoral Zone" See color scale for water depths in meters	Figure 47	Carry Bay Wave Study
	Grids & Depths	
Plane of reference is 99.5 ft MSL (mean stage is 95.6 ft MSL)	Binkerd Environmental	March 2008

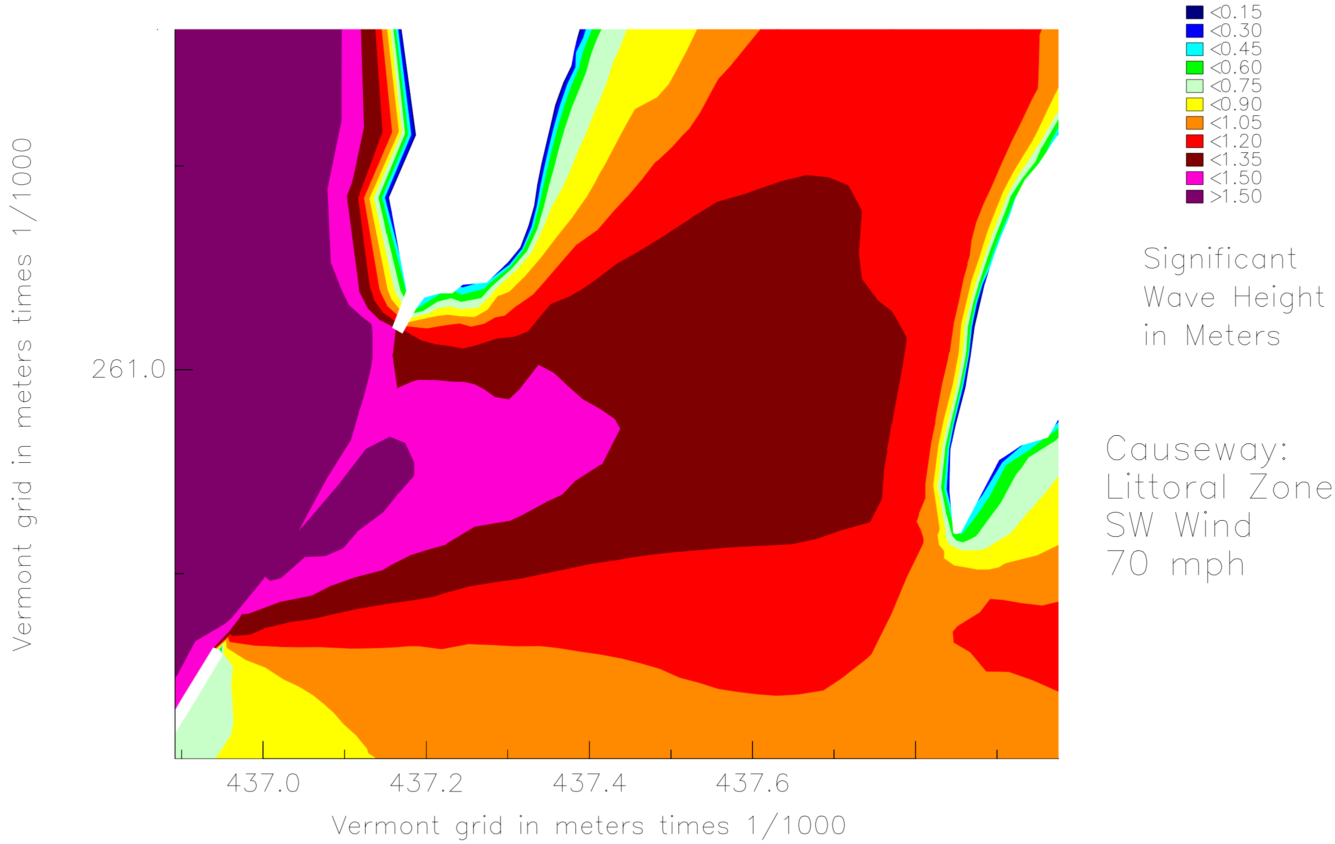


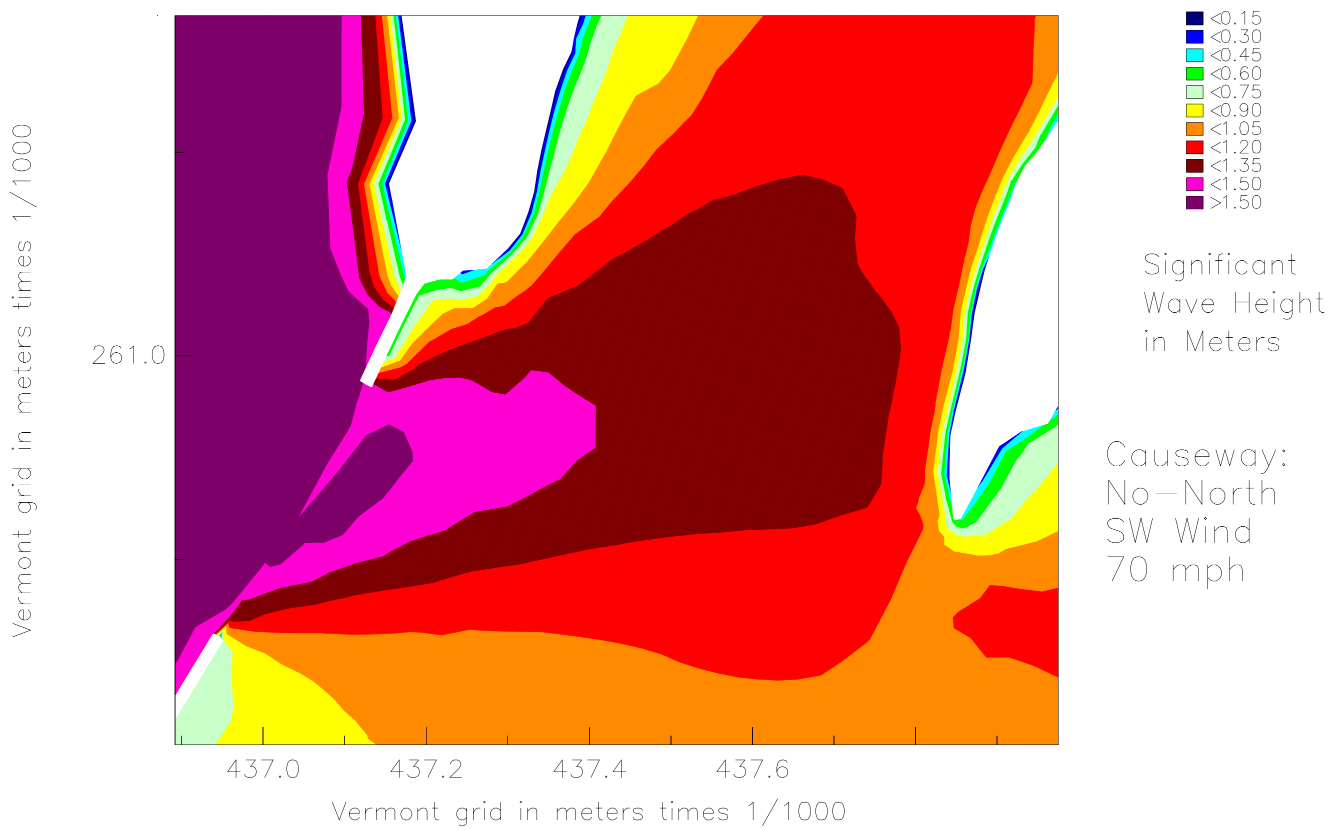
Causeway congfiguration shown is "Littoral Zone" Water depths in meters relative to 99.5 ft MSL See color scale for water depths in meters	Figure 48	Carry Bay Wave Study
	Grid & Depths (meters) Littoral Zone	
Plane of reference is 99.5 ft MSL (mean stage is 95.6 ft MSL)	Binkerd Environmental	March 2008



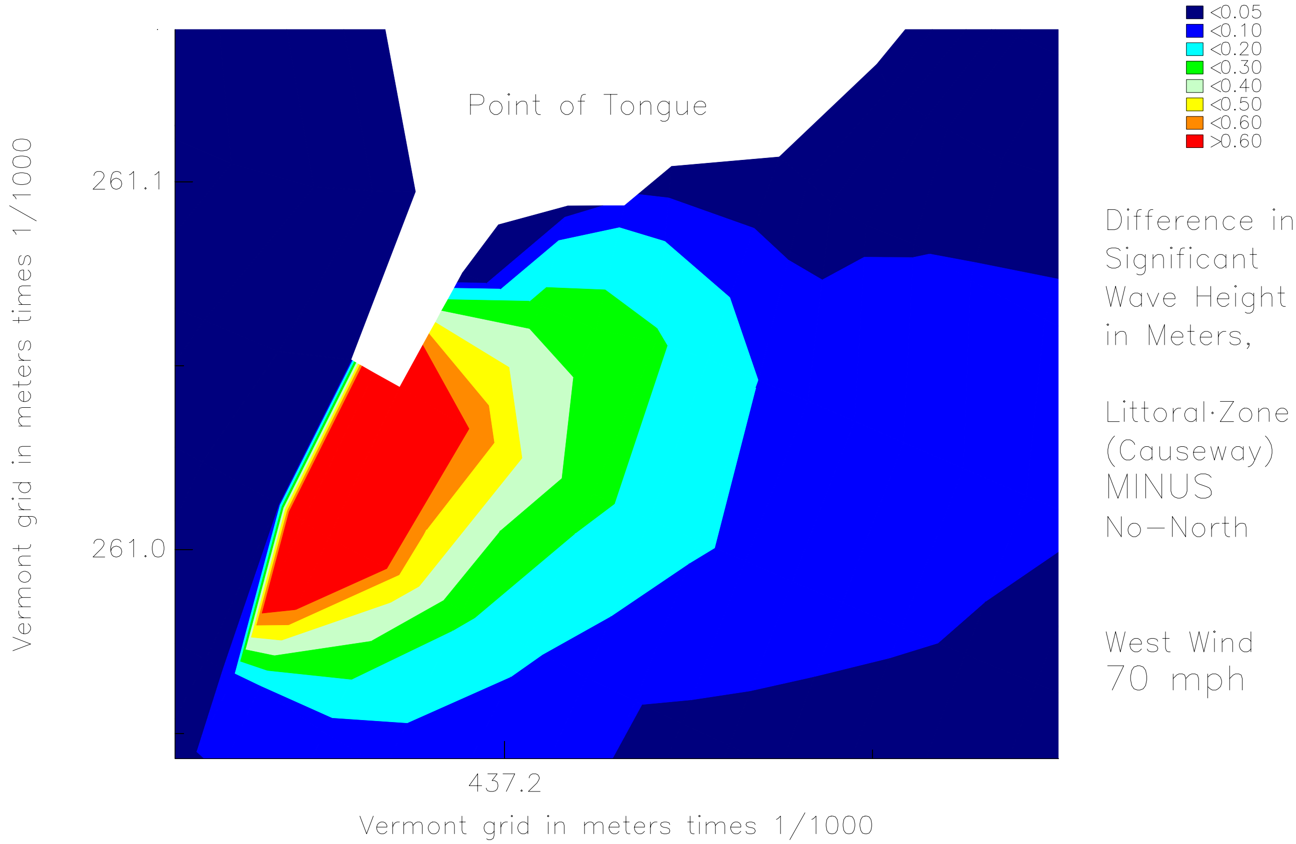


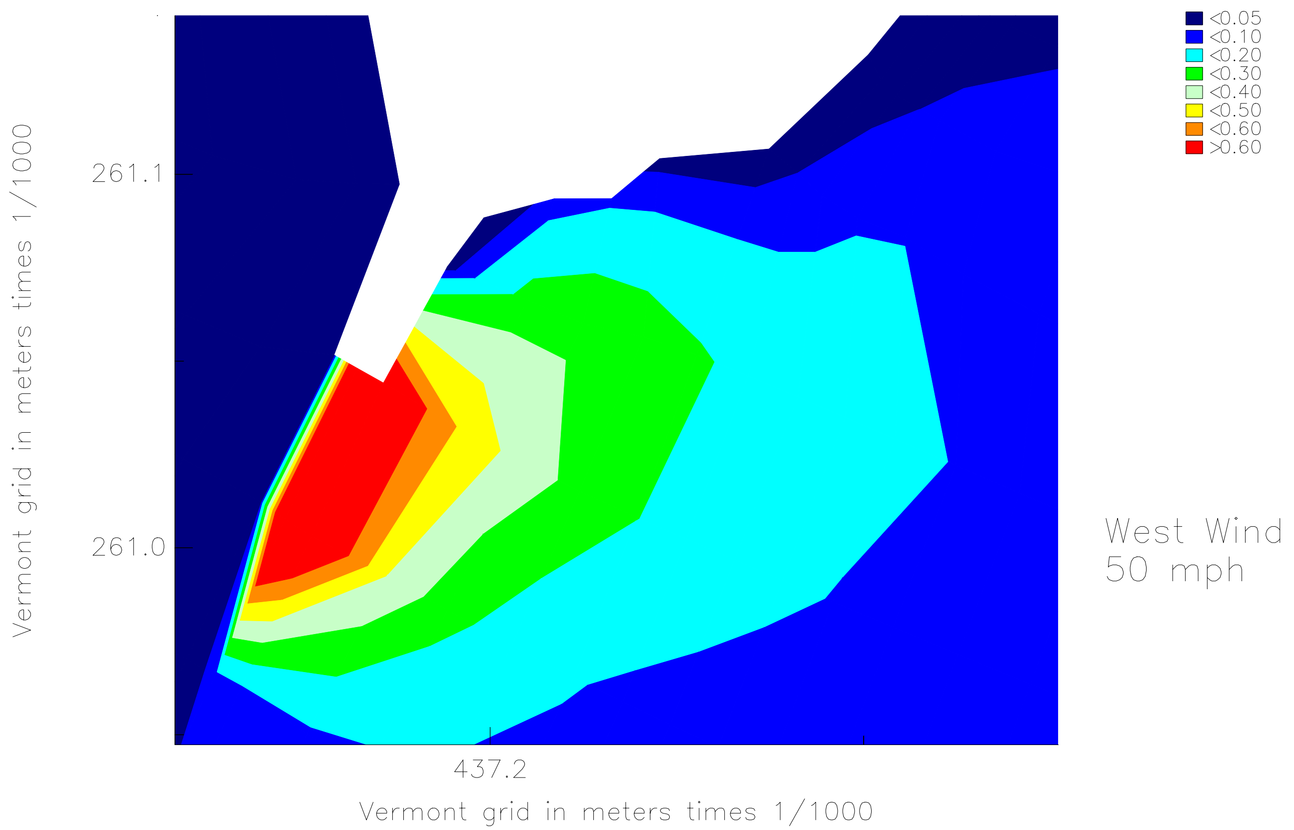
Top – Significant Wave Height (meters) – Causeway Littoral·Zone Bottom – Significant Wave Height (meters) – No–North Section See color scale for wave height information	Figure 49	Carry Bay Wave Study
	Significant Wave Height	
Wind from West at 70 mph	Binkerd Environmental	March 2008



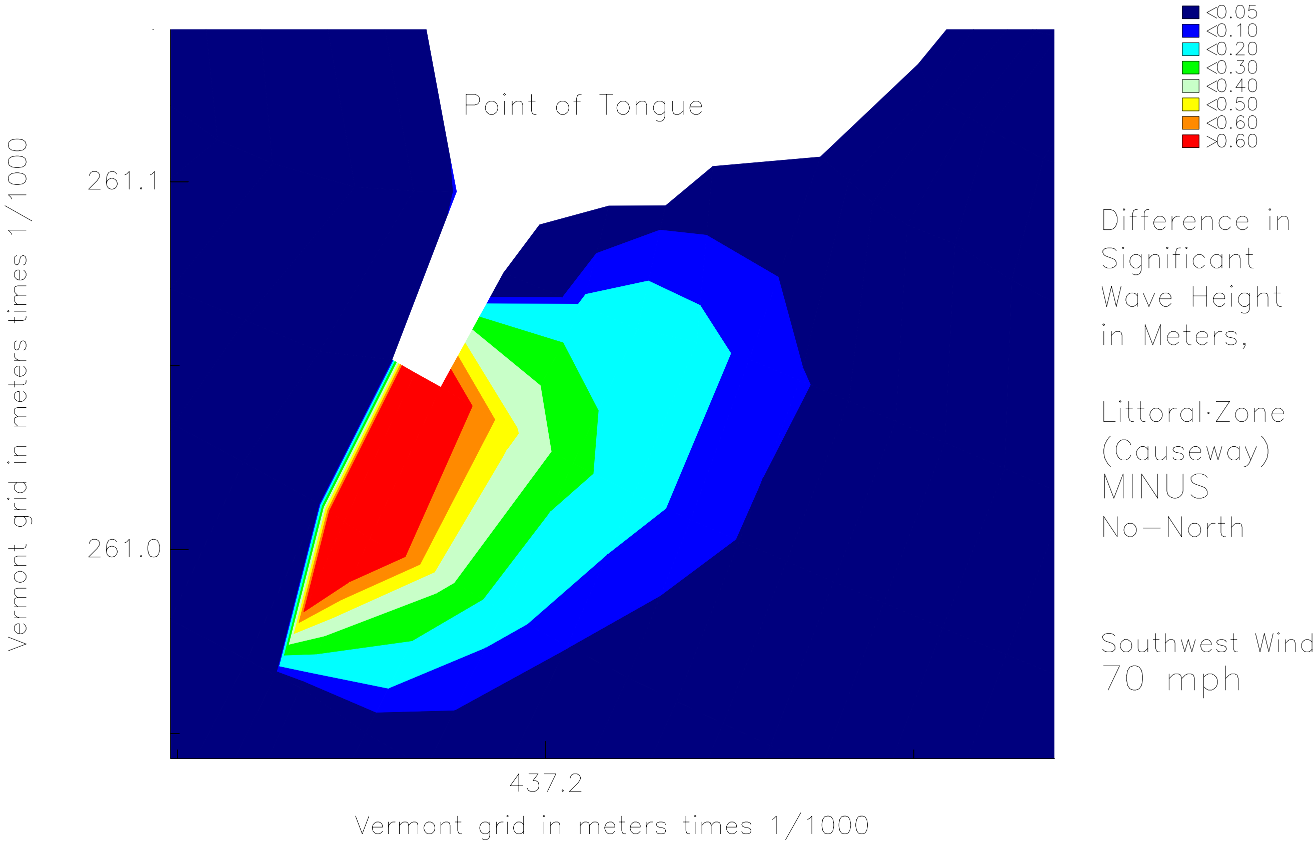


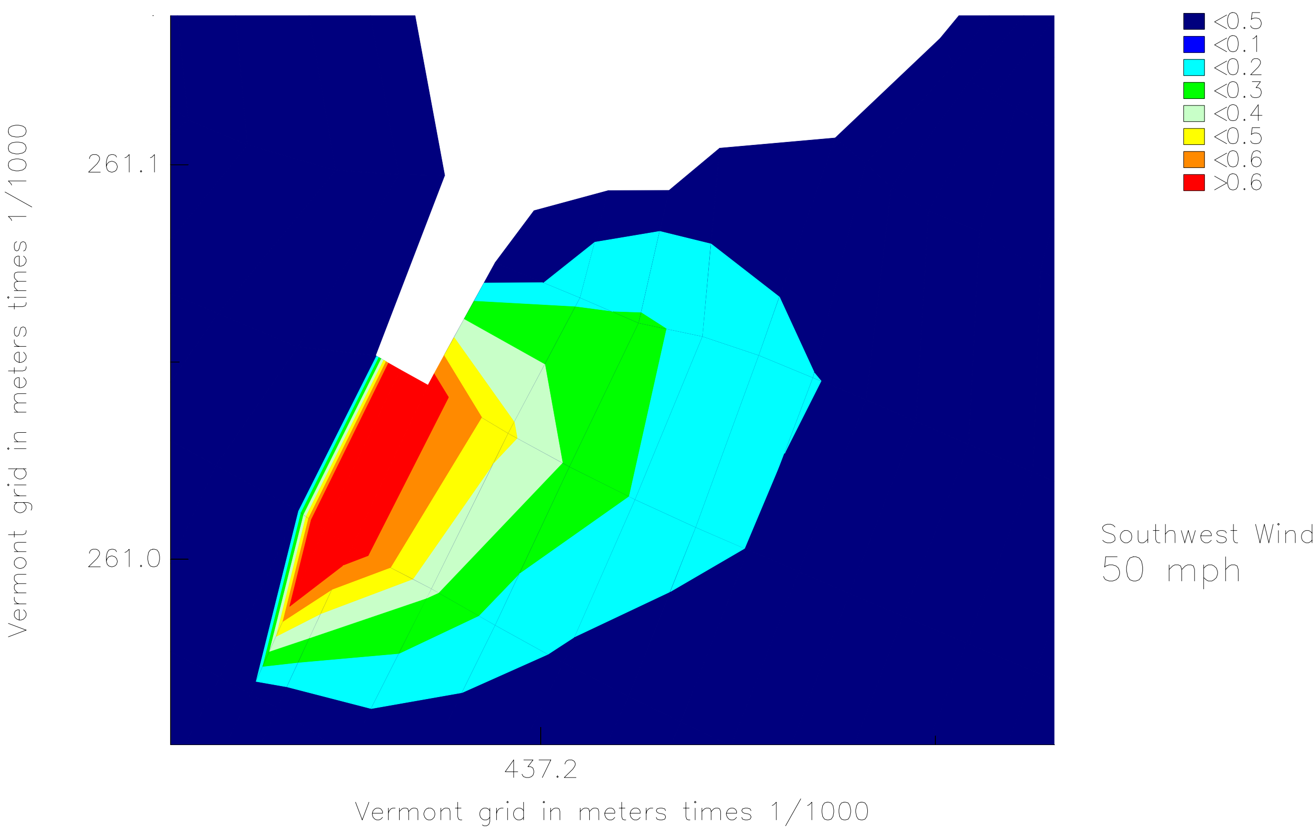
Top – Significant Wave Height (meters) – Littoral Zone Bottom – Significant Wave Height (meters) – No-North Section See color scale for wave height information	Figure 50	Carry Bay Wave Study
	Significant Wave Height	
Wind from Southwest at 70 mph	Binkerd Environmental	March 2008



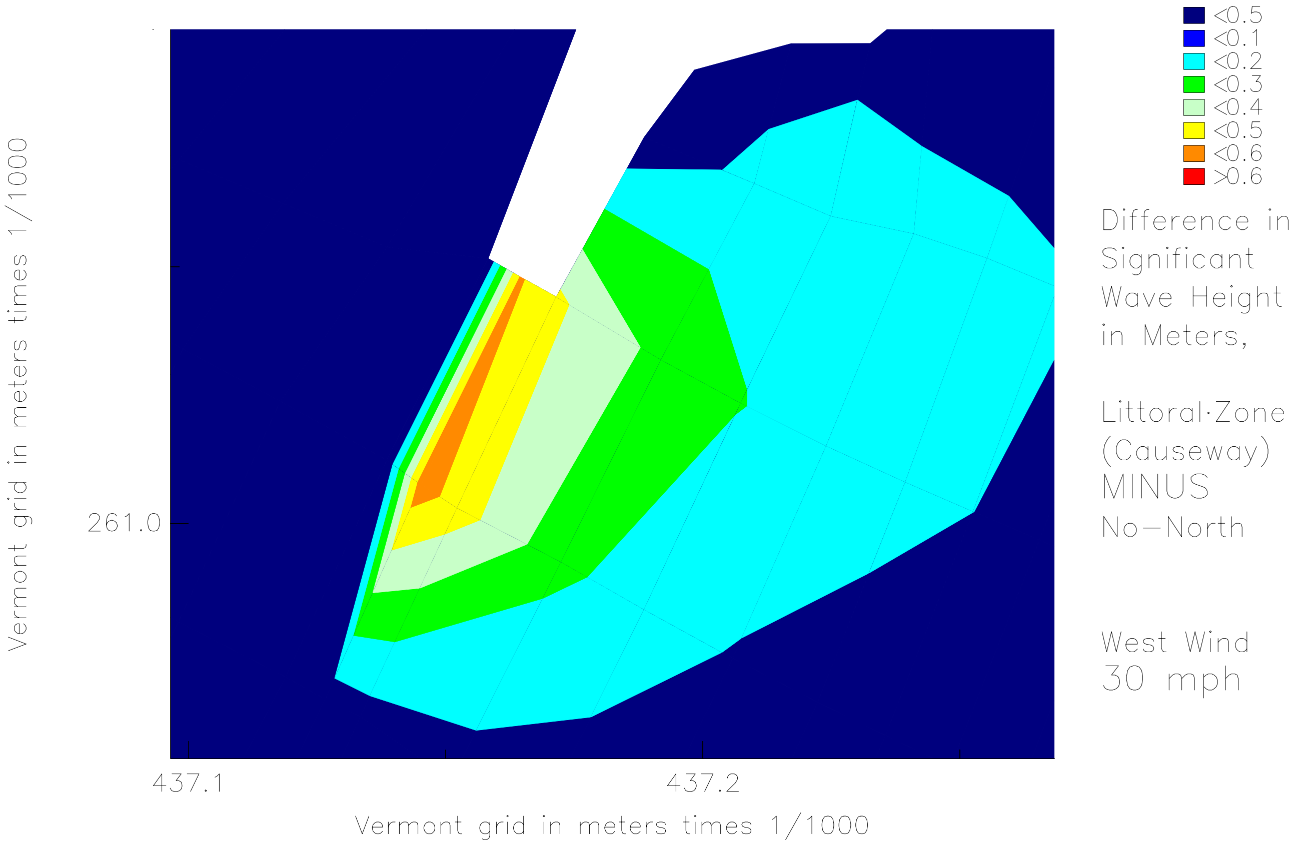


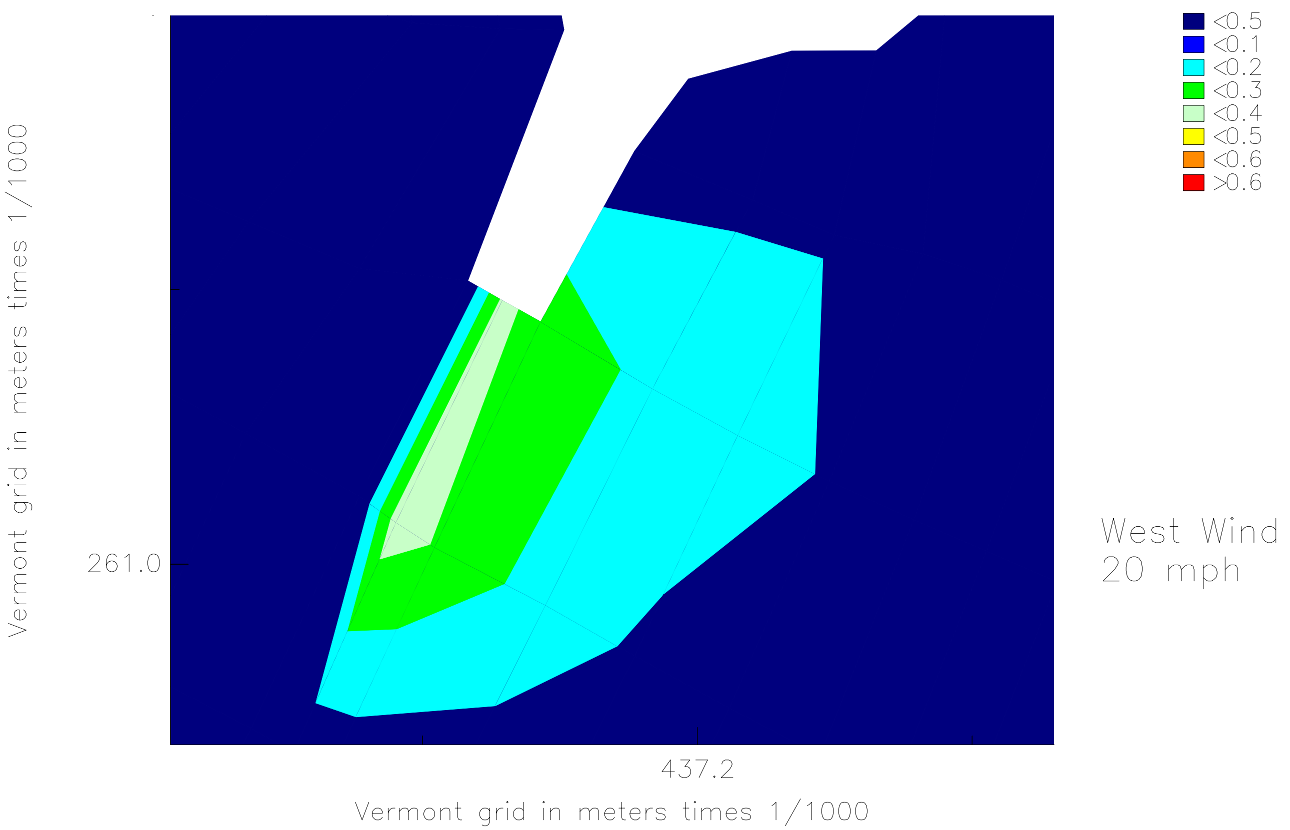
Top—Difference in Significant Wave Height — West wind 70 mph Bottom—Difference in Significant Wave Height — West wind 50 mph See color scale for wave height information	Figure 51	Carry Bay Wave
	Difference in Significant Wave Height	
Difference in wave height: Littoral Zone MINUS No—North	Binkerd Environmental	March 2008





Top–Difference in Significant Wave Height, Southwest wind 70 mph Bottom–Difference in Significant Wave Height, Southwest wind 50 mph See color scale for wave height information	Figure 52	Carry Bay Wave
	Difference in Significant Wave Height	
Difference in wave height: Littoral Zone MINUS No–North	Binkerd Environmental	March 2008





Top–Difference in Significant Wave Height – West wind 30 mph Bottom–Difference in Significant Wave Height – West wind 20 mph See color scale for wave height information	Figure 53	Carry Bay Wave
	Difference in Significant Wave Height	
Difference in wave height: Littoral Zone MINUS No–North	Binkerd Environmental	March 2008