Region II Storm Surge Project – Model Calibration and Validation

September 2014

Federal Emergency Management Agency
Department of Homeland Security
500 C Street, SW
Washington DC, 20472

Contract: HSFEHQ-09-D-0369
Task Order: HSFE02-09-J-0001

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Figures

Tables

Appendices

ADCIRC	ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters
CO-OPS	[NOAA] Center for Operational Oceanographic Products and Services
dd	decimal degrees
deg	degrees
DEM	Digital Elevation Model
DFIRM	Digital Flood Insurance Rate Map
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
ft	feet
GIS	Geographic Information System
HWM	High Water Mark
m	meter
min	minutes
NAD83	North American Datum of 1983
NAN	North Atlantic [Division], New York District (USACE)
NAVD88	North American Vertical Datum of 1988
NDBC	National Data Buoy Center
NJLU	New Jersey Land Use
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NTDE	National Tidal Datum Epoch
OWI	Oceanweather, Inc.
QA/QC	Quality Assurance/Quality Control
RAMPP	Risk Assessment, Mapping, and Planning Partners
RMSE	Root Mean Square Error
SMS	Surface-water Modeling System
SWAN	Simulating WAves Nearshore model
SWEL	Stillwater Elevation
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UnSWAN	Unstructured version of SWAN model
VDATUM	Vertical Datum Transformation
WHAFIS	Wave Height Analysis for Flood Insurance Studies

SECTION ONE INTRODUCTION

The Federal Emergency Management Agency (FEMA) contracted Risk Assessment, Mapping, and Planning Partners (RAMPP), a joint venture of Dewberry, URS, and ESP, under its Risk Mapping, Assessment, and Planning (Risk MAP) program to provide comprehensive floodplain mapping, Geographic Information System (GIS), and hazard risk mitigation services. This report summarizes the methodologies and results from the storm surge model calibration and validation process undertaken as part of the coastal hazard analysis to support Flood Insurance Studies (FIS) in Region II.

SECTION TWO MODEL DESCRIPTION

Storm surge modeling is being conducted for the Region II study area using the two-dimensional (2D) ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC), which is dynamically coupled with the unstructured version of the wave field model Simulating WAves Nearshore (UnSWAN).

ADCIRC is based on the 2D, vertically integrated shallow water equations that are solved in Generalized Wave Continuity Equation form. Model inputs include specifying the elevation data (land and underwater surface taken from a Digital Elevation Model (DEM)) at defined node locations throughout the model mesh, as well as the forcing conditions for each storm, including tides, winds, and atmospheric pressure fields. In addition, ADCIRC allows the specification of Manning's *n* bottom friction coefficients for the overland and underwater portions of the model. Roughness lengths and canopy cover can also be specified for overland portions of the model in order to properly compute the wind stress in areas that have become inundated, accounting for vegetation and other land use characteristics. Manning's *n* roughness lengths, and canopy cover were determined from the U.S. Geological Survey (USGS) Gap Analysis Program and the New Jersey Land Use (NJLU) statewide dataset The ADCIRC model computes water levels and current velocities throughout the model extent at each node location that is defined in the mesh.

The storm surge model incorporates an unstructured version of the SWAN coastal wave model. SWAN is a third-generation, phase-averaged numerical wave model for the simulation of waves in waters of deep, intermediate and finite depth. Recent updates to the SWAN model include an unstructured version of the SWAN model (referred to as UnSWAN), which allows for use of the same model mesh generated for the storm surge model, ADCIRC. Additionally, UnSWAN allows for direct communication of model output with the ADCIRC model, which achieves efficiencies in the overall model system. UnSWAN is used in this project to compute significant wave heights and the wave-induced radiation stresses that ADCIRC requires for total storm surge computation.

The coastal study effort encompasses all coastal counties in the State of New Jersey, Westchester County, New York, and the five boroughs of New York City. In addition, the study team identified the need to extend the model up the Hudson River to Troy, New York, into Nassau County, New York and into Fairfield County, Connecticut.

SECTION THREE MODEL SET-UP

The three primary input files to the ADCIRC model are the Nodal Attributes File (fort.13), the Grid and Boundary Information File (fort.14), and the Model Parameter and Periodic Boundary Condition File (fort.15). The fort.13 file and the development of nodal attributes are discussed in the Region II Storm Surge Project - Spatially Varying Land Use Parameters report (RAMPP, 2014a). The fort.14 file and the development of the ADCIRC mesh are discussed in the Region II Storm Surge Project - Mesh Development report (RAMPP, 2014b).

The fort.15 file includes parameters that affect model physics and numerics. The parameters used for this study closely match those used in other ongoing and previously conducted FEMA studies. The options selected for these simulations and their justifications are presented in Appendix E. Parameter descriptions listed have been taken from the ADCIRC User Manual (http://www.unc.edu/ims/adcirc/documentv49/fort_15.html). The options in the fort.15 file were kept consistent for both the tidal calibration and storm validation simulations, with the exception of parameters controlling the time of tidal forcing and the use of meteorological and radiation stress forces associated with storms.

Tidal forcing is applied at the open boundary by eight tidal constituents (K_1, K_2, M_2, N_2, O_1, Q_1, S_2, and P_1). All tidal forcing constituents are taken from the most recent (2001) version of the Eastcoast tidal database (see http://adcirc.org/products/adcirc-tidal-databases/) except for P_1, which was not modeled in the Eastcoast model and was taken from the LeProvost tidal database. Because tides vary in time, two parameters representing this variation must be provided—the nodal factor (a multiplier) and the equilibrium argument (a phase).

For the storm simulations developed here, wind and pressure fields developed by Oceanweather, Inc. (OWI) were used as forcing conditions for the combined surge and wave model. As the OWI-provided winds are 30-minute averages and ADCIRC expects 10-minute average winds, the 30 minute winds were increased by 4 percent as recommended by OWI to convert to 10 minute winds. In addition, ADCIRC applies a wind drag coefficient defined by Garratt (1977), and after consultation with the ADCIRC development team, and a review of ongoing and previous FEMA studies, the default cap on the wind drag was used for this study ($C_d \leq 0.0035$). This cap limits the drag coefficient being applied at higher wind speeds as is shown to occur from measured data obtained in tropical cyclones (Powell, et al., 2003).

Model Adjustments

Throughout the calibration and validation process, typical adjustments were made to the model mesh when instabilities were observed or when it was determined that the model performance could be improved. Adjustments included modifying elevations within the model mesh to ensure correct representation of channels and features. These adjustments helped to limit the model instabilities and improve model performance, as further discussed in Section 5. The modifications to the mesh included:

- Adjustments in the offshore bathymetry portion of the mesh where abrupt slope changes caused erroneously large wave heights;
- Modifications to bathymetry within Jamaica Bay/Head of the Bay to ensure correct representation and that tidal inundation occurred in smaller back bay channels and marsh systems; and

- Modifications to bathymetry at the entrance to the Shrewsbury/Navesink Rivers and in back bay channels to ensure correct representation of hydraulic conductivity.

In addition, sensitivity testing was conducted to assess how other model parameters affected the model results. Adjustments were made to the spatial attributes defined for the mesh, including varying the bottom roughness and the directional surface roughness coefficients within acceptable ranges. These adjustments were shown to have a minimal effect on the results, affecting peak surge elevations by 0.1 foot or less. Because of the limited sensitivity, the values originally defined for these parameters were used throughout model validation and subsequent simulations.

SECTION FOUR TIDAL CALIBRATION

Model calibration involves the adjustment of model inputs and parameters to obtain a better match to measured data. To ensure the ADCIRC model is capable of predicting water levels and coastal hydrodynamics during periods of low energy, the model was utilized to predict tidal conditions within the study region for a period of 45 days. The model was forced with tidal constituents at the open ocean boundary in order to simulate water levels that were then compared with known tidal conditions at seven National Oceanic and Atmospheric Administration (NOAA) stations.

The seven NOAA stations selected for tidal comparisons are listed in Table 1 and are also shown in Figure 1. These locations were chosen based on their relevance to the current study and the availability of tidal harmonic data from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) website (www.tidesandcurrents.noaa.gov).

The ADCIRC tidal simulations consisted of a 15-day ramping period, allowing the model to enter a steady state, followed by a 30-day period with full tidal forcing. Tidal harmonic analyses were performed using the 30-day model output at the NOAA station locations. Modeled amplitudes and phases for eight predominant tidal constituents (K_1, K_2, M_2, N_2, O_1, Q_1, S_2, and P_1) were compared with the values NOAA reported at each of the stations.

Table 1 lists the modeled and measured constituent parameters, and Figure 2 shows scatter plots comparing modeled and measured amplitudes and phases for all the NOAA stations. Appendix A contains individual scatter plots comparing modeled and measured amplitudes and phases for each NOAA station evaluated. It should be noted that a phase of 360 degrees is equivalent to 0 degrees (i.e. a modeled phase of 3 degrees and a measured phase of 357 degrees results in a difference in 6 degrees). The tidal constituents listed for each NOAA station in Table 1 are sorted by amplitude (largest to smallest). The table also shows the cumulative percentage of the overall tidal amplitude and the contribution of these eight constituents to the tidal signal at each location.

Overall, there is good agreement between modeled and measured data; differences in amplitude are less than 20 percent for all significant constituents with amplitudes greater than 0.1 meter (0.33 foot). Amplitude errors are less than 10 percent for the primary M2 constituent (the largest tidal component) at all stations except Cape May, NJ, and Bergen Point West Reach, NY, where errors are 12 percent and 18 percent, respectively. The Cape May and Bergen Point West Reach stations are located in dynamic narrow channels where the minimum model resolution may limit the model's capability to reproduce the tidal dynamics, although the maximum differences for the M2 constituent range from 3 to 5 inches. Larger amplitude and phase differences exist for stations outside the detailed study area, such as Montauk, NY, and Bridgeport, CT, where the mesh resolution is not sufficient to fully capture the complexities of the harbor and inlet hydrodynamics at these locations.

Based on the results of the tidal simulation where reasonable agreement existed between the modeled and measured data, no further calibration or adjustment of model parameters was warranted.

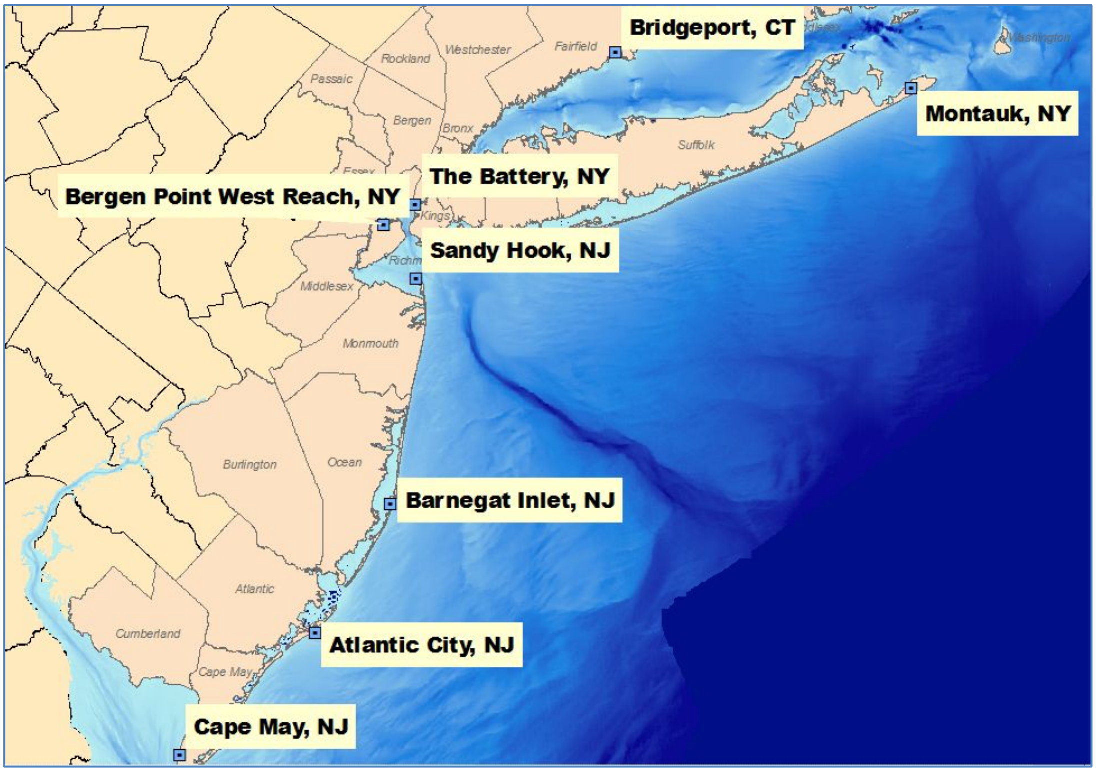

Figure 1. NOAA Water Level Stations Used for Tidal Calibration and Model Validation

Table 1. Tidal Calibration Constituent Comparisons

Station Name, ID	Constituent	Cumulative % of Tide	NOAA Amplitude (ft)	Model Amplitude (ft)	Amplitude Difference (%)	NOAA Phase (deg.)	Model Phase (deg.)	Phase Difference (min.)
Montauk NY, 8510560	M2	34%	0.99	1.00	0.7%	46.8	45.8	-2
	N2	43%	0.26	0.26	1.6%	22.2	25.9	8
	K1	51%	0.24	0.29	20.3%	178.7	181.4	11
	S2	58%	0.21	0.26	19.8%	56.6	37.5	-38
	O1	64%	0.18	0.19	7.2%	209.8	207.6	-9
	P1	67%	0.08	0.09	23.5%	193.7	189.8	-16
	K2	69%	0.06	0.03	57.4%	61.6	209	294
	Q1	71%	0.05	0.04	19.3%	192.6	198.8	28
Cape May NJ, 8536110	M2	46%	2.34	2.06	12.0%	28.6	19.3	-19
	N2	56%	0.52	0.46	11.7%	9.7	5.3	-9
	S2	65%	0.41	0.36	11.8%	55.3	42.5	-26
	K1	71%	0.34	0.32	8.1%	200.4	186.4	-56
	O1	77%	0.28	0.26	6.4%	185.6	196.7	48
	P1	79%	0.12	0.09	22.8%	199.2	187.7	-46
	K2	81%	0.11	0.11	3.0%	54.5	52.2	-5
	Q1	82%	0.04	0.04	0.8%	184.1	178	-27
Atlantic City NJ, 8534720	M2	43%	1.95	1.80	7.7%	355.4	352.5	-6
	N2	54%	0.46	0.42	9.0%	335.9	337.7	4
	S2	62%	0.38	0.36	4.7%	17.8	9.6	-16
	K1	70%	0.36	0.30	17.9%	183.2	176.8	-26
	O1	76%	0.25	0.24	2.8%	166.1	180.6	62
	P1	78%	0.11	0.09	17.0%	178.5	167.5	-44
	K2	80%	0.10	0.07	32.9%	18.7	20	3
	Q1	81%	0.04	0.04	6.7%	168.7	164.1	-21
Sandy Hook NJ, 8531680	M2	44%	2.26	2.18	3.5%	6	1.5	-9
	N2	55%	0.52	0.50	3.8%	348.6	348.9	1
	S2	63%	0.44	0.46	3.5%	32.6	24.9	-15
	K1	70%	0.34	0.32	4.1%	175.7	177.7	8
	O1	73%	0.18	0.21	18.1%	172.5	184.7	53
	K2	76%	0.12	0.11	12.9%	31.5	20.5	-22
	P1	78%	0.10	0.09	11.0%	180.2	181.7	6
	Q1	79%	0.04	0.03	7.3%	183.1	181.2	-9
Bergen Point West Reach NY, 8519483	M2	44%	2.44	2.01	17.9%	21.2	32.4	23
	N2	53%	0.54	0.45	17.9%	5.1	20.7	33
	S2	62%	0.47	0.39	16.6%	51.2	61.6	21
	K1	68%	0.35	0.32	8.1%	182.9	194.9	48
	O1	71%	0.17	0.20	17.7%	179.3	203.2	103
	K2	73%	0.13	0.12	7.0%	47.9	54.5	13
	P1	75%	0.11	0.09	19.4%	181.8	205.1	93
	Q1	76%	0.04	0.03	7.3%	191.3	202.6	51
The Battery NY, 8518750	M2	43%	2.19	2.09	4.3%	19	11.8	-15
	N2	53%	0.51	0.48	6.6%	360	358.6	-3
	S2	62%	0.42	0.42	0.4%	43.3	34	-19
	K1	68%	0.33	0.32	2.0%	179.6	182.1	10
	O1	72%	0.17	0.21	22.5%	176.3	189.3	56
	K2	74%	0.11	0.10	8.3%	43.9	36.8	-14
	P1	76%	0.10	0.09	14.2%	183.9	187.5	14
	Q1	77%	0.04	0.03	6.4%	190.7	186.2	-20
Bridgeport CT, 8467150	M2	51%	3.25	3.18	2.2%	109.6	101.6	-17
	N2	62%	0.66	0.68	2.8%	87.6	83.8	-8
	S2	70%	0.52	0.44	13.9%	135.9	122.2	-27
	K1	75%	0.32	0.40	26.2%	191.6	196.1	18
	O1	78%	0.21	0.25	18.1%	219.5	218.4	-5
	K2	81%	0.15	0.23	49.8%	134.7	153.4	37
	P1	82%	0.10	0.11	9.3%	204.1	210	24
	Q1	83%	0.06	0.05	15.0%	205.7	214.3	39

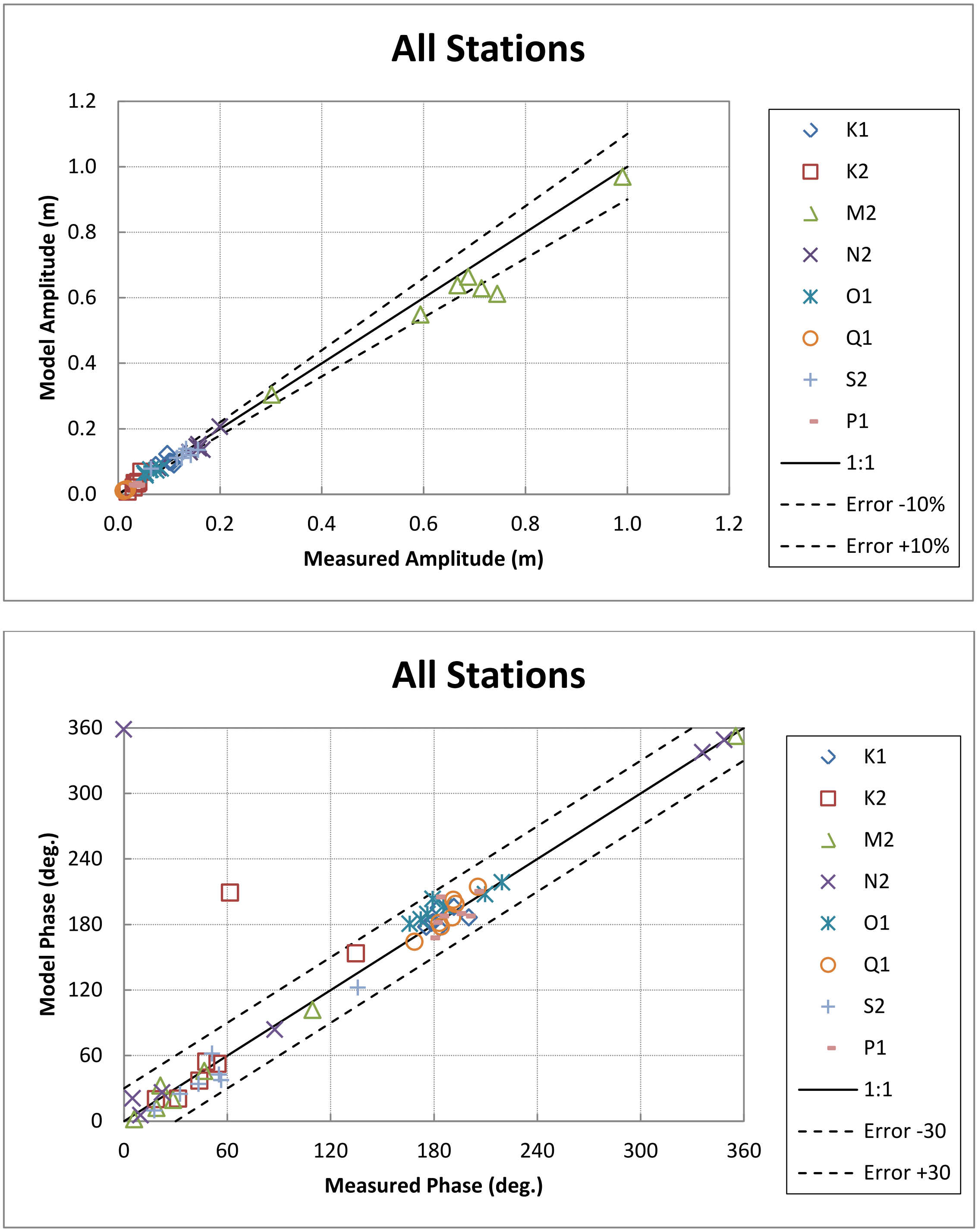

Figure 2. Comparison of Tidal Constituents from Tidal Calibration

SECTION FIVE MODEL VALIDATION PROCESS

Model validation is a process to measure the performance of the model in replicating historical storm events. Model validation was conducted by comparing the ADCIRC-UnSWAN model output, both maxima and time series of water elevations, with observed data for historical storm events. The ADCIRC-UnSWAN model was also validated by comparing the modeled wave heights with available collected wave data.

The historical storms selected for validation included both tropical and extratropical events. The tropical storm events included:

H1938 – Hurricane of 1938 (Long Island Express)

H1944 – Great Atlantic Hurricane of 1944

H1960 – Hurricane Donna

H1985 – Hurricane Gloria

The extratropical events included Nor'easter storms that impacted the region:

N1984 – March 28-29, 1984 Nor'easter

N1991 – October 30-31, 1991 Nor'easter (Perfect Storm or Halloween Storm)

N1992 – December 11-14, 1992 Nor'easter

These storms were selected for validation because they are well documented, major storm events affecting the region and because observed water level and high water mark (HWM) data are available. Figure 3 shows the storm tracks for the tropical validation storms.

During the model validation process, it was determined that the N1991 storm would not be included in the validation storm set used to evaluate the model's performance in simulating peak water levels; this decision is further detailed in the sections to follow. The N1991 storm did have the most recorded wave observations within the study area, however, and provided an indication of the model's capability for simulating wave conditions.

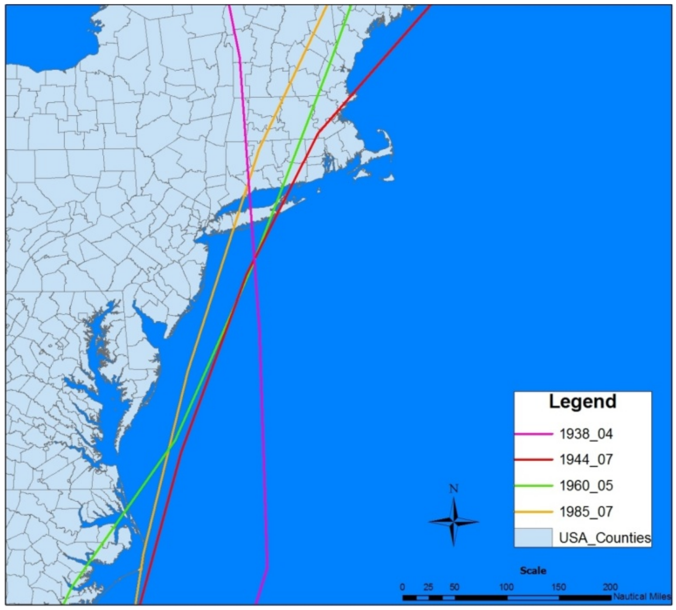

Figure 3. Tracks of Tropical Storms Used for Model Validation

A 15-day ramping period, including only tidal forcing, was completed prior to each validation storm run to ensure water levels were correctly represented at the start of the ADCIRC-UnSWAN simulations.

Measured Data

For each storm, the modeled water levels were compared with verified water level data obtained at NOAA tidal stations located throughout the study area (see Figure 1). At each NOAA water level gauge the modeled water-surface elevation (WSEL) was extracted for comparison with observed data. These NOAA stations are also listed in Table 2, with data availability for each validation storm.

Peak water levels were also extracted from the NOAA measured hourly time series data for each validation storm event. For some NOAA stations where measured hourly water level data were not available, the monthly mean data were used, which also included the peak water level observed during the specified month.

Table 2. NOAA Stations Used for Model Validation

Station	Station Name	State	Lat (dd)	Long (dd)	Availability of Verified Data						
					1992 Nor'easter	1991 Nor'easter	1985 Hurricane Gloria	1984 Nor'easter	1960 Hurricane Donna	1944 Hurricane	1938 Hurricane
8467150	Bridgeport	CT	41.1733	-73.1817	Monthly	Monthly	Monthly	Monthly	No data exists.		
8518750	The Battery	NY	40.7000	-74.0133	Hourly WL	Hourly WL	Hourly WL	Hourly WL	Hourly WL	Monthly	Monthly
8519483	Bergen Point West Reach	NY	40.6367	-74.1417	Monthly	Ver hourly from 10/29/91 onwards, ver H/L for entire	Hourly WL	Hourly WL	No data exists.		
8510560	Montauk	NY	41.0483	-71.9600	Hourly WL	Hourly WL	Hourly WL	Hourly WL	Hourly WL	No data exists.	
8531680	Sandy Hook	NJ	40.4667	-74.0083	Hourly WL	Hourly WL	Hourly WL	Hourly WL	Hourly WL	Hourly WL	Hourly WL
8534720	Atlantic City	NJ	39.3550	-74.4183	Monthly	Hourly WL	Hourly WL	Monthly	Hourly WL	Monthly	Monthly
8533615	Barnegat Inlet	NJ	39.7617	-74.1117	Hourly WL	Hourly WL	Hourly WL	No data exists.			
8536110	Cape May	NJ	38.9683	-74.9600	Hourly WL	Hourly WL	Hourly WL	Hourly WL	No data exists.		

HWM data were available for six of the validation storms, with the exception of the 1991 Nor'easter. The U.S. Army Corps of Engineers (USACE) was the primary source for the HWM data, which were either provided directly by the USACE, New York District, or gathered from various historical reports. For the earlier 1938 and 1960 tropical storms, many of the HWM points were digitized from maps obtained from the NY Sea Grant publication *Storm Surge* by Pore and Barrientos (1976). The amount of HWM data available and the sources of data for each storm are listed in Table 3. As noted above, HWMs were not available for the 1991 Nor'easter storm.

The HWM data were converted to the North American Vertical Datum of 1988 (NAVD88) using NOAA's VDATUM (http://vdatum.noaa.gov) software. For the older storms (H1938, H1944, and H1960), it was first necessary to account for the Sea Level Rise (SLR) that occurred from the time the HWM was collected to the present National Tidal Datum Epoch (NTDE). Rates of SLR for the nearest NOAA tidal station were applied to those HWMs referenced to Mean Sea Level (MSL) so that all were relative to the current 1983-2001 NTDE prior to converting to NAVD88.

Each HWM observation was then reviewed to identify any outliers that were not consistent with surrounding HWM observations. The HWM observations were also reviewed to identify those at the open coast that would likely include surface waves above the still water elevation (SWEL). The ADCIRC model output is the storm-induced SWEL that includes the wave-induced setup due to radiation stresses, but the modeled water level is not inclusive of wave amplitudes. The HWM data were also reviewed to identify those outside of the study area where the ADCIRC mesh was not sufficiently detailed to provide overland relief for the surge events. Where the HWM was located outside of the detailed overland ADCIRC mesh, the HWM was located in an exposed area where water elevation would include contribution of waves, or the HWM was an apparent outlier compared to other HWMs, these data were filtered out prior to making comparisons with the modeled storm output. The reduced number of HWMs (after filtering) is also shown for each storm in Table 3.

Table 3. HWM Data Available for Validation Storms

Storm	HWMs available	HWMs after filtering*	Source	Publications**
H1938	89	43	USACE	4, 5, 6
H1944	61	31	USACE	5, 6
H1960	119	84	USACE	1, 2, 3, 5, 6
N1984	11	6	USACE	1, 2, 4
H1985	13	2	USACE	1, 2
N1992	20	19	USACE; USGS	4, 7, 8

*Data filtered where the HWM was located outside of the detailed overland ADCIRC mesh, where the HWM was located in an exposed area at which the water elevation would include contribution of waves, or the HWM was an apparent outlier compared to other HWMs.
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1 USACE North Atlantic Division, New York District (NAN) Beach Erosion Control Project, Atlantic Coast of Long Island from Jones Inlet to East Rockaway Inlet (1994)
2 USACE NAN Beach Erosion Control Project Atlantic Coast of New York City from Norton Point to Rockaway Inlet, Coney Island Area
3 USACE NAN Report on Hurricane Donna of 12 September 1960, Feb 1961
4 North Shore of Long Island, NY, Storm Damage Protection and Beach Erosion Control Reconnaissance Study, August 1995
5 Pore and Barrientos, 1976. Storm Surge: MESA New York Bight Atlas Monograph 6, New York Sea Grant, Albany NY
6 USACE Raritan Bay and Sandy Hook Bay NJ: Cooperative Beach Erosion Control and Interim Hurricane Study, Nov. 1960
7 Union Beach, NJ Final Feasibility Report, September 2003
8 USGS Water-Supply Paper 2499, Summary of Floods 1992, December 11-12, 1992, in New Jersey (1998)

In addition to validation of ADCIRC-UnSWAN modeled water levels, modeled wave heights were also compared with wave height measurements obtained at NOAA’s National Data Buoy Center (NDBC) stations within the study area. Observed wave data were available for the more recent extratropical storms: N1984, N1991 and N1992. Table 5 lists the NDBC wave stations with location, water depth, and data availability for the Nor’easter storms. Figure 4 shows the locations of the NDBC wave buoys offshore of New York and New Jersey.

Table 4. NDBC Wave Stations Used for Model Validation

Station	Lon (dd)	Lat (dd)	Depth in ADCIRC (m)	Data Availability		
				N1984	N1991	N1992
44004	-70.4330	38.4840	3170	X		X
44008	-69.2470	40.5020	67	X	X	
44012	-74.6000	38.8000	18		X	
44025	-73.1660	40.2500	41		X	X
44009	-74.7020	38.4640	29		X	
ALSN6	-73.8000	40.4500	30			X

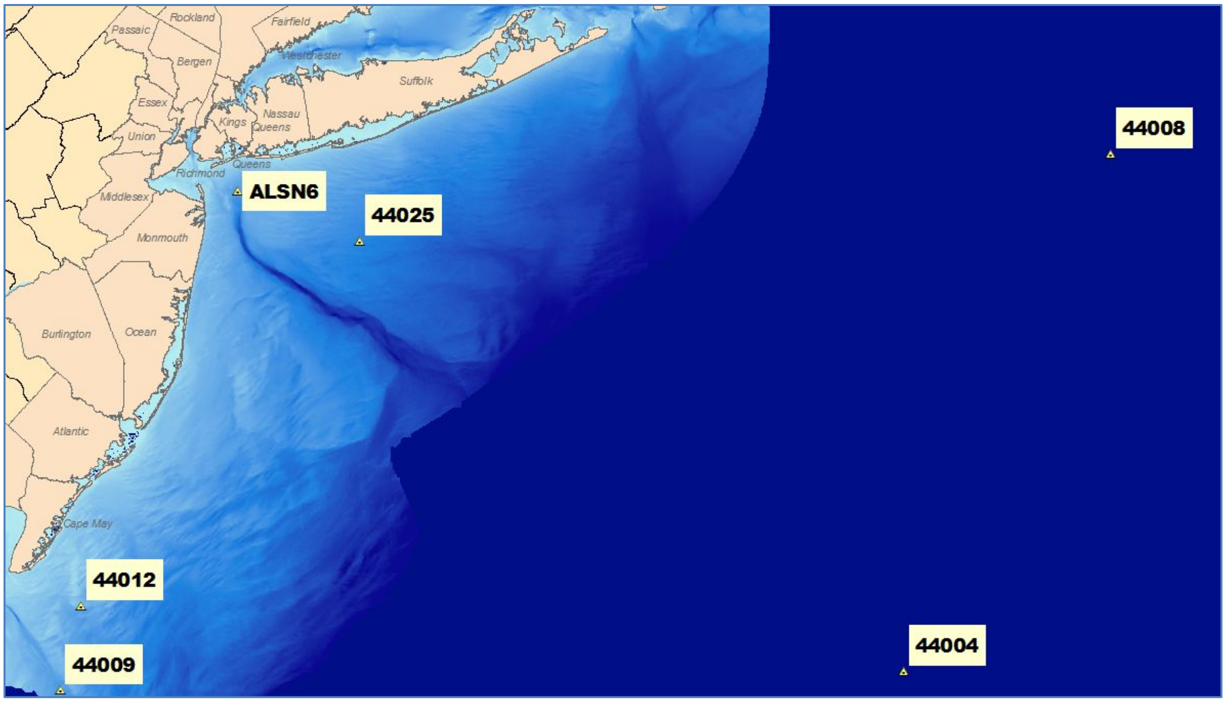

Figure 4. NDBC Wave Buoys Used for Model Validation.

5.1 VALIDATION RESULTS

5.1.1 NOAA Hydrograph Comparisons

The seven validation storm simulations were conducted and time series of water elevations were output from the model at locations coinciding with the NOAA water level stations listed in Table 2. The modeled water levels were then plotted with the observed water levels for the NOAA stations where hourly data were available. Figures showing the measured and simulated hydrographs for each validation storm can be found in Appendix B.

The comparisons of the simulated hydrographs to measured NOAA data revealed that the model is capable of simulating water levels attributed to the combined forcing of tides and storm effects. In general, the results revealed that the modeled and measured water levels are in phase, as the peaks and valleys (highs and lows) are largely coincident. The hydrographs also demonstrate the model's capability to simulate the hydrodynamics of the study area, as the tidal ranges are closely matched before the storm's arrival. This especially can be seen in the extratropical storm hindcasts, which are of longer duration.

An initial review of the hydrograph comparisons indicate that the maximum water levels may not have been captured at the NOAA stations where the available water level data were captured at hourly intervals. Examples of when this may have occurred at the Sandy Hook, NJ, station are shown in Figures B-1, B-2, B-3, and B-4A for the H1983, H1944, H1960, and H1985 storms, respectively. The peaks would have been better captured in the plots of time series data from the NOAA stations if data had been available at a more frequent interval. A quantitative analysis evaluating the peak water level comparisons is presented in the following section.

The hydrographs for the N1991 storm shown in Figures B-6A and B-6B reveal good agreement between the modeled and measured data for the first three days of the storm simulation, after which the observed water level gradually increased between Day 3 and Day 6 of the simulation, but this increase was not captured in the model. This suggested the wind and pressure fields may be a source of error for the N1991 extratropical storm event. In consultations with the developers of the wind and pressure fields for the hindcast events, it was determined that the ADCIRC-UnSWAN model mesh does not extend far enough east across the Atlantic Basin to fully capture the meteorological conditions that induced the surge during the large, complex 1991 Nor'easter event. It was then decided the N1991 storm would not be used in evaluating the model's performance in simulating peak water levels.

5.1.2 Peak Water Level Comparisons

The maximum simulated surge levels were compared with the collected HWM data and the maximum water levels measured at the NOAA stations for six of the validation storms. The 1991 extratropical storm was excluded from the peak water level comparisons, as no HWM data were available for the storm, and it was apparent from the NOAA hydrograph comparisons that the ADCIRC-UnSWAN model, using the current extent of the model domain, could not conduct an adequate hindcast of the storm.

Figures 5 though 10 show the peak water level comparisons for the validation storms H1938, H1944, H1960, H9185, N1984, and N1992, respectively. In these figures the peak water level comparisons are color-coded to reflect the model's agreement with the observed data. Also embedded in Figures 5 through 10 are scatter plots showing the distribution of the measured vs. simulated peak water levels. Appendix C contains figures that show the same peak water level comparisons at a more regional level. The figures in Appendix C also denote the measured elevations at the comparison locations, and again the color-coded markers denote the level of agreement with the simulated maximum surge.

A summary of the peak water level comparison results is shown in Table 5, where the percentages of comparisons within defined difference ranges are listed. Based on past and ongoing FEMA surge studies and consultation with the project team, an acceptable criterion for evaluating model performance was established where 70 percent or more of the peak water level comparisons have a difference of less than 1.5 feet. Table 6 shows peak water level comparison summaries that were compiled for other completed FEMA surge studies.

It is evident that for the H1960 Hurricane Donna and H1985 Hurricane Gloria storms, less than 70 percent of the comparisons are within 1.5 feet. The most measured peak water level data were available for Hurricane Donna, while limited data were available for Hurricane Gloria. For the other four validation storms, H1938, H1944, N1984 and N1992, more than 75 percent of the modeled surge levels are within 1.5 feet of the measured peaks.

Further discussion of the model's performance in simulating the validation storms is included in Section 5.1.3.

Table 5. Difference Ranges For Peak Water Level Comparisons

Storm	Number of Comparisons	Difference between Maximum Simulated and Measured Surge				
		< 1 ft	< 1.5 ft	< 2 ft	< 2.5 ft	< 3 ft
H1938	45	71.1%	80.0%	93.3%	97.8%	97.8%
H1944	34	58.8%	76.5%	91.2%	97.1%	100.0%
H1960	88	48.9%	61.4%	69.3%	79.5%	89.8%
H1985	10	40.0%	60.0%	80.0%	100.0%	100.0%
N1984	14	50.0%	92.9%	92.9%	92.9%	92.9%
N1992	27	70.4%	81.5%	88.9%	88.9%	96.6%

Table 6. Summary of Peak Water Level Comparisons for Other FEMA Studies

Study	Storm	Difference between Maximum Simulated and Measured Surge				
		< 1 ft	< 1.5 ft	< 2 ft	< 2.5 ft	< 3 ft
South Carolina	Hugo	37%	58%	85%	92%	95%
	Hugo and Ophelia	41%	62%	87%	95%	95%
Mississippi	Katrina	56%	74%	88%	92%	100%
	Camille	55%	75%	85%	95%	100%
	Betsy	78%	95%	100%	100%	100%
Louisiana	H. Rita	-	70%	100%	100%	84%
Region III	Isabel	100%	100%	100%	100%	100%
	Ernesto	89%	100%	100%	100%	100%
	Nor'Ida	100%	100%	100%	100%	100%

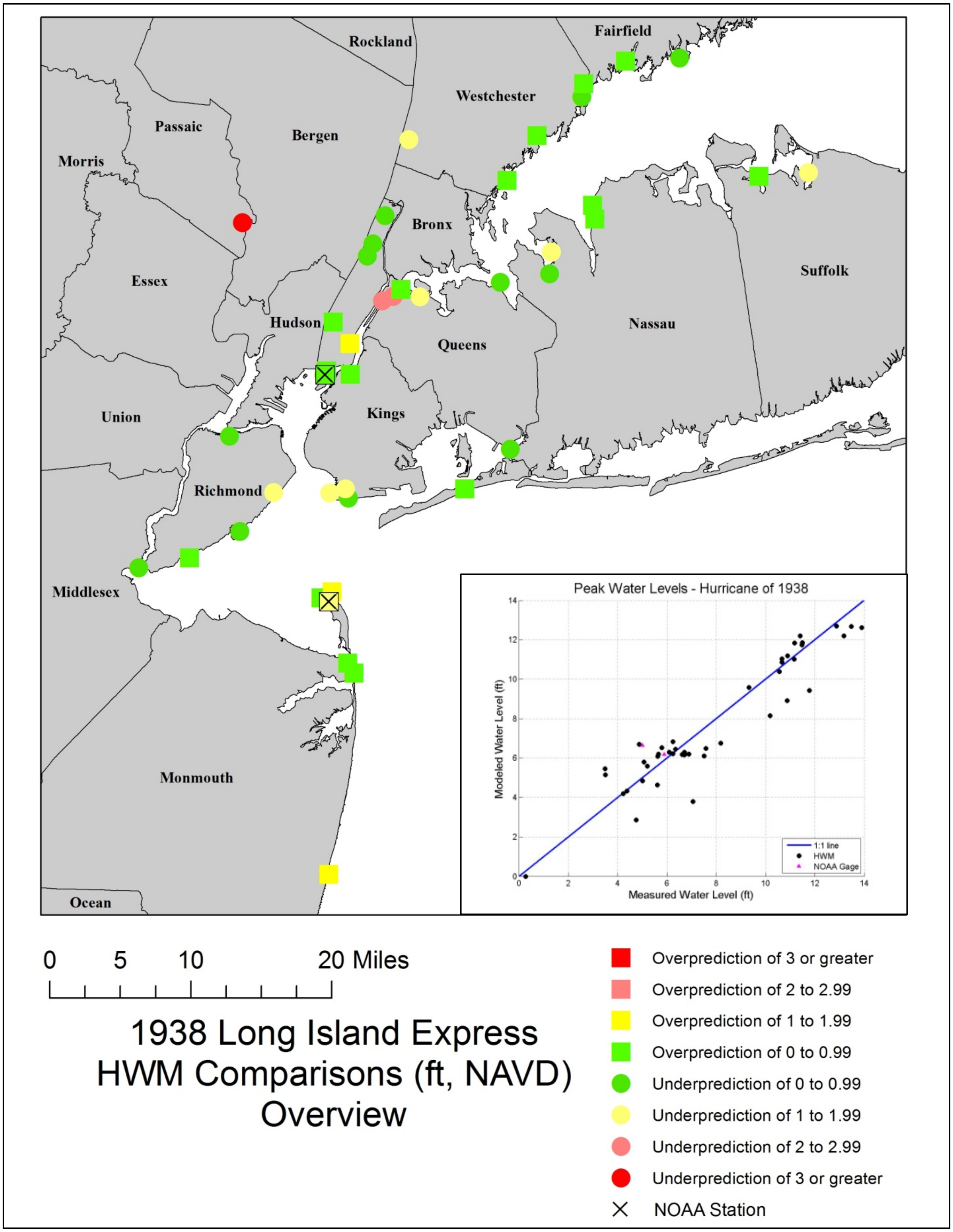

Figure 5. HWM comparisons for H1938

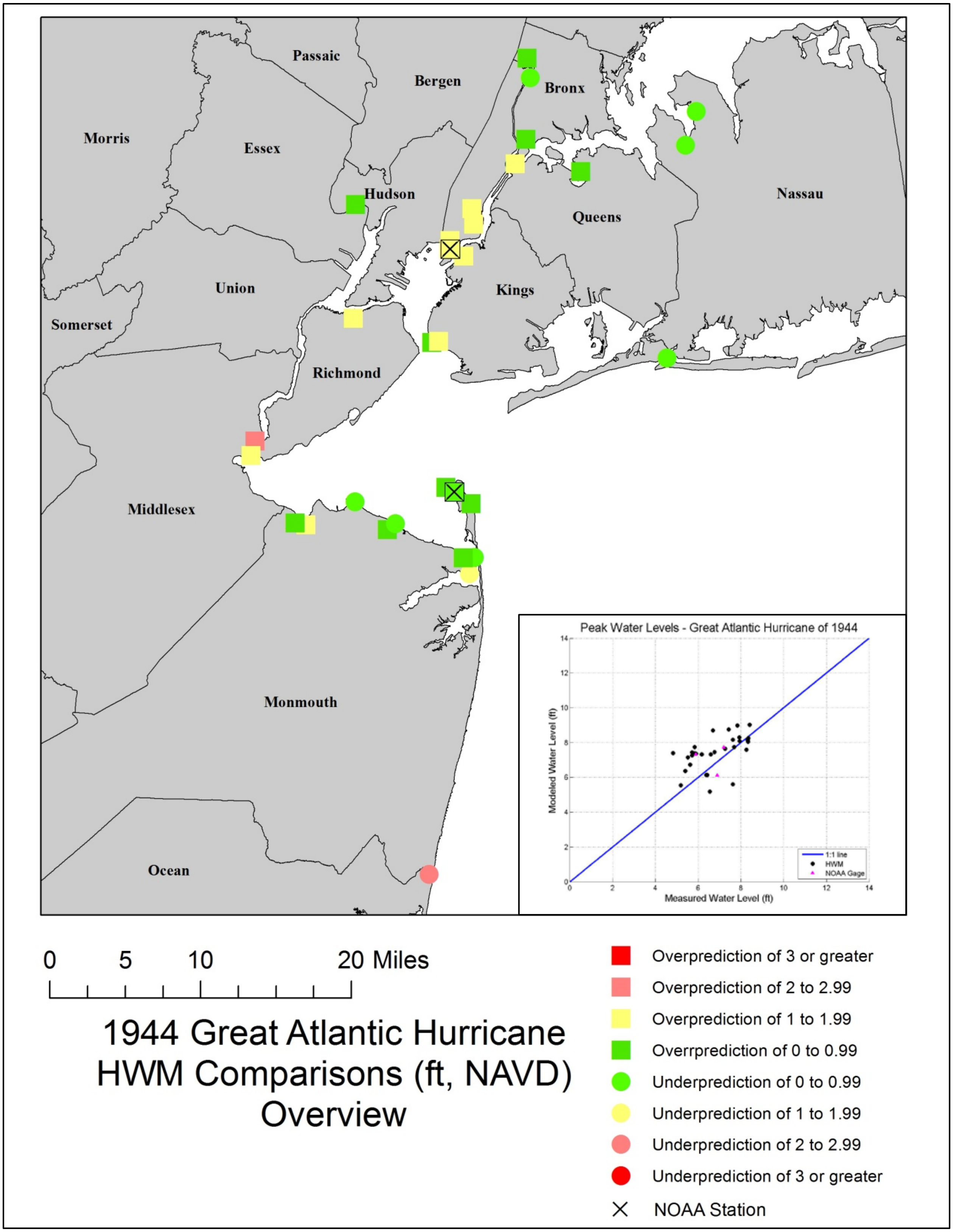

Figure 6. HWM comparisons for H1944

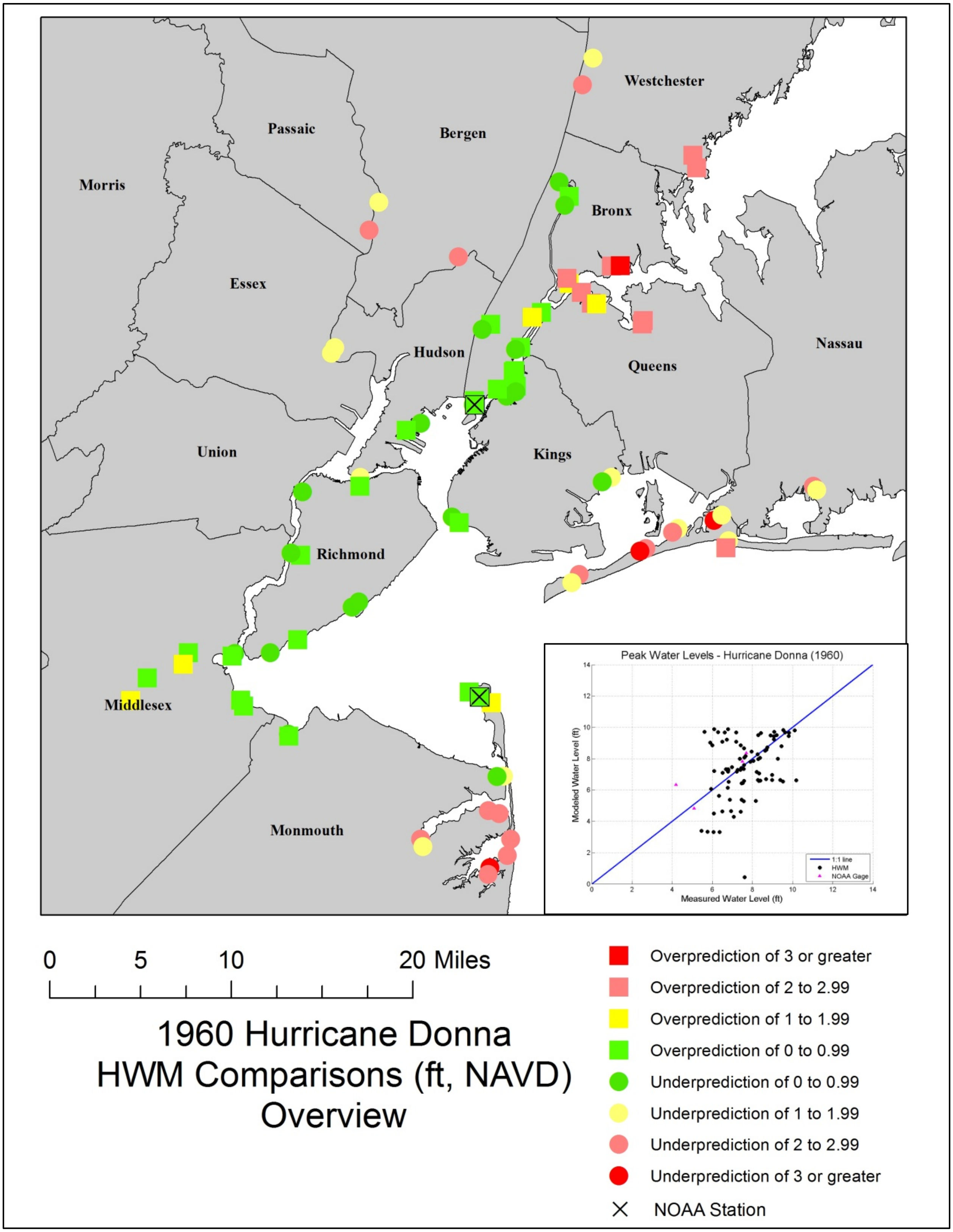

Figure 7. HWM comparisons for H1960

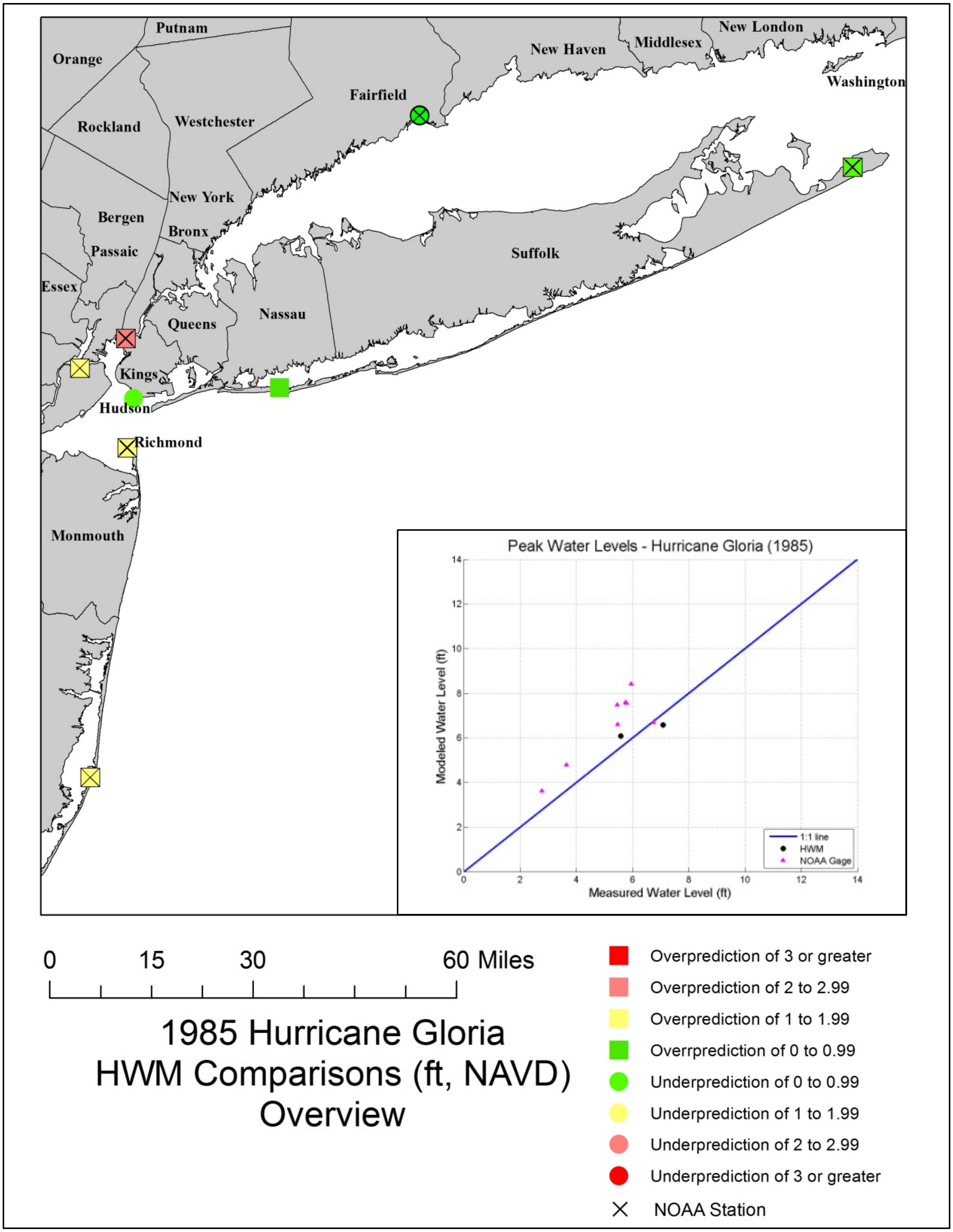

Figure 8. HWM comparisons for H1985

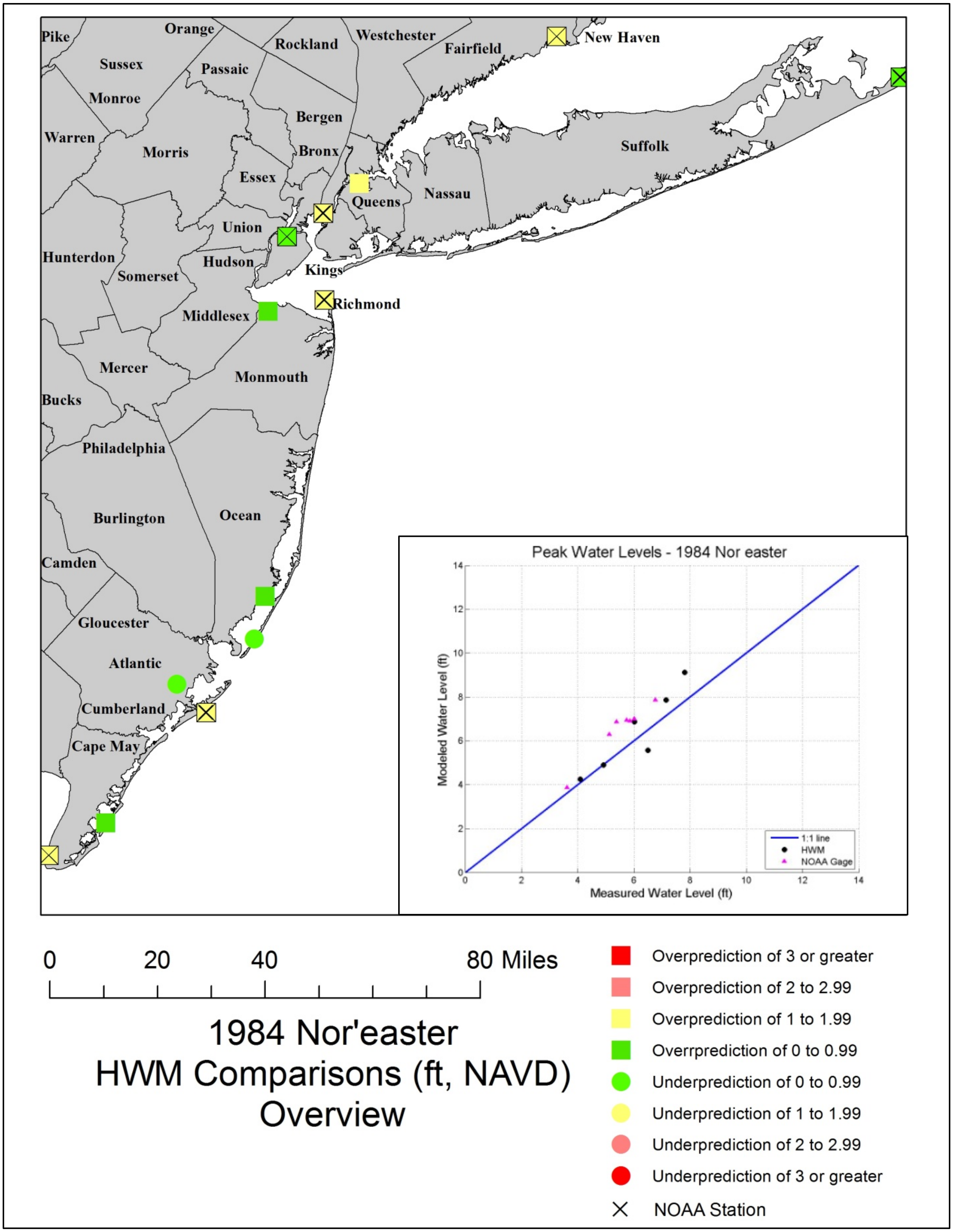

Figure 9. HWM comparisons for N1984

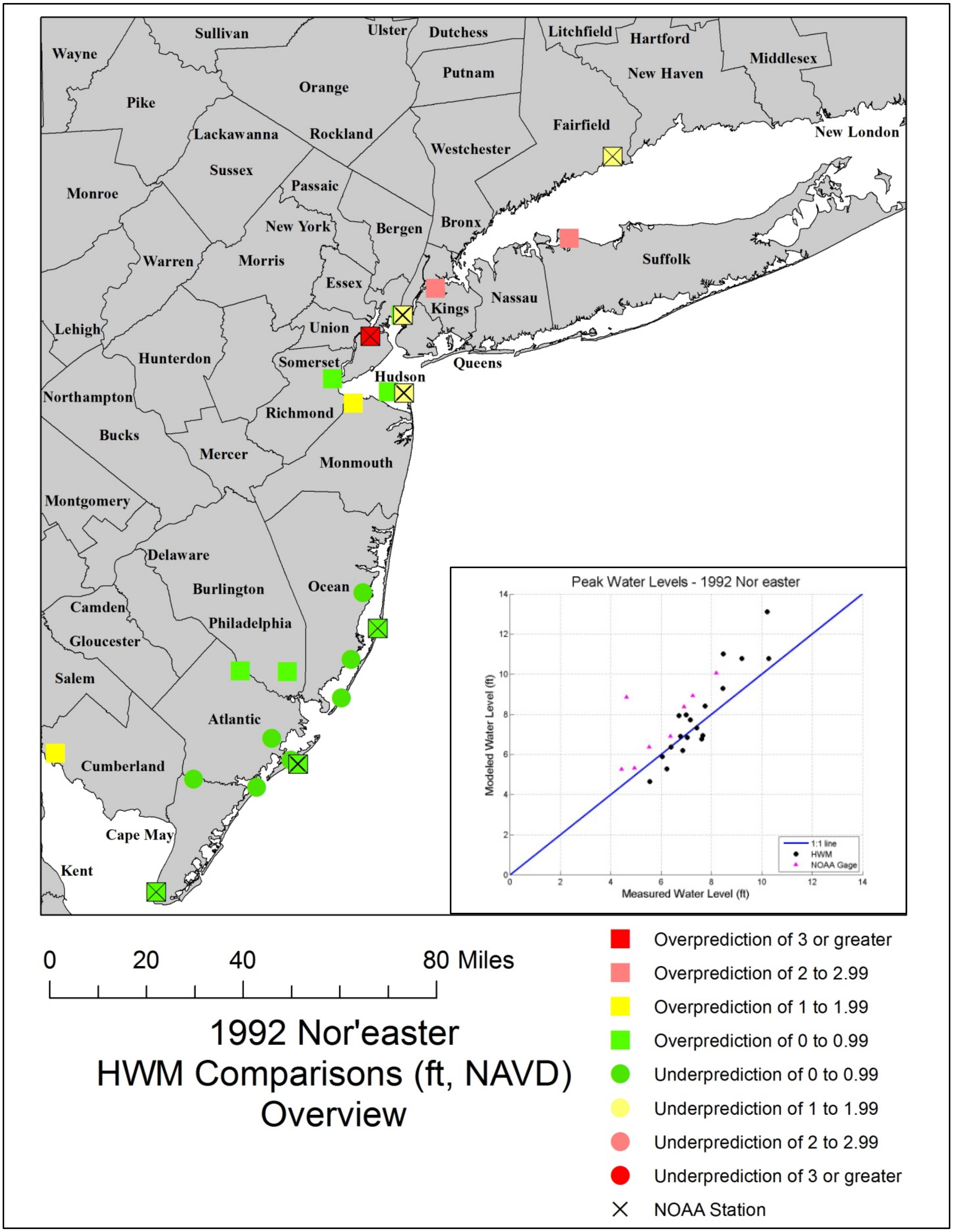

Figure 10. HWM comparisons for N1992

5.1.3 Discussion of Peak Water Level Comparisons

In validating the combined surge and wave model for the H1938 storm, initially the model over predicted surge values within Raritan Bay and under predicted within Long Island Sound. RAMPP consulted with the developers of the wind and pressure fields (OWI) and determined that some uncertainty existed in the storm track and intensity because of the lack of data and reliability of the data for this older storm. A reanalysis conducted by Landsea et al. (2008) concluded adjustments to the storm were warranted, and the wind and pressure fields were adjusted based on this reanalysis.

The results shown in Figure 5 for the revised H1938 storm indicate good agreement within the study area with differences of less than 2 feet. With the reanalyzed forcing conditions, a general trend on the spatial variability of differences is no longer observed (no bias shown in specific regions). This can also be said for the H1944 storm, where differences are within a reasonable range of 1 to 2 feet.

For Hurricane Donna, H1960, larger differences result from the comparisons, and certain generalizations can be made with respect to the peak water level comparisons shown in Figure 7. The model performs well within the Raritan Bay/New York/New Jersey Harbor area with differences of +/-1 foot. Larger differences (greater than 1 and up to 3 feet) are found within the Navesink and Shrewsbury River back bay areas in Monmouth County, where the model under predicts the measured surge values. The model is also shown to under predict further upstream in the Passaic and Hackensack Rivers, and along the Jamaica Bay side of the barrier spit that forms Jamaica Bay in Queens, NY. Lastly, with similar differences of 1 to 3 feet, the model over predicts at the western end of Long Island Sound.

After the initial H1960 validation storm run, the ADCIRC-UnSWAN mesh was reviewed in the areas noted above, where larger differences were seen between the simulated maximum surge and the collected HWMs. Adjustments were made to the mesh at the entrance to the Navesink/Shrewsbury River and in back bay channels, as well as within the Passaic River, to ensure adequate representation. These adjustments resulted in minor improvements in the model results seen in the Navesink and Shrewsbury River back bay areas; however, as shown in Appendix C, Figure C-5, the model is still under predicting by 2 to 3 feet in this area. This could be explained by any over wash or overtopping which may have occurred during this storm along the barrier that divides the Atlantic Ocean from the back bay areas. Historical accounts in the *Red Bank Register* (September 13, 1960) indicate heavy seas poured over the seawall in Sea Bright and Monmouth Beach, NJ. In the ADCIRC-UnSWAN model, however, using present day topography, this barrier remains dry, and there is no overflow from the Atlantic to the leeward side.

The larger differences seen in the H1960 HWM comparisons along the barrier spit in Jamaica Bay (more closely seen in Appendix C, Figure C-6) may again be attributed to overtopping of the Rockaway Peninsula that occurred during the storm, according to historical accounts (USACE, 1961). In addition, wave heights likely contributed to the HWMs collected in the area during this storm. Since these HWMs were on the Jamaica Bay side of the barrier spit, they were not identified as having wave heights contributing to the measured water level. However, as the storm tracked east of the bay, winds were directed from north to south, leading to wind-generated waves that pushed along the bay side of the barrier. Wave heights output from the

ADCIRC-UnSWAN model were shown to be up to 3 feet within the bay along this section of shoreline. This would account for the differences seen in the HWM comparisons, where the model is shown to under predict by 2 to 3 feet.

Limited peak water level data are available for Hurricane Gloria (H1985), and the HWMs show model agreement within +/- 1 foot, while the NOAA stations show differences of 1 to 2 feet in Raritan Bay and the Upper Bay of New York Harbor. Again there are limited data for the N1984 Nor'easter storm, but the model shows reasonable agreement with measured values along the New Jersey coast and up into New York Harbor. For the N1992 Nor'easter storm, more HWM data were available, and good agreement also exists in the comparisons along the New Jersey coast, with differences of +/- 1 foot. Larger differences exist for the N1992 storm in the western end of Long Island Sound and the Upper Bay of New York Harbor, as shown in Figure 10.

To assist in assessing the model performance related to the prediction of the maximum surge values, Table 7 lists the average difference and the absolute average difference of the peak water level comparisons made for each storm, as well as collectively for all validation storms.

Table 7. Model Performance for Peak Water Levels

Validation Storm	Number of Comparisons	Avg. Difference (ft)	Abs. Avg. Difference (ft)
H1938	45	-0.20	0.81
H1944	34	0.59	0.94
H1960	88	-0.15	1.28
H1985	14	1.12	1.23
N1984	10	0.72	0.86
N1992	27	0.58	0.93
All Storms	**218**	**0.15**	**1.06**

It should be noted that for the validation storms that occurred over 50 years ago (H1938, H1944, and H1960), the reliability of the collected HWM data, as well as the meteorological data used to characterize the storms, comes into question. Only recently has the collection of HWMs become a more standardized process. In many instances the HWMs were referenced to the MSL tidal datum, which would introduce some error when converting to NAVD88. Many of the HWMs were also digitized from historical maps that could introduce error in HWM locations.

In addition, very limited meteorological data are available to reconstruct the wind and pressure fields for these earlier tropical storms. Aircraft reconnaissance into hurricanes first commenced in 1943, and it was not until the 1990s that aircraft reconnaissance could measure the winds in tropical storms directly with more accuracy (URI, 2013). This lack of data means that the forcing conditions cannot be fully resolved in space and time for these storms. Another consideration with these earlier storms is that certain changes in the topography and bathymetry have occurred from the dates these storms occurred to the present day, as was discussed in looking at some of the differences seen in the results for Hurricane Donna. The ADCIRC mesh reflects the most recent elevation data available, and any differences in channel hydraulics or landforms at the times these earlier storms occurred are not represented in the model.

Given the many sources of uncertainty in hindcasting these storms, including the data collection, meteorology, wave model, surge model, and topographic data, and given the lack of general trends observed in looking at the peak water level comparisons collectively for all of the storms, the model validation results compare well to the available data. An average difference of 0.15 foot and a mean absolute difference of just over 1 foot show the model is capable of simulating both tropical and extratropical storm events for the purposes of this study.

5.1.4 Wave Height Comparisons

For each validation storm simulation, significant wave heights and the peak wave periods were output from the model, and time series were extracted to compare with the available measured wave data. As listed in Table 4, measured wave data were available for the three extratropical storms. The simulated and measured time series of wave heights and periods at the NDBC buoy locations were plotted for comparison, and are included in Appendix D. Figure D-1 shows the results for the N1984 Nor'easter. Figures D-2A and D-2B show the results for the N1991 storm, while the results for the N1992 Nor'easter are shown in Figures D-3A and D-3B.

The time series comparisons of simulated and NDBC buoy measured wave heights reveal the model performs well at capturing the general wave height trends during the Nor'easter storm events. The model output is consistent with the measured data with respect to the phase or timing of the peak wave heights, and the simulated wave heights are generally within 20 percent of the measured values. In order to better quantify the model performance, Table 8 lists the root mean square error (RMSE) and the bias for each wave height time series comparison, along with the correlation coefficient describing how the modeled waves correlate with the measured waves. A negative bias indicates the model is under predicting the wave heights, while a positive bias indicates over prediction. A correlation coefficient of 1 suggests perfect correlation between the modeled and measured data.

Table 8. Error Statistics for Wave Height Comparisons

NDBC Buoy	N1984			N1991			N1992		
	RMSE (ft)	Bias (ft)	Correlation Coef.	RMSE (ft)	Bias (ft)	Correlation Coef.	RMSE (ft)	Bias (ft)	Correlation Coef.
44004	2.19	-0.03	0.94	-	-	-	2.47	-0.50	0.96
44008	2.00	-0.08	0.96	2.78	0.46	0.97	-	-	-
44009	-	-	-	1.66	-0.12	0.94	-	-	-
44012	-	-	-	2.06	0.41	0.91	-	-	-
44025	-	-	-	1.78	0.09	0.95	1.82	0.22	0.98
ALSN6	-	-	-	-	-	-	1.29	0.19	0.99

The results from the N1984 comparisons at the offshore 44004 and 44008 buoys indicate the model is slightly negatively biased (under prediction of waves), and this is evident in the time series data shown in Figure D-1, where the simulated maximum wave heights are lower than the measured values at these offshore locations.

The model is shown to be positively biased (over prediction of waves) at three of the four NDBC buoys that gathered data during the N1991 storm. However, the time series data shown in Appendix D reveal the modeled and measured maximum wave heights are in good agreement (within 1 to 2 feet) offshore (buoy 44008) and moving closer to shore. The RMSE is shown to be lower at the buoys located closer to shore (buoys 44009, 440012, and 440025), when compared to the offshore location.

It also should be noted, as previously discussed, that the water level hydrograph comparisons showed the model did not produce an adequate hindcast of the N1991 storm as a result of the model's limited domain. The N1991 wave comparisons are included to give an indication of the model's capability for simulating wave conditions, as this storm had the most recorded wave observations at the buoys located in the study area.

The N1992 Nor'easter wave height comparisons show good agreement between the modeled and measured data. The model under predicts the maximum wave height at the offshore buoy (44004), but shows better performance moving closer to shore at the 44025 and ALSN6 buoys. This is also indicated in the RMSE values.

The results indicate good correlation between the simulated and measured wave heights for the extratropical storm runs (> 90%) at all NDBC buoy locations, and that the model is capable of simulating the propagation of storm-generated swell.

The comparison of wave periods at the buoy locations again shows the model does well at capturing the trends associated with the storm events, and there is reasonable agreement with the measured wave periods.

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Appendix A

Tidal Calibration Constituent Comparison Figures

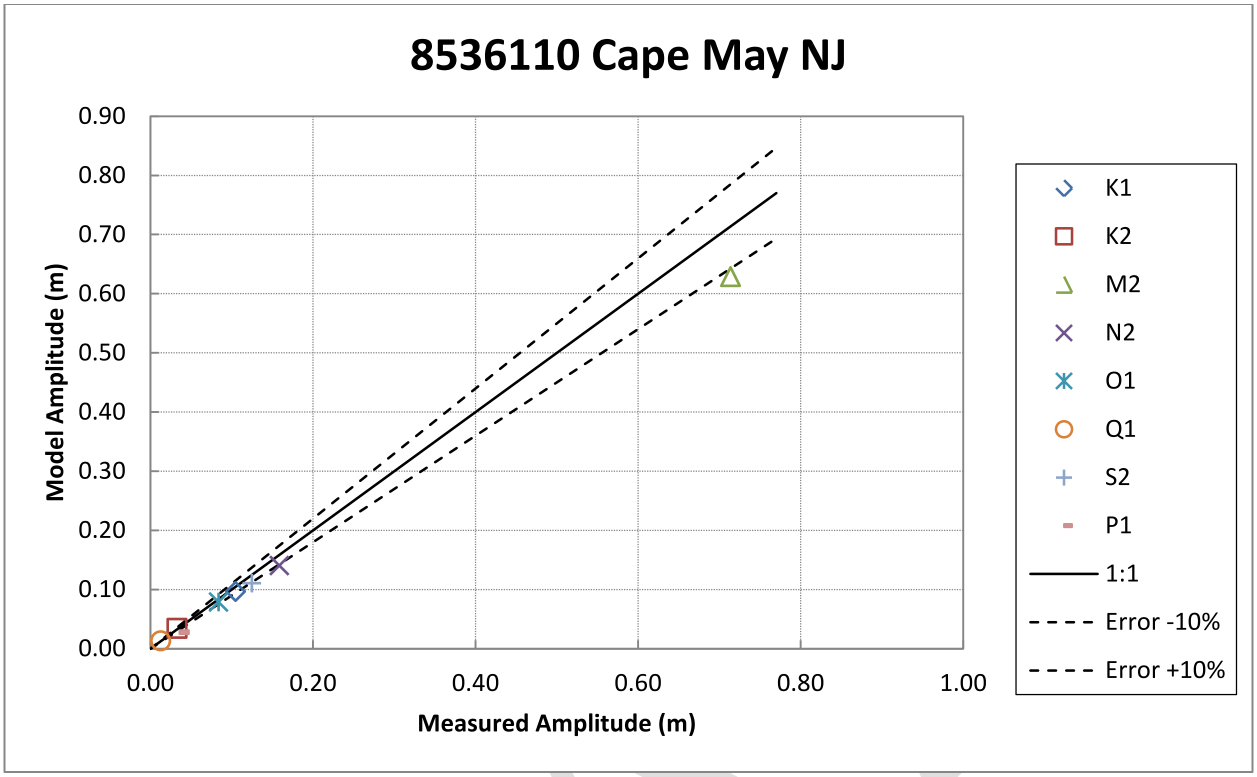


Figure A-1. Cape May, NJ, Modeled/Measured Amplitude

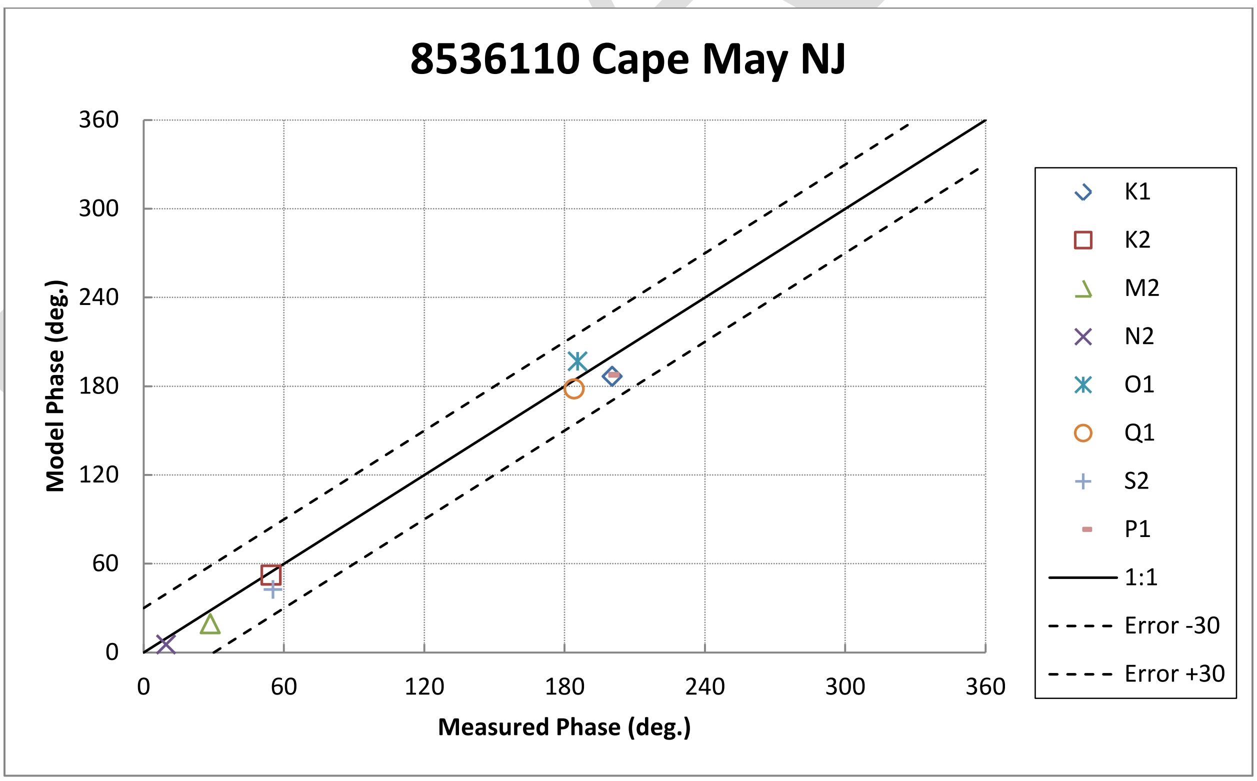


Figure A-2. Cape May, NJ, Modeled/Measured Phase

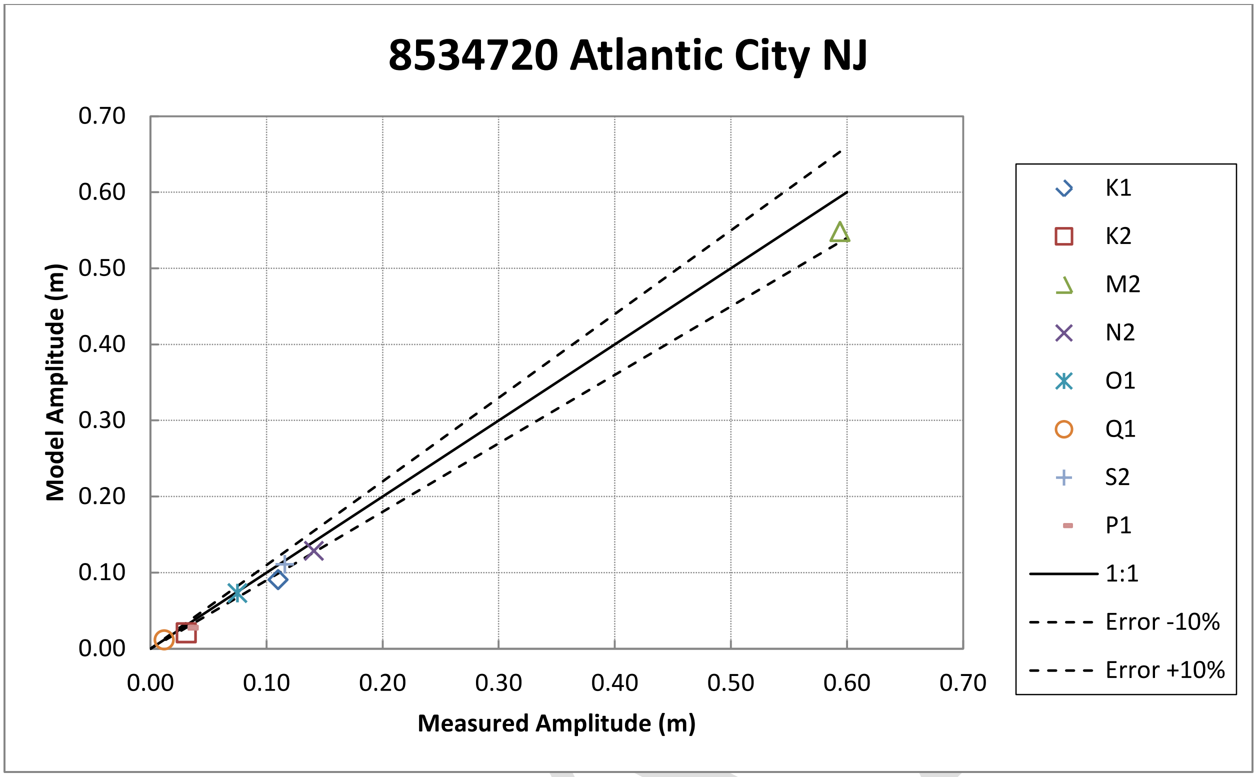


Figure A-3. Atlantic City, NJ, Modeled/Measured Amplitude

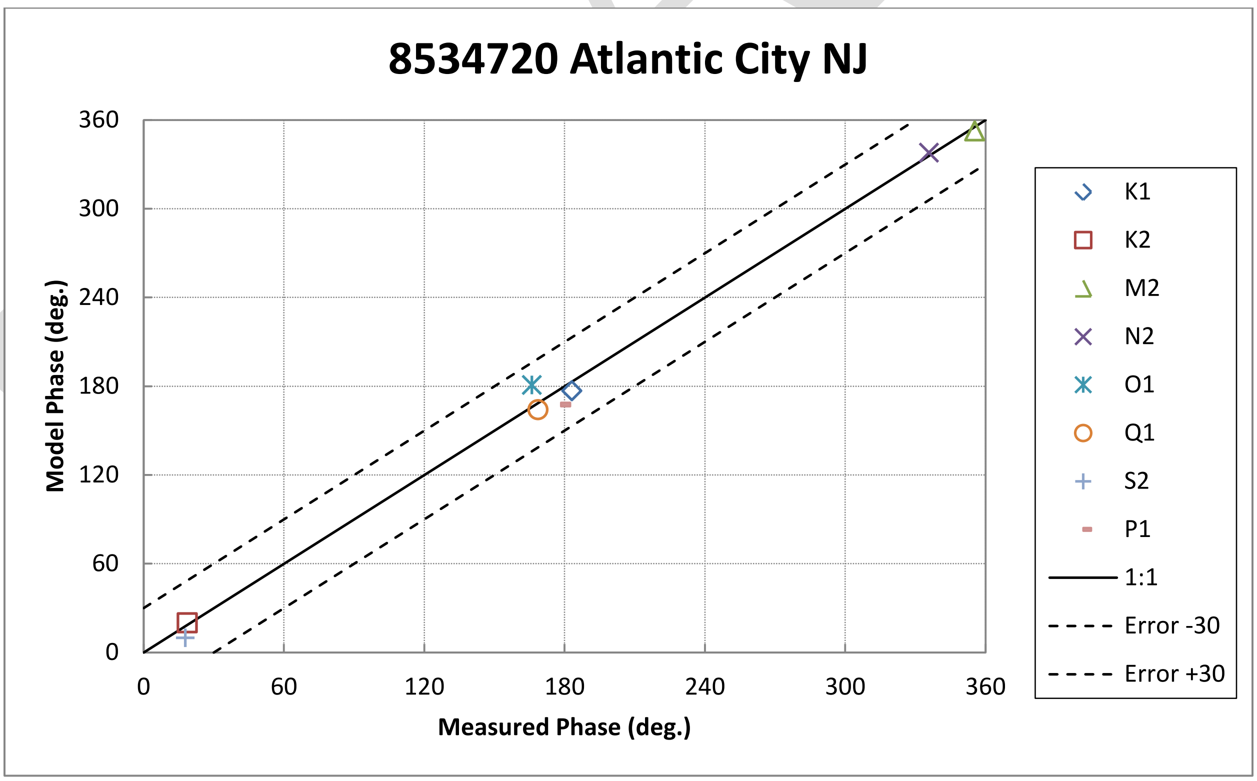


Figure A-4. Atlantic City, NJ, Modeled/Measured Phase

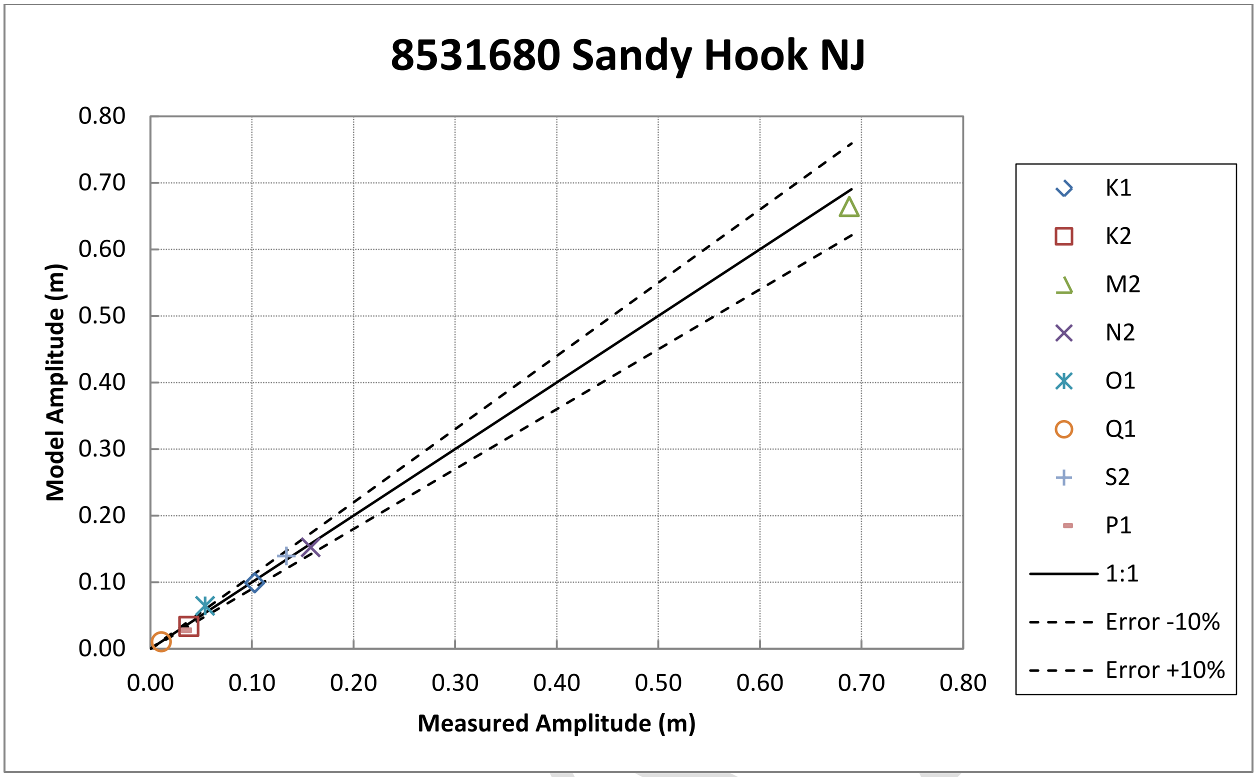


Figure A-5. Sandy Hook, NJ, Modeled/Measured Amplitude

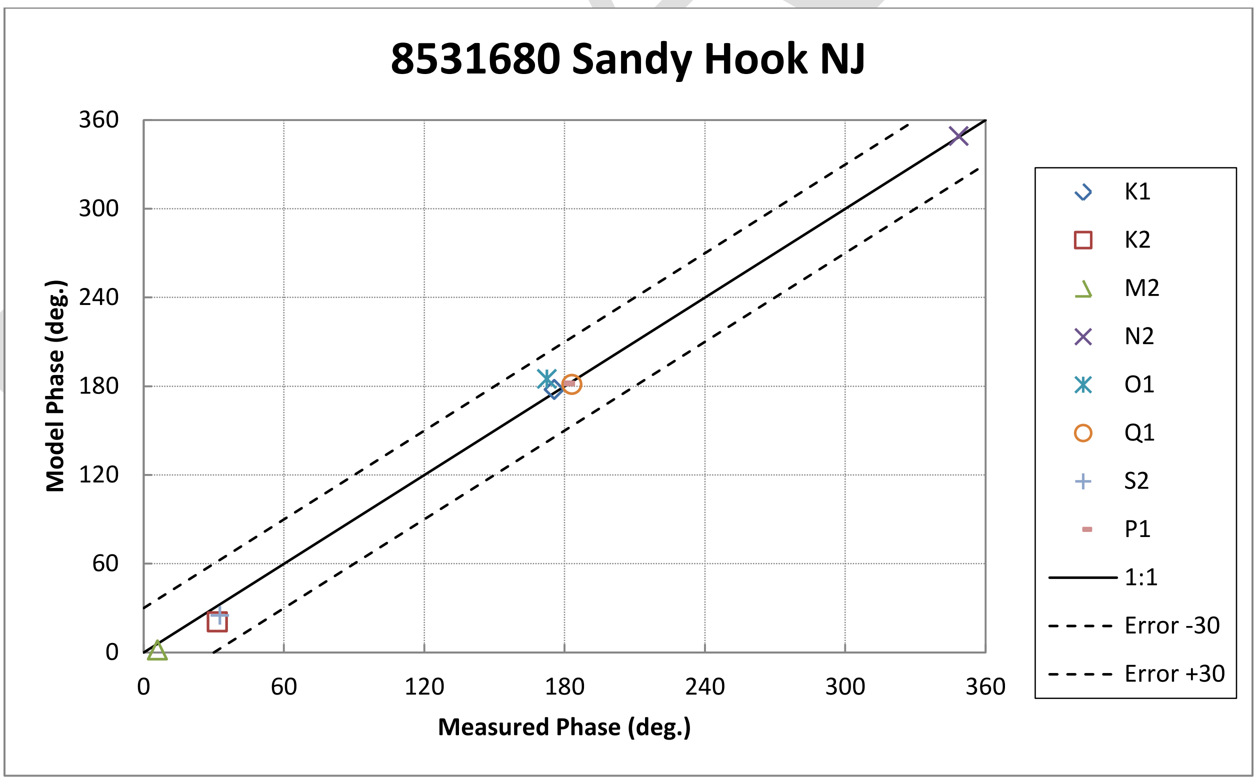


Figure A-6. Sandy Hook, NJ, Modeled/Measured Phase

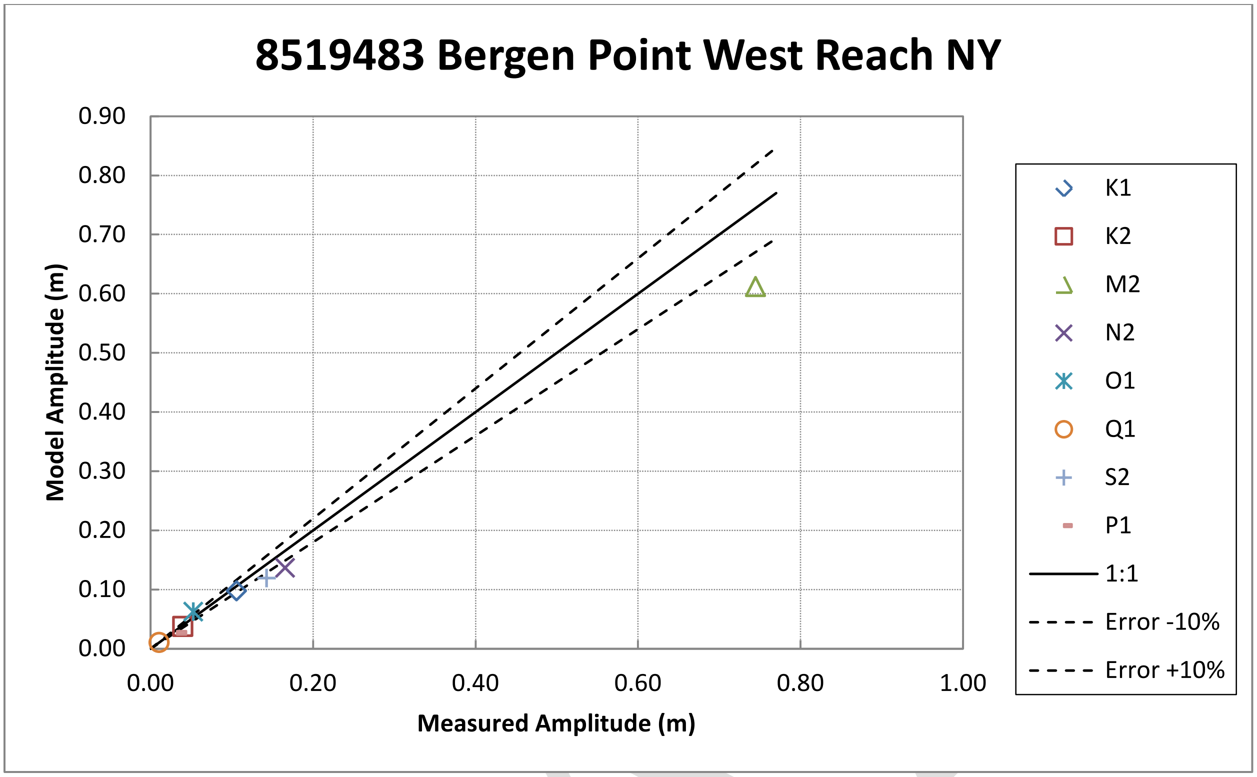


Figure A-7. Bergen Point West Reach, NY, Modeled/Measured Amplitude

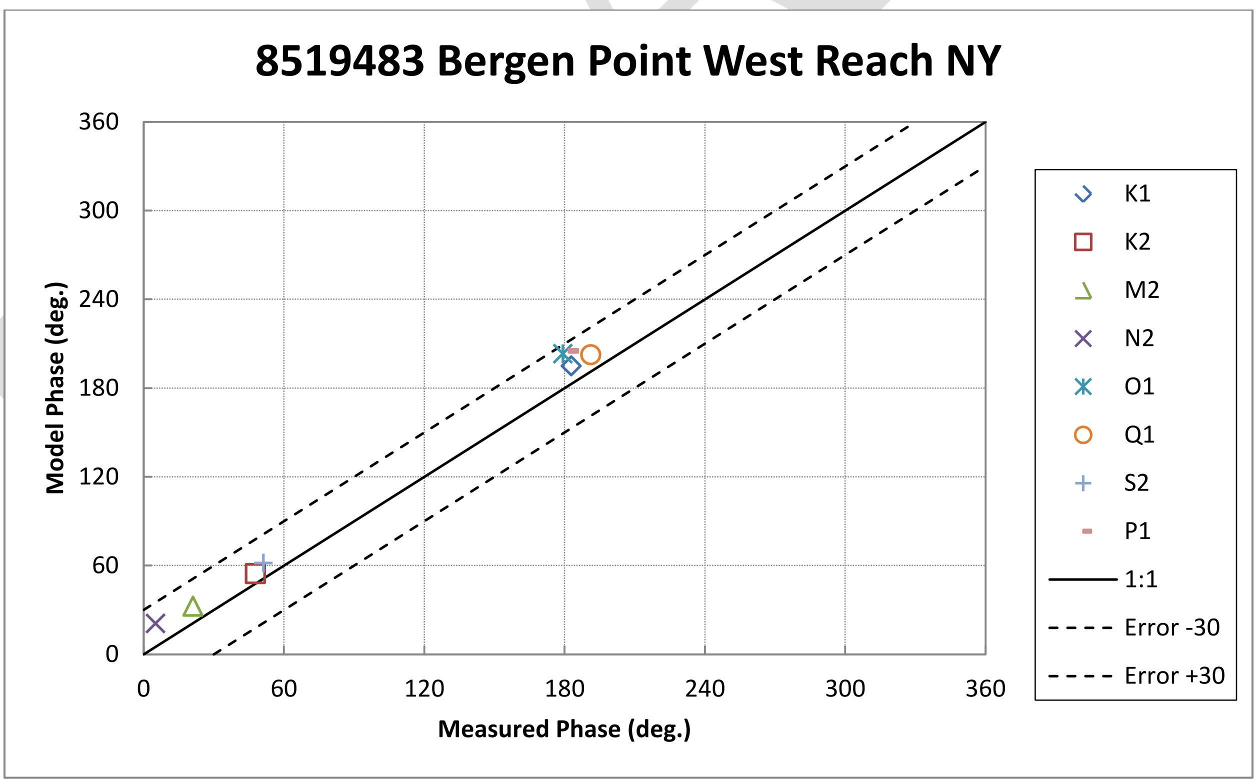


Figure A-8. Bergen Point West Reach, NY, Modeled/Measured Phase

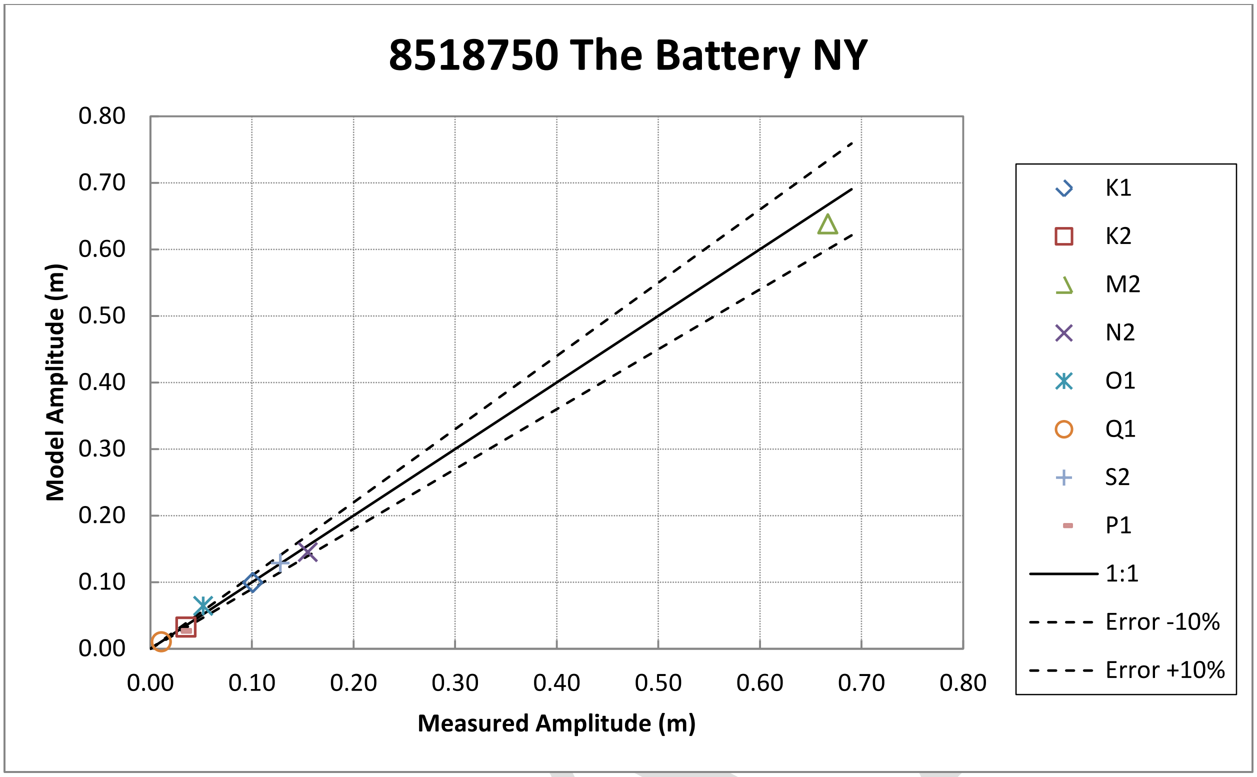


Figure A-9. The Battery, NY, Modeled/Measured Amplitude

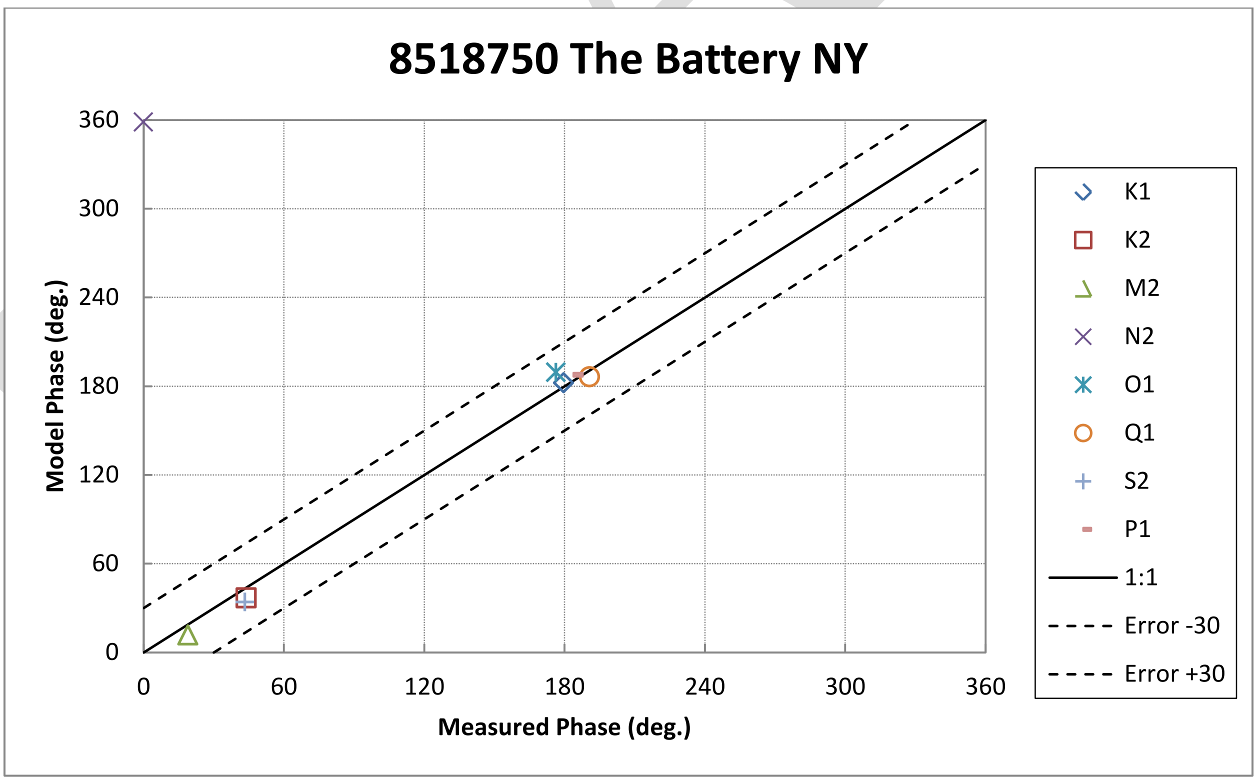


Figure A-10. The Battery, NY, Modeled/Measured Phase

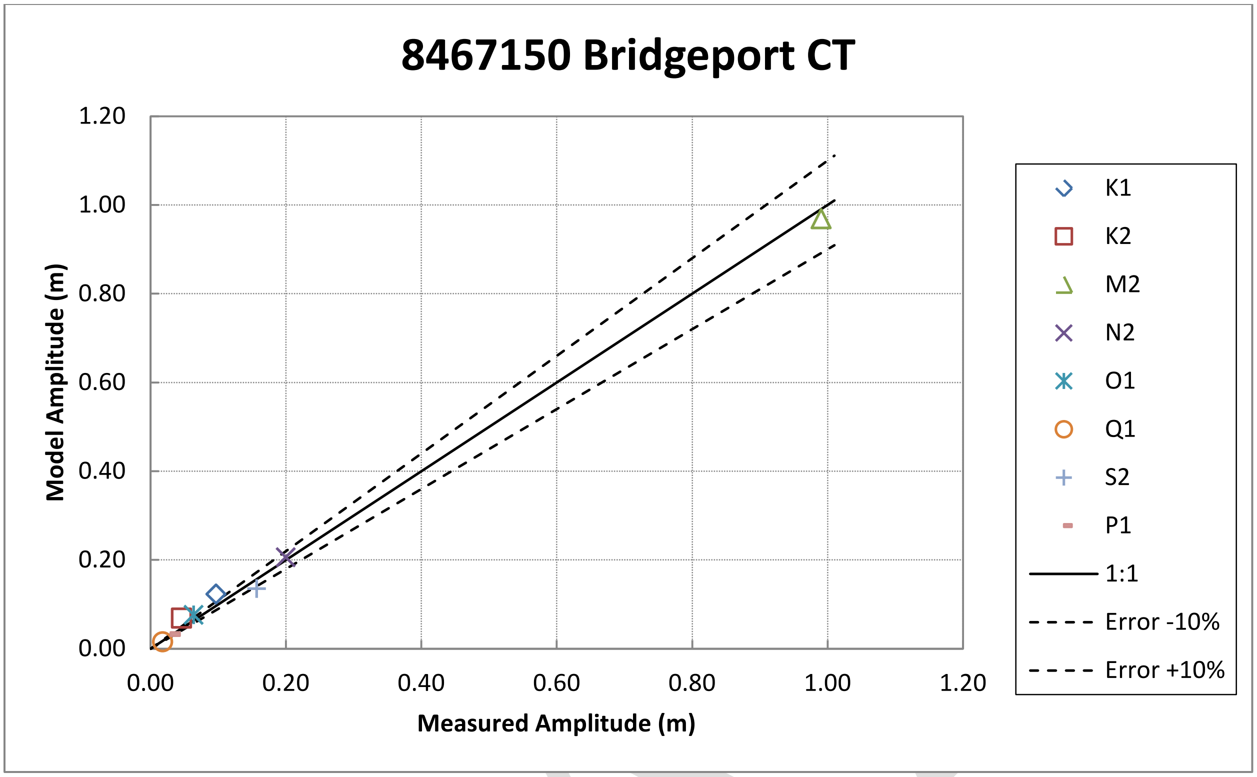


Figure A-11. Bridgeport, CT, Modeled/Measured Amplitude

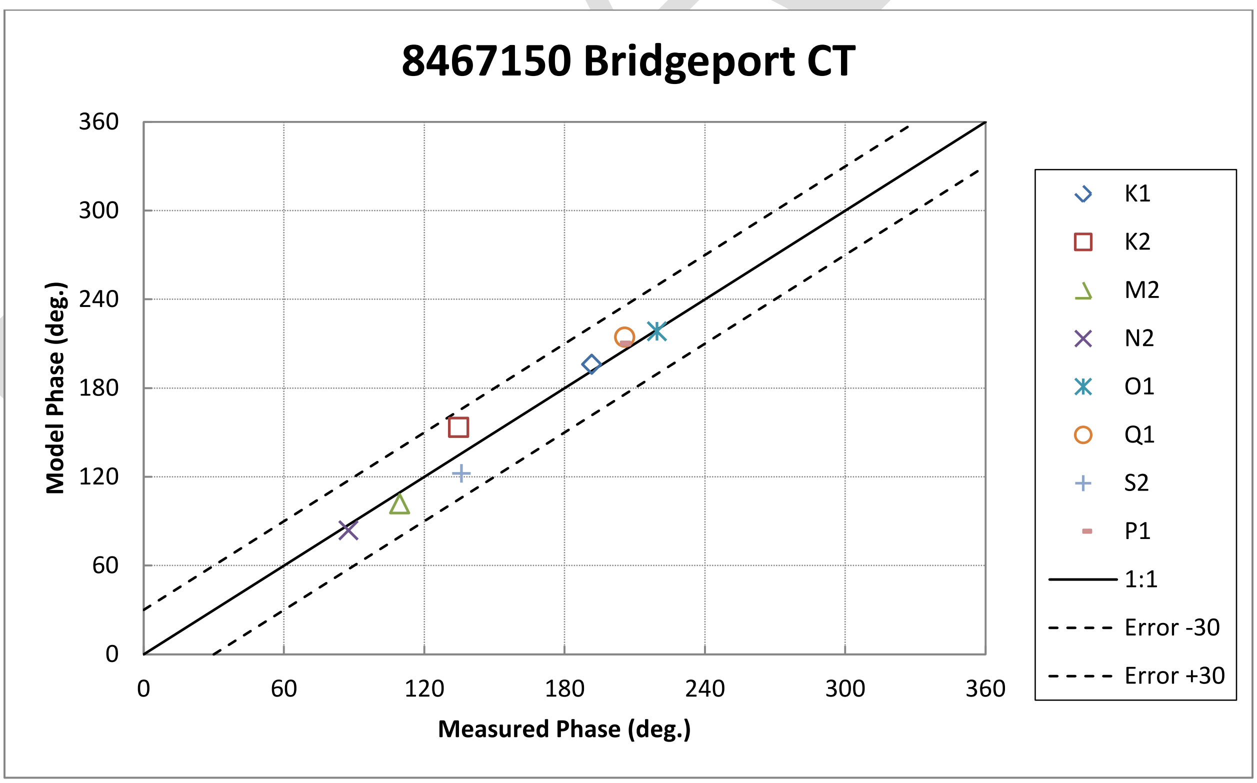


Figure A-12. Bridgeport, CT, Modeled/Measured Phase

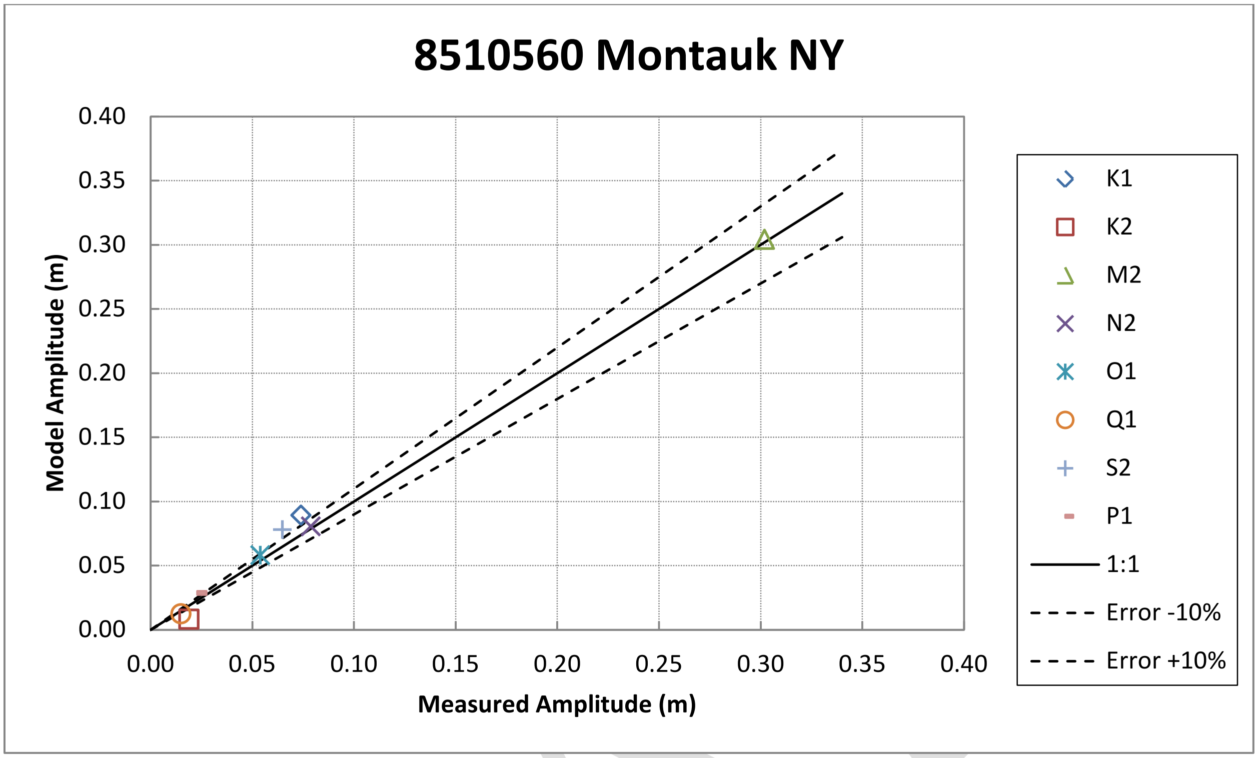


Figure A-13. Montauk, NY, Modeled/Measured Amplitude

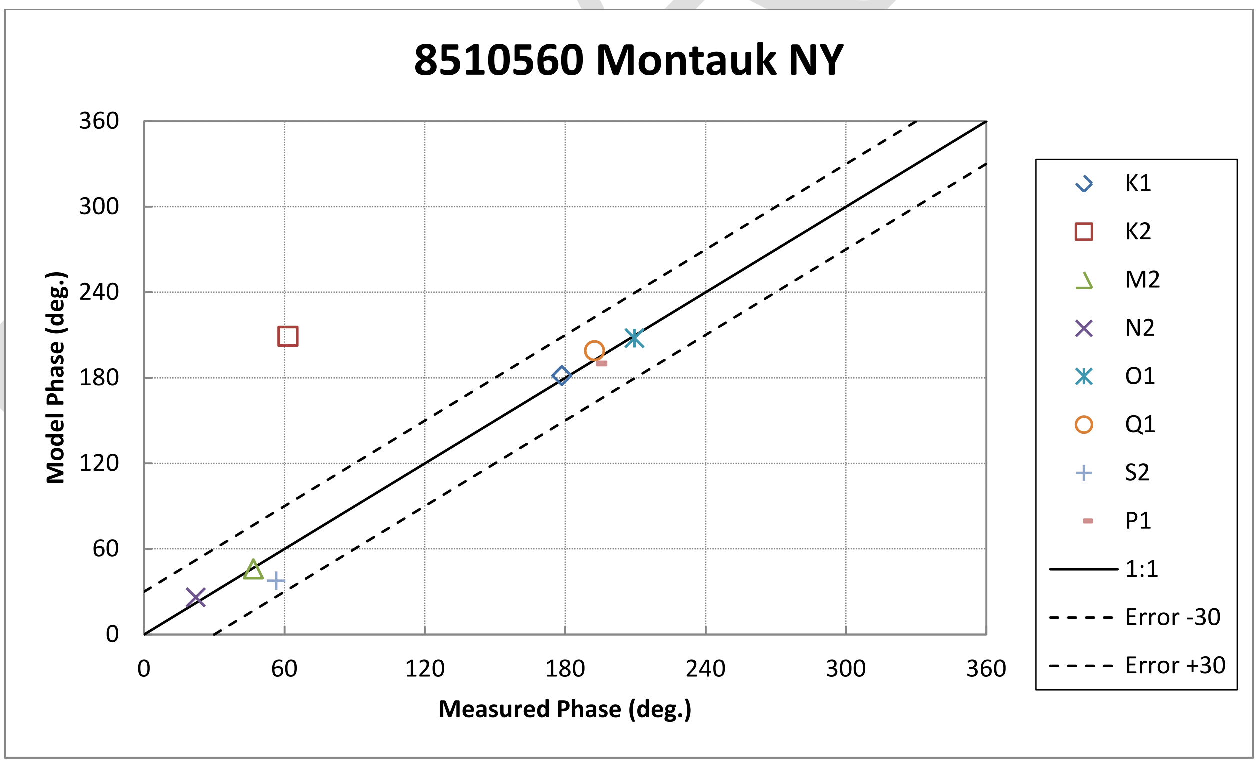


Figure A-14. Montauk, NY, Modeled/Measured Phase

Appendix B

NOAA Hydrograph Comparison Figures

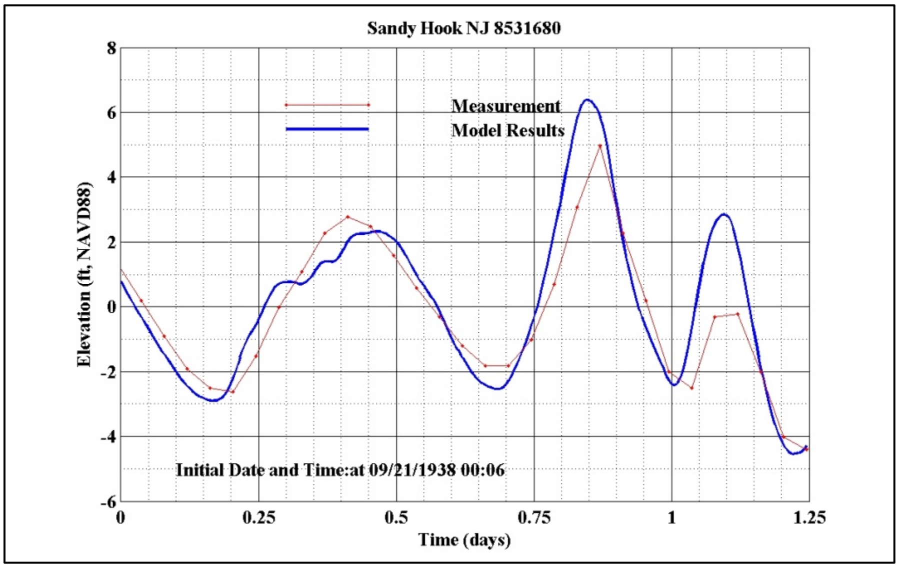


Figure B-1. Comparison of Measured and Simulated Hydrograph: H1938

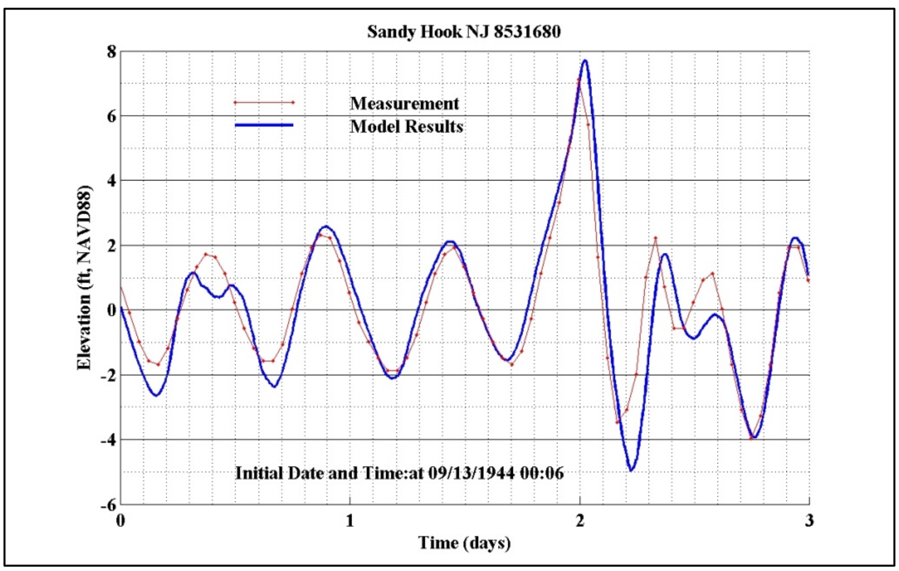


Figure B-2. Comparison of Measured and Simulated Hydrograph: H1944

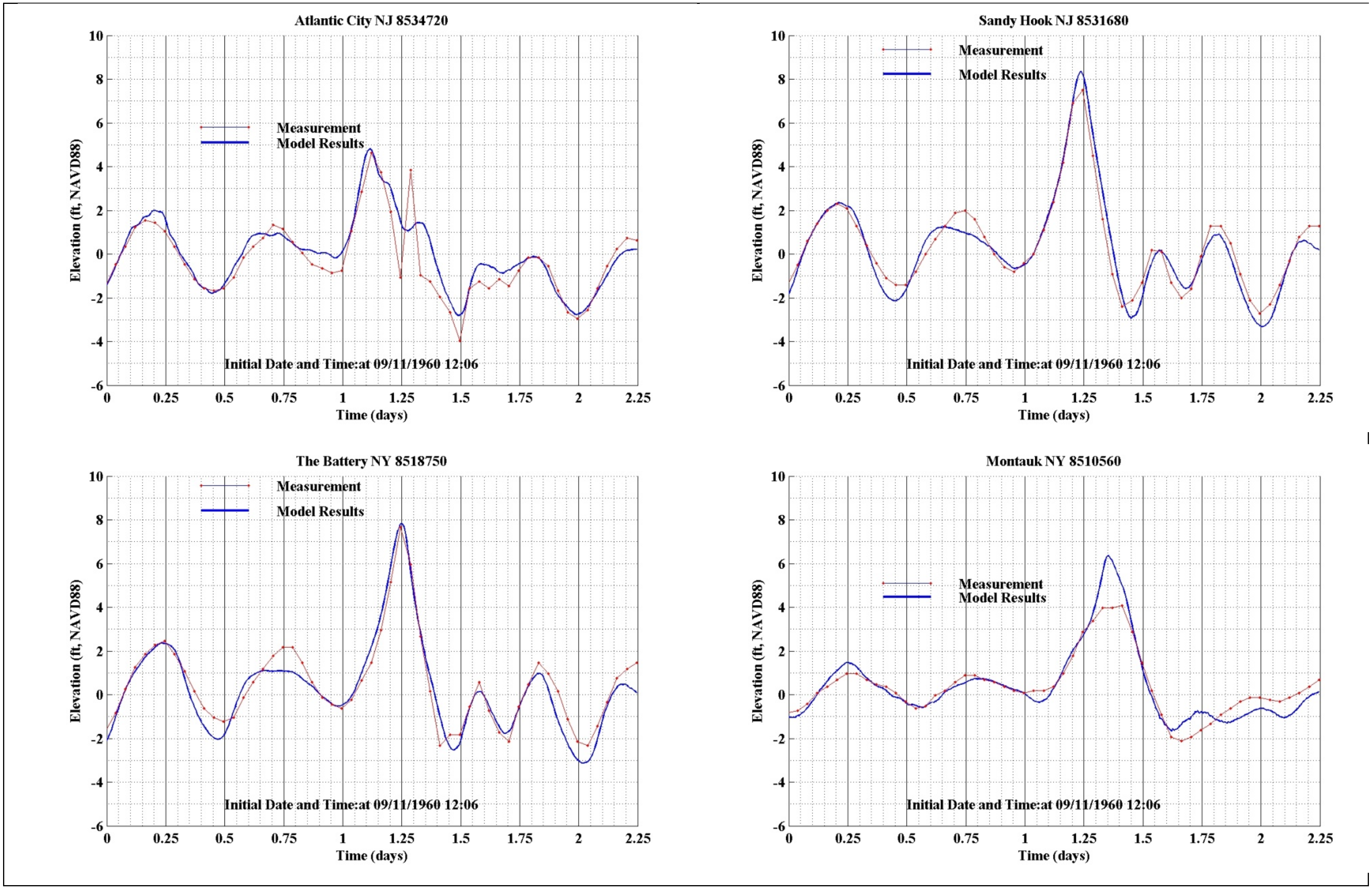


Figure B-3. Comparison of Measured and Simulated Hydrograph: H1960

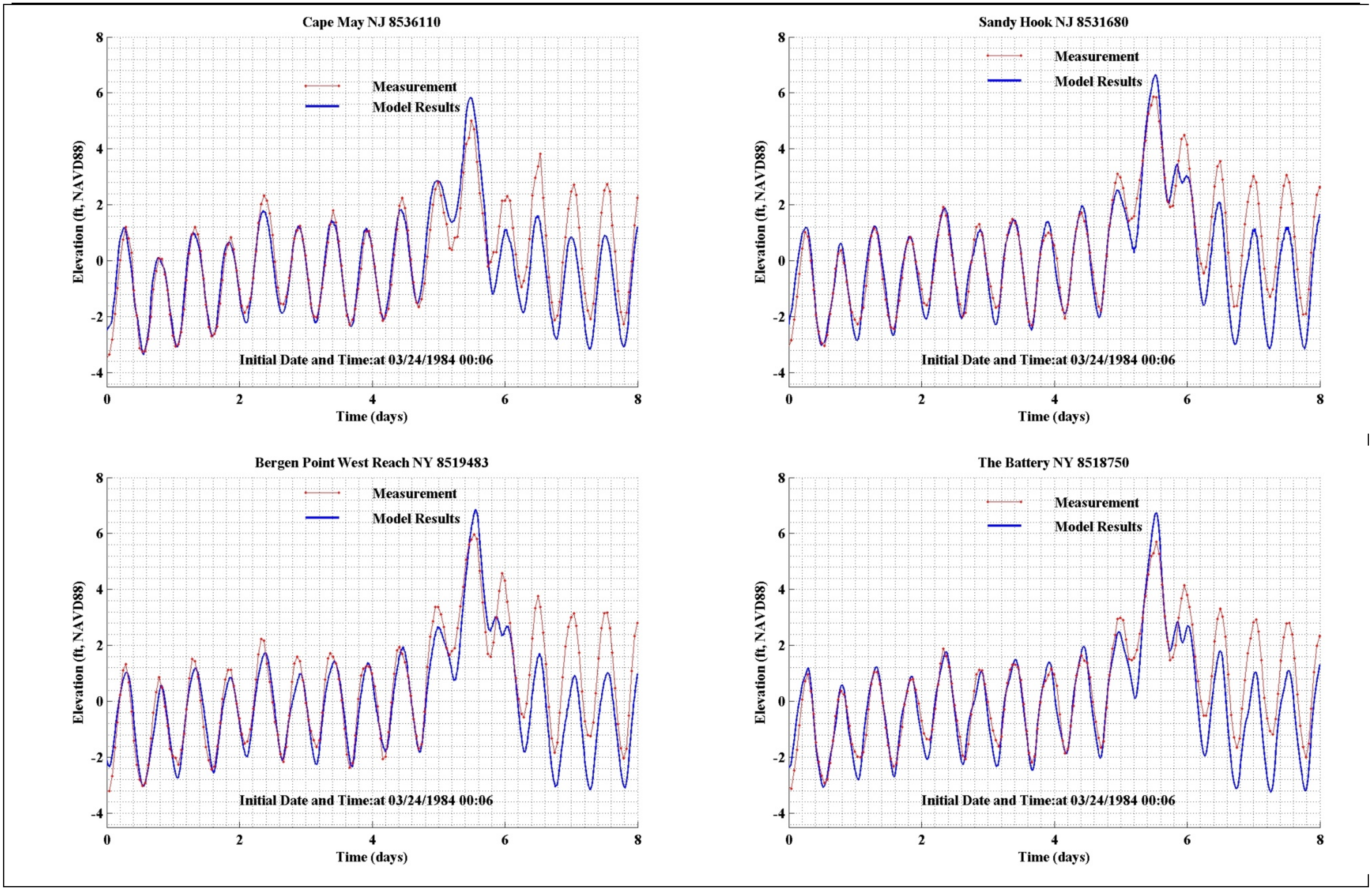


Figure B-4a. Comparison of Measured and Simulated Hydrograph: N1984

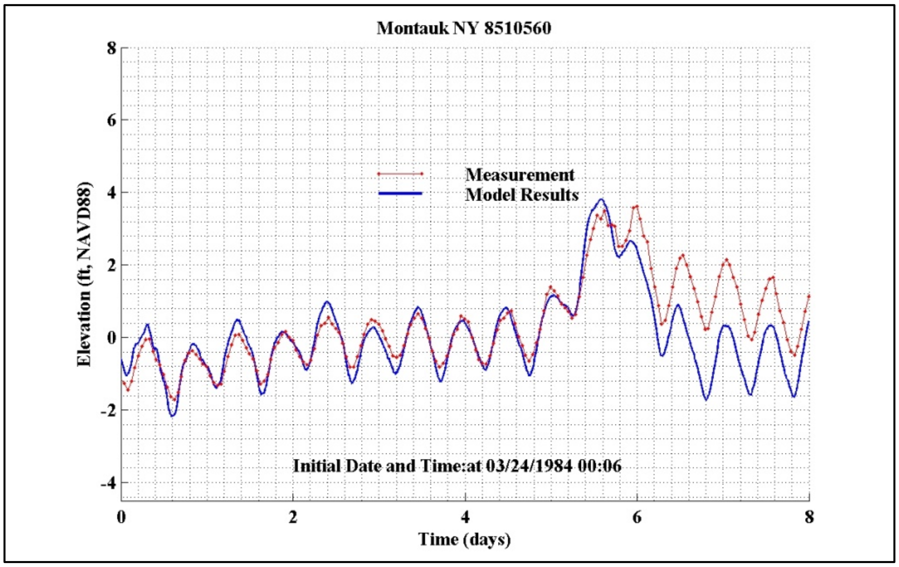


Figure B-4b. Comparison of Measured and Simulated Hydrograph: N1984

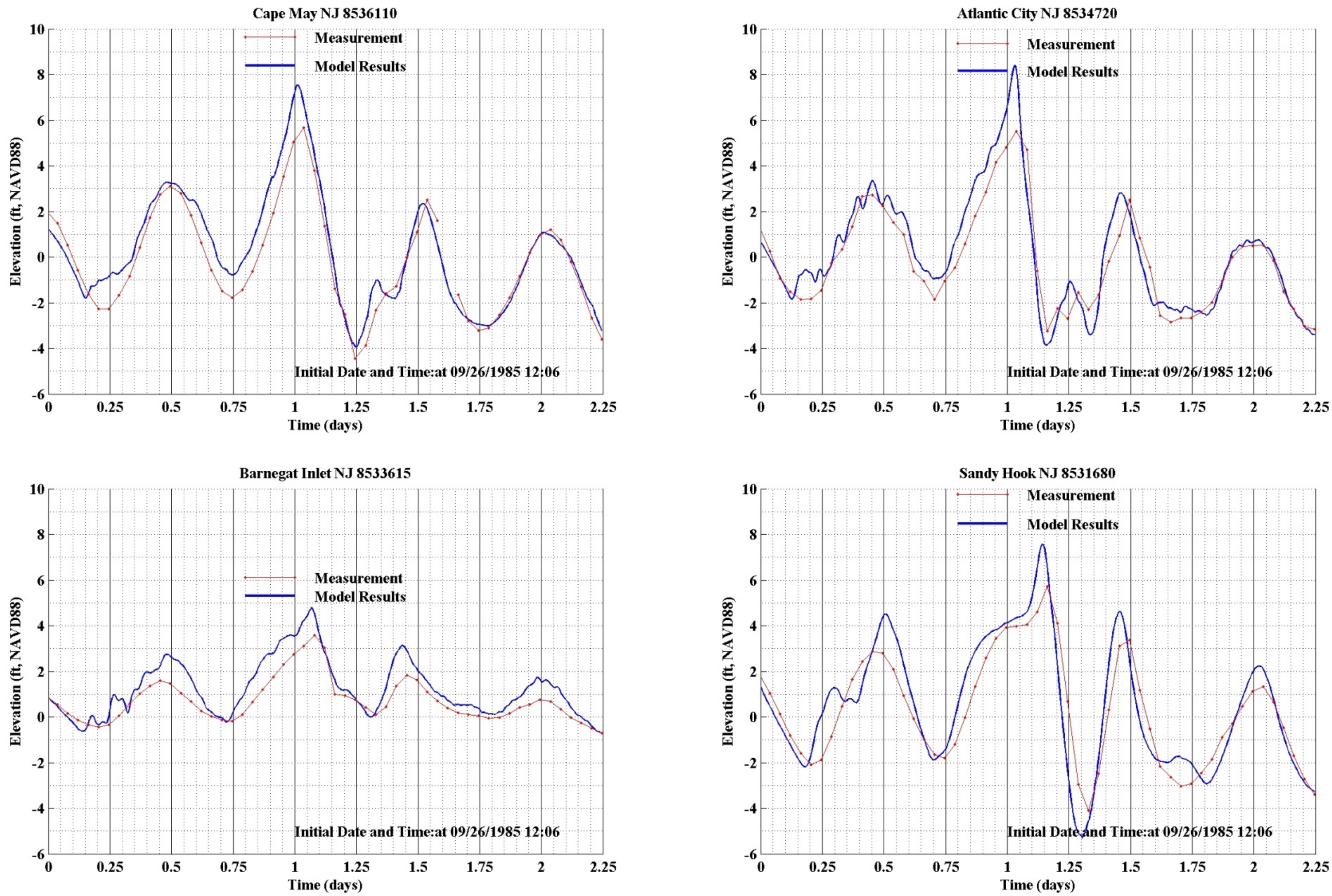


Figure B-5a. Comparison of Measured and Simulated Hydrograph: H1985

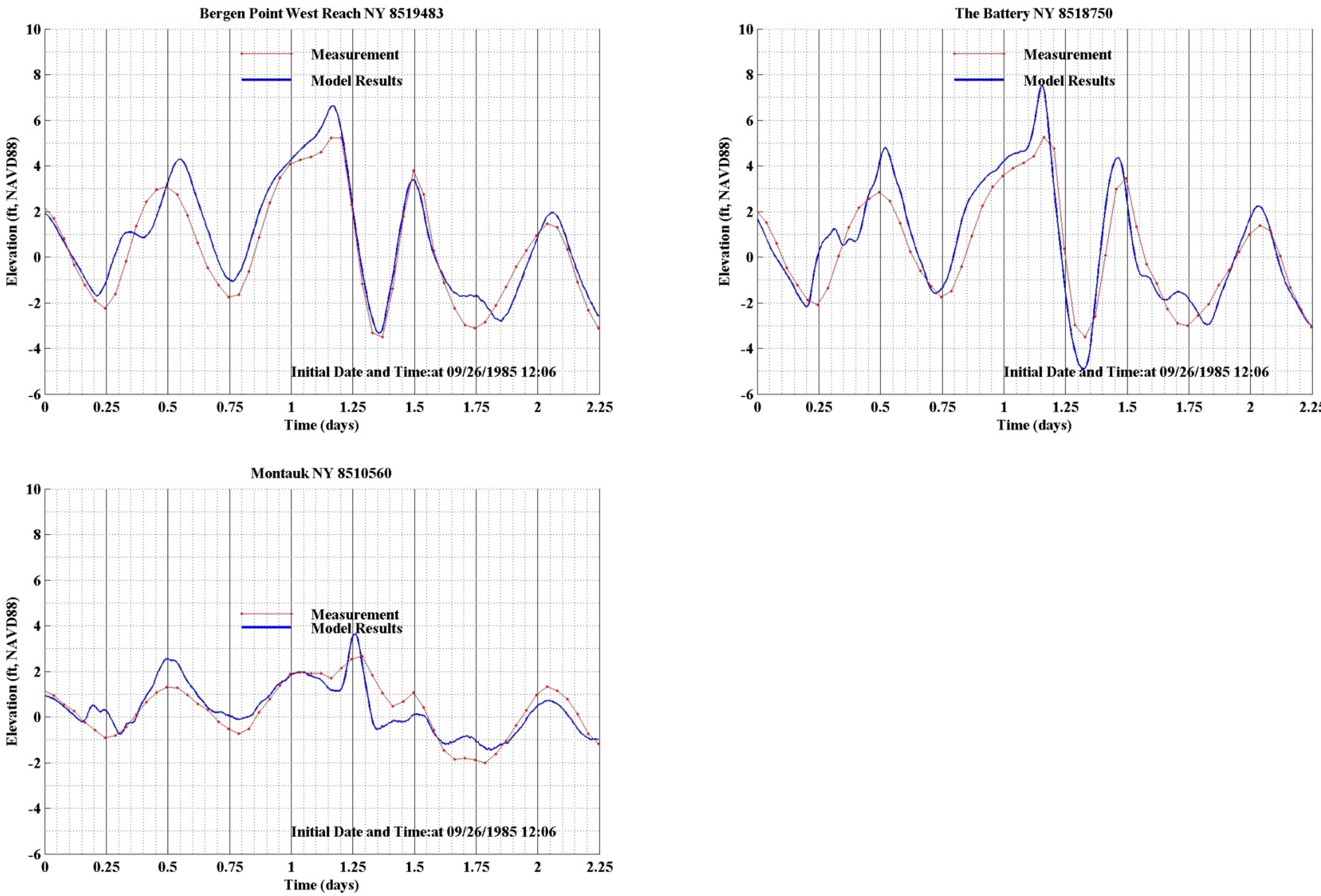


Figure B-5b. Comparison of Measured and Simulated Hydrograph: H1985

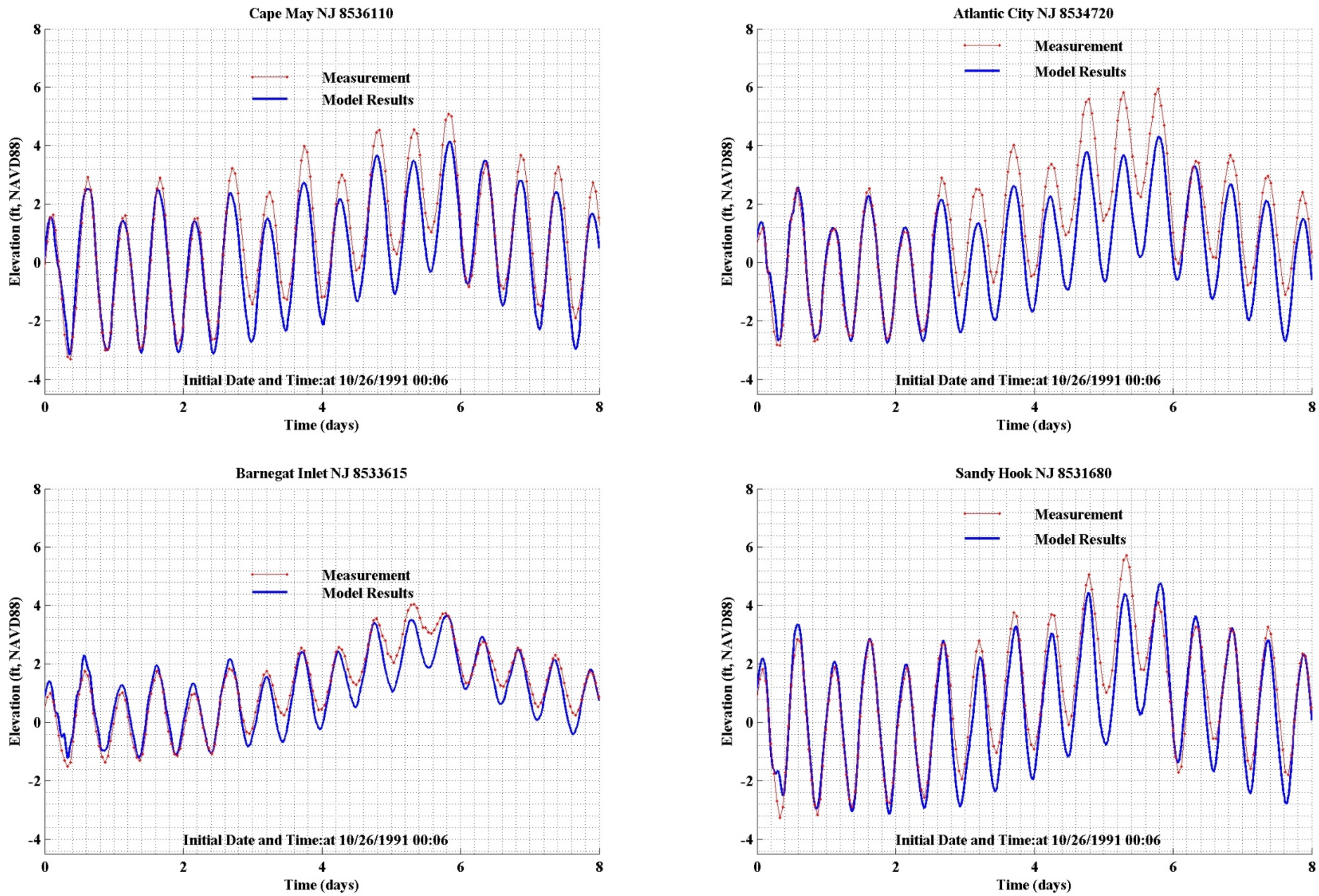
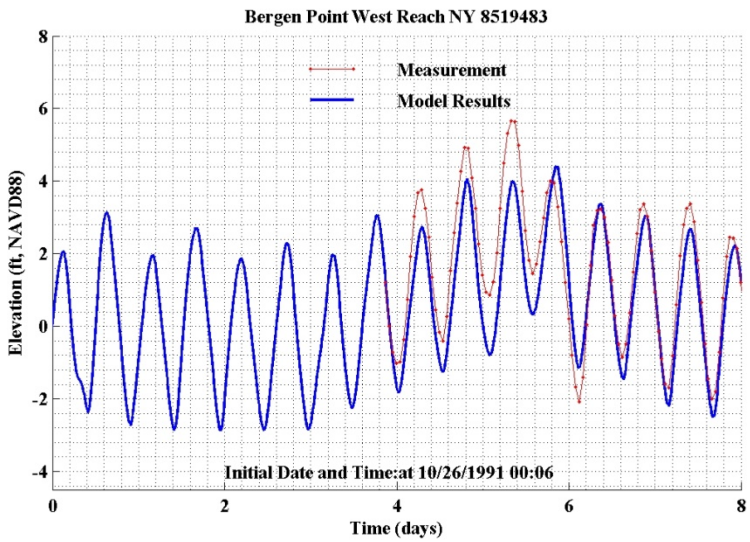
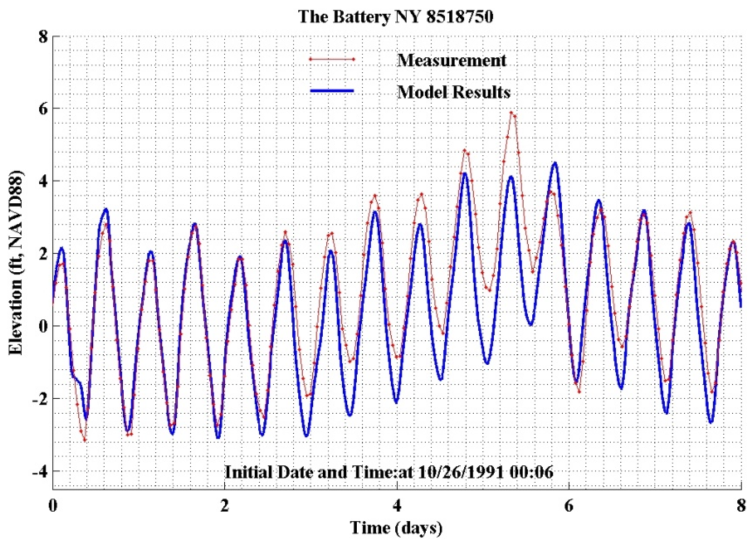


Figure B-6a. Comparison of Measured and Simulated Hydrograph: N1991





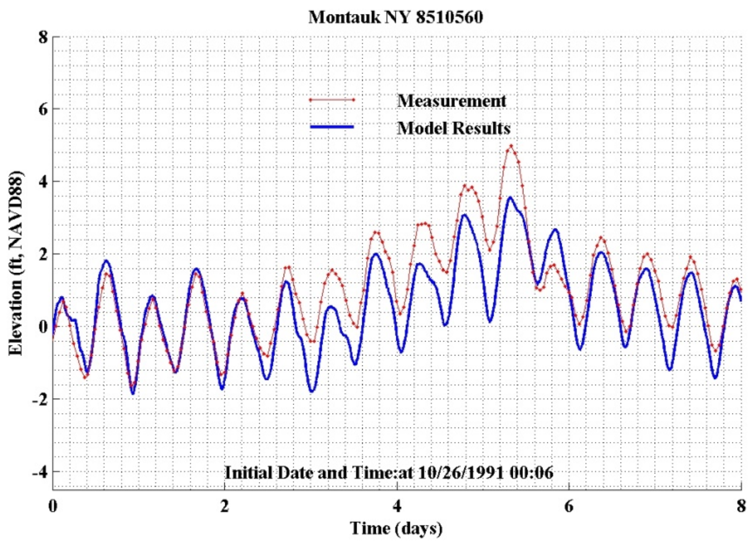


Figure B-6b. Comparison of Measured and Simulated Hydrograph: N1991

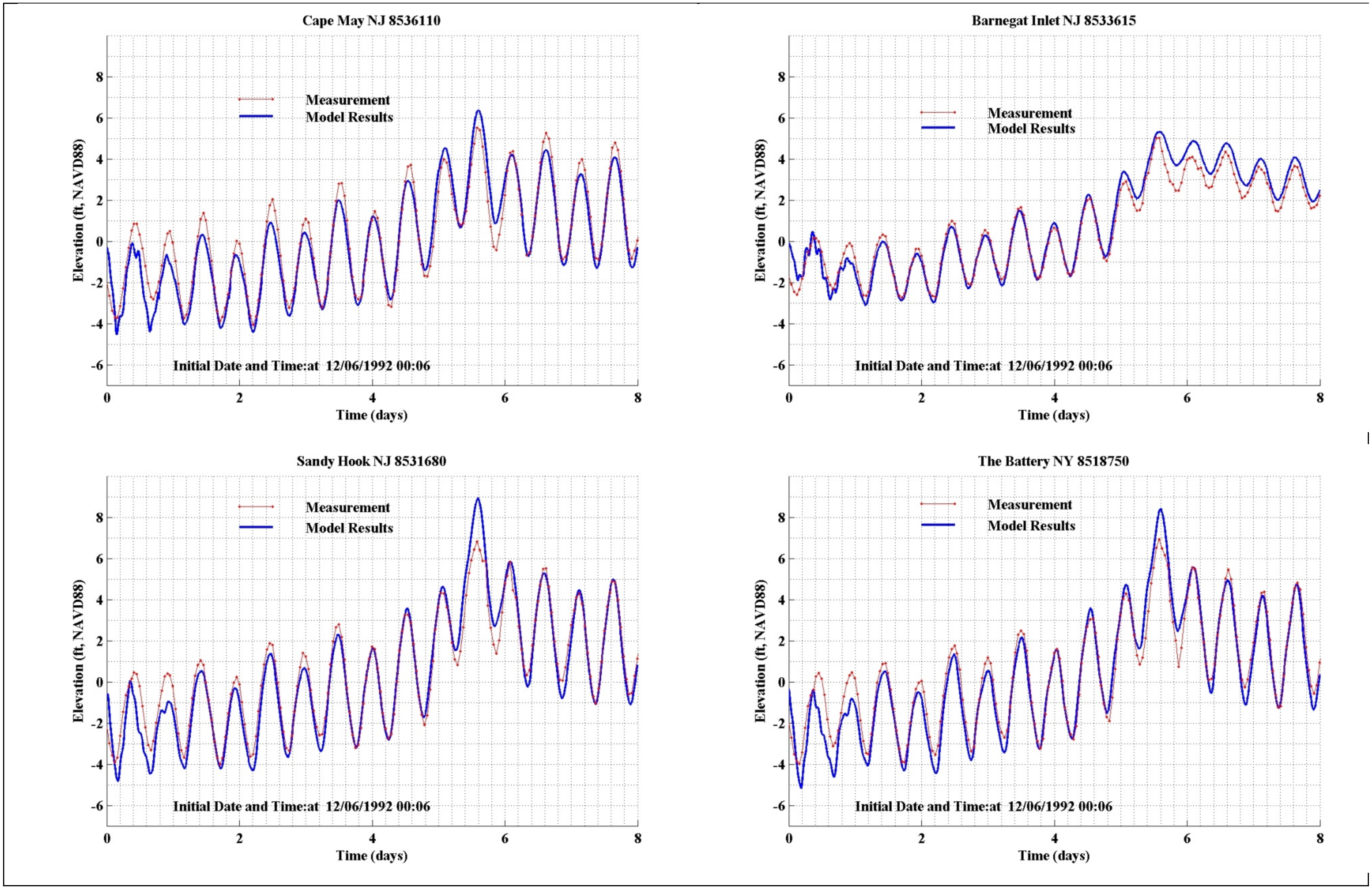


Figure B-7a. Comparison of Measured and Simulated Hydrograph: N1992

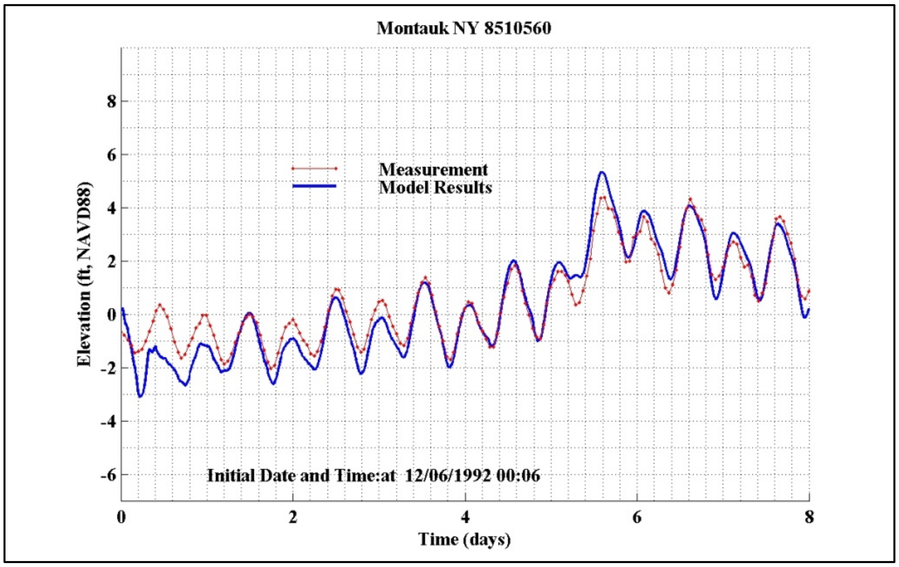


Figure B-7b. Comparison of Measured and Simulated Hydrograph: N1992

Appendix C

Peak Water Level Comparison Figures

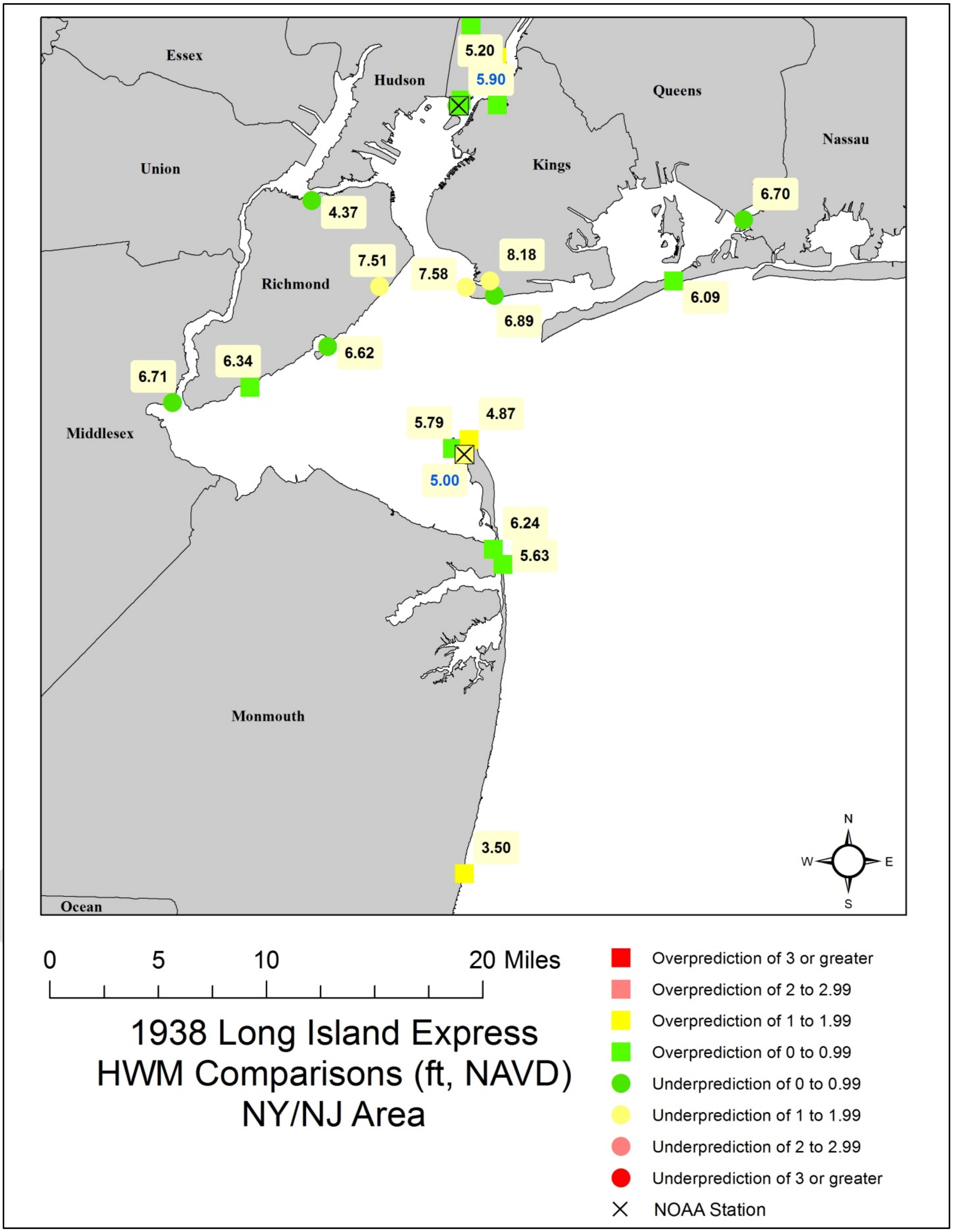


Figure C-1. 1938 Long Island Express HWM Comparisons NY/NJ Area (measured elevations shown)

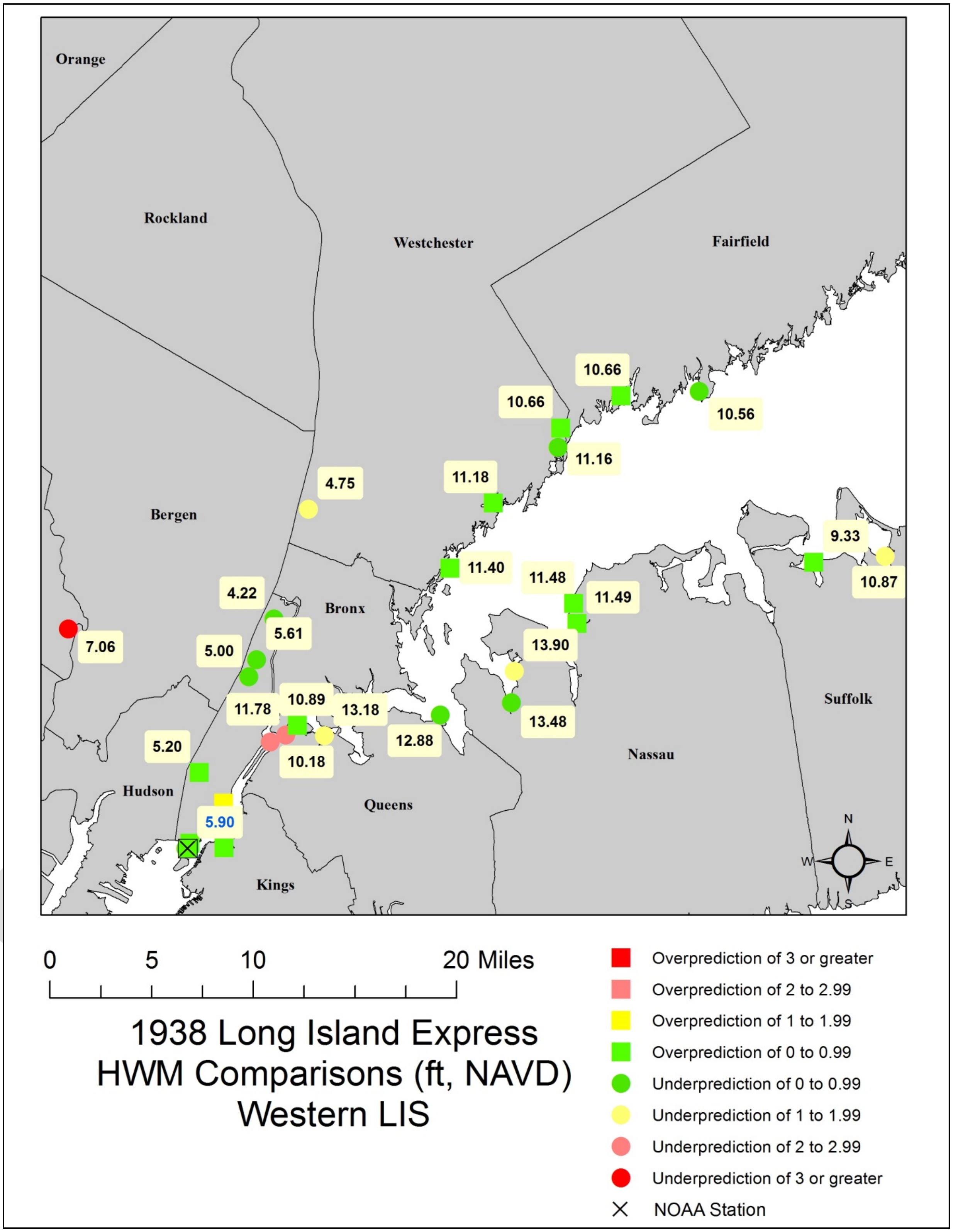


Figure C-2. 1938 Long Island Express HWM Comparisons Western LIS (measured elevations shown)

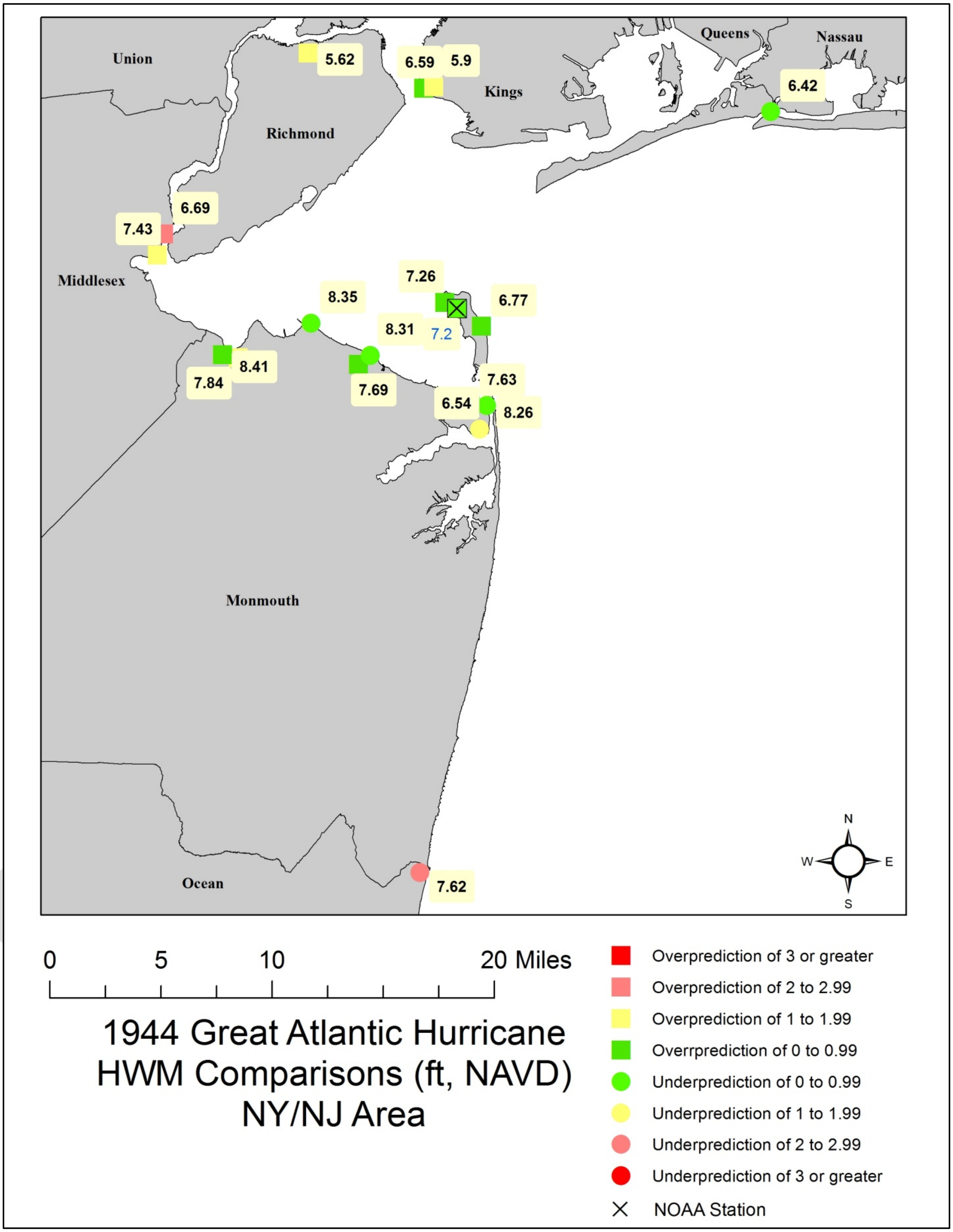


Figure C-3. 1944 Great Atlantic Hurricane HWM Comparisons NY/NJ Area (measured elevations shown)

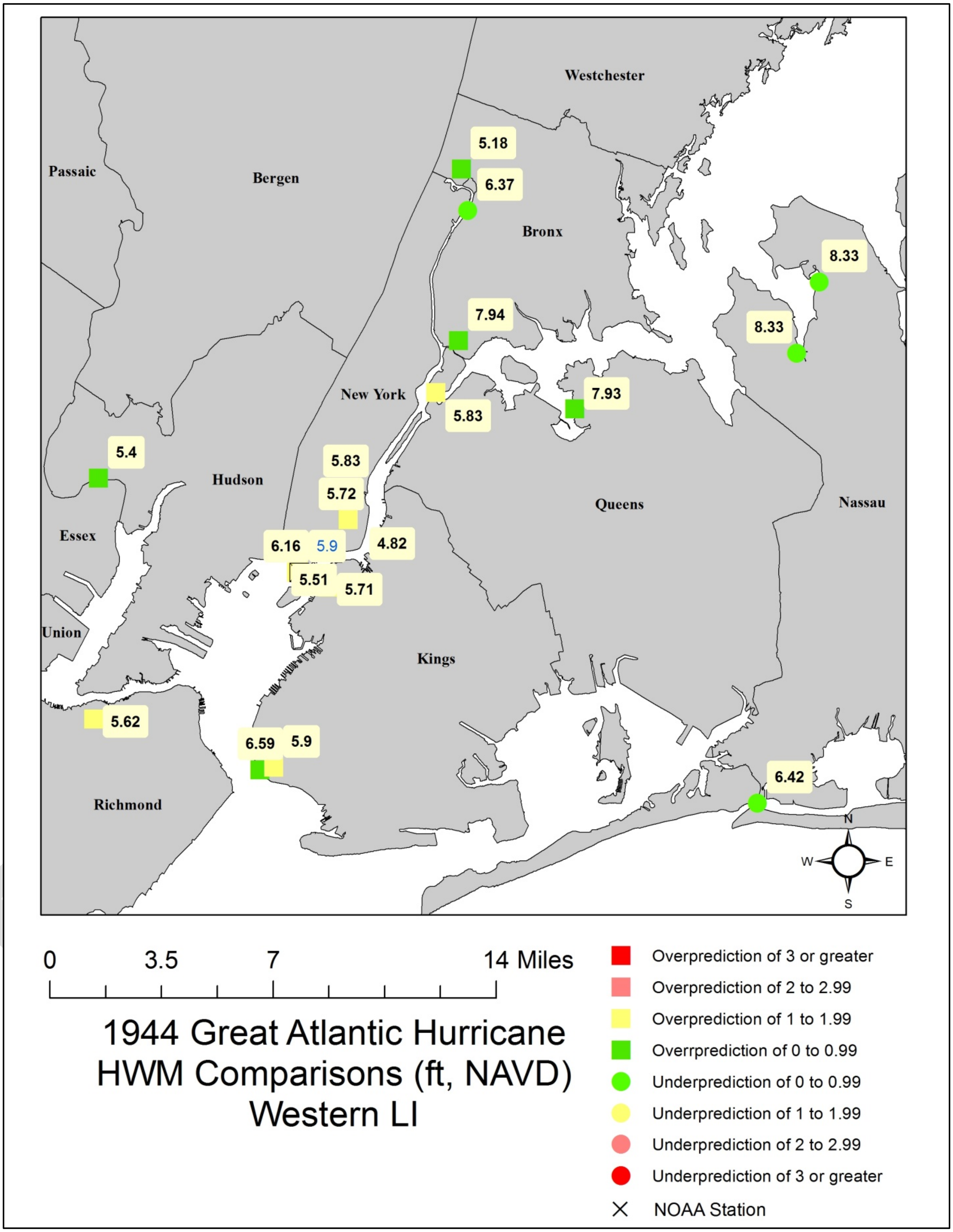


Figure C-4. 1944 Great Atlantic Hurricane HWM Comparisons Western LI (measured elevations shown)

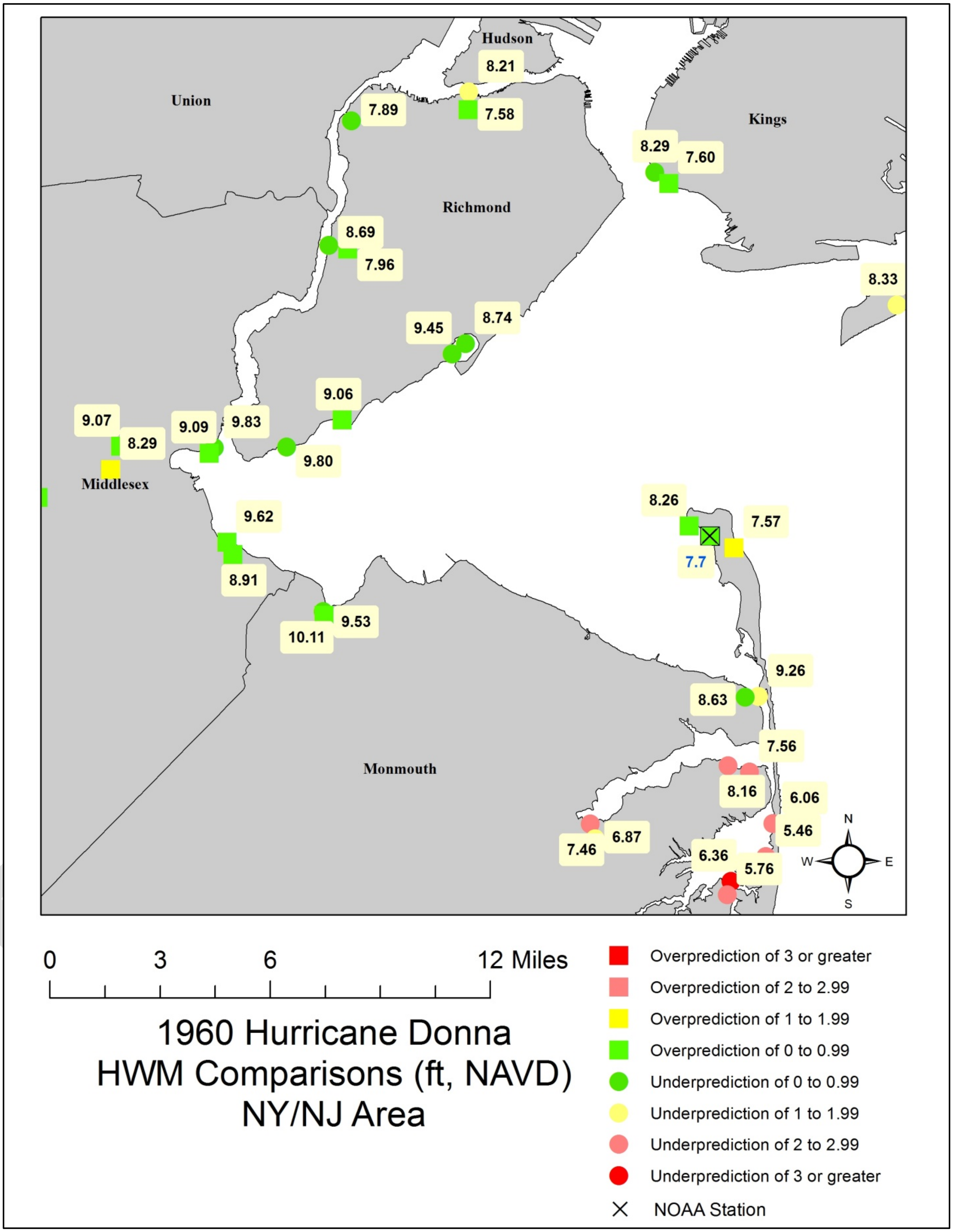


Figure C-5. 1960 Hurricane Donna HWM Comparisons NY/NJ Area (measured elevations shown)

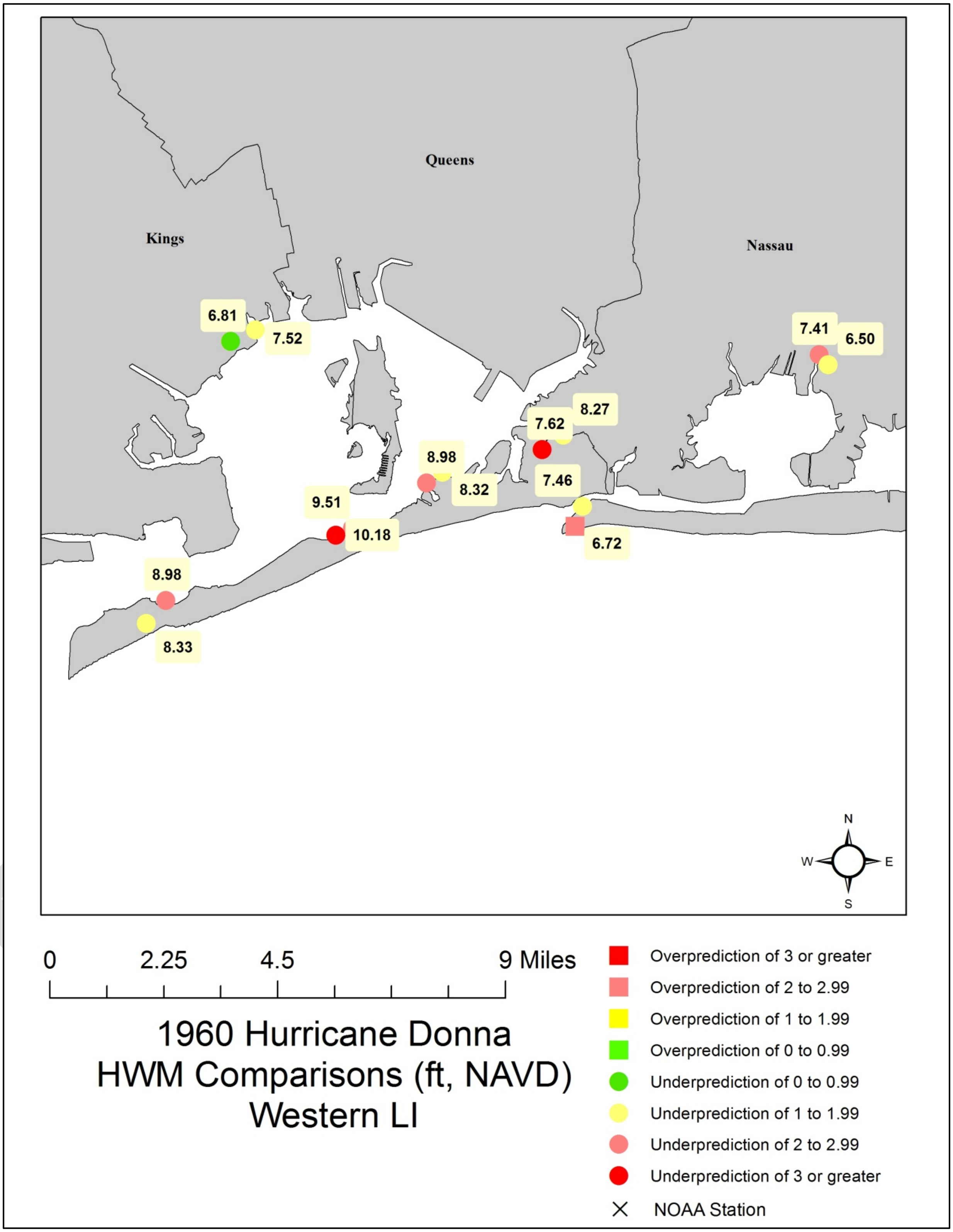


Figure C-6. 1960 Hurricane Donna HWM Comparisons (measured elevations shown)

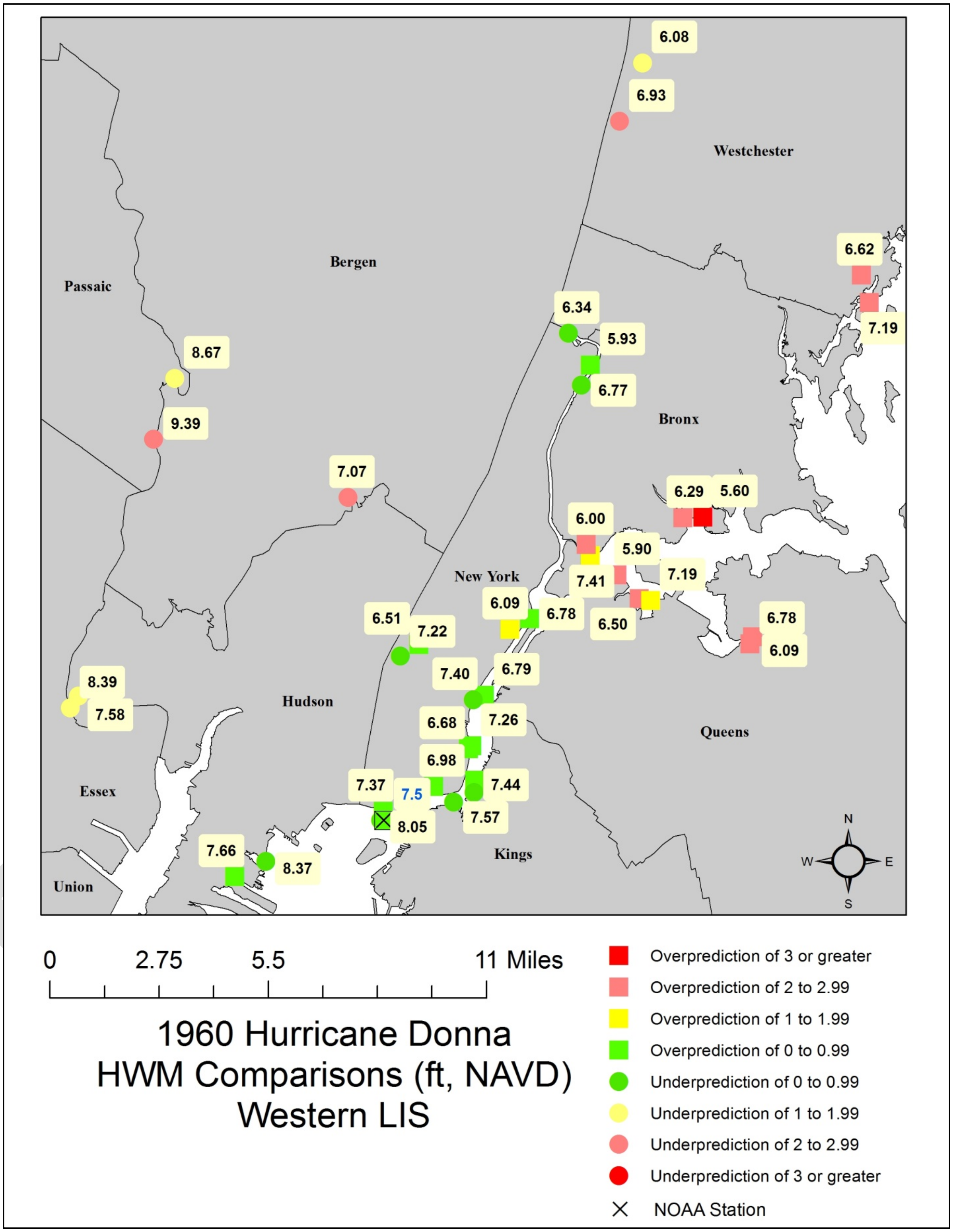


Figure C-7. 1960 Hurricane Donna HWM Comparisons Western LIS (measured elevations shown)

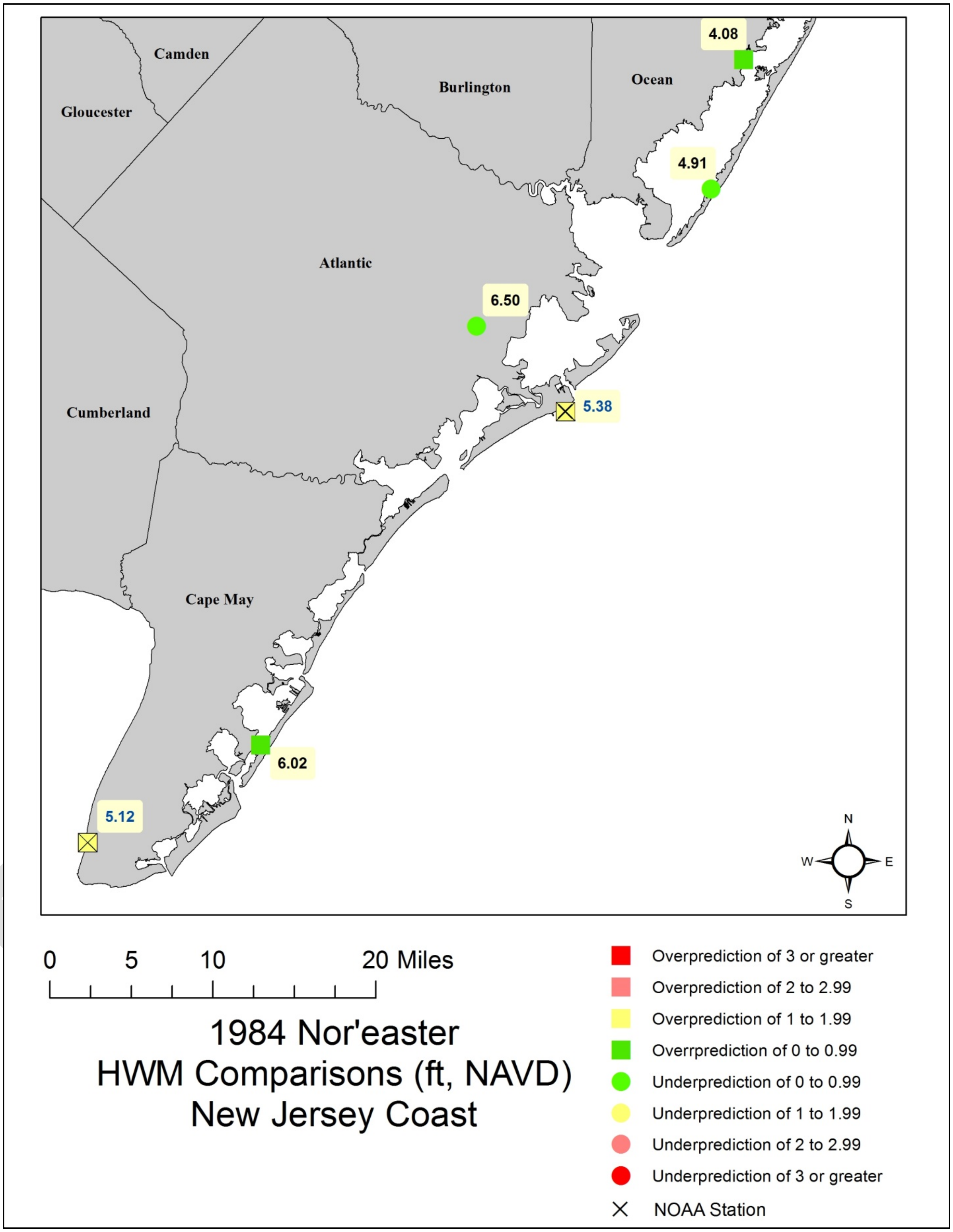


Figure C-8. 1984 Nor'easter HWM Comparisons New Jersey Coast (measured elevations shown)

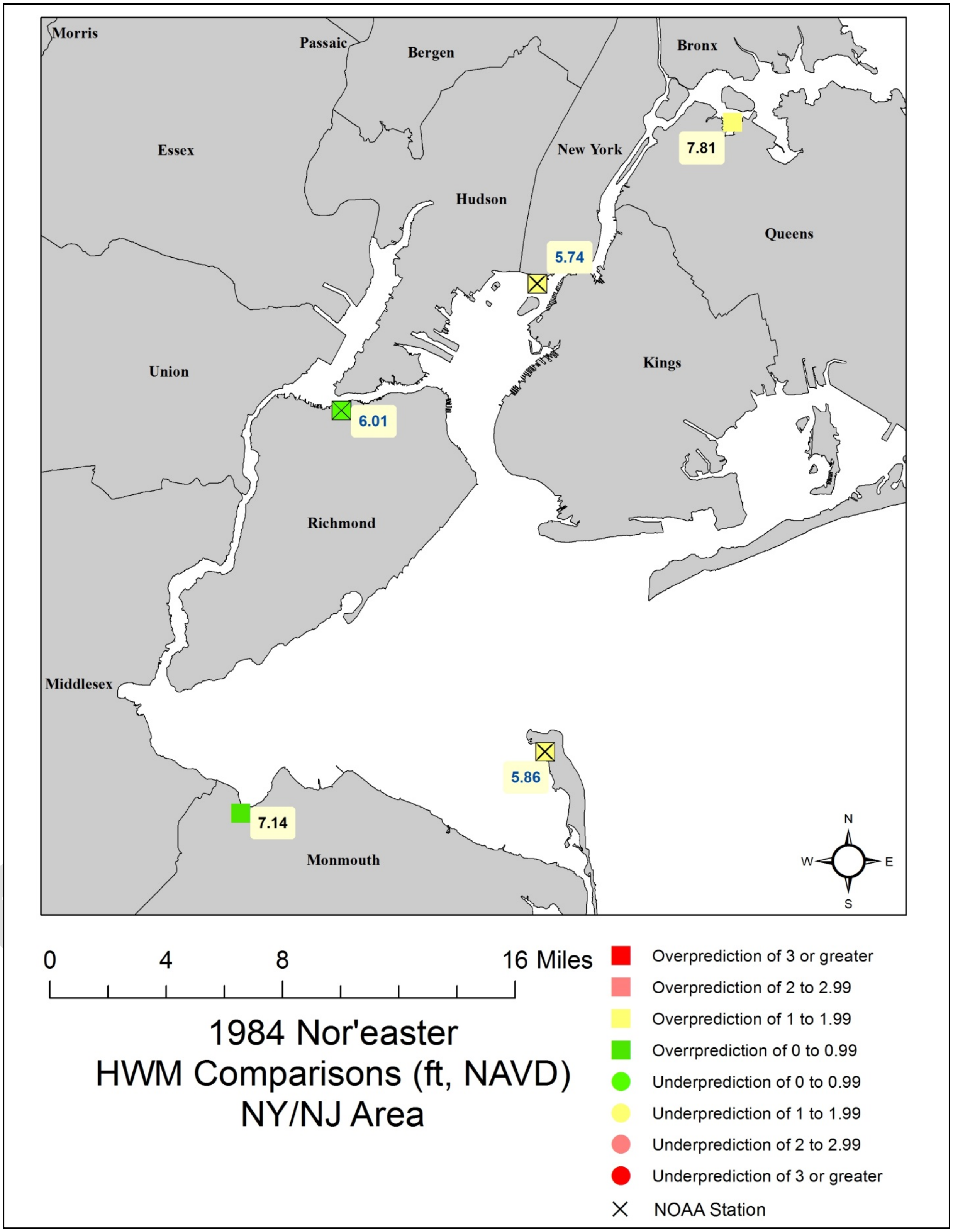


Figure C-9. 1984 Nor'easter HWM Comparisons NY/NJ Area (measured elevations shown)

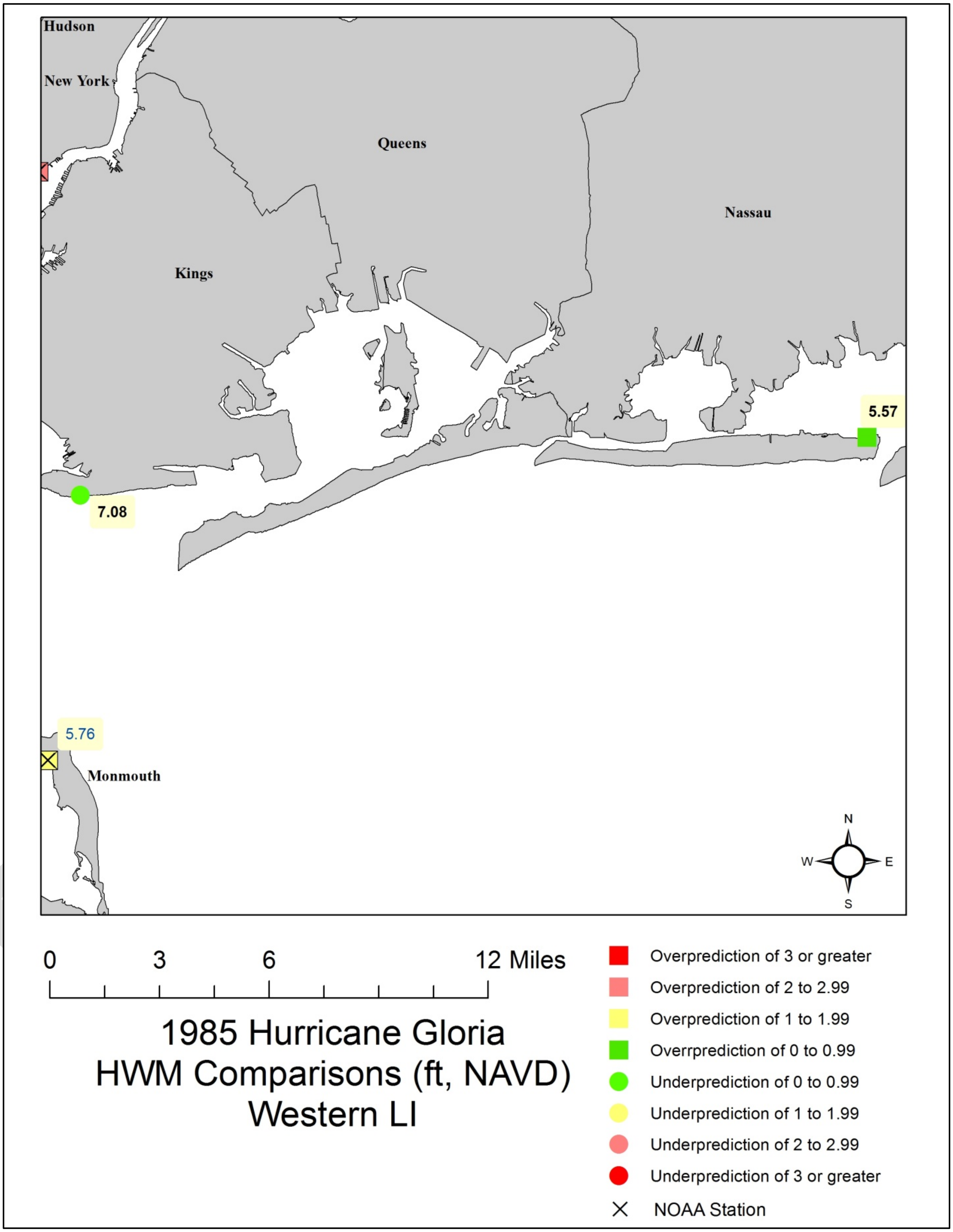


Figure C-10. 1985 Hurricane Gloria HWM Comparisons Western LI (measured elevations shown)

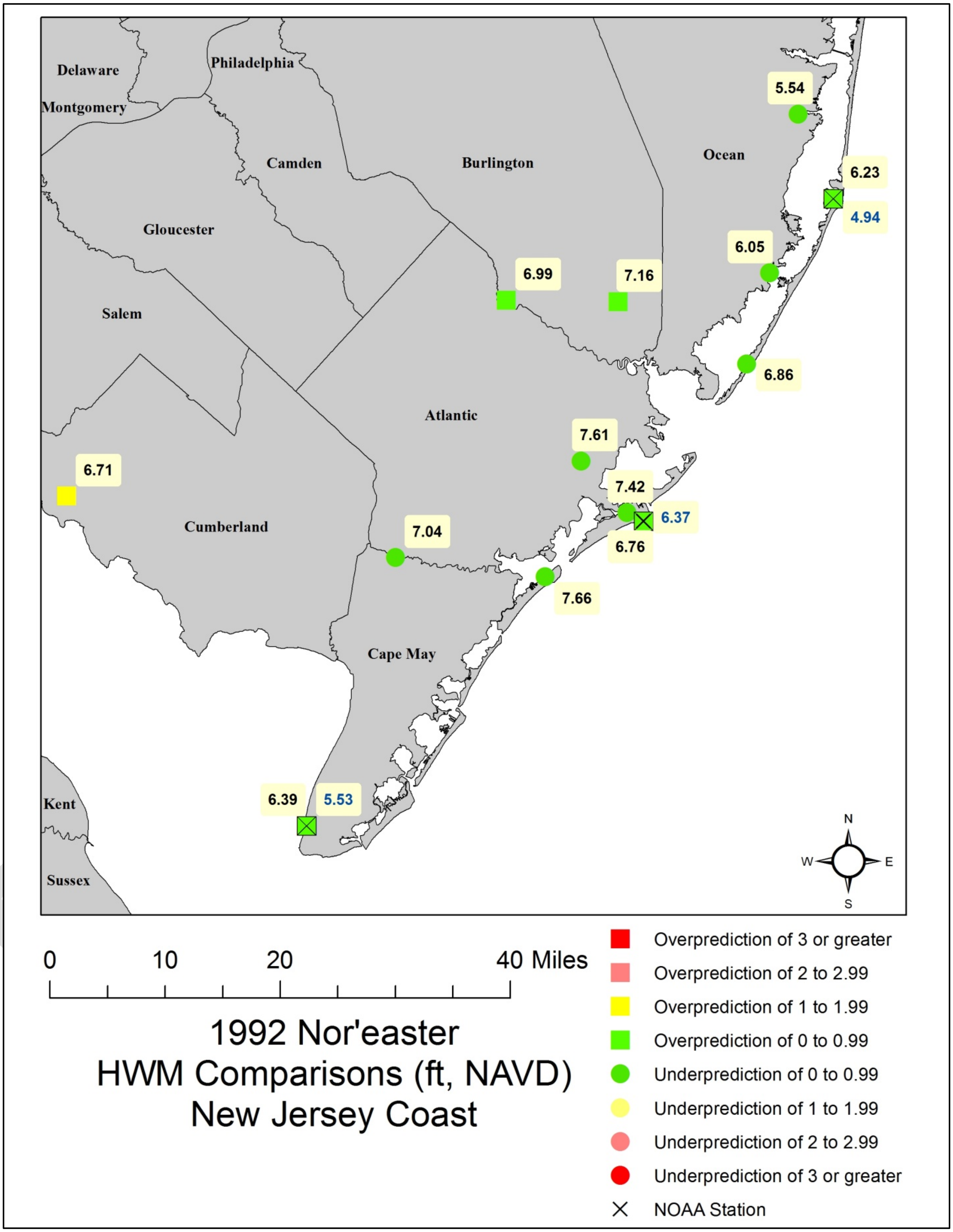


Figure C-11. 1992 Nor'easter HWM Comparisons New Jersey Coast (measured elevations shown)

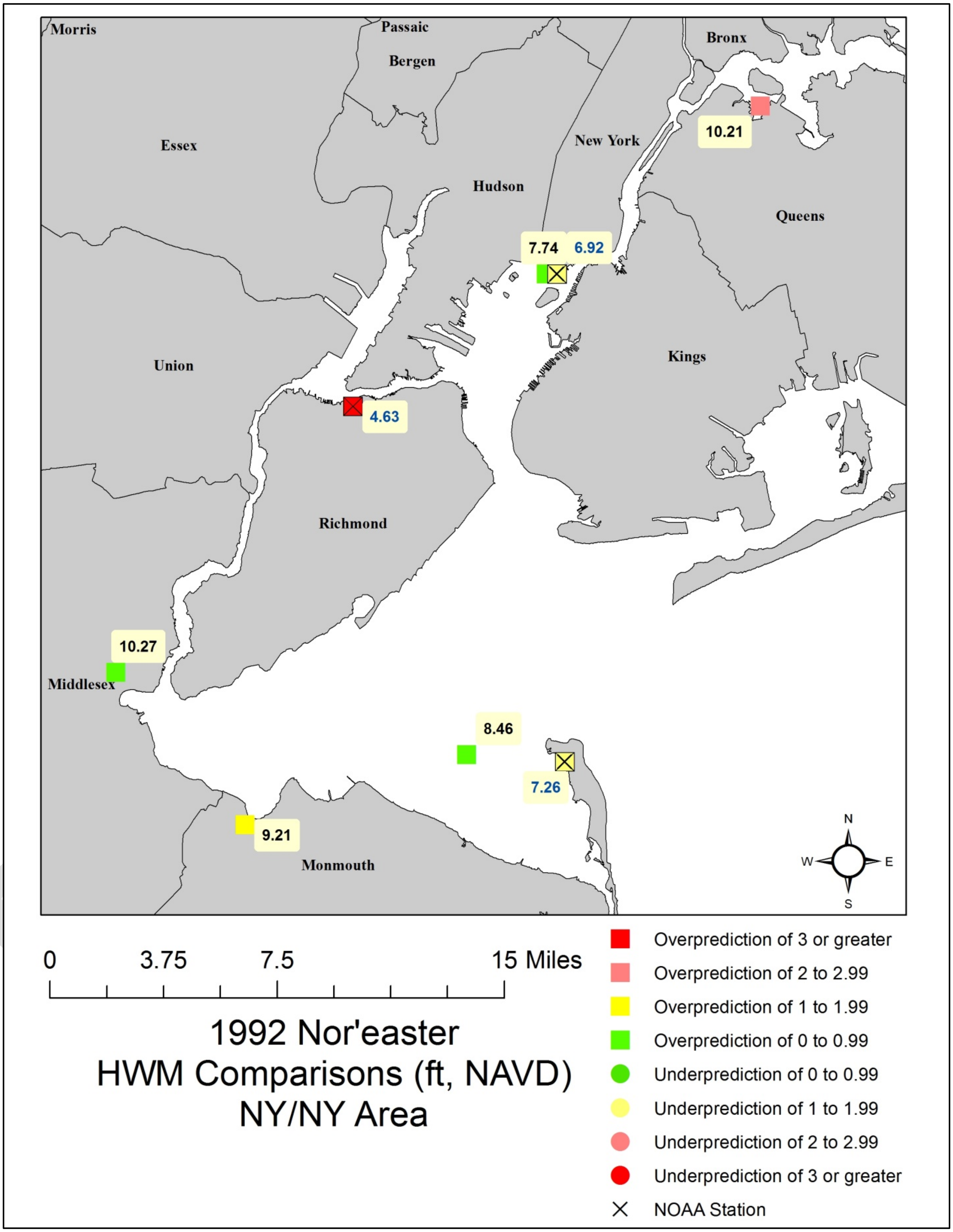


Figure C-12. 1992 Nor'easter HWM Comparisons NY/NJ Area (measured elevations shown)

Appendix D

Wave Height and Period Comparison Figures

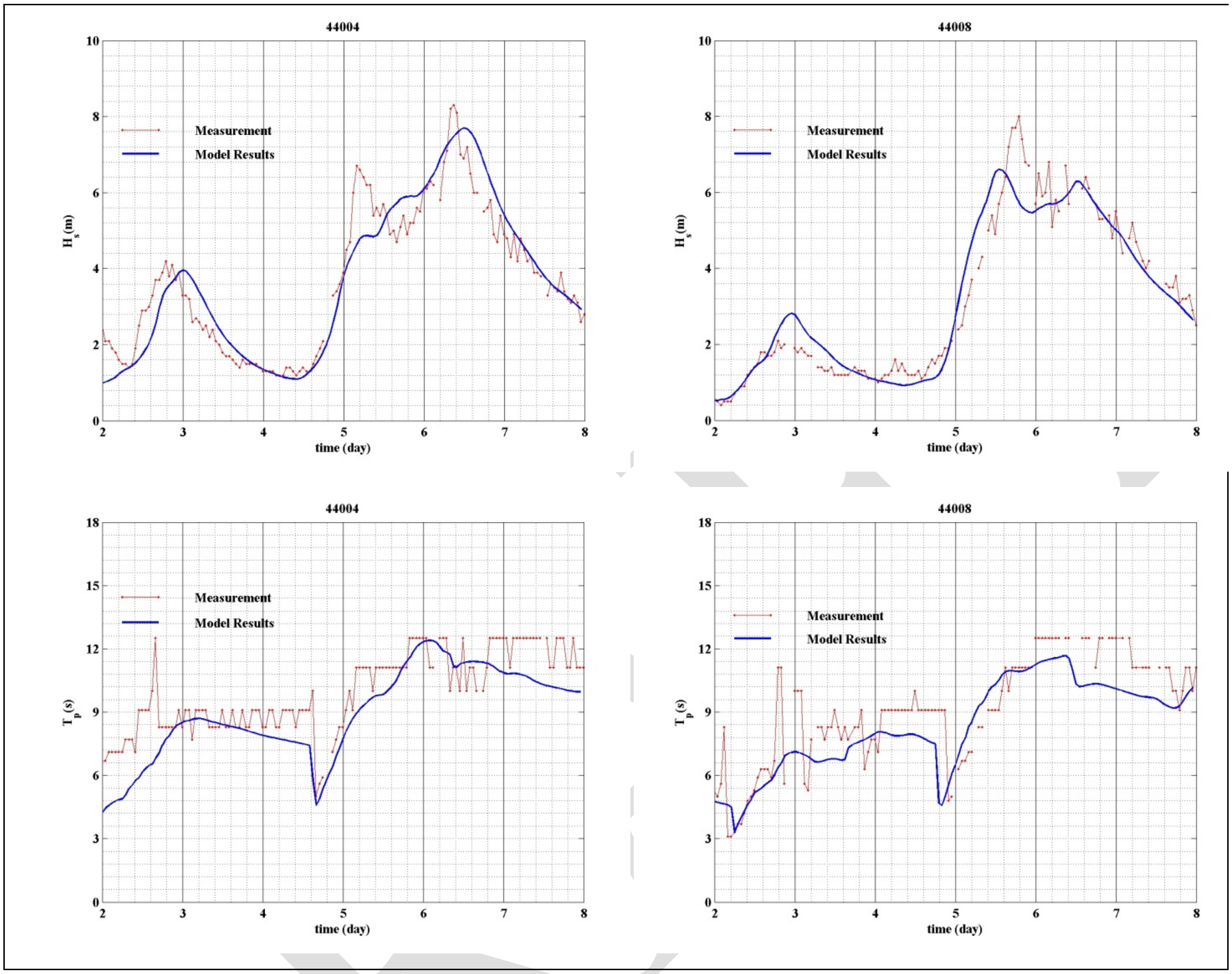


Figure D-1. Simulated and Measured Wave Comparisons: N1984

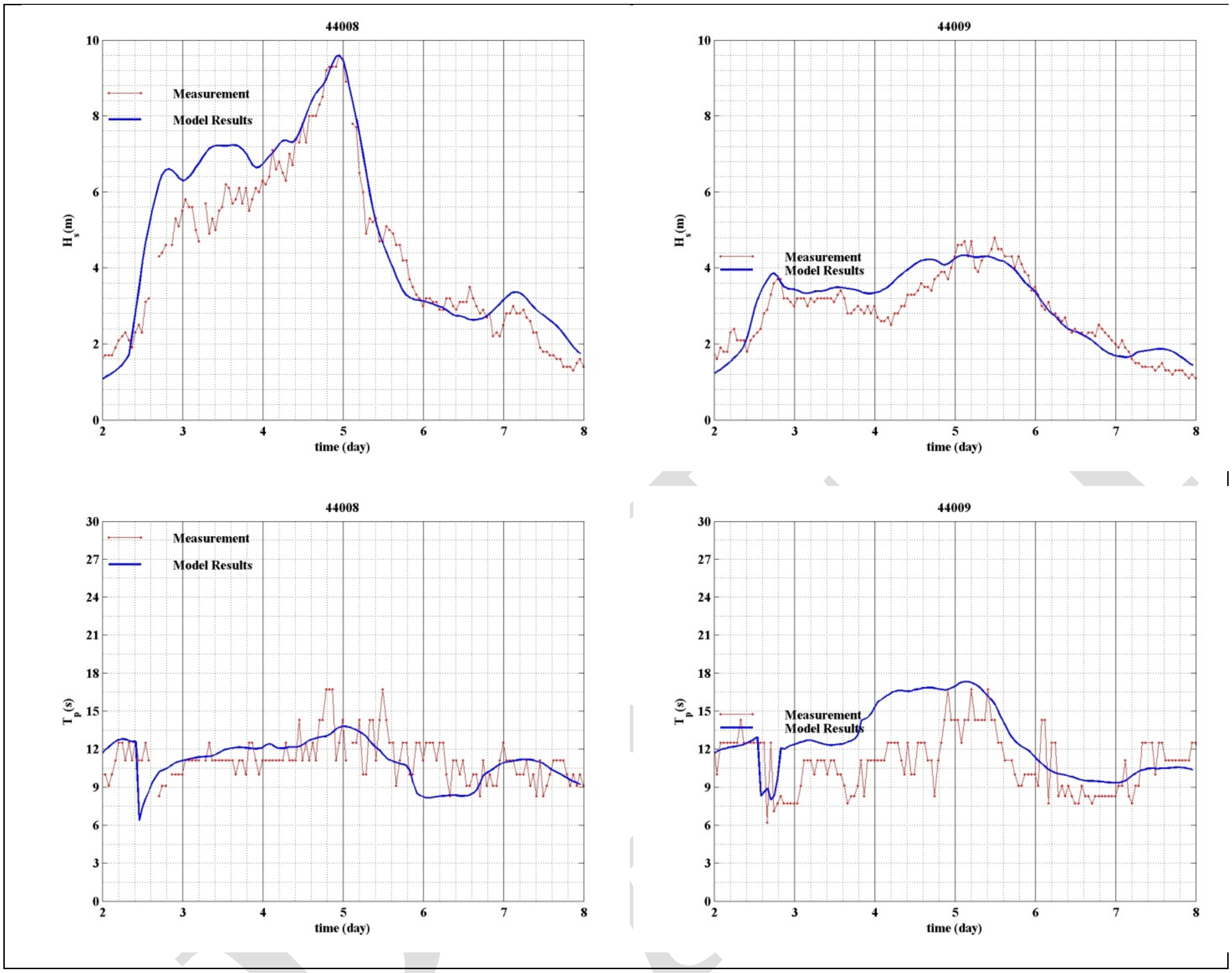


Figure D-2a. Simulated and Measured Wave Comparisons: N1991

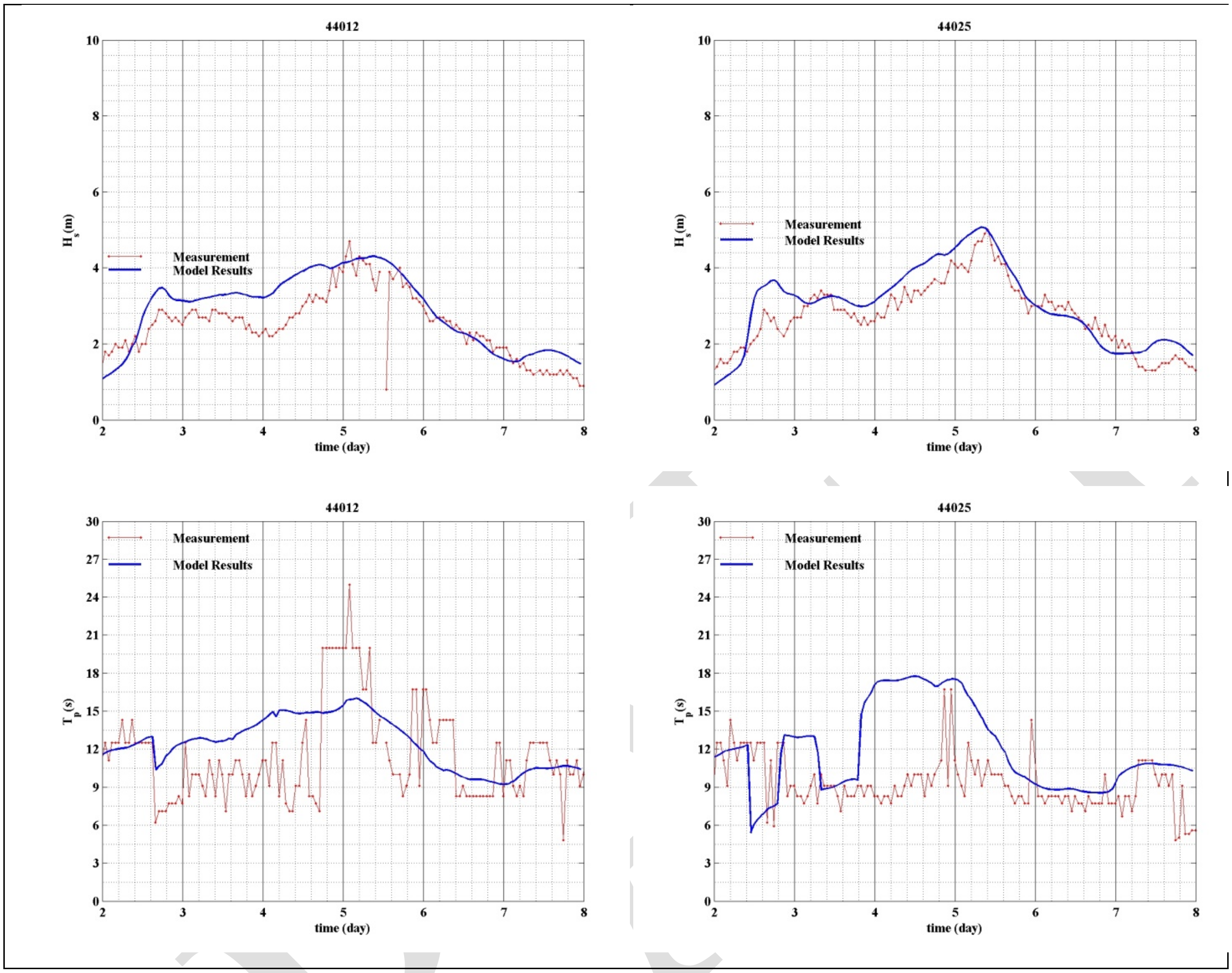


Figure D-2b. Simulated and Measured Wave Comparisons: N1991

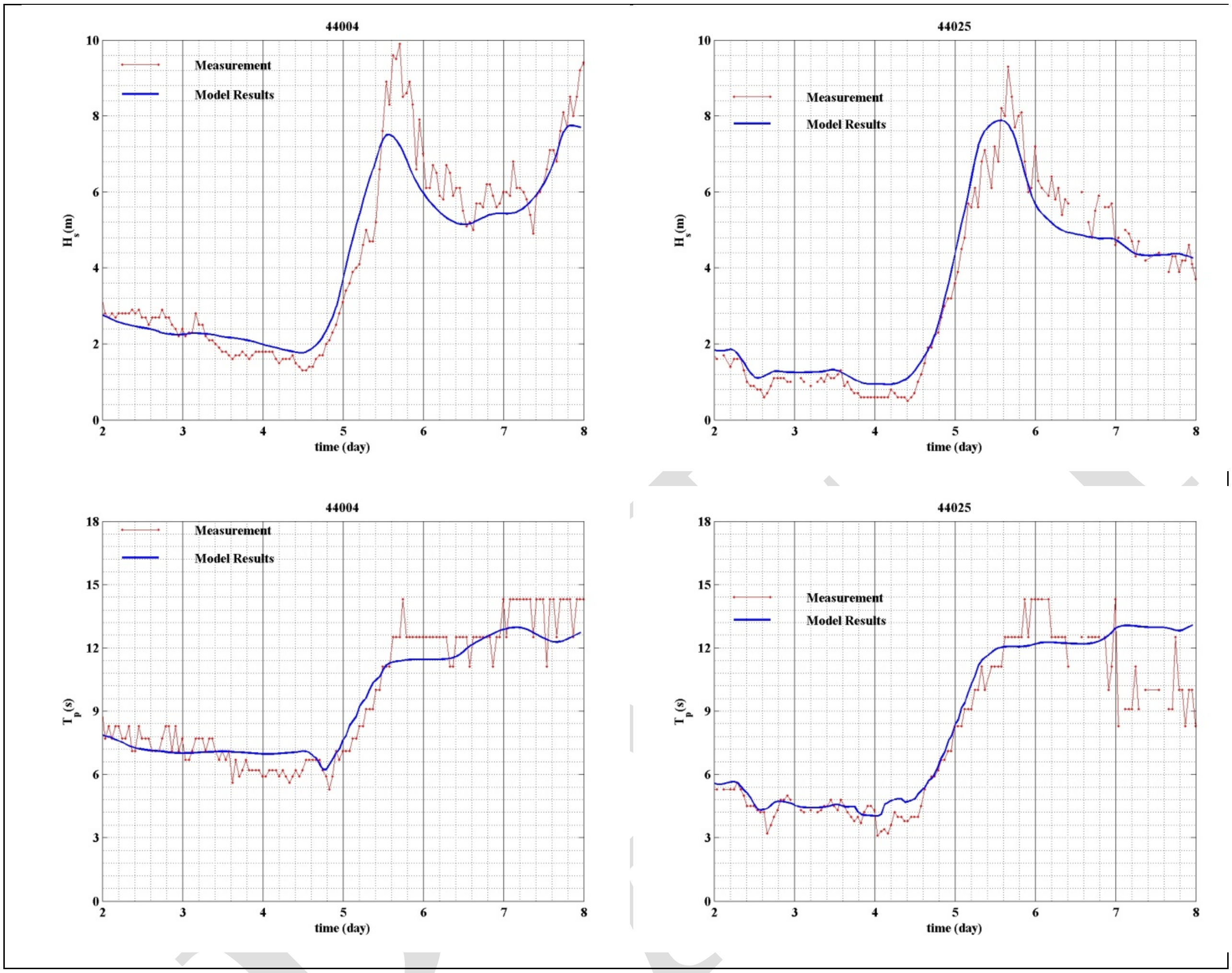


Figure D-3a. Simulated and Measured Wave Comparisons: N1992

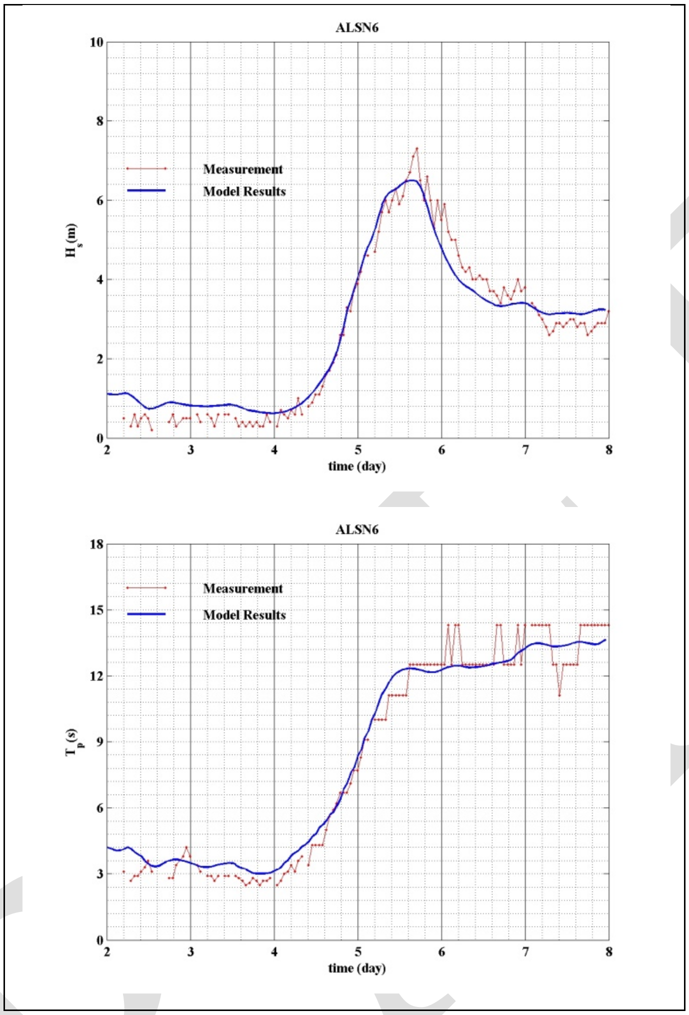


Figure D-3b. Simulated and Measured Wave Comparisons: N1992

Appendix E

ADCIRC Model Control Parameters

Parameter	Description	Value	Justification
IM	Model type – Digits to specify model solvers: First 1= Kolar-Gray, flux based lateral stress in GWCE (default) Second 1= Non conservative advection in GWCE (default) Third 1= Integration by parts, velocity based lateral stress in Momentum Eqs. (default) Fourth 1=Non conservative advection in Momentum Eqs. (default) Fifth 2= Original Area Integration in Momentum Eqs. Sixth 2= Lumped GWCE mass matrix	111122	Value recommended by ADCIRC development team in 2010.
NOLIBF	Parameter controlling the type of bottom stress parameterization used in a 2DDI ADCIRC run. 1 = quadratic bottom friction law	1	This value is necessary for using the “mannings_n_at_sea_floor” nodal attribute in the fort.13 file
NOLIFA	Parameter controlling the finite amplitude terms in ADCIRC. 2 = finite amplitude terms are included in the model run and wetting and drying of elements is enabled	2	Recommended value to adequately simulate the physics of coastal flooding.
NOLICA	Parameter controlling the advective terms in ADCIRC (with the exception of a time derivative portion that occurs in the GWCE form of the continuity equation). 1 = advective terms are included in the computations	1	Standard value. This value is most representative of the system physics.
NOLICAT	Parameter controlling the time derivative portion of the advective terms that occurs in the GWCE form of the continuity equation in ADCIRC. 1 = the time derivative portion of the advective terms that occur in the GWCE continuity equation are included in the computations	1	This value should be used when NOLICA = 1. This value is most representative of the system physics.
NCOR	Parameter controlling whether the Coriolis parameter is spatially varying as computed from the y-coordinates of the nodes in the grid. 1 = compute a spatially variable Coriolis parameter	1	Standard recommended value. This value is most representative of the system physics.

Parameter	Description	Value	Justification
DTDP	ADCIRC time step (in seconds).	2	This value selected for stability based on mesh resolution and found appropriate based on model results.
NRAMP	Ramp option parameter controlling whether a ramp is applied to ADCIRC forcing functions. 1 = a hyperbolic tangent ramp function is specified and applied to forcing from surface elevation specified boundary conditions, nonzero flux boundary conditions, tidal potential, wind and atmospheric pressure and wave radiation stress	1	Standard recommended value. The ramping function helps maintain model stability in the early stage of the simulation and helps to avoid an impulsive response from the system at the start of the simulation.
DRAMP	Value (in decimal days) used to compute the ramp function that ramps up ADCIRC forcings from zero (if NRAMP=1).	15	Determined through testing model stability.
A00, B00, C00	Time weighting factors (at time levels k+1, k, k-1, respectively) in the GWCE.	0, 1, 0	Standard value used in previous studies.
H0	Nominal water depth for a node (and the accompanying elements) to be considered dry (in meters).	0.05	Standard recommended value.
NODEDRYMIN	Minimum number of time steps after a node dries that it must remain dry before it can wet again.	10	Standard recommended value.
NODEWETMIN	Minimum number of time steps after a node wets that it must remain wet before it can dry again.	10	Standard recommended value.
VELMIN	Minimum velocity for wetting (in meters per second).	0.05	Standard recommended value.
ESLM	Spatially constant horizontal eddy viscosity for the momentum equations (units of length^2/time).	50	Standard value used in previous studies.
ANGINN	Flow boundary nodes which are set up to have a normal flow essential boundary condition and have an inner angle less than ANGINN (specified in degrees) will have the tangential velocity zeroed.	110	Standard recommended value used in previous studies.