APPENDIX H

MIKE3 MODEL INPUTS

HDR | ONE COMPANY *Many Solutions*℠

Memo

To:	Mike Donnelly, Ecology & Environment, Inc.		
From:	Scott Lowe	Project:	Broadwater
CC:	John Duschang		
Date:	2/20/07	Job No:	25917

RE: Request For Additional Information on MIKE 3 Model Calibration

The MIKE 3 model used in the Broadwater Project was originally developed for the Corps of Engineers to support work in New York-New Jersey Harbor. The calibration and verification efforts undertaken as part of the development of the original model are described in this memo. Additional data along the pipeline route was collected as part of the Broadwater project. This was used to provide site specific calibration of the model. This is described in the Water Quality/Sedimentation Report that has already been submitted.

Memo Contents:

HDR | LMS
Henningson, Durham & Richardson Architecture and Engineering, P.C.
In association with HDR Engineering, Inc.

One Blue Hill Plaza, 12th Floor
P.O. Box 1509
Pearl River, NY 10965-8509

Phone (845) 735-8300
Fax (845) 735-7466
www.hdrinc.com

1. MIKE 3 Model Calibration and Verification Overview

Data for the three dimensional hydrodynamic model calibration/verification consisted of measured tidal elevations and currents from USACE field surveys performed in 1991 and 1994-1995, detailed below. NOAA harmonic predictions for elevations and currents were also used to increase the geographic extent of the comparison data. Water quality data, including salinity and temperature were also available for the 1991 and 1994-1995 periods. Additional data used in the 3-D model include: (1) air temperature, (2) wind speed, (3) precipitation (all from NOAA records), and (4) river discharges from USGS stream gauging stations.

Tidal boundary conditions at the offshore locations were created from USACE's tidal constituent database, which is based on large-domain tidal simulations using the Eastcoast 2001 ADCIRC coastal/ocean model (Mukai et al, 2001). Temperature and salinity boundary conditions were obtained from measured NOAA salinity and temperature profiles, where available, and from climatological data. Measured wind speed and direction were obtained from Newark Airport, John F. Kennedy Airport, and from data recorded off shore at Ambrose Light. Air temperature data were obtained from the Central Park National Weather Service station as well as the Ambrose Light data set.

Average daily freshwater discharges at the Hudson, Passaic, Raritan, Rahway, Hackensack, Saddle, Second, and Third Rivers were specified in the model, as were discharges from the Connecticut, Quinnipaic, Norwalk, and Housatonic Rivers, all of which discharge into Long Island Sound. Additional sources of freshwater specified in the model included wastewater treatment plant discharges, which were estimated from operating records at over 70 different locations; and stormwater runoff derived from daily rainfall estimates.

As noted above, calibration and verification data were collected during 1991 and 1994-1995 field surveys. Data were collected by means of tide gauges, moored velocity meters, moored and cast conductivity-temperature-density (CTD) probes, and grab samples. Hydrodynamic data from 1991 were collected for a 4-6 week period, with weekly and biweekly temperature and salinity measurements taken. The hydrodynamic model calibration was performed for approximately 36 days, from 24 June through 30 July 1991. Hydrodynamic and water quality data from 1994-1995 were collected from November 1994 to October 1995. The hydrodynamic verification period was from 21 August to 30 September 1995. Results of these calibration and verification tests indicated that the model results reasonably matched measured data for both periods.

Additional salinity data for the Hudson River were taken by the Woods Hole Oceanographic Institute (WHOI) during the 1995 verification period. A comparison of the WHOI data was made to the MIKE3 model results and a good agreement was found. This exercise provided additional confidence in the reliability and predictive skill of the MIKE 3 model.

Model sensitivity analyses were conducted in order to test the model response to different grid resolutions and time steps. The results of these investigations indicated that the grid setup produces an accurate and computationally efficient solution.

The agreements between measured/predicted tides and velocities, and computed tides and velocities are excellent. The calibration water levels have an average correlation of 0.96 and an average RMS error below 7.5%. The calibration current velocities have an average correlation coefficient and RMS error of 0.88 and 15.6%, respectively. The calibration results also agree reasonably with measured salinity and temperature. Specifically, the calibrated temperatures and salinities have similar overall magnitudes and tidal variations as the measurements and the model was able to reproduce salinity stratification observed during neap tides.

The agreement between model and measured water levels for the verification period is similar to that for the calibration period. Specifically, modeled and measured elevations for the verification period have an average correlation coefficient of 0.96 and a RMS error of 8.0%. Modeled verification currents are in good agreement with measured and predicted currents. The verification statistics for velocity have an average correlation of 0.94 and RMS error of 17.1%. As was the case for calibration, the verification temperatures and salinities closely follow the field measurements. The modeled data were also found to match the WHOI salinity data described above without a specific calibration effort.

2. Calibration and Verification Data

Model calibration and verification efforts utilized field data collected in 1991 and 1995, respectively. These data consist of measured elevations, currents, temperature and salinity at a number of locations within the project area. Locations of the measurement sites for these two surveys are shown in Figures 1 - 4. An overview of the model domain is shown in Figure 5.

Model results were also compared with data available from NOAA, which consist of measured elevations as well as harmonically derived elevations and currents throughout the domain. Locations for these stations are included in Figure 3. These data provide the means for model skill assessment over a wide area. All of the data used in model calibration and validation are summarized in Table 1 and Table 2.

The salinity and temperature transport in the model was calibrated and verified using data collected by Battelle Ocean Science (Battelle, 1995). The Battelle data set was supplemented with water quality data collected as part of the NYC Harbor Survey. Figure 4 depicts the spatial distribution of the water quality sampling stations. Figure 4a is a subset of Figure 4 that shows the stations in Long Island Sound. It is these stations that are used in the calibration and verification transects for salinity and temperature in the next sections.

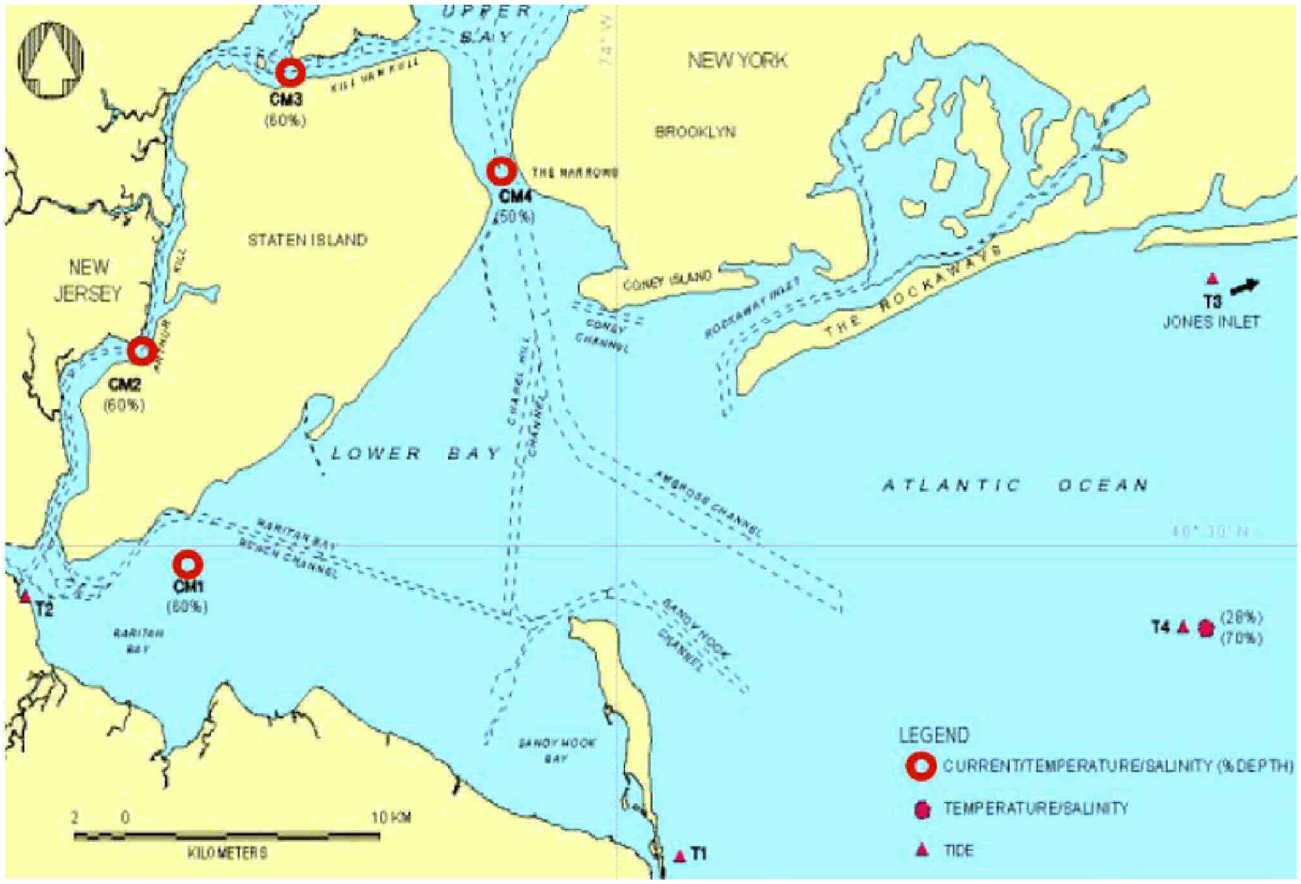


Figure 1. Field survey locations in 1991

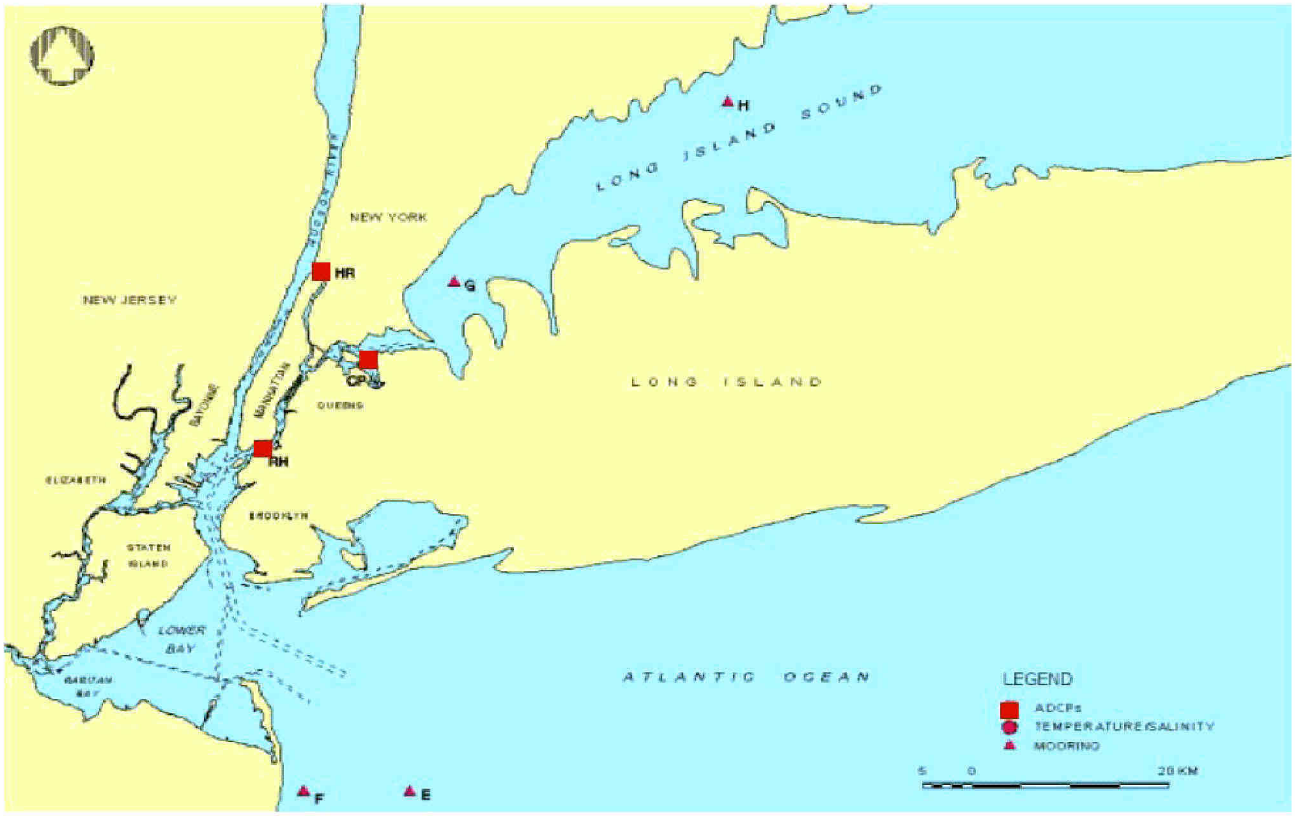


Figure 2. Field survey locations in 1994-1995.

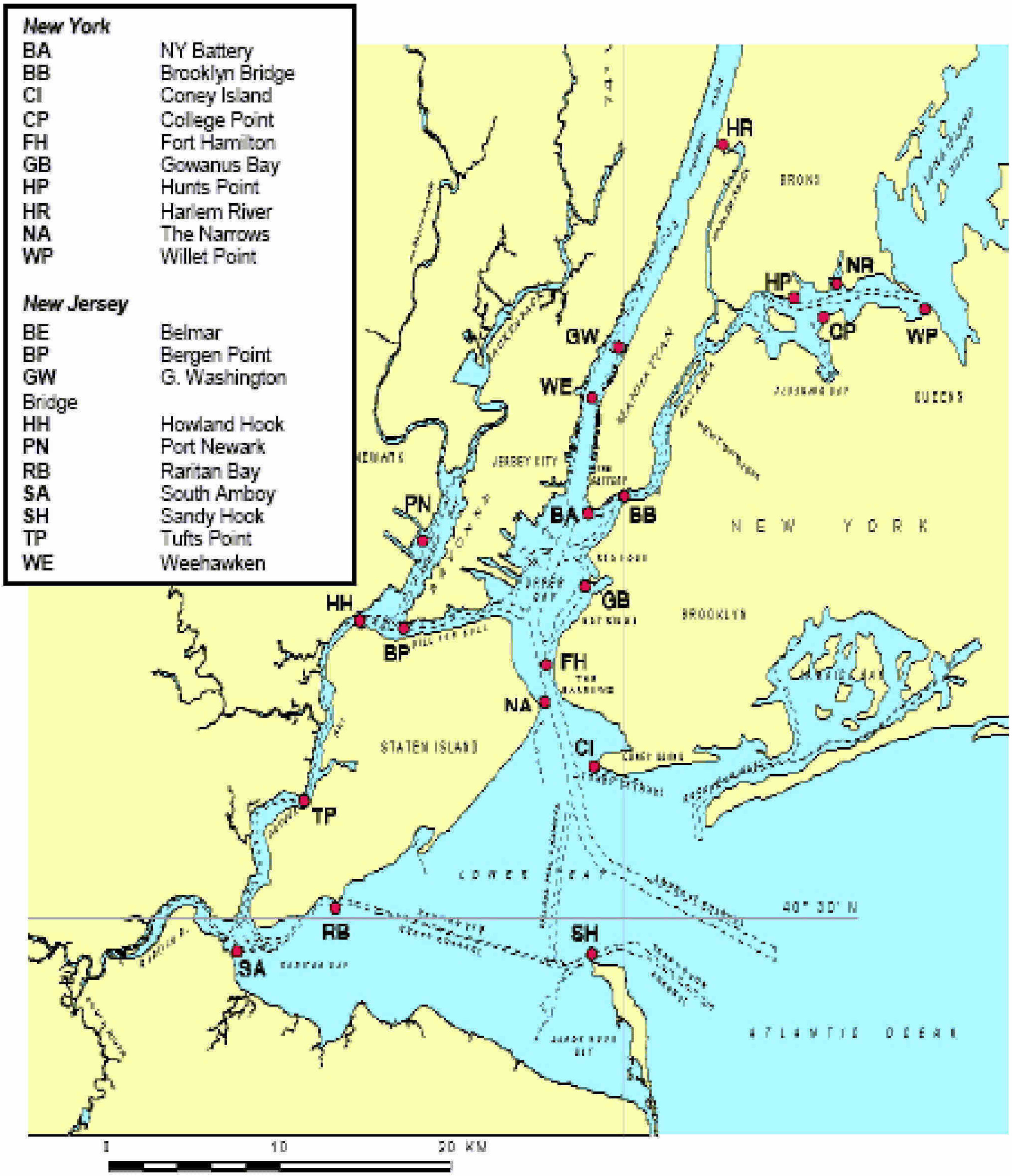


Figure 3. Location of NOAA tide and current stations.

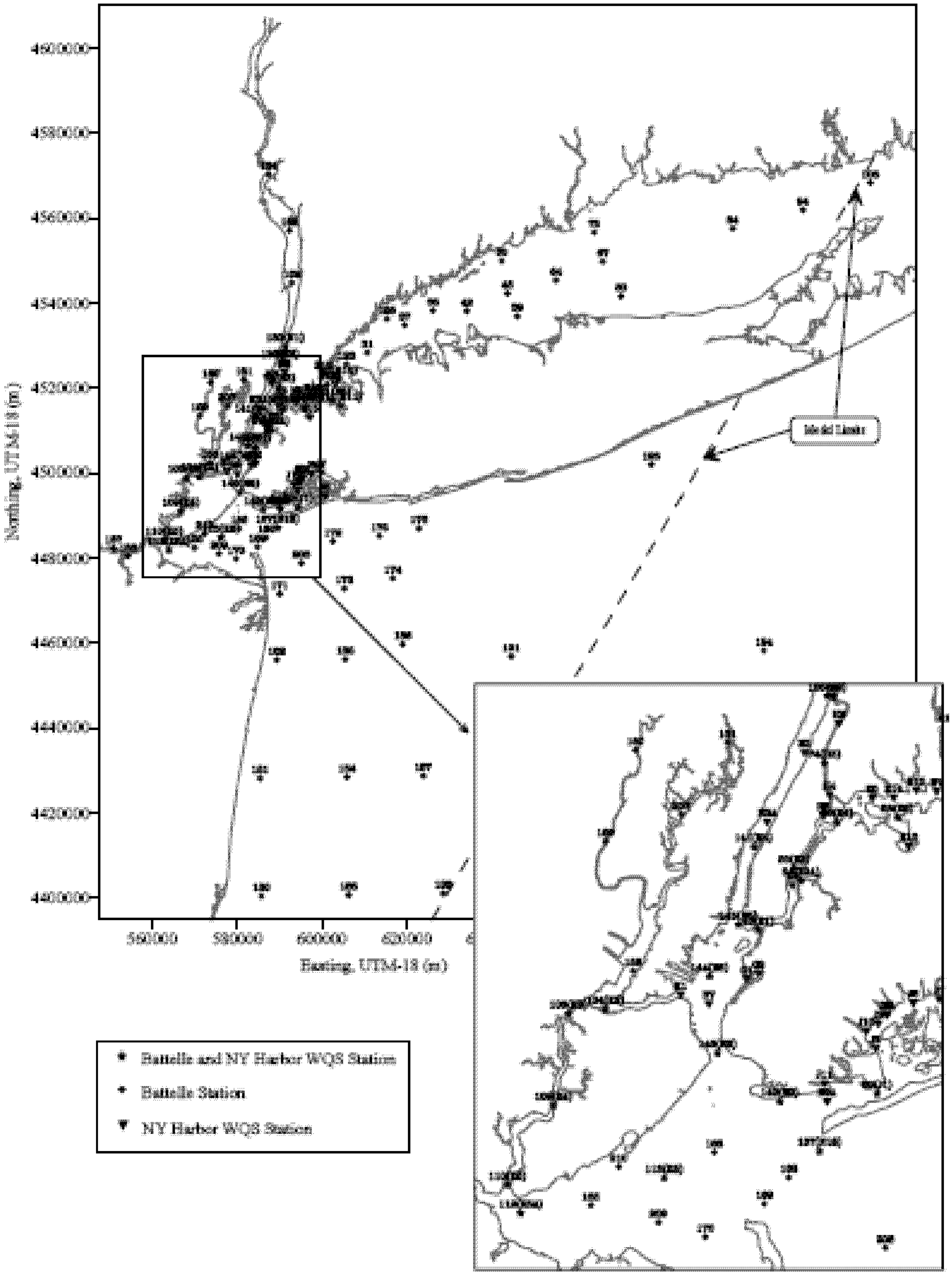


Figure 4. Location of sampling stations for Battelle and NYCDEP.

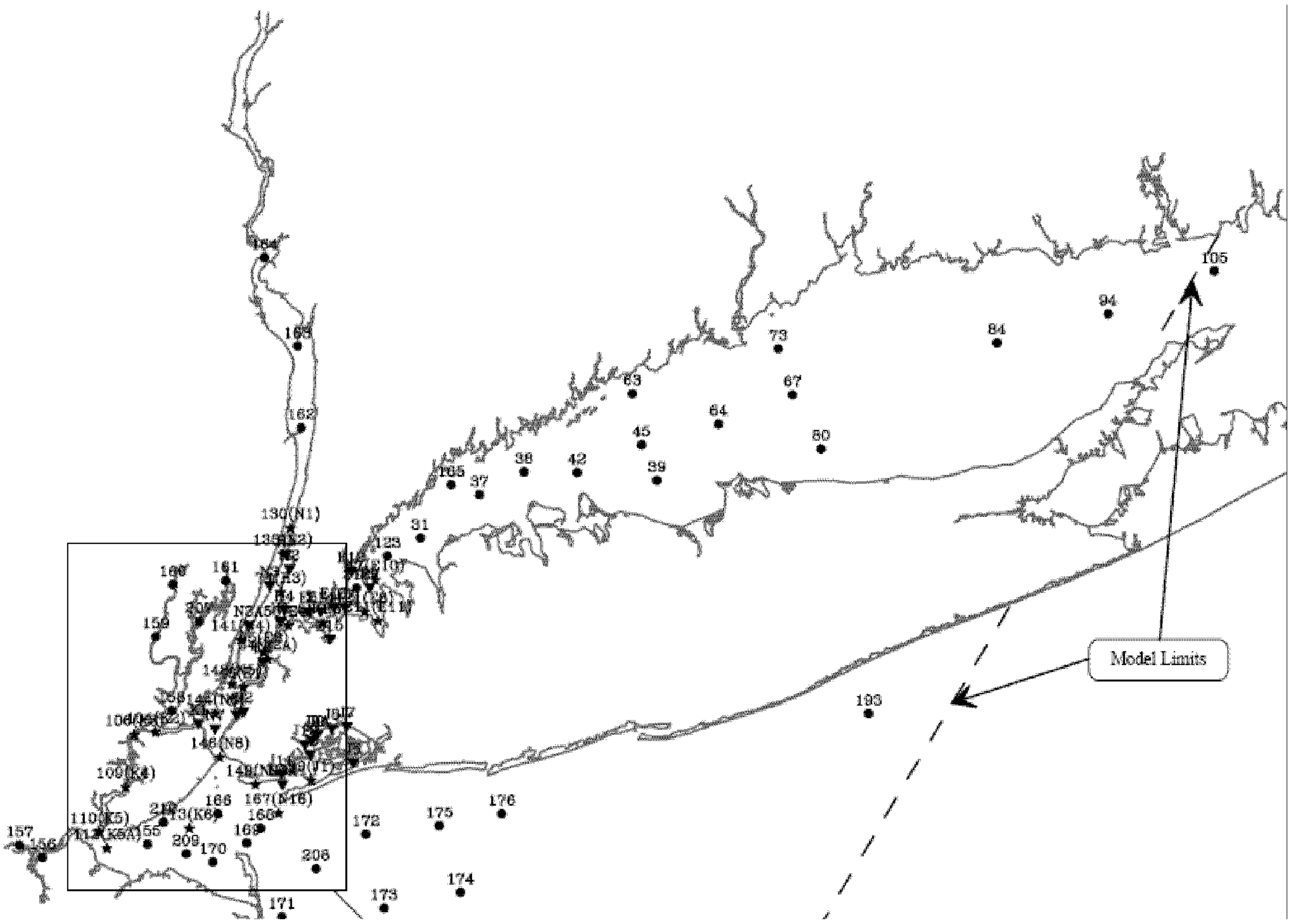


Figure 4a. Sampling stations in Long Island Sound for Battelle and NYCDEP.

3. Boundary Conditions

The model boundaries illustrated in Figure 5 extend to approximately Atlantic City, New Jersey, to the south, to Shinnecock Inlet and Orient Point (on the Atlantic Ocean and Long Island Sound, respectively) to the east, and up the Hudson River to the Federal Dam at Troy, New York. Tidal boundary conditions at the offshore locations were created from USACE's tidal constituent database, which is based on large-domain tidal simulations using the coastal/ocean model ADCIRC (EASTCOAST 2001, Westerink et al. 1993). The boundaries on New York Bight were specified as elevation boundary conditions based on constructed time series from the EASTCOAST 2001 model. However, the Eastcoast 2001 model is not as well calibrated within Long Island Sound. To create the Long Island Sound boundary, a two-dimension hydrodynamic model of NY Bight and Long Island Sound was created and forced with offshore tidal constituents from EASTCOAST 2001. Tidal elevations along the Long Island Sound boundary in the three-dimensional model were extracted from the two-dimensional simulation. The computed boundary current and elevations were also calibrated to the data described above.

Temperature and salinity boundary conditions were obtained from measured salinity and temperature profiles, where available, and from climatological data (Levitus et al. 1994). Measured wind speed and direction were obtained from Newark Airport, John F. Kennedy Airport, and from data recorded off shore at Ambrose Light. Air temperature data were obtained from the Central Park National Weather Service station as well as the Ambrose Light data set.

Daily averaged freshwater discharges at the Hudson, Passaic, Raritan, Rahway, Hackensack, Saddle, Second, and Third Rivers were specified in the model, as were discharges from the Connecticut, Quinnipaic, Norwalk, and Housatonic Rivers, all of which discharge into Long Island Sound. Additional sources of freshwater specified in the model included wastewater treatment plant discharges, which were estimated from operating records at over 70 different locations, and stormwater runoff derived from daily rainfall estimates. All sources of freshwater were entered at a constant temperature of 71.6°F.

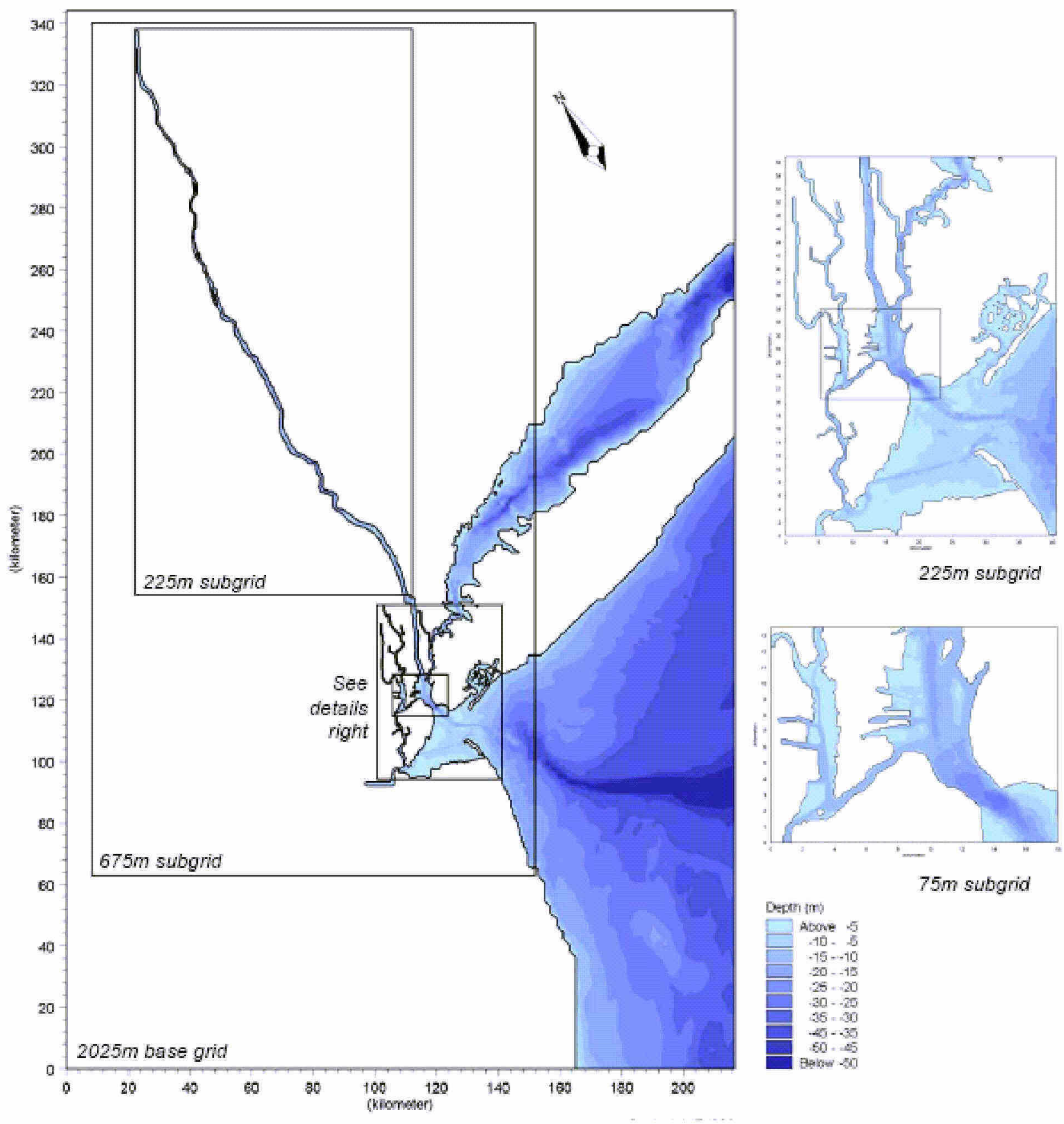


Figure 5. Hydrodynamic model domain.

Table 1. Model calibration data for 1991 simulation period

Location	Data Type	Latitude	Longitude	Instrument Depth (m)	Water Depth (m)
Bergen Point	Measured Currents	40° 38.55N	74° 8.15W	6.4	10.7
Raritan Bay	Measured Currents	40° 30.06N	74° 9.80W	6.6	11.0
The Narrows	Measured Currents	40° 36.33N	74° 2.90W	15.2	30.5
Tufts Point	Measured Currents	40° 33.53N	74° 13.05W	7.0	11.6
Ambrose Light	Measured Tide	40° 46.00N	73° 83.00W	N/A	N/A
Sandy Hook	Measured Tide	40° 28.00N	74° 0.60W	N/A	N/A
South Amboy	Measured Tide	40° 29.39N	74° 16.74W	N/A	N/A
The Battery	Measured Tide	40° 42.00N	74° 0.90W	N/A	N/A
Willets Point	Measured Tide	40° 48.00N	73° 47.00W	N/A	N/A
Bayonne Br. (Bergen Point)	Predicted Tide	40° 38.50N	74° 08.60W	N/A	N/A
Bridgeport	Predicted Tide	41° 10.40N	73° 10.90W	N/A	N/A
College Point	Predicted Tide	40° 47.00N	73° 51.40W	N/A	N/A
Fort Wadsworth	Predicted Tide	40° 36.40N	74° 03.30W	N/A	N/A
G.W. Bridge.	Predicted Tide	40° 51.00N	73° 57.00W	N/A	N/A
Horns Hook	Predicted Tide	40° 46.40N	73° 56.50W	N/A	N/A
Port Elizabeth	Predicted Tide	40° 40.40N	74° 08.40W	N/A	N/A
Sandy Hook	Predicted Tide	40° 28.00N	74° 00.60W	N/A	N/A
South Amboy	Predicted Tide	40° 29.50N	74° 16.90W	N/A	N/A
Tarrytown	Predicted Tide	40° 04.70N	73° 52.20W	N/A	N/A
The Battery	Predicted Tide	40° 42.00N	74° 00.90W	N/A	N/A
Weehawken	Predicted Tide	40° 46.00N	74° 01.10W	N/A	N/A
Willets Point	Predicted Tide	40° 48.00N	73° 47.00W	N/A	N/A
Bayonne Bridge	Predicted Currents	40° 38.50N	74° 08.60W	N/A	N/A
Brooklyn Bridge	Predicted Currents	40° 42.00N	74° 00.00W	N/A	N/A
College Point	Predicted Currents	40° 47.00N	73° 51.40W	N/A	N/A
Coney Island	Predicted Currents	40° 34.20N	74° 00.50W	N/A	N/A
George Washington Bridge	Predicted Currents	40° 51.00N	73° 57.00W		
Hunts Point	Predicted Currents	40° 48.00N	73° 52.40W	N/A	N/A
Narrows	Predicted Currents	40° 36.60N	74° 02.80W	N/A	N/A
Newark Bay	Predicted Currents	40° 39.60N	74° 08.40W	N/A	N/A
Tufts Point	Predicted Currents	40° 33.40N	74° 13.40W		

Table 2. Model validation data for 1995 simulation period

Location	Data Type	Latitude	Longitude	Instrument Depth (m)	Water Depth (m)
College Point	Measured Currents (ADCP)	40° 48.03N	73° 50.90W	1m bins	21.3
Harlem River	Measured Currents (ADCP)	40° 52.46N	73° 54.71W	0.5m bins	5.5
Harlem River	Measured Tide	40° 52.46N	73° 54.71W	N/A	N/A
Red Hook	Measured Currents (ADCP)	40° 42.44N	73° 59.04W	1m bins	15.5
Harlem River	Measured Tide				
Sandy Hook	Measured Tide	40° 28.00N	74° 0.60W	N/A	N/A
The Battery	Measured Tide	40° 42.00N	74° 0.90W	N/A	N/A
Willets Point	Measured Tide	40° 48.00N	73° 47.00W	N/A	N/A
Bayonne Br. (Bergen Point)	Predicted Tide	40° 38.50N	74° 08.60W	N/A	N/A
Bridgeport	Predicted Tide	41° 10.40N	73° 10.90W	N/A	N/A
College Point	Predicted Tide	40° 47.00N	73° 51.40W	N/A	N/A
Fort Wadsworth	Predicted Tide	40° 36.40N	74° 03.30W	N/A	N/A
G.W. Bridge.	Predicted Tide	40° 51.00N	73° 57.00W	N/A	N/A
Horns Hook	Predicted Tide	40° 46.40N	73° 56.50W	N/A	N/A
Port Elizabeth	Predicted Tide	40° 40.40N	74° 08.40W	N/A	N/A
Sandy Hook	Predicted Tide	40° 28.00N	74° 00.60W	N/A	N/A
South Amboy	Predicted Tide	40° 29.50N	74° 16.90W	N/A	N/A
Tarrytown	Predicted Tide	40° 04.70N	73° 52.20W	N/A	N/A
The Battery	Predicted Tide	40° 42.00N	74° 00.90W	N/A	N/A
Weehawken	Predicted Tide	40° 46.00N	74° 01.10W	N/A	N/A
Willets Point	Predicted Tide	40° 48.00N	73° 47.00W	N/A	N/A
Bayonne Bridge	Predicted Currents	40° 38.50N	74° 08.60W	N/A	N/A
Brooklyn Bridge	Predicted Currents	40° 42.00N	74° 00.00W	N/A	N/A
College Point	Predicted Currents	40° 47.00N	73° 51.40W	N/A	N/A
Coney Island	Predicted Currents	40° 34.20N	74° 00.50W	N/A	N/A
George Washington Bridge	Predicted Currents	40° 51.00N	73° 57.00W		
Hunts Point	Predicted Currents	40° 48.00N	73° 52.40W	N/A	N/A
Narrows	Predicted Currents	40° 36.60N	74° 02.80W	N/A	N/A
Newark Bay	Predicted Currents	40° 39.60N	74° 08.40W	N/A	N/A
Tufts Point	Predicted Currents	40° 33.40N	74° 13.40W		

4. Calibration Procedure

The objective of a model calibration is to adjust certain model parameters until model results compare well with equivalent measured data. The following variables were compared to measured (and predicted) values for the calibration efforts:

- Water level
- Current
- Temperature
- Salinity

Comparisons were made for all available fixed measurement stations. Additional comparisons were made for predicted water level/current stations.

Two levels of analysis were performed:

- Graphical
- Statistical

The graphical analysis consists of visual comparison of modeled and measured time series. Examples of the graphical results are shown in the next section.

The statistical analysis comprises statistical measures of error (or deviation) in the computed and measured time series. Statistics include the correlation coefficients and root mean square (RMS) error. With respect to currents, these analyses were performed for the velocity in the flood and ebb direction at each station.

The statistical measures used are defined as follows:

- *Correlation Coefficient*: Uses the Pearson product moment correlation coefficient, r, (a dimensionless index that ranges from -1.0 to 1.0 inclusive) which reflects the extent of a linear relationship between two data sets. This parameter indicates how closely the modeled data is in phase with the calibration data.

- *Root Mean Square (RMS) Error*: Compares the root of the average square of the difference (error) between the two data sets.

- *RMS Error Percentage*: Computes the RMS Error as a percentage of the range of the predicted/measured data. This gives perspective on the magnitude of the RMS error.

The correlation coefficient and RMS error percentage statistics serve as the indicator for determining when model calibration is satisfactory. With regard to correlation coefficients, the target of the model simulations was at least 80% of the comparison stations should have correlation coefficients greater than or equal to the threshold values of 0.90 for water levels and 0.80 for currents. Similarly, percentage RMS or absolute RMS error values for at least 80% of the stations should be less than 10% for water levels and 20% for currents. These calibration criteria are repeated in Table 3.

Table 3. Target Threshold values for hydrodynamic calibration parameters (Satisfied at 80% of the Comparison Stations)

Measured	Water Levels	Currents
Correlation Coefficient	0.90	0.80
RMS Error	10%	20%

Correlation coefficients for temperature and salinity were not computed as part of the analysis, and calibration was based on visual inspection of the modeled/measured time series compared with sampled data. This approach was taken because the measured data are available only as samples at a single instant in time and therefore correlation and RMS variations over time cannot be computed.

5. Calibration Parameters

Hydrodynamic calibration parameters in the MIKE3 model are:

- The bed roughness scale k_s
- The Smagorinsky turbulence closure parameter, c_{smag}, for the horizontal direction
- The Prandtl number, σ_T, for the horizontal diffusion of salinity and temperature

The parameters for the 1D (vertical) k-ε model found in the literature (ASCE, 1988) are considered to be accepted values and are not changed during the calibration process.

Model calibration for the present model resulted in a variable bed roughness k_s ranging from 0.1 cm (in shallow water) to 3 cm (in deep water). There is no direct relationship between values of k_s in the model and a physical quantity such as grain size. The *model* bed roughness (k_s) is a calibration parameter, which is a result of both the *physical* resistance and the numerical implementation of resistance.

A range of values of 0.02 to 0.06 was used for the 2D (horizontal) Smagorinsky model parameter c_{smag} as a result of the model calibration. This calibration approach resulted in good model results for salinity and temperature. The range of c_{smag} values is in line with those used by other researchers. For example, Reynolds (1976) used a value of 0.06, Lilly (1967) used a value of 0.17, Deardorff (1971) used a value of 0.21, and Smagorinsky (1993) cited values from the literature in the range 0.0649-0.336.

The diffusivity of salt is assumed to vary linearly with eddy viscosity. In the horizontal directions, a constant value $\sigma_T = 10$ was found for the diffusivity of salt, while in the vertical direction σ_T yielded values in the range from 1 (for unstable and neutral stratification) to about 90 (for stable stratification and high Richardson numbers). The corresponding Prandtl numbers in the temperature equation have been taken as 1.4 times lower than those for salt. A value of σ_T greater than 1 implies that diffusive transport is weaker for salt/temperature than for momentum.

6. Calibration Results

6.1 Water Surface Elevations

Water surface elevation results from the model are dependent on a combination of forcing from both tidal harmonics and measured data. Offshore tidal elevations are based on harmonic constituents, while river flows, winds, and temperatures are based on measured data. Therefore to assess model performance it is necessary to consider both harmonic predictions inside the model as well as measured data.

Water levels have been compared with measurements at 6 stations and with harmonic predictions at 13 stations. Measured elevation data were obtained from the NOAA internet site, while elevation predictions were computed from NOAA harmonics using tidal prediction software (Tides and Currents Pro, Version 3.3). Samples of the graphical comparisons are shown in Figure 6.

As shown in Tables 4 and 5, the agreement between measured/predicted tides and computed tides is excellent. Overall, the water levels have an average correlation of 0.96 at the comparison points and an average RMS error below 7.5%. These values are comparable to those achieved in other models (e.g., Blumberg, et al, 1999). Comparisons with measured tides (Table 4) do not meet the calibration target at 1 of 5 stations, while comparisons with predicted tides do not meet the calibration target at 2 of the 13 stations. Those stations not meeting the criteria are nonetheless very close to the target threshold. Therefore, the goal of 80% compliance with the criteria is met, and the model hydrodynamics were considered satisfactorily calibrated.

6.2 Instantaneous Currents

Currents were evaluated at 4 measured and 9 predicted stations (those shown in Figures 1-3). Model results at these stations were extracted at depths appropriate to the depths at which the meters were deployed, while surface results are used to compare with predicted current stations. Samples of the model and predicted current speed and direction are shown in Figure 7.

In general, the agreement between the model and measured currents is excellent with correlations exceeding the target of 0.8 and RMS error values lower than the 20% criteria. Correlations with measured data show lower values than the predicted, however measured currents are notoriously difficult to match exactly due to variations in natural current fields and larger gradients in current speed and direction. A review of the time series plots illustrates the overall accuracy of the computed results.

Overall, the average correlation coefficient and RMS error for all of the measured/predicted stations is 0.88 and 15.6%, respectively. In summary, the agreement between the model and the data is very good. Additionally, these results are similar to Blumberg et al (1999) who report an average calibration coefficient of 0.94 and an RMS error less than 15% for New York Harbor measurements.

Table 4 Model calibration results: comparisons with field measurements

Location	Data Type	Correlation	RMS Error	RMS Error %
Bergen Point	Currents	0.67	14.45 cm/s	10.4
Raritan Bay	Currents	0.81	12.70 cm/s	30.4
The Narrows	Currents	0.89	46.78 cm/s	18.7
Tufts Point	Currents	0.90	14.59 cm/s	19.2
Ambrose Light	Water Level	0.97	8.98 cm	6.8
The Battery	Water Level	0.94	12.81 cm	9.7
Bergen Point	Water Level	0.88	13.43 cm	9.2
Sandy Hook	Water Level	0.96	11.88 cm	8.6
South Amboy	Water Level	0.92	13.96 cm	9.5
Willets Point	Water Level	0.94	30.20 cm	14.0

Table 5 Model calibration results: comparisons with NOAA predictions

Location	Data Type	Correlation	RMS Error	RMS Error %
Bergen Point	Water Level	0.96	7.51 cm	4.9
Bridgeport	Water Level	0.94	23.90 cm	12.2
College Point	Water Level	0.90	8.33 cm	3.7
Fort Wadsworth	Water Level	0.99	6.96 cm	4.9
G. Washington Br	Water Level	0.98	6.12 cm	5.3
Horns Hook	Water Level	0.95	14.41 cm	10.0
Port Elizabeth	Water Level	0.95	7.55 cm	4.9
Sandy Hook	Water Level	0.99	4.54 cm	3.3
South Amboy	Water Level	0.99	8.40 cm	5.5
Tarrytown	Water Level	0.98	6.18 cm	6.6
The Battery	Water Level	0.99	6.30 cm	4.5
Weekhawken	Water Level	0.98	5.69 cm	4.5
Willets Point	Water Level	0.99	30.56 cm/s	13.7
Bayonne Bridge	Current	0.87	22.51 cm/s	14
Brooklyn Bridge	Current	0.91	43.17 cm/s	16
College Point	Current	0.97	4.65 cm/s	3
Coney Island	Current	0.91	12.58 cm/s	12
G. Washington Br	Current	0.92	15.11 cm/s	8
Hunts Point	Current	0.97	51.63 cm/s	34
Narrows	Current	0.95	9.20 cm/s	5.1
Newark Bay	Current	0.74	15.86 cm/s	23
Tufts Point	Current	0.97	9.71 cm/s	9

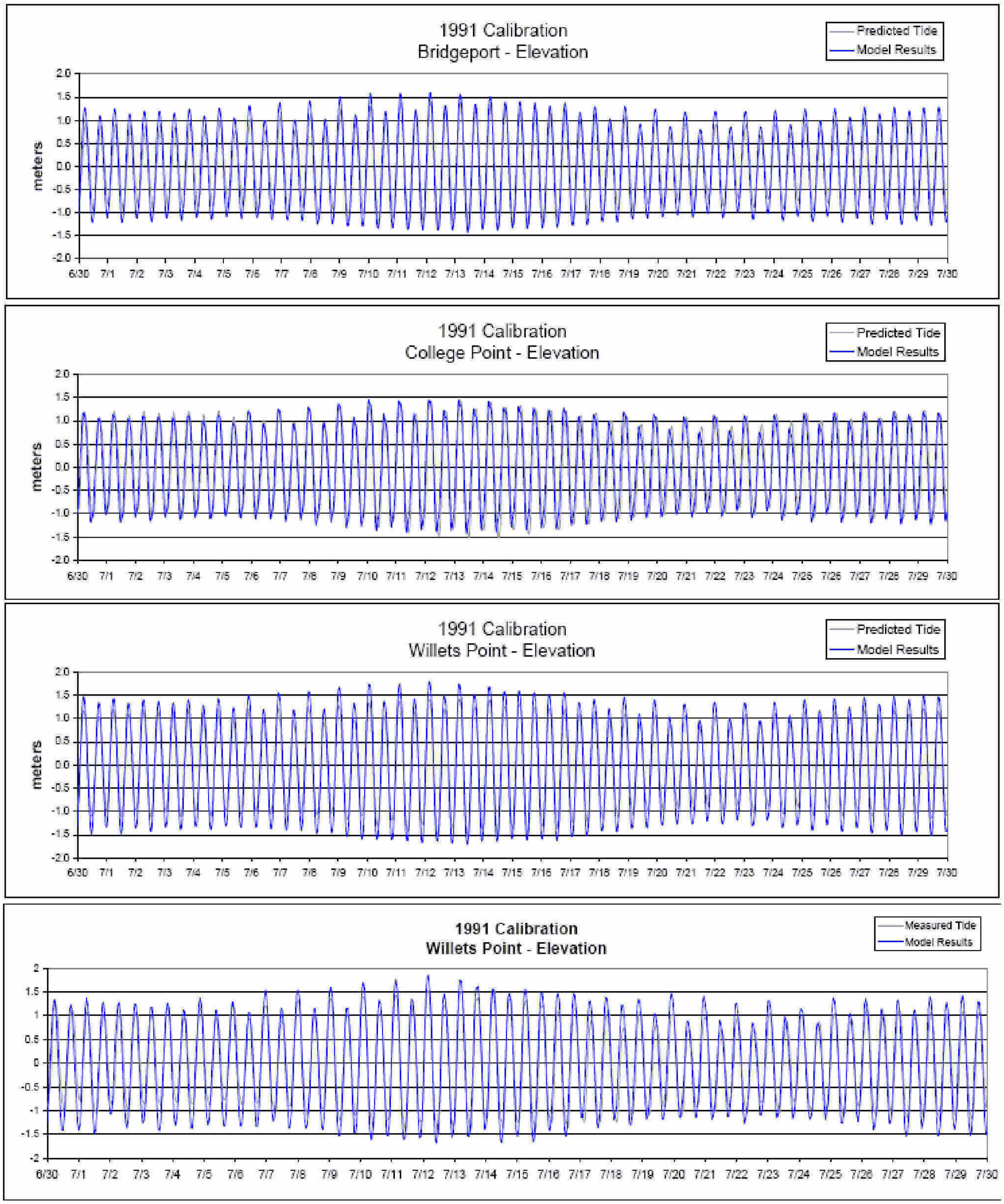


Figure 6. Example comparisons of model and harmonically predicted/measured surface elevations for calibration period.

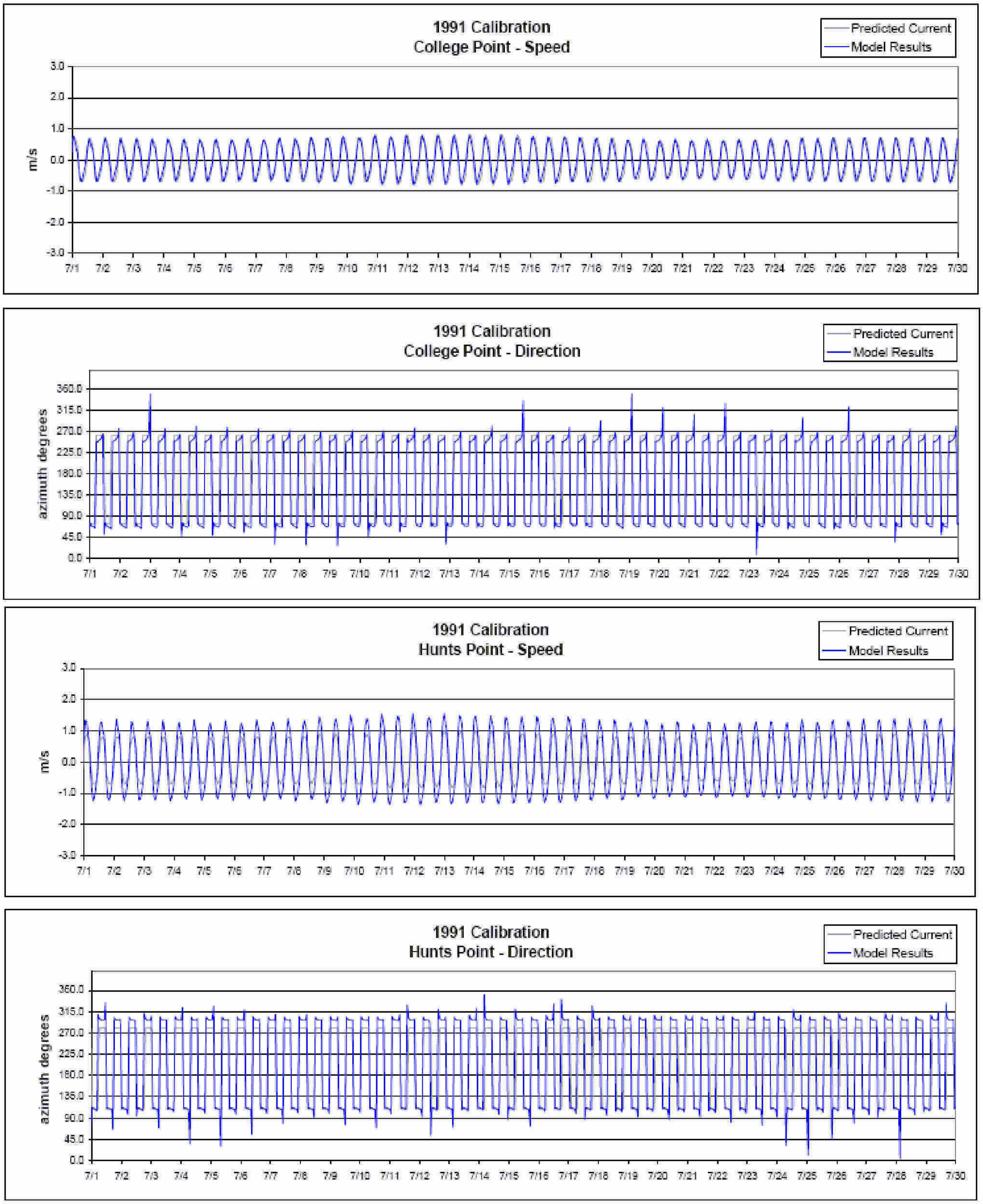


Figure 7. Samples of model and harmonically predicted current speed and direction for calibration period.

6.3 Salinities and Temperatures

The model results were compared to the previously described Battelle and NYCDEP stations (Figures 4 and 4a). A comparison of the measurements and the model results are shown in Figure 8. Figure 8 shows a transect beginning at The Battery, progressing up the East River and out into Long Island Sound. The data from the sampling stations shown in Figure 4a is used to compute the transect. Overall, the model results compare very well to the measurements throughout the model domain.

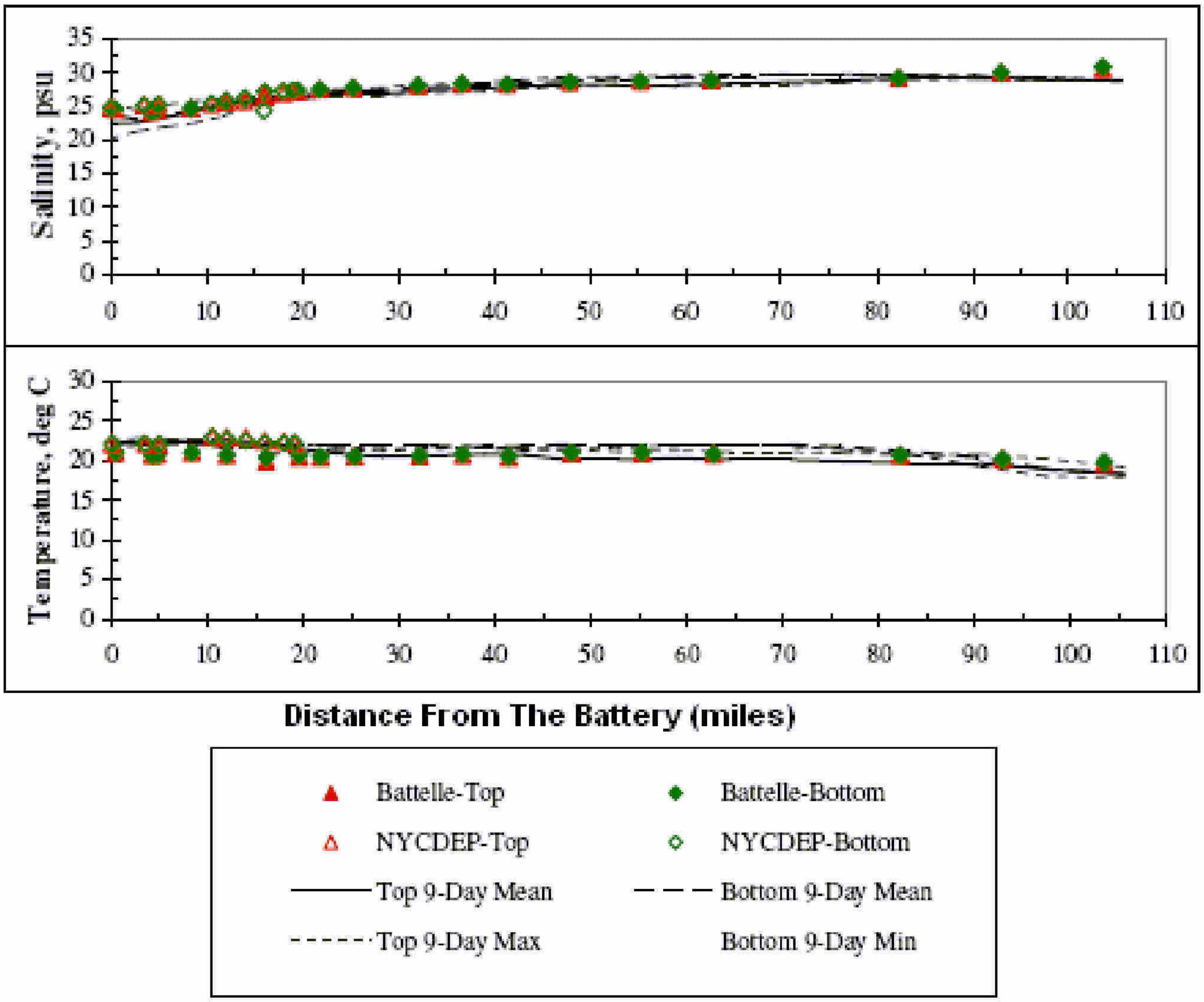


Figure 8. Model calibration for salinity and temperature in Long Island Sound.

7 Verification

7.1 Procedure

The objective for the verification (or validation) phase is to demonstrate the universality of the model. Specifically, a model that has been calibrated to simulate hydrodynamics during one period should perform equally well for other periods keeping all model parameters unchanged.

7.2 Results

The verification period was August 21, 1995 – 30 September 1995. Measured surface elevation and ADCP data were available for this period along with predicted surface elevations and currents. The ADCP current meter profiles were taken in the Harlem and East Rivers.

Results for the validation period are summarized below in Tables 6 and Table 7. Time series plots for sample stations are shown in Figures 9-11. Overall, the verification correlation/RMS error statistics are better than those for the calibration period.

7.3 Water Levels

Water levels were compared at many of the same measured and predicted stations as for the calibration period. A total of 15 stations were used in the comparisons. In general, the agreement for computed water levels is similar to that for the calibration period. Specifically, modeled and measured elevations have an average correlation coefficient of 0.96 and a RMS error of 7.1%. Figure 9 shows sample plots of the results for elevation.

7.4 Currents

Currents were compared at 3 measured and 9 predicted stations. Measured and modeled currents at 2 of the 3 ADCP stations (College Point and Red Hook) were compared at the near surface, mid depth and near bottom. Currents at the Harlem River were only compared at the near surface and near bottom since the depth was less than 6 meters at this location. Figures 10 and 11 show sample plots of the results for current speed and direction.

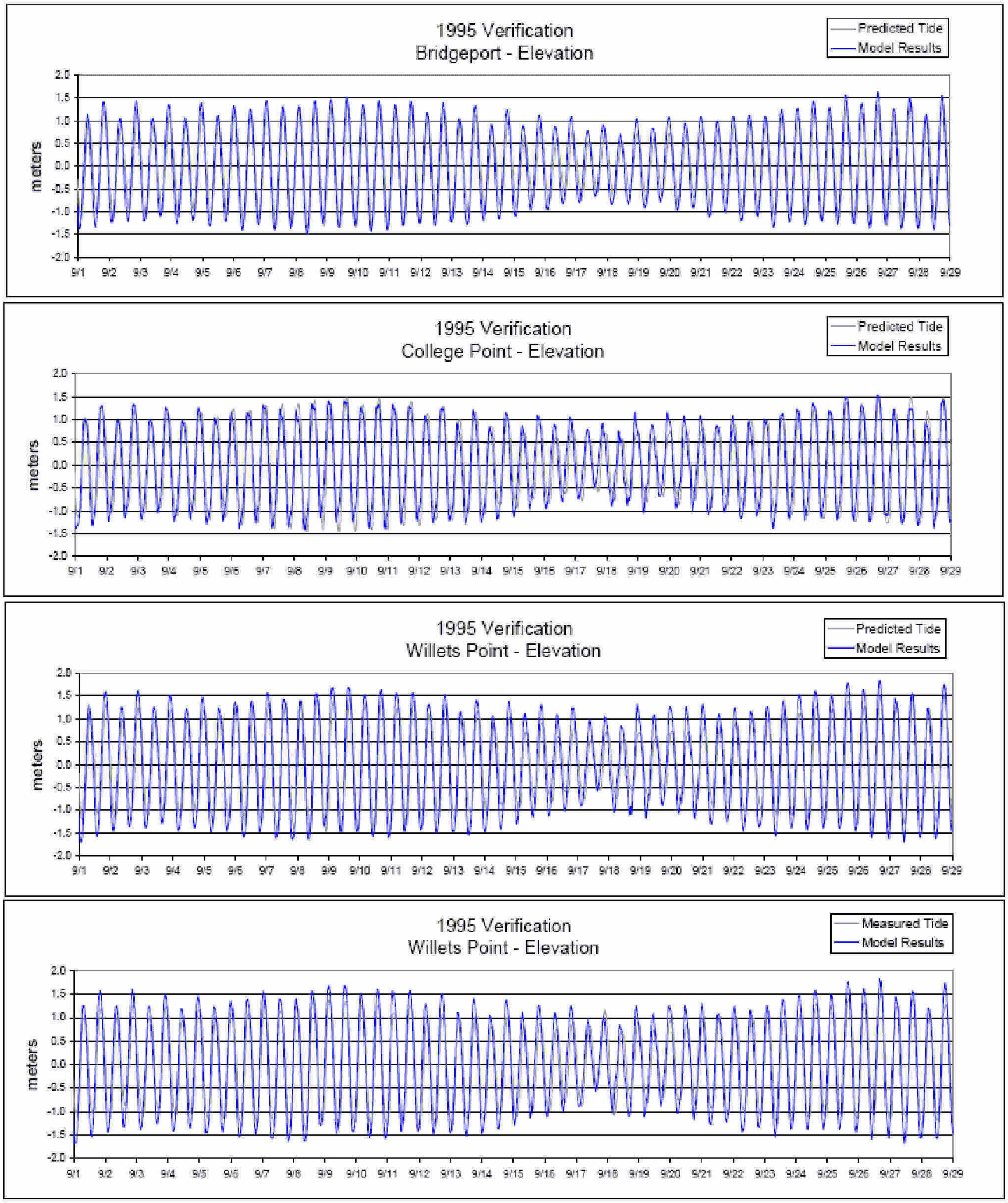


Figure 9. Samples of model and harmonically predicted/measured elevations for verification period.

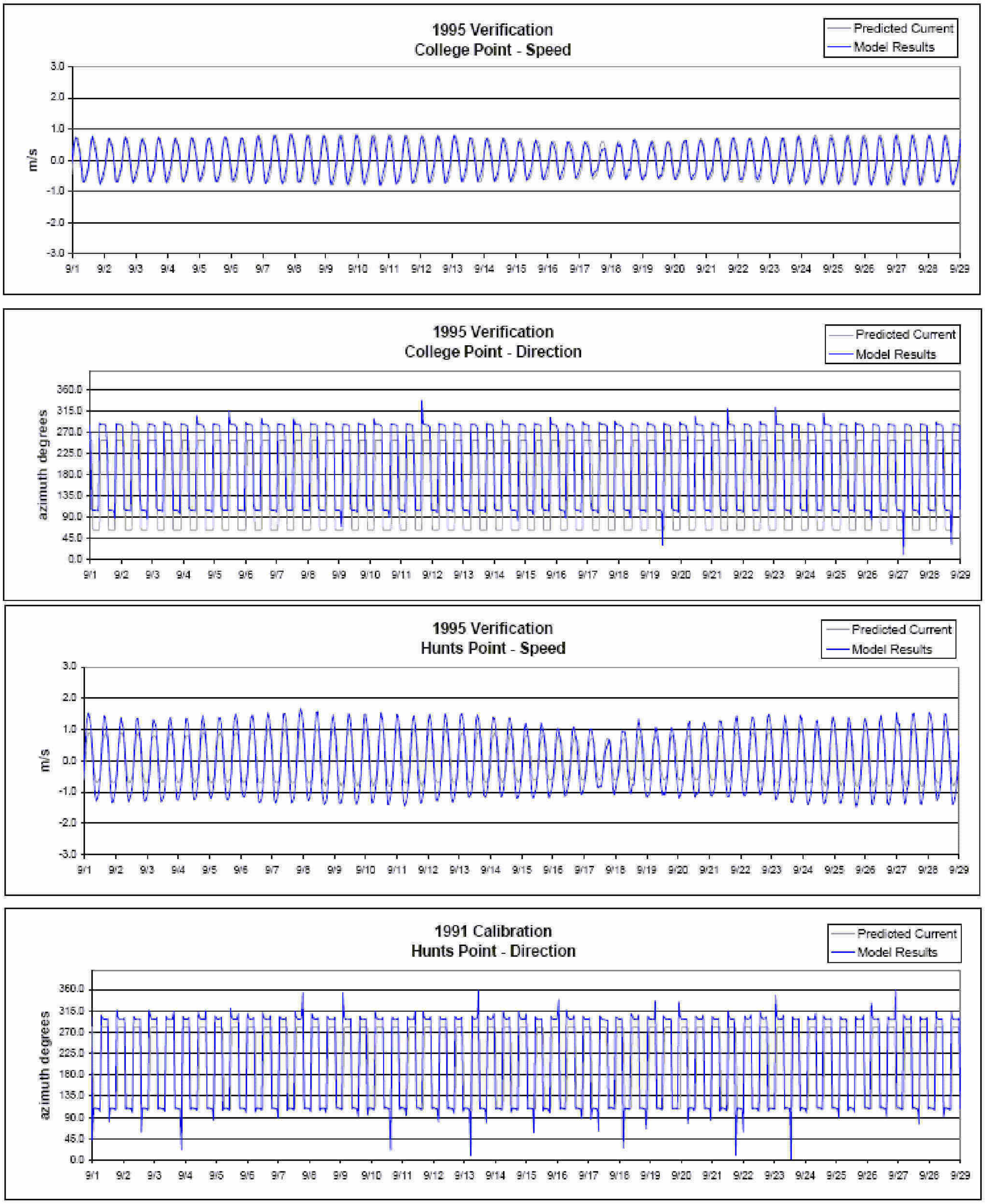


Figure 10. Samples of model and harmonically predicted current speed and direction for verification period.

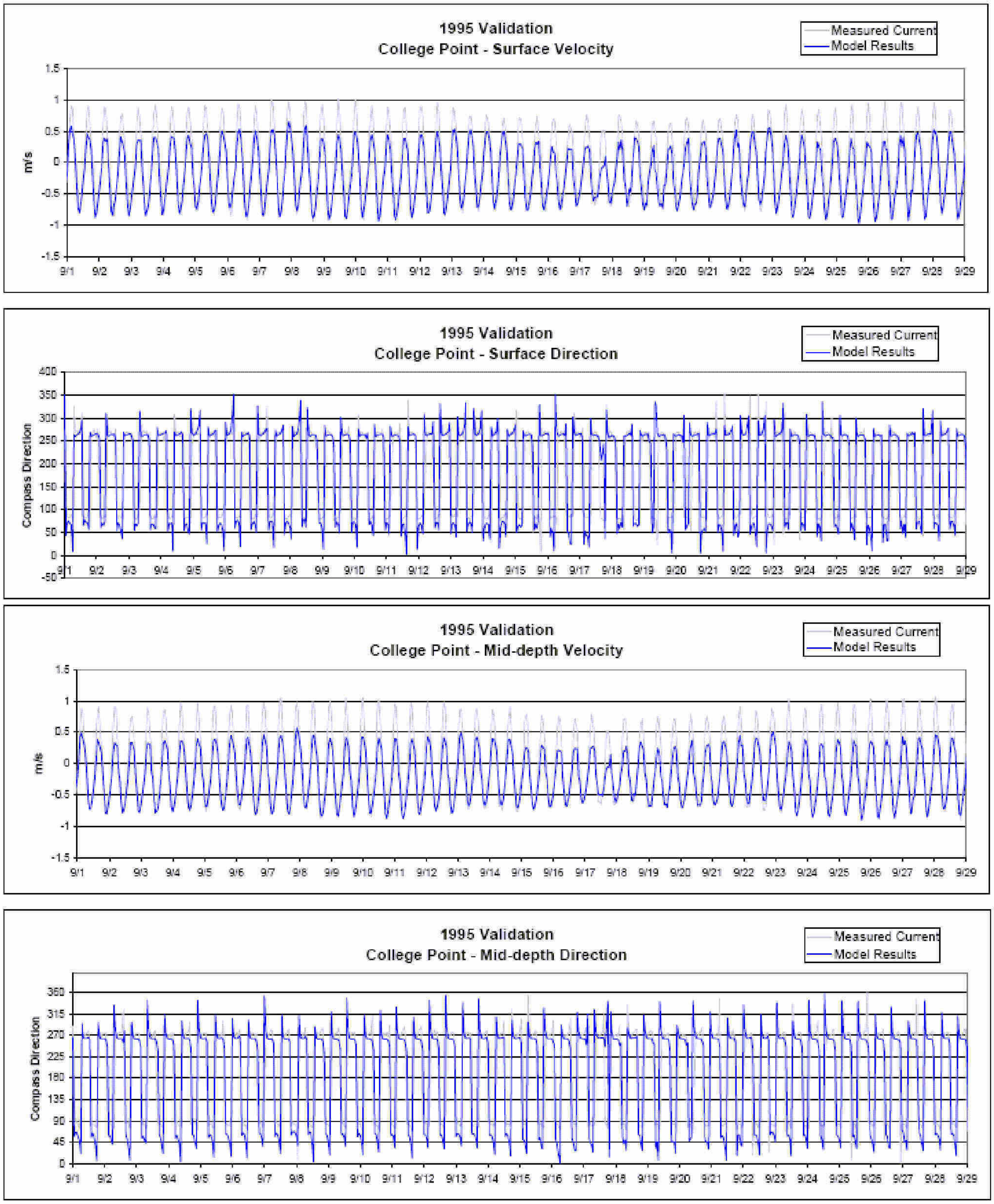
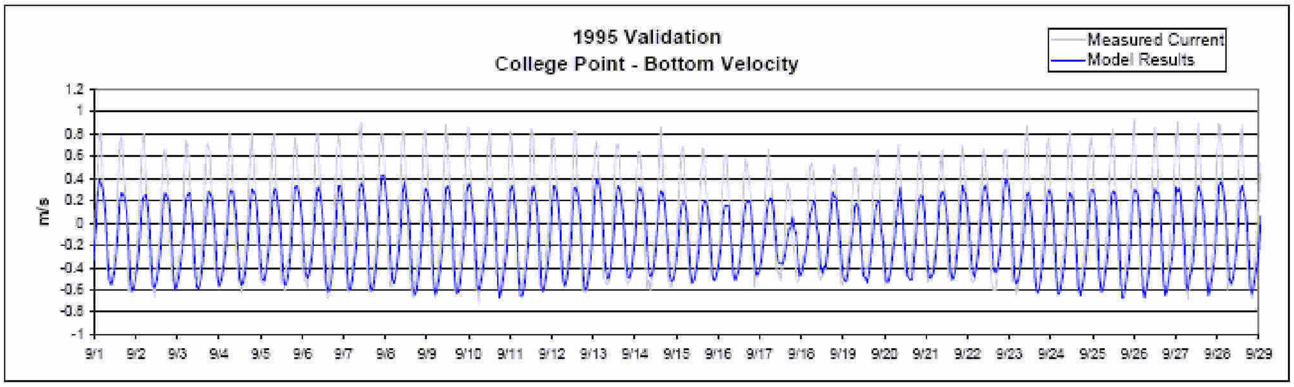


Figure 11. Samples of model and measured current speed and direction for verification period.



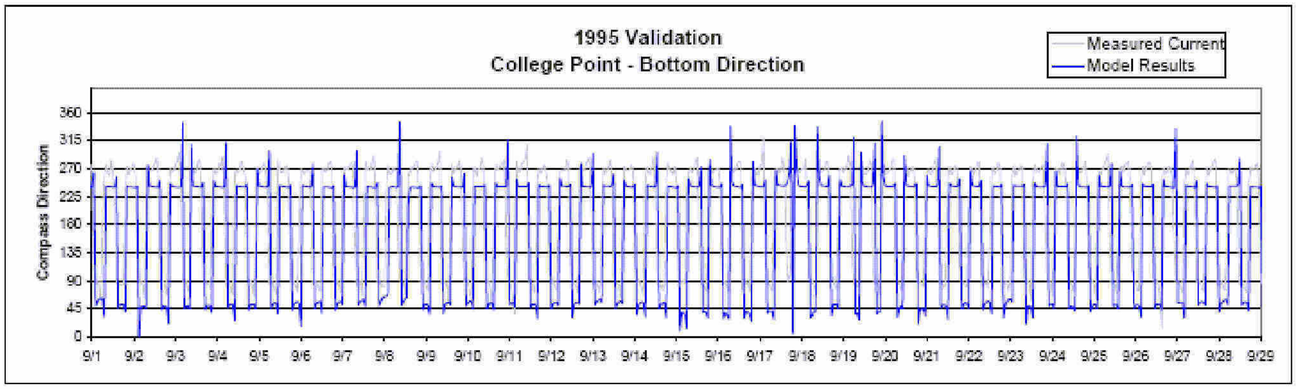


Figure 11 (cont). Samples of model and measured current speed and direction for verification period.

Table 6 Model validation results: comparisons with field measurements

Location	Data Type	Correlation	RMS Error	RMS Error %
College Point	Currents (surface)	0.96	32.68 cm/s	19.8
College Point	Currents (mid-depth)	0.96	37.87 cm/s	23.4
College Point	Currents (bottom)	0.87	34.14 cm/s	26.1
Harlem River	Currents (surface)	0.98	10.60 cm/s	5.3
Harlem River	Currents (bottom)	0.98	9.69 cm/s	5.5
Red Hook	Currents (surface)	0.98	73.96 cm/s	21.6
Red Hook	Currents (mid-depth)	0.99	74.24 cm/s	23.2
Red Hook	Currents (bottom)	0.98	32.20 cm/s	11.6
Bergen Point	Water Level	0.96	9.06 cm	5.9
Sandy Hook	Water Level	0.94	9.04 cm	6.2
The Battery	Water Level	0.98	8.44 cm	6.0
Willets Point	Water Level	0.98	31.24 cm	14.2

As shown in Table 6, modeled currents are in good agreement with measured and predicted currents. The statistics at all stations achieve the current calibration criterion of 0.8 for correlation coefficients and 20% for RMS error, with averages above these limits; i.e., 0.92 for correlation and 13.6% for RMS error.

Modeled and predicted currents also match closely (see Table 7). The RMS errors are acceptable at all locations.

Table 7 Model validation results: comparisons with NOAA harmonic stations

Location	Data Type	Correlation	RMS Error	RMS Error %
Bergen Point	Water Level	0.98	8.00 cm	5.4
Bridgeport	Water Level	0.91	18.45 cm	8.8
College Point	Water Level	0.89	15.09 cm	7.1
Fort Wadsworth	Water Level	0.99	8.21 cm	5.8
G.W. Bridge	Water Level	0.98	9.45 cm	8.1
Horns Hook	Water Level	0.93	18.94 cm	13.5
Port Elizabeth	Water Level	0.97	9.21 cm	5.9
Sandy Hook	Water Level	0.98	8.00 cm	5.4
South Amboy	Water Level	0.97	14.16 cm	9.3
Tarrytown	Water Level	0.97	7.22 cm	7.6
The Battery	Water Level	0.99	8.04 cm	5.7
Weehawken	Water Level	0.97	8.20 cm	6.5
Willets Point	Water Level	0.90	32.22 cm	14.7
Bayonne Bridge	Currents	0.86	23.37 cm/s	13.3
Brooklyn Br.	Currents	0.89	49.19 cm/s	17.3
College Point	Currents	0.97	5.80 cm/s	4.1
Coney Is. Chan.	Currents	0.96	13.32 cm/s	11.9
G.W. Bridge	Currents	0.91	21.09 cm/s	11.1
Hunts Point	Currents	0.95	142.28 cm/s	34.1
Newark Bay	Currents	0.96	53.01 cm/s	33.7
The Narrows	Currents	0.93	10.91 cm/s	5.7
Tufts Point	Currents	0.78	16.91 cm/s	23.4

7.5 Salinities and Temperatures

As was the case for calibration, the model reproduced the Battelle and NYSDEP salinity and temperature data throughout the model domain. The model results were compared to the previously described Battelle and NYCDEP stations. A comparison of the measurements and the model results are shown in Figure 12. Figure 12 shows a transect beginning at The Battery, progressing up the East River and out into Long Island Sound. The data from the sampling stations shown in Figure 4a is used. Overall, the model results compare very well to the measurements throughout the model domain.

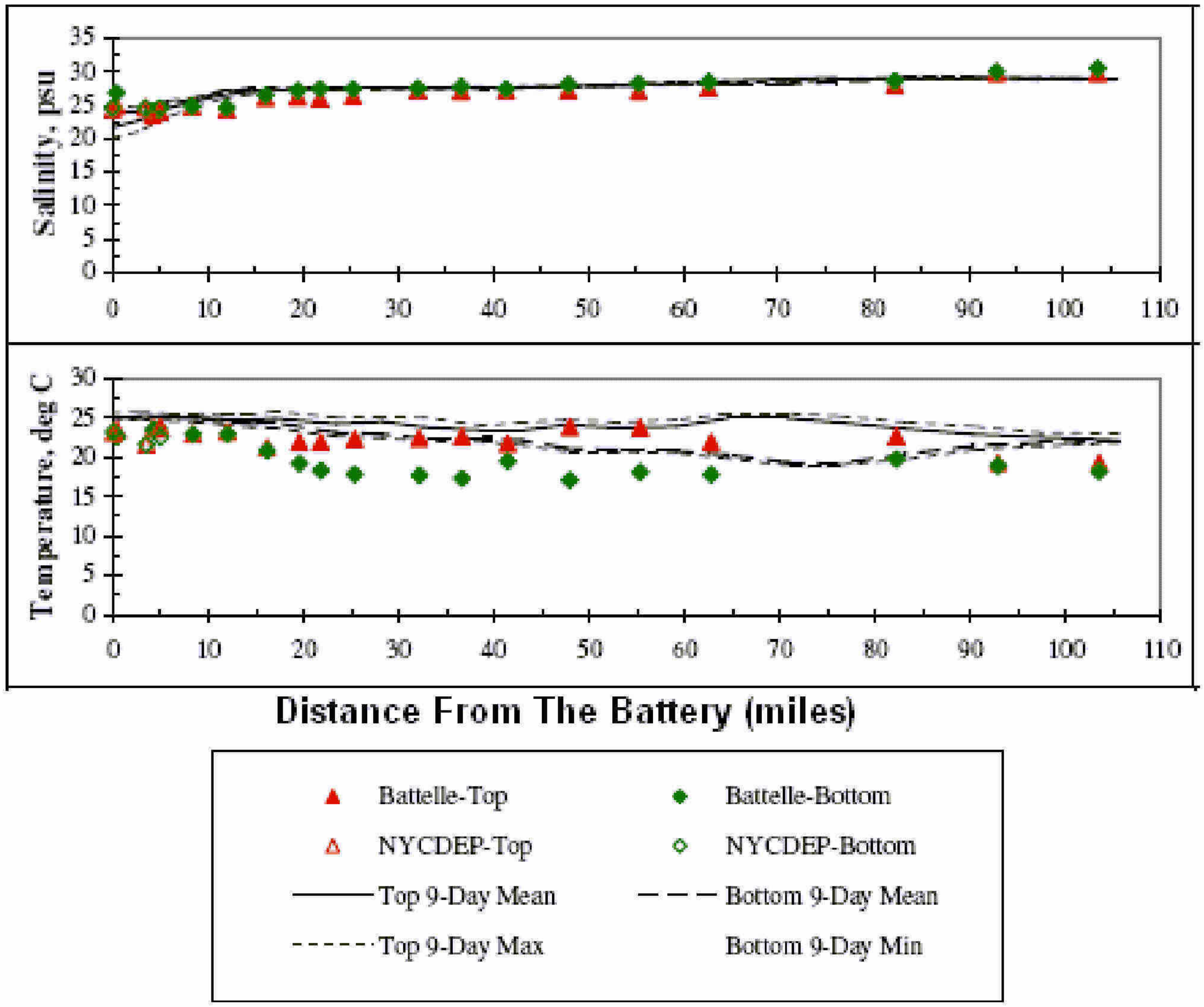


Figure 12. Model verification for salinity and temperature in Long Island Sound.

8 References

ASCE Task Committee on Turbulence Models in Hydraulic Computations (1988) Turbulence modeling of surface water flow and transport, ASCE, Journal of Hydraulic Engineering, Vol. 114, No. 9.

Battelle Ocean Sciences (1995) Data Reports for New York City Newton Creek Facilities Upgrade Planning Project. Prepared for Greeley and Hansen Engineers.

Blumberg, A.F., Kahn, L.A. and J.P. St. John (1999) Three-Dimensional Hydrodynamic Model of the New York Harbor Region, ASCE, Journal of Hydraulic Engineering, Vol. 125, No. 8.

Deardorff, J.W. (1971) On the magnitude of the subgrid scale eddy coefficient (Nonlinear subgrid scale eddy viscosity formulation for turbulence generated by mean shear or thermal instability at large Reynolds number), Journal Of Computational Physics, Vol. 7.

Levitus, S., Antonov, J.I and Boyer, T.P. (1994) Interannual Variability of Temperature at a Depth of 125 Meters in the North Atlantic Ocean , Science, Vol. 266, No. 5182.

Lilly, D.k. (1967) Representation of small scale turbulence in numerical simulations, Proc. IBM Scientific Computing Symposium on Environmental Sciences, White Plains, NY.

Mukai, A. Y., Westerink, J. J., Luettich, R. A., and Mark, D. J. (2002). Eastcoast 2001, a tidal constituent database for the western North Atlantic, Gulf of Mexico and Caribbean Sea, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Reynolds, W.C. (1976) Computation of Turbulent flows, Annual Review of Fluid Mechanics, Vol. 8.

Smagorinsky, J.I (1993) Some historical remarks on the use of non linear viscosities, In Large Eddy Simulation of Complex Engineering and Geophysical Flows, Cambridge University Press.

Westerink, J.J., Luettich, R.A.,Jr., and N.W. Scheffner (1993), ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries; Report 3, Development of a Tidal Constituent Database for the Western North Atlantic and Gulf of Mexico, TR DRP-92-6, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.