Coastal Hydraulics and Hydrology

Cumberland, York, Sagadahoc, Lincoln, Knox, Waldo, & Hancock Counties
Maine

STARR
Strategic Alliance for Risk Reduction

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1. Introduction

Coastal hydrology and hydraulics were performed under Contract No. HSFEHQ-09-D-0370, Task Order Nos. HSFE01-11-J-0007 and HSFE01-11-J-0008. Task order HSFE01-11-J-0007 developed coastal hydrology (storm surge) in the following five Maine coastal counties: Sagadahoc, Lincoln, Waldo, Knox, and Hancock; and coastal hydraulics (waves) in the following seven Maine coastal counties: Sagadahoc, Lincoln, Waldo, Knox, and Hancock. Task order HSFE01-11-J-0008 developed coastal hydraulics (waves) in the following two Maine coastal counties: York and Cumberland. The coastal hydrology and hydraulics performed under these two contracts are used in the development of coastal flood hazard risk analysis for the coastlines of the seven counties in Maine comprising the study area of this report, as shown in Figure 1-1.

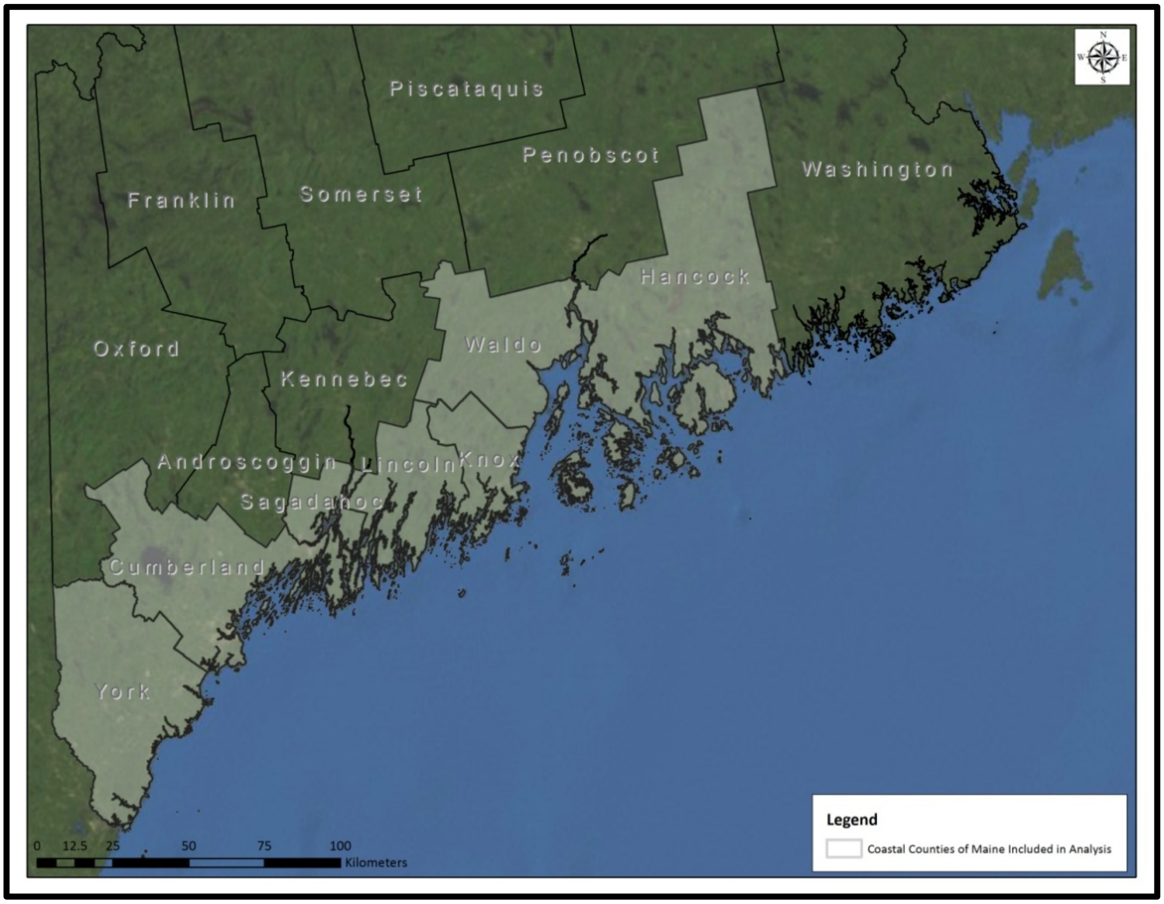

Figure 1-1 : Counties Considered for Coastal Flood Hazard Risk Analysis in this Study

Coastal flood hazards are defined as a combination of wave action and associated high water levels. For the National Flood Insurance Program (NFIP), the Federal Emergency Management Agency (FEMA) develops risk information associated with the 1-percent-annual-chance storm event. The 1-percent-annual-chance event impacting coastal portions of the State of Maine are associated with low pressure systems that commonly occur in the winter months and are referred to locally as Nor'easters due to the wind direction associated with this counterclockwise rotating storm (FEMA, 2007). There are two types of coastal flood hazards analyzed, coastal flooding and tidal flooding. Tidal flooding is the inundation of land as a result of higher water levels, often associated with a storm surge. Coastal flooding considers wave action in addition to the tidal flooding.

The State of Maine's coastline is considered a glaciated coast in the *Coastal Engineering Manual* (U.S. Army Corps of Engineers [USACE], 2002). Glaciated coasts are characteristically deeply indented and bordered by numerous rocky islands. This geographical setting can impact the coastal flood hazards. Normal return period water level analysis considers the water level along the open coastline and does not consider deeply indented shorelines. Additionally, there are over 3000 islands along the Maine coast, and these islands influence the wave energy and provide shelter to portions of the mainland. Applying standard deepwater wave and surge conditions to the coastal flood hazard analysis would not be representative of true conditions associated with a storm event for much of the glaciated Maine coastline.

A storm surge routing model was developed to determine the 1-percent-annual-chance stillwater elevations for Sagadahoc, Lincoln, Waldo, Knox, and Hancock counties. These counties are fjord-like in nature and are deeply indented. The 1-percent-annual-chance stillwater elevation obtained at the open coast through gage record analysis is not applicable to the indented features. A finite-element hydrodynamic model, RMA2 (USACE, 2009), was used to route the storm surge up the rivers and bays that comprise the glaciated coast. To determine the 1-percent-annual-chance stillwater elevation, the modeled results will be used to define the tidal flooding in Sagadahoc, Lincoln, Waldo, Knox, and Hancock counties, while the results of tide gage record analysis will be applied per FEMA guidelines (FEMA, 2007) to the open coast portions of the coastal flood hazard studies in the counties, as well as to the coasts of York and Cumberland counties.

In areas subject to coastal flooding, the wave action component of coastal flood hazards for York, Cumberland, Sagadahoc, Lincoln, Waldo, Knox, and Hancock counties will be determined from wave transformation models using STWAVE (USACE, 2001). A series of nested, two-dimensional spectral wave models (STWAVE) developed at coarse, mid-sized, and local scales was used to transform the 1-percent-annual-chance deepwater spectral wave conditions to a more representative shoaling zone in the study area. These transformed wave conditions will then be paired with the 1-percent-annual-chance stillwater elevation to identify coastal flood hazard areas in all seven counties.

The data that were used to execute the storm surge routing and wave transformation models are discussed in Section 2. The section describes data availability, including historical data that are used in model calibration. Section 2 also discusses data analysis for development of model boundary conditions and inputs for model calibration and validation simulations. Finally, Section 2 discusses how data were used to generate RMA2 and STWAVE boundary conditions and model inputs for simulations of the 1-percent-annual-chance storm event.

The storm routing model (RMA2) development, including model construction, calibration and validation, and simulation of the 1-percent-annual-chance event are described in Section 3. The wave transformation model (STWAVE) development, including model construction, validation, and simulation of the 1-percent-annual-chance event are described in Section 4.

2. Data Acquisition, Analysis, and Development of 1-Percent-Annual-Chance Event Model Input Conditions

This section describes the types of data acquired for this study as well as additional data analysis performed. The following types of data were collected and are discussed in this section:

- Bathymetry
- Water Surface Elevation from Tide Gages
- High Water Marks
- 1-Percent-Annual-Chance Water Surface Elevation
- Streamflow Data
- National Data Buoy Center Measurements (Wave Characteristics and Wind Speeds)

2.1 Data Acquisition

2.1.1 Bathymetry

Bathymetry was obtained from the National Oceanic and Atmospheric Administration National Ocean Service (NOAA NOS) hydrographic surveys available from the National Geophysical Data Center (NGDC) (NOAA NGDC, 2012) website. All surveys in the study area with digital XYZ data were converted to the North American Vertical Datum of 1988 (NAVD88) meters and incorporated into an Environmental Systems Research Institute (ESRI) Geodatabase Terrain dataset as mass points. In locations where more recent higher resolution Bathymetric Attributed Grid (BAG) format surveys were available, older surveys were superseded. In areas where NOAA surveys did not provide sufficient coverage, the terrain surface was supplemented with Digital Bathymetric Data Base Variable (DBDB-V) data available from the Naval Oceanographic Office.

For the STWAVE model, the bathymetry dataset for the nested York and Cumberland County grids was supplemented with an additional dataset provided by Sebago Technics (2009). The coarse grid, as well as the mid-sized and local nested STWAVE grids in York and Cumberland Counties, were also supplemented with elevation data extracted from the United States Geological Survey (USGS)'s Digital Bathymetry for the Gulf of Maine (Roworth and Signell, 1998).

2.1.1.1 RMA2 Bathymetry Processing

The compiled scatter dataset was used to define bathymetry for the RMA2 surge models discussed in Section 3. Bathymetric data was cropped to the RMA2 study area extents. Extrapolation as a single value of -1.0 meter elevation was used at the shoreline and at edges of the model domain where no bathymetric data was present. Spurious data points were removed from the bathymetry data. The scatter dataset used to develop the RMA2 mesh is shown in Figure 2-1.

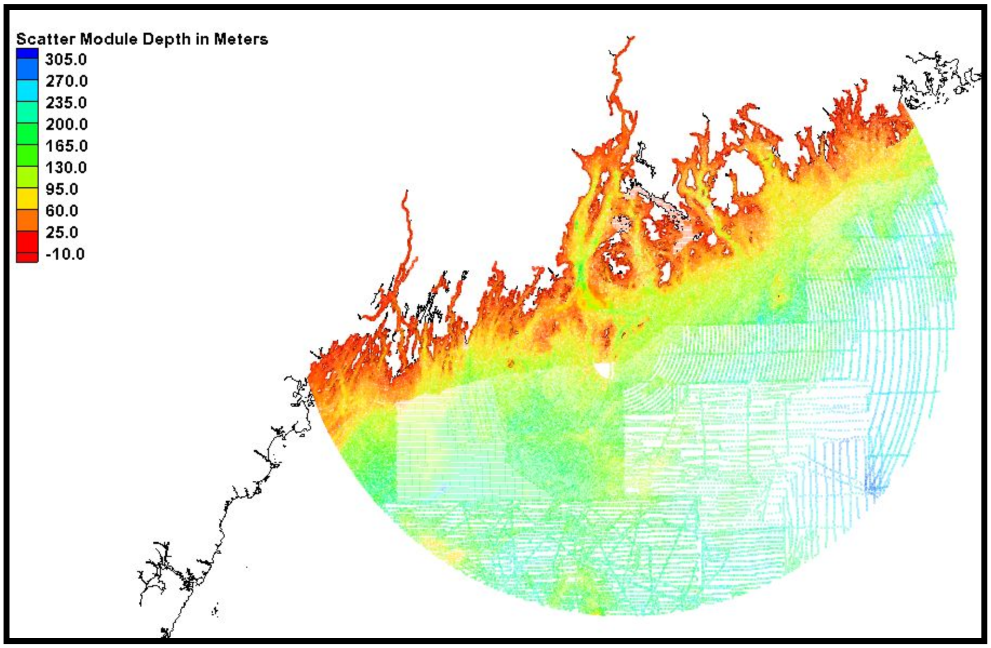

Figure 2-1 : Bathymetry Scatter Dataset Used for RMA2 Mesh

2.1.1.2 STWAVE Bathymetry Processing

The compiled ESRI Geodatabase Terrain scatter dataset was used to define bathymetry for the nested STWAVE wave transformation models that are discussed in Section 4. For the STWAVE coarse model grid, the bathymetric dataset was sampled and converted to a 200-meter grid resolution raster dataset. The raster dataset used to develop the coarse model grid is shown in Figure 2-2. In most cases, a scatter data set is desirable for model grid development; however, the coarse grid uses large enough grid cells that the additional information contained in a detailed scatter set rendering was not utilized. The nested mid-sized and refined local nested STWAVE model grids utilized scatter datasets.

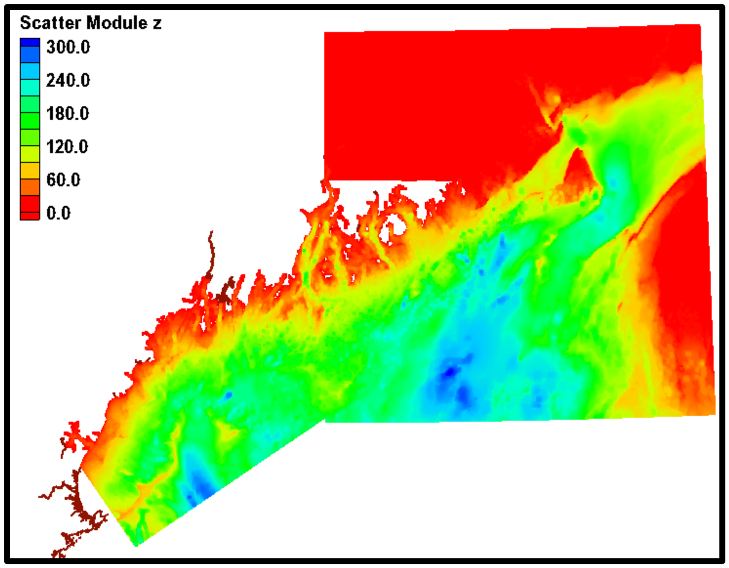

Figure 2-2 : 200 Meter Resolution Bathymetry Raster Dataset Used for STWAVE Coarse Grid

The bathymetric scatter datasets used to generate mid-sized and refined local nested STWAVE grids are shown in Figures 2-3 and 2-4. The scatter datasets were supplemented with synthetic on-shore data points, which were added by hand to the landward portion of the bathymetry datasets in areas with a complex shoreline. This synthetic data prevents the STWAVE model from incorrectly propagating shallow waves to the on-shore areas, and does not decrease the accuracy of model results.

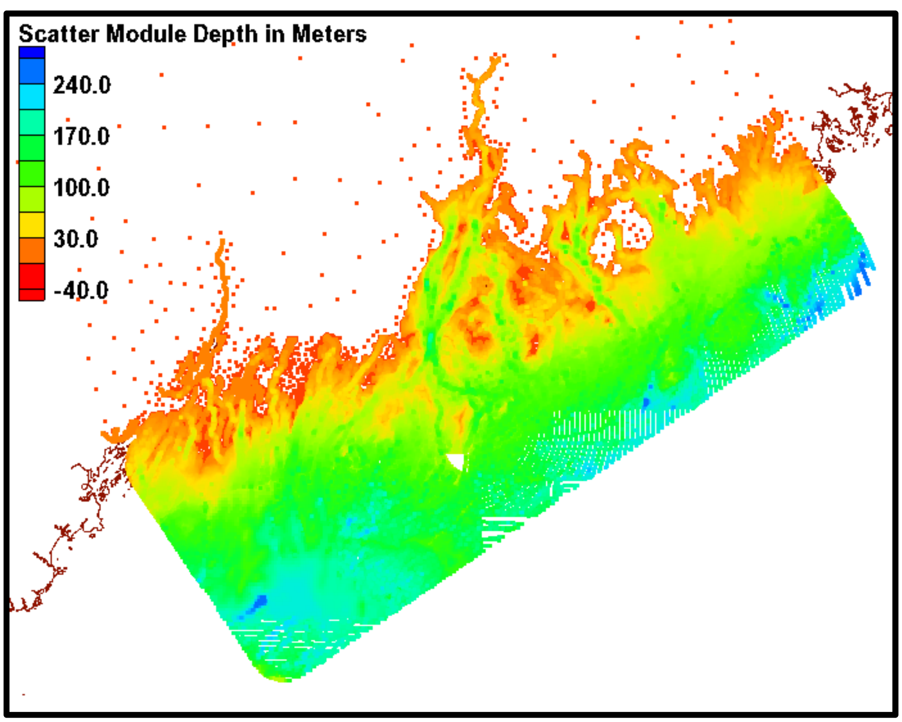

Figure 2-3 : Scatter Dataset Used to Generate the Mid-sized and Local Nested STWAVE Grids for Hancock, Waldo, Knox, Lincoln and Sagadahoc Counties

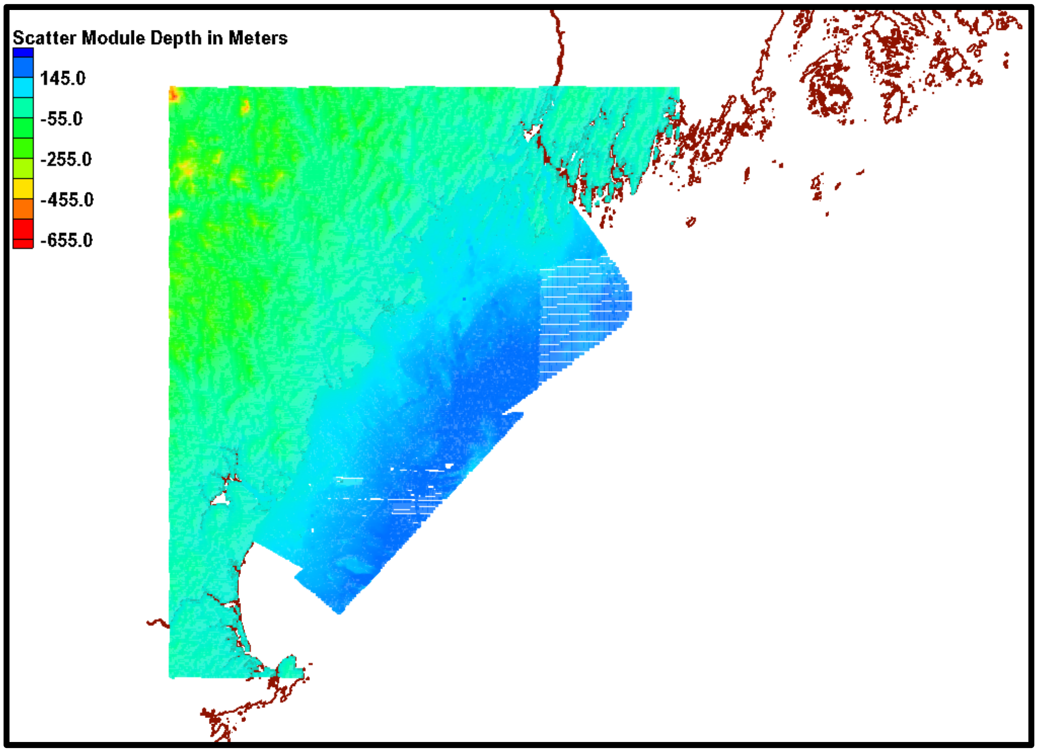

Figure 2-4 : Scatter Dataset Used to Generate the Mid-sized and Local Nested STWAVE Grids for York and Cumberland Counties

2.1.2 Water Surface Elevations Measured by Tide Gage

The National Oceanic and Atmospheric Administration (NOAA) maintains coastal tidal, current, and water level data through their Center for Operational Oceanographic Products and Services (NOS/CO-OPS). NOAA provides historic long-term water level data records from four gages within or near the study area. Information on those four gages is provided in Table 2-1. Figure 2-5 shows the locations of the four gages. Data from these gages were used to develop boundary conditions for the RMA2 and STWAVE models for calibration, validation, and simulation of the 1-percent-annual-chance event. The selection and manipulation of the data used in the RMA2 and STWAVE models is discussed further in Sections 2.2 and 2.3.

Table 2-1: Water Surface Elevation Data Available from NOAA (NOAA Tides and Currents, 2012)

Station Name	Station ID	Installation Date	Date Removed	Hourly Water Level Data Availability	Six Minute Water Level Data Availability
Wells	8419317	6/10/1999	--	7/01/1999 – 7/31/2012	7/01/1999 – 7/31/2012
Portland	8418150	3/4/1910	--	3/4/1910 – 7/31/2012	1/1/1996 – 8/13/2012
Rockland	8415490	5/14/1945	7/9/1987	--	--
Bar Harbor	8413320	8/16/1947	--	3/2/1950 – 7/31/2012	2/1/1997 – 7/31/2012

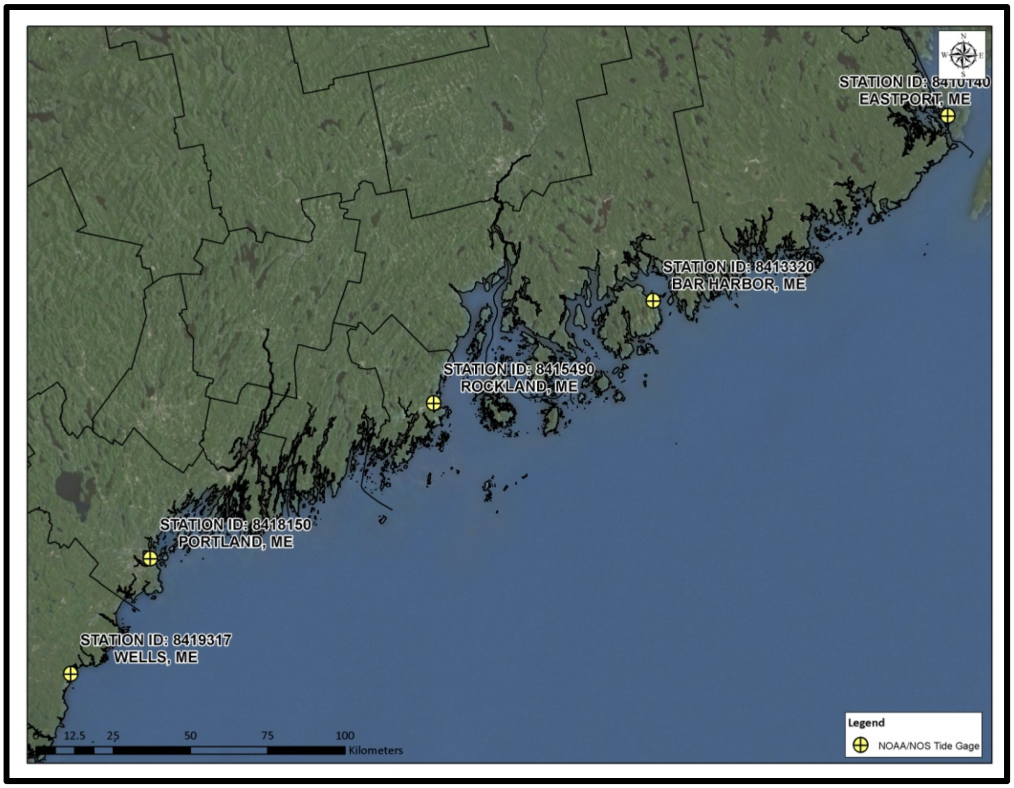

Figure 2-5 : Historic Water Surface Elevation Tide Gages

2.1.3 Historic High Water Marks

Historic high water marks were used for RMA2 model calibration and verification by comparing the observed data with the simulated surge model output. High water marks at locations along the shoreline were available from two sources: (1) the effective Flood Insurance Study (FIS) reports for communities located within the study area (FEMA, Various), and (2) the USGS report titled *Coastal Flood of February 7, 1978 in Maine, Massachusetts, and New Hampshire* (USGS, 1979).

Data points from these available sources were extracted from the reports and compared for the January 1978 and February 1978 storm events. The USGS report offered more detailed information associated with each reported high water mark and more data overall than the effective FIS reports. Therefore, the USGS high water marks were used for the purposes of this study.

The USGS reported all high water marks in feet above National Geodetic Vertical Datum of 1929 (NGVD29), with an associated latitude and longitude, quality of high water mark, and description of the recording location. Table 2-2 summarizes the USGS data within the study area for the February 7, 1978 coastal storm event. Figure 2-6 shows the location of the high water marks within the study area.

Table 2-2 : High Water Mark Data from the USGS Report *Coastal Flood of February 7, 1978 in Maine, Massachusetts, and New Hampshire* (USGS, 1979)

Site Number	Elevation (feet) NGVD29	Latitude	Longitude	City	Rating	Source
7	10.37	44°30'28"	67°43'22"	Addison	Excellent	Tidal Surge
8	10.06	44°37'04"	67°44'43	Addison	Excellent	Tidal Surge
9	9.97	44°37'10"	67°48'35"	Harrington	Good	Tidal Surge
10	9.70	44°35'48"	67°55'34"	Cherryfield	Excellent	Tidal Surge
11	10.10	44°31'53"	67°52'58"	Milbridge	Excellent	Tidal Surge
12	9.91	44°23'36"	68°05'08"	Winter Harbor	Good	Tidal Surge
13	9.54	44°16'31"	68°18'47"	Southwest Harbor	Good	Tidal Surge
14	11.53	44°32'25"	68°25'34"	Ellsworth	Excellent	Tidal Surge
15	11.42	44°24'47"	68°35'14"	Blue Hill	Excellent	Tidal Surge
16	9.12	44°18'14"	68°36'45"	Sedgwick	Excellent	Tidal Surge
17	9.54	44°17'48"	68°41'15"	Sedgwick	Excellent	Tidal Surge
18	9.24	44°23'52"	68°42'19"	Brooksville	Excellent	Tidal Surge
19	8.24	44°23'16"	68°47'48"	Castine	Excellent	Tidal Surge
20	10.16	44°34'20"	68°47'50"	Bucksport	Excellent	Tidal Surge
21	11.16	44°47'14"	68°46'35"	Bangor	Excellent	Tidal Surge
22	10.62	44°41'40"	68°50'55"	Winterport	Good	Tidal Surge
23	9.56	44°33'19"	68°51'33"	Prospect	Excellent	Tidal Surge
24	9.03	44°26'59"	69°02'08"	Belfast	Good	Tidal Surge
25	10.25	44°25'43"	69°00'19"	Belfast	Excellent	Tidal Surge
26	9.98	44°16'58"	69°00'34"	Lincolnville Beach	Excellent	Tidal Surge
27	9.02	44°12'35"	69°03'51"	Camden	Excellent	Tidal Surge
28	9.75	43°59'09"	69°12'16"	St. George at Long Cove	Excellent	Tidal Surge
29	9.60	44°04'20"	69°11'17"	Thomaston	Excellent	Tidal Surge
30	9.50	44°01'54"	69°22'41"	Waldoboro	Excellent	Tidal Surge
31	9.26	44°01'54"	69°32'48"	Newcastle	Excellent	Tidal Surge
32	9.48	44°00'07"	69°39'48"	Wiscasset	Excellent	Tidal Surge
33	9.29	43°58'25"	69°40'47"	Westport	Excellent	Tidal Surge
34	9.18	43°48'16"	69°44'52"	Georgetown	Excellent	Tidal Surge
35	12.04	43°49'24"	69°42'38"	Georgetown	Excellent	Tidal Surge
36	8.62	43°47'01"	69°43'27"	Georgetown	Excellent	Tidal Surge
37	11.18	43°45'20"	69°46'35"	Georgetown	Excellent	Tidal Surge
38	7.43	43°48'22"	69°46'43"	West Georgetown	Excellent	Tidal Surge
39	9.04	43°50'55"	69°46'34"	Arrowsic	Excellent	Tidal Surge
40	6.95	44°02'00"	69°50'23"	Bowdoinham	Good	Tidal Surge
41	8.89	44°00'24"	69°53'42"	Bowdoinham	Excellent	Tidal Surge
42	8.00	43°54'52"	69°48'48"	Phippsburg	Excellent	Tidal Surge
43	8.94	43°49'50"	69°48'52"	Phippsburg	Excellent	Tidal Surge
44	8.65	43°48'58"	69°48'36"	Phippsburg	Excellent	Tidal Surge
45	7.71	43°47'23"	69°48'27"	Phippsburg	Excellent	Tidal Surge
46	10.41	43°45'12"	69°49'33"	Phippsburg	Excellent	Tidal Surge

Site Number	Elevation (feet) NGVD29	Latitude	Longitude	City	Rating	Source
47	11.32	43°43'10"	69°51'11"	Phippsburg	Excellent	Tidal Surge
48	9.19	43°43'48"	69°50'20"	Phippsburg	Excellent	Tidal Surge
49	10.15	43°46'27"	69°52'03"	Phippsburg	Excellent	Tidal Surge
50	9.66	43°50'16"	69°51'00"	West Bath	Excellent	Tidal Surge
51	10.91	43°51'10"	69°53'19"	Harpswell	Excellent	Tidal Surge
52	9.00	43°49'15"	69°55'12"	Harpswell	Excellent	Tidal Surge
53	9.06	43°47'13"	69°56'04"	Harpswell	Excellent	Tidal Surge
54	9.30	43°47'40"	69°56'49"	Harpswell	Excellent	Tidal Surge
55	10.84	43°45'34"	69°58'25"	Harpswell	Excellent	Tidal Surge
56	10.35	43°44'56"	69°59'32"	Harpswell	Excellent	Tidal Surge
57	9.38	43°51'29"	69°54'51"	Harpswell	Excellent	Tidal Surge
58	9.38	43°51'56	69°54'58"	Brunswick	Excellent	Tidal Surge
59	9.02	43°46'39"	70°01'06"	Harpswell	Excellent	Tidal Surge
60	9.03	43°48'26"	69°59'39"	Harpswell	Excellent	Tidal Surge
61	9.02	43°52'06"	69°59'37"	Brunswick	Excellent	Tidal Surge
62	8.57	43°51'48"	70°01'14"	Brunswick	Excellent	Tidal Surge
63	9.33	43°48'39"	70°06'08"	Freeport	Excellent	Tidal Surge
64	9.08	43°51'25"	70°05'06"	Freeport	Excellent	Tidal Surge
65	9.26	43°50'27"	70°06'01"	Freeport	Excellent	Tidal Surge

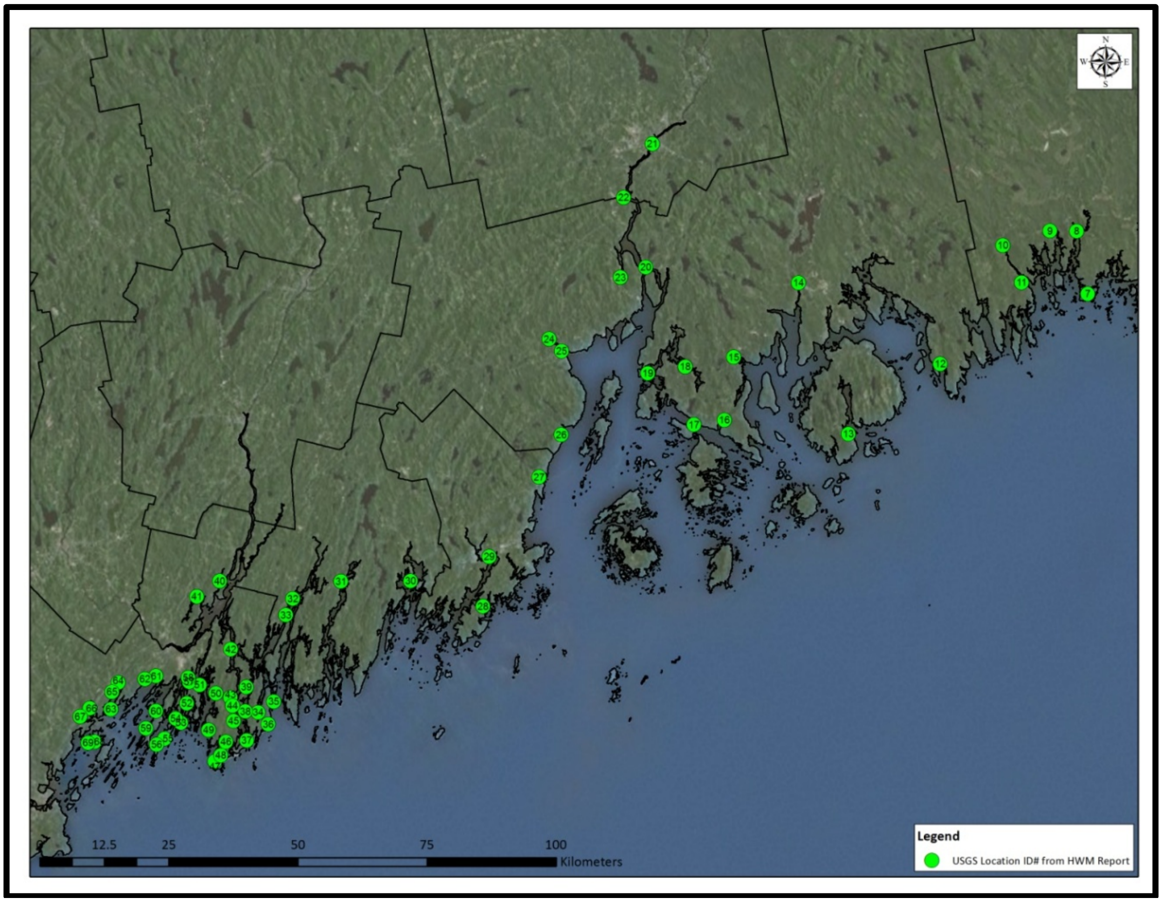

Figure 2-6 : USGS High Water Mark Locations

2.1.4 Tidal Flood Profile Information

Tidal flood profile information was used to generate boundary conditions for the STWAVE and RMA2 models for the 1-percent-chance-annual event simulation. Offshore 1-percent-annual-chance stillwater levels were taken from *Updated Tidal Profiles for the New England Coastline* (Strategic Alliance for Risk Reduction [STARR], 2012). Figure 2-7 shows the tidal flood profiles for the offshore section of the study area along the Maine coast.

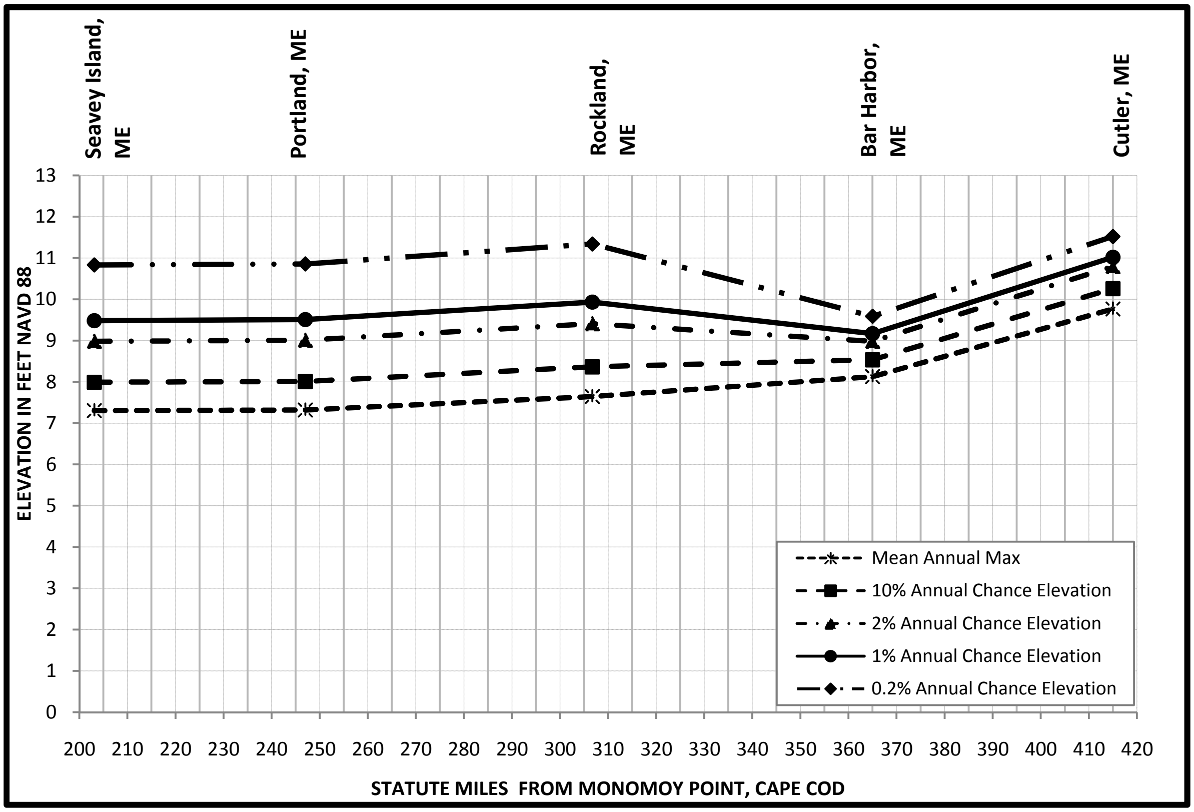

Figure 2-7 : New England Tidal Flood Profiles

2.1.5 Streamflow

Several major rivers discharge to the ocean within the study area. Average monthly streamflow values were obtained from the USGS (USGS, 2012) for locations within the study area where data was available. Table 2-3 shows available streamflow data within the study area. These data were used to estimate river discharges during the 1-percent-annual-chance storm event for RMA2 simulations of storm surge, as described in Section 3.

Table 2-3 : USGS Stream Gage Locations and Streamflow Information

Gage ID	Location	Period of Record	Average Streamflow (m^3/sec)
USGS 01059000	Androscoggin River near Auburn, Maine	1928-2011	145
USGS 01049265	Kennebec River at North Sidney, Maine	1978-2011	240
USGS 01036390	Penobscot River at Eddington, Maine	1979-1996	285

2.1.6 NDBC Wave and Wind Characteristics

The original approach to develop input wave conditions relied on using data from the USACE Wave Information Study (USACE, 2010) for the Atlantic Coast, for which WIS model results are available from 1980 to 1999. Bulk wave parameters are available online for public download along the entire Atlantic coastline. Two-dimensional wave spectra can be obtained by coordinated with USACE. As the two-dimensional wave spectrum is the desired input for STWAVE, the WIS data is an excellent source for boundary conditions. WIS station 63037 was selected as being representative of the offshore deepwater wave conditions for York and Cumberland counties, and WIS station 63233 was selected as being representative of offshore deepwater wave conditions for all other counties. During validation of the storm event, it was discovered that the transformation of the WIS data by the STWAVE model resulted in a negative bias of wave height at observations within the model domain. A comparison was made to the WIS model output at that same observation point, and it also indicated a negative bias of wave height. Personal communication with B. Jensen of the USACE Engineering Research and Development Center (March 15, 2012) indicated that there is the potential that the WIS grid may be the problem such that Nova Scotia blocked distant winds or that the wave model could have dropped low frequency energy during the event simulations. It was felt that the model was more at cause as WIS output at two other observation points in the Gulf of Maine did not have the same negative bias.

In order to address the negative bias in the WIS model in this area, a decision was made to switch to a different offshore data source. Data for wave heights, wave periods, wind speeds and wind directions were collected from the National Data Buoy Center (NDBC) Buoy 44005 (NDBC, 2012). The location of NDBC Buoy 44005 is shown in Figure 2-8. Most data was recorded hourly, with some data recorded every 3 hours. Data from this buoy were collected from 1979 through 2011. Data gaps lasting two weeks or more were noted and totaled. Accounting for these long-term data gaps limits the total useable data from 33 years (1979 through 2011) to 28 years of wave and wind data. Data recording methods did not vary with recording frequency.

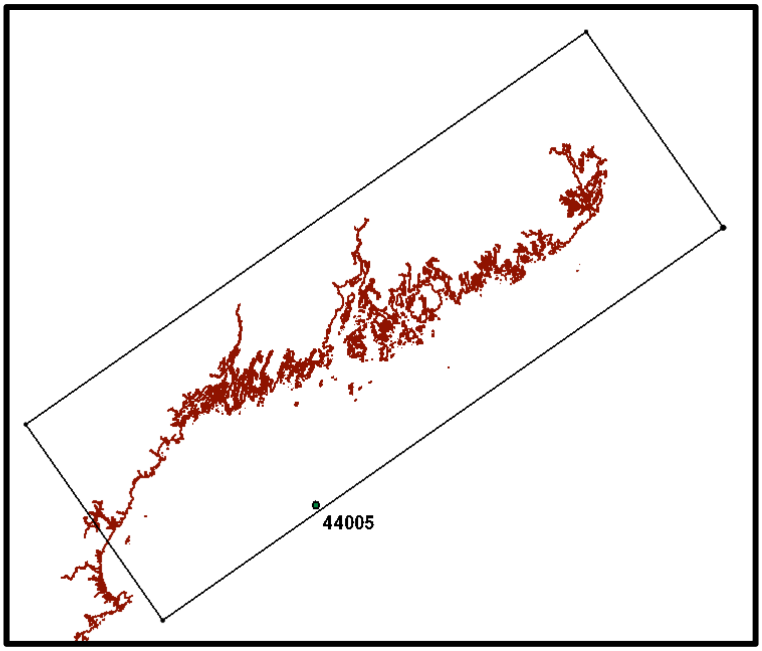

Figure 2.8 : NDBC Buoy 44005 Relative to the STWAVE Model Grid

NDBC Buoy Data (wave height and wind speed and direction) was also collected from the following buoys for the years 2007 and 2009 as available:

- 44007
- 44030
- 44031
- 44032
- 44033
- 44034

The locations of these buoys are shown in Figure 2-9. Because of Buoy 44005's location, wave heights at this buoy were representative of wave conditions at the coarse grid's offshore boundary. This observational data was used to develop boundary conditions for model validation and the 1-percent-annual-chance simulation. Wave heights recorded at all buoys were used to select validation storms, and to validate the STWAVE model.

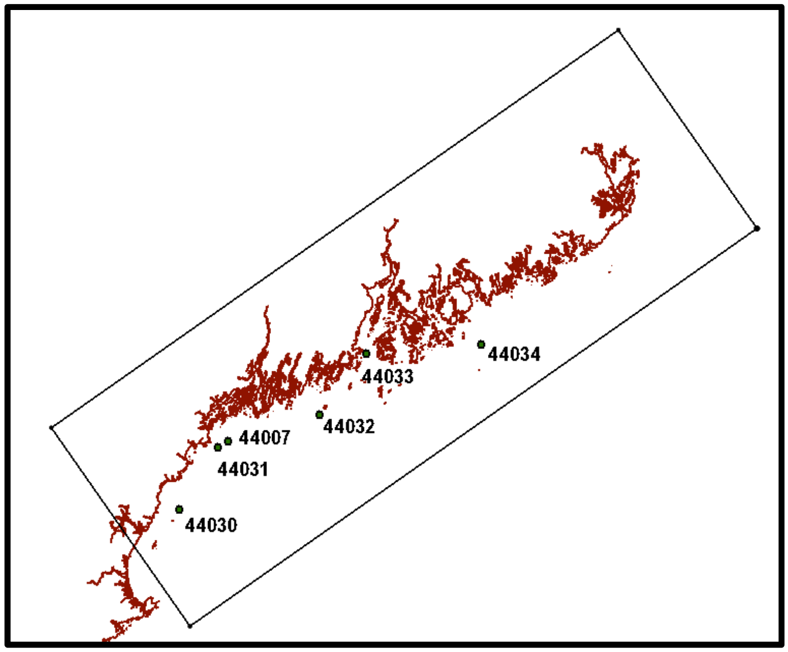

Figure 2-9 : NDBC Buoys Used to Validate STWAVE Model

2.2 Development of Calibration and Validation Data

The STWAVE and RMA2 models were calibrated and/or validated to observed data from recorded extreme storm events identified from the historical period of record. Calibration and validation simulations were performed of the historical storm events prior to simulation of the 1-percent-annual-chance event.

2.2.1 RMA2 Calibration / Validation Data

The February 7, 1978 storm event was selected for the RMA2 model calibration, because detailed high water mark data throughout the study area is available from USGS for this storm event, as discussed in Section 2.1.3. This storm has been considered "one of the most severe winter storms of record" (USGS, 1979).

The January 9, 1978 storm event was selected for RMA2 model validation. High water mark data is available for several locations for this storm event.

Both the Portland and Bar Harbor tide gages recorded hourly water level data during the RMA2 model calibration and validation storm events. There were slight differences in water surface elevations recorded during the storm event between the two tide gages. Figure 2-10 shows the water surface elevation of both the Portland and Bar Harbor gages for the February 1978 storm event. Figure 2-11 shows the water surface elevation of both the Portland and Bar Harbor gages for the January 1978 storm event. During both storm events, the Bar Harbor tide gage reported slightly higher water surface elevations than the Portland tide gage. Since the Bar Harbor gage falls within the study area, the Bar Harbor hourly observations were applied to the RMA2 model to route the storm surge to the backwater areas of the model domain.

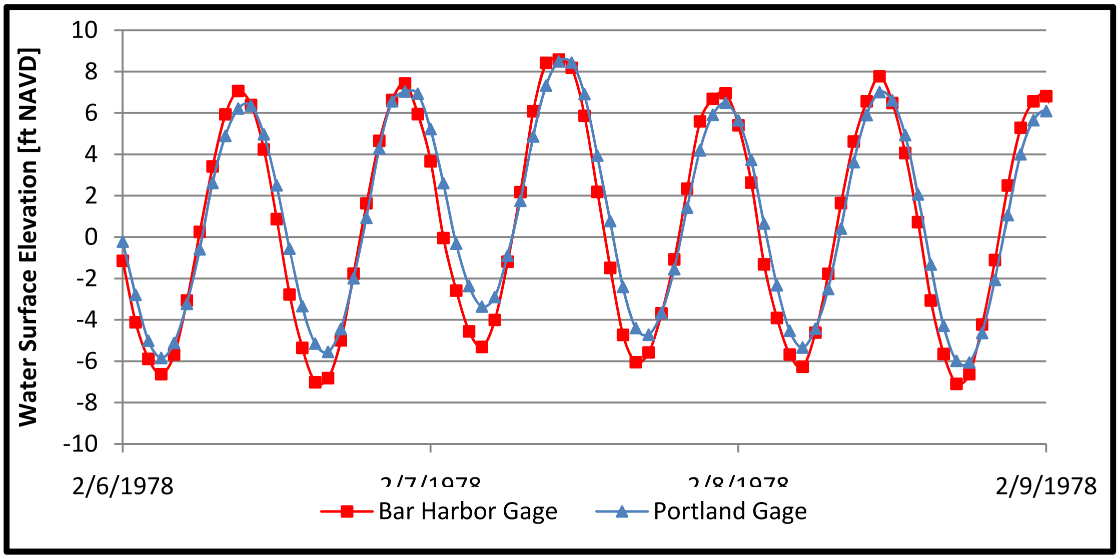

Figure 2-10 : Water Surface Elevation Data from the Bar Harbor and Portland Tide Gages for the February 7, 1978 Storm Event

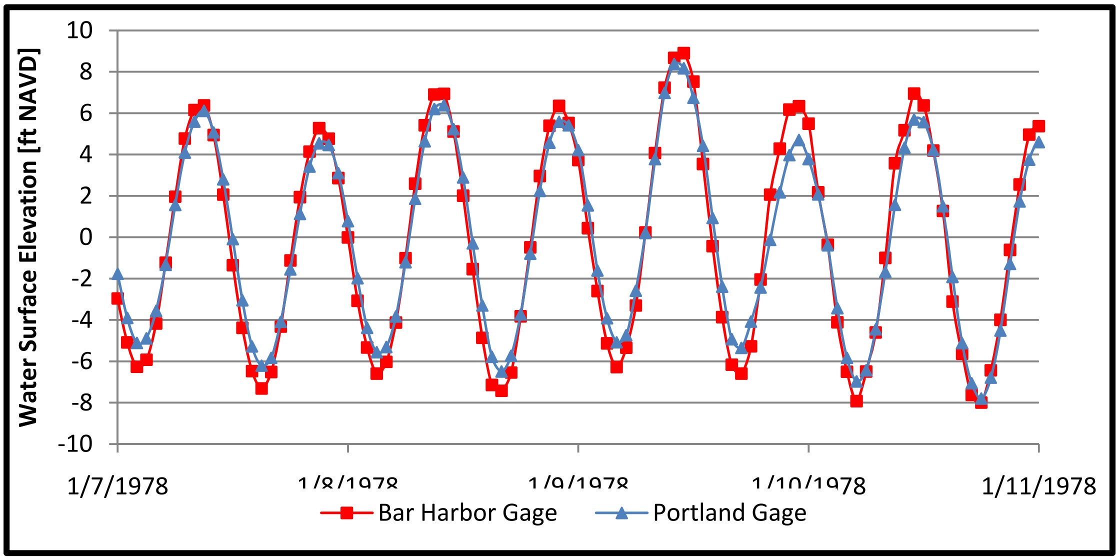

Figure 2-11 : Water Surface Elevation Data from the Bar Harbor and Portland Tide Gages for the January 9, 1978 Storm Event

For the February storm event, the maximum water surface elevation at the Bar Harbor tide gage of 2.61 meters (8.58 feet) occurred on February 7, 1978 at 10:00 AM. For the January storm event, the maximum water surface elevation at the Bar Harbor tide gage of 2.71 meters (8.90 feet) occurred on January 9, 1978 at 11:00 AM. These high-tide maximum water surface elevation time series were used as inputs to the RMA2 models. Adjustments to these time series are discussed further in Section 3 of this report.

2.2.2 STWAVE Validation Data

As discussed in Section 4, sufficient data is not available to calibrate the boundary conditions applied in the STWAVE model. As a result, the STWAVE model was not calibrated. However, two validation simulations were performed. Methodologies for developing model boundary and input conditions for the validation simulations are discussed below.

2.2.2.1 Validation Event Selection

Nor'easters were selected as validation storms in the STWAVE model. Nor'easters are winter storms occurring between September and April. Like hurricanes, they are cyclonic storm systems. While less intense than hurricanes, they are more slow-moving and often result in larger waves as a consequence (USGS, 2010).

Model validation is more robust if multiple data observations are available to make model-data comparisons. Because many NDBC buoys along the Maine coast have been installed since the late 1990's, validation events were selected from the wave record between 2000 and 2011. Several nor'easters were identified from the recent record and two were selected because of NDBC buoy data availability; collectively they allow for STWAVE model validation at the six NDBC buoys shown in Figure 2-9 above. The two storms selected were: (1) December 16-18, 2007 and (2) December 9-10, 2009. Characteristics of these events are discussed in the following section.

The wave height characteristics, wind speed and direction, and tidal elevations used to characterize these storms are summarized in Table 2-4. Methodologies for determining the values presented the table are discussed in the following sections. Because STWAVE is a steady state model, characteristic values are used to represent the events. As a result, the points in time where characteristic values were recorded in the observational data may not correspond perfectly with each other.

Table 2-4 : STWAVE Validation Storm Characteristics

Characteristic	December 2009 Storm	December 2007 Storm
Wave Height at Buoy 44005	7.1 meters	7.4 meters
Wind/Wave Direction	125 degrees	132 degrees
Wind Speed	15 meters/second	17 meters/second
Tidal Elevation	None applied to coarse model (as explained in Section 4)	1.81 meters NAD88 for Hancock area 1.71 meters NAVD88 for York/Cumberland

2.2.2.2 Wave Spectrum Development

A Joint North Sea Wave Project (JONSWAP) parameterization (Aquaveo, 2011) was used to generate a wave energy spectrum for the STWAVE models, based on the determined wave height, wave period, total water depth, and dominant energy direction. For each of the STWAVE model validation events, wave data used to determine off-shore incident wave energy for the model was collected from the National Data Buoy Center (NDBC) Station 44005. The recorded wave heights for each storm are shown in Figures 2-12 and 2-13. The wave height considered to represent the storm is the maximum wave height during the storm event's duration. The maximum wave height for the December 2007 storm was 7.4 meters on December 17, 2007. For the December 2009 storm, the maximum wave height of 7.1 meters occurred on December 9, 2009. The wind directions during these peak wave heights were 125 degrees from North for the 2009 storm and 132 degrees from North for the 2007 storm.

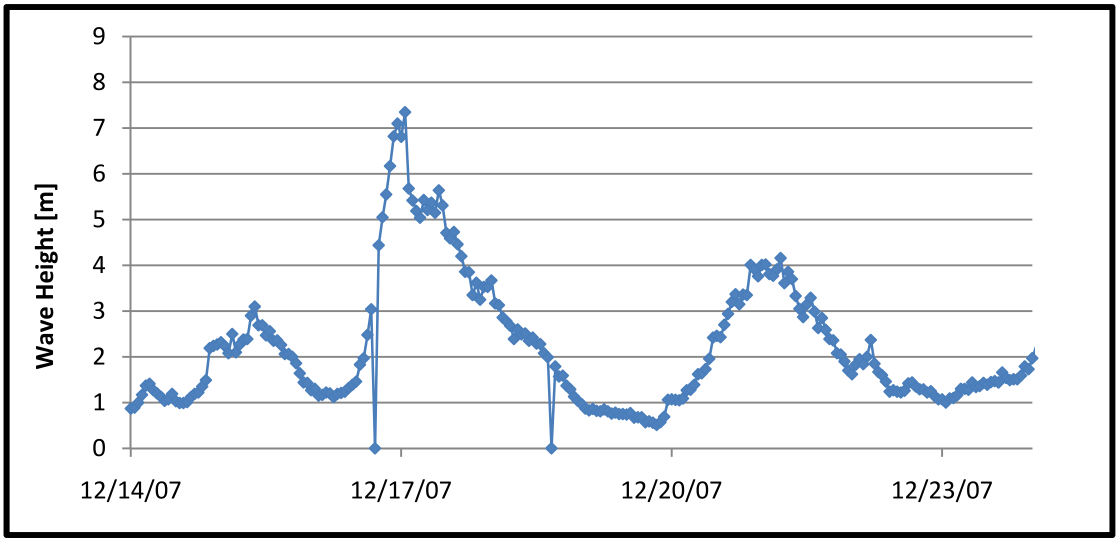

Figure 2-12 : Wave Height Recorded at NDBC Buoy 44005 During December 2007 Storm Event

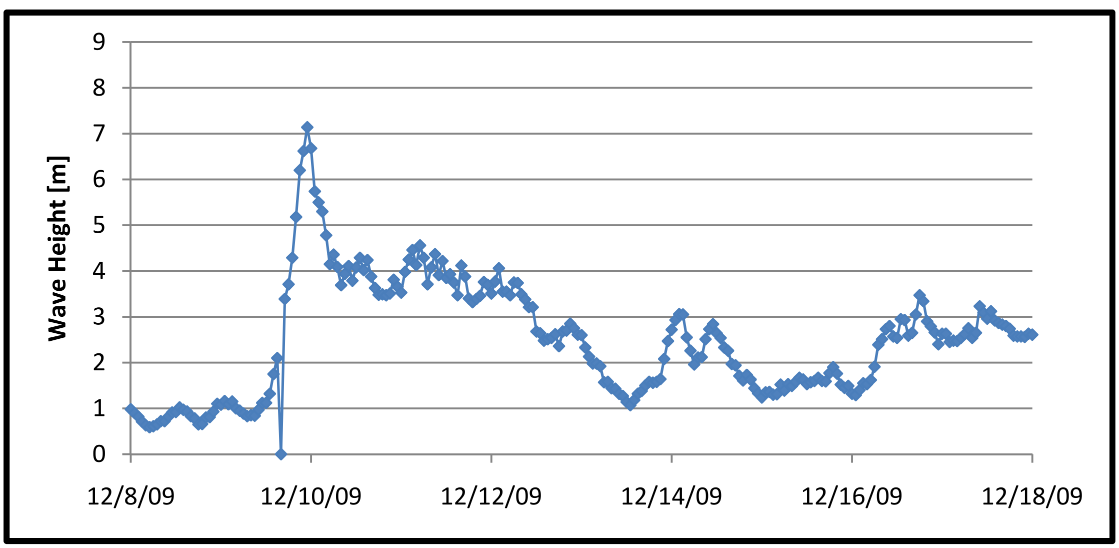

Figure 2-13 : Wave Height Recorded at NDBC Buoy 44005 During December 2009 Storm Event

Because Buoy 44005 does not record wave spectrum directional data, wave height and dominant wave period data were used to parameterize a JONSWAP spectrum. The parameterized spectrum was applied at the offshore boundary of the coarse grid. Buoy 44005 does record energy frequency, and the JONSWAP spectrum calculated within

STWAVE was compared with the frequency observations. The frequency distribution compared well between observed and parameterized spectra; both the parameterized and observed energy spectra had qualitatively similar distributions, and peak energy density frequencies differed by less than 0.05 Hertz.

Because Buoy 44005 is 6 kilometers within the model domain, the JONSWAP wave spectrum applied at the boundary was adjusted using a larger wave height parameter than was observed at Buoy 44005, such that the modeled wave height at Buoy 44005 matched the observed wave height.

2.2.2.3 Wind and Tide Development

The wind speed at Buoy 44005 at the time of the peak wave height for the December 2009 storm was 15 meters/second, with wind speeds above 18 meters/second in the hours preceding the peak wave height, as shown in Figure 2-14. The wind speed during the peak wave height for the December 2007 storm is 10.6 meters/second, while peak wind speeds before and after the peak wave height are closer to 17 meters/second (with a peak above 18 meters/second), as shown in Figure 2-15. This discrepancy between peak wind and wind observed during the peak wave height in 2007 suggests that the wind speed during the peak wave height may have been an anomalous, or potentially an erroneous, reading. A wind speed of 17 meters/second is used to characterize the December 2007 storm.

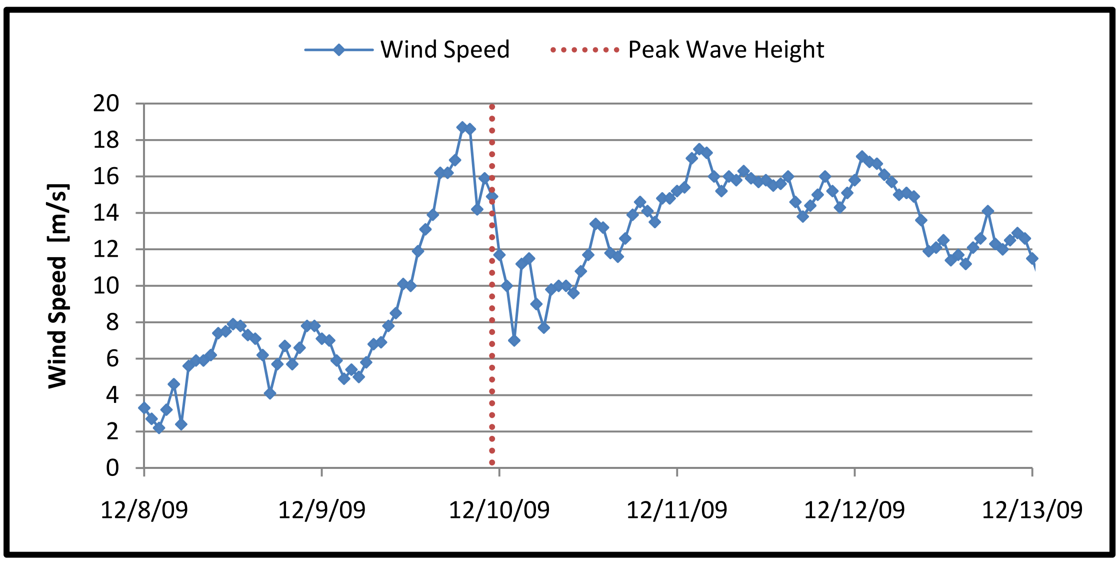

Figure 2-14 : Wind Speed Recorded at NDBC Buoy 44005 During December 2009 Storm Event

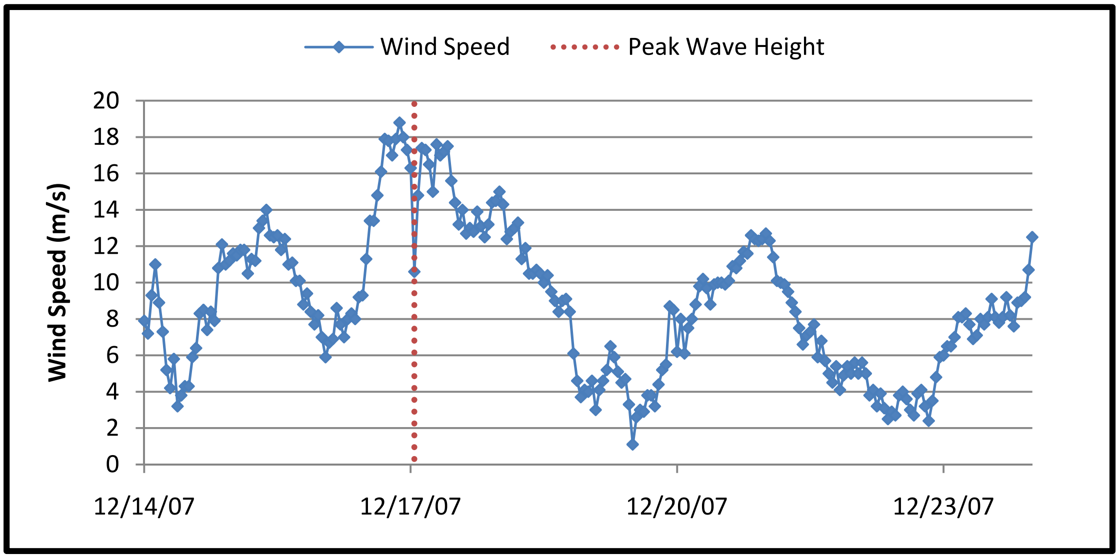

Figure 2-15 : Wind Speed Recorded at NDBC Buoy 44005 During December 2007 Storm Event

For Hancock, Waldo, Knox, Lincoln and Sagadahoc Counties, peak tide elevations observed at the Bar Harbor (1.88 meters NAVD88) and Portland (1.73 meters NAVD88) tide gages during each event were averaged, giving a tide elevation of 1.81 meters NAVD 88. For York and Cumberland Counties, peak tide elevations at the Wells (1.69 meters NAVD88) and Portland (1.73 meters NAVD88) tide gages were averaged, giving a tide elevation of 1.71 meters NAVD88.

2.3 Development of 1-Percent-Annual-Chance Event Characteristics

The development of model boundary conditions and applied stresses for the RMA2 and STWAVE model simulations of the 1-percent-annual-chance storm from the available data records are described below.

2.3.1 RMA2 1-Percent-Annual-Chance Data

The 1-percent-chance-annual stillwater levels were obtained from the tidal flood profile information discussed in Section 2.1.4. There are three gage locations within or near the RMA2 study area with values for the 1-percent-annual-chance water surface elevations. They are the Portland, Rockland, and Bar Harbor, Maine gages. The 1-percent-annual-chance water surface elevation values, however, are statistically derived water surface elevations and are not associated with a tidal signal. To accurately represent the propagation of the 1-percent-annual-chance water surface elevation into the backwater areas, a tidal signal must be applied to the offshore boundary of the RMA2 model. Therefore, a tidal signal was generated to represent the 1-percent-annual-chance event.

The statistical analysis of the Rockland tide gage data record produces the highest 1-percent-annual-chance water surface elevation peak water surface elevation value of 3.03 meters (9.93 feet) for the 1-percent-annual-chance surge event. However, the length of the data record used to produce the Rockland gage 1-percent-annual-chance water surface elevation (6 years) was less than the Portland or Bar Harbor gages (95 and 62 years, respectively). Since the Bar Harbor tide gage is within the study area, the Bar Harbor tide gage was selected to generate the water surface elevation time series applied to the off-shore boundary of the RMA2 model for simulation of the 1-percent-annual-chance event. The peak water surface elevation value calculated for the Bar Harbor gage 1-percent-annual-chance event was 2.79 meters (9.17 feet).

2.3.2 STWAVE 1-Percent-Annual-Chance Data

The 1-percent-annual chance event is characterized with a wave energy spectrum, wind speed and direction, and tidal elevation.

2.3.2.1 Wave Characteristics

Input data applied to the STWAVE model simulations of the 1-percent-annual-chance event include a JONSWAP wave energy spectrum parameterized by wave height, wave period, and incident wave direction.

The 1-percent-annual-chance wave height was determined in accordance with the Generalized Extreme Value (GEV) Analysis described in the FEMA Guidelines (FEMA, 2007). Wave height observations at Buoy 44005 between 1979 and 2011 (the time period for which recordings are available) were analyzed for annual maximum wave heights. The annual maximum wave heights were fit to the GEV family of distributions, including normal, log normal, Weibull, Frechet, Gumbel, 2-Parameter Gamma, and 3-Parameter Pearson distributions. The Gumbel distribution resulted in the largest 1-percent-annual-chance wave height (10.6 meters) with a correlation coefficient of 0.992.

A qualitative examination of the observed relationship between wave period and wave height suggested that the wave period of the largest storm on record at Buoy 44005 (10.1 meter wave height, 12.5 second period) is appropriate to use for the STWAVE simulation of the 1-percent-annual-chance storm. The wave direction perpendicular to the off-shore boundary was selected to develop the energy spectrum, to be conservative; the model grid should transfer incident waves normal to the boundary with minimal numerical dispersion of wave energy.

2.3.2.2 Wind Field

Wind speed applied to the STWAVE simulation of the 1-percent-annual-chance event was calculated using an extremal analysis similar to the analysis used for calculating wave height described in section 2.3.2.1. Wind speed observations at Buoy 44005 between 1979 and 2011 (the period of record) were analyzed for annual maximum wind speeds. The annual maximum wind speeds were fit to several statistical distributions, including normal, log normal, Weibull, Gumbel, GEV, 2-Parameter Gamma, and 3-Parameter Pearson distributions. The GEV distribution resulted in the largest 1-percent-annual-chance wind speed (25.1 meters/second) with a correlation coefficient of 0.996.

The wind direction was applied perpendicular to the off-shore model grid. This wind direction angle varies depending on the grid orientation, but was used to be represent a conservative scenario. Wind blowing in a direction aligned with the grid cell orientation will be incorporated into model solutions with minimal numerical dispersion.

2.3.2.3 Tidal Elevations

Tidal elevations were determined for the 1-percent-annual-chance event from the *Updated Tidal Profiles for the New England Coastline,* March 2012 Report (STARR, 2012). For Hancock, Waldo, Knox, Lincoln and Sagadahoc Counties, the tidal elevation was set to 3.05 meters NAVD88 (10 feet) per the 1-percent-annual-chance elevation at the Rockland gage (STARR, 2012). For York and Cumberland Counties, the tidal elevation was set to 2.9 meters NAVD88 (9.5 feet) per the 1-percent-annual-chance elevation at the Portland gage (STARR, 2012). These gages were selected because of their locations close to the middle of each of the mid-sized model domains. Elevations were rounded to the nearest 0.15 meter.

3. Storm Surge Model

3.1 Introduction

This section describes the development, calibration, and verification of the numerical models used to simulate spatially variable storm surge for the 1-percent-annual-chance storm within the Gulf of Maine and its embayments and estuaries.

The study area of the RMA2 models spans Knox, Lincoln, Sagadahoc, Waldo, and Hancock Counties and is represented by three non-overlapping model domains due to the size of the study area, the complexity of the shoreline, and the model code's solution matrix limitation. Figure 3-1 shows the layout of the three model domains. The westernmost model covers the coastline from Freeport to South Thomaston, Maine, including the northeast portion of Casco Bay and the mouths of the Androscoggin, Kennebec, Sheepscot, and Damariscotta Rivers. The central model covers Penobscot Bay, including the Bagaduce River and Penobscot River up to the Eddington dam, and the coastline from South Thomaston to Brooklin, Maine. The easternmost model covers Blue Hill Bay, Frenchman Bay, and Jericho Bay including the coastline from Brooklin to South Addison, Maine.

The RMA2 models were calibrated to the historic coastal storm event of February 7, 1978 and validated to the January 9, 1978 coastal storm event. The calibrated and validated models were used to simulate the 1-percent-annual-chance storm event.

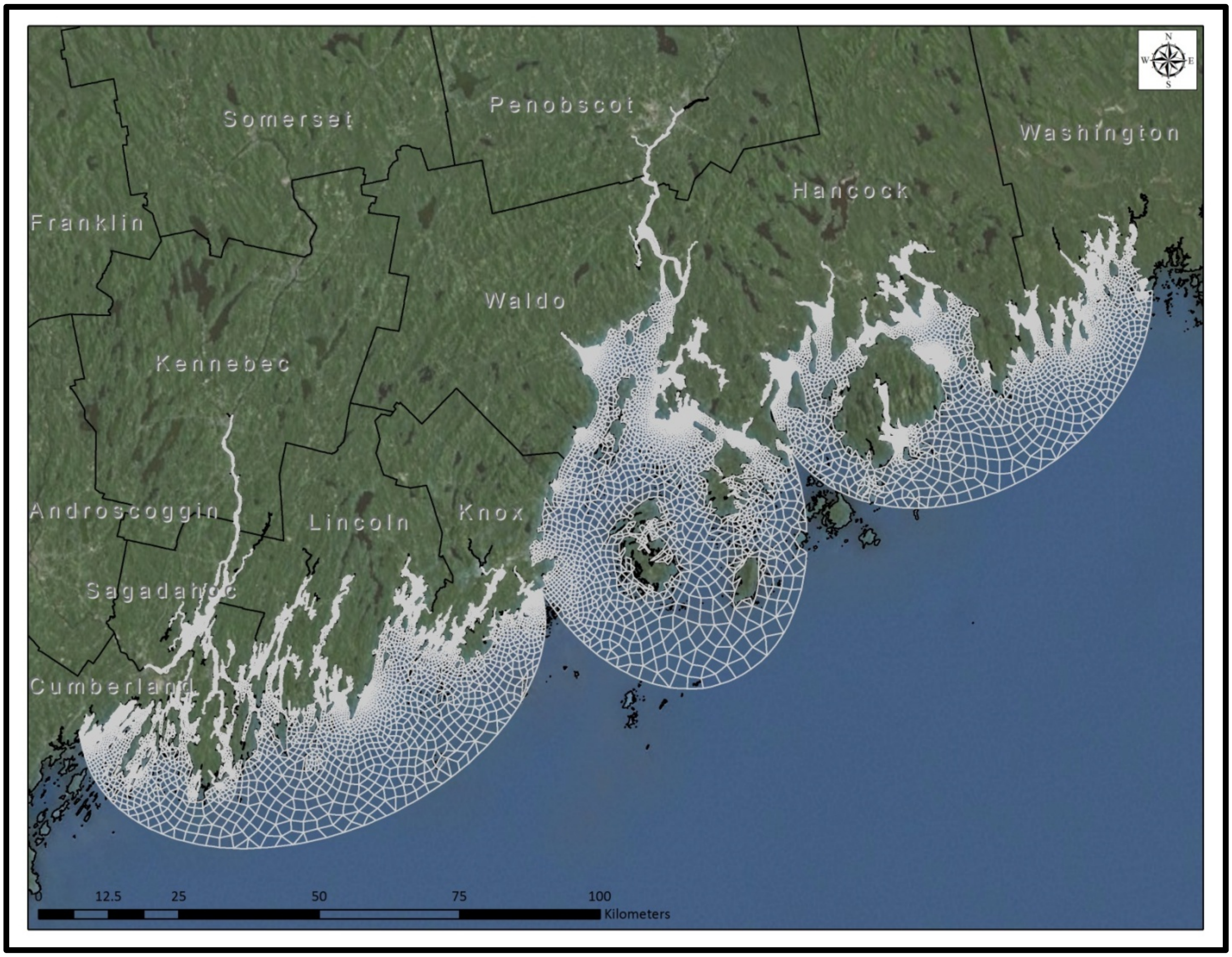

Figure 3-1 : RMA2 Model Domains

3.2 Model Development

This section describes the development of the RMA2 models, including a description of the model code, generation of the finite-element mesh, boundary conditions and applied stresses, and simulation parameters.

3.2.1 Numerical Model Description

This study utilized modeling code RMA2 version 4.58 (last modified on September 15, 2009), which was originally developed by Resource Management Associates (King, 1990). RMA2 is a two-dimensional, depth-averaged finite element hydrodynamic modeling code. It computes water surface elevation and depth-averaged horizontal velocity at the coastline from a tidal boundary condition. RMA2 solves the depth averaged Navier-Stokes equations and accounts for bed friction dissipation (Manning's n or Chezy equations) and turbulent eddy viscosity. RMA2 was incorporated into the TABS analysis package written by the U.S. Army Corps of Engineers Waterways Experiment Station (USACE-WES) (USACE, 2012).

The RMA2 models for this study were generated in the Maine State Plane West (NAD83) meters horizontal coordinate system with a vertical datum of NAVD88 meters.

3.2.2 Mesh Generation

The study area was divided into three separate model domains due to computing limitations. There is no overlap between the three models. The three independent models were created from portions of one larger grid, or mesh, which extended across the entire study area. The original study-wide mesh of variably sized quadratic and triangular elements was generated within the Surface-Water Modeling Solution (SMS) software (Aquaveo, 2011) platform using a linearly interpolated scalar paving density, which resulted in a grid cell size range between approximately 100 kilometers in width far offshore to 50 meters in width in the upstream reaches. Any island with an area greater than 250,000 square meters was included as an obstruction within the model domain. Any island smaller than 250,000 square meters was not considered in the mesh generation process.

Figures 3-2 through 3-4 show the individual RMA2 model domains from west to east.

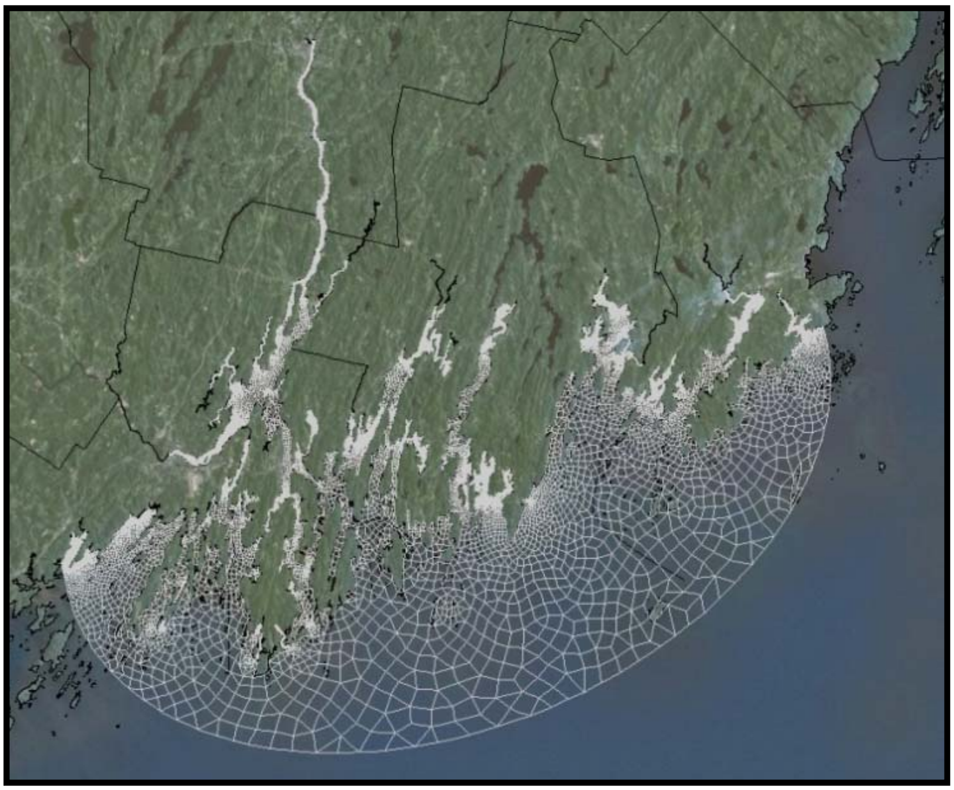

Figure 3-2 : RMA2 Western Model Domain

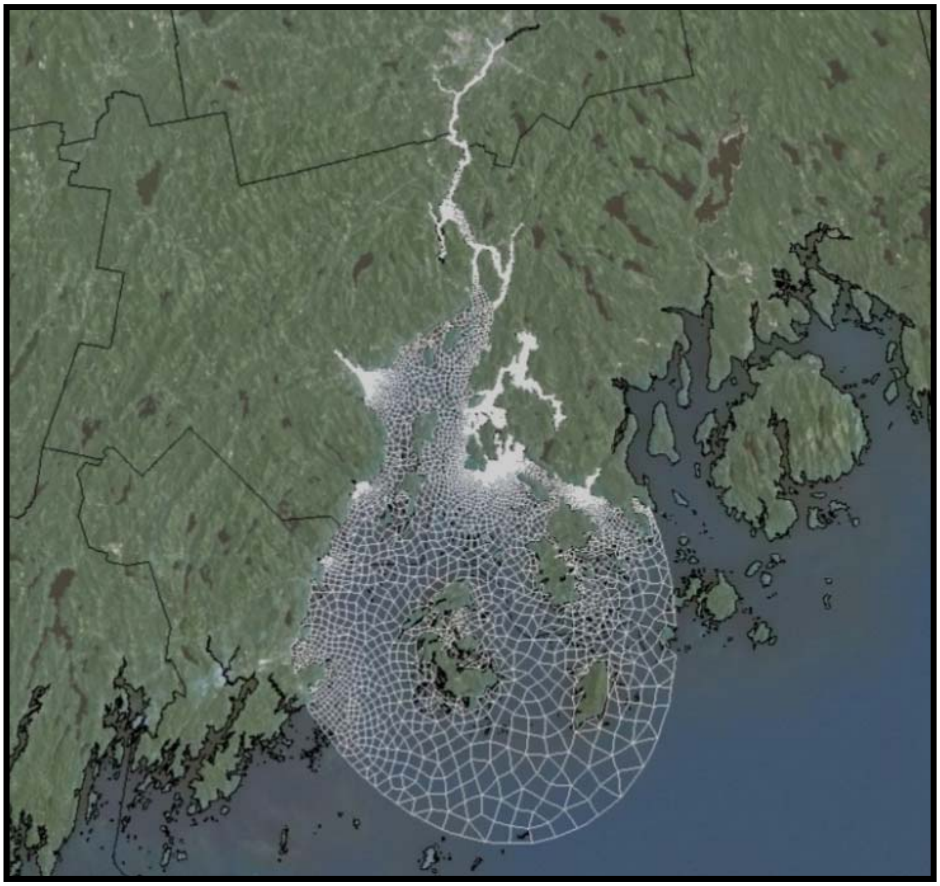

Figure 3-3 : RMA2 Penobscot Bay Model Domain

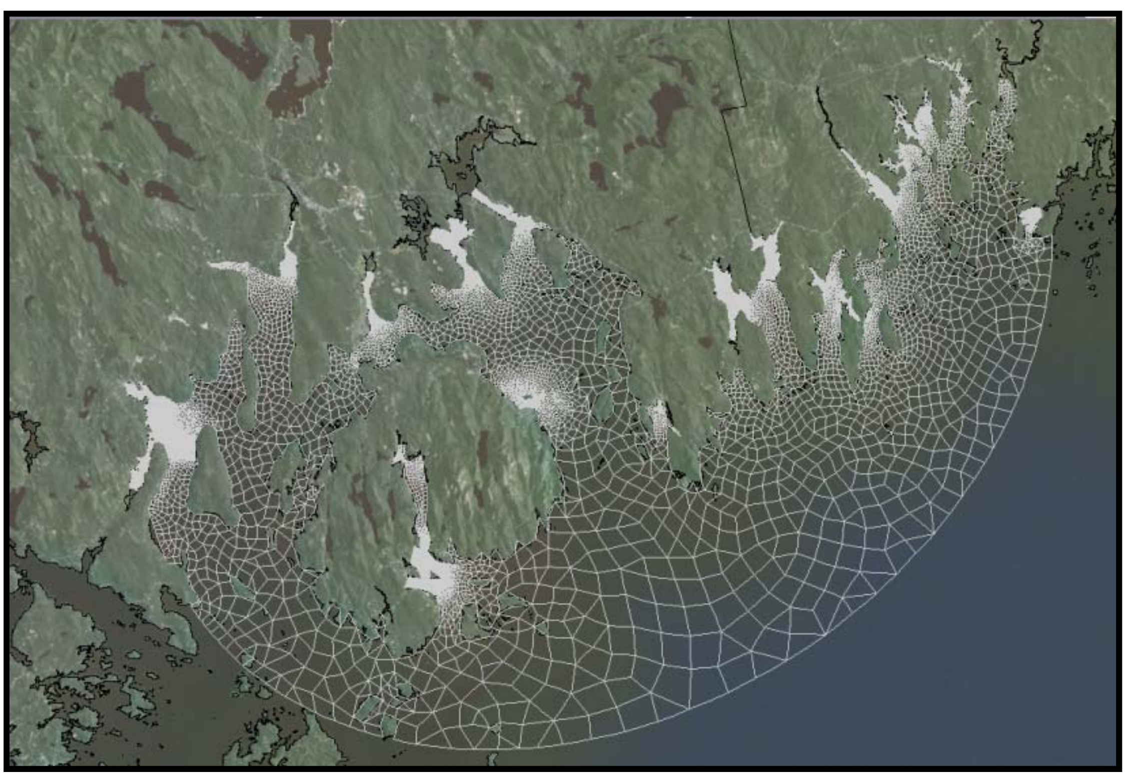

Figure 3-4 : RMA2 Eastern Model Domain

3.2.3 Bathymetric Interpolation

Bathymetric data, as discussed in Section 2.1.1, was linearly interpolated onto the model meshes. For islands that were not removed from the model domain, bathymetric data was interpolated across the landform.

3.2.4 Model Simulation Parameters

A dynamic (time-varying) simulation period of 16 hours at 15 minute time steps with dynamic depth convergence of 0.05 meters was set for all RMA2 model runs.

3.2.5 Boundary Conditions

The offshore model boundaries, each with a semi-circular shape, were assigned a water surface elevation time series as discussed in Section 2.2.1.

The upstream reaches of rivers within the model domains were forced with monthly average streamflows in locations where USGS monthly average streamflow data was available. These streamflows were input as constant flow boundaries. Section 2.1.5 provides more detail regarding the streamflow data available within the study area. The months over which streamflows were averaged were based on model calibration, which is discussed in Section 3.3.

All other boundaries of the model domain were considered “slip” boundaries, where the direction of flow was constrained to shore parallel.

3.2.6 Turbulence

Turbulence was assigned by RMA2 iteratively to each model element for each time step using the Peclet equation. The Peclet equation defines the relationship between the average elemental velocity magnitude, elemental length, fluid density, and eddy viscosity. A sensitivity analysis was performed and a Peclet number of 20 with a minimum velocity of 0.5 meters/second was assigned for all models for eddy viscosity determination. The “User’s Guide to RMA2 WES Version 4.5” (USACE, 2011) recommends a Peclet number between 15 and 40.

3.3 Numerical Storm Surge Model Calibration

This section describes the technical approach for RMA2 model calibration and validation. The minor differences in calibration approach between the Penobscot, Eastern, and Western Models described in detail below are justified due to the shape of the offshore model domains and the representation of a singular embayment configuration versus a multiple embayment configuration.

The reported USGS high water mark locations were superimposed upon the model domain. Simulated model results were obtained from these locations to compare to the USGS high water marks. Where the USGS high water mark was located beyond the model domain, model results were obtained from the closest model element.

As described in more detail in the remainder of this section, the model was calibrated by adjusting the following:

- Specification of bottom roughness (bed friction)
- Mesh configuration
- Average streamflow for major rivers
- Input tidal signal

3.3.1 Bottom Roughness

RMA2 calculates bed friction by using Manning's equation with a user-specified n-value. All elements were initially assigned a global roughness coefficient of 0.03. Calibration of the model involved manually changing roughness coefficients for specific groups of elements. RMA2 has the capability to automatically assign a roughness coefficient during each model iteration as a function of water depth. Table 3-1 summarizes the range of roughness values used. Figure 3-5 shows a plot of the automatic roughness assignment used among the three models, the default setting within SMS. Figures 3-6 through 3-8 show the distribution of the roughness coefficients by material property for each model.

Table 3-1 : Model Roughness Values

Material ID	Roughness Coefficient
Ocean	0.03
Riverine	0.06-0.08
Upper Reaches	0.06-0.08
Embayments	Roughness by Depth

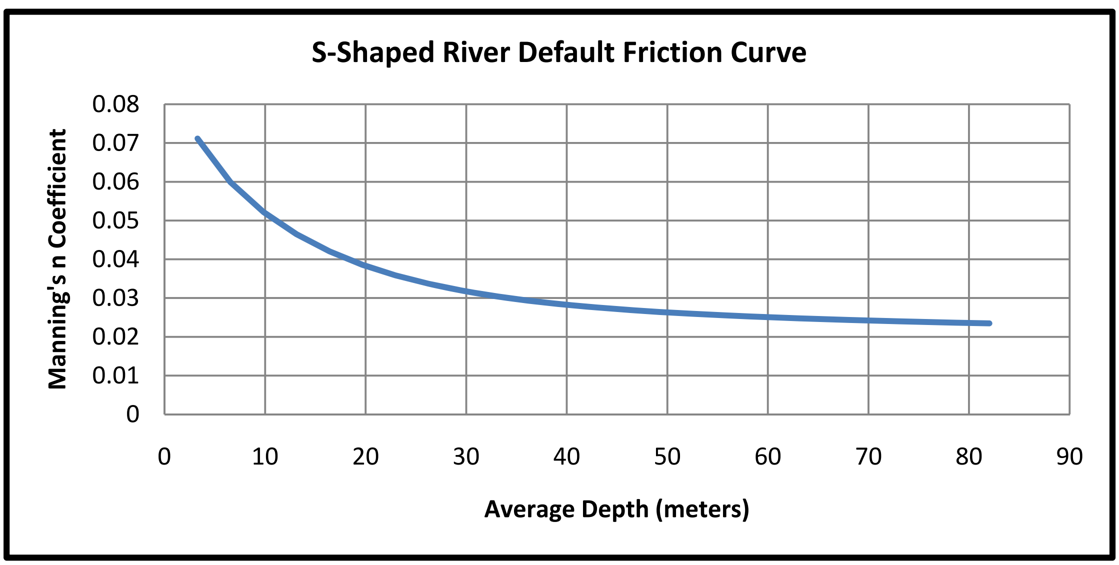

Figure 3-5 : Automatic Roughness by Depth Default Curve as defined in RMA2

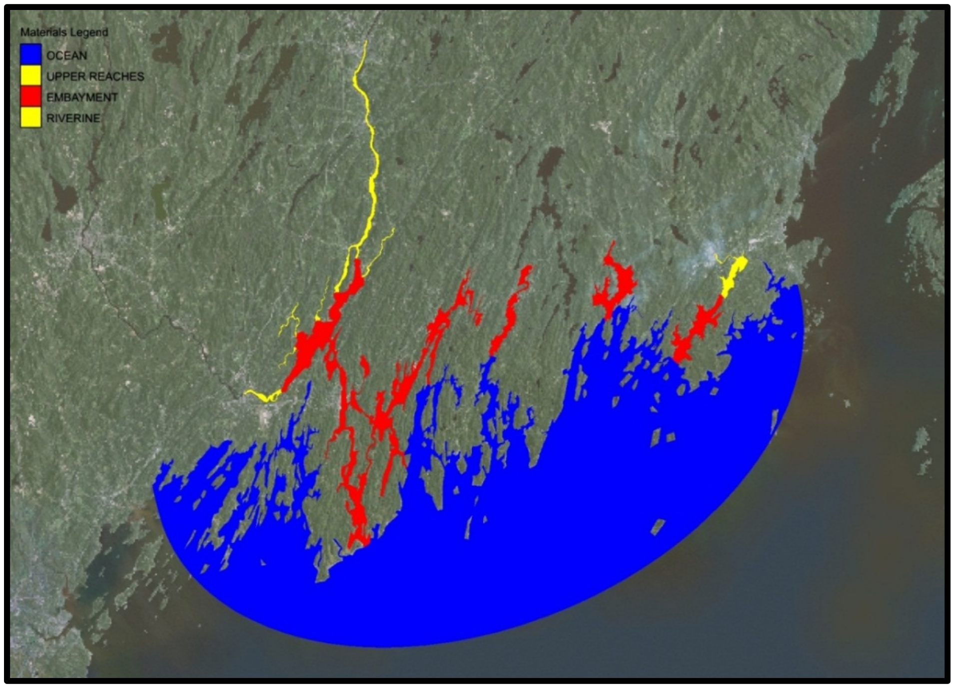

Figure 3-6 : Materials Applied to the Western RMA2 Model

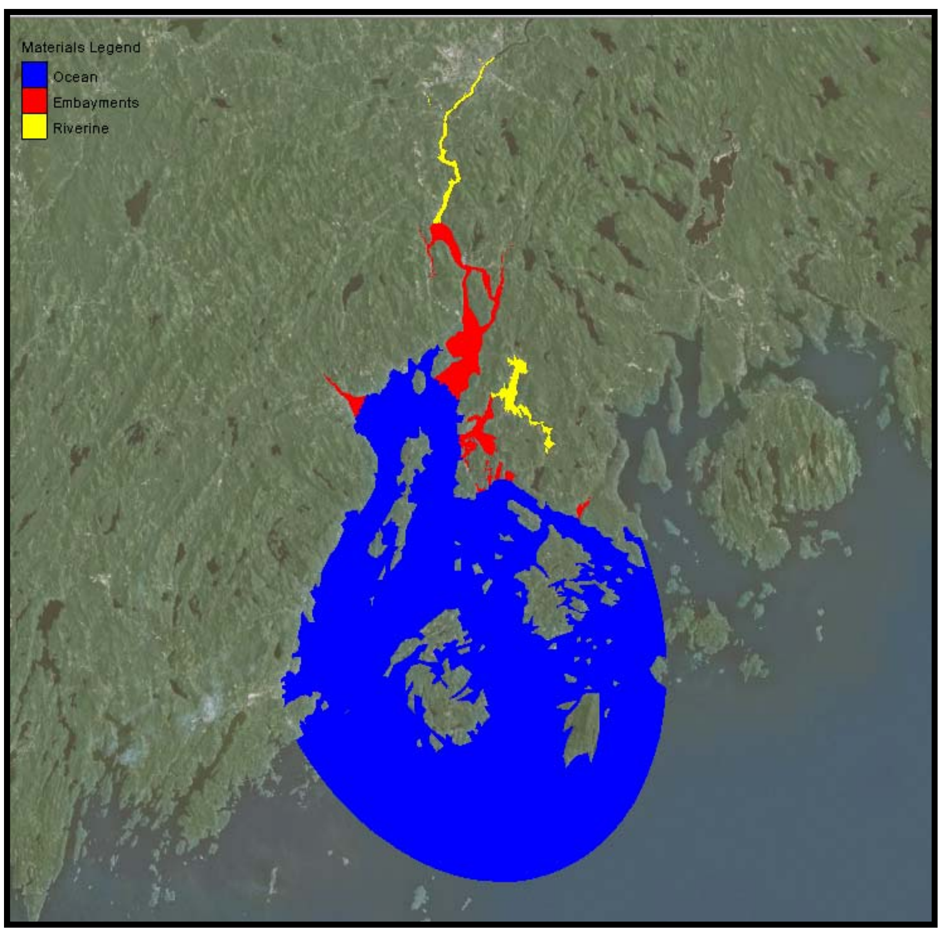

Figure 3-7 : Materials Applied to the Penobscot RMA2 Model

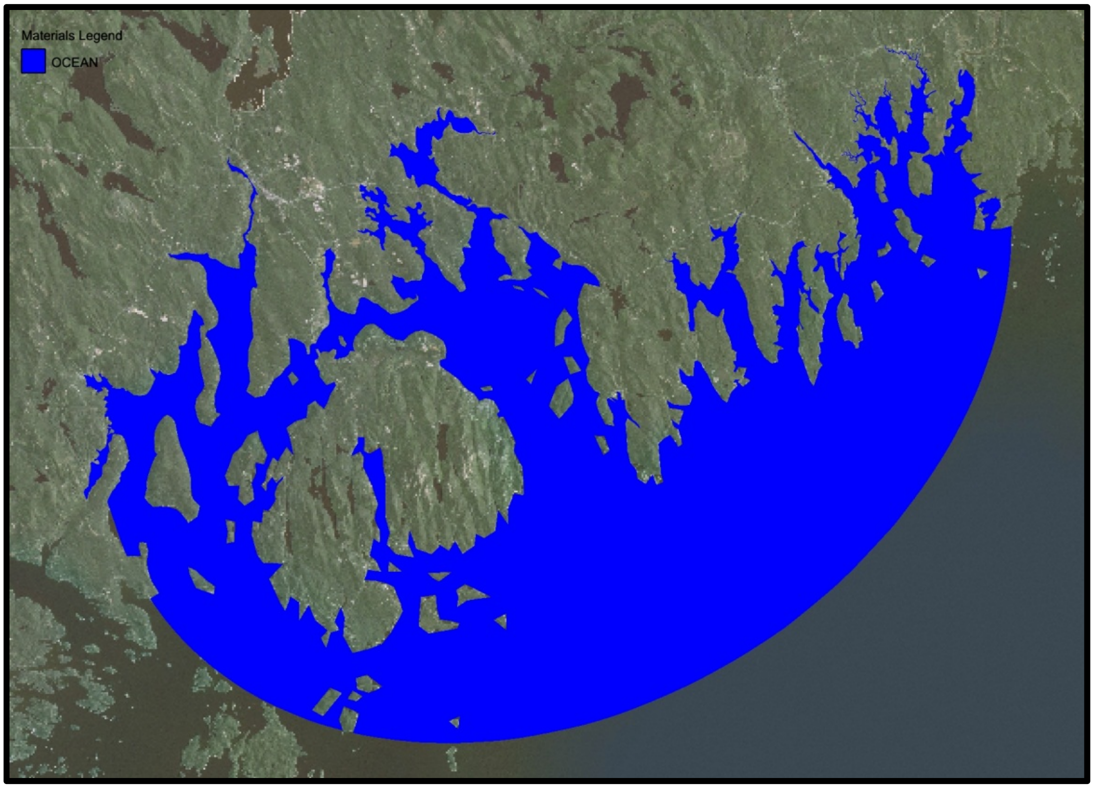

Figure 3-8 : Materials Applied to the Eastern RMA2 Model

3.3.2 Mesh Configuration

Due to the nature of the algorithm used to generate the meshes, there were locations in each model that required either greater detail or adjustments. Refinements of the mesh were performed to adequately capture complex bathymetric changes or complex shoreline configurations. To capture funneling around islands or obstructions, model nodes and elements were adjusted to define specific flow paths. In some instances, islands which were initially not considered as obstructions were removed from the model domain during this process. Each iteration of mesh editing constituted a full-scale re-interpolation of the bathymetric dataset to the mesh.

3.3.3 Streamflow

As an input condition, a constant streamflow value was applied at three major rivers: the Penobscot, Androscoggin, and Kennebec Rivers. All three rivers are regulated by a series of dams, which reduce the correlation of recorded streamflows to storm events.

During the calibration process, the months over which streamflows were averaged was adjusted to match model results to USGS high water marks. However, focus was paid to winter months (September through April) when nor'easters can be particularly dangerous (NOAA, 2012). Table 3-2 summarizes the constant streamflow applied to the model simulations for each river.

Table 3-2 : Modeled Streamflow

River	Months for Average	Average Streamflow (m^3/sec)
Androscoggin River	Sep - Mar	145
Kennebec River	Sep - Mar	240
Penobscot River	Jan - Feb	285

3.3.4 Input Tide Signal

The offshore boundary condition is the controlling tidal forcing mechanism for the RMA2 models, and development of the time series data to represent the tidal conditions at the model boundaries is discussed in detail in Section 2.2.1. The tidal time series from Bar Harbor was used as the primary tidal signal across all models. Eleven hours of a smooth sinusoidal repetitive water surface elevation was appended to the start of the water surface elevation time series as model spin-up, allowing the model to start at a high water level and drain slightly before approaching the five hours of actual recorded maximum hourly water surface elevations from the Bar Harbor tide gage.

During the calibration process for the Penobscot model, the Bar Harbor tide gage water surface elevation time series was scaled to 95 percent of the original time series. The Eastern and Western models were configured in such a way that multiple inlets and embayments are being simulated, but the Penobscot model is configured to represent only one large inlet. The configuration of the major and minor axes of the semi-circular offshore boundary may have led to differences in the hydrodynamic model response to the tidal forcing mechanism. By scaling the offshore water surface elevation time series to 95 percent, Penobscot model simulations of water surface elevations produce a better match of the high water marks of the USGS Report *Coastal Flood of February 7, 1978 in Maine, Massachusetts, and New Hampshire* (USGS, 1979). The 95 percent scaling factor for the Penobscot model was applied to the water surface elevation boundary condition for calibration, validation, and the 1-percent-annual-chance event simulations.

3.3.5 Calibration Results

Table 3-3 summarizes the comparison between the reported USGS high water marks and the simulated water surface elevations for the February 7, 1978 coastal storm surge event.

Table 3-3 : Comparison of Results at High Water Mark Locations for the February 7, 1978 Event

Location	USGS ID	Model	USGS High Water Mark [NAVD88 meters]	Model High Water Elevation [NAVD88 meters]	Difference [meters]	% Error
Addison, Maine	7	Eastern	2.95	2.63	-0.33	11%
Addison, Maine	8	Eastern	2.86	2.76	-0.09	3%
Harrington, Maine	9	Eastern	2.84	2.94	0.11	4%
Cherryfield, Maine	10	Eastern	2.75	2.73	-0.02	1%
Milbridge, Maine	11	Eastern	2.87	2.70	-0.17	6%
Winter Harbor, Maine	12	Eastern	2.81	2.70	-0.12	4%
Southwest Harbor, Maine	13	Eastern	2.72	2.68	-0.04	1%
Ellsworth, Maine	14	Eastern	3.33	3.11	-0.21	6%
Blue Hill, Maine	15	Eastern	3.29	2.84	-0.45	14%
Sedgwick, Maine	16	Penobscot	2.56	2.72	0.16	6%
Sedgwick, Maine	17	Penobscot	2.69	2.77	0.07	3%
Brooksville, Maine	18	Penobscot	2.60	2.65	0.05	2%
Castine, Maine	19	Penobscot	2.30	2.96	0.67	29%
Bucksport, Maine	20	Penobscot	2.88	3.20	0.32	11%
Bangor, Maine	21	Penobscot	3.19	3.42	0.24	7%
Winterport, Maine	22	Penobscot	3.02	3.24	0.22	7%
Prospect, Maine	23	Penobscot	2.70	3.46	0.76	28%
Belfast, Maine	24	Penobscot	2.54	3.03	0.49	19%
Belfast, Maine	25	Penobscot	2.91	3.01	0.10	3%
Lincolnville Beach, Maine	26	Penobscot	2.83	2.78	-0.05	2%
Camden Harbor, Maine	27	Penobscot	2.53	2.70	0.16	6%
St. George at Long Cove,	28	Western	2.76	2.65	-0.11	4%
Thomaston, Maine	29	Western	2.72	3.01	0.29	11%
Waldoboro, Maine	30	Western	2.69	2.92	0.23	9%
Newcastle, Maine	31	Western	2.61	2.91	0.30	11%
Wiscasset, Maine	32	Western	2.68	2.74	0.06	2%
Westport, Maine	33	Western	2.62	2.72	0.10	4%
Georgetown, Maine	34	Western	2.59	2.68	0.10	4%
Georgetown, Maine	35	Western	3.46	2.66	-0.80	23%
Georgetown, Maine	36	Western	2.41	2.65	0.23	10%
Georgetown, Maine	37	Western	3.19	2.62	-0.58	18%
West Georgetown, Maine	38	Western	2.05	2.61	0.56	27%
Arrowsic, Maine	39	Western	2.55	2.64	0.09	4%
Bowdoinham, Maine	40	Western	1.91	2.48	0.56	29%
Bowdoinham, Maine	41	Western	2.50	2.48	-0.02	1%
Phippsburg, Maine	42	Western	2.23	2.58	0.35	16%
Phippsburg, Maine	43	Western	2.51	2.61	0.10	4%
Phippsburg, Maine	44	Western	2.42	2.61	0.19	8%
Phippsburg, Maine	45	Western	2.14	2.62	0.48	23%

Location	USGS ID	Model	USGS High Water Mark [NAVD88 meters]	Model High Water Elevation [NAVD88 meters]	Difference [meters]	% Error
Phippsburg, Maine	46	Western	2.96	2.65	-0.32	11%
Phippsburg, Maine	47	Western	3.24	2.63	-0.61	19%
Phippsburg, Maine	48	Western	2.59	2.66	0.07	3%
Phippsburg, Maine	49	Western	2.89	2.67	-0.22	8%
West Bath, Maine	50	Western	2.74	2.77	0.03	1%
Harpswell, Maine	51	Western	3.12	2.84	-0.29	9%
Harpswell, Maine	52	Western	2.54	2.66	0.12	5%
Harpswell, Maine	53	Western	2.56	2.66	0.10	4%
Harpswell, Maine	54	Western	2.64	2.71	0.07	3%
Harpswell, Maine	55	Western	3.11	2.64	-0.47	15%
Harpswell, Maine	56	Western	2.96	2.64	-0.32	11%
Harpswell, Maine	57	Western	2.66	2.87	0.21	8%
Brunswick, Maine	58	Western	2.66	2.87	0.21	8%
Harpswell, Maine	59	Western	2.55	2.65	0.10	4%
Harpswell, Maine	60	Western	2.56	2.69	0.13	5%
Brunswick, Maine	61	Western	2.55	2.71	0.15	6%
Brunswick, Maine	62	Western	2.42	2.70	0.29	12%
Freeport, Maine	63	Western	2.64	2.61	-0.03	1%
Freeport, Maine	64	Western	2.57	2.64	0.06	2%
Freeport, Maine	65	Western	2.63	2.63	0.00	0%

3.4 Model Validation

The model was validated with the January 9, 1978 data from the USGS report *Coastal Flood of February 7, 1978, in Maine, Massachusetts, and New Hampshire* (USGS, 1979). There were fewer recorded high water marks reported for the January validation event than for the February calibration event. Table 3-4 summarizes measured and modeled high water marks from the January 9, 1978 event.

Table 3-4 : Comparison of Results at High Water Mark Locations for the January 9, 1978 Event

Location	USGS ID	Model	USGS High Water Mark [NAVD88 meters]	Model High Water Elevation [NAVD88 meters]	Difference [meters]	% Error
Addison, Maine	7	Eastern	3.26	2.71	-0.54	17%
Addison, Maine	8	Eastern	2.92	2.77	-0.14	5%
Harrington, Maine	9	Eastern	2.93	2.87	-0.06	2%
Cherryfield, Maine	10	Eastern	2.87	2.74	-0.13	5%
Milbridge, Maine	11	Eastern	3.00	2.75	-0.25	8%
Winter Harbor, Maine	12	Eastern	2.93	2.74	-0.20	7%

Location	USGS ID	Model	USGS High Water Mark [NAVD88 meters]	Model High Water Elevation [NAVD88 meters]	Difference [meters]	% Error
Ellsworth, Maine	14	Eastern	3.17	2.94	-0.23	7%
Blue Hill, Maine	15	Eastern	3.14	2.81	-0.33	11%
Sedgwick, Maine	16	Penobscot	3.00	2.73	-0.91	9%
Sedgwick, Maine	17	Penobscot	3.48	2.75	-2.39	21%
Brooksville, Maine	18	Penobscot	2.81	2.71	-0.32	4%
Castine, Maine	19	Penobscot	2.73	2.85	0.41	5%
Bucksport, Maine	20	Penobscot	3.23	3.06	-0.57	5%
Bangor, Maine	21	Penobscot	3.34	3.34	-0.02	0%
Winterport, Maine	22	Penobscot	3.17	3.18	0.01	0%
Prospect, Maine	23	Penobscot	2.74	3.19	1.46	16%
Belfast, Maine	24	Penobscot	2.74	2.89	0.49	5%
Belfast, Maine	25	Penobscot	3.15	2.88	-0.91	9%
Lincolnville, Maine	26	Penobscot	2.94	2.76	-0.60	6%
Camden Harbor, Maine	27	Penobscot	2.71	2.71	-0.01	0%
Thomaston, Maine	29	Western	2.93	2.92	-0.01	0%
Waldoboro, Maine	30	Western	3.20	2.85	-0.35	11%
Newcastle, Maine	31	Western	2.98	2.91	-0.07	2%
Wiscasset, Maine	32	Western	2.98	2.83	-0.15	5%
Harpswell, Maine	52	Western	2.67	2.73	0.06	2%
Harpswell, Maine	53	Western	2.78	2.71	-0.06	2%
Harpswell, Maine	54	Western	2.70	2.75	0.05	2%
Harpswell, Maine	56	Western	2.72	2.71	-0.01	0%
Harpswell, Maine	57	Western	3.13	2.83	-0.30	10%
Harpswell, Maine	59	Western	2.65	2.71	0.05	2%
Harpswell, Maine	60	Western	2.66	2.73	0.07	3%
Brunswick, Maine	62	Western	2.69	2.74	0.04	2%
Freeport, Maine	65	Western	2.86	2.72	-0.14	5%

3.5 Discussion of Results

For the February 1978 RMA2 model calibration event, there were 59 reported high water marks that were used as a basis of comparison to the simulated water surface elevations. Of the 59 high water marks, the calibrated models generated a percent error greater than 10 percent at 19 locations and a percent error greater than 20 percent at six locations. The average percent error across all RMA2 models for the storm surge calibration event was 9 percent. There was no apparent spatial bias in the errors throughout the models.

For the January 1978 validation event, there were 33 reported high water marks that were used as a basis of comparison to the simulated water surface elevations. Of the 33 high water marks, the validation simulation generated a percent error greater than 10 percent at four locations and a percent error greater than 20 percent at one location. The average percent error across all models for this event was 6 percent.

The RMA2 models were calibrated to match the USGS high water marks within a tolerance of 1 foot. Data availability limitations and two-dimensional model capabilities impact the accuracy of the model results. There were, however, several known model and data limitations which were not accurately represented by the RMA2 models including:

- Correlating observations with nearest model element
- Bathymetric differences from time of storm events and time of bathymetric data collection
- Streamflows in ungaged rivers
- Spatially variable wind speeds and directions
- Impacts of obstructions (such as bridges or ice jams) not included in the model
- Vertical turbulence and vertical mixing
- Salt wedges and density gradients

The % error shown in Table 3.3 for locations such as Castine, Prospect, West Georgetown, Bowdoinham, and Phippsburg; can be attributed to these model and data limitations. In other locations, the model did not accurately simulate the water surface elevation for the calibration event, but did perform well in simulating the water surface elevation for the validation event. The opposite is also true in some locations, where the calibration event matched the water surface elevations reported by the USGS with good agreement, but the validation event did not match as well. Most likely, there are localized conditions for the particular event that the model could not describe. During the model calibration process, best attempts were made to match model results to reported high water mark elevations by adjusting the parameters listed in Section 3.3.

3.6 Execution of the 1-Percent-Annual-Chance Event

This section describes the RMA2 model simulations of the nearshore 1-percent-annual-chance stillwater levels within the study area, including the shorelines of Knox, Lincoln, Sagadahoc, Waldo, and Hancock Counties.

For the RMA2 model, a 1-percent-annual-chance water surface elevation time series was created as discussed in Section 2.3.1. The time series was generated from the January 1978 Bar Harbor water surface elevation validation time series, which included model spin-up. The time series was scaled up by approximately 3 percent to match the 1-percent-annual-chance stillwater level calculated for the Bar Harbor gage of 2.79 meters (9.17 feet). This time series was applied to the offshore boundary of the Eastern and Western models. The 1-percent-annual-chance time series for the Penobscot model was scaled to 95 percent of the time series applied to the Eastern and Western models, as was done during the model calibration and validation discussed in Section 3.3.4. Results for the 1-percent-annual-chance simulation were used to generate spatial datasets of the 1-percent-annual-chance flood hazard caused by storm surge throughout the study area. Figures 3-9, 3-10, and 3-11 contain images of the max stillwater level at each node for the 1-percent-annual-chance event for the Western, Penobscot, and Eastern RMA2 model domains.

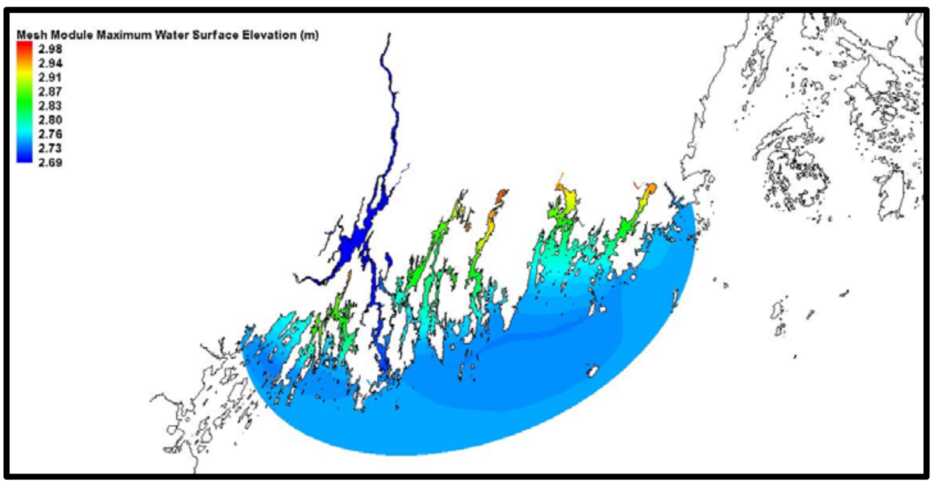

Figure 3-9 : Maximum Stillwater Level in the Western RMA2 Model

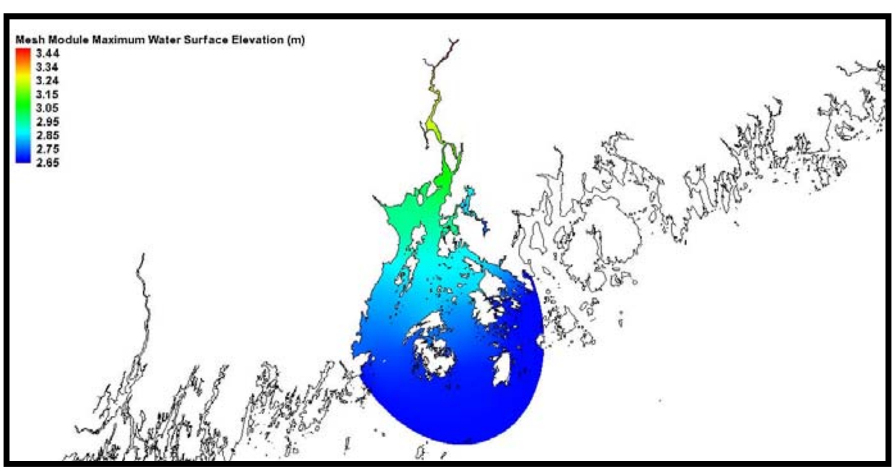

Figure 3-10 : Maximum Stillwater Level in the Penobscot RMA2 Model

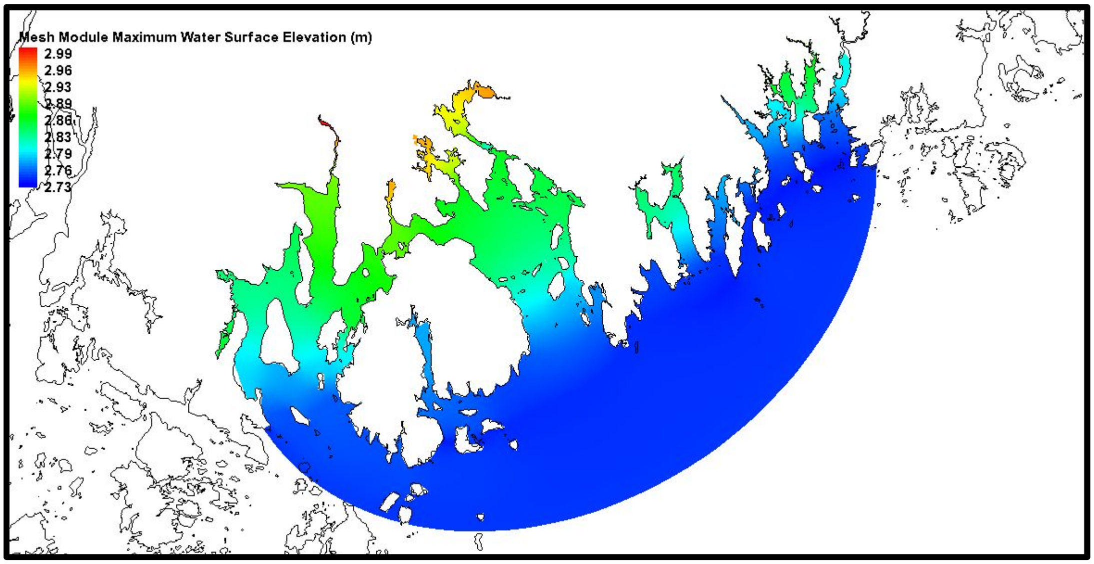

Figure 3-11 : Maximum Stillwater Level in the Eastern RMA2 Model

4. STWAVE Model

4.1 Introduction

A series of nested wave models was developed to assess 1-percent-annual-chance deep water significant wave heights off the coast of Hancock, Penobscot, Waldo, Knox, Lincoln, Sagadahoc, York and Cumberland Counties using STWAVE. This section documents the development of the STWAVE models, the model validation process, and development of the 1-percent-annual-chance event simulation.

Contents of this section are as follows:

- STWAVE Model Software
- Grid Development
- Boundary Conditions
- Model Validation
- 1-Percent-Annual-Chance Event

STWAVE is a second generation, steady state wave transformation model developed by the US Army Corps of Engineers (USACE, 2001). The model solves the wave action balance equation using a finite difference solution method. STWAVE incorporates physics of wave breaking, shoaling, diffraction, wind generation, and wave-wave generation. The model's inputs are simplified to wind, an incident wave energy spectrum, water surface elevation and bottom friction. Because of these simplifications, the model was not formally calibrated as part of this study.

STWAVE model applications use square grid cells with uniform grid spacing throughout the model grid. For areas that require a higher level of detail, smaller grids are nested into the model structure. Nested grids apply boundary conditions established in models with coarser grids, and provide detailed model results in localized areas. Multiple levels of nesting can occur within an STWAVE model. The STWAVE model developed for this study contains ten model grids: one large coarse grid, two mid-sized grids that rely on coarse grid model results for boundary conditions and seven smaller localized grids that rely on mid-sized grid model results for boundary conditions.

The STWAVE model developed for this study was created and run in the Surface-Water Modeling System (SMS) version 11 environment (Aquaveo, 2011). SMS is a graphical user interface that supports model grid generation and interfaces with the STWAVE model. SMS facilitates visualization of model grid features and model results. The version used during this analysis was STWAVE Halfplane 6.0.15.

4.2 Grid Development

The STWAVE model was developed using three levels of nested grids. A large, coarse grid spans the Maine coastline. Two mid-sized grids span (1) York and Cumberland Counties and (2) Hancock, Waldo, Knox, Lincoln and Sagadahoc Counties. A series of seven smaller, refined grids are located near the shoreline. Though no nested grids were developed to include Washington County, the coarse model grid includes this portion of the Maine Coast. This will facilitate future analysis of Washington County. This section discusses the relationship among the various levels of nested grids.

A total of ten rectangular grids were used to develop significant wave heights for this study. Table 4-1 lists the grids and their specifications. The grids are shown in Figure 4-1, and are also discussed in the following subsections. All grids used for the STWAVE modeling study are Cartesian with square grid cells.

Bathymetry data was acquired and processed for the STWAVE models as discussed in Section 2. To the extent possible, each STWAVE model grid was oriented so that the grid was generally aligned with the local shoreline.

Table 4-1 : STWAVE Nested Grids

Grid	Driving Boundary Condition Spectrum	Subsequent Nested Grid(s)	Grid Dimensions	Grid Cell Resolution	Total Number of Grid Cells (millions)
Coarse Grid	NDBC Buoy 44005 Wave height (buoy location shown in Figure 4-3), parameterized by JONSWAP Wave	Mid-sized Grid	430 Km X 150 Km	500 m	0.3
Hancock Mid-Sized Grid	Coarse Grid Model Results	Hancock Penobscot Bay Knox Lincoln-Sagadahoc	206.1 Km X 88.2 Km	150 m	0.8

Grid	Driving Boundary Condition Spectrum	Subsequent Nested Grid(s)	Grid Dimensions	Grid Cell Resolution	Total Number of Grid Cells (millions)
Hancock Grid	Hancock Mid-Sized Grid Model Results	--	70 Km X 46 Km	20 m	8
Penobscot Bay Grid	Hancock Mid-Sized Grid Model Results	--	62.9 Km X 59.6 Km	30 m	4.2
Knox Grid	Hancock Mid-Sized Grid Model Results	--	56 Km X 48.5 Km	20 m	6.8
Lincoln-Sagadahoc Grid	Hancock Mid-Sized Grid Model Results	--	65 Km X 25 Km	15 m	7.5
York Mid-sized Grid	Coarse Grid Model Results	Casco Bay Biddeford Wells	125.6 Km X 46.7 Km	100 m	0.6
Casco Bay Grid	York Mid-sized Grid Model Results	--	41.7 Km X 26.8 Km	15 m	5.0
Biddeford Grid	York Mid-sized Grid Model Results	--	36 Km X 23 Km	10 m	8.3
Wells Grid	York Mid-sized Grid Model Results	--	45.6 Km X 14.7 Km	10 m	6.7

In all local nested STWAVE grids, grid cell sizes were made as small as was practical for computational purposes, while ensuring that grid resolution was sufficiently refined to provide accurate data for wave analysis. In the case of Penobscot Bay, large grid cells were necessary (30 meters) to include all features influencing wave transformations into the bay. Refining the grid further to a 10 meter grid cells would have required removing part of the model domain, and potentially losing modeled wave energy transport around islands and through inlets.

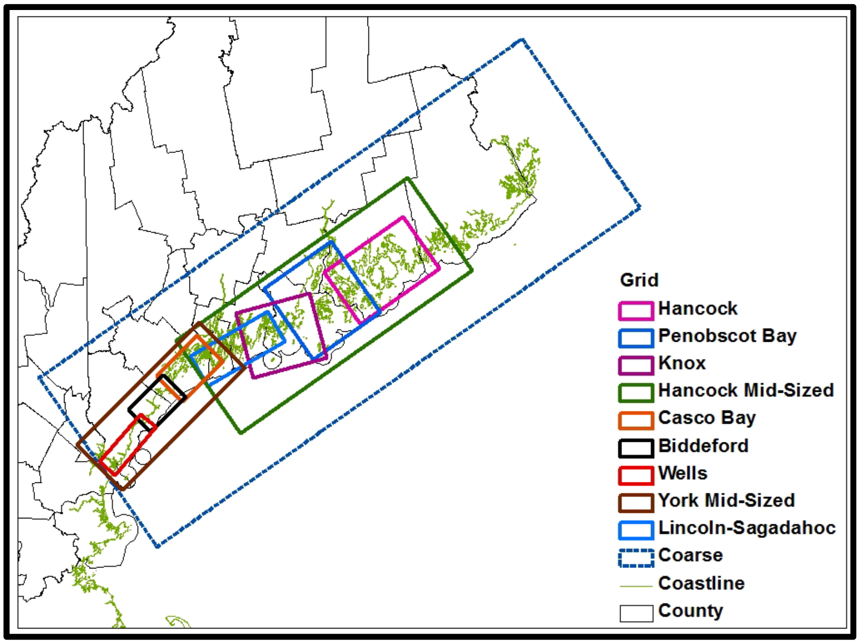

Figure 4-1 : Grids Developed for STWAVE Model

As is shown in Figure 4-1, all coastal areas of this study are included in the nested grids. Overlap was created to the extent practical between adjacent grids, to minimize the need to extract model results close to a model boundary.

4.2.1 Coarse Grid

The STWAVE coarse grid was developed to cover the Maine Coast (Figure 4-2). This grid was used to generate boundary conditions for the smaller nested grids in this study. The coarse grid's offshore boundary is oriented to be perpendicular to 145 degrees from North. The grid's bathymetric features are shown in Figure 4-2.

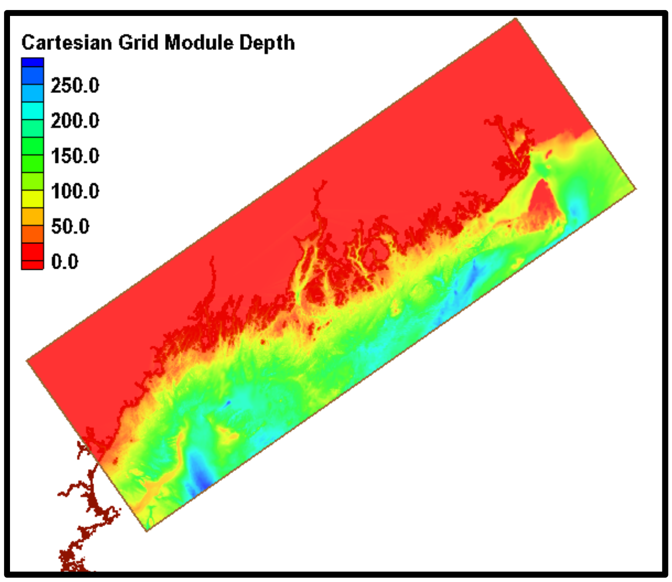

Figure 4-2 : Extent and Depth of the Coarse STWAVE Grid (meters)

4.2.2 Mid-Sized Grids

Two mid-sized STWAVE grids were developed in this study. The Hancock mid-sized grid (Figure 4-3) was developed to encompass Sagadahoc, Lincoln, Knox, Waldo and Hancock Counties. The Hancock mid-sized grid has the same orientation as the coarse grid, at perpendicular to 145 degrees from North. The York mid-sized grid (Figure 4-4) was developed to include York and Cumberland Counties, and the off-shore boundary is oriented perpendicular to 135 degrees from North. Bathymetries applied to the mid-sized grids are also illustrated in Figures 4-3 and 4-4.

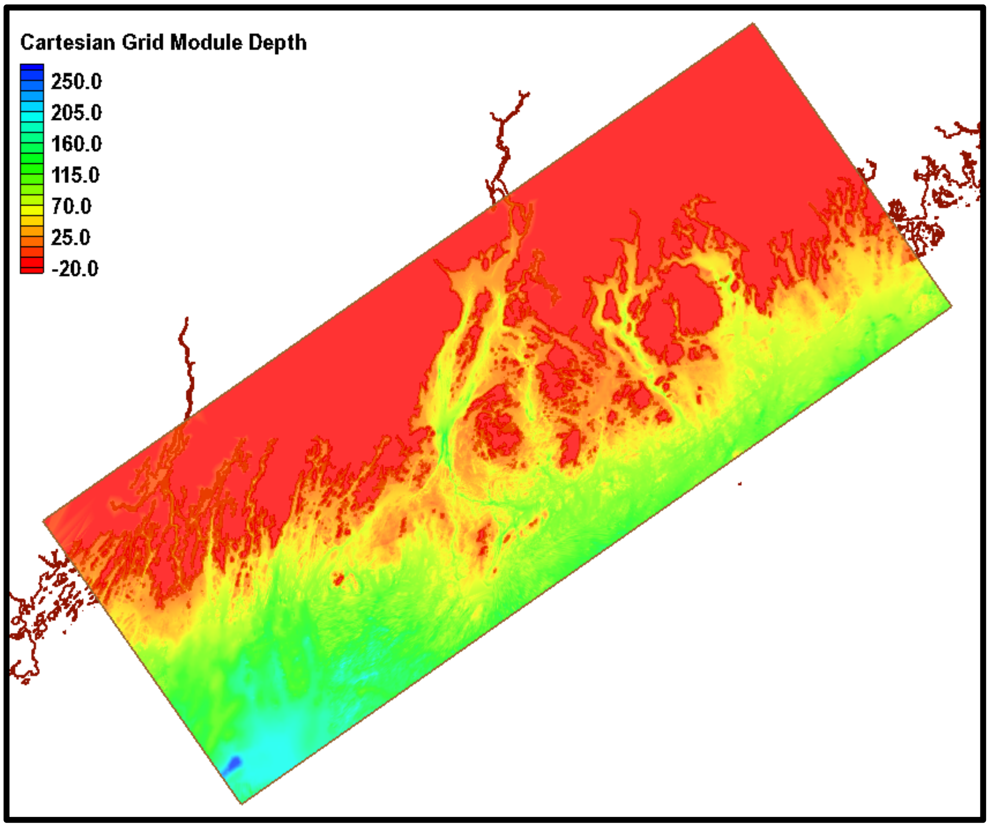

Figure 4-3 : Extent and Depth of the Hancock Mid-Sized STWAVE Grid (meters)

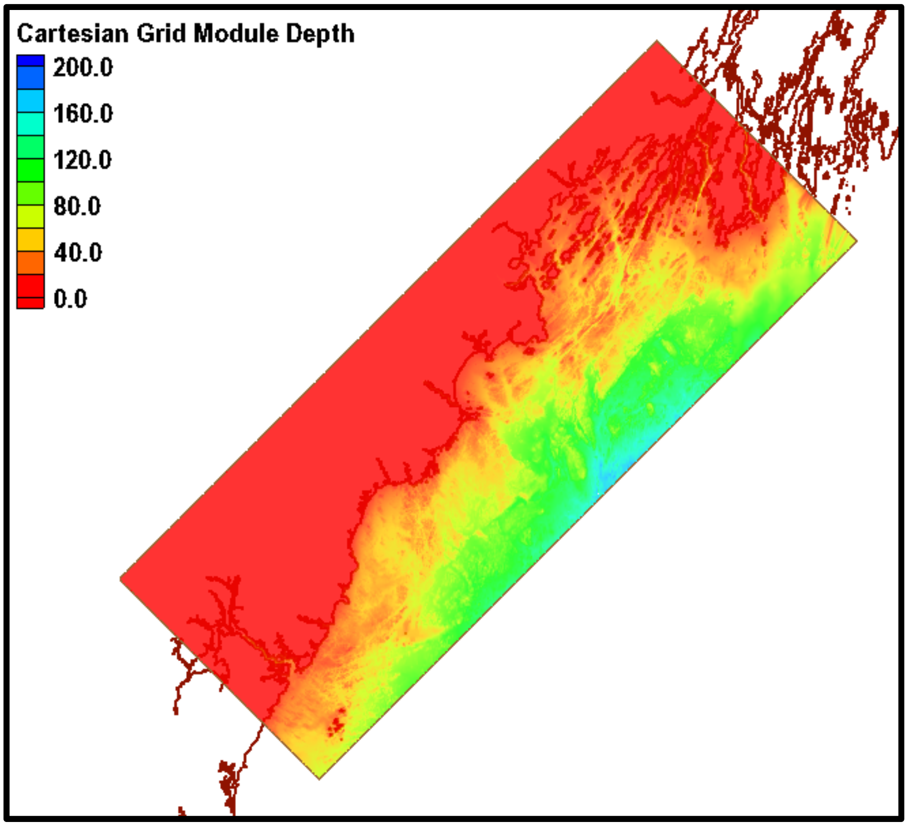

Figure 4-4 : Extent and Depth of the York Mid-Sized STWAVE Grid (meters)

4.2.3 Refined Local Grids

Four refined local grids (Hancock, Penobscot Bay, Knox, and Lincoln-Sagadahoc grids) were developed to accept wave spectrum boundary conditions from the Hancock mid-sized grid (Figures 4-5 through 4-8). Three refined local grids (Wells, Biddeford, and Casco Bay grids) were developed to accept wave spectrum boundary conditions from the York mid-sized grid (Figures 4-9 through 4-11).

In the northeastern portion of the study area, the off-shore boundaries of the refined local Hancock and Penobscot Bay grids are both oriented consistently with the Hancock mid-sized and coarse grid, perpendicular to 145 degrees from North. The Knox grid is at 165 degrees from North, and the Lincoln-Sagadahoc grid is at 150 degrees from North. These deviations from the coarse grid orientation were necessary to generate a refined grid that followed the coastline; however, care was taken to avoid distortions of the wave spectrum in the transformation process between grids; for each refined local grid, the model results (wave heights and directions) were compared with coarser grids to evaluate qualitative consistency.

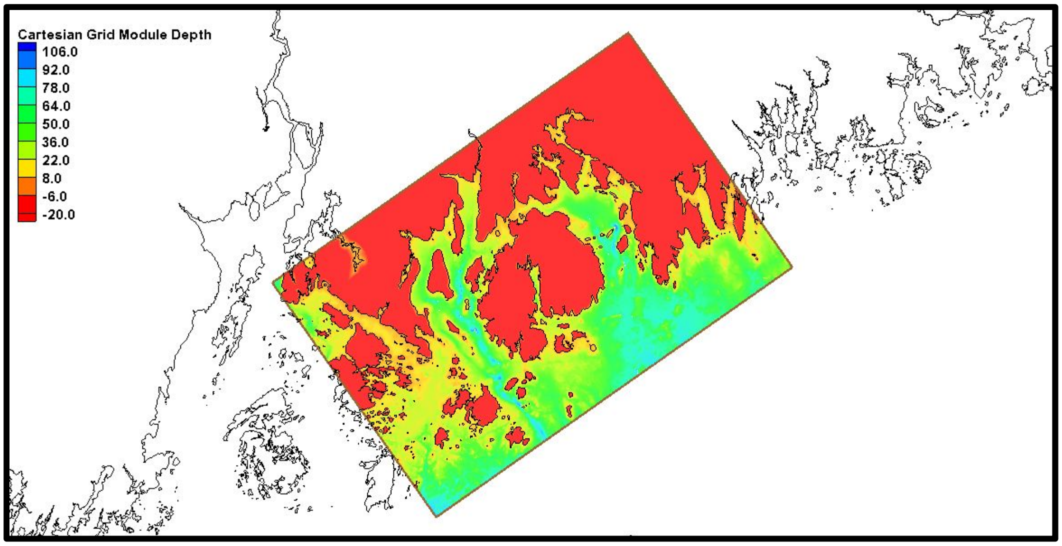

Figure 4-5 : Extent and Depth Contours for the Hancock STWAVE Grid (meters)

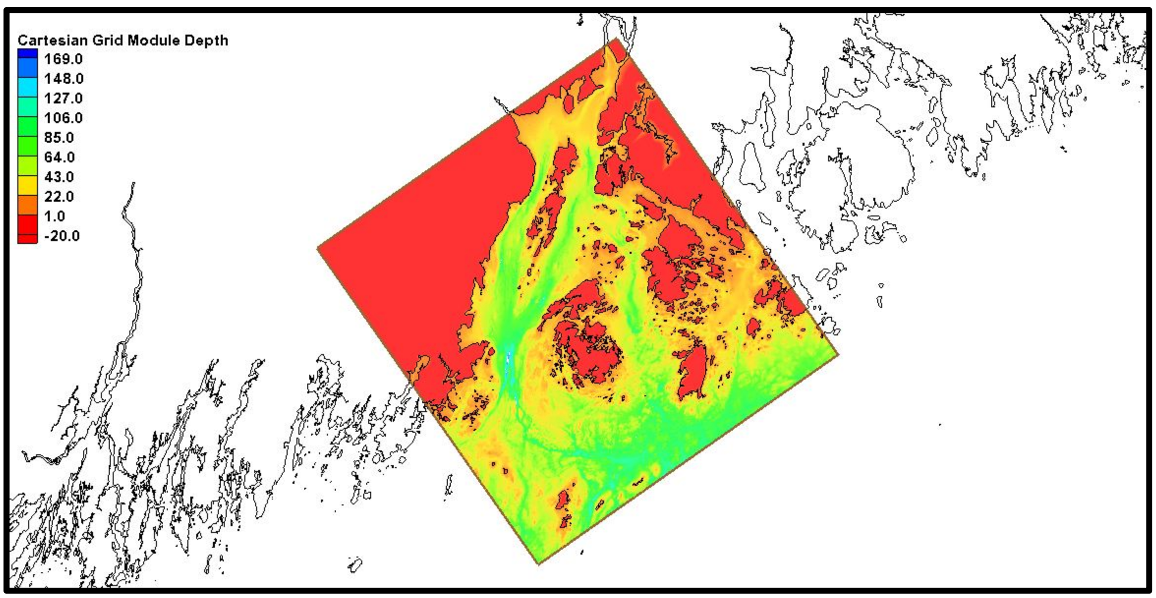

Figure 4-6 : Extent and Depth Contours for the Penobscot Bay STWAVE Grid (meters)

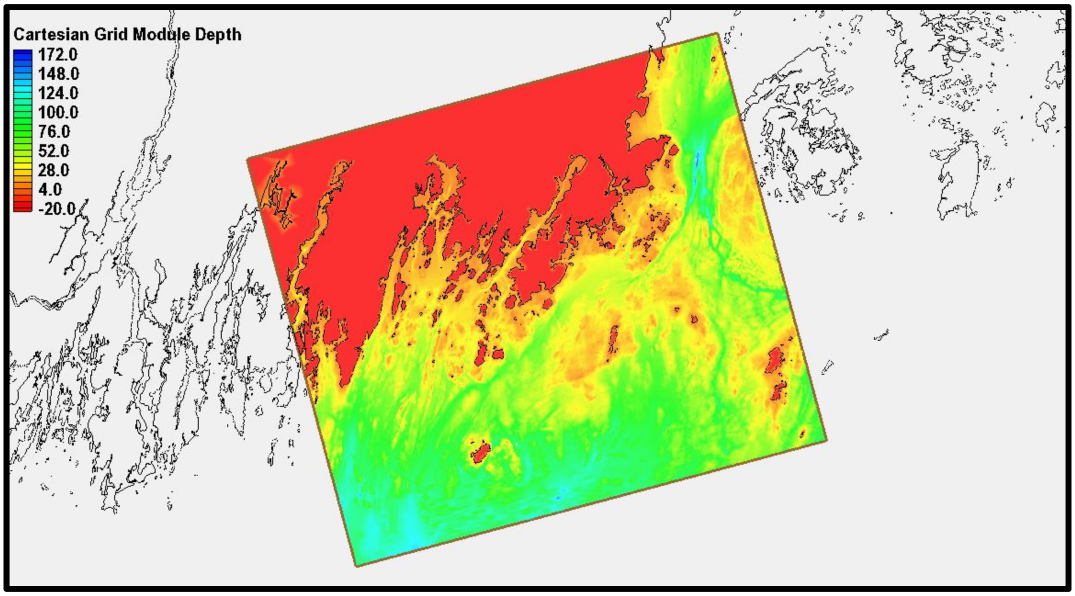

Figure 4-7 : Extent and Depth Contours for the Knox STWAVE Grid (meters)[1]

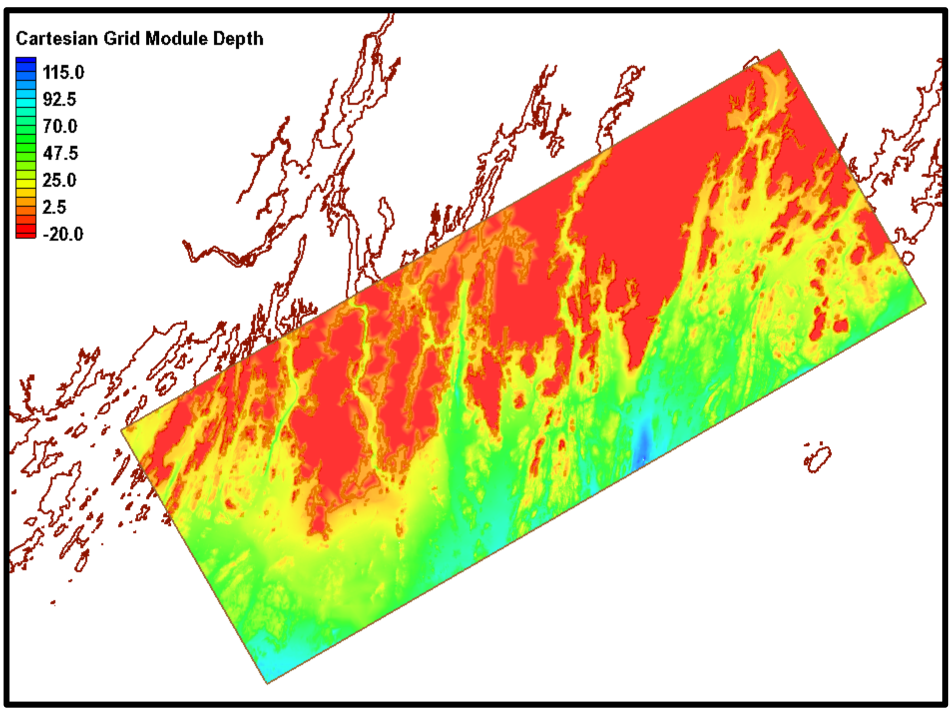

Figure 4-8 : Extent and Depth Contours for the Lincoln-Sagadahoc STWAVE Grid (meters)

In the southern part of the study area, the Wells grid is oriented perpendicular to 140 degrees from North. The Biddeford and Casco Bay Grids are both oriented at the same angle as the York mid-sized grid, with off-shore boundaries perpendicular to 135 degrees from North. For the Wells grid, this deviation from the York mid-sized grid orientation was necessary to generate a

[1] For Knox County, contour lines were plotted in place of color-filled contours, due to computational limitations in visualizing the large number of grid cells within SMS.

refined grid that followed the coastline; however, care was taken to avoid distortions of the wave spectrum in the transformation process between grids. For each refined local grid, the model results (wave heights and directions) were compared with coarser grids to evaluate qualitative consistency.

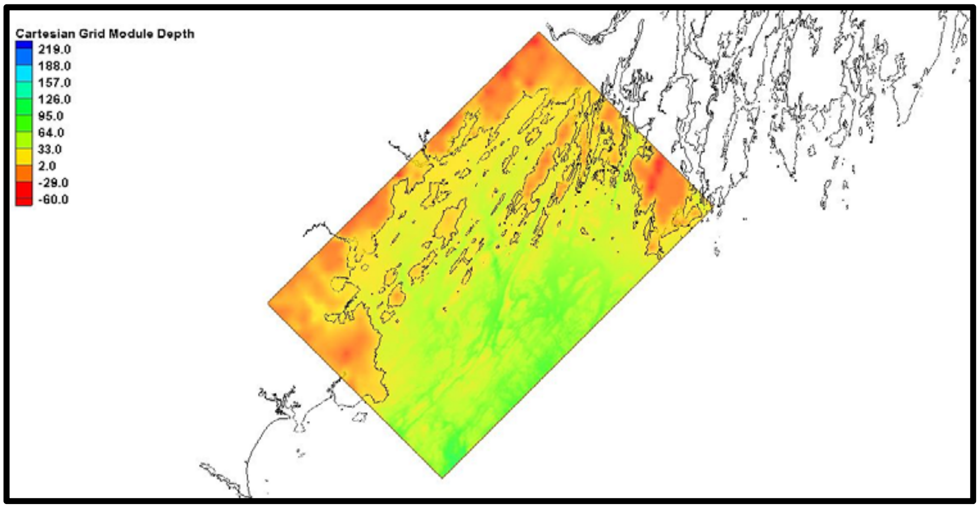

Figure 4-9 : Extent and Depth Contours for the Casco Bay STWAVE Grid (meters)

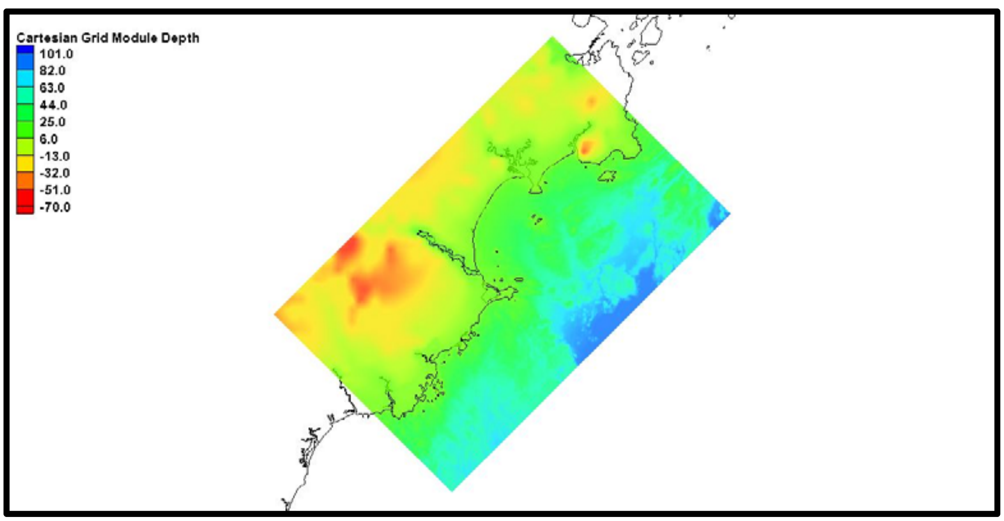

Figure 4-10 : Extent and Depth Contours for the Biddeford STWAVE Grid (meters)

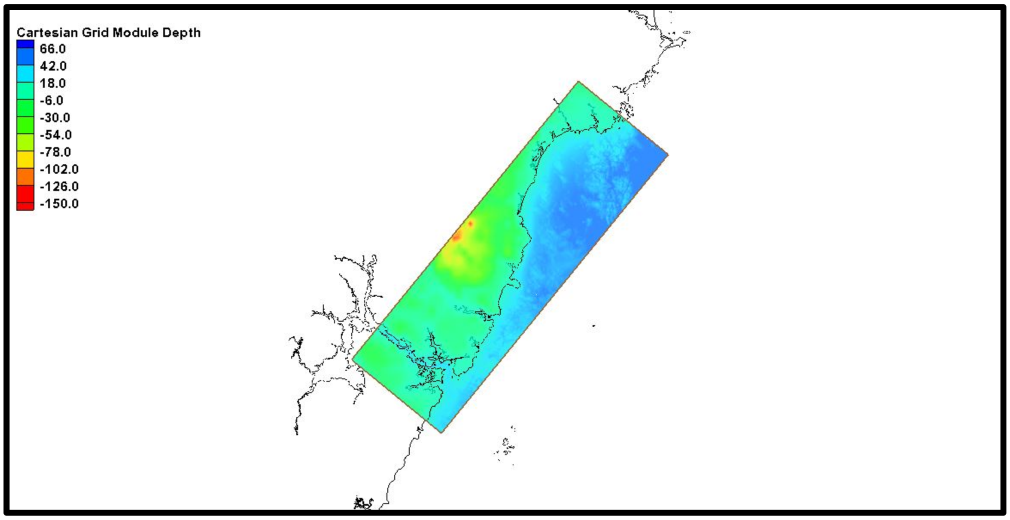

Figure 4-11 : Extent and Depth Contours for the Wells STWAVE Grid (meters)

4.3 Boundary Conditions

STWAVE boundary conditions consist of incident wave energy, winds, tides, water currents and bottom friction. These boundary conditions are summarized in Table 4-2, and are discussed in detail below.

Table 4-2 : Model Boundary Conditions

Boundary Condition	Where Applied in STWAVE
Wave Energy Spectrum	Along offshore boundary
Wind Field	Throughout model domain
Tidal Elevation	Throughout model domain
Bottom Friction	Throughout model domain
Water Currents	Throughout Model domain (not applied to this study)

4.3.1 Wave Energy Spectrum

For the STWAVE coarse model simulations, off-shore wave energy was determined based on wave height, direction and period observations at National Data Buoy Center (NDBC) Buoy 44005. The off-shore wave energies applied to the nested STWAVE models are taken from coarser models, as documented in Table 4-1. As discussed in Section 2, the wave height, period and direction that characterize conditions at NDBC buoy 44005 were used to develop a wave energy spectrum. A JONSWAP parameterization was used to generate the wave energy spectrum. SMS spectral parameterization methods are discussed in the SMS help material (Aquaveo, 2011).

Standard values provided by SMS were used for other JONSWAP spectral parameters. Because Buoy 44005 is 6 kilometers inside of the coarse grid's off-shore boundary, an iterative process was used to scale the wave height used to generate the JONSWAP spectrum applied at the STWAVE model boundary, such that the modeled wave height at Buoy 44005 matched the desired wave height.

All STWAVE simulations developed for this study were run in half plane mode, such that only wave energy within 87.5 degrees of the direction perpendicular to the model grid is included in the model solution. For this reason, nested grids were oriented as closely to the coarse grid's orientation as possible to conserve wave energy transfer between grids.

All grids apply a uniform wave spectrum along the off-shore boundary. This spectrum for nested grids is calculated by taking a morphic average of the spectra modeled along the location of the nested grid's off-shore boundary by the larger grid model. Morphic spectral merging helps to maintain spectral peaks when merging wave energy spectra with peaks in varied directions (Smith and Smith, 2002).

4.3.2 Incident Wave Direction

Because directional wave data was not available at Buoy 44005, wave directions were aligned with wind directions in all validation and 1-percent-annual-chance event STWAVE model simulations conducted in this study. To evaluate potential impacts of this boundary condition assignment, a sensitivity analysis was conducted using the boundary conditions identified for the December 2007 storm event. The incident wave direction was varied by up to 15 degrees from the baseline simulation, in which the wave spectrum was aligned with the wind direction. The maximum variation from the baseline in any of the sensitivity simulations is 0.2 meters. Sensitivity analysis results are summarized in Table 4-3.

Table 4-3 : Sensitivity Analysis Results for December 2007 Storm Event

		15 Degrees Plus	10 Degrees Plus	5 Degrees Plus	No adjustment	5 Degrees Minus	10 Degrees Minus	15 Degrees Minus
NDBC Buoy	Observed	Modeled						
44005	7.4	7.5	7.5	7.5	7.5	7.6	7.6	7.6
44030	6.5	6.1	6.2	6.2	6.3	6.3	6.3	6.3
44031	6.4	6.1	6.1	6.0	6.0	6.0	6.0	6.0
44032	6.7	6.4	6.4	6.4	6.4	6.4	6.3	6.3
44033	3.2	4.5	4.5	4.5	4.5	4.6	4.4	4.3
44034	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.6

4.3.3 Wind Speed and Direction

Spatially uniform wind fields were applied to all model grids. Wind speeds and direction were determined for validation simulations and the 1-percent-annual-chance event as discussed in Section 2.

4.3.4 Tidal Elevations

Spatially uniform tidal elevations were applied to all model grids. Elevations were determined for validation simulations and the 1-percent-annual-chance event as discussed in Section 2. Because coarse grid model results fee into all nested grids at locations far off-shore, tide has no impact on coarse grid model results. As a result, no tide was applied to the coarse grid.

4.3.5 Water Currents

Impacts of water currents were not accounted for in the STWAVE models developed in this study.

4.3.6 Bottom Friction

A JONSWAP bottom friction parameterization was applied to all model grids in this study (Hasselmann et al., 1973). A spatially uniform JONSWAP friction coefficient of 0.0055 was applied to all model grids, per Smith (2007).

4.4 Model Validation

Parameters in numerical models are often calibrated using a simulated event independent of events modeled in the validation process. For the STWAVE model developed in this study, sufficient data is not available to calibrate model parameters such as bottom friction.

As discussed in Section 2, two storms were used to validate the STWAVE coarse grid model: (1) December 16-18, 2007 and (2) December 9-10, 2009. For each validation storm, boundary conditions were calculated as discussed in Section 2 and applied as discussed above in Section 4.2.3. Boundary condition values applied to the models are summarized in Table 4-4. Models were considered validated where modeled wave heights were within 0.3 meters of observed peak wave heights (as defined in Section 2).

Table 4-4 : Model Boundary Conditions Applied for Validation Simulations

Boundary Condition	Values December 2009	Values December 2007
Wave Energy Spectrum	Wave Height of 7.1 m at 44005	Wave Height of 7.4 m at 44005
Wind Field	15 m/s at 125 degrees from North	17 m/s at 132 degrees from North
Tidal Elevation	None applied to coarse grid (not modeled on nested grids)	None applied to coarse grid 1.81 meters NAVD88 for Hancock mid-sized grid 1.71 meters NAVD88 for York mid-sized grid
JONSWAP Coefficient	0.0055	0.0055
Water Currents	--	--

4.4.1 Coarse Grid Validation

Both the December 2007 and December 2009 storms were verified with the coarse grid by comparing modeled and observed peak wave heights at NDBC buoy locations. The NDBC Buoys with validation comparison data for each storm are shown in Figures 4-12 and 4-13. Table 4-5 summarizes observed and modeled wave height comparisons. Model results are within 0.4 meters of observed wave heights for all model results, with the exception of Buoy 44033. Buoy 44033 is located within Penobscot Bay, and it is probable that the coarse model grid resolution of 500 meters is not able to incorporate important smaller-scale bathymetric variations. As discussed below, the more refined nested grids are better able to match observed wave heights at Buoy 44033.

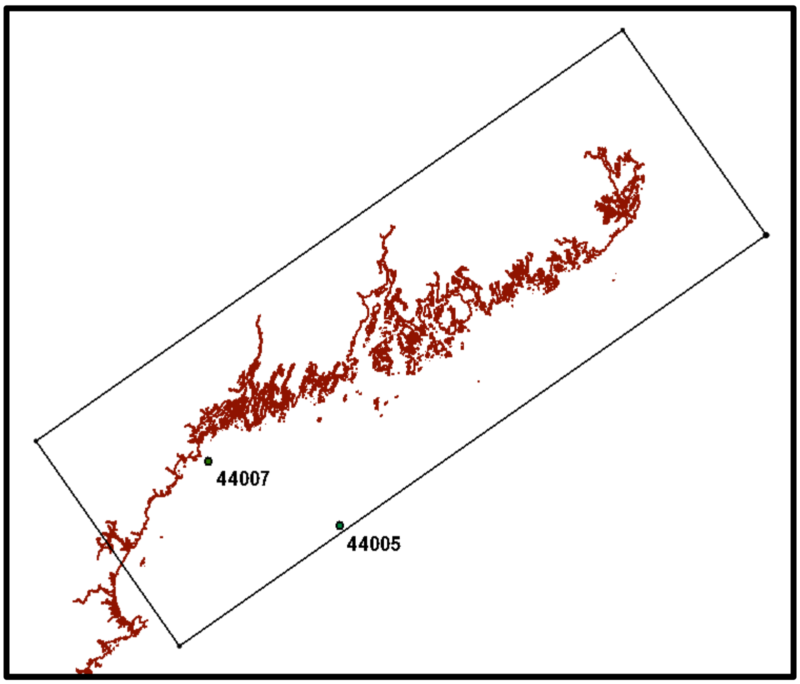

Figure 4-12 : Locations of Buoy 44005 Used for Establishing Boundary Conditions and Buoy 44007 Used for Validation of the December 2009 Storm Event

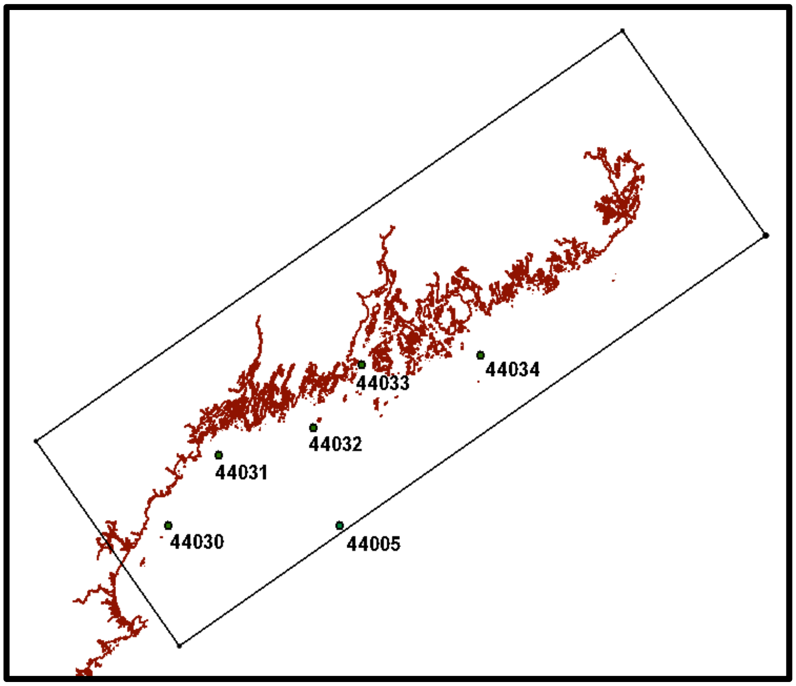

Figure 4-13 : Locations of Buoy 44005 Used for Establishing Boundary Conditions and Buoys 44030, 44031, 44032, 44033 and 44034 Used for Validation of the December 2007 Storm Event

Table 4-5 : STWAVE Model Validation Results Summary

	December 2009 Storm			December 2007 Storm		
NDBC Buoys[2]	Observed Value	Simulated Value	Difference (Simulated Minus Observed)	Observed Value	Simulated Value	Difference (Simulated Minus Observed)
Wave Height at 44005 (meters)	7.1	7.2	0.06	7.4	7.5	0.1
Wave Height at 44007 (meters)	6.2	5.9	-0.3	-	-	-
Wave Height at 44030 (meters)	-	-	-	6.5	6.3	-0.2
Wave Height at 44031 (meters)	-	-	-	6.4	6.0	-0.4

[2] Locations of NDBC buoys are shown in Figures 4-12 and 4-13.

	December 2009 Storm			December 2007 Storm		
NDBC Buoys[2]	Observed Value	Simulated Value	Difference (Simulated Minus Observed)	Observed Value	Simulated Value	Difference (Simulated Minus Observed)
Wave Height at 44032 (meters)	-	-	-	6.7	6.7	< 0.1
Wave Height at 44033 (meters)	-	-	-	3.2	4.5	1.3
Wave Height at 44034 (meters)	-	-	-	6.7	6.7	< 0.1

4.4.2 Nested Grid Validation

The December 2007 model results were validated with the mid-sized and refined local nested grids where NDBC buoys were present within nested model domains. In all cases but one, nested model results were within 0.1 meters of the coarse grid model results. At Buoy 44033 in Penobscot Bay, the coarse grid modeled wave height was 1.2 meters higher than the observed wave height (3.2 meters). The Hancock Mid-Sized grid results in a wave height of 3.7 meters, which is within 0.5 meters of the observed wave height. The refined local Penobscot Bay grid results in a wave height of 2.9 meters, which is within 0.3 meters of the observed wave height.

Where no validation point was contained in a nested grid model domain, qualitative comparisons of wave height and direction between coarser and nested grid model results were made to ensure that no physical transformation processes were lost in the nesting process.

4.5 1-Percent-Annual-Chance Storm

Once the STWAVE model was adequately verified, simulations were run to characterize wave heights and wave periods for the 1-percent-annual-chance event. Boundary conditions for the 1-percent-annual-chance event were calculated as discussed in Section 2 and applied as discussed above in Section 4.2.3. Boundary condition values corresponding to the 1-percent-annual-chance event are summarized in Table 4-6. Model results were qualitatively evaluated to ensure that modeled wave heights and directions were reasonable.

Table 4-6 : Model Boundary Conditions Applied for 1-Percent-Annual-Chance Event

Boundary Condition	Hancock Mid-Sized Grid and subsequent Nested Grids	York Mid-Sized Grid and subsequent Nested Grids
Wave Energy Spectrum	Wave Height of 10.6 m at 44005	Wave Height of 10.6 m at 44005
Wind Field	25.1 m/s at 145 degrees from North	25.1 meters/second at 145 degrees from North
Tidal Elevation	2.9 meters NAVD88	3.1 meters NAVD88
JONSWAP Coefficient	0.0055	0.0055
Water Currents	--	--

Plots of simulated wave heights representing the 1-percent-annual-chance event are shown in Figures 4-14 through 4-22 for all nested grids. Digital text files containing wave heights and wave periods for the 1-percent-annual chance event accompany this report for the following model grids:

- Coarse Grid
- Hancock Mid-Sized Grid
- Hancock Grid
- Penobscot Bay Grid
- Knox Grid[3]
- Lincoln-Sagadahoc Grid

All coastal areas of this study are included in the nested grids. Overlap was created to the extent practical between adjacent grids, to minimize the need to extract model results close to a model boundary. For example, the Hancock grid includes most of Hancock County's coastline. However, the portion of the coastline that is within Penobscot Bay is more accurately captured in the Penobscot Bay model grid, which also extends to Waldo and portions of Knox County. The portion of Knox County extending south and west of Penobscot is included in the Knox County grid. More generally, it is recommended that model results be extracted from models as far from boundaries as is practical.

[3] While the Hancock and Knox grids contain portions of Penobscot Bay, they are included for boundary purposes only. The intricacies of wave transformations in the Bay may not be accurately reflected in these two nested grids. It is recommended that for transects within Penobscot Bay, model results be extracted from the Penobscot Bay grid.

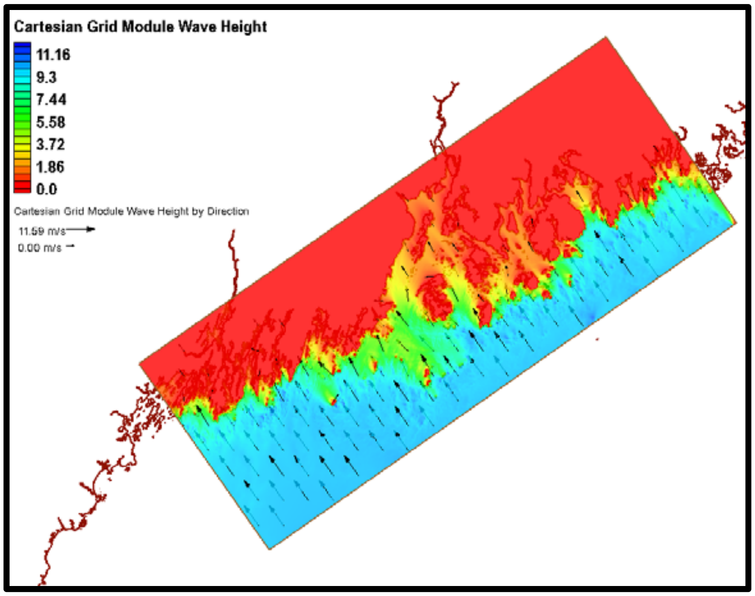

Figure 4-14 : Hancock Mid-Sized STWAVE Grid Wave Heights (meters) and Direction Resulting from the 1-Percent-Annual-Chance Event Simulation

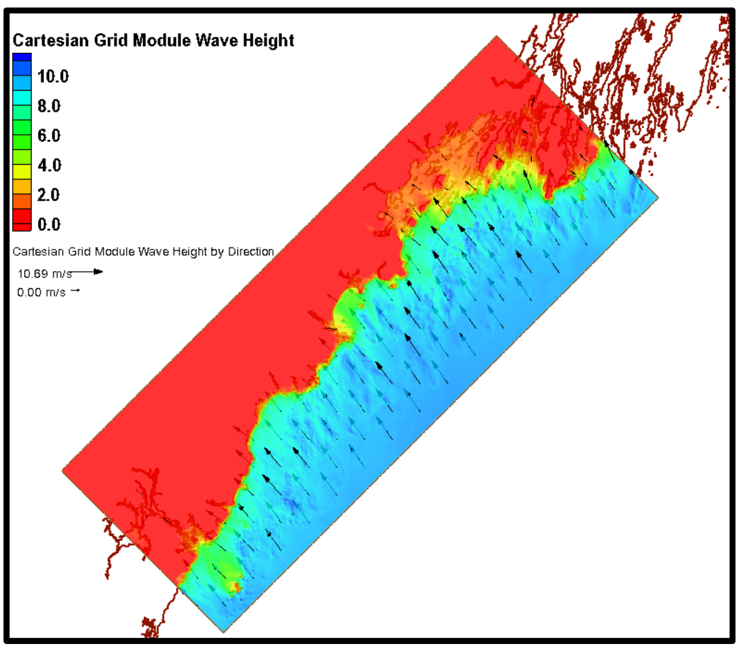

Figure 4-15 : York Mid-Sized STWAVE Grid Wave Heights (meters) and Direction Resulting From the 1-Percent-Annual-Chance Storm Simulation

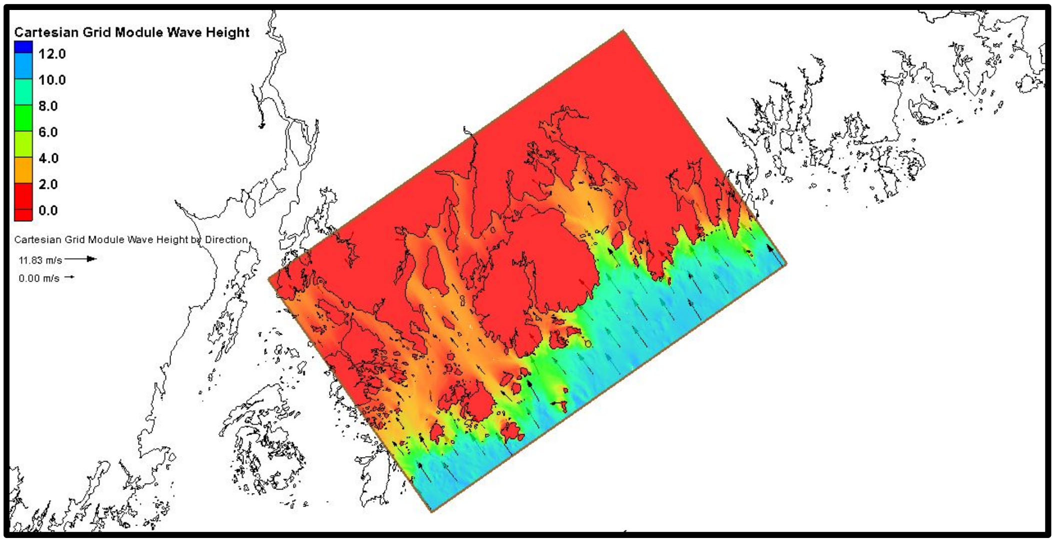

Figure 4-16 : Hancock STWAVE Grid Wave Heights (meters) and Direction Resulting From the 1-Percent-Annual-Chance Storm Simulation

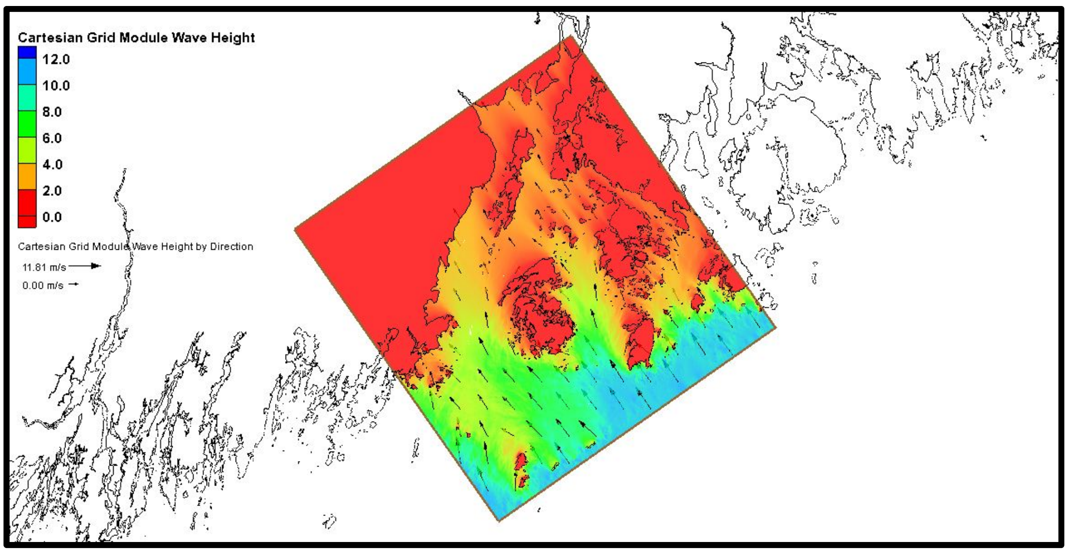

Figure 4-17 : Penobscot Bay STWAVE Grid Wave Heights (meters) and Direction Resulting From the 1-Percent-Annual-Chance Storm Simulation

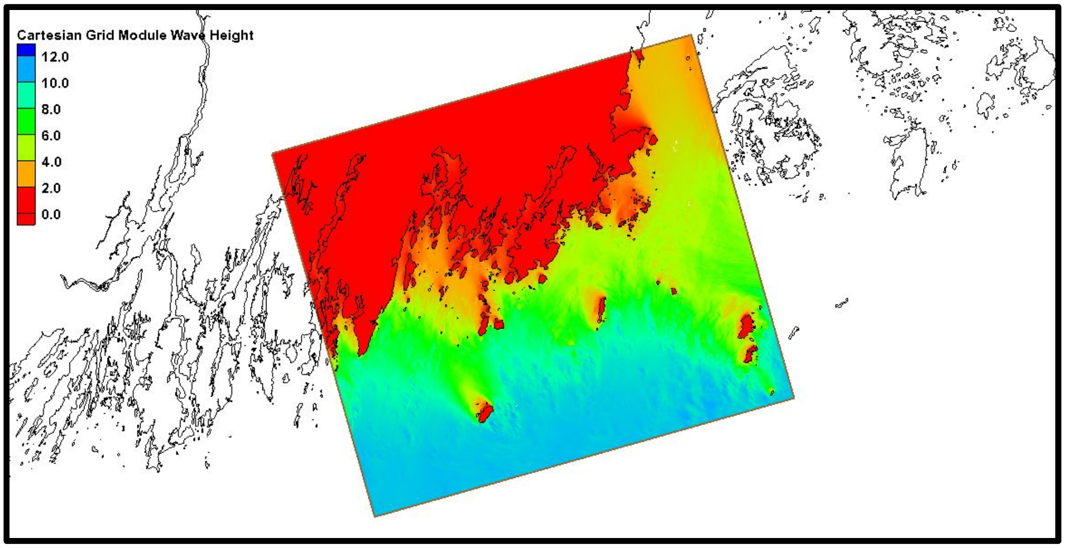

Figure 4-18 : Knox STWAVE Grid Wave Heights (meters) and Direction Resulting from the 1-Percent-Annual-Chance Storm Simulation

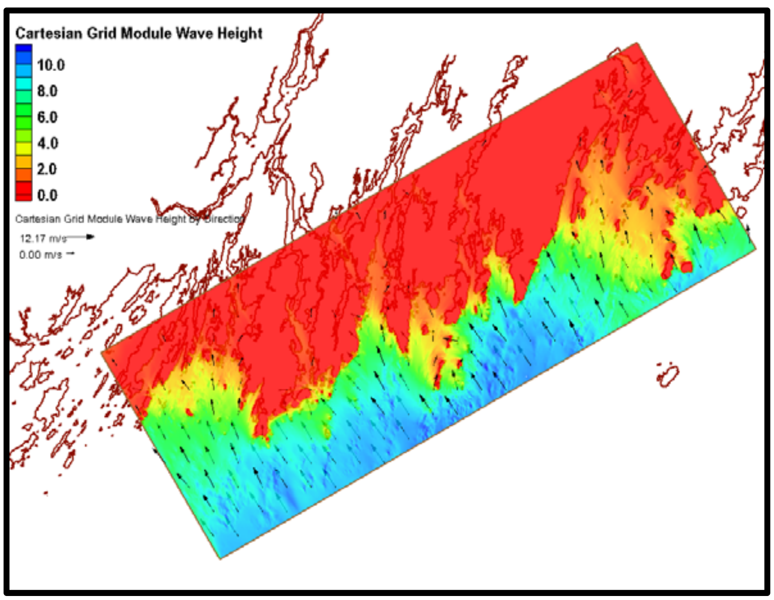

Figure 4-19 : Lincoln-Sagadahoc STWAVE Grid Wave Heights (meters) and Direction Resulting from the 1-Percent-Annual-Chance Storm Simulation

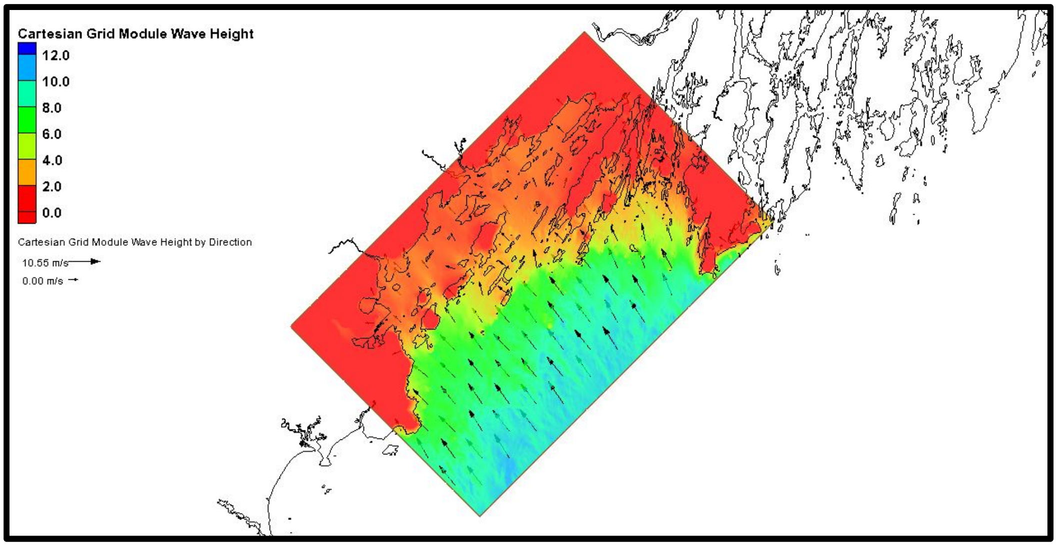

Figure 4-20 : Casco Bay STWAVE Grid Wave Heights (meters) and Direction Resulting from the 1-Percent-Annual-Chance Storm Simulation

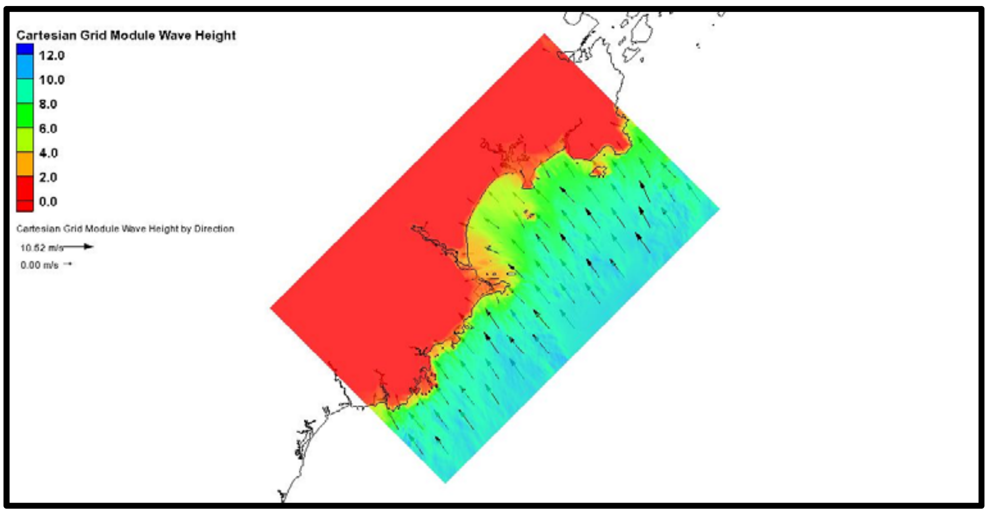

Figure 4-21 : Biddeford STWAVE Grid Wave Heights (meters) and Direction Resulting from the 1-Percent-Annual-Chance Storm Simulation

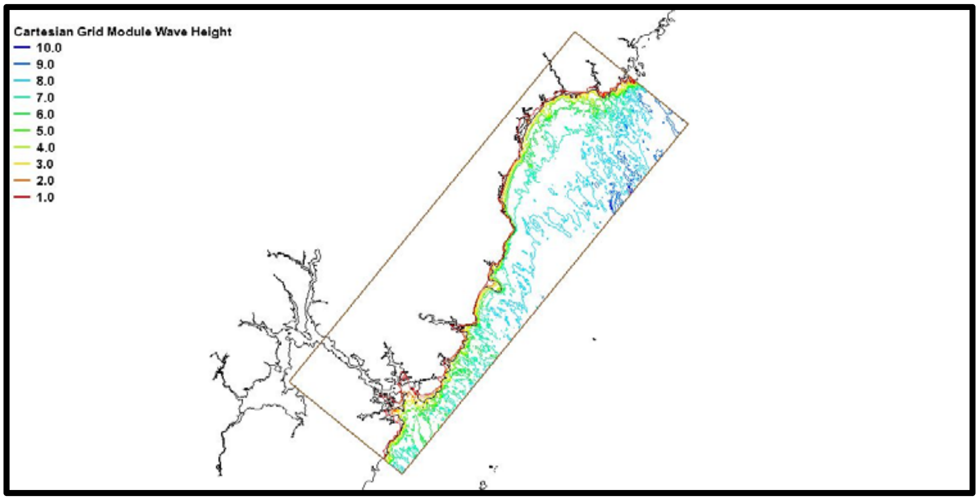

Figure 4-22 : Wells STWAVE Grid Wave Heights (meters) and Direction Resulting from the 1-Percent-Annual-Chance Storm Simulation

5. Conclusion

Tidal surge and coastal wave hydrodynamic models were developed for York, Cumberland, Sagadahoc, Lincoln, Knox, Waldo, Hancock, and Washington Counties in Maine. Several model grids were developed for each modeling effort. These surge and wave models were validated and used to generate 1-percent-annual-chance storm surge and wave characteristics that will support coastal flood hazard analysis in these counties under the Risk Map program. Please check the individual county study for the appropriate stillwater elevation and wave conditions used to define the coastal flood hazards.

5.1 Summary of the RMA2 Model

Storm surges were estimated using the two-dimensional hydrodynamic model, RMA2. Three independent RMA2 models were developed to simulate the 1-percent-annual-chance water surface elevation for the five counties of Sagadahoc, Lincoln, Knox, Waldo, and Hancock. The models were calibrated to the February 7, 1978 coastal storm surge event and validated to the January 9, 1978 coastal storm surge event using high water marks reported by the USGS in the *Coastal Flood of February 7, 1978, in Maine, Massachusetts, and New Hampshire* report (USGS, 1979). The average percent error between the simulated and reported high water marks was 9 percent and 6 percent for the February and January events, respectively, indicating a suitable model calibration.

The 1-percent-annual-chance stillwater levels along the northeast were identified in the *Updated Tidal Profiles for the New England Coastline* (STARR, 2012). A time series of water surface elevation from the Bar Harbor gage for the January 9, 1978 event was adjusted to match the water levels associated with the 1-percent-annual-chance stillwater level at Bar Harbor. This time series was used to establish the offshore boundary condition for the models to simulate routing of storm surge into inlets and embayments along the coastline. The result was a water surface elevation for the study area representing 1-percent-annual-chance surge conditions.

5.2 Summary of the STWAVE Model

Wave characteristics including wave height and wave period were estimated for York, Cumberland, Sagadahoc, Lincoln, Knox, Waldo, and Hancock counties using the 2D hydrodynamic wave action model STWAVE. The model structure consists of a large coarse grid that spans most of the Maine Coast, within which a mid-sized grid is nested that spans the study area. The large coarse grid covered Washington County as well for potential future flood hazard mapping activities in that county. The mid-sized grid is used to establish boundary conditions for four finely resolved nested grids, which are used to develop accurate1-percent-annual-chance wave characteristics. The STWAVE model therefore consists of six model grids of varying levels of grid resolutions.

The coarse grid STWAVE model was validated using the December 2007 and December 2009 high wave height events. Model results were compared with NDBC buoy wave height recordings. Overall agreement between the model and observed wave heights indicated a validated model; model results were within 0.3 meters of observed wave heights at all buoys.

The STWAVE model development also included an analysis of 1-percent-annual-chance event conditions, including wave height, wave and wind direction, and wind speed. The 1-percent-annual-chance stillwater levels used in the STWAVE model were identified in the *Updated Tidal Profiles for the New England Coastline* (STARR, 2012).

The results of these models represent the 1-percent-annual-chance surge and wave characteristics. The surge evaluated in the RMA2 model is applicable in embayments, inlets, and upper reaches of rivers for which the offshore conditions as identified in the *Updated Tidal Profiles for the New England Coastline* (STARR, 2012) are not appropriate. The RMA2 and STWAVE model results will serve as the basis for performing the coastal flood hazard analysis and development of new Flood Insurance Rate Maps (FIRMs) for the study area of Maine under coastal analyses performed in Maine for the FEMA Risk Map program.

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