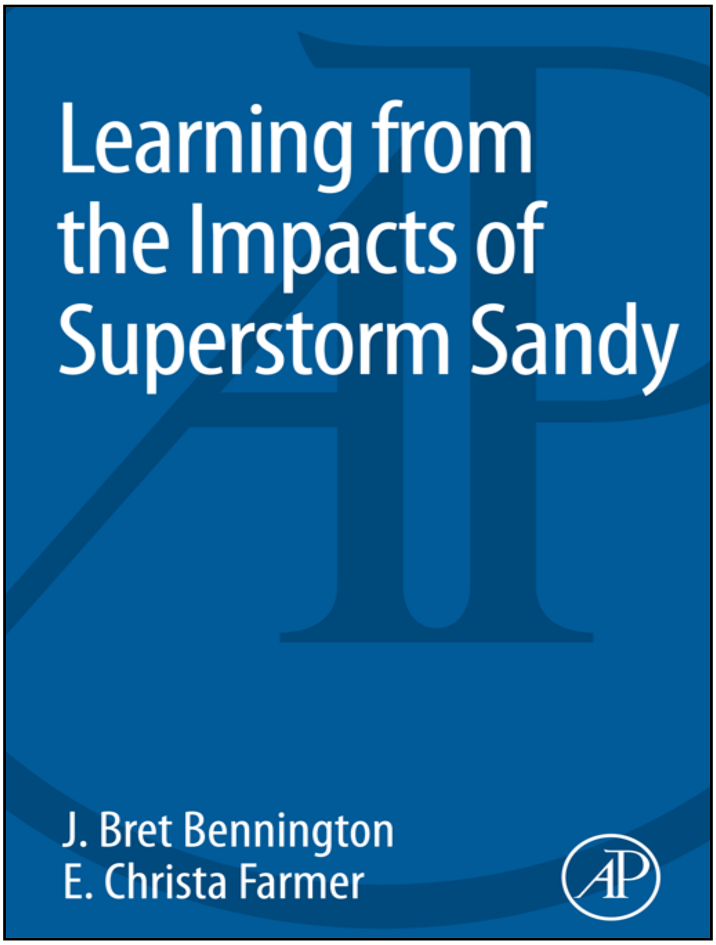

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CHAPTER 2

Measuring Storm Tide and High-water Marks Caused by Hurricane Sandy in New York

A.E. Simonson and R. Behrens

ABSTRACT

In response to Hurricane Sandy, personnel from the U.S. Geological Survey (USGS) deployed a temporary network of storm-tide sensors from Virginia to Maine. During the storm, real-time water levels were available from tide gages and rapid-deployment gages (RDGs). After the storm, USGS scientists retrieved the storm-tide sensors and RDGs and surveyed high-water marks. These data demonstrate that the timing of peak storm surge relative to astronomical tide was extremely important in southeastern New York. For example, along the south shores of New York City and western Suffolk County, the peak storm surge of 6–9 ft generally coincided with the astronomical high tide, which resulted in substantial coastal flooding. In the Peconic Estuary and northern Nassau County, however, the peak storm surge of 9 ft and nearly 12 ft, respectively, nearly coincided with normal low tide, which helped spare these communities from more severe coastal flooding.

Keywords: storm surge; storm tide; high-water marks; Hurricane Sandy; coastal flooding; New York emergency management

2.1 INTRODUCTION

On the evening of October 30, 2012 at approximately 1:00 am GMT Post-Tropical Cyclone Hurricane Sandy made landfall 5 miles southwest of Atlantic City, New Jersey (National Hurricane Center, 2012), producing Category 1 hurricane force winds and coastal flooding in the Northeast region of the United States (Fanelli et al., 2013). Prior to landfall, the USGS deployed a temporary monitoring network of

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water-level and barometric-pressure sensors at 224 locations along the Atlantic coast from Virginia to Maine, which recorded the timing, areal extent, and magnitude of storm tide and coastal flooding (McCallum et al., 2013).

As defined by the National Oceanic and Atmospheric Administration (NOAA), storm tide is the maximum water level elevation during storm events, and can be a combination of storm surge, astronomical tide, and river runoff (Fanelli et al., 2013). Storm surge is the onshore rush of seawater caused by the high wind and the low-pressure center of a hurricane or other storm, and the magnitude of storm surge is dependent upon the orientation of the coastline with the storm track, the intensity of the storm, and the local bathymetry (Fanelli et al., 2013).

After the storm, more than 950 HWMs were flagged with an emphasis on New Jersey and New York, of which 653 marks were surveyed to establish elevation (McCallum et al., 2013). These efforts were undertaken as part of a larger coordinated Federal emergency response as outlined by the Stafford Act under a directed mission assignment by the Federal Emergency Management Agency (FEMA). The USGS has conducted similar deployments and other studies to examine the effects of hurricanes and tropical storms and to understand potential impacts on coastal communities and habitats; details are available online at http://coastal.er.usgs.gov/hurricanes.

2.2 BACKGROUND: HURRICANE SANDY STORM-TIDE MONITORING

2.2.1 Before the Storm: Long-term Network

The low-lying, highly-populated coastal areas of southeastern New York are vulnerable to tidal flooding, and emergency managers need adequate flood warnings during hurricanes and other coastal storms. To address this need for instantaneous information on coastal flooding, the USGS has operated a network of real-time tidal water-elevation stations since 1997 in southeastern New York, with the cooperative support of state and local municipalities. Each tidal water-elevation station, or tide gage, is equipped with a pressure sensor connected to a data-collection platform inside a weather-resilient shelter. Data are recorded at 6-minute intervals, transmitted via satellite every hour, and uploaded to the

USGS National Water Information System (NWIS). When a station detects water levels above the National Weather Service (NWS) minor coastal-flood elevation threshold, it increases the frequency of satellite transmissions to 6-minute intervals. Real-time tidal water-elevation data at New York sites are available at http://waterdata.usgs.gov/ny/nwis/current/?type=tidal. During Hurricane Sandy, there were 13 long-term tide gages in southeastern New York, 10 of which were equipped with telemetry. Data from the USGS permanent monitoring sites were used to compute the residual water level (storm surge, when positive) by subtracting the predicted astronomical tide level from the observed water level (Fanelli et al., 2013). The water-level elevations and storm-surge calculations were available to emergency managers and residents during the storm.

In addition to the coastal network, there is a long-term network of more than 200 stream gages in New York, which is part of a nation-wide network of more than 9000 gages (Lurry, 2011). During the hurricane, there were six real-time stream gages in southeastern New York that recorded storm tide. These sites measured water levels at 15-min intervals and transmitted data hourly to the NWIS website: http://waterdata.usgs.gov/ny/nwis/current/?type=flow. Because many Long Island stream gages have data records extending back to the 1930s (Wells, 1960), they provide valuable historical context to this and other recent storms.

2.2.2 Before the Storm: Short-term Network

From October 26 to 28, 2012, the NY USGS deployed 39 storm-tide sensors, 4 wave-height sensors, 11 barometric-pressure sensors, and 4 RDGs throughout Long Island, New York City, and Westchester County as part of a larger, coordinated multicenter effort. Sensor locations were selected to supplement the existing USGS long-term tide gage network and to ensure that sufficient data were collected in areas where NOAA models predicted significant coastal flooding. Storm-tide and wave-height sensors are non-vented pressure transducers programmed to record at 30-s and 2-s intervals, respectively. Both the storm-tide and wave-height sensors are unvented, so barometric-pressure sensors are installed nearby to compensate for the pressure change during the storm. Pressure transducers were installed in aluminum or PVC housings and attached to stable structures, such as bulkheads and pilings.

Sensors were deployed at low tide, preferably submerged below the water surface to collect complete tidal cycles. RDGs equipped with sensors to record water level and meteorological data were usually attached to bridge railings. The RDG data were transmitted with telemetry to the NWIS website during the storm.

Further details of this deployment are available in McCallum et al. (2013) and in the online mapper at: http://water.usgs.gov/floods/events/2012/sandy/sandymapper.html. Additional storm-surge analysis of short-term storm-tide sensors is available in Behrens (2013).

2.2.3 After the Storm: High-water Marks and Surveying

Within 10 days of landfall, the short-term water-level sensors were collected, surveyed to the North American Vertical Datum of 1988 (NAVD 88) and processed following standard USGS protocols (McGee et al., 2005; McCallum et al., 2012), which included correcting water pressure for changes in barometric pressure and salinity, and comparing recorded elevations to nearby independent high-water marks and long-term gages. In southeastern New York alone, more than 350 high-water marks were flagged and surveyed. High-water marks – such as debris, seed lines, and mud lines – were documented as verification of the storm-tide sensor data and as indicators of peak storm tide. Because precipitation and clean-up efforts can easily destroy such marks, they must be identified as soon as possible after an event. To determine the elevation of the HWMs and short-term network sensors, a combination of differential leveling and survey-grade Global Navigation Satellite Systems (GNSS) equipment was used to determine the elevation above NAVD 88 (Rydlund and Densmore, 2012). For quality assurance, National Geodetic Survey (NGS) benchmarks with known elevations were surveyed throughout the study area for vertical control (see Table 2 in McCallum et al., 2013).

2.3 RESULTS

This paper describes a subset of the overall USGS effort, and focuses on four representative geographic areas and their adjacent water bodies: (1) southern Suffolk County along the shore of Great South Bay; (2) New York City along the shore of Lower New York Bay/Raritan Bay; (3) eastern Suffolk County along the shore of the Peconic Estuary; and

(4) northern Nassau County along the shore of western Long Island Sound (see Figure 2.1). The data shown in Table 2.1 were chosen to demonstrate the range in storm-tide elevations and the fidelity of the record for nearby sites and were rounded to 0.1 ft for simplicity. Our storm-tide data are from Tables 3, 4, and 6 of McCallum et al. (2013), which is available online at http://pubs.usgs.gov/of/2013/1043, and storm-surge data are from the NWIS tide gage graphics recorded during the hurricane (USGS, 2012a–d). Peak storm-tide data are affected by wave action to various degrees, depending on the measurement techniques and site conditions under which the storm-tide elevations were collected (C. Schubert, U.S. Geological Survey, written communications, 2014).

In southern Suffolk County along the shore of Great South Bay, data were collected at two real-time stations during Hurricane Sandy, a long-term USGS tide gage (01309225, Great South Bay at Lindenhurst, NY) and an RDG (403836073154775, State Boat Channel at Captree Island, NY). The RDG recorded a peak storm-tide elevation of 5.2 ft and the tide

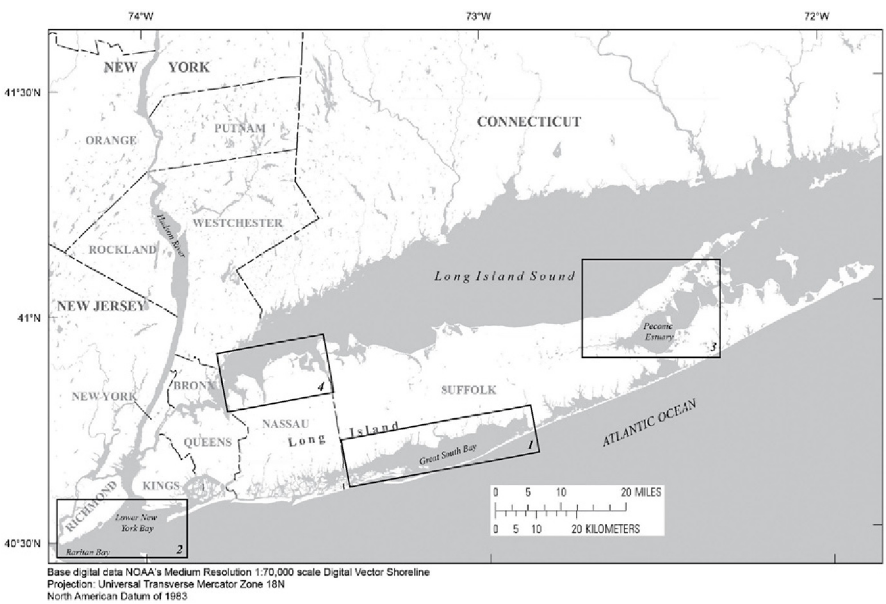

Fig. 2.1. Map showing location of study areas along their adjacent water bodies: (1) southern Suffolk County along the shore of Great South Bay; (2) New York City along the shore of Lower New York Bay/Raritan Bay; (3) eastern Suffolk County along the shore of the Peconic Estuary; and (4) northern Nassau County along the shore of western Long Island Sound.

Table 2.1 Select Peak Storm-tide Data from Hurricane Sandy for U.S. Geological Survey Permanent Monitoring Sites, Temporarily Deployed Sites, and High-water Mark Data, Modified from McCallum et al. (2013)

Site Identification	County	Latitude North, Decimal Degrees	Longitude West, Decimal Degrees	Site Type	Type of Data Recorded	Peak Storm Tide, Feet NAVD 88
Southern Suffolk County, Great South Bay						
HWM-NY-SUF-403	Suffolk	40.6853	–73.2799	High-water mark	Storm tide	7.4
SSS-NY-SUF-022WL	Suffolk	40.6852	–73.2799	Water level	Storm tide	6.8
SSS-NY-SUF-021WL	Suffolk	40.7492	–73.0134	Water level	Storm tide	6.7
HWM-NY-SUF-622	Suffolk	40.6783	–73.3330	High-water mark	Storm tide	6.6
01309225	Suffolk	40.6693	–73.3557	Real-time tide gage	Storm tide	6.5
SSS-NY-SUF-027WL	Suffolk	40.7476	–73.1504	Water level	Storm tide	6.1
HWM-NY-SUF-405	Suffolk	40.6912	–73.2772	High-water mark	Storm tide	5.8
SSS-NY-SUF-019WL	Suffolk	40.6593	–73.2649	Water level	Storm tide	5.6
403836073154775	Suffolk	40.6433	–73.2631	Real-time RDG	Storm tide	5.2
SSS-NY-SUF-018WL	Suffolk	40.6347	–73.2022	Water level	Storm tide	4.1
New York City, Raritan Bay						
SSS-NY-RIC-003WL	Richmond	40.5019	–74.2303	Water level	Storm tide	16.0
SSS-NY-RIC-001WV	Richmond	40.5939	–74.0598	Wave height	Wave height	15.1
SSS-NY-RIC-001WL	Richmond	40.5939	–74.0598	Water level	Storm tide	15.0
HWM-NY-RIC-982	Richmond	40.5458	–74.1238	High-water mark	Storm tide	14.0
SSS-NY-KIN-001WL	Kings	40.5800	–74.0116	Water level	Storm tide	13.3
SSS-NY-RIC-004WL	Richmond	40.5435	–74.1277	Water level	Storm tide	13.2
HWM-NY-RIC-704	Richmond	40.5024	–74.2311	High-water mark	Storm tide	13.2
HWM-NY-RIC-719	Richmond	40.5939	–74.0683	High-water mark	Storm tide	12.7
01311875	Kings	40.5737	–73.8851	Real-time tide gage	Storm tide	10.7
Eastern Suffolk County, Peconic Estuary						
SSS-NY-SUF-005WL	Suffolk	40.9161	–72.6377	Water level	Storm tide	7.9
01304562	Suffolk	40.9178	–72.6387	Real-time tide gage	Storm tide	7.7
SSS-NY-SUF-014WL	Suffolk	40.9907	–72.4707	Water level	Storm tide	7.4
HWM-NY-SUF-307	Suffolk	40.9898	–72.4708	High-water mark	Storm tide	7.1
SSS-NY-SUF-008WL	Suffolk	40.8933	–72.5030	Water level	Storm tide	6.5
01304200	Suffolk	41.1366	–72.3068	Real-time tide gage	Storm tide	6.4
SSS-NY-SUF-015WL	Suffolk	41.1010	–72.3614	Water level	Storm tide	6.4
SSS-NY-SUF-009WL	Suffolk	41.0020	–72.2903	Water level	Storm tide	6.3
HWM-NY-SUF-436	Suffolk	40.8935	–72.5033	High-water mark	Storm tide	6.3
SSS-NY-SUF-024WL	Suffolk	41.0732	–71.9344	Water level	Storm tide	6.1

Table 2.1 Select Peak Storm-tide Data from Hurricane Sandy for U.S. Geological Survey Permanent Monitoring Sites, Temporarily Deployed Sites, and High-water Mark Data, Modified from McCallum et al. (2013) *(cont.)*

Site Identification	County	Latitude North, Decimal Degrees	Longitude West, Decimal Degrees	Site Type	Type of Data Recorded	Peak Storm Tide, Feet NAVD 88
Northern Nassau County, Long Island Sound						
HWM-NY-NAS-518	Nassau	40.8350	–73.7287	High-water mark	Storm tide	10.8
01302250	Nassau	40.8662	–73.7102	Real-time tide gage	Storm tide	10.3
SSS-NY-NAS-008WL	Nassau	40.8662	–73.7102	Water level	Storm tide	10.3
HWM-NY-NAS-700	Nassau	40.8875	–73.5636	High-water mark	Storm tide	10.2
SSS-NY-NAS-006WL	Nassau	40.8875	–73.5636	Water level	Storm tide	10.2
SSS-NY-NAS-001WL	Nassau	40.8779	–73.5306	Water level	Storm tide	10.1
01302845	Nassau	40.9051	–73.5932	Real-time tide gage	Storm tide	10.1
HWM-NY-NAS-938	Nassau	40.8915	–73.6357	High-water mark	Storm tide	10.0
SSS-NY-NAS-007WL	Nassau	40.8572	–73.4633	Water level	Storm tide	10.0
01302600	Nassau	40.8886	–73.6380	Real-time tide gage	Storm tide	9.9

gage recorded 6.5 ft NAVD 88, with surrounding storm-tide data in the Great South Bay ranging from 4.1 to 7.4 ft (Table 2.1). The graph of data from the aforementioned long-term tide gage showed a calculated storm surge of approximately 6.4 ft (Figure 2.2a), which generally coincided with astronomical high tide in the area, resulting in widespread coastal flooding.

In New York City, along the shore of Lower New York Bay/Raritan Bay, storm-tide sensors and long-term tide gages in Richmond and Kings Counties recorded peak storm-tide elevations of 10.7–16.0 ft NAVD 88 (Table 2.1). Some of the variation in peak storm tide is related to wave action. For example, Figure 2.3 shows the data variability of the wave-height sensor near the Verrazano Bridge (SSS-NY-RIC-001WV) relative to data from the water-level sensor that was sheltered from wave action in Great Kills Harbor (SSS-NY-RIC-004WL). As shown in Figure 2.2b, the nearby USGS tide gage at Rockaway Inlet (01311875) indicated a peak storm surge of approximately 9.1 ft, which generally coincided with astronomical high tide and resulted in extensive coastal flooding in the area.

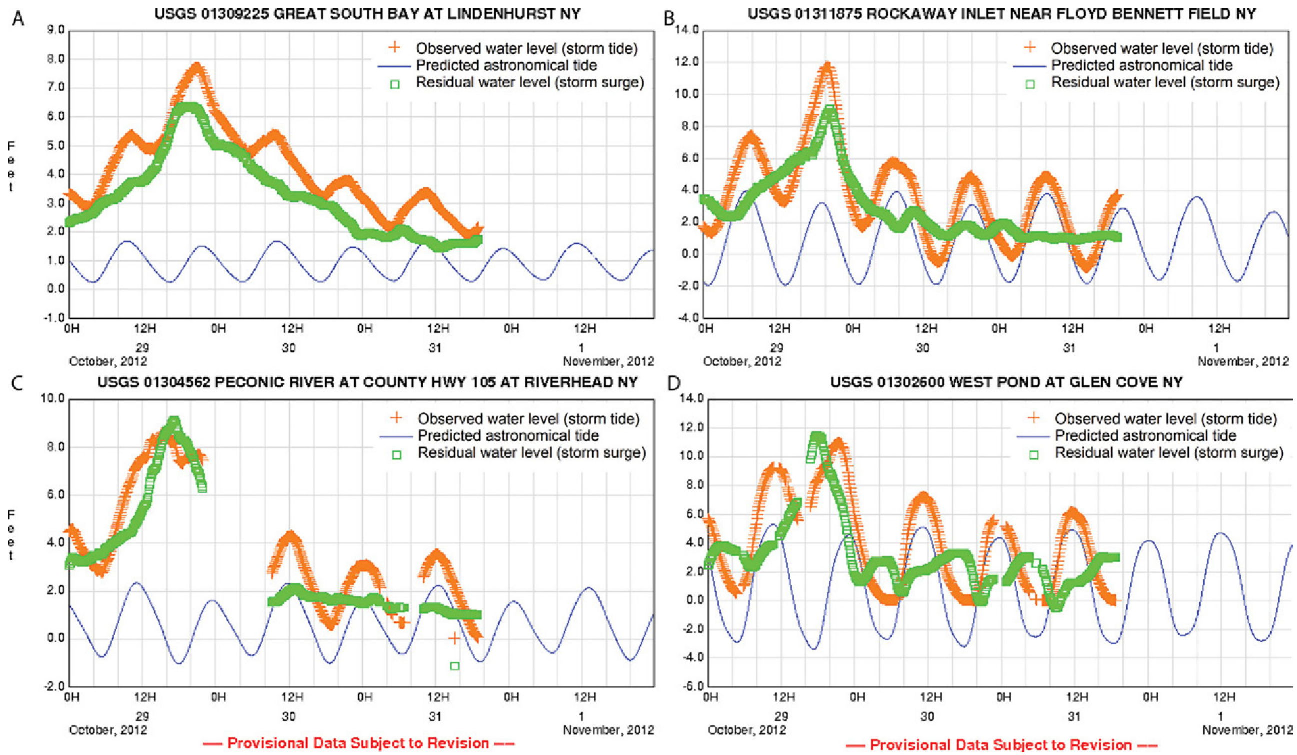

Fig. 2.2. Hydrographs for October 29–November 1, 2012, at (A) 01309225 Great South Bay at Lindenhurst, (B) 01311875 Rockaway Inlet near Floyd Bennett Field, (C) 01304562 Peconic River at County Highway 105 at Riverhead, and (D) 01302600 West Pond at Glen Cove. Residual water level (green squares) is shown in feet and is calculated from difference between observed water elevation and predicted (astronomical) tide elevation. Water elevation record (orange crosses) is shown in feet above NGVD 1929 (National Geodetic Vertical Datum of 1929). Predicted astronomical tide (blue line) is shown in feet above NGVD 1929 for nearby National Ocean Service (NOS) tidal-prediction stations, (A) NOS 1255; (B) NOS 1281; (C) NOS 1209; (D) NOS 1165. Time is shown in Eastern Standard Time. Data are provisional and subject to revision. Figures modified from USGS (2012a–d).

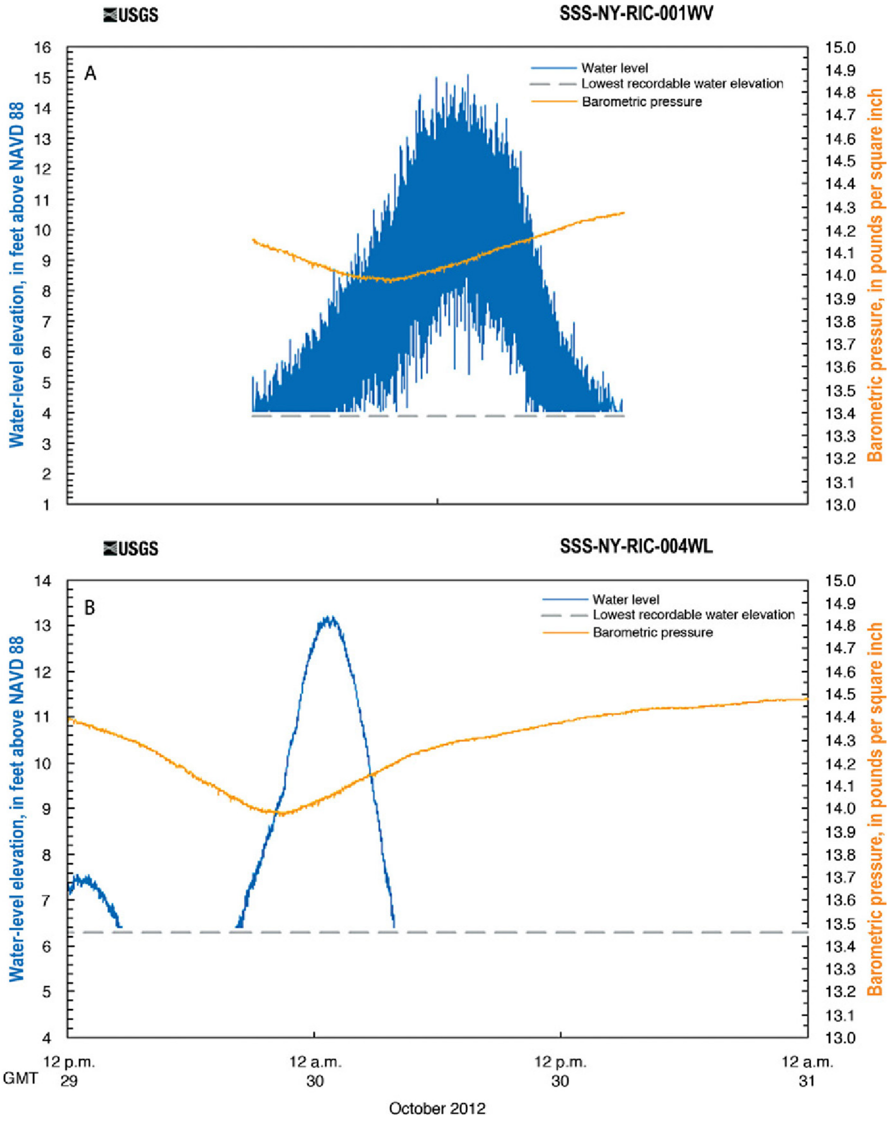

Fig. 2.3. Hydrographs for October 30, 2012 for SSS-NY-RIC-001WV wave-height sensor (A) and for October 29–31, 2012 for SSS-NY-RIC-004WL water-level sensor (B). Water level elevation (blue line) is shown in feet above NAVD 1988. Barometric pressure (yellow line) is shown in pounds per square inch. Time is shown in Eastern Standard Time. Data are provisional and subject to revision. Figures are available from the online mapper at: http://water.usgs.gov/floods/events/2012/sandy/sandymapper.html.

In contrast, eastern Suffolk County along the shore of the Peconic Estuary experienced less coastal flooding because maximum surge nearly coincided with astronomical low tide. Peak storm-tide elevation in this area ranged from 6.1 to 7.9 ft NAVD 88. The USGS real-time tide gage at Riverhead (01304562) and a nearby storm-tide sensor (SSS-NY-SUF-005WL) recorded maximum water-level elevations of 7.7 and 7.9 ft, respectively (Table 2.1), and the peak storm surge calculated at the Riverhead tide gage was approximately 9.2 ft (Figure 2.2c).

The northern shore of Nassau County along western Long Island Sound also experienced widespread coastal flooding. Overall, storm-tide data in this area ranged from 9.9 to 10.8 ft NAVD 88 (Table 2.1). The peak storm surge calculated in the area was approximately 11.5 ft (Figure 2.2d) at the West Pond tide gage (01302600), which nearly coincided with astronomical low tide, sparing surrounding communities from much greater flooding. For historical context, the Mill Neck stream gage (0130300) was established in 1937 and its highest recorded water level occurred during the unnamed 1938 hurricane (Busciolano et al., 2009). Although this permanent monitoring site was discontinued in 2011, both the temporary sensor (SSS-NY-NAS-006WL) and high-water mark (HWM-NY-NAS-700) from inside of the gage indicated water levels of 10.2 ft NAVD 88, only 0.06 ft less than the historical 1938 peak water-level elevation (C. Schubert, U.S. Geological Survey, written communications, 2014), which emphasizes both the historical nature of this storm and what could have happened if peak storm surge had occurred during high tide.

A summary of peak storm-tide data are shown for southeastern New York in Figure 2.4, which is derived from the permanent network of tide and stream gages, the short-term network of RDGs, storm-tide and wave-height sensors, and the post-storm collection of high-water marks. These data are also available in the interactive USGS online mapper at: http://water.usgs.gov/floods/events/2012/sandy/sandymapper.html. As evidenced by the red and pink circles, the western part of the study area – Richmond, Kings, Queens, and Nassau counties – experienced storm tide from about 8 to 19.5 ft NAVD 88. The yellow and blue circles, however, indicate that most of southern and eastern Suffolk County experienced storm tide of about 4 to 8 ft NAVD 88. For all peak storm-tide data, see McCallum et al. (2013).

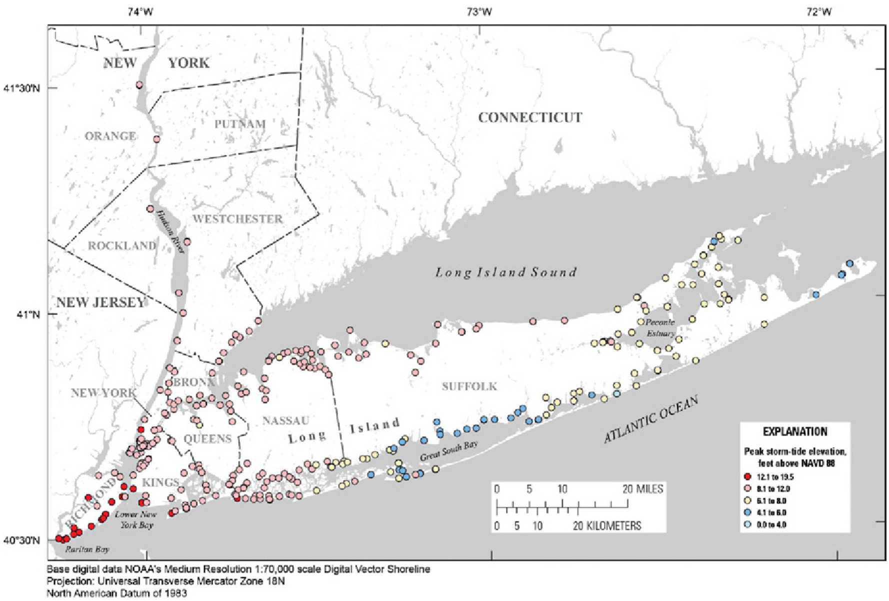

Fig. 2.4. Map showing peak storm-tide elevations produced by Hurricane Sandy in New York, in feet above NAVD 88. These data are also available from the USGS interactive storm-tide mapper at http://water.usgs.gov/floods/events/2012/sandy/sandymapper.html. Data are provisional and subject to revision.

2.4 SUMMARY AND CONCLUSIONS

In the days before Hurricane Sandy, the USGS installed numerous sensors along the northeastern coast of the United States to measure storm-tide elevation and provide the timing, water depth, and duration of storm-tide flooding. During Hurricane Sandy's approach and landfall, local emergency managers and NOAA forecasters were able to observe water levels in real time from the existing USGS network of tide gages and from the temporary RDGs installed in advance of the storm. As shown in Figure 2.4, the peak water levels recorded by the storm-tide sensors and surveyed HWMs ranged from 4 to 10 ft (above NAVD 88) in southern Suffolk County, from 6 to 8 ft in the Peconic Estuary of eastern Suffolk County, from 8 to 12 ft in northern Nassau County, and from 9 to 17 ft in New York City.

Data from permanent monitoring sites in the USGS network were used to compute the storm surge magnitude. The timing of peak storm surge relative to astronomical tide was extremely important. For example, along the south shores of New York City and western Suffolk County, the peak storm surge of 6–9 ft generally coincided with the astronomical high tide (Figure 2.2a and b), which resulted in widespread coastal flooding in these areas. In the Peconic Estuary and northern Nassau County, however, the peak storm surge of 9 ft and nearly 12 ft, respectively, nearly coincided with normal low tide (Figure 2.2c and d), which helped spare these communities from much greater coastal flooding.

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