NEW YORK STATE HURRICANE EVACUATION RESTUDY TECHNICAL DATA REPORT

for New York City, Nassau, Suffolk, and Westchester Counties

2 | HAZARDS ANALYSIS

INTRODUCTION

PURPOSE

The purpose of the hazards analysis is to quantify the still-water surge heights for hurricanes that have a reasonable meteorological probability of occurring in the study area. Freshwater flooding from heavy rainfall accompanying hurricanes is an additional hazard which must be considered.

The primary objective of the hazards analysis is to determine the probable worst-case effects from hurricanes of various intensities that could strike the region. For the purposes of this study, the term worst-case is used to describe the peak surges that can be expected at all locations within the study area without regard to hurricane track.

FORECASTING INACCURACIES

The worst-case approach is used in the hazards analysis because of inaccuracies in forecasting the precise tracks and other parameters of approaching hurricanes. The National Hurricane Center (NHC) has made an analysis of tropical cyclone forecasts to determine the normal magnitude of error. The current average position error in the official 24-hour track forecasts is about 58.2 nautical miles left or right of the forecast track, and an average error of about 34 nautical miles left or right in the 12-hour forecasts.

The average error in the official 24-hour wind speed (intensity) forecasts is about 10 miles per hour (mph), and the average error in the 12-hour official forecasts is about 6.7 mph. Hurricane evacuation decision makers should note that an error no greater than average could raise the intensity value of the approaching

hurricane one category on the Saffir/Simpson Hurricane Scale, which is discussed in the following paragraph. In addition, other factors may work to increase apparent hurricane surge heights above the values calculated by the SLOSH model (see New York State Modeling Process, Adjustments to SLOSH Model Values). Because of potential forecast and modeling inaccuracies, public officials who are faced with an imminent evacuation should consider preparing for a hurricane one category above the forecast intensity.

For more on forecasting inaccuracies, see Table 2-1 and other information on the NHC website.

	0 h		12 h		24 h		36 h		48 h		72 h		96 h		120 h	
	Error	N	Error	N	Error	N	Error	N	Error	N	Error	N	Error	N	Error	N
Atlantic track (n mi)	7.6	1898	34.0	1742	58.2	1574	82.2	1407	106.2	1254	154.2	996	207.5	787	272.5	627
Atlantic intensity (kt)	1.9	1898	6.7	1742	10.0	1574	12.3	1407	14.3	1254	18.2	996	19.7	787	21.8	627
Eastern Pacific track (n mi)	9.2	1428	31.9	1282	55.1	1129	77.4	979	97.9	849	136.2	620	180.1	439	226.1	293
Eastern Pacific intensity (kt)	1.6	1428	6.2	1282	10.4	1129	13.9	979	16.3	848	18.7	620	19.2	439	19.1	293

Notes:
* Verification based on NHC best track database as of 29 January 2008.
** Verification sample is homogeneous with current operational 5-day CLIPER/Decay-SHIFOR (run retrospectively), and includes subtropical cyclones.

Table 2-1: *Average NHC 5-Year Average Forecast Errors (2003-2007) / All Tropical Cyclones*

SAFFIR/SIMPSON HURRICANE SCALE

One of the early guides developed to describe the potential storm surge generated by hurricanes is the Saffir/Simpson Hurricane Scale. Herbert Saffir, Dade County, Florida, Consulting Engineer, and Dr. Robert H. Simpson, former Director of the National Hurricane Center, developed the Saffir/Simpson Scale. Saffir developed the first version of the scale in the late 1960s for a United Nations report on construction that could stand up to high winds. In the early 1970s, Simpson correlated Saffir's wind damage rankings with surge potential to better communicate what a storm is capable of doing, creating the scale used today. The NHC later added a range of central barometric pressures associated with each category of hurricane described by the Saffir/Simpson Scale. The related damage potential of each hurricane category is described in Table 2-2. A condensed version of the Saffir/Simpson Hurricane Scale with the barometric pressure ranges by category is shown in Table 2-3.

Category	Damage
1	Winds of 74 to 95 miles per hour. Damage primarily to shrubbery, trees, foliage, and mobile homes. No real wind damage to other structures. Some damage to poorly constructed signs. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorage torn from moorings.
2	Winds of 96 to 110 miles per hour. Considerable damage to shrubbery and tree foliage; some trees blown down. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofing materials of buildings; some window and door damage. No major wind damage to buildings. Considerable damage could occur to piers. Marinas flooded. Small craft may be torn from moorings.
3	Winds of 111 to 130 miles per hour. Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed. Serious flooding at coast and many smaller structures near coast destroyed; larger structures near coast damaged by battering waves and floating debris.
4	Winds of 131 to 155 miles per hour. Many shrubs and trees are blown down and most street signs are damaged. Extensive damage to roofing materials, windows, and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Major erosion of beaches.
5	Winds greater than 155 miles per hour. Shrubs and trees are blown down; considerable damage to roofs of buildings and all signs are damaged or destroyed. There would be very severe and extensive damage to windows and doors. Complete failure of roofs on many residences and industrial buildings. Extensive shattering of glass in windows and doors would occur. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes.

Table 2-2: *Saffir/Simpson Hurricane Damage Scale*

Category	Central Pressure		Winds		Surge Potential (ft) *	Damage
	Millibars	Inches	(mph)	(kts)		
1	> 980	> 28.9	74-95	64-83	4-5	Minimal
2	965-979	28.50-28.91	96-110	84-96	6-8	Moderate
3	945-964	27.91-28.47	111-130	97-113	9-12	Extensive
4	920-944	27.17-27.88	131-155	114-135	13-18	Extreme
5	< 920	< 27.17	> 155	> 135	> 18	Catastrophic
* Note: Surge Potential is highly dependent upon storm characteristics and local offshore bathymetry.						

Table 2-3: *Saffir/Simpson Hurricane Scale with Central Barometric Pressure Ranges*

STORM SURGE

INTRODUCTION

Storm surge is the abnormal rise in water level caused by extreme wind and pressure forces. Various storm events can cause storm surge, but it is generally the result of a very large scale meteorological disturbance. Along the mid-Atlantic seaboard, extra-tropical storms known as "nor'easters" have produced some of the highest storm surges and resultant damages in recent history. However, hurricanes, because of their vast energy and relative compactness, have the potential to produce much higher storm surges. Storm surges can affect a shoreline over distances of more than 100 miles; however, there may be significant spatial variations in the magnitude of the surge due to local bathymetric (water depth) and topographic features. Wind is the primary cause of storm surge. Wind blowing over the surface of the water exerts a horizontal force that induces a surface current in the general direction of the wind. The surface current, in turn, forms currents in subsurface water. In the case of a hurricane, the depth affected by this process of current creation depends upon the intensity and forward motion of the storm. For example, a fast-moving hurricane of moderate intensity may only induce currents to a depth of a hundred feet, whereas a slow moving hurricane of the same intensity might induce currents to several hundred feet. As the hurricane approaches the coastline, these horizontal currents are impeded by a sloping continental shelf, thereby causing the water level to rise. The amount of rise increases shoreward to a maximum level that is often inland from the usual coastline.

FACTORS AFFECTING SURGE HEIGHT

The elevation reached by the storm surge depends upon the meteorological parameters of the hurricane and the physical characteristics along the coastline. The meteorological parameters affecting the height of the storm surge include the intensity of the hurricane, measured by the storm-center sea-level pressure, track (path) of the storm, forward speed, and radius of maximum winds. This radius, which is measured from the center of the hurricane eye to the location of the highest wind speeds within the storm, can vary from as little as 4 miles to greater than 50 miles. Due to the complementary effects of forward motion and the counterclockwise rotation of the wind field (in the northern hemisphere), highest surges from a hurricane usually occur on the right side of the storm's track in the region of the radius of maximum winds. Peak storm surge may vary drastically within a relatively short distance along the coastline, depending on the radius of maximum winds and the point of hurricane eye landfall. The geophysical characteristics that influence the surge heights include the basin bathymetry, roughness of the continental shelf, configuration of the coastline, and natural or man-made barriers. A wide, gently sloping continental shelf or a large bay may produce particularly large storm surges.

TOTAL FLOOD ELEVATION

Other factors that contribute to the total flood elevation, or storm tide, are the initial water level within the basin at the time the hurricane strikes, and wave effects. Since storm surge increases the water level above the normal astronomical tide, a low-tide event is the best possible timing for landfall, while a high-tide event is the worst. The timing of the arrival of storm surge relative to the astronomical tide cycle is very important in that the difference in total flood elevation can be as much as 8 feet in the study area. This can mean the difference between a moderate flood event and a catastrophe. Output of the Long Island Sound SLOSH model was produced for both mean tide and high tide conditions.

Wave action can also increase the storm tide, and is not accounted for in the SLOSH model's calculations of storm surge. One factor that increases storm tide is a phenomenon known as "wave setup." Waves breaking near the shore transport water shoreward. During severe storms, there is a significant increase in wave height and volume, and water cannot flow back to the sea as rapidly as it comes ashore. This increases the water level along the beachfront. Since waves break and dissipate their energy in shallow water, wave setup allows the waves to move further shoreward than under normal conditions. Also, a relatively steep offshore beach slope allows large ocean waves to get closer to the shore before breaking, resulting in greater wave setup than on a gradually-sloping beach. Since large waves are generally not transmitted inland of the coastline, even if the beach has been overtopped, wave setup is primarily a concern near the beachfront.

Another contributing factor to storm tide is the height of the waves themselves. The SLOSH model does not provide data concerning the additional heights of waves generated on top of the still-water storm surge. Generally, waves do not add significantly to the area flooded and will add little to the number of people that will be required to evacuate. Since near-shore wave phenomena under hurricane conditions are not well understood, it is assumed that for the open coast, maximum theoretical wave heights occur near the time of landfall. Immediately along the coastline or the shorelines of very large sounds and estuaries, wave crests can increase the expected still-water depth above the terrain by one-third, thus greatly increasing the hazard. Due to the presence of barriers such as structures, dunes, or vegetation, the waves break and dissipate a tremendous amount of energy within a few hundred yards of the coastline. Buildings within that zone that are not specifically designed to withstand the forces of wave action are often heavily damaged or destroyed.

Figure 2-1 illustrates the relationship of astronomical tide, storm surge, storm tide and wave height.

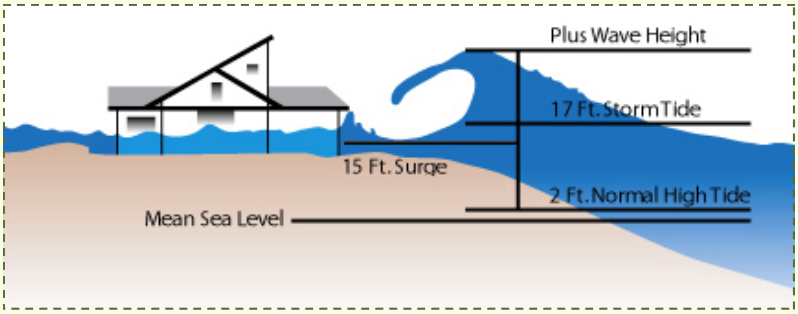

Figure 2-1: *Example of Storm Surge Representation*

THE SLOSH MODEL

GENERAL

The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) numerical storm surge model was developed by the National Weather Service to calculate potential surge heights from hurricanes. To create SLOSH, Jelesnianski and Taylor coupled a hurricane model to a model for storm surge. The SLOSH model was first conceived for real-time forecasting of surges from approaching hurricanes. In addition to computing surge heights for the open coast, the SLOSH model has the added capability to simulate the routing of storm surge

into sounds, bays, estuaries, and coastal river basins, as well as calculating surge heights for overland locations.

Geophysical characteristics of an area covered by a SLOSH model are constructed as input data within the model. These characteristics include the topography of inland areas; river basins and waterways; bathymetry of near-shore areas, sounds, bays, and large inland water-bodies; significant natural and manmade barriers such as barrier islands, dunes, roads, levees, etc.; and a segment of the continental shelf. The SLOSH model simulates inland flooding from storm surge and permits flow through barrier gaps and barrier overtopping.

The SLOSH model uses time-dependent meteorological data to determine the driving forces of a simulated storm. These data are as follows:

(1) Central barometric pressure at 6-hour intervals.

(2) Latitude and longitude of storm positions at 6-hour intervals.

(3) The storm size measured by the radius of maximum winds. Wind speed is not an input parameter, since the model calculates a wind-field for the modeled storm based on meteorological input parameters.

The height of the water surface well before the storm directly affects the area of interest and is also required. This initial height is the observed water surface elevation occurring about 2 days before storm arrival. In addition to mean tide, astronomical high tide was also set in the model.

The Long Island Sound SLOSH model was used for the *New York State Hurricane Evacuation Restudy TDR*. After being initialized with observed geophysical values (depths of water and heights of terrain and barriers), the SLOSH model output provides heights of storm surge for various combinations of hurricane strength, forward speed, and approach direction. Storm strength is modeled using the minimum central pressure and radius of maximum winds for four of the five categories of storm intensity. Because of their extremely low chance of occurrence, Category 5 hurricanes were not modeled. Six storm track headings and up to six approach speeds were selected as being representative of storm behavior in this region.

SLOSH GRID CONFIGURATION

Figure 2-2 illustrates the area covered by the grid for the Long Island Sound SLOSH model. The area covered by the grid is called a “basin;” in this case the Long Island Sound Basin. The Long Island Sound Basin covers the Atlantic coastline from Cape May, New Jersey, to Cape Cod, Massachusetts. The grid is a telescoping polar coordinate (fan-shaped) grid system with 90 arc lengths and 83 radials. The pole of the grid is located at 40 degrees, 43 minutes, 20 seconds N and 74 degrees, 20 minutes, 30 seconds W. The advantage of this grid system is that it offers good resolution in areas of primary interest, while conserving computer resources by minimizing the number of calculations in areas of secondary interest. Telescoping grids are used to put more grid cells over land for good surge delineation, but they also include a large area offshore for adequate surge calculations. As shown in Figure 2-2, the grid squares constantly expand in size and become

progressively larger farther from the coastline. The resolution of the model for inland locations near the pole (or origin) is approximately 0.1 square mile per grid square, and increases to approximately 106 square miles at the outer fringe. The fine resolution toward the pole permits the inclusion of topographic details such as highways, railroad embankments, causeways, and levees, as well as more detailed emulation of constraints and obstructions to water flow in rivers, bays, and harbors.

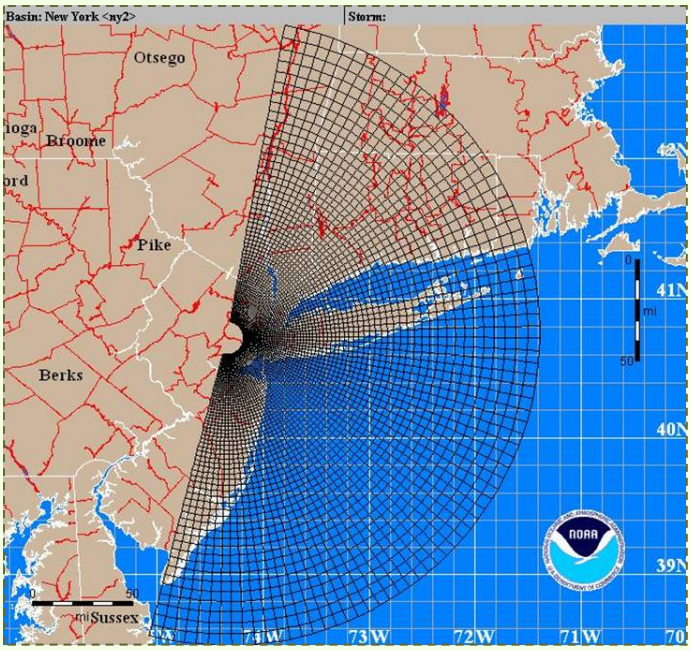

Figure 2-2: *SLOSH Grid for New York*

VERIFICATION OF THE MODEL

After a SLOSH model has been constructed for a coastal basin, verification is conducted as real-time operational runs in which available meteorological data from historical storms are input into the model. The computed surge heights are compared with those measured from the historical storms and, if necessary, adjustments are made to the input or basin data. These adjustments are not made to force agreements between computed and measured surge heights from historical storms but to more accurately represent the basin characteristics or historical storm parameters. In instances where the model has given realistic results in one area of a basin, but not in another, closer examination has often revealed inaccuracies in the representation of barrier heights or missing values in bathymetric or topographic data.

MODEL OUTPUT

The SLOSH model output for a modeled storm consists of envelopes of high water, and contains the maximum surge height values calculated for each grid point in the model. Maximum surges along the coastline do not necessarily occur at the same time. The time of the maximum surge for one location may differ by several hours from the maximum surge that occurs at another location. Therefore, at each grid point, the water height value shown is the maximum that was computed at that point during the 72 hours of model time, irrespective of the time during the simulation that the maximum surge height occurred. The datum used in the model is National Geodetic Vertical Datum (NGVD), formerly known as mean sea level of 1929 (MSL).

Time-history data of surge heights, wind speeds, and wind directions are tabulated in the model. These data are listed at 30-minute intervals for a 72-hour segment of a simulated storm track, starting 48 hours prior to landfall and continuing for 24 hours after landfall or closest approach. The surge heights are in feet, the wind speeds in statute miles per hour, and the wind directions in azimuths from which the wind is blowing. Table 2-4 provides maximum surge height information for 100 critical grid points that were selected for the study area. Since that time, SLOSH calculation methods and the geophysical input has been updated. In Table 2-4,

the latest (year 2000) computed mean tide and high tide values are compared to the 1987 SLOSH results used in the original New York State HES, 1993.

The SLOSH model time-history values for the Battery on the southern tip of Manhattan Island were analyzed for hypothetical storm surge rate-of-rise. The time-history analysis shows that the maximum rate of rise could vary from 6 feet per hour for a Category 1 hurricane to 17 feet per hour for a Category 4 storm. The implication of these rates is that the rapidly rising flood waters could trap initial victims and rescuers alike. Life-threatening situations in the roadway tunnels and throughout the rail tunnel network can be avoided only by making timely decisions to close and evacuate affected facilities prior to the onset of the flood event. Stringent measures should be used to prevent the public from taking shelter in these facilities.

Table 2-4: *Maximum Surge Height in Feet Above NGVD*

	Location	1987 Slosh Surge Heights				2000 Slosh Surge Heights							
		Mean Tide				Mean Tide				High Tide			
		Hurricane Saffir/Simpson Category											
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
1.	Monmouth Beach	6.2	10.2	13.8	17.4	6.0	10.0	13.9	17.6	8.5	12.4	16.1	19.5
	Differs from '87					**-0.2**	**-0.2**	**+0.1**	**+0.2**	**+2.3**	**+2.2**	**+2.3**	**+2.1**
2.	Sandy Hook	7.7	12.3	16.5	21.7	7.6	12.3	16.0	21.1	10.0	14.1	18.7	23.5
	Differs from '87					**-0.1**	**0**	**-0.5**	**-0.6**	**+2.3**	**+1.8**	**+2.2**	**+1.8**
3.	Keansburg	9.7	15.6	20.8	26.2	9.2	14.8	20.3	25.2	11.8	17.0	22.7	27.4
	Differs from '87					**-0.5**	**-0.8**	**-0.5**	**-1.0**	**+2.1**	**+1.4**	**+1.9**	**+1.2**
4.	Keyport Harbor	10.3	16.6	22.4	27.4	9.7	15.7	21.3	25.7	12.3	18.1	23.5	28.0
	Differs from '87					**-0.6**	**-0.9**	**-1.1**	**-1.7**	**+2.0**	**+1.5**	**+1.1**	**+0.6**
5.	Sayreville	8.2	11.6	17.1	27.8	7.6	12.7	18.5	30.5	9.7	14.7	22.1	33.2
	Differs from '87					**-0.6**	**+1.1**	**+1.4**	**+2.7**	**+1.5**	**+3.1**	**+5.0**	**+5.4**
6.	Amboy	10.8	18.7	23.8	26.9	10.1	16.7	23.0	26.6	12.5	19.7	24.1	29.2
	Differs from '87					**-0.7**	**-2.0**	**-0.8**	**-0.3**	**+1.7**	**+1.0**	**+0.3**	**+2.3**
7.	Victory Bridge	10.7	18.0	19.7	24.9	9.8	17.6	19.9	27.0	12.8	19.2	21.2	29.6
	Differs from '87					**-0.9**	**-0.4**	**+0.2**	**+2.1**	**+2.1**	**+1.2**	**+0.5**	**+4.7**
8.	Tottenville	10.4	20.0	23.2	26.9	9.9	17.6	22.1	26.6	12.2	21.2	24.0	29.1
	Differs from '87					**-0.5**	**-2.4**	**-1.1**	**-0.3**	**+1.8**	**+1.2**	**+0.8**	**+2.2**
9.	Woodbridge	10.0	12.5	19.3	21.9	9.7	13.8	19.1	21.5	11.4	17.8	20.9	22.6
	Differs from '87					**-0.3**	**+1.3**	**-0.2**	**-0.4**	**+1.4**	**+5.3**	**+1.6**	**+0.7**
10.	Fresh Kills Landfill	8.6	10.5	12.8	24.0	17.3	8.7	11.5	14.5	22.1	10.8	13.5	16.4
	Differs from '87					**+0.1**	**+1.0**	**+1.7**	**+4.8**	**+2.2**	**+3.0**	**+3.6**	**+6.7**
11.	Travis	9.0	10.5	14.3	17.7	8.9	11.1	14.6	20.1	10.7	12.9	16.4	22.2
	Differs from '87					**-0.1**	**+0.6**	**+0.3**	**+2.4**	**+1.7**	**+2.4**	**+2.1**	**+4.5**
12.	Linden	9.0	10.6	14.3	18.0	8.8	11.2	14.9	20.2	10.7	13.0	16.5	22.5
	Differs from '87					**-0.2**	**+0.6**	**+0.6**	**+2.2**	**+1.7**	**+2.4**	**+2.2**	**+4.5**
13.	Goethals Bridge	8.9	10.7	14.4	17.8	8.8	11.3	15.0	20.1	10.6	13.0	16.5	22.3
	Differs from '87					**-0.1**	**+0.6**	**+0.6**	**+2.3**	**+1.7**	**+2.3**	**+2.1**	**+4.5**
14.	Elizabeth	8.4	10.3	13.6	17.2	8.2	10.7	14.3	19.3	10.2	12.6	15.9	21.6
	Differs from '87					**-0.2**	**+0.4**	**+0.7**	**+2.1**	**+1.8**	**+2.3**	**+2.3**	**+3.4**
15.	Newark Bay Bridge	7.1	9.1	11.8	15.0	7.3	9.3	12.8	17.2	9.2	11.2	14.8	19.0
	Differs from '87					**+0.2**	**+0.2**	**+1.0**	**+2.2**	**+2.1**	**+2.1**	**+3.0**	**+4.0**
16.	US 1 @ Passaic River	7.4	9.2	11.9	17.9	14.0	7.2	9.3	12.6	16.2	8.7	11.3	14.2
	Differs from '87					**-0.2**	**+0.1**	**+0.7**	**+2.2**	**+1.3**	**+2.1**	**+2.3**	**+3.9**
17.	Passaic River	8.5	10.0	13.4	15.9	8.1	10.2	13.4	19.6	9.0	11.8	14.9	21.2
	Differs from '87					**-0.4**	**+0.2**	**0**	**+3.7**	**+0.5**	**+1.8**	**+1.5**	**+5.3**

Table 2-4: *Maximum Surge Height in Feet Above NGVD (continued)*

	Location	1987 Slosh Surge Heights				2000 Slosh Surge Heights							
		Mean Tide				Mean Tide				High Tide			
		Hurricane Saffir/Simpson Category											
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
18.	Pulaski Skyway	6.8	9.0	11.8	14.4	6.9	9.2	12.6	16.1	8.6	11.6	14.7	17.9
	Differs from '87					**+0.1**	**+0.2**	**+0.8**	**+1.7**	**+1.8**	**+2.6**	**+2.9**	**+3.5**
19.	N.J. Turnpike	6.9	7.4	8.5	12.2	6.1	7.6	9.0	15.4	7.8	8.9	11.0	17.5
	Differs from '87					**-0.8**	**+0.2**	**+0.5**	**+3.2**	**+0.9**	**+1.5**	**+2.5**	**+5.3**
20.	Route 3	5.2	6.3	7.7	11.4	5.5	7.0	8.4	15.3	7.2	8.4	10.2	17.4
	Differs from '87					**+0.3**	**+0.7**	**+0.7**	**+3.9**	**+2.0**	**+2.1**	**+2.5**	**+6.0**
21.	Ridgefield Park	Dry	Dry	Dry	9.9	Dry	Dry	8.3	16.1	Dry	Dry	8.9	17.5
	Differs from '87					**Dry**	**Dry**	**+NA**	**+6.2**	**Dry**	**Dry**	**NA**	**+7.6**
22.	Palisades Park	Dry	Dry	Dry	9.2	Dry	Dry	7.3	16.3	Dry	7.0	8.2	17.9
	Differs from '87					**Dry**	**Dry**	**Dry**	**+7.1**	**Dry**	**NA**	**NA**	**+8.7**
23.	Stapleton	9.9	15.4	21.1	26.0	9.8	15.4	21.2	26.2	11.8	17.6	23.2	28.2
	Differs from '87					**-0.1**	**0**	**+0.1**	**+0.2**	**+1.9**	**+2.2**	**+2.1**	**+2.2**
24.	St. George	10.0	16.0	22.0	26.7	9.8	15.8	21.8	27.2	11.9	17.6	24.1	28.6
	Differs from '87					**-0.2**	**-0.2**	**-0.2**	**+0.5**	**+1.9**	**+1.6**	**+2.1**	**+1.9**
25.	Bayonne	9.2	12.5	19.3	27.9	8.9	13.9	19.4	26.1	10.5	15.5	23.4	27.4
	Differs from '87					**-0.3**	**+1.4**	**+0.1**	**-1.8**	**+1.3**	**+3.0**	**+4.1**	**-0.5**
26.	Bush Terminal	10.4	15.7	22.3	27.6	10.2	15.8	22.2	28.1	12.2	17.9	24.2	29.6
	Differs from '87					**-0.2**	**+0.1**	**-0.1**	**+0.5**	**+1.8**	**+2.1**	**+1.9**	**+2.0**
27.	Liberty Island	10.3	15.7	22.8	28.0	10.0	15.8	22.6	28.4	12.1	17.9	24.4	29.9
	Differs from '87					**-0.3**	**+0.1**	**-0.2**	**+0.4**	**+1.8**	**+2.2**	**+1.6**	**+1.9**
28.	Battery	10.5	16.6	23.9	28.7	10.1	16.4	22.6	28.7	12.1	18.3	24.8	30.4
	Differs from '87					**-0.4**	**-0.2**	**-1.3**	**0**	**+1.6**	**+1.7**	**+0.9**	**+1.7**
29.	Lincoln Tunnel	7.5	17.2	20.5	30.8	8.1	15.2	26.2	27.9	10.4	15.8	26.7	29.4
	Differs from '87					**+0.6**	**-2.0**	**+5.7**	**-2.9**	**+2.9**	**-1.4**	**+6.2**	**-1.4**
30.	W 96th Street	8.2	15.0	17.7	28.1	8.0	14.2	21.6	27.6	9.8	15.0	22.4	28.5
	Differs from '87					**-0.2**	**-0.8**	**+3.9**	**-0.5**	**+1.6**	**0**	**+4.7**	**+0.4**
31.	George Washington Bridge	6.9	14.1	16.8	26.7	7.2	13.1	18.4	26.3	9.2	14.1	20.0	27.0
	Differs from '87					**+0.3**	**-1.0**	**+1.6**	**-0.4**	**+2.3**	**0**	**+3.2**	**+0.3**
32.	Spuyten Duyvil	6.1	13.0	14.8	24.6	6.5	12.1	17.5	23.7	8.5	12.9	18.0	24.4
	Differs from '87					**+0.4**	**-0.9**	**+2.7**	**-0.9**	**+2.4**	**-0.1**	**+3.2**	**-0.2**
33.	City Line	5.5	11.6	13.4	22.5	5.8	10.7	15.5	21.4	7.8	11.8	16.6	22.7
	Differs from '87					**+0.3**	**-0.9**	**+2.1**	**-1.1**	**+2.3**	**+0.2**	**+3.2**	**+0.2**
34.	Tappan	4.6	9.5	10.5	17.5	4.5	8.8	12.8	17.2	6.6	10.4	14.2	18.8
	Differs from '87					**-0.1**	**-0.7**	**+2.3**	**-0.3**	**+2.0**	**+0.9**	**+3.7**	**+1.3**

Table 2-4: *Maximum Surge Height in Feet Above NGVD (continued)*

	Location	1987 Slosh Surge Heights				2000 Slosh Surge Heights							
		Mean Tide				Mean Tide				High Tide			
		Hurricane Saffir/Simpson Category											
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
35.	Ossining	2.9	7.6	8.7	14.6	3.4	6.4	9.4	13.7	5.7	8.5	11.4	15.7
	Differs from '87					**+0.5**	**-1.2**	**+0.7**	**-0.9**	**+2.8**	**+0.9**	**+2.7**	**+0.9**
36.	Peekskill/Indian Point	2.0	6.6	7.8	13.7	3.6	6.8	10.3	15.3	5.9	8.9	12.3	17.3
	Differs from '87					**+1.6**	**+0.2**	**+2.5**	**+1.6**	**+3.9**	**+2.3**	**+4.5**	**+3.6**
37.	Manhattan Bridge	10.1	15.8	22.4	25.6	10.0	15.7	22.8	26.2	12.2	18.0	24.6	28.2
	Differs from '87					**-0.1**	**-0.1**	**+0.4**	**+0.6**	**+2.1**	**+2.2**	**+2.2**	**+2.6**
38.	Newtown Creek	9.6	14.4	21.0	23.6	9.5	14.8	20.7	25.8	12.1	17.7	23.3	28.5
	Differs from '87					**-0.1**	**+0.4**	**-0.3**	**+2.2**	**+2.5**	**+3.3**	**+2.3**	**+4.9**
39.	Hellgate	7.9	11.7	14.9	18.1	7.8	12.0	16.0	25.4	11.4	15.7	19.5	27.0
	Differs from '87					**-0.1**	**+0.3**	**+1.1**	**+7.3**	**+3.5**	**+4.0**	**+4.6**	**+8.9**
40.	La Guardia	6.4	11.2	15.7	20.8	6.5	11.6	16.6	21.5	10.5	15.7	20.2	26.1
	Differs from '87					**+0.1**	**+0.4**	**+0.9**	**+0.7**	**+4.1**	**+4.5**	**+4.5**	**+5.7**
41.	Flushing Bay	6.6	11.6	16.3	20.9	6.6	11.9	17.3	20.1	10.6	15.9	20.5	24.0
	Differs from '87					**0**	**+0.3**	**+1.0**	**-0.8**	**+4.0**	**+4.3**	**+4.2**	**+3.1**
42.	Whitestone (Bronx)	6.5	11.3	16.6	26.3	22.2	6.7	11.8	18.6	22.7	10.7	15.8	21.1
	Differs from '87					**+0.2**	**+0.5**	**+2.0**	**+0.5**	**+4.2**	**+4.5**	**+3.5**	**+4.1**
43.	Pelham Bay	6.4	11.6	17.5	22.4	6.9	12.1	19.2	21.8	10.9	16.1	21.5	25.9
	Differs from '87					**+0.5**	**+0.5**	**+1.7**	**-0.6**	**+4.5**	**+4.5**	**+4.0**	**+3.5**
44.	Willets Point	6.3	11.4	18.3	23.0	6.7	11.7	19.9	22.1	10.7	15.7	22.3	26.5
	Differs from '87					**+0.4**	**+0.3**	**+1.6**	**-0.9**	**+4.4**	**+4.3**	**+4.0**	**+3.5**
45.	City Island	6.3	11.5	17.3	22.2	6.7	11.7	17.2	21.6	10.8	15.8	20.6	25.5
	Differs from '87					**+0.4**	**+0.2**	**-0.1**	**-0.6**	**+4.5**	**+4.1**	**+3.3**	**+3.3**
46.	Manorhaven	6.5	11.7	17.8	22.7	6.8	11.7	17.2	22.0	10.8	15.7	21.4	26.5
	Differs from '87					**+0.3**	**0**	**-0.6**	**-0.7**	**+4.3**	**+4.0**	**+3.6**	**+3.8**
47.	Sands Point	6.1	11.1	16.3	21.5	6.6	11.5	16.5	21.0	10.6	15.5	20.3	25.0
	Differs from '87					**+0.5**	**+0.4**	**+0.2**	**-0.5**	**+4.5**	**+4.4**	**+4.0**	**+3.5**
48.	Roslyn	6.2	11.3	16.5	21.8	6.5	11.3	16.3	21.1	10.6	15.3	20.3	25.4
	Differs from '87					**+0.3**	**0**	**-0.2**	**-0.7**	**+4.4**	**+4.0**	**+3.8**	**+3.6**
49.	Glen Cove	6.0	10.9	16.0	21.0	6.4	11.2	16.0	20.5	10.5	15.2	20.1	24.6
	Differs from '87					**+0.4**	**+0.3**	**0**	**-0.5**	**+4.5**	**+4.3**	**+4.1**	**+3.6**
50.	Mill Neck	5.7	10.3	15.2	19.8	6.0	10.3	14.9	19.5	10.0	14.2	18.9	23.3
	Differs from '87					**+0.3**	**0**	**-0.3**	**-0.3**	**+4.3**	**+3.9**	**+3.7**	**+3.5**
51.	Centre Island	5.7	10.3	15.2	19.8	5.9	10.3	14.9	19.4	9.8	14.3	18.9	23.3
	Differs from '87					**+0.2**	**0**	**-0.3**	**-0.4**	**+3.1**	**+4.0**	**+3.7**	**+3.5**

Table 2-4: *Maximum Surge Height in Feet Above NGVD (continued)*

	Location	1987 Slosh Surge Heights				2000 Slosh Surge Heights							
		Mean Tide				Mean Tide				High Tide			
		Hurricane Saffir/Simpson Category											
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
52.	Cold Spring Harbor	5.7	10.3	15.1	23.2	19.8	5.9	10.3	15.0	19.5	9.8	14.4	18.9
	Differs from '87					**+0.2**	**0**	**-0.1**	**-0.3**	**+4.2**	**+4.1**	**+3.8**	**+3.4**
53.	Northport Bay	5.4	9.8	13.7	18.1	5.9	10.1	13.9	18.0	9.7	14.1	17.8	21.9
	Differs from '87					**+0.5**	**+0.3**	**+0.2**	**-0.1**	**+4.3**	**+4.3**	**+4.1**	**+3.8**
54.	Asharoken	5.2	9.3	13.6	18.0	5.4	9.6	13.8	18.0	9.2	13.3	17.6	21.7
	Differs from '87					**+0.2**	**+0.3**	**+0.2**	**0**	**+4.0**	**+4.0**	**+4.0**	**+3.7**
55.	Port Jefferson	5.0	9.0	13.1	17.3	5.2	9.1	13.1	17.0	8.8	12.7	16.8	20.7
	Differs from '87					**+0.2**	**+0.1**	**0**	**-0.3**	**+3.8**	**+3.7**	**+3.7**	**+3.4**
56.	Shoreham	4.6	8.1	11.8	15.5	4.8	8.2	11.9	15.4	8.1	11.6	15.3	18.8
	Differs from '87					**+0.2**	**+0.1**	**+0.1**	**-0.1**	**+3.5**	**+3.5**	**+3.5**	**+3.3**
57.	Mattituck	4.3	7.6	11.0	14.6	4.5	7.8	11.3	14.6	7.4	10.7	14.2	17.6
	Differs from '87					**+0.2**	**+0.2**	**+0.3**	**0**	**+3.1**	**+3.1**	**+3.2**	**+3.0**
58.	Orient	4.5	7.4	10.4	13.4	4.4	7.3	10.2	13.1	5.9	8.7	11.6	14.6
	Differs from '87					**-0.1**	**-0.1**	**-0.2**	**-0.3**	**+1.4**	**+1.3**	**+1.2**	**+1.2**
59.	Shelter Island	5.1	8.5	12.0	15.5	4.9	8.2	11.6	14.9	6.4	9.7	13.0	16.4
	Differs from '87					**-0.2**	**-0.3**	**-0.4**	**-0.6**	**+1.3**	**+1.2**	**+1.0**	**+0.9**
60.	Jamesport	3.8	6.8	10.2	13.8	3.9	6.9	10.3	13.9	5.6	8.7	12.3	15.9
	Differs from '87					**+0.1**	**+0.1**	**+0.1**	**+0.1**	**+1.8**	**+1.8**	**+2.1**	**+2.1**
61.	Ward Point	10.7	17.5	23.2	27.6	10.1	16.3	22.2	26.8	12.6	18.8	24.1	29.3
	Differs from '87					**-0.6**	**-1.2**	**-1.0**	**-0.8**	**+1.9**	**+1.3**	**+0.9**	**+1.7**
62.	Huguenot	10.2	16.6	22.1	27.4	9.7	15.6	21.7	26.5	12.1	17.9	23.7	28.9
	Differs from '87					**-0.5**	**-1.0**	**-0.4**	**-0.9**	**+1.9**	**+1.3**	**+1.6**	**+1.5**
63.	Great Kill	10.1	15.9	21.2	27.1	9.6	15.3	21.0	26.4	12.2	17.4	23.4	28.6
	Differs from '87					**-0.5**	**-0.6**	**-0.2**	**-0.7**	**+2.1**	**+1.5**	**+2.2**	**+1.5**
64.	Oakwood Beach	9.7	15.7	21.0	27.0	9.2	15.1	20.7	26.2	11.7	17.2	23.1	28.4
	Differs from '87					**-0.5**	**-0.6**	**-0.3**	**-0.8**	**+2.0**	**+1.5**	**+2.1**	**+1.4**
65.	Midland Beach	9.4	15.3	20.7	26.8	9.0	14.9	20.2	25.9	11.5	17.0	22.5	28.3
	Differs from '87					**-0.4**	**-0.4**	**-0.5**	**-0.9**	**+2.1**	**+1.3**	**+1.8**	**+1.5**
66.	South Beach	9.1	15.0	20.4	26.4	8.8	14.6	20.0	25.5	11.3	16.7	22.4	28.1
	Differs from '87					**-0.3**	**-0.4**	**-0.4**	**-0.9**	**+2.2**	**+1.7**	**+2.0**	**+1.7**
67.	Fort Hamilton	9.3	15.2	20.9	27.0	8.9	14.5	20.0	25.6	11.4	16.7	22.4	28.2
	Differs from '87					**-0.4**	**-0.7**	**-0.9**	**-1.4**	**+2.1**	**+1.5**	**+1.5**	**+1.2**
68.	Gravesend Bay	9.2	15.2	20.8	27.2	8.9	14.6	20.3	26.3	11.4	16.8	22.8	28.7
	Differs from '87					**-0.3**	**-0.6**	**-0.5**	**-0.9**	**+2.2**	**+1.6**	**+2.0**	**+1.5**

Table 2-4: *Maximum Surge Height in Feet Above NGVD (continued)*

	Location	1987 Slosh Surge Heights				2000 Slosh Surge Heights							
		Mean Tide				Mean Tide				High Tide			
		Hurricane Saffir/Simpson Category											
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
69.	Seagate	9.1	15.0	20.5	26.4	8.8	14.4	19.8	25.4	11.3	16.5	22.3	27.8
	Differs from '87					**-0.3**	**-0.6**	**-0.7**	**-1.0**	**+2.2**	**+1.5**	**+1.8**	**+1.4**
70.	Sheepshead Bay	7.8	15.1	21.0	27.4	7.6	14.6	20.8	26.5	10.4	16.4	23.2	29.1
	Differs from '87					**-0.2**	**-0.5**	**-0.2**	**-0.9**	**+2.6**	**+1.3**	**+2.2**	**+1.7**
71.	Floyd Bennett	6.7	14.0	21.7	28.5	6.4	14.0	21.4	27.7	8.7	17.4	24.1	30.3
	Differs from '87					**-0.3**	**0**	**-0.3**	**-0.8**	**+2.0**	**+3.4**	**+2.4**	**+1.8**
72.	Pennsylvania Ave.	6.2	15.7	25.0	31.3	6.3	14.8	24.2	30.6	8.9	18.8	26.9	32.9
	Differs from '87					**+0.1**	**-0.9**	**-0.8**	**-0.7**	**+2.7**	**+3.1**	**+1.9**	**+1.6**
73.	Kennedy	6.6	15.6	24.5	31.2	6.7	14.6	24.0	30.8	9.4	18.7	26.7	33.1
	Differs from '87					**+0.1**	**-1.0**	**-0.5**	**-0.4**	**+2.8**	**+3.1**	**+2.2**	**+0.9**
74.	Breezy Point	9.1	14.3	20.0	25.9	8.9	14.0	19.7	25.2	11.1	16.0	22.3	27.7
	Differs from '87					**-0.2**	**-0.3**	**-0.3**	**-0.7**	**+2.0**	**+1.7**	**+2.3**	**+1.8**
75.	Rockaway Beach	9.1	14.0	20.4	26.6	9.1	14.0	20.2	26.0	11.4	16.6	22.9	28.5
	Differs from '87					**0**	**0**	**-0.2**	**-0.6**	**+2.3**	**+2.6**	**+2.5**	**+1.9**
76.	East Rockaway Inlet	9.0	14.8	20.0	27.4	25.2	8.9	14.6	19.7	24.9	11.1	16.4	22.1
	Differs from '87					**-0.1**	**-0.2**	**-0.3**	**-0.3**	**+2.1**	**+1.6**	**+2.1**	**+2.2**
77.	Lawrence	6.7	15.7	20.4	25.4	6.2	15.2	20.0	25.1	11.3	17.2	22.3	27.6
	Differs from '87					**-0.5**	**-0.5**	**-0.4**	**-0.3**	**+4.6**	**+1.5**	**+1.9**	**+2.2**
78.	Long Beach	8.7	15.5	20.1	24.8	8.6	15.1	19.7	24.5	11.0	17.2	21.7	26.9
	Differs from '87					**-0.1**	**-0.4**	**-0.4**	**-0.3**	**+2.3**	**+1.7**	**+1.6**	**+2.1**
79.	Island Park	8.3	16.0	21.0	25.7	5.5	15.6	20.7	25.5	10.9	17.5	22.3	27.4
	Differs from '87					**-2.8**	**-0.4**	**-0.3**	**-0.2**	**+2.6**	**+1.5**	**+1.3**	**+1.7**
80.	East Rockaway	6.1	17.0	22.1	26.9	5.4	16.3	21.5	26.7	11.6	18.7	23.7	29.2
	Differs from '87					**-0.7**	**-0.7**	**-0.6**	**-0.2**	**+5.5**	**+1.7**	**+1.6**	**+2.3**
81.	Oceanside	Dry	16.7	23.0	28.3	Dry	16.1	22.1	27.5	10.1	17.6	23.9	28.4
	Differs from '87					**Dry**	**-0.6**	**-0.9**	**-0.8**	**NA**	**+0.9**	**+0.9**	**+0.1**
82.	Jones Beach	8.4	13.8	19.1	24.1	8.3	13.7	19.2	23.4	9.9	15.7	21.2	25.5
	Differs from '87					**-0.1**	**-0.1**	**-0.1**	**-0.7**	**+1.5**	**+1.9**	**+2.1**	**+1.4**
83.	Loop Parkway	7.7	14.9	21.0	26.3	7.6	14.7	20.9	25.7	9.4	16.1	22.3	26.8
	Differs from '87					**-0.1**	**-0.2**	**-0.1**	**-0.6**	**+1.7**	**+1.2**	**+1.3**	**+0.5**
84.	Freeport	Dry	14.9	23.2	29.4	Dry	14.7	22.3	28.2	Dry	16.6	24.2	29.6
	Differs from '87					**NA**	**-0.2**	**-0.9**	**-1.2**	**NA**	**+1.7**	**+1.0**	**+0.2**
85.	Wantagh Parkway	2.3	13.3	20.5	27.0	2.5	12.7	20.5	26.2	4.2	15.7	22.0	28.1
	Differs from '87					**+0.2**	**-0.6**	**0**	**-0.8**	**+1.9**	**+2.4**	**+1.5**	**+1.1**

Table 2-4: *Maximum Surge Height in Feet Above NGVD (continued)*

	Location	1987 Slosh Surge Heights				2000 Slosh Surge Heights							
		Mean Tide				Mean Tide				High Tide			
		Hurricane Saffir/Simpson Category											
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
86.	Gilgo Beach	8.0	13.6	17.3	23.5	7.8	13.2	17.3	23.5	9.7	14.8	19.6	25.8
	Differs from '87					**-0.2**	**-0.4**	**0**	**0**	**+1.7**	**+1.2**	**+2.3**	**+2.3**
87.	Amityville	2.5	8.7	19.7	26.8	2.1	8.3	19.1	25.6	3.9	12.2	21.3	27.6
	Differs from '87					**-0.4**	**-0.4**	**-0.6**	**-1.2**	**+1.4**	**+3.5**	**+1.6**	**+0.8**
88.	West Islip	3.2	8.4	15.9	22.6	2.3	7.6	15.4	22.7	4.0	10.5	18.4	24.1
	Differs from '87					**-0.9**	**-0.8**	**-0.5**	**+0.1**	**+0.8**	**+2.1**	**+2.5**	**+1.5**
89.	Atlantique	6.8	11.4	15.4	19.8	6.6	11.2	15.1	19.1	8.6	12.9	17.2	20.8
	Differs from '87					**-0.2**	**-0.2**	**-0.3**	**-0.7**	**+1.8**	**+1.5**	**+1.8**	**+1.0**
90.	Davis Park	6.5	11.3	15.9	19.6	6.4	11.1	15.6	19.3	8.3	13.0	17.3	20.2
	Differs from '87					**-0.1**	**-0.2**	**-0.3**	**-0.3**	**+1.8**	**+1.7**	**+1.4**	**+0.6**
91.	Patchogue	2.4	4.8	9.2	15.1	1.6	4.6	9.8	15.6	3.3	7.3	13.5	17.6
	Differs from '87					**-0.8**	**-0.2**	**+0.6**	**+0.5**	**+0.9**	**+2.5**	**+4.3**	**+2.5**
92.	Smith Pt./Moriches	19.3	6.2	10.6	14.8	18.2	6.1	10.5	14.7	18.0	7.8	12.2	16.1
	Differs from '87					**-0.1**	**-0.1**	**-0.1**	**-0.2**	**+1.6**	**+1.6**	**+1.3**	**+1.1**
93.	Center Moriches	5.5	9.7	13.2	19.7	5.3	9.7	13.2	18.0	7.0	11.0	15.1	20.5
	Differs from '87					**-0.2**	**0**	**0**	**-1.7**	**+1.5**	**+1.3**	**+1.9**	**+0.8**
94.	West Hampton	6.0	10.4	14.1	18.1	5.9	10.3	14.0	17.8	7.4	11.7	15.4	19.4
	Differs from '87					**-0.1**	**-0.1**	**-0.1**	**-0.3**	**+1.4**	**+1.3**	**+1.3**	**+1.3**
95.	Mecox	5.7	9.9	14.0	17.9	5.6	9.7	13.7	17.4	7.0	11.1	15.1	18.8
	Differs from '87					**-0.1**	**-0.2**	**-0.3**	**-0.5**	**+1.3**	**+1.2**	**+1.1**	**+0.9**
96.	Napeague	5.2	8.9	12.6	16.2	5.0	8.7	12.3	15.5	6.5	10.1	13.7	16.9
	Differs from '87					**-0.2**	**-0.2**	**-0.3**	**-0.7**	**+1.3**	**+1.2**	**+1.1**	**+0.7**
97.	Montauk Point	4.9	7.9	10.7	13.5	5.0	8.2	11.2	14.2	6.4	9.5	12.5	15.5
	Differs from '87					**+0.1**	**+0.3**	**+0.5**	**+0.7**	**+1.5**	**+1.6**	**+1.8**	**+2.0**
98.	New Rochelle	6.1	11.2	16.4	21.5	6.7	11.7	16.8	21.3	10.7	15.7	20.6	25.4
	Differs from '87					**+0.6**	**+0.5**	**+0.4**	**-0.2**	**+4.6**	**+4.5**	**+4.2**	**+3.9**
99.	Mamaroneck Harbor	6.0	11.0	15.9	21.0	6.6	11.6	16.3	20.9	10.6	15.4	20.4	25.0
	Differs from '87					**+0.6**	**+0.6**	**+0.4**	**-0.1**	**+4.6**	**+4.4**	**+4.5**	**+4.0**
100.	Port Chester	5.8	10.6	15.6	20.5	6.4	11.1	15.8	20.4	10.4	15.1	20.0	24.5
	Differs from '87					**+0.6**	**+0.5**	**+0.2**	**-0.1**	**+4.6**	**+4.5**	**+4.4**	**+4.0**

NEW YORK STATE MODELING PROCESS

SIMULATED HURRICANES

A total of 3,872 hypothetical hurricanes were modeled for the New York State Hurricane Evacuation Restudy, 1936 at mean tide, and 1936 at high tide. The characteristics of the simulated hurricanes were determined from an analysis of historical hurricanes that have occurred within the study area. The parameters selected for the modeled storms were the intensities, forward speeds, approach directions, and radii of maximum winds that are considered to have the highest meteorological probability of occurrence within the Long Island Sound Basin.

The initial sea surface height set in the Long Island Sound SLOSH model for mean sea level conditions was 1.0 foot above NGVD. This initial height, known as tide anomaly, represents the height of the water surface above MSL existing several days in advance of approaching hurricanes. The value for the tide anomaly used in the SLOSH model represents the average sea surface height recorded at tide gauges for historical hurricanes prior to landfall.

Emulating conditions at high tide presented some difficulties. In this region, the tide range on the Atlantic coast is about 3 feet near Montauk Point, on Long Island's eastern tip, but increases to about 5 feet at Coney Island, near the island's western end. Inside Long Island Sound, the tide range also increases westward, with a maximum range of about 8 feet near La Guardia Airport and the upper East River. Both the lower and upper New York Harbor have tide ranges of about 5 feet, while the Hudson River has a range of about 3-4 feet as far upriver as Albany.

Therefore, simulations of storm surge for high tide required that each of the 1,936 runs for mean tide be run a second time. The initial datum was +2.5 feet NGVD (one-half of the tide range of 3 feet, plus the 1.0 foot NGVD noted above), which should simulate high tide in the basin's Atlantic coastal region. The following processes were applied to the results: water height was incrementally raised, with values that gradually increased, up to about 4 feet (one-half of the 8 foot range) in the Sound's western end, and up to about 2.5 feet offshore of Coney Island. These values added height to the modeled surge results for each of the individual envelopes of high water. The results were the SLOSH model depictions of hypothetical hurricane storm surge conditions at the time of high tide.

MAXIMUM ENVELOPES OF WATER (MEOWS)

The highest surges reached at all locations within the affected area of the coastline during the passage of a hurricane are called the maximum surges for those locations; the highest maximum surge in the affected area is called the peak surge. The location of the peak surge depends on where the eye of a hurricane crosses the coastline, hurricane intensity, basin bathymetry, configuration of the coastline, approach direction, and radius of maximum winds. As discussed previously, the peak surge from a hurricane usually occurs to the right of the storm path and within a few miles of the radius of maximum winds.

Due to the National Hurricane Center's (NHC) inability to precisely forecast the landfall locations of hurricanes, the NHC Storm Surge Group developed the Maximum Envelopes of Water (MEOWs). MEOWs determine the potential peak surge at every location within the SLOSH basin. For example, if there were two

storms, identical in every respect and they followed parallel tracks separated by 50 miles, then very likely there would be locations having markedly different surge values resulting from the two storms. This dependency of surge height on storm track can be troublesome in evacuation planning. Accordingly, MEOWs were produced by running the SLOSH model to create a group of storms, all having the same characteristics, but with parallel tracks 10 miles apart. At each grid square, the maximum surge value that was calculated was saved. The result was a "maximum envelope of water." Thus the MEOW is the "worst-case" surge that could be produced at any location by a storm with a particular combination of approach direction, forward speed, and intensity, regardless of where landfall may have occurred. Since the MEOW is the "worst-case" at all locations, no one storm can duplicate the flooding depicted by a MEOW. Hypothetical storm and MEOW data are presented in Table 2-5.

Direction	Speed (mph)	Intensities	Tracks	Runs	MEOWS
WNW	10, 20, 30	1 through 4	16	192	12
NW	10, 20, 30, 40	1 through 4	19	304	16
NNW	10, 20, 30, 40, 50, 60	1 through 4	21	504	24
N	10, 20, 30, 40, 50, 60	1 through 4	16	384	24
NNE	10, 20, 30, 40, 50, 60	1 through 4	15	360	24
NE	10, 20, 30, 40, 50, 60	1 through 4	8	192	24
		MEAN TIDE	TOTALS:	1,936	124
		HIGH TIDE	TOTALS:	1,936	124
			TOTALS:	3,872	248

Table 2-5: *Long Island Sound Basin Hypothetical Storm Scenarios*

To create the MEOWs for the Long Island Sound Basin, ninety-five storm tracks were modeled. They are shown on Figures 2-3, 2-4, 2-5, 2-6, 2-7 and 2-8. The simulated hurricanes moving along these tracks had combinations of parameters representing hurricane intensity categories 1 through 4, as described by the Saffir/Simpson Hurricane Scale; one of six constant speeds, as summarized in Table 2-5; six approach directions for hurricanes making landfall or paralleling the coast (west-northwestward, northwestward, north-northwestward, northward, north-northeastward, and northeastward); and numerous landfall or closest approach locations, separated by 10 miles along the coastline. Because of their extremely low chance of occurrence, Category 5 hurricanes were not modeled. Forward speeds of 10, 20, and 30 miles per hour were used for west-northwestward moving hurricanes and 10, 20, 30, and 40 miles per hour for northwestward moving hurricanes. Forward speeds of 10, 20, 30, 40 50, and 60 miles per hour were used for all other approach directions. The radius of maximum winds varied from 30 miles to 40 miles at landfall. There are 248 MEOWs for the Long Island Sound Basin, 124 for mean tide conditions and 124 for high tide conditions.

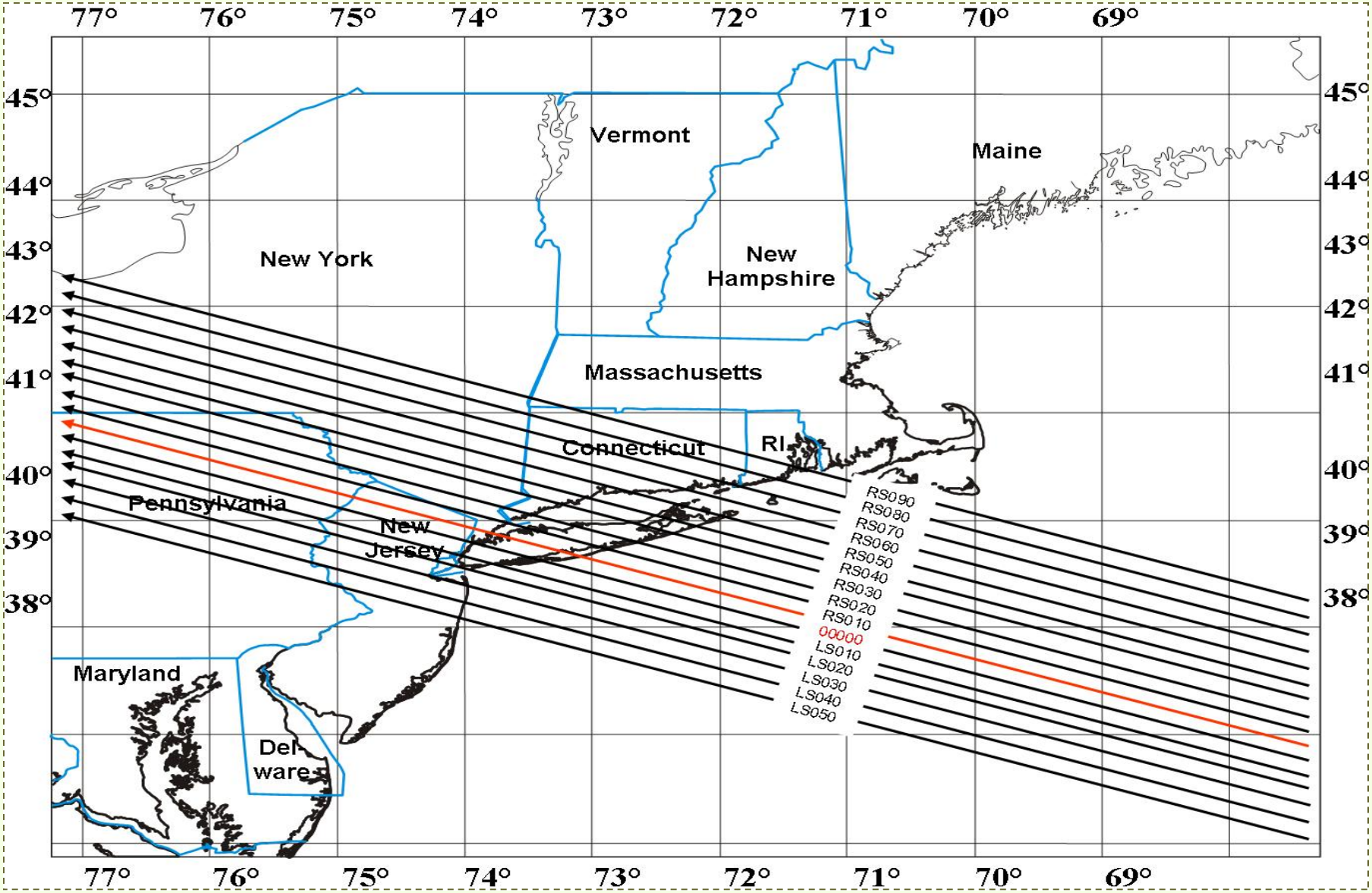

Figure 2-3: *WNW Hypothetical Tracks*

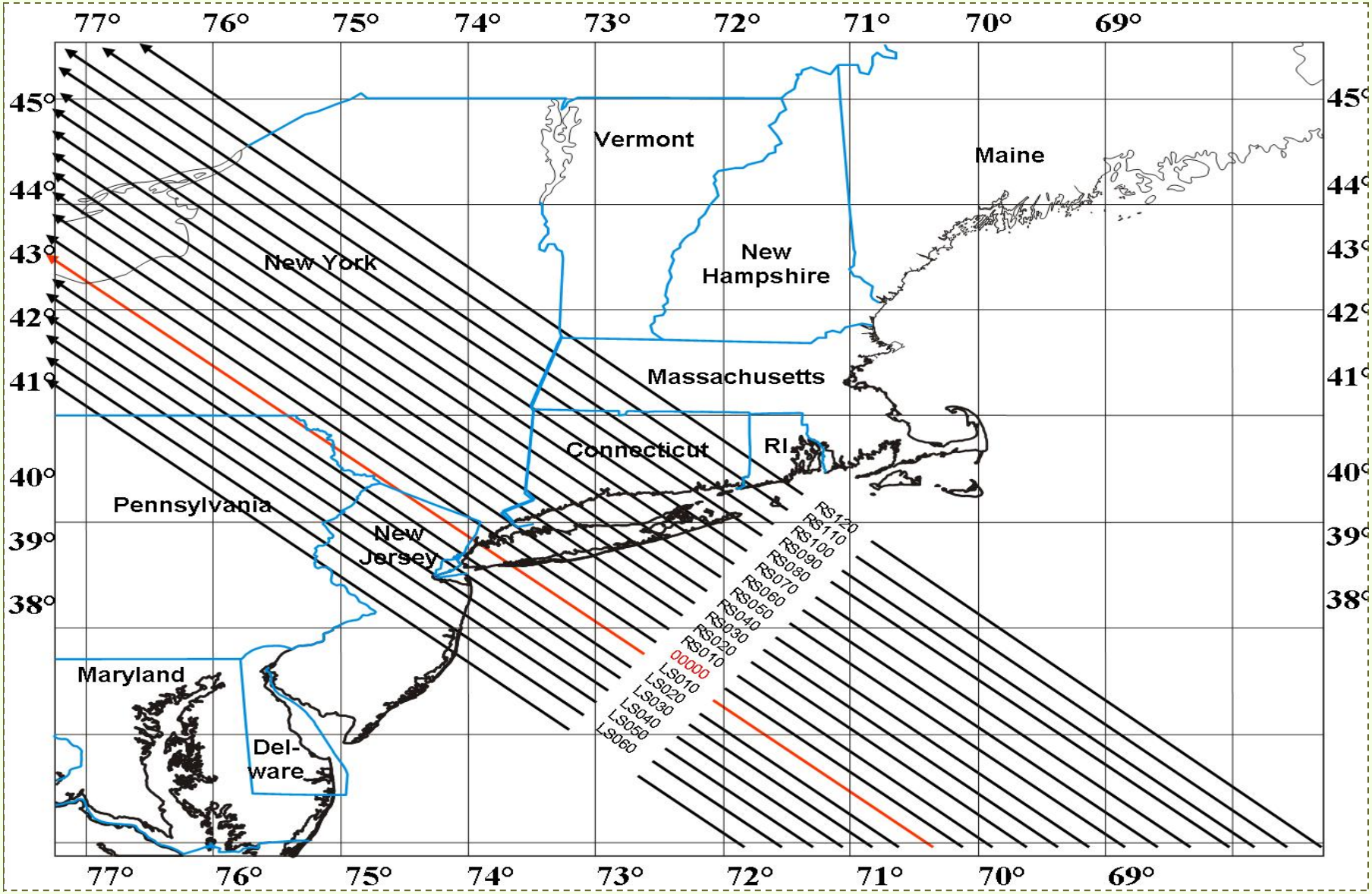

Figure 2-4: *NW Hypothetical Tracks*

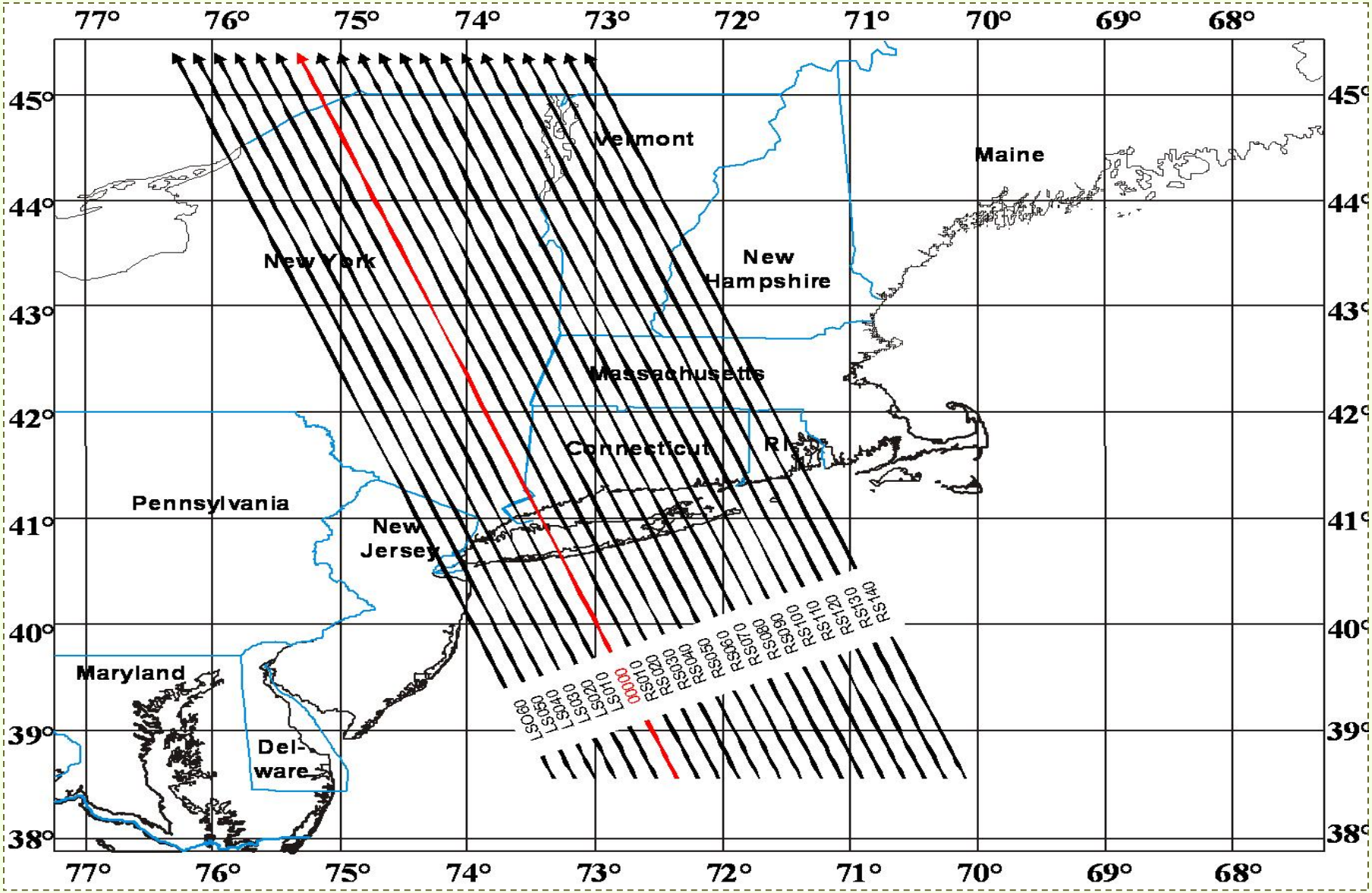

Figure 2-5: *NNW Hypothetical Tracks*

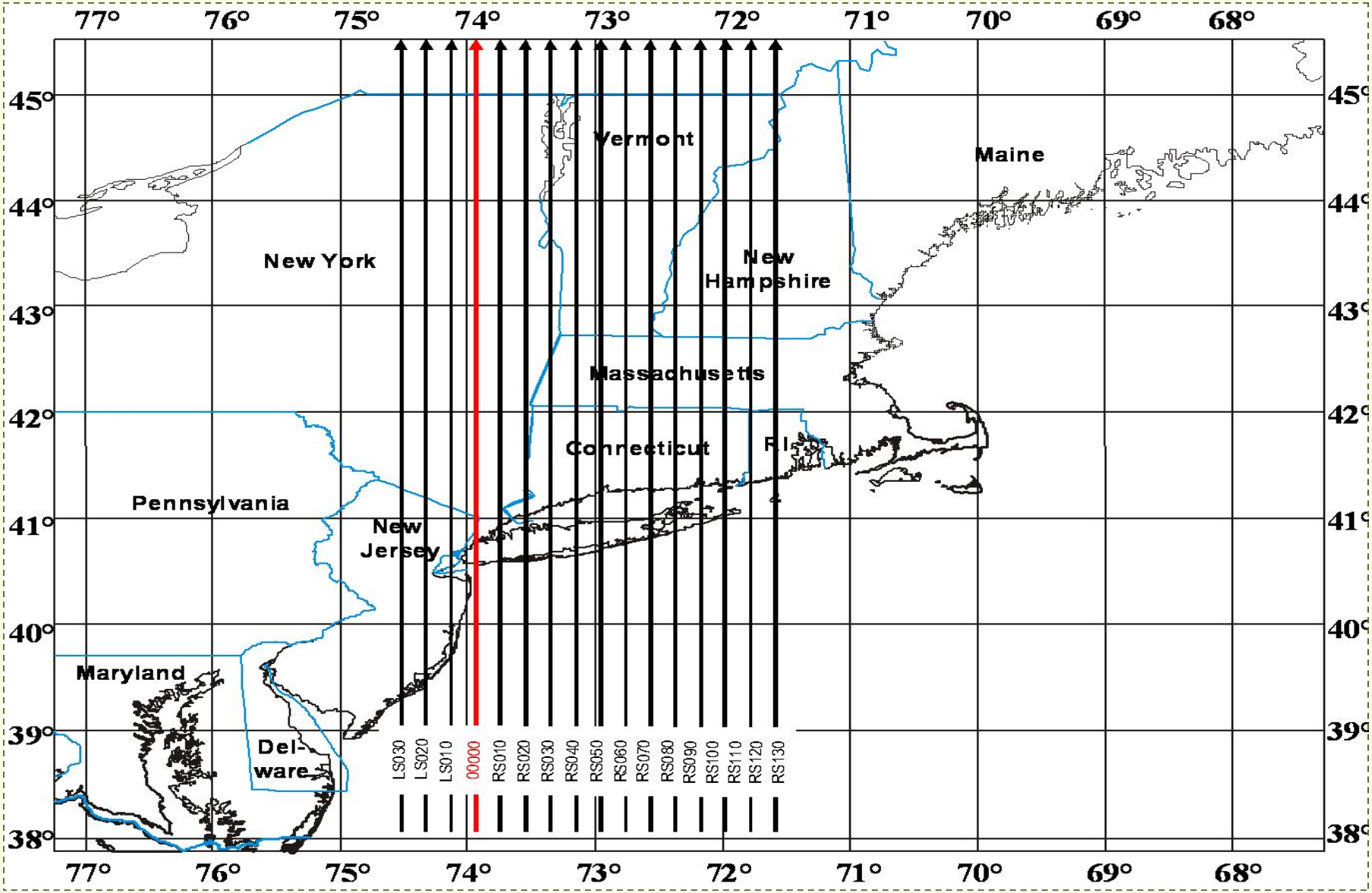

Figure 2-6: *North Hypothetical Tracks*

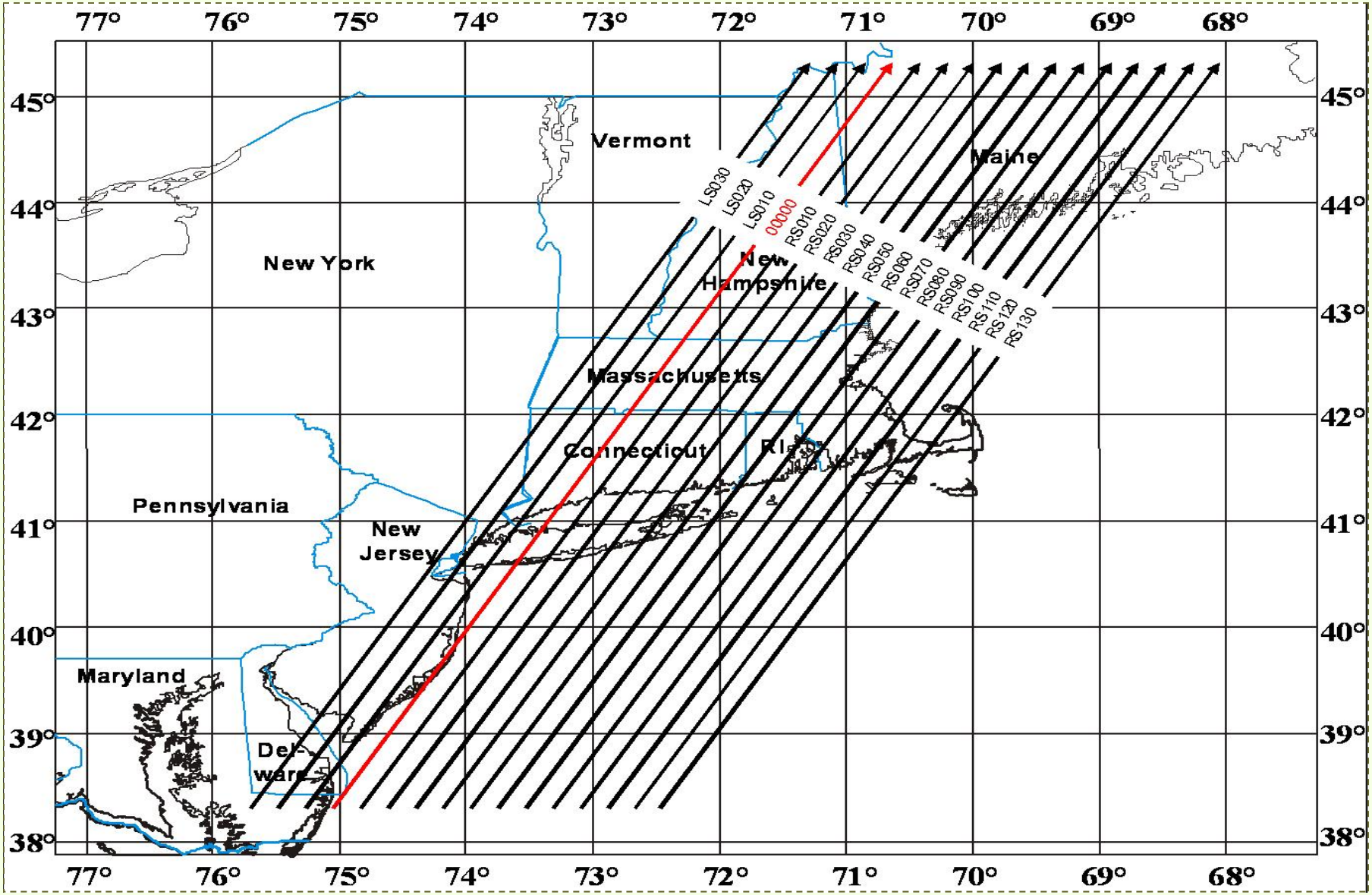

Figure 2-7: *NNE Hypothetical Tracks*

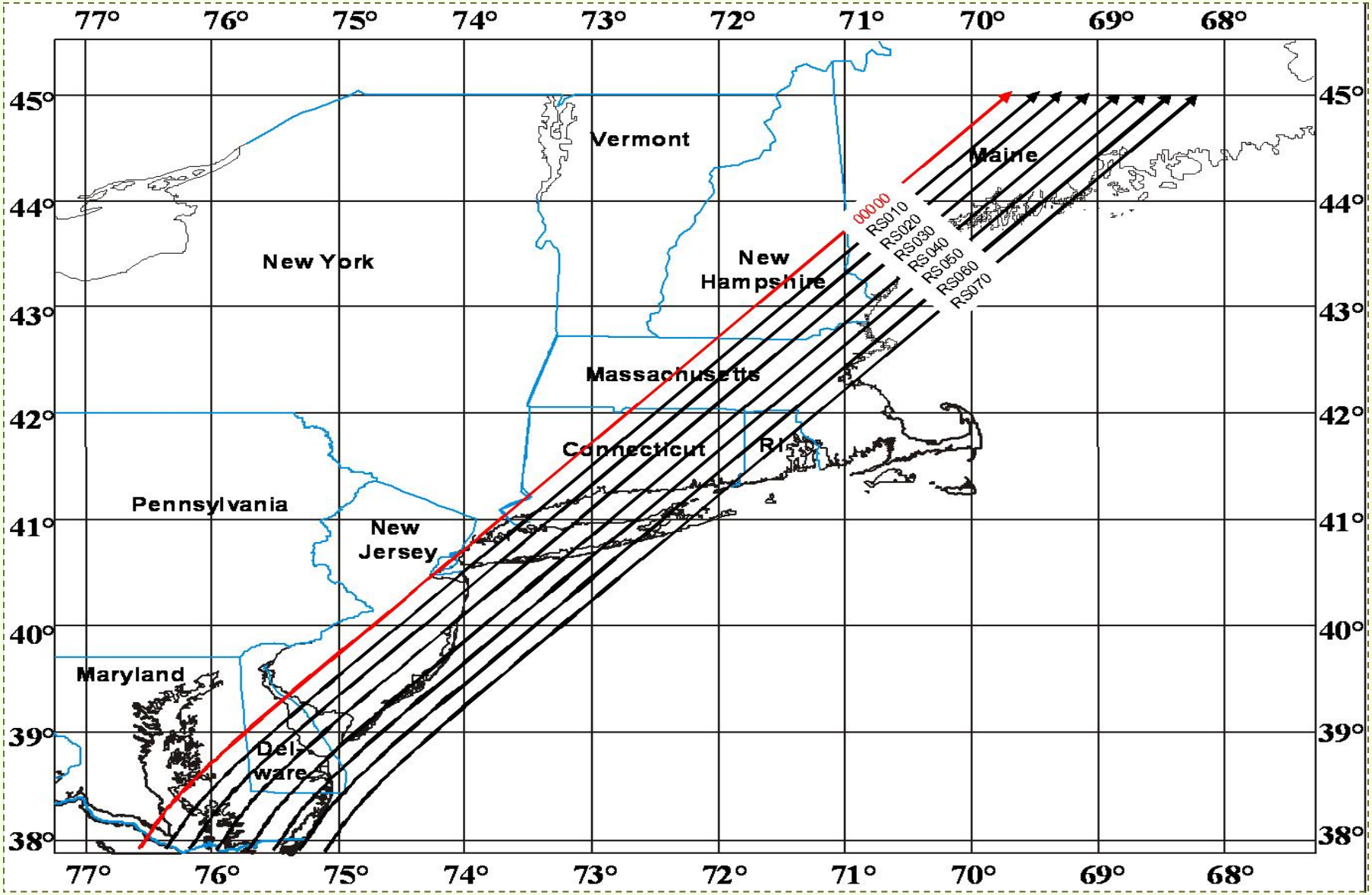

Figure 2-8: *NE Hypothetical Tracks*

MAXIMUMS OF THE MEOWS (MOMS)

The results of the 248 MEOWs were analyzed to determine which storm parameters (i.e., intensity, approach speed, and approach direction) resulted in the greatest values of the peak surges for all locations, and those that could reasonably be combined to facilitate evacuation decision making. Changes in storm category had substantial influence on peak storm surge heights for the Long Island Sound SLOSH Basin. Careful consideration was given to the impacts of various combinations of storm parameters on hurricane evacuation planning and decision making. To simplify these processes, the NHC was asked to compile additional MEOWs.

The NHC subsequently combined MEOWs to create MOMs (Maximums of the MEOWs), eliminating consideration of hurricane approach speed and direction, but maintaining the separation of categories 1, 2, 3, and 4. It was from those MOMs that 8 inundation maps were developed, 4 for mean tide and 4 for high tide conditions. Those inundation maps depict the limits of inundation from peak storm surge heights that could be generated by the four categories of storm intensity, without regard to approach speed, direction, or track. Table 2-4 shows maximum surge heights by Saffir/Simpson hurricane categories. Figures 2-9, 2-10, 2-11, 2-12, 2-13, 2-14, 2-15, and 2-16 are MOMs showing computed storm surge heights above NGVD.

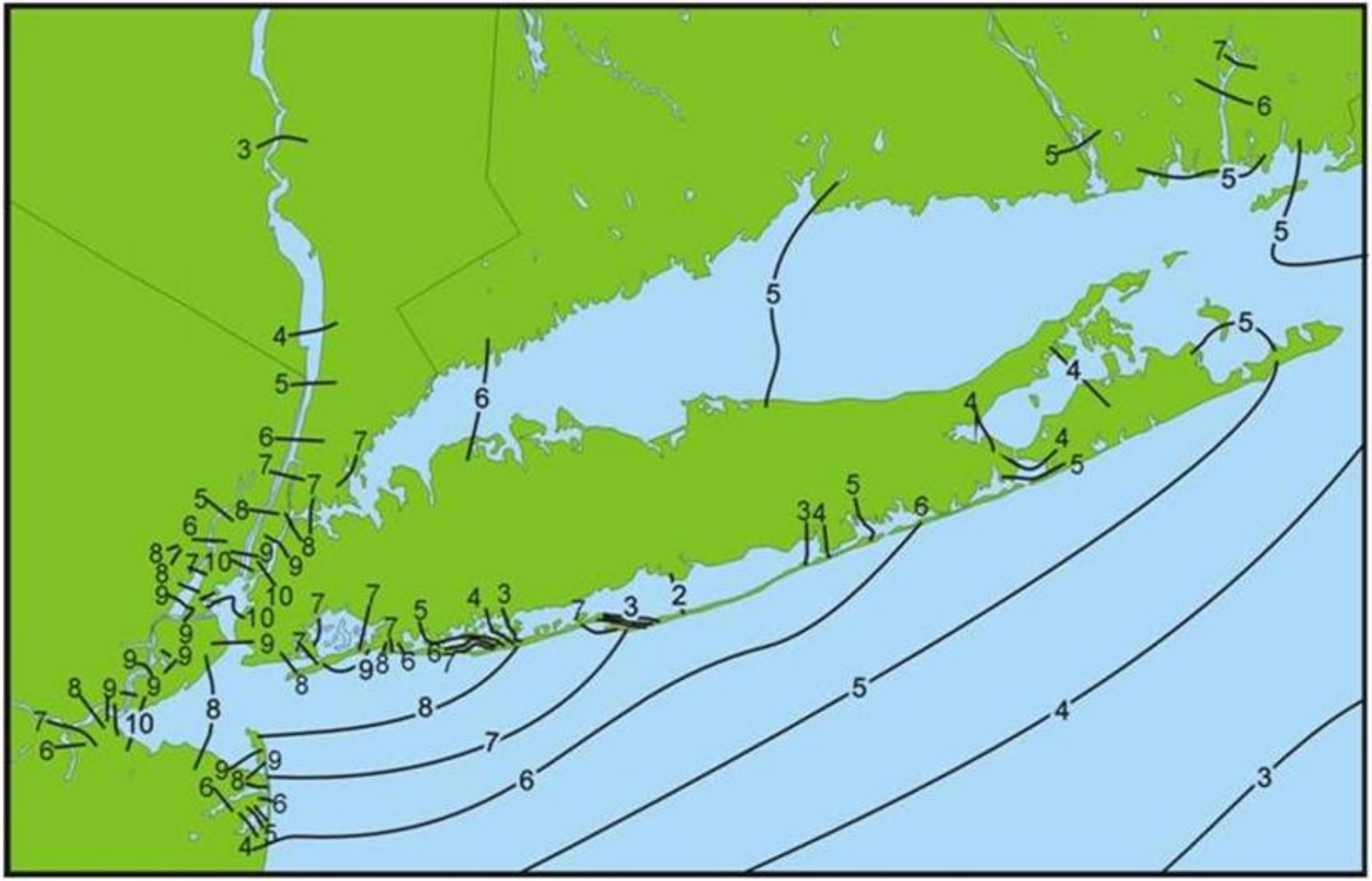

Figure 2-9: *MOM—Mean Tide—Cat 1*

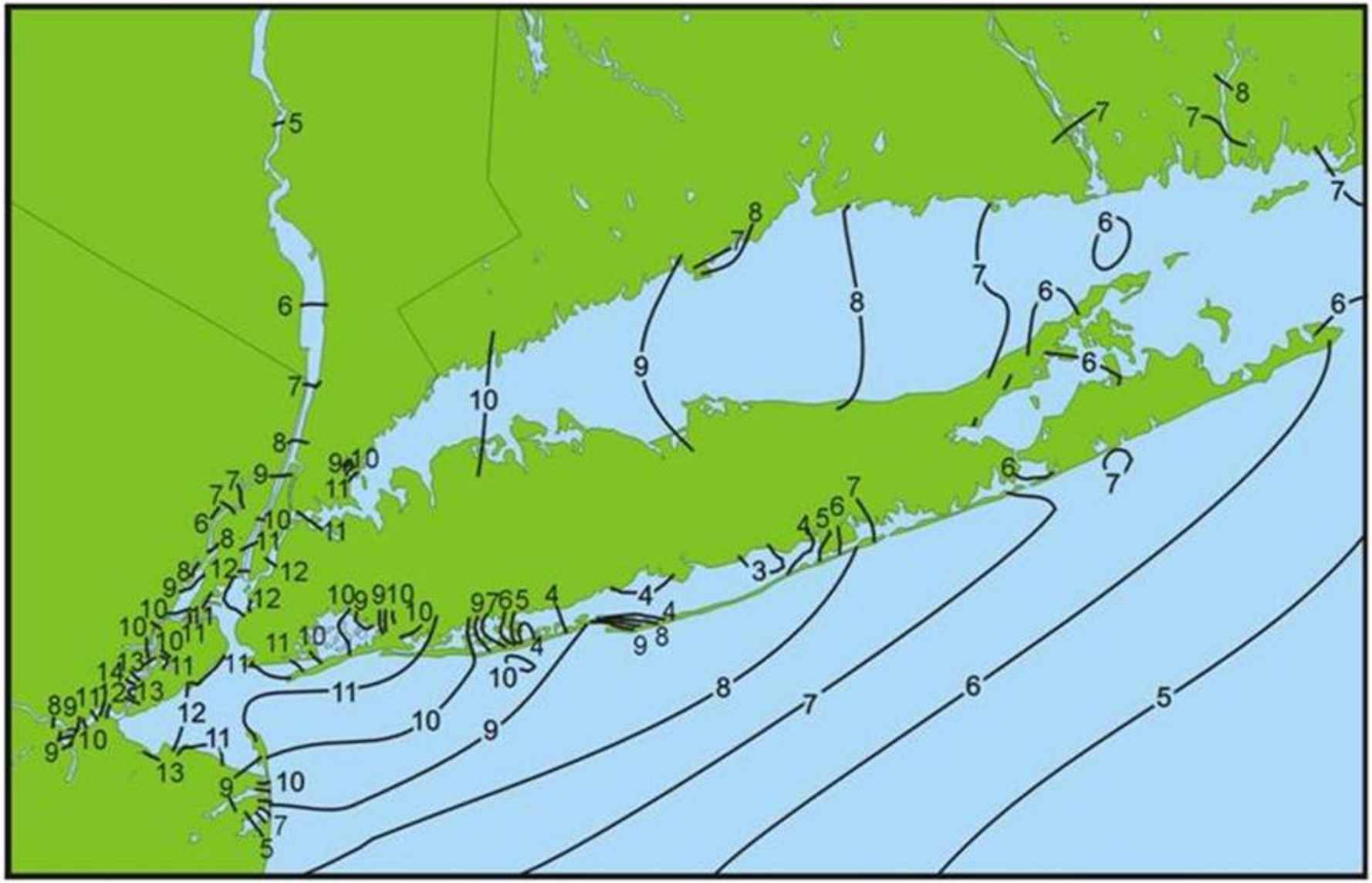

Figure 2-10: *MOM—High Tide—Cat 1*

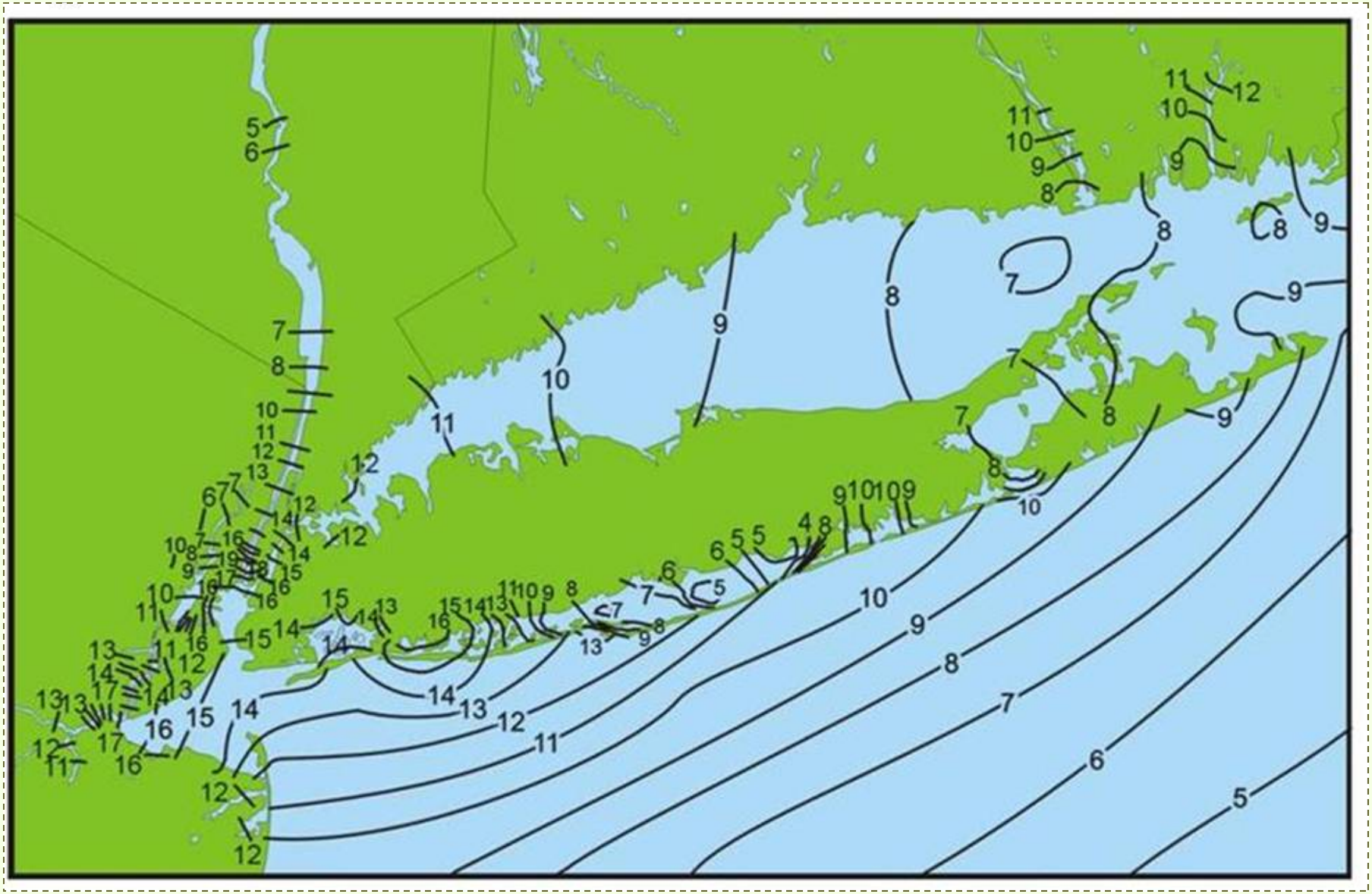

Figure 2-11: *MOM—Mean Tide—Cat 2*

Figure 2-12: *MOM—High Tide—Cat 2*

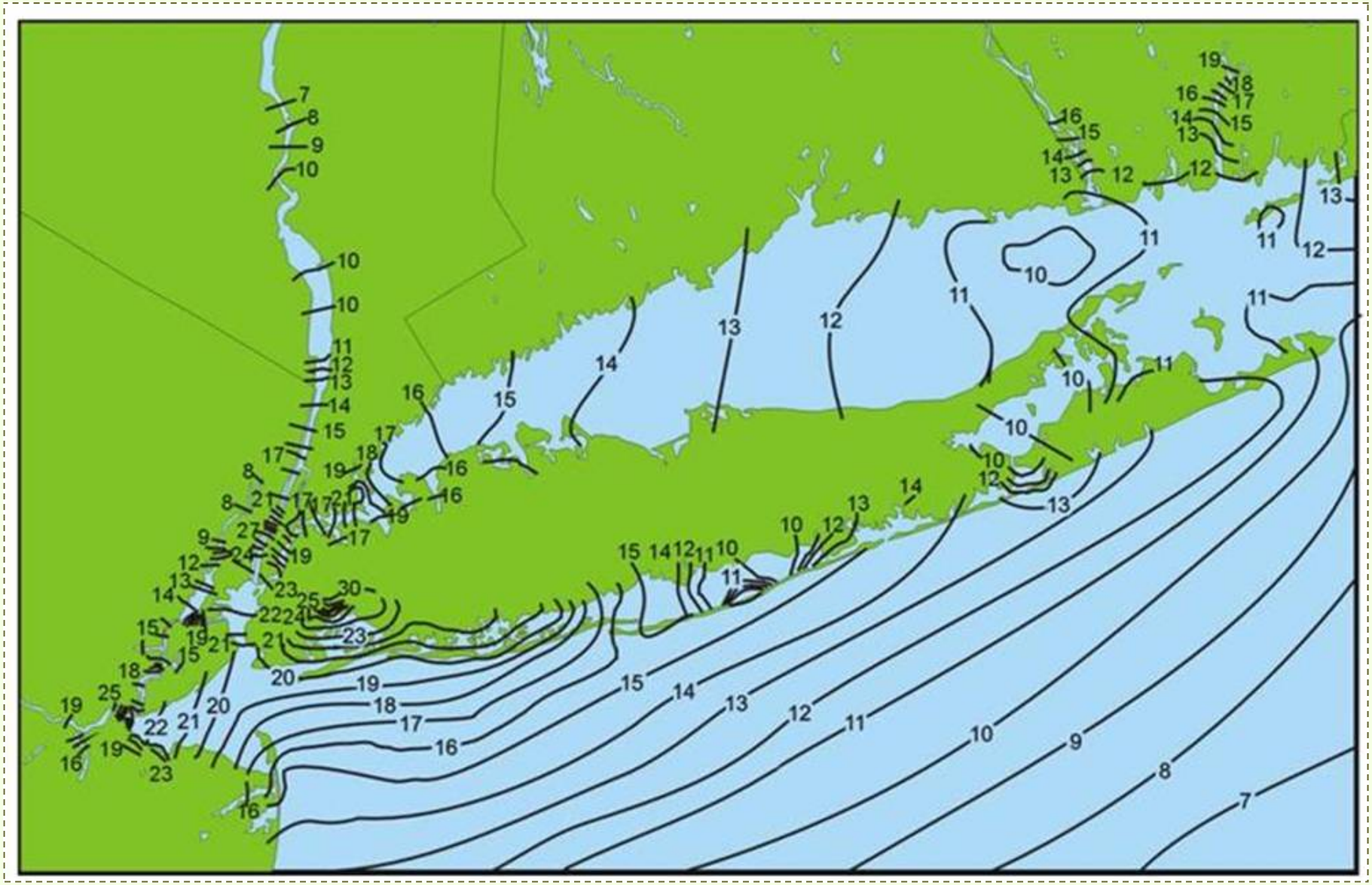

Figure 2-13: *MOM—Mean Tide—Cat 3*

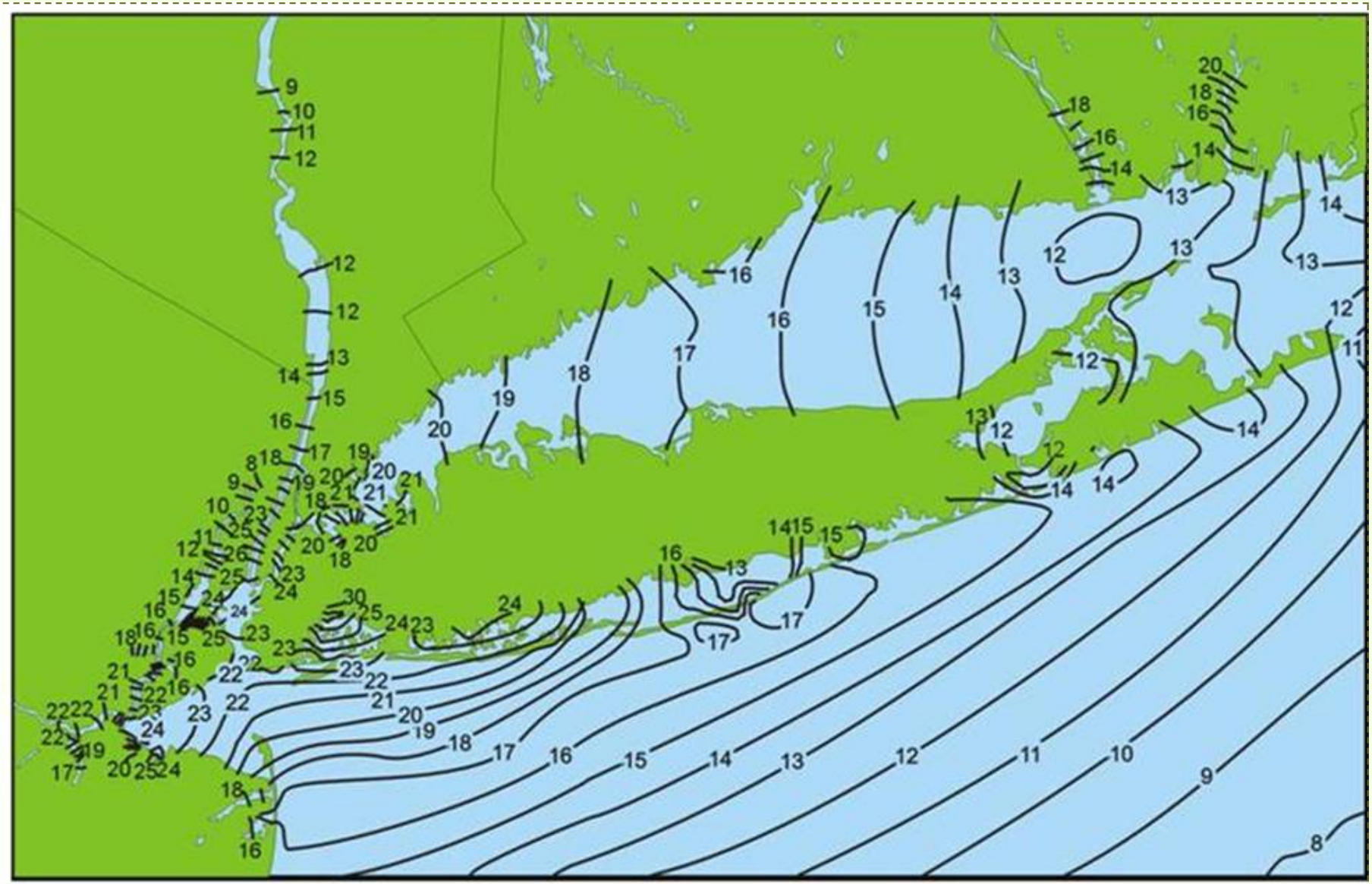

Figure 2-14: *MOM—High Tide—Cat 3*

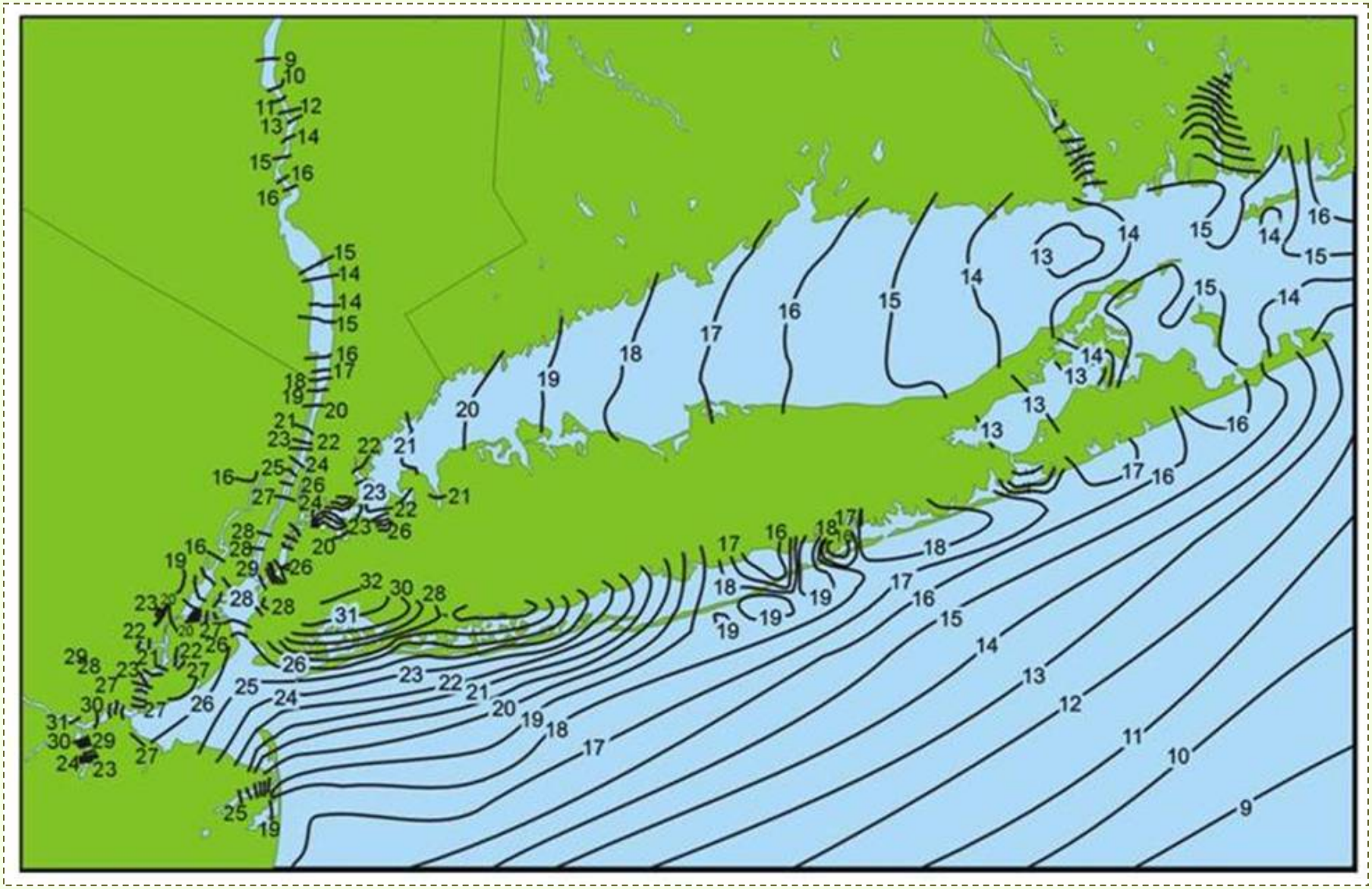

Figure 2-15: *MOM—Mean Tide—Cat 4*

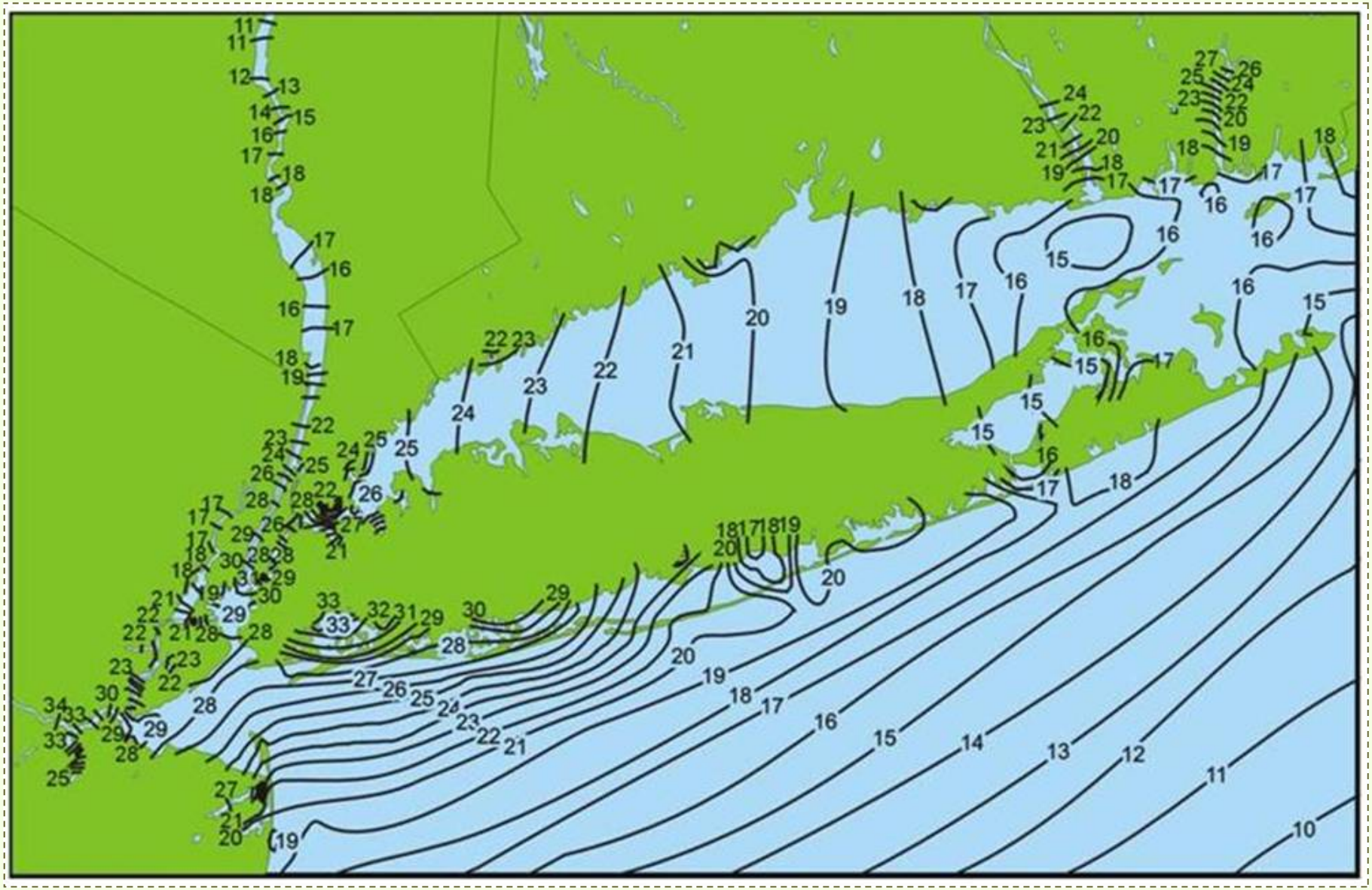

Figure 2-16: *MOM—High Tide—Cat 4*

ADJUSTMENTS TO SLOSH MODEL VALUES / STATISTICAL ANALYSIS

Hurricane evacuation decision makers should keep in mind that the SLOSH model is a mathematical model and does not always produce perfect results. To determine the accuracy of the SLOSH model, computations were made by the National Weather Service for 13 historical land-falling hurricanes in 8 separate coastal basins. A total of 523 observations of storm surge heights were made and compared to the SLOSH model values for the same locations (i.e., SLOSH model height minus observed height). A negative difference meant the SLOSH model underestimated the storm surge. Tide gage readings accounted for 14 percent of the observations, while the remainder were high-water mark readings. The range of error was from -7.1 feet to +8.8 feet. The arithmetic mean was -0.3 feet, which indicates a slight negative bias. The standard deviation was 2.0 feet. Most of the errors, 79 percent, fell within one standard deviation, compared to 68 percent for a normal distribution.

Based on the results of the statistical analysis conducted by the National Weather Service, a +20 percent adjustment to the SLOSH values would eliminate nearly all of the potential negative errors occurring from the model. However, such an adjustment would also add additional surge height to those values that already contain positive errors, possibly endangering the credibility of the SLOSH results. Therefore, a general adjustment was not made to the computed surge heights. Evacuation planners should remain cognizant of the potential 20 percent underestimate of some SLOSH surge values.

OTHER HURRICANE HAZARDS

HURRICANE WINDS AND VULNERABILITY

In addition to storm surge, extreme winds can be a life-threatening feature of hurricanes. To some degree, all structures exposed to hurricane-force winds are vulnerable to wind-related hazards (see Table 2-2). This is especially true of intense storms, generally considered Category 3 and greater hurricanes. However, high-rise buildings merit special consideration. Wind pressures on upper portions of tall structures can be much greater than those at ground level. These pressures can cause significant problems during even a moderate hurricane. In the study area, complete structural failure of tall buildings due to wind is not a major concern. However, past wind storms in other locations have shown that combinations of wind forces on multi-story buildings can result in window breakage, the destruction of interior partitions, and loss of exterior cladding, creating the potential for high numbers of casualties. Not only could occupants be endangered, but debris falling onto the streets from high above could create an extreme hazard to pedestrians.

Within the transportation network, high-rise bridges are particularly vulnerable to the hazards of extreme winds. Although some could experience wind-related structural problems, traffic hazards will probably stop travel before this can become a significant factor. Several major high-rise bridges in the study area have been closed during past storms after gale-force winds caused high profile vehicles to overturn.

Destructive hurricane force winds and tornadoes can also affect many inland counties as far as 100 miles from the coast. Studies by the NHC have resulted in modifying the Tropical Cyclone Advisory to include additional information to help inland counties prepare for threatening high wind conditions. An inland wind

analysis option is included in the new HURREVAC 2000 software program to assist inland communities in estimating when damaging winds might hit their area. The inland wind analysis should be used ONLY A FEW HOURS before the hurricane makes landfall. This is when the NHC track and wind-field forecast errors are relatively low.

FRESHWATER FLOODING

Amounts and arrival times of rainfall associated with hurricanes are highly unpredictable. For most hurricanes, the heaviest rainfall begins near the time of arrival of sustained tropical storm winds; however, heavy rains in amounts exceeding 20 inches can precede an approaching hurricane by as much as 24 hours. Unrelated weather systems can also contribute significant rainfall amounts within a basin in advance of a hurricane.

Tropical systems and their remnants can produce widespread torrential rains and many residents living inland could experience severe flooding. These residents may feel they are safe just because they do not live on or near the coast but can be faced with life threatening flooding from rivers and streams that could persist long after the storm moves inland and begins to deteriorate. This could be especially problematic for counties to the north and west of the immediate coastal area. Also, if a storm were to track up the Hudson River, storm surge and astronomical tidal conditions combined with heavy rainfall could cause transportation infrastructure to funnel floodwater to unexpected places which could create severe localized flooding in the Bronx, Westchester County, and other counties along the river.

Due to the unpredictability of rainfall from hurricanes, no attempt was made to employ sophisticated modeling or analysis in quantifying those effects for the study area. It should be assumed that locations and facilities which have historically flooded during periods of heavy rainfall are vulnerable to freshwater flooding from hurricane conditions.