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The Surge, Wave, and Tide Hydrodynamics (SWaTH) Network of the U.S. Geological Survey

Past and Future Implementation of Storm-Response Monitoring, Data Collection, and Data Delivery

Circular 1431

U.S. Department of the Interior
U.S. Geological Survey

Cover. Background images: Satellite images of Hurricane Sandy on October 28, 2012. Images courtesy of the National Aeronautics and Space Administration.
Inset images from top to bottom:
Top, sand deposited from washover and inundation at Long Beach, New York, during Hurricane Sandy in 2012. Photograph by the U.S. Geological Survey.
Center, Hurricane Joaquin washed out a road at Kitty Hawk, North Carolina, in 2015. Photograph courtesy of the National Oceanic and Atmospheric Administration.
Bottom, house damaged by Hurricane Sandy in Mantoloking, New Jersey, in 2012. Photograph by the U.S. Geological Survey.

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By Richard J. Verdi, R. Russell Lotspeich, Jeanne C. Robbins, Ronald J. Busciolano, John R. Mullaney, Andrew J. Massey, William S. Banks, Mark A. Roland, Harry L. Jenter, Marie C. Peppler, Tom P. Suro, Chris E. Schubert, and Mark R. Nardi

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

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Abstract

After Hurricane Sandy made landfall along the northeastern Atlantic coast of the United States on October 29, 2012, the U.S. Geological Survey (USGS) carried out scientific investigations to assist with protecting coastal communities and resources from future flooding. The work included development and implementation of the Surge, Wave, and Tide Hydrodynamics (SWaTH) network consisting of more than 900 monitoring stations. The SWaTH network was designed to greatly improve the collection and timely dissemination of information related to storm surge and coastal flooding. The network provides a significant enhancement to USGS data-collection capabilities in the region impacted by Hurricane Sandy and represents a new strategy for observing and monitoring coastal storms, which should result in improved understanding, prediction, and warning of storm-surge impacts and lead to more resilient coastal communities.

As innovative as it is, SWaTH evolved from previous USGS efforts to collect storm-surge data needed by others to improve storm-surge modeling, warning, and mitigation. This report discusses the development and implementation of the SWaTH network, and some of the regional stories associated with the landfall of Hurricane Sandy, as well as some previous events that informed the SWaTH development effort. Additional discussions on the mechanics of inundation and how the USGS is working with partners to help protect coastal communities from future storm impacts are also included.

U.S. Geological Survey scientist deploying an acoustic doppler current profiler to measure water velocity profiles in a new inlet formed during Hurricane Sandy on Fire Island, New York. Photograph by the U.S. Geological Survey.

Introduction

Hurricane Sandy made landfall on the New Jersey coast on October 29, 2012, and highlighted the vulnerability of the northeastern Atlantic coast of the United States to extreme tidal surges and coastal flooding (fig. 1). Following this devastating event, the U.S. Geological Survey (USGS) received $43.2 million in congressional supplemental appropriations from the U.S. Department of the Interior (DOI) to carry out scientific research needed to guide storm response, recovery, and rebuilding activities and to develop effective strategies for protecting coastal communities and resources from future storm-surge flooding.

Storms such as Hurricane Sandy have shown that energy from storm surge and waves is a primary driver of coastal-community destruction and dramatic changes to the coastal environment. With climate-change scientists predicting more frequent and intense storms and a greater risk of coastal flooding because of the effects of predicted sea-level rise (Horton and others, 2015), there is a need for increased scientific understanding of coastal processes. Reliably obtained and applied science can strengthen efforts to build resilient coastal communities before storms strike and guide response and recovery strategies after landfall.

Response activities by the USGS relating to Hurricane Sandy are guided by the USGS science plan for support of restoration and recovery (Buxton and others, 2013), which uses an integrated approach to understand the impact of the storm and to inform management decisions that support the recovery and restoration of coastal communities and natural resources and that enhance resilience in preparation for future floods. This comprehensive science plan facilitates the coordination of USGS activities with those of other agencies and stakeholders. New and ongoing research, along with supporting data collection and analysis, will focus on developing and refining understanding of past and potential future coastal-storm impacts in five thematic study areas:

- coastal topography and bathymetry data, to support hurricane impact assessment and response;
- impacts to coastal beaches and barrier islands;
- impacts of storm surge, including disturbed estuarine and bay hydrology;
- impacts on environmental quality, including exposure to chemical and microbial contaminants; and
- impacts to coastal ecosystems, habitats, and fish and wildlife, particularly for U.S. Department of Interior lands and trust resources.

Figure 1. Hurricane Sandy made landfall in the United States in New Jersey on the northeastern coast of the Atlantic Ocean on October 29, 2012. Satellite imagery from the National Aeronautics and Space Administration Geostationary Operational Environmental Satellite 13 shows the size of the hurricane on October 28, 2012, at 1:45 p.m. eastern daylight time.

The information presented in this report focuses on the components of the third theme—the Surge, Wave, and Tide Hydrodynamics (SWaTH) network and storm-response monitoring, data collection, and data delivery.

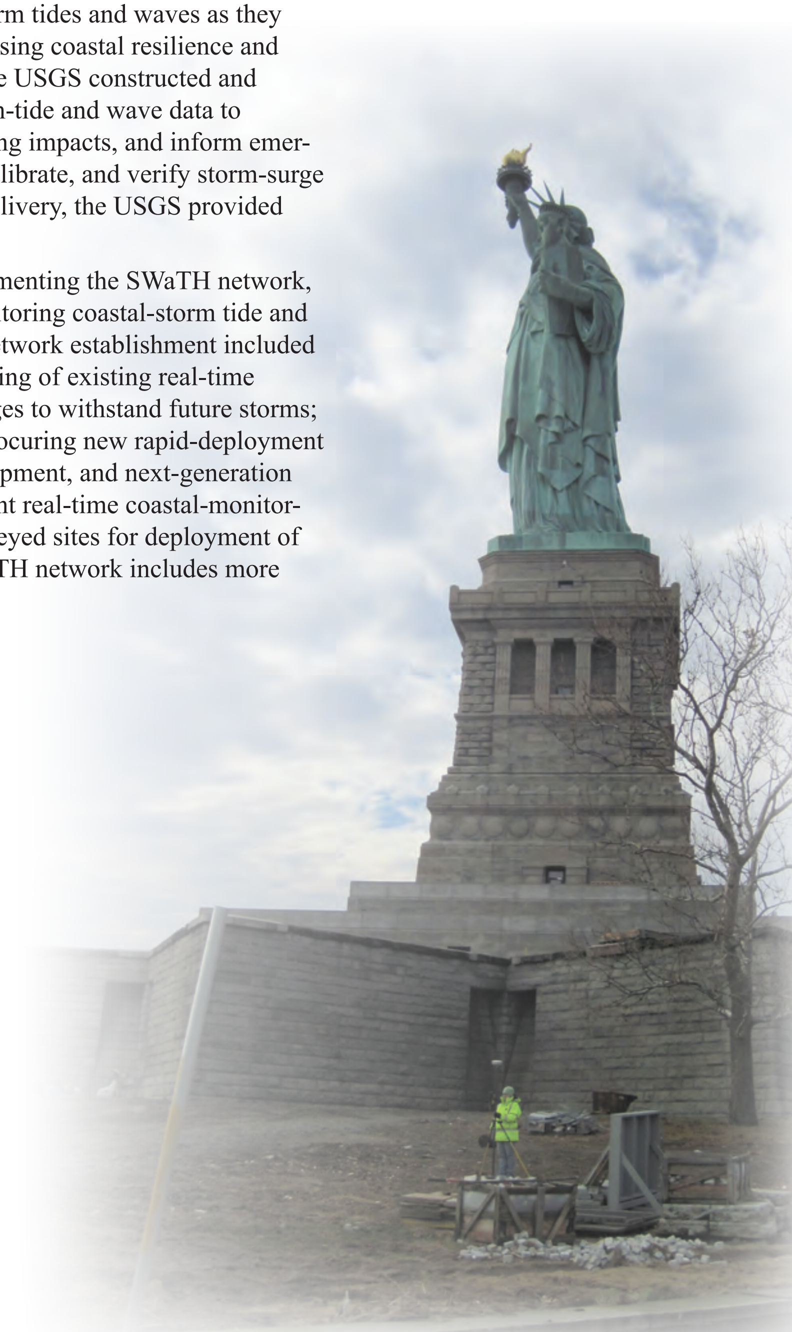
Following Hurricane Sandy, the USGS began construction of an overland SWaTH network along the northeastern Atlantic coast from North Carolina to Maine (fig. 2). This network, developed collaboratively with numerous Federal and State partner agencies, features the integration of long-term, permanent monitoring stations with real-time rapid-deployment gages and mobile storm-tide and wave sensors. Elevations for most SWaTH rapid-deployment gages and storm-tide and wave sensors have been pre-surveyed to the North American Vertical Datum of 1988 (NAVD 88) and equipped with preinstalled receiving brackets for quick deployment in advance of coastal storms and the timely recovery of instrumentation and dissemination of data in the hours and days immediately after a storm. Locations in the SWaTH network were selected according to the following criteria: a distributed array of stations representing the range of landscape types and infrastructure subject to surge and wave forces; subnetwork transects extending from the Atlantic shore coastline hundreds (and in a few cases, thousands) of feet through the inland resource of concern (for example, a wetland or coastal community); and storm-hardening of existing tide and river monitoring stations where new data can be integrated with long-term records.

Understanding the evolution and dissipation of overland storm tides and waves as they move across natural and manmade landscapes is critical to increasing coastal resilience and establishing early warning systems for coastal-storm hazards. The USGS constructed and implemented the SWaTH network (fig. 2) to provide timely storm-tide and wave data to enhance public awareness, help forecasters predict coastal-flooding impacts, and inform emergency responders, and to also provide data needed to improve, calibrate, and verify storm-surge models. To improve storm-tide data collection efforts and data delivery, the USGS provided the following:

- *Enhanced storm-tide monitoring capabilities.*—By implementing the SWaTH network, the USGS is able to improve its response time when monitoring coastal-storm tide and riverine flooding related to hurricanes and nor’easters. Network establishment included surveying reference points to the NAVD 88; flood-hardening of existing real-time coastal-monitoring stations and tidally affected streamgages to withstand future storms; increasing data collection and real-time capabilities by procuring new rapid-deployment gages, Global Navigation Satellite System surveying equipment, and next-generation storm-tide and wave sensors; installing new and permanent real-time coastal-monitoring; and developing a network of preselected and presurveyed sites for deployment of temporary sensors before future coastal storms. The SWaTH network includes more than 900 stations.

- *Enhanced data recovery and display capabilities through development of a short-term network (STN) mapper and database online application.*—The STN (http://wimcloud.usgs.gov/STN/) is a web-based set of tools that includes historical and newly established monitoring sites in an interactive database and map interface that aids in network creation and development, storm-response data management, capture and analysis of storm-tide data, and data and product delivery to the scientific community and the public. The STN will provide a unified and consistent source of current and archived storm-tide, wave, and high-water-mark (HWM) data.

Understanding the evolution and dissipation of overland storm tides and waves as they move across natural and manmade landscapes is critical to increasing coastal resilience and establishing early warning systems for coastal-storm hazards.



U.S. Geological Survey scientist surveying a high-water mark on Liberty Island, New York. Photograph by Michael Noll, U.S. Geological Survey.

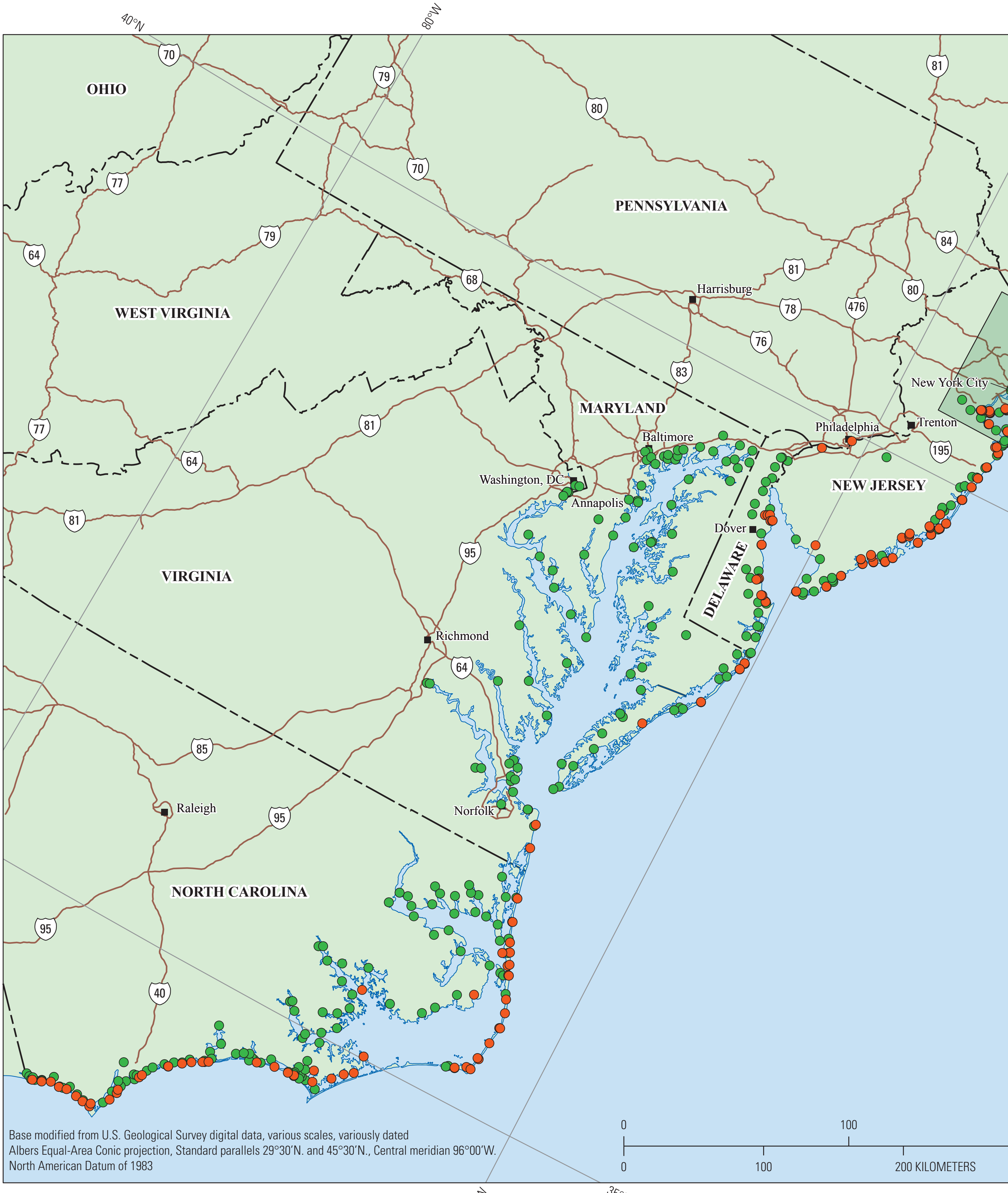
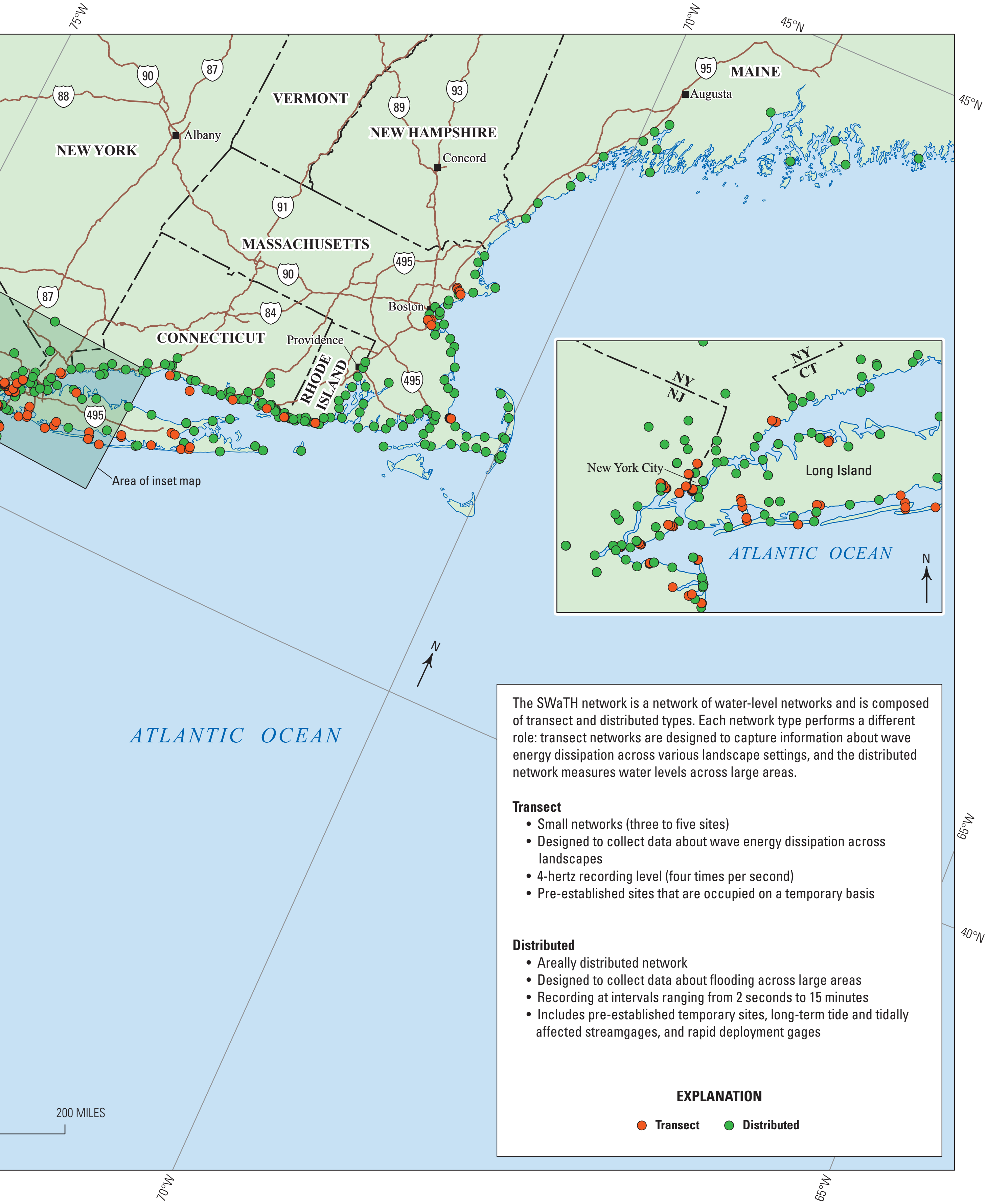


Figure 2. The Surge, Wave, and Tide Hydrodynamics (SWaTH) network.


75°W
70°W
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65°W
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NEW YORK
Albany
VERMONT
NEW HAMPSHIRE
Concord
MAINE
Augusta
MASSACHUSETTS
Boston
CONNECTICUT
Providence
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Area of inset map
NY
NJ
NY
CT
New York City
Long Island
ATLANTIC OCEAN
N
N
ATLANTIC OCEAN
200 MILES
The SWaTH network is a network of water-level networks and is composed of transect and distributed types. Each network type performs a different role: transect networks are designed to capture information about wave energy dissipation across various landscape settings, and the distributed network measures water levels across large areas.
Transect
• Small networks (three to five sites)
• Designed to collect data about wave energy dissipation across landscapes
• 4-hertz recording level (four times per second)
• Pre-established sites that are occupied on a temporary basis
Distributed
• Areally distributed network
• Designed to collect data about flooding across large areas
• Recording at intervals ranging from 2 seconds to 15 minutes
• Includes pre-established temporary sites, long-term tide and tidally affected streamgages, and rapid deployment gages
EXPLANATION
Transect
Distributed

Powerful waves erode beaches and destroy infrastructure along the shore.

Mechanics of Inundation

As a large storm approaches a coast, the extreme winds and rapidly changing air pressure cause the ocean surface to respond in ways that can have significant implications for the safety and economic well-being of coastal communities. Rising waters can flood coastal communities and cut off evacuation routes. Powerful waves erode beaches and destroy infrastructure along the shore. These storm-driven motions can range over spatial scales from meters to hundreds of kilometers and can range over time scales from seconds to many hours; as with weather forecasts, we have much to gain by being able to forecast these movements in a timely and accurate manner.

When forecasting oceanic responses to a large storm, having terminology (fig. 3) that describes each type of motion is particularly helpful, as each motion must be analyzed differently.

- Storm surge is the slow—over the course of minutes to hours—rise and fall of the ocean near the shoreline in response to the change of air pressure and to the force of the wind pushing large quantities of water onshore or offshore during the passing of a storm.
- Tide is the slow—over the course of hours to days—rise and fall of the ocean caused by centrifugal and gravitational forces from the rotation of the Earth and from orbital paths of the Earth, Sun, and Moon.
- Storm tide is the superimposed combination of storm surge and tide, observed at the coastline as flooding during the passage of a storm; storm tide inundates coastal towns and cuts off coastal evacuation routes.
- Storm waves are the rapid—over the course of seconds—rise and fall of the ocean surface caused by wind during the passage of a storm; storm waves are the short, choppy, breaking, quasiperiodic motions that are superimposed on top of the storm tide; when storm waves break or crash against the beach and coastal structures, significant energy is expended commonly resulting in the destruction of beaches, roads, piers and buildings. Storm waves also force water up onto the beach. Wave setup is the mean level of wave-induced uprush of water above the storm tide, and wave runup is the maximum vertical extent of the uprush.

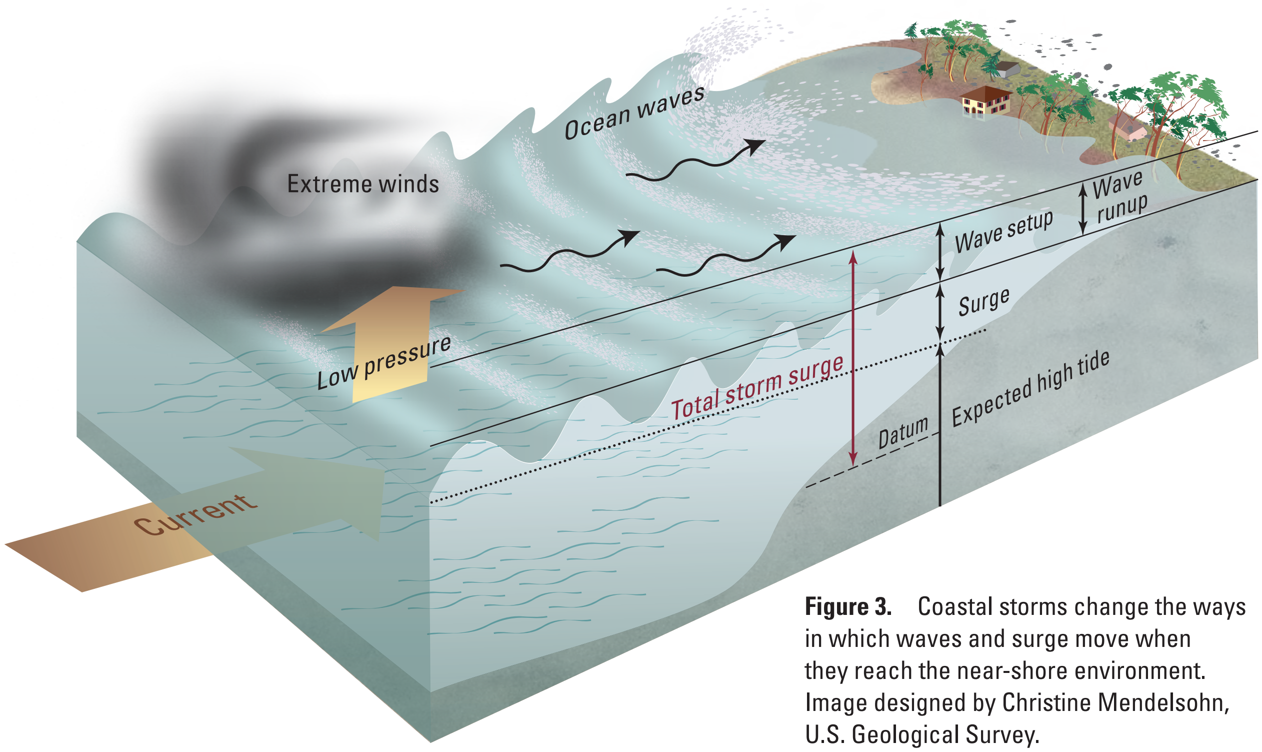


Figure 3. Coastal storms change the ways in which waves and surge move when they reach the near-shore environment. Image designed by Christine Mendelsohn, U.S. Geological Survey.

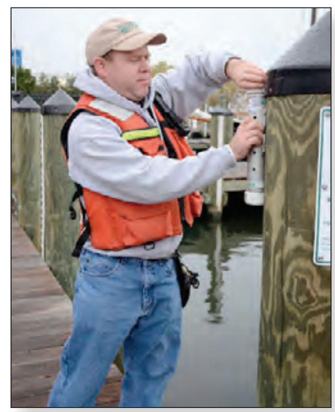
Most operational coastal-flooding forecast models include storm-surge and storm-wave modeling components. The former is used to estimate the spatial and temporal distribution of water depths and flows, and the latter is used to estimate the spatial and temporal distribution of wave heights and wave energy during a storm. The SWaTH network is designed to collect data from all these components employing a broad, aerial coverage with intense temporal resolution of as little as 0.25 second. Networked together, the data represent thousands of individual snapshots of the entire near-shore and overland water surface (tide, surge, and waves) throughout the approach, landfall, and retreat of storm-driven coastal flooding.

The USGS provides critical information on near-shore storm hydrodynamics data for emergency response and resource allocation decision making before, during, and immediately after landfall of hurricanes and nor'easters.

USGS Storm Response Since 1993

Storm-tide flooding historically has been a post-storm activity, involving the collection and preservation of HWMs after the passage of a storm. Once the HWMs were identified and preserved, subsequent surveys followed to determine their elevation. This process, however, can be long and arduous, with the need to rapidly flag HWMs in a timely manner and then to survey in the HWMs before they are affected by subsequent events or disturbed by public or private storm-cleanup activities. Historically, the USGS has been involved in the collection and preservation of HWMs, often working with Federal partners, State and local governments, and academic institutions to adequately document storm impacts for use in scientific endeavors including the calibration and validation of models used to forecast storm surge (Buxton and others, 2013).

SWaTH is a product of the continued, though somewhat episodic evolution of USGS coastal flooding data-collection capabilities and strategies. For decades, the USGS has provided critical information on near-shore storm hydrodynamics data for emergency response and resource allocation decision making before, during, and immediately after landfall of hurricanes and nor'easters. Prior to SWaTH, much of this information was provided by way of a few real-time tide gages (Hoppe, 2007) that supplemented and extended the National Oceanic and Atmospheric Administration (NOAA) tidal gage network but focused on near-shore and shallow coastal waters. The USGS gages, however, were rarely storm-hardened and were often overtopped or damaged during storms, causing loss of continuous data.



U.S. Geological Survey scientist recovering a storm-surge sensor after Hurricane Sandy in Annapolis, Maryland. Photograph by the U.S. Geological Survey.

To supplement the tidal gage network, HWMs were frequently obtained at the gages and along coastlines to provide documentation after a storm for land-use planning, improvement of building codes, and evaluation of storm-surge forecast models. However, HWMs do not provide adequate information for modeling because they inform the modeler only about the maximum storm tide, but do not provide information about when or why that maximum occurred.

When the category 5 Hurricane Katrina made landfall (August 29, 2005) near Pearlington, Mississippi (not shown), and Slidell, Louisiana (not shown), many of the tidal and coastal streamgages in the area were damaged by storm flooding. Less than a month later, on September 26, Hurricane Rita, also a category 5 hurricane, made landfall just west of the Texas-Louisiana border and caused substantial flooding in many of the same areas as Hurricane Katrina. Because there had not been enough time to repair all the gages in the area, the USGS developed an innovative way to use equipment on hand: small pressure transducers that were typically used for groundwater monitoring and experimentally in crest-stage gages in support of "continuous-slope area computations" (Smith and others, 2010) were hung in small protective housings and deployed close to the ground. Because the sensors were deployed as the storm was forming and moving toward land, there were no pre-established or presurveyed sensor sites. This situation delayed the deployment of sensors as hydrographers sought to identify appropriate locations. The lack of pre-established or presurveyed sensor sites also hampered the swift delivery of the resulting data because the elevations of the sites had to be surveyed to the NAVD 88 datum after the storm. The Hurricane Rita data were collected, processed, and then released in McGee and others (2006).

In the decade since Hurricane Rita, USGS storm-response activities focused on providing storm-tide data to researchers working to improve storm-tide models.

U.S. Geological Survey scientists installing a rapid deployment gauge to measure water-surface elevation and other data in Myrtle Beach, South Carolina, in October 2016, prior to Hurricane Matthew reaching the eastern coast of the United States. Photograph by Chris Henry, U.S. Geological Survey.

During the next 6 years, the USGS has followed a similar plan for coastal storm deployment. Supplemental water-level data and HWMs were collected and frequently though not always published for a series of storms:

- Hurricane Rita (gulf coast)—September 2005 (McGee and others, 2006)
- Hurricane Wilma (southern Florida)—2005 (Soderqvist and Byrne, 2007)
- Hurricane Ernesto (east coast)—August 2006 (unpublished)
- Hurricane Humberto (gulf coast)—September 2007 (unpublished)
- Hurricane Gustav (gulf coast)—September 2008 (McGee and others, 2008)
- Hurricane Ike (gulf coast)—September 2008 (East and others, 2008)
- Hurricane Earl (east coast)—September 2010 (unpublished)
- Hurricane Irene (east coast)—August 2011 (McCallum and others, 2012b)
- Hurricane Isaac (gulf coast)—August 2012 (McCallum and others, 2012a)
- Hurricane Sandy (east coast)—October 2012 (McCallum and others, 2013)

In the decade since Hurricane Rita, USGS storm-response activities have focused on providing storm-tide data to researchers working to improve storm-tide models. The storm-response activities used centralized caches of water-level sensors and rapid-deployment gages to locations identified for a particular storm. The USGS collected substantial coastal data during and after Hurricane Sandy to promote the understanding of storm tides (McCallum, 2013). Following Hurricane Sandy, the USGS established the SWaTH network along the Atlantic coast from North Carolina to Maine to improve the data-collection process and provide needed storm-tide, wave, and selected metrological data to further aid understanding of storm-surge impacts and help emergency managers with storm response.

There was a dramatic shift in delivering the data to the end user during the Hurricane Irene response efforts in 2011. For previous storms, the data had been collected and surveyed several months after the storm and delivered by way of a traditional USGS series report within a year. As the storm deployments were underway for Hurricane Irene, the USGS built an online data delivery system (a mapping application and database) to make the data available to decision makers faster than previously possible. Emergency management personnel need data as soon as possible following an event to support emergency response in flooded areas. The faster turnaround was at the request of the Federal Emergency Management Agency (FEMA); with a new data system in place and recent staff training, the USGS personnel were able to collect the sensors and survey the locations in less time than it took for previous storms. As a result, decision makers were able to use preliminary data within days of when Hurricane Irene made landfall, and a report was published 6 months later.

Similar efforts were mounted for Hurricanes Isaac and Sandy, with more sites deployed and faster delivery of the data. With Hurricane Isaac, efforts were better coordinated to determine prelandfall sites for sensor deployment. For Hurricane Sandy, the largest effort to date, the USGS focused on surveying HWMs and increasing the processing and data delivery efficiency.

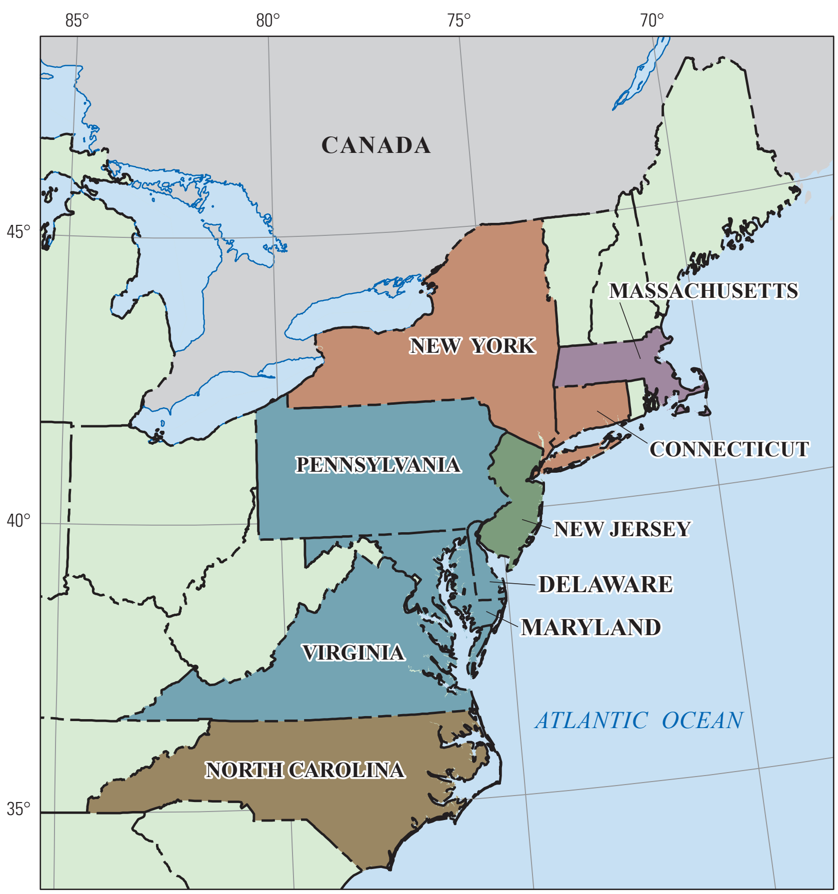
Since 2011, the USGS has been working on a system to more efficiently collect, deliver, and archive these short-term, high-frequency pressure-transducer data and HWMs. By establishing a database to store the surveyed locations, the sensors can be deployed and the data can be retrieved and processed faster than before. Following the quiet seasons in terms of storm and flooding in 2013 and 2014, the STN system was developed to support data collection, approval, and delivery using the flood event viewer (http://water.usgs.gov/floods/FEV/).

Regional Stories

Five regional stories (fig. 4) presented here illustrate past USGS storm-surge monitoring activities and the effect the work has had on understanding local storm-surge and data uses. These studies also examine how the SWaTH network may help local, State, and Federal agencies and the coastal communities they serve better prepare for future coastal storms and access and respond to the flooding that will follow. The following regional stories are presented in this report:

- North Carolina—Historic storms and their impacts on the State, with particular emphasis on barrier islands and beaches;
- Mid-Atlantic States (Pennsylvania, Maryland, Delaware, and Virginia)—Overview of the impacts of Hurricane Sandy on this region;
- New Jersey—Effects of storm-tide flooding caused by Hurricane Sandy at two coastal communities;
- New York and Connecticut—Examination of the impacts of Hurricane Sandy, timing of maximum storm tide, and comparison with past storms; and
- Massachusetts—Exploring the history that set the stage for recent and future property loss.

U.S. Geological Survey scientist installing an auxiliary wave sensor at U.S. Geological Survey station 01409335, Little Egg Inlet near Tuckerton, New Jersey. Photograph by Michal Niemonczynski, U.S. Geological Survey.



Base modified from U.S. Geological Survey digital data, 1:10,000,000, variously dated
Universal Transverse Mercator projection, zone 18N
North American Datum of 1983

0 200 400 MILES
0 200 400 KILOMETERS

Figure 4. The areas of the five regional stories in this report.

U.S. Geological Survey scientists installing storm surge sensors before Hurricane Sandy. Photograph by Christopher Schubert, U.S. Geological Survey.

North Carolina

The barrier islands, estuaries, and sounds of North Carolina are among the most valuable resources for the State and include more than 3,000 miles of tidal shoreline (fig. 5). The Albemarle-Pamlico estuary system is the second largest estuarine complex in the United States, second only to the Chesapeake Bay, and drains an area more than 30,000 square miles. This complex and dynamic system can be greatly affected by storm events, including tropical storms and nor'easters.

Tropical storms and nor'easters, which typically can produce high winds and heavy rains, can wreak havoc on the coastal system in North Carolina. In some cases intense coastal storms can create new inlets from ocean overwash and

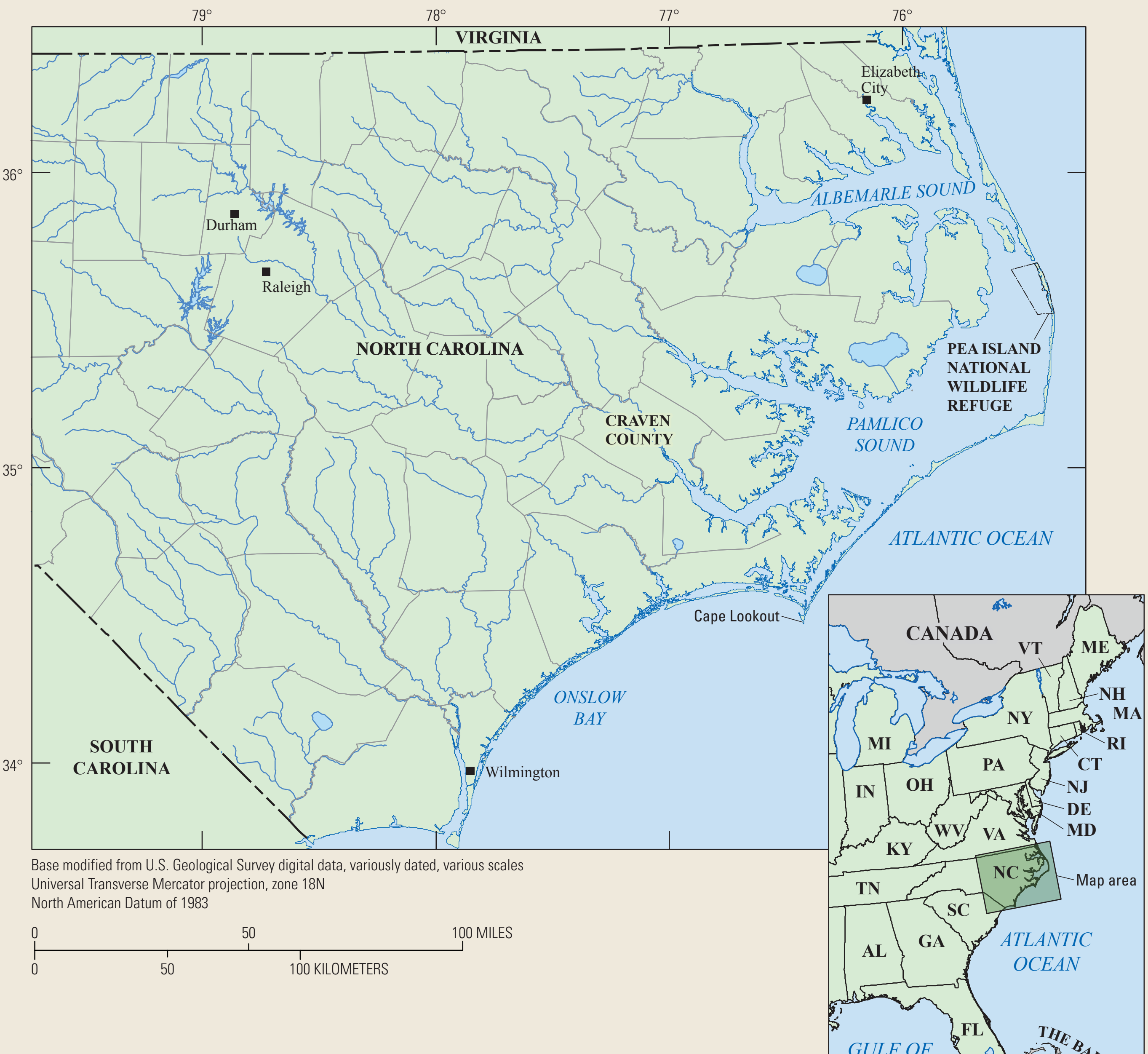


Figure 5. Barrier islands are one of the main characteristics of the coast of North Carolina.

sound-side flooding and inundate vast areas of coastal North Carolina. The frequency or estimated return period for hurricanes passing within 50 miles of the coast of North Carolina is generally 5 to 7 years, the highest frequency of any coastal area along the Atlantic and gulf coasts (fig. 6).

North Carolina has a long history of hurricane impacts, from historic events such as Hurricane Hazel in 1954 still resonating in the minds of residents to more recent damaging events, including the passage of Hurricane Irene in August 2011. Hurricane Hazel brought widespread damage and destruction to the State at the same time as providing much needed relief from an extreme drought in eastern North Carolina where many rivers were at or near minimum recorded flows. Hurricane Hazel also brought saltwater intrusion in many North Carolina estuaries at or near the maximums witnessed; storm tides associated with the event along the coast drove saline water far upstream in many localities. The probability of two such rare events (drought followed by storm-driven saltwater intrusion) happening concurrently was not known but has since been reported by Giese and others (1985) to have a recurrence interval that may be reckoned in hundreds of years. USGS streamgage networks reported the impacts of inland flooding related to rainfall associated with Hurricane Hazel; however, a systematic program for storm tide documentation was not in place at that time. The U.S. Weather Bureau (now known as the National Weather Service) in Raleigh reported that "all traces of civilization on the immediate waterfront between the State line and Cape Fear were practically annihilated," and Davis (1954, p. 372–373) stated that "every pier in a distance of 170 miles of coastline was demolished."

In recent history, Hurricane Irene brought substantial flooding to eastern North Carolina. The storm intensified to a category 3 hurricane in the Atlantic Ocean as it hit the Bahamas, but gradually weakened and made landfall near Cape Lookout, N.C., as a category 1 hurricane, still causing widespread damage across a large part of the eastern United States (Avila and Cangialosi, 2011). Hurricane Irene was the first hurricane to hit the United States since Hurricane Ike struck Texas in 2008 and was the first to threaten the New York City area since Hurricane Gloria in 1985 (National Oceanic and Atmospheric Administration, 2011). Hurricane Irene was reported by NOAA to be the 10th billion dollar disaster in 2011. The passage of Irene resulted in several breaches across

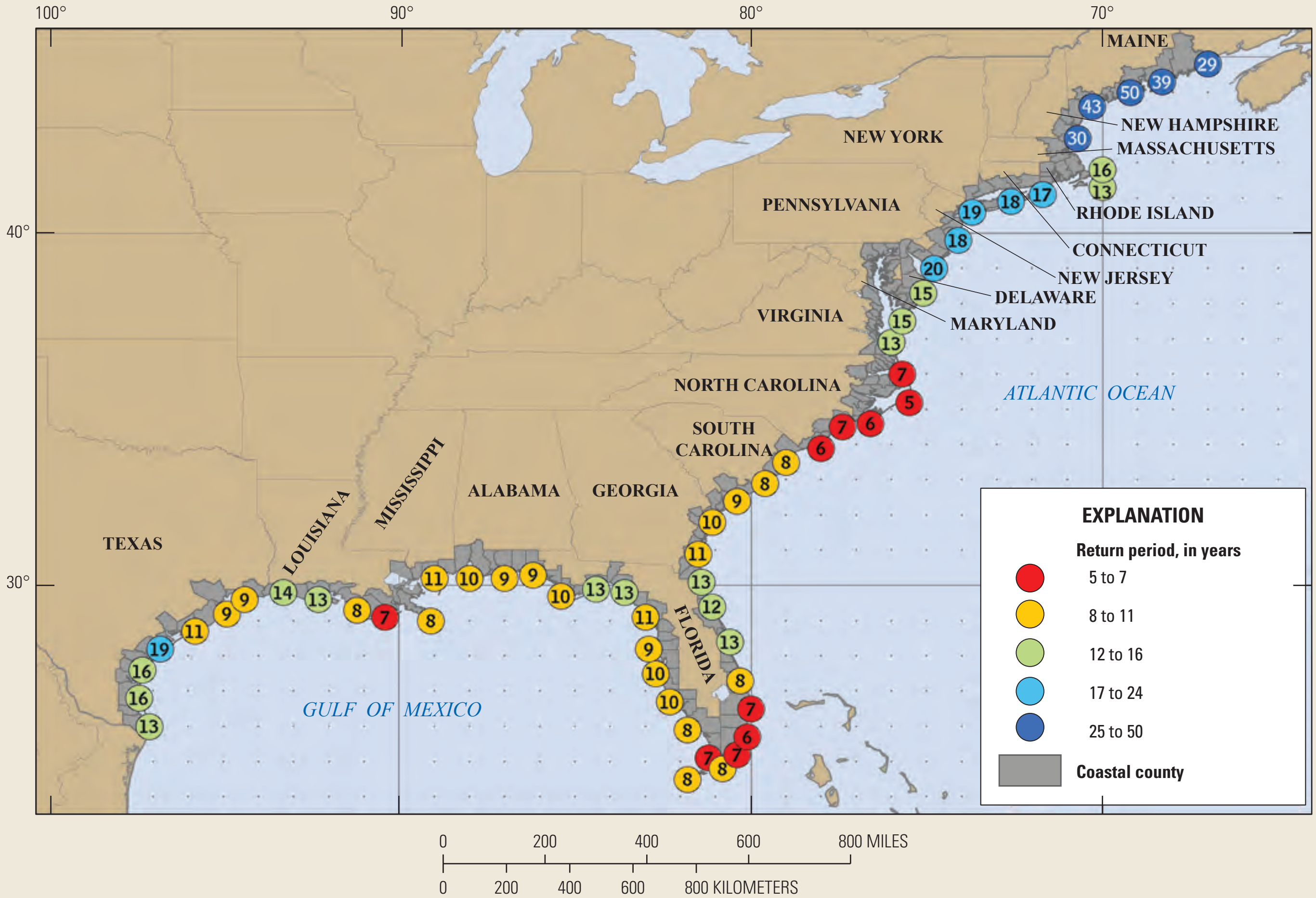


Figure 6. Hurricanes return to the eastern and southern coasts of the United States as much as every 5 to 50 years. Map modified from National Oceanic and Atmospheric Administration (2015b).

the barrier islands and widespread storm-tide flooding across the coastal plain of North Carolina.

One of the barrier island breaches just south of the Pea Island National Wildlife Refuge severed North Carolina Highway 12 and effectively cut off access to the barrier islands south of the breach. The USGS reported that ocean-side surge and subsequent sound-side flooding (as the winds blew from west to east across the vast Pamlico Sound) contributed to the breach (fig. 7). A temporary bridge was subsequently installed to restore access to these areas, which remained in place until March 2016 when construction of an interim bridge replacement project began. The interim bridge will be easier to maintain and provide safe access pending the results of a North Carolina Department of Transportation study of permanent solutions for maintaining access at Pea Island.

After the passage of Hurricane Emily in 1993, the USGS identified a total of 108 HWMs on the outer banks of North Carolina. Sixty-two of these HWMs were subsequently selected to provide a representation of the flooded area and surveying was completed to determine the latitude, longitude, and elevation of each mark. After the passage of Hurricanes Bertha and Fran in 1996, the USGS also collected HWMs in coastal surge-affected environments and in riverine settings where inland flooding from excess rainfall also was evident. HWM data collection in riverine environments after the passage of Hurricane Floyd in 1999 was the primary post-storm data collection activity by the USGS in North Carolina. This post-storm data collection supplemented the monitoring of inland streamgages and measurement of streamflow used to document this epic event, which resulted in flooding in excess of the 500-year (0.20-percent exceedance) event in each of the major coastal river basins in the State (Bales and others, 2000). Hurricane Floyd and events just before and after the storm resulted in 2 months of flooding in eastern North Carolina, with rainfall totals for September through October 1999 exceeding 30 inches in some locations, or more than one-half the annual rainfall average (Bales and others, 2000) for the region.

With the advent of the mobile storm-tide network developed by the USGS in Ruston, Louisiana, after Hurricane Katrina, storm-tide monitoring became a prestorm and post-storm event that has allowed for the collection of peak (or HWM) data for the documentation of storm-tide and inland riverine flooding at ungaged locations and has provided time series data of the entire storm-tide flood. Placement of small, submersible pressure transducers in advance of coastal storms and at locations forecast to be affected by storm-tide flooding has allowed the USGS to supplement traditional HWM data with information about the flood timing and about the rise, fall, and duration of the event. In North Carolina, these mobile storm-tide networks were deployed for Tropical Storm Ernesto (2006), Hurricane Earl (2010), and Hurricane Irene (2011).

The largest deployment of the mobile storm-tide network in North Carolina was for Hurricane Irene and consisted of 42 storm-tide sensors and 19 barometric pressure sensors. This deployment was part of a large effort of storm-tide sensor deployments from South Carolina to Maine, where 224 locations were monitored for storm tide. Independent HWMs were also collected at an additional 137 locations. Storm-tide elevations above 7 feet relative to the NAVD 88 were reported in selected areas in Craven County, N.C. (fig. 8).

With the passage of Hurricane Sandy and in accordance with the USGS Hurricane Sandy science plan (Buxton and others, 2013) to provide continued data collection and analysis for severe coastal storms and to ensure support for recovery and restoration efforts, the mobile storm-tide network has evolved to include permanent locations with known elevations that can quickly be instrumented with sensors. In North Carolina, the USGS has identified more than 150 locations that can be considered for storm-tide sensor deployment in

Figure 7. Satellite images show the effects of Hurricane Irene on North Carolina State Highway 12 south of Pea Island National Wildlife Refuge, N.C. (not shown), in *A*, March 2011 and *B*, August 2011. Images from Google Earth, accessed March 28, 2015.

advance of future storms expected to make landfall. With the passage of Hurricane Matthew off the coast of the southeastern United States in October 2016, the USGS deployed its largest network of storm-tide sensors to date. A temporary network of water-level and barometric pressure sensors were deployed at 288 locations along the Atlantic coast from Florida to North Carolina to record the timing, areal extent, and magnitude of hurricane storm tide and coastal flooding. The collection of 543 HWMs following Matthew was the second largest HWM recovery effort after Hurricane Sandy in 2012.

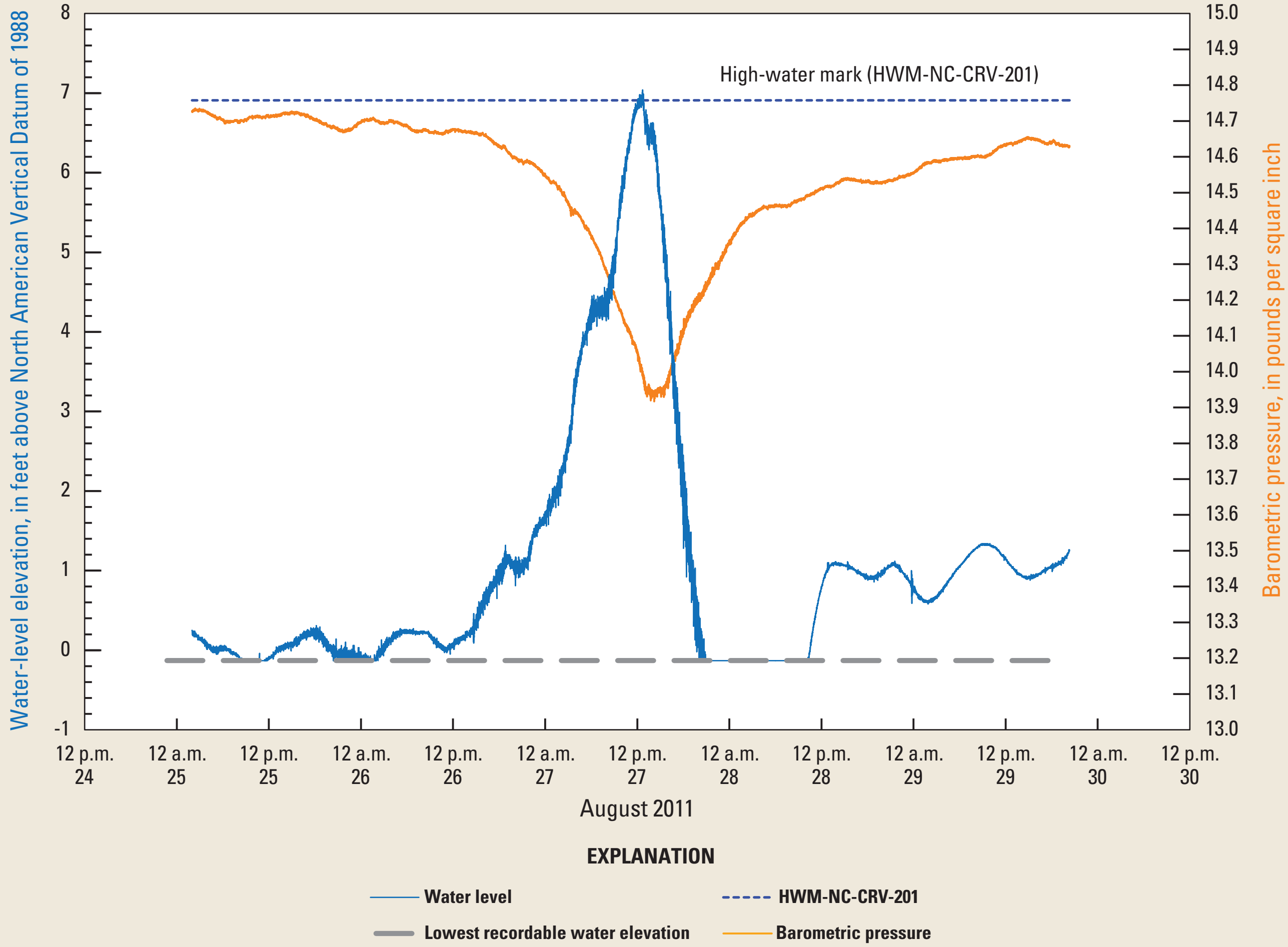


Figure 8. In general terms, as barometric pressure drops, the elevation of the storm tide rises, as happened during Hurricane Irene between August 24 and 30, 2011, at a high-water mark recorded at the Bridgeport Hotel and Marina in Craven County, North Carolina. Graph modified from McCallum and others (2012b).

House damaged by Hurricane Irene. Photograph by Jonathan J. Graham, U.S. Geological Survey.

Mid-Atlantic States

The Mid-Atlantic region of the east coast comprises Pennsylvania, Maryland, Delaware, and Virginia. In this region, three coastal water bodies are impacted by tropical systems and nor'easters: the Delaware River, the Delaware Bay, the Chesapeake Bay, and the Atlantic Ocean (fig. 9). Each system has its own unique hydrology, land use, and population matrices that create varying degrees of issues related to coastal flooding and other impacts.

The Delaware River and Delaware Bay form a natural boundary between parts of New York, Pennsylvania, New Jersey, and Delaware. The total length of the Delaware River is approximately 400 miles, which drains more than 11,000 square miles of land-surface area (Encyclopedia Britannica, 2014). The Delaware River is subject to tidal influence from the Atlantic Ocean through the Delaware Bay, continuing upstream to Trenton, N.J., which is about 130 miles above the mouth of the Delaware River. The Delaware River flows between the cities of Philadelphia, Pa., and Camden, N.J. Philadelphia is the fifth largest city (by population) in the United States (U.S. Census Bureau, 2010). The lower end of the Delaware River and estuary host the world's largest horseshoe crab population and an active commercial fishery, yet are marked by heavy industry and busy shipping traffic (Delaware Riverkeeper Network, 2016). To facilitate traffic on the river, channels have been dredged from the Delaware Bay to Philadelphia and from Philadelphia to Trenton (Encyclopedia Britannica, 2014).

The Chesapeake Bay is a 200-mile-long estuary that lies between the eastern edge of North America and the Delmarva Peninsula (Phillips, 2001). The Chesapeake Bay watershed includes parts of six States and Washington, D.C. The Susquehanna River feeds the northern part of the Chesapeake Bay, with the Potomac, Rappahannock, York, and James Rivers serving as the major tributaries travelling south to the mouth of the Chesapeake Bay. The Chesapeake Bay and its adjoining estuaries are subject to tidal influence from the Atlantic Ocean upstream from the Fall Line, which runs from Roanoke Rapids, N.C., through Washington, D.C., and into Philadelphia (fig. 9).

Much of the Chesapeake Bay region is rural with agriculture forming a large component of land use. Increased runoff and pollution have created major issues in the Chesapeake Bay, especially affecting the lucrative shellfish industry. Major cities along the Chesapeake Bay are Baltimore and Annapolis, Md., and the sprawling Hampton Roads, Va., metropolitan region near the mouth of the bay. Hampton Roads is a large natural harbor, incorporating the mouths of the Elizabeth, James, and Nansemond Rivers along with several smaller rivers and emptying into the Chesapeake Bay near its mouth. Hampton Roads is populated by more than 1 million people and is home to Naval Station Norfolk, the largest naval complex in the world (U.S. Department of the Navy, 2016). The combination of population demands, geography, and topography of the Hampton Roads region has contributed to above-average land subsidence rates, which, in combination with sea-level rise, have raised concerns about the long-term viability of this area (Eggleston and Pope, 2013).

Parts of Delaware, Maryland, and Virginia front the Atlantic Ocean. A robust network of barrier islands along the coast dampen some of the impacts from storms, but resort communities such as Rehoboth Beach, Del., Ocean City, Md., and Chincoteague Island, Va., are all subject to substantial coastal flooding and erosion issues that result from coastal storms. Much of the Atlantic coast in this area is not heavily developed or populated; nonetheless, the area has unique marine and terrestrial habitats, provides a buffer to the mainland against storms, and is the home to national infrastructure such as the National Aeronautics and Space Administration Wallops Flight Facility in Chincoteague, Va., and the Virginia Commercial Space Flight Authority Mid-Atlantic Space Port on Wallops Island, Va. (Banks and others, 2012).

Impacts of Hurricane Sandy

Hurricane Sandy began to batter the Mid-Atlantic coast during the afternoon of October 29, 2012. Within hours, the storm surge from the westward moving hurricane coupled with a high tide was causing unprecedented damage along the eastern seaboard. In Baltimore, 150 miles south of Atlantic City, N.J., where the storm made landfall, rain from the storm continued to fall through October 30, producing 6.8 inches of precipitation. As Hurricane Sandy continued west into Pennsylvania, a strong southeasterly flow on the backside of the storm directed up Delaware Bay produced dangerously high water levels in the tidal sections of the Delaware River at and near Philadelphia.

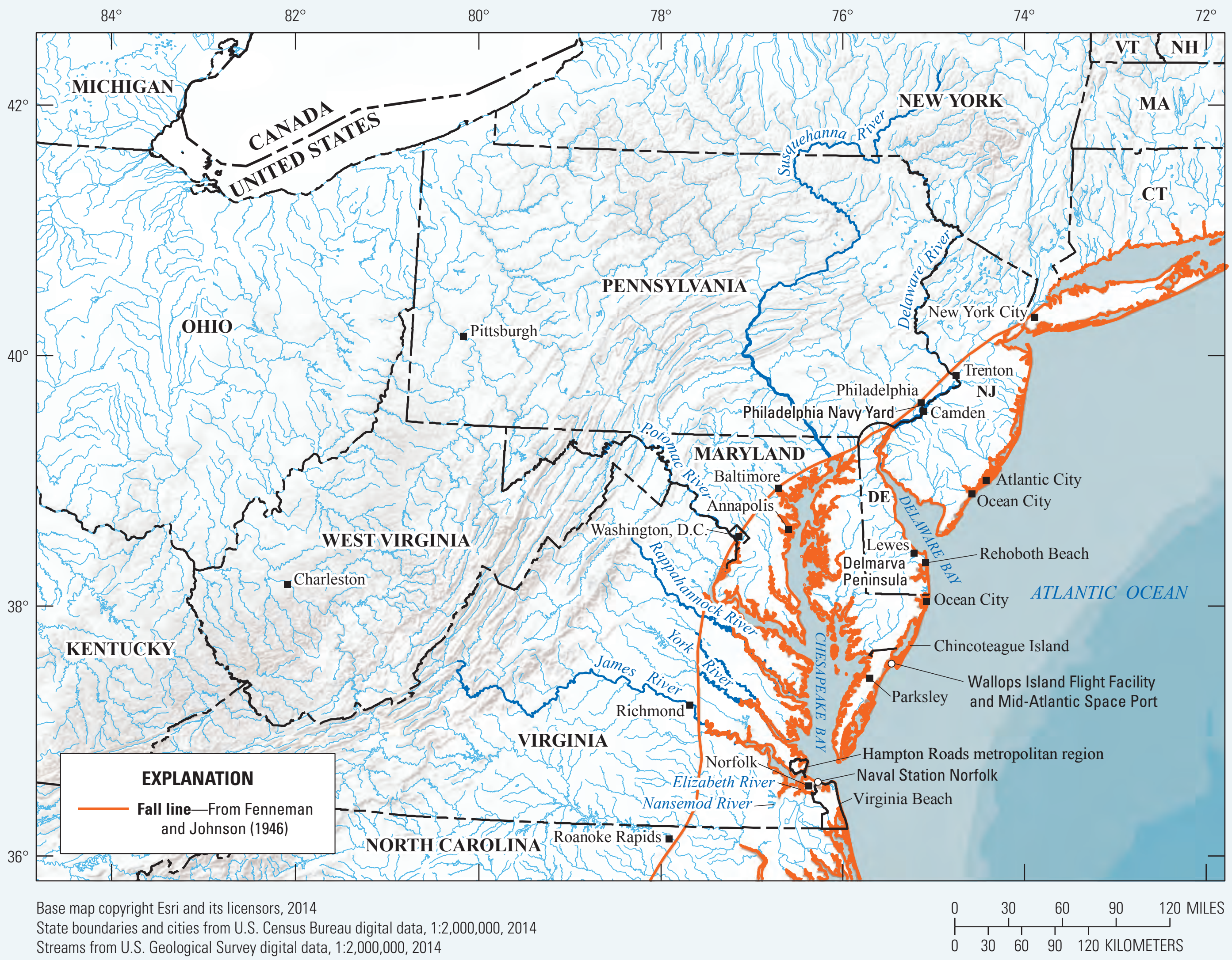
For nearly 3 days during the storm, commuter train and bus services in the Baltimore-Washington area were inoperative and schools and government offices were closed. Damages in Ocean City, Maryland's Atlantic beach resort, included the destruction of an iconic fishing pier, whereas further west, cars were stranded and roads were closed as a result of heavy snows. Hurricane Sandy provided some areas of the Mid-Atlantic region with damaging wind gusts, especially in New Jersey and eastern Pennsylvania, resulting in many downed trees and power lines.

At the Philadelphia Navy Yard, a peak water-surface elevation of 7.5 feet exceeded the top of the protective seawall and bulkhead by approximately 1 foot. Near Lewes, Del., the peak water level recorded was 8.2 feet, and further south on the Chesapeake Bay side of the Delmarva Peninsula, water levels reached just over 6 feet on Hunting Creek near Parksley, Va. (U.S. Geological Survey, 2012).

Tidal Monitoring by the USGS

In advance of Hurricane Sandy, the USGS water science centers in Delaware, Maryland, Pennsylvania, and Virginia, deployed a variety of temporary water-level monitors throughout the region. The locations for the sensors were determined in the field as crews searched for places to install them; in most cases, little preplanning went into the site selection or surveying at any of these locations. In the end, 27 sensors were deployed and 31 HWMs were retrieved. None of these sensors were real-time, meaning that the data were not transmitted to the database on an hourly basis, as is done with other continuous recording streamgages and groundwater observation wells.

With the development and implementation of the SWaTH network, the USGS water science centers in the Mid-Atlantic region now [2016] have 20 temporary real-time rapid-deployment gages along with 129 temporary storm-tide and wave sensors. Additionally, 17 permanent real-time tide gages have been installed as part of this effort in cooperation with Federal, State, and local entities. As a result, the coastal communities of the Mid-Atlantic States will now have much more real-time data available to make better-informed decisions, and modelers will have more data available to enhance existing and develop new storm-surge models.



Base map copyright Esri and its licensors, 2014
State boundaries and cities from U.S. Census Bureau digital data, 1:2,000,000, 2014
Streams from U.S. Geological Survey digital data, 1:2,000,000, 2014
Universal Transverse Mercator projection, zone 18N
North American Datum of 1983

Figure 9. The rivers and streams of the Mid-Atlantic region drain into three main waterbodies that are impacted by tropical systems and nor'easters.

New Jersey

Although Hurricane Sandy made landfall near Atlantic City, the effects to coastal communities were measurably different for areas on the north (or the right side) of the storm compared with communities to the south (or the left side) of the storm. Tropical systems like hurricanes have a counterclockwise rotation; as hurricanes approach the east coast, the upper-right quadrant of the storm can be considered the most dangerous area for creating wind driven storm tide and surge (Graham and Riebeek, 2015). For Hurricane Sandy, the National Weather Service reported sustained onshore winds of 50 to 60 miles per hour along the coast of New Jersey from north of Atlantic City to New York City, with much higher speeds for wind gusts.

The USGS tide gages in the areas of Cape May and the Wildwoods recorded new period-of-record maximum tide elevations resulting from the effects of Hurricane Sandy (figs. 10 and 11). The USGS tide and tidal crest-stage gages near Cape May, North Wildwood, and Wildwood recorded

Figure 10. The surge at Cape May on October 29, 2012, during Hurricane Sandy reached as much as 6 feet, whereas the tide gages at Raritan Bay, Sea Bright, and Point Pleasant recorded surges between 8 and more than 12 feet.

peak storm-tide elevations that ranged from about 5 to 7 feet above NAVD 88. Although the storm tide was a new record elevation for Cape May Harbor, the peak storm tide was slightly out of phase with the predicted astronomical high tide, which resulted in the estimated peak storm surge being computed between high and low tide. The peak storm surge for the USGS Cape May Harbor at Cape May tide gage (USGS station 01411390; fig. 10) was estimated to be greater than 6 feet above NAVD 88 in the evening of October 29, 2012.

For the communities to the north along the coast of New Jersey, the conditions and events were different. The communities north of Atlantic City were on the right side of the storm and as a result experienced much higher storm tides associated with this storm. As Hurricane Sandy turned and approached the coast, the extremely wide wind field was directed onshore from the east. The USGS tide gages in the areas of Point Pleasant and Sea Bright recorded much higher wind-driven storm tides with peak storm-tide elevations in excess of 9 feet above NAVD 88 (figs. 10 and 11). In addition to stronger winds directed onshore, the timing of the storm tide with the predicted tide was more in phase for the areas of Point Pleasant, Sea Bright, and Raritan Bay. The estimated storm surge for the Point Pleasant (USGS station 01408050) and Sea Bright (USGS station 01407600) tide gages was greater than 8 feet, and for Raritan Bay at the USGS tide gage at Keansburg, N.J. (USGS station 01407081), greater than 12 feet.

The average elevation at the communities of Cape May and Wildwood is generally less than about 9 feet above NAVD 88, whereas the general elevations of selected locations in the areas of Point Pleasant and Sea Bright are generally at or above about 8 to 9 feet above NAVD 88. The storm track and magnitude of Hurricane Sandy made it an extremely dangerous storm for all communities along the coast of New Jersey, but strong winds directed onshore from the east in combination with high tide produced higher peak tide elevations for communities to the north of where the eye of the storm made landfall than for communities to the south.

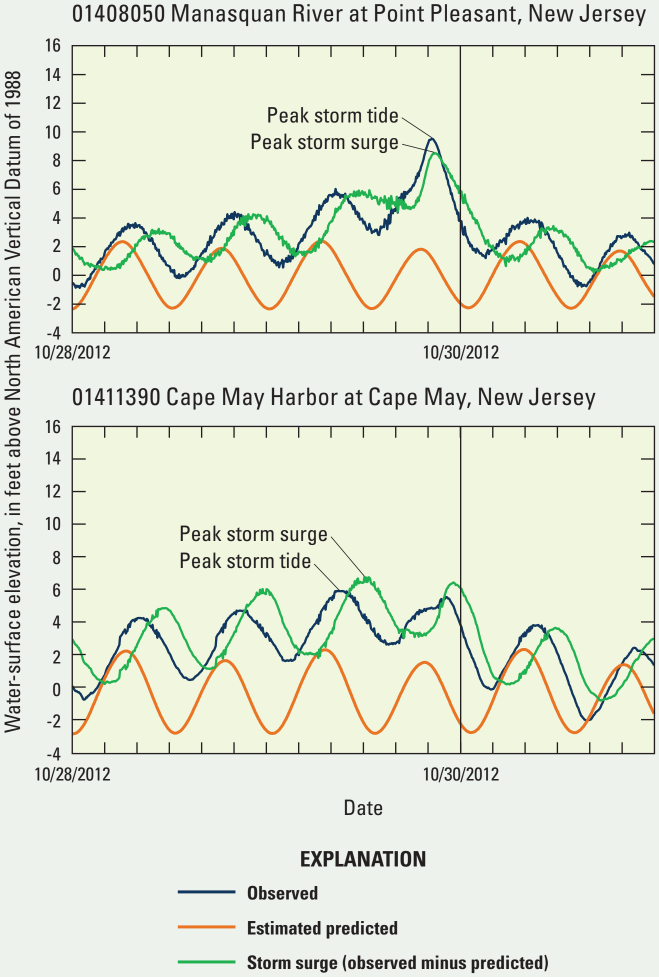
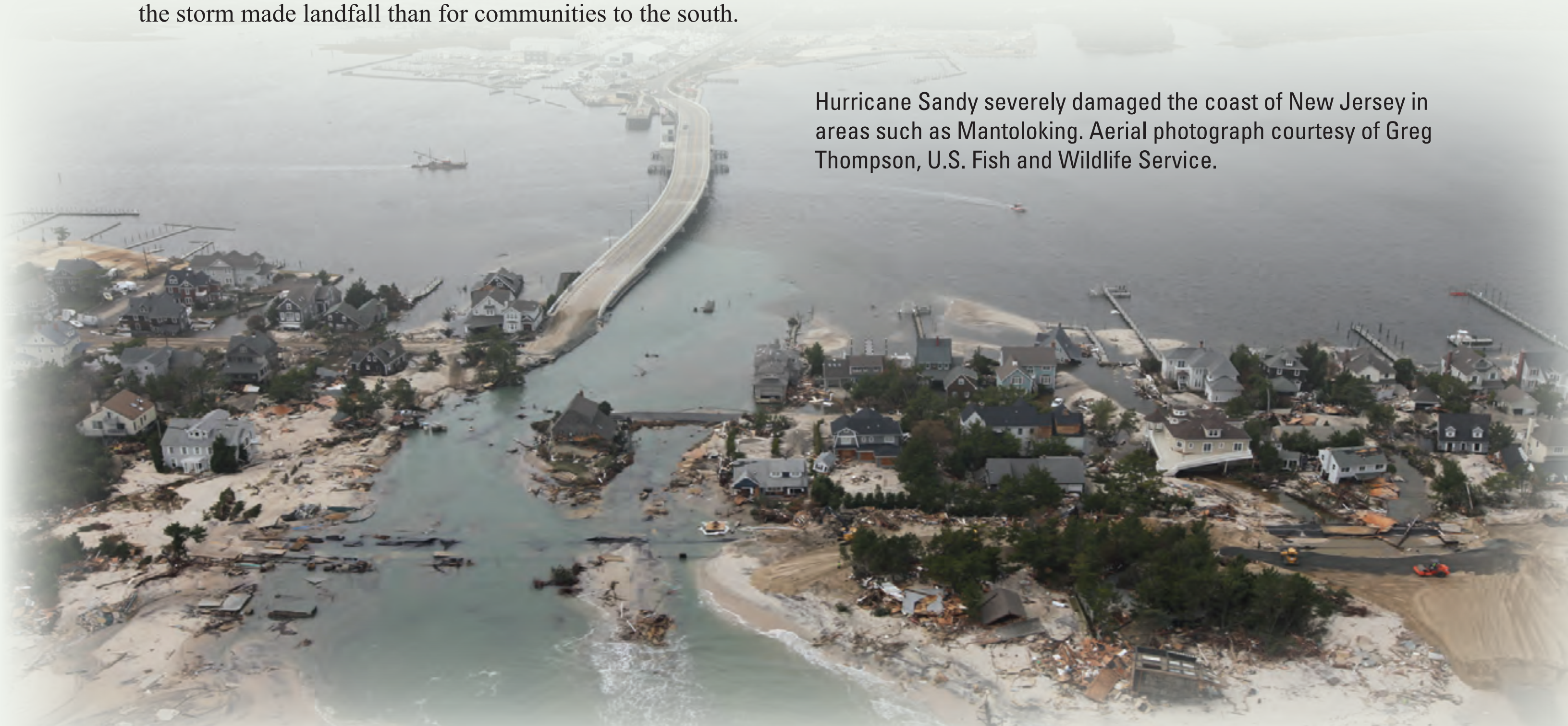


Figure 11. The National Oceanic and Atmospheric Administration predicts tidal elevations and the U.S. Geological Survey measures observed tidal elevations and storm surge for storms such as Hurricane Sandy.



Hurricane Sandy severely damaged the coast of New Jersey in areas such as Mantoloking. Aerial photograph courtesy of Greg Thompson, U.S. Fish and Wildlife Service.

New York and Connecticut

The coastline of New York and Connecticut are highly diverse, from the rocky shorelines of Long Island Sound in southern Connecticut to the highly urbanized communities in and around New York City to the pristine barrier beaches and tidal estuaries along Long Island's Atlantic coast. The coastal communities in this region are a major part of the area's vitality. Coastal tourism, fisheries, and maritime transportation are a major part of the economy for the area, and severe coastal storms can have substantial economic impact on the region.

Hurricane Sandy made landfall in southern New Jersey on October 30, 2012, and severely impacted the New York and Connecticut coastline. Many areas that had been hit by Hurricane Irene a year before, in August 2011, were again battered by strong waves and tidal flooding. Severe erosion of beaches and dunes occurred, barrier islands were breached, and extensive inundation and wave damage to homes and business along the coastal flood plain occurred (fig. 12). Loss of life attributed to Hurricane Sandy was estimated to be 53 persons in New York and 4 in Connecticut (Center for Disease Control and Prevention, 2012). Economic losses from the storm were estimated to be $42 billion in New York (New York State Governor's Office, 2012).

Monitoring the Storm

The extremely large fetch of winds associated with Hurricane Sandy combined with the hurricane's anomalous track piled large amounts of ocean water, over multiple tidal cycles, north and west of the center of the counterclockwise circulation. This onshore flow pushed a substantial tidal surge towards the coastline, producing major to historical coastal flooding along parts of the New York and Connecticut coastlines (National Oceanic and Atmospheric Administration, 2013).

Before the storm made landfall, the USGS deployed a temporary network of 71 storm-tide and wave sensors along the coastline of southeastern New York and southern Connecticut (fig. 13*A*), as part of a larger deployment of 224 sensors from South Carolina to Maine, to record the elevation of storm-tide flooding generated by Hurricane Sandy. This sensor network augmented NOAA, U.S. Army Corps of Engineers (USACE), and USGS networks comprising 32 permanent tide monitoring or tidally affected streamgaging stations in the region that also documented storm surge and storm tide from the storm (fig. 13*A*). Continuous data from these networks

Figure 12. Coastal communities across coastal New York were damaged by Hurricane Sandy. *A*, Photograph by William Capurso, U.S. Geological Survey. *B*, Photograph by David Bjerklie, U.S. Geological Survey. *C*, Photograph by Amy Simonson, U.S. Geological Survey. *D*, Photograph by Michael Como, U.S. Geological Survey. *E*, Photograph by Karen Morgan, U.S. Geological Survey.

A

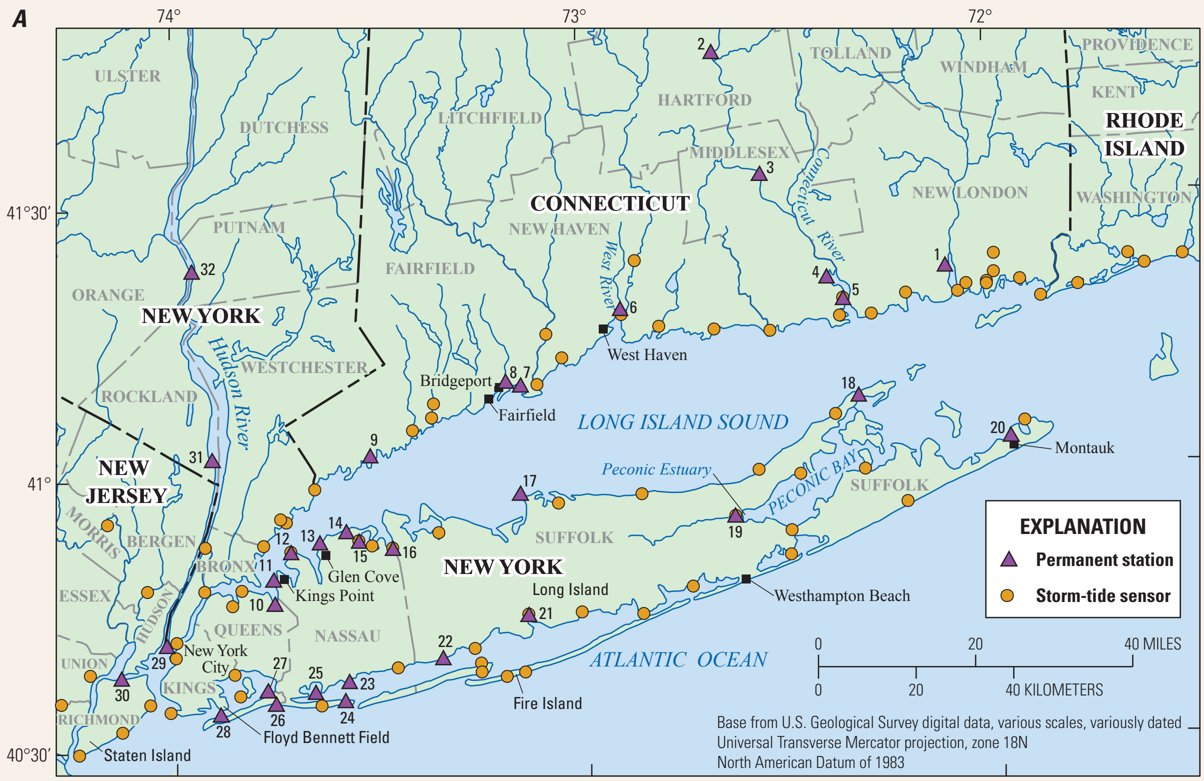


Figure 13. Permanent stations and storm-tide sensor locations, storm-surge magnitudes, and peak storm-tide elevations for Hurricane Sandy. *A*, Location of 32 permanent stations and 71 temporary storm-tide sensors deployed for Hurricane Sandy in southeastern New York and southern Connecticut.

B

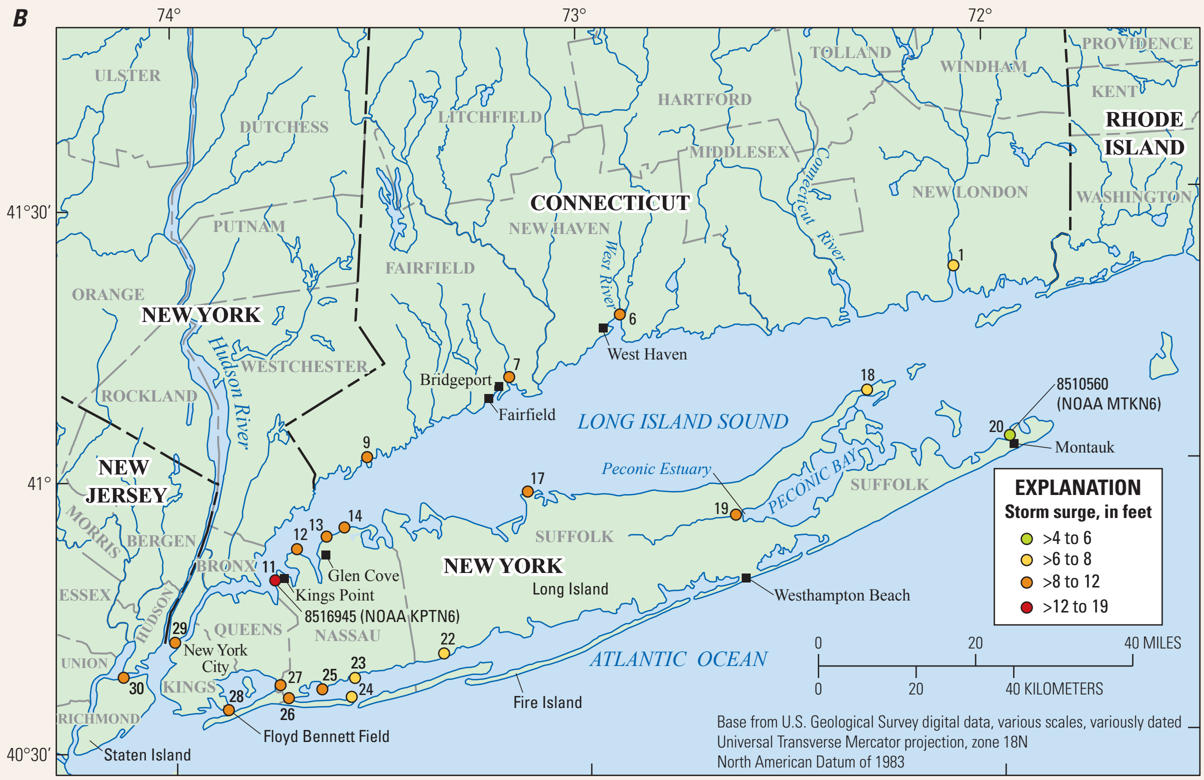


Figure 13. Permanent stations and storm-tide sensor locations, storm-surge magnitudes, and peak storm-tide elevations for Hurricane Sandy. *B*, Storm-surge magnitudes produced by Hurricane Sandy at 21 permanent stations in southeastern New York and southern Connecticut.—Continued

C

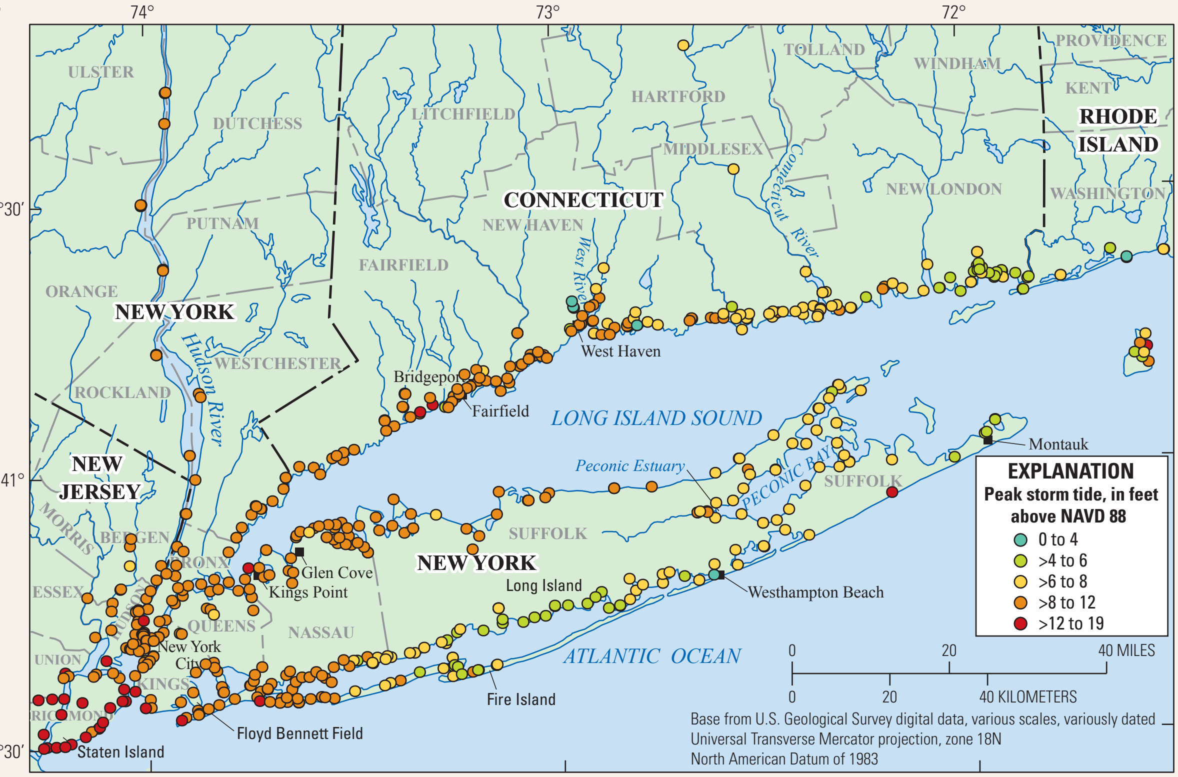


Figure 13. Permanent stations and storm-tide sensor locations, storm-surge magnitudes, and peak storm-tide elevations for Hurricane Sandy. *C*, Peak storm-tide elevations produced by Hurricane Sandy at permanent gages, deployed temporary storm-tide sensors, and collected high-water mark locations in southeastern New York and southern Connecticut. NAVD 88, North American Vertical Datum of 1988.—Continued

were supplemented by an extensive post-storm HWM flagging and surveying campaign at about 500 sites along the coast. The sensor deployment and HWM campaigns were completed by the USGS under a directed mission assignment from FEMA.

Data from selected permanent stations in the USGS network and from sites in the NOAA and USACE networks document Hurricane Sandy's storm surge. For these stations and sites, residual water levels were calculated to assess the storm-surge magnitude associated with the peak storm tide and the magnitude and timing of the peak storm surge. As shown by data collected from this network, the phasing of maximum storm surge with that of astronomical high tide was a major factor in determining which areas received the greatest storm-tide inundation.

Peak Storm Surge

Most magnitudes of peak storm surge from Hurricane Sandy at 21 permanent stations along the southeastern New York and southern Connecticut coasts (fig. 13*B*) were greater than about 8.2 feet, with the greatest magnitude along the shorelines of central and western Long Island Sound and the southern shore of New York City. The maximum magnitude of peak storm surge was 12.65 feet above NAVD 88 at permanent station 8516945 (NOAA tide gage KPTN6) in western Long Island Sound at Kings Point, N.Y. (table 1). The minimum magnitude of peak storm surge was 5.89 feet above NAVD 88 at permanent station 8510560 (NOAA tide gage MTKN6) at Montauk, N.Y., near the extreme eastern tip of Long Island, N.Y.

Peak Storm Tide

Most peak storm-tide elevations from Hurricane Sandy along the southeastern New York and southern Connecticut coasts (fig. 13*C*; table 1) were greater than about 8 feet above NAVD 88. This level, however, was greatly exceeded at most of the sites located along the shorelines of central and western Long Island Sound, the southern shore of western Long Island and New York City, and the lower Hudson River, where storm-tide flooding was greatest. In the remaining areas—the shorelines of southeastern Connecticut and the southern shore of central and eastern Long Island—peak storm-tide elevations were greater than about 6 feet above NAVD 88 at most sites.

The maximum peak storm-tide elevation for New York was 16.9 feet above NAVD 88 at site HWM–NY–RIC–717 on Staten Island, N.Y. (fig. 13*C*), and the maximum peak storm-tide elevation for Connecticut was 12.2 feet above NAVD 88 at site HWM–CT–FFD–628 in Fairfield, Conn. The minimum peak storm-tide elevation for New York was 3.5 feet above NAVD 88 at site HWM–NY–SUF–638 in Westhampton

Table 1. Storm-surge magnitude, peak storm tide, and magnitude and timing of the peak storm surge associated with the peak storm tide produced by Hurricane Sandy at 32 permanent stations in southeastern New York and southern Connecticut.

[Negative time difference denotes a peak storm surge that preceded the peak storm tide. Permanent stations are shown in figure 12*A*. Peak storm-tide and surge records for Hurricane Sandy at National Oceanic and Atmospheric Administration (NOAA) sites from Fanelli and others (2013). Storm-tide elevation associated with the peak storm surge at NOAA sites from National Ocean Service (2013). Peak storm-tide elevations in North American Vertical Datum of 1988. USACE, U.S. Army Corps of Engineers; —, no value]

Map number	Station number	Station name	Peak storm-surge magnitude (feet)	Peak storm-tide elevation (feet)	Storm surge at time of peak storm tide	Peak surge/tide time difference (minutes)
1	8461490–NOAA	Station NLNC3 at New London, Connecticut	6.50	6.16	5.91	–78
2	01190070	Connecticut River at Hartford, Connecticut	—	7.91	—	—
3	01193050	Connecticut River at Middle Haddam, Connecticut	—	7.45	—	—
4	01194750	Connecticut River at Essex, Connecticut	—	6.98	—	—
5	01194796	Connecticut River at Old Lyme, Connecticut	—	7.04	—	—
6	8465705–NOAA	Station NWHC3 at New Haven, Connecticut	9.14	—	8.13	–90
7	8467150–NOAA	Station BRHC3 at Bridgeport, Connecticut	9.83	9.30	7.84	–108
8	01208873	Rooster River at Fairfield, Connecticut	—	9.40	—	—
9	01209788–USACE	Stamford Hurricane Barrier at Stamford, Connecticut	11.24	9.99	8.73	–180
10	01302050	Alley Creek near Oakland Gardens, New York	—	9.69	—	—
11	8516945–NOAA	Station KPTN6 at Kings Point, New York	12.65	—	8.54	–186
12	01302250	East Creek at Sands Point, New York	11.84	10.31	8.24	–174
13	01302600	West Pond at Glen Cove, New York	11.52	9.87	7.26	–222
14	01302845	Frost Creek at Sheep Lane Bridge at Lattingtown, New York	10.76	10.06	7.59	–192
15	[1]01303000	Mill Neck Creek at Mill Neck, New York	—	10.22	—	—
16	[2]01303500	Cold Spring Brook at Cold Spring Harbor, New York	—	9.98	—	—
17	01304057	Flax Pond at Old Field, New York	9.56	9.35	7.99	–102
18	01304200	Orient Harbor at Orient, New York	7.18	6.43	6.00	–204
19	01304562	Peconic River at County Highway 105 at Riverhead, New York	9.16	7.65	8.31	114
20	8510560–NOAA	Station MTKN6 at Montauk, New York	5.89	5.55	5.24	–120
21	[2]01306499	Connetquot River near North Great River, New York	—	6.06	—	—
22	01309225	Great South Bay at Lindenhurst, New York	6.38	6.54	6.27	–126
23	01310521	Hudson Bay at Freeport, New York	7.92	8.98	7.85	24
24	01310740	Reynolds Channel at Point Lookout, New York	7.78	8.97	7.66	30
25	01311143	Hog Island Channel at Island Park, New York	8.32	9.77	8.14	36
26	01311145	East Rockaway Inlet at Atlantic Beach, New York	8.21	9.70	8.08	30
27	01311850	Jamaica Bay at Inwood, New York	8.47	10.55	8.38	24
28	01311875	Rockaway Inlet near Floyd Bennett Field, New York	9.13	10.65	8.72	36
29	8518750–NOAA	Station BATN6 at The Battery, New York	9.40	11.28	9.40	0
30	8519483–NOAA	Station BGNN4 at Bergen Point West Reach, New York	9.56	—	9.43	24
31	[2]01376269	Hudson River at Piermont, New York	—	9.70	—	—
32	[2]01374019	Hudson River at South Dock at West Point, New York	—	8.60	—	—

[1]Permanent streamflow monitoring station was discontinued in February 2011; peak elevation for Hurricane Sandy uses value from temporary storm-tide sensor deployed at the station.

[2]Measurement limit at permanent streamflow monitoring station was exceeded during Hurricane Sandy; peak elevation for this storm uses value from collocated temporary storm-tide sensor or high-water mark.

Beach, N.Y., and for Connecticut was 2.5 feet above NAVD 88 at site HWM–CT–NHV–327 in West Haven, Conn., upstream from the tide gates on the West River. A table of peak storm-tide elevations for all Hurricane Sandy sensor locations and most of the collected HWMs is available from McCallum and others (2013) and from the flood event viewer (https://stn.wim.usgs.gov/fev/#Sandy).

Timing of Maximum Surge

Of the 21 permanent stations that recorded surge (table 1), the peak storm surge arrived within 36 minutes of the time of peak storm tide at 8 sites, all of which are along the Atlantic Ocean shorelines of western Long Island and New York City. This condition resulted from the peak storm surge arriving in phase with the astronomical tide—generally coinciding with astronomical high tide—at the 21 permanent stations (Schubert and Busciolano, 2013). In contrast, the peak storm surge preceded the time of peak storm tide by 78 minutes or more at 12 sites mainly along the Connecticut and New York shorelines of Long Island Sound and extreme eastern Long Island and followed the time of peak storm tide by 114 minutes at 1 site at the head of the Peconic Estuary on eastern Long Island. In both cases, peak storm surge arrived out of phase with the astronomical tide; nearly coinciding with the normal mid to low tide locally at these sites.

Hydrographs of selected sites showing timing of maximum storm surge with that of peak storm tide and predicted local astronomical tide are shown in figure 14. The hydrographs in figure 14*A*, 14*B*, and 14*C* show stations where peak storm surge occurred out of phase, and the hydrograph in figure 14*D* shows peak storm surge in phase with astronomical tide.

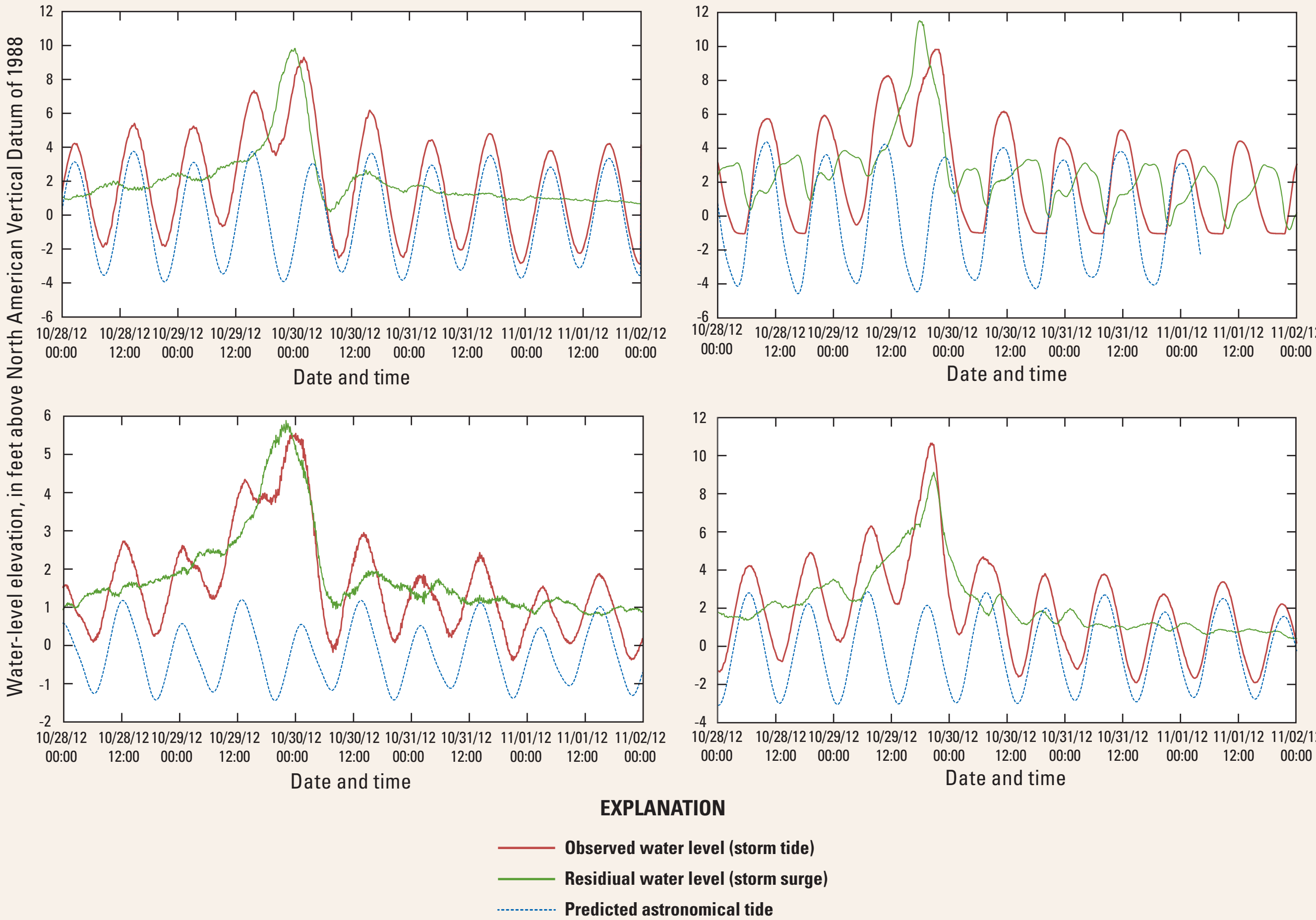


Figure 14. A comparison of storm tide and storm surge resulting from Hurricane Sandy in October 2012 with astronomical predicted tides (without the effects of a storm) shows the magnitude of the storm surge and tide from the hurricane. *A*, National Oceanic and Atmospheric Administration (NOAA) station 8467150 at Bridgeport, Conn.; *B*, U.S. Geological Survey (USGS) station 01302600 at Glen Cove, N.Y.; *C*, NOAA station 8510560 at Montauk, N.Y.; and *D*, USGS station 01311875 at Floyd Bennett Field, N.Y.

Timing of peak storm surge arrival with respect to local phase of astronomical tide controlled the location of the most extreme peak storm-tide levels and coastal flooding. This finding has bearing not only for locations impacted by the highest storm tides from Hurricane Sandy but also for locations that had the greatest storm surges yet were spared the worst flooding because of fortuitous timing during this storm.

Comparison With Previous Storms and Historical Peaks

Peak storm-tide elevations from Hurricane Sandy were compared with data from other storms of record in the region including Hurricane Irene (which made landfall near New York City in August 2011), the nor’easter of December 1992 (which affected the region for 3 days in December 1992), Hurricane Donna (which made landfall on eastern Long Island as a category 3 hurricane and then eastern Connecticut as a category 2 hurricane in September 1960), Hurricane Carol (which made landfall on eastern Long Island and eastern Connecticut as a category 3 hurricane in August 1954), and the Great New England Hurricane of 1938 (which made landfall over central Long Island and central Connecticut as a category 3 hurricane in September 1938).

Of the 29 permanent stations along the southeastern New York and southern Connecticut coasts that recorded storm tide, the peak storm-tide elevation from Hurricane Sandy exceeded the historical peak water-level elevation produced by past storms at 18 of the 23 sites (table 2). Six of the 29 sites are streamgages where historical peaks were produced by high streamflow; therefore, these peaks were omitted for comparison.

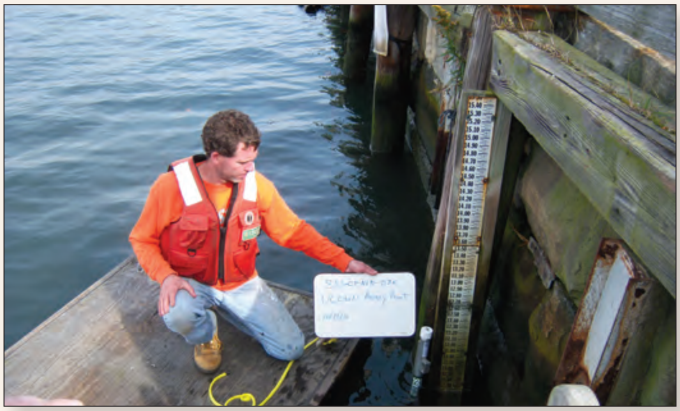
Peak storm-tide elevations from Hurricane Sandy were lower than elevations produced by the unnamed hurricane of 1938 at two sites in central and western Long Island Sound; however, because only 5 of the 29 stations have historical records going back to the unnamed hurricane of 1938, the unnamed hurricane of 1938 possibly could have produced higher storm tides than Hurricane Sandy throughout much of the New York and Connecticut shorelines of central and eastern Long Island Sound and along parts of eastern Long Island. Based on a comparison with published profiles (U.S. Army Corps of Engineers, 1988), storm-tide elevations measured during Hurricane Sandy were greater than those from the unnamed hurricane of 1938 for most parts of western Long Island Sound by as much as 1.5 feet, whereas in eastern Long Island Sound, storm-tide elevations were more than 2.5 feet lower during Hurricane Sandy.

Peak storm-tide elevations from Hurricane Sandy were also lower than elevations produced by Hurricane Carol at one site located on eastern Long Island. Because only 7 of the 29 stations have historical records going back to Hurricane Carol in 1954, it is probable that this hurricane produced higher storm tides than Hurricane Sandy in many parts of eastern Long Island Sound and along the eastern end of Long Island.

For the three other storms of record, peak storm-tide elevations from Hurricane Sandy were lower than elevations produced by the unnamed intense nor’easter of 1992 at one site in western Long Island Sound and one site in Peconic Bay on the eastern end of Long Island, and peak storm-tide elevations from Hurricane Sandy were higher than elevations at all sites for both Hurricane Donna and Hurricane Irene.

Improved Monitoring Through the SWaTH Network

For the southeastern New York and southern Connecticut coastline, the SWaTH network upgrade entailed the installation of 7 new flood-hardened, permanent stations to supplement the 32 existing stations, the addition of 17 storm-deployed rapid-deployment gages, and as many as 125 storm-deployed storm-tide and wave sensors. Documenting the height, extent, and timing of overland storm tide and wave dynamics across natural and manmade landscapes is critical for improved storm-surge modeling for flood-plain mapping and real-time forecasting. Improved mapping will lead to better planning, more effective early warning of storm-driven flooding, and strengthening of coastal resilience.



U.S. Geological Survey scientist obtaining water-surface elevation data and deploying a storm-tide sensor at Avery Point, Connecticut. Photograph by the U.S. Geological Survey.

Table 2. Peak storm-tide elevations produced by Hurricane Sandy at 29 permanent stations in southeastern New York and southern Connecticut, with a comparison to other storms of record in the region.

[Permanent stations are shown in figure 12*A*. Peak storm tides for Hurricane Sandy occurred on October 29–30, 2012, for Hurricane Irene on August 28, 2011, for the unnamed storm of December 1992 on December 11, 1992, for Hurricane Donna on September 11–12, 1960, for Hurricane Carol on August 31, 1954, and for the unnamed hurricane of 1938 on September 21, 1938. Storm-tide elevations associated with the peak storm surge at National Oceanic and Atmospheric Administration (NOAA) sites from National Ocean Service (2013). Peak storm-tide elevations in North American Vertical Datum of 1988. Dates in Greenwich Mean Time. USACE, U.S. Army Corps of Engineers; —, no value]

Map number	Station number	Station period of record	Historical peak water level (feet)	Estimated date of historical peak	Sandy peak storm-tide elevation (feet)	Irene peak storm-tide (feet)	December 1992 peak storm-tide elevation (feet)	Donna peak storm-tide elevation (feet)	Carol peak storm-tide elevation (feet)	September 1938 peak storm-tide elevation (feet)
1	8461490–NOAA	1938–2013	8.74	09/21/1938	6.16	4.72	4.34	5.04	[1]7.74	[1]8.74
2	[2]01190070	—	—	—	7.91	—	—	—	—	—
3	[2]01193050	—	—	—	7.45	7.62	—	—	—	—
4	[2]01194750	—	—	—	6.98	5.97	—	—	—	—
5	[2]01194796	—	—	—	7.04	5.89	—	—	—	—
6	8467150–NOAA	1970–2013	9.30	10/29/2012	9.30	8.24	8.17	—	[3]8.1	[3]8.4
8	01208873	—	—	—	9.40	—	—	—	—	—
9	01209788–USACE	1969–2013	9.99	10/29/2012	9.99	8.49	8.99	7.19	9.19	9.89
10	[2]01302050	1993–2013	—	—	9.69	9.46	[1]9.5	—	—	—
12	01302250	2007–2013	10.31	10/29/2012	10.31	8.39	—	—	—	—
13	01302600	2009–2013	9.87	10/29/2012	9.87	8.21	[1]9.1	—	—	—
14	01302845	2007–2013	[1]10.8	12/11/1992	10.06	8.04	[1]10.8	—	—	—
15	01303000	1937–2012	10.26	09/21/1938	[4]10.22	[1]8.4	[5]9.8	[2]7.01	9.66	10.26
16	01303500	1950–2013	[5]9.98	10/29/2012	[5]9.98	9.14	[1]9.5	[2]6.35	9.67	—
17	01304057	2007–2013	9.35	10/29/2012	9.35	7.81	[1]8.3	—	—	—
18	01304200	2012–2013	6.43	10/29/2012	6.43	—	[1]4.5	—	—	—
19	01304562	2012–2013	[1]8.0	12/11/1992	7.65	—	[1]8.0	—	—	—
20	8510560–NOAA	1947–2013	6.87	08/31/1954	5.55	3.82	4.24	3.54	6.87	—
21	01306499	1943–2013	[5]6.06	10/29/2012	[5]6.06	—	[1]2.9	—	—	—
22	01309225	2002–2013	6.54	10/29/2012	6.54	4.08	—	—	—	—
23	01310521	1999–2013	8.98	10/29/2012	8.98	6.22	[6]6.1	—	—	—
24	01310740	1997–2013	8.97	10/29/2012	8.97	5.94	—	—	—	—
25	01311143	2010–2013	9.77	10/29/2012	9.77	6.63	[1]6.2	—	—	—
26	01311145	2002–2013	9.70	10/29/2012	9.70	6.33	[1]6.6	—	—	—
27	01311850	2002–2013	10.55	10/29/2012	10.55	6.42	[1]7.8	—	—	—
28	01311875	2002–2013	10.65	10/29/2012	10.65	6.48	[1]7.8	—	—	—
29	8518750–NOAA	1920–2013	11.28	10/29/2012	11.28	6.73	6.93	7.24	4.24	4.84
30	01376269	2010–2013	[5]9.70	10/29/2012	[5]9.70	6.56	—	—	—	—
32	01374019	1991–2013	[5]8.60	10/29/2012	[5]8.60	6.69	—	—	—	—

[1]Peak storm-tide elevation outside period of record estimated from nearby high-water mark or local observation.

[2]Historical peak water levels affected by riverine flooding.

[3]Peak storm-tide elevation estimated from U.S. Army Corps of Engineers (1988).

[4]Permanent streamflow monitoring station discontinued; peak elevation from temporary storm-tide sensor deployed at the station.

[5]Measurement limit at permanent streamflow monitoring station was exceeded; peak elevation value from collocated temporary storm-tide sensor or high-water mark.

[6]Peak storm-tide elevation estimated from information provided by Town of Hempstead Department of Conservation and Waterways.

Massachusetts

Plum Island, so named for the wild *Prunus maritima* Marshall (beach plum) shrub, which grows on its sandy dunes, is a barrier island in northeastern Massachusetts (fig. 15); the island encompasses the towns of Newburyport, Newbury, Rowley, and Ipswich, to the south of the mouth of the Merrimack River and extending south for about 11 miles. The island is bounded by the mouth of the Merrimack River to the north, Plum Island River to the northwest, Plum Island Sound to the southwest, and the mouth of the Ipswich River to the south; the Atlantic Ocean lies to the east. Plum Island Sound is a tidal estuary. The Village of Plum Island, a beach community in the towns of Newbury and Newburyport, is a typical New England seaside subdivision dating back to the 1920s; other undeveloped lands are managed by the U.S. Fish and Wildlife Service as part of the Parker River National Wildlife Refuge (fig. 15).

Plum Island, like other barrier islands in the northeastern United States, is a relatively recent geologic feature. The distribution of barrier islands in this region is directly related to coastal areas where Quaternary glacial deposits provide the supply of unconsolidated sand and gravel necessary for the formation of barrier islands. At the time of origin (more than 6,300 years before present) the sea was lower and the land was relatively higher in elevation than today. The island is continuously being shaped as a result of transgressive sea erosion, which is reworking and depositing the sediments along an unstable coast (McIntire and Morgan, 1962). Storms throughout the past several decades have resulted in substantial beach erosion, and in developed areas, property loss is a constant concern.

Barrier islands buffer the coastline from the erosive force of higher than normal tides and powerful wave action during storms. In the northeastern United States, tropical storms and nor'easters during winter and spring strike annually and cause much of the movement and reshaping of barrier islands. These storms mobilize and redeposit sediments and are an important component in the evolution of beach, dune, and sandbar form and position. Barrier islands are not static land masses; rather they are transient features that are reworked and reshaped storm by storm. During periods of sea-level rise and a warming climate, storm impacts typically are greater with greater inundation and beach erosion than at other times (Morris, 2015). Barrier beaches tend to maintain themselves during periods of sea-level rise by "rolling-over" themselves, essentially migrating landward through processes of dune movement, storm wave overwash, and tidal inlet deposition (Giese, 1997). Along the northern one-half of Plum Island, long-term (146-year) shoreline change rates are dominantly low-level erosional, averaging about –0.2 meter per year from 1850 to 2000, but erosion rates since 1978 have averaged nearly –0.5 meter per year (Town of Newbury, 2010).

Impacts of Recent Storms on Plum Island

An early account by Captain John Smith described the area along the Massachusetts coast that would become Plum Island: "On the east is an Ile two or three leagues in length; the one halfe, plaine morish grasse fit for pasture, with many faire high groves of mulberrie trees gardens; and there is also Okes, Pines and other woods to make this place an excellent habitation, being a good and safe harbor" (Smith, 1616). A few colonial settlements dotted the island during the 17th and 18th centuries. With the industrial revolution and an increase in the standard of living during the late 19th and early 20th centuries, Plum Island became a site for several hotels and a robust beachside community. Today [2016], Plum Island remains a destination and summer retreat for vacationers from nearby metropolitan cities; however, lots that were subdivided in the early 20th century and then set back from the beach are now closer to the edge of the shifting coastline.

Early land use on Plum Island was limited to pasture and grazing. A few farm houses were built far from the coast. During the late 19th and 20th century, northern parts of Plum Island were extensively developed as a seaside community atop the dune system. In the Roaring Twenties, Plum Island real estate boomed. The Plum Island Beach Company acquired a large parcel of land north of Turnpike Road and installed electrical power lines, paved Northern Boulevard, and surveyed and subdivided almost 12,000 lots on 1,400 acres (fig. 16; Fitzsimons, 2014). During the development process, dunes were flattened and vegetation removed from northern Plum Island. Lots were sold and cottages were constructed, some in locations more vulnerable than others. Because of the proximity to Boston and other metropolitan areas, demand for property on the island was and remains high.

Since early development, the beach has, in some areas, migrated closer and closer to the first row of homes. Many of the original cottages on the desirable beach-front lots have since been rebuilt in favor of grander structures. Buildings on these lots are the first to be destroyed when storms erode and reshape the island. Today [2016], many of the largest homes on Plum Island stand at the edge of the shifting island; these are places where the testimonies of long-time residents include memories of beach fronts hundreds of meters away from current shorelines and recollections of many powerful storms

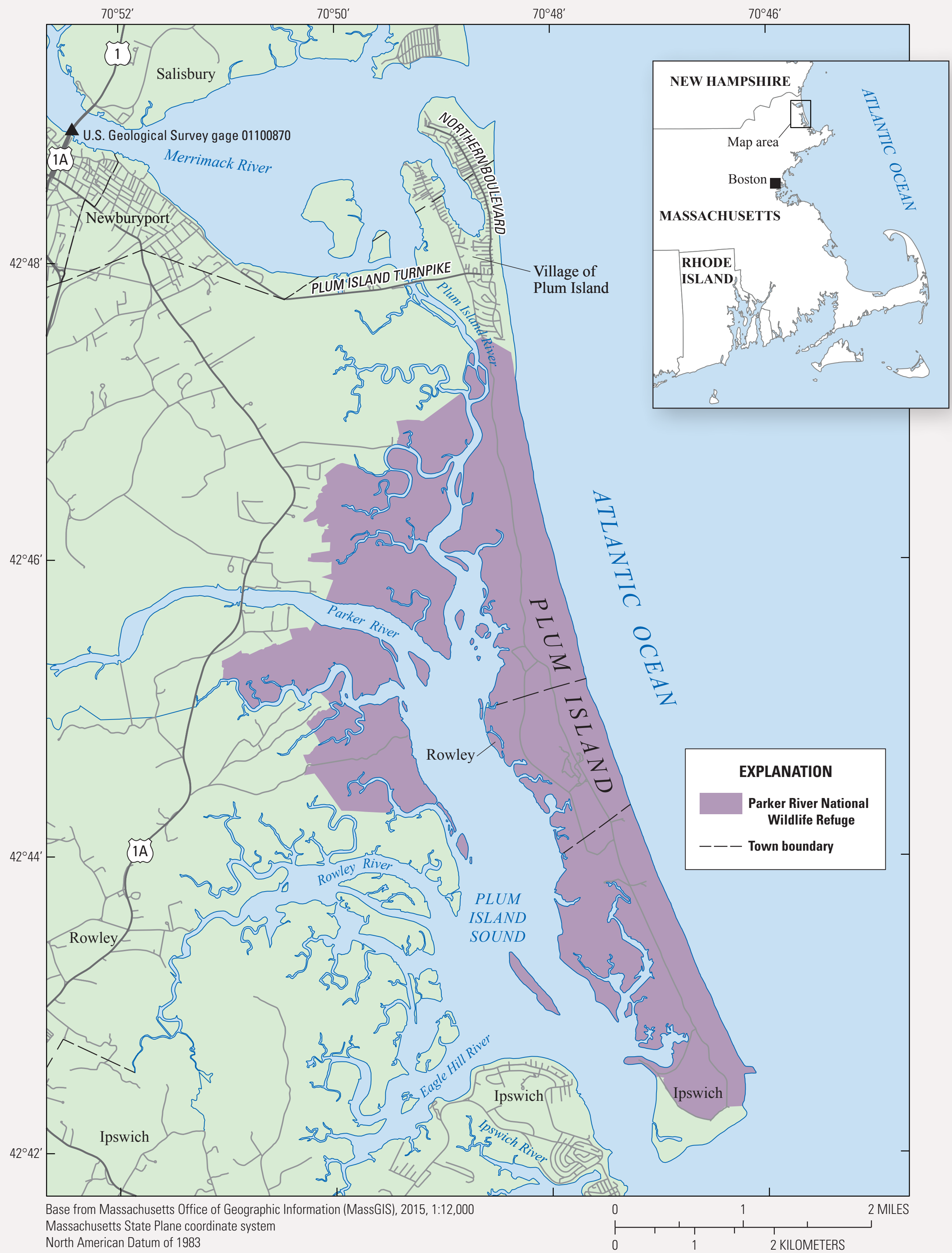


Figure 15. The barrier Plum Island, which lies in the tidal estuary of Plum Island Sound in Massachusetts, is reworked and reshaped storm by storm.

Figure 16. In the Roaring Twenties, development on Plum Island boomed and as many as 12,000 houses were built on about 1,400 acres.

over the years. In some places, the shoreline has encroached to the foundations and supports of several houses and some houses have been destroyed as the beach continues to migrate. Dozens of houses in the most vulnerable locations were damaged or destroyed by a string of powerful storms during winter 2013, and emergency managers and residents of the island continue to keep a watchful eye on each approaching storm. Houses that were made uninhabitable during the winter storms of 2013 are shown in figure 17.

Foundation-supported structures built on barrier islands will eventually be affected as beach fronts shift position. Additionally, roads, landscaping, and other manmade features threaten dune rebuilding and may exacerbate future storm impacts. For example, sea walls and other similar fortifications designed to stabilize land and protect buildings at the edge of the beach may actually exacerbate shoreline erosion by deflecting waves to other unfortified locations.

Figure 17. Many houses on Plum Island, Massachusetts, were undermined by the storms of winter 2013. Photographs by Sergeant Patty Fisher, Newburyport [Mass.], Police Department.

Storm Surge and Real-Time Tide Monitoring

The USGS has recorded storm surge and tide height at the northern end of Plum Island and surrounding locations since Hurricane Earl in 2010. During Hurricane Irene in 2011, the USGS expanded tidal monitoring with a network of storm-surge sensors along the southern New England coast, and during Hurricane Sandy in 2012, storm-surge sensors and real-time data collection on tide height and weather conditions were measured and available on the Internet from temporary rapid-deployment gages that were installed before the storm. In 2014, the USGS installed the SWaTH network along the Atlantic coast in the northeastern United States with 163 storm surge-sensors and rapid-deployment gages in New England. By 2015, six permanent real-time tide monitoring stations had been installed to help inform the public and local officials about current tidal, flow, and weather conditions. An example of data from one of these six new gages and a photograph of the gage are shown in figure 18.

Additionally, during large storm events a temporary rapid-deployment gage will be deployed to the west of Plum Island at Parker River in Newbury, along with a widely dispersed network of storm-surge and wave height recorders, all part of the USGS SWaTH network. During the blizzard of January 2015, SWaTH storm-surge sensors were deployed at six sites along the coast of eastern Massachusetts, including Plum Island (Massey and Verdi, 2015). These data collection platforms will help warn of changing weather and tide conditions during a storm in real time and help record the data necessary to characterize storm events of varying magnitudes for a more thorough understanding of the severity of impacts to coastal areas.

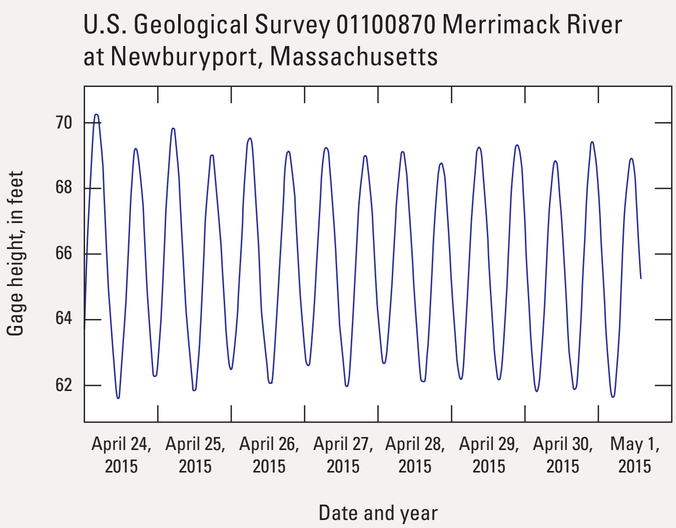


Figure 18. Gages such as the U.S. Geological Survey gage at the U.S. Route 1A bridge on the Merrimack River at Newburyport, Massachusetts (station 01100870), collect information on water levels, which can be used to evaluate the storm surge at that location during large storms. Photograph by the U.S. Geological Survey.

Wetlands at Parker River National Wildlife Refuge on Plum Island, Massachusetts. Photograph courtesy of Kelly Fike, U.S. Fish and Wildlife Service.

Forecasting, Monitoring, and Reporting for the Future

Working With Partners

The USGS has a long history of working with other Federal, tribal, State, and local governments, regional planning districts, and other natural resource organizations to provide useful environmental data. By interacting with these groups and understanding the needs and applications of each group, the USGS ensures its data and science remain relevant and useful to the community. The following are examples that demonstrate cooperation between the USGS and Federal, State, and local agencies in response to impacts of Hurricanes Irene and Sandy.

As Hurricane Irene raced towards the North Carolina coast in August 2011, the USGS North Carolina Water Science Center deployed a dense network of storm surge monitors along the coast. At the same time, the North Carolina Sea Grant program was doing the same thing. After the event, the sensors were retrieved and the data were processed, and the USGS agreed to host the data from the State-funded program on the USGS website at http://water.usgs.gov/floods/events/2011/irene/. The data were also published along with other USGS data in McCallum and others (2012b). Placing all the data in one location online enabled quick and easy access for the public.

A global positioning system used to survey storm-tide elevation at HWM-NJ-HUD-108 at Liberty State Park in Jersey City, New Jersey, after Hurricane Sandy. Photograph by Crystal Hammer, U.S. Geological Survey.

In Virginia, the USGS has worked with the University of Virginia (UVA) Long-Term Ecological Research Laboratory to help facilitate serving their continuous tide monitor data to the National Weather Service (NWS) Advanced Hydrologic Prediction Service (AHPS) web page. Originally, the USGS had been approached by local county authorities who were interested in installing a tide gage in the same community where the UVA gage is located. At that time, the county was unaware of the presence of the UVA gage because the data from the UVA gage were not available through AHPS. In response, the USGS first made the county aware of the UVA gage and then introduced UVA personnel to NWS personnel and helped coordinate efforts to ensure the UVA data were served on the AHPS page. This coordination effort also provided an opportunity for the USGS to work directly with the county to help place their new county gage in a different location to ensure a better network footprint was provided for the community. As a result of these efforts, more data are now [2016] being served to the AHPS network, and the relationship between the USGS and UVA has been strengthened.

In New Jersey, the USGS began working with local cooperators after the damaging nor'easter of 1992 to build a coastal tide telemetry network to provide tidal elevation data for coastal communities. This network of tide gages was built using mostly existing infrastructure and provided invaluable data during and after Hurricane Sandy despite being seriously damaged by the storm.

Leveraging SWaTH at the Federal, State, and Local Levels—The development and implementation of SWaTH was a collaborative effort between the USGS and many Federal, State, and local agencies that needed enhanced access to coastal flood data. Personnel from various USGS water science centers worked with personnel from local and State agencies to identify potential sites and identify appropriate equipment and data delivery formats and methods. The SWaTH network was a result of both supplemental funding from Congress as well as cooperative funding from the States; frequently, the funding for SWaTH enabled for the construction and instrumentation of a site and the local agencies typically agreed to provide for long-term operation and maintenance.

The resulting SWaTH network and the data from the network have had a positive effect on local capabilities. In New Jersey, for example, SWaTH has strengthened and greatly improved the New Jersey Tide Telemetry System (NJTTS) to make it a more resilient network for future storms. The USGS New Jersey Water Science Center has had a long-standing relationship with FEMA Region II for flood documentation and mitigation support. The combined support from the SWaTH network and the NJTTS has helped to improve FEMA's situational awareness and has provided various State and local emergency managers with a more reliable and robust network of tide gages and flood data for purposes of planning and preparing for the next major storm. SWaTH provided the opportunity for the USGS to add secondary sensors (backup data collection equipment) at many tide gages and facilitate a conversation with the NOAA National Ocean Service (NOS) to include some of the NJTTS gages into their tidal gage network. SWaTH publications and informational material have enriched USGS conversations with State and local emergency managers and have informed the general public about USGS data, the NJTTS, and flood risk in general.

In New York, SWaTH provided an opportunity to revisit a two-decades-old proposal developed jointly by the USGS and the NWS for a regional network of flood-warning tide gages. Although about one-half of the proposed network of 26 tide gages had been installed during the intervening years, several priority sites for the mitigation of flood hazards remained without gages. These priority ungaged sites and the counties or municipalities in which they are located became the focus of a collaborative outreach effort by the USGS and the NWS. SWaTH included installation of new tide gages at priority sites with long-term agreements with State and local agencies to fund gage operation and maintenance expenses. Ultimately, the effort was successful in arranging for the establishment of three new flood-warning tide gages in cooperation with county and municipal offices of emergency management. A parallel effort in cooperation with the National Park Service succeeded in arranging for the establishment of a fourth tide gage with a colocated weather station within the Fire Island National Seashore and Wilderness (fig. 19).

In New England, SWaTH provided an opportunity for the USGS to reach out to stakeholders and offer more data that would be mutually beneficial. For example, SWaTH provided for the installation of network sites, and the tribal oyster industry agreed to fund the operation and maintenance of a new continuous tide gage. The water-level and meteorological data from this gage will assist the tribal oyster industry in making more informed decisions regarding their operations and will also provide data that are publically available for others in the community to use. In addition to this tide gage, 12 others were installed across New England.

These examples demonstrate how the USGS works with partners around the country. Many USGS data-collection activities are funded cooperatively with partnering agencies. Often, these same stakeholders and communities who have a financial role in the data-collection activity become passionate about the data and how they can use these data to better protect their coastal communities from future storm impacts.

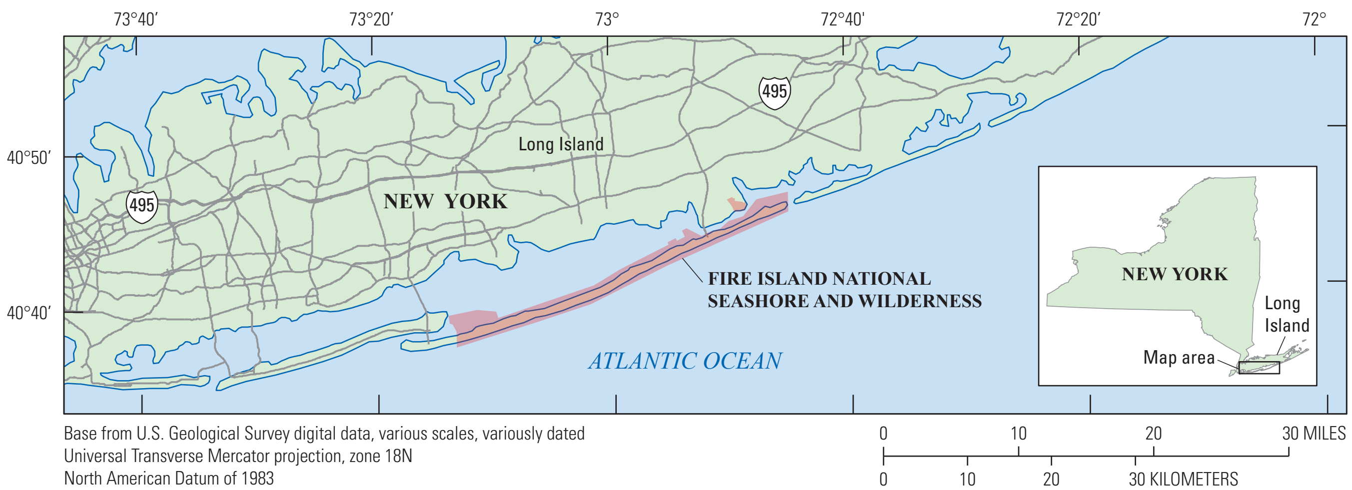


Figure 19. Fire Island National Seashore and Wilderness on Fire Island, New York, has long been affected by storms and hurricanes.

SWaTH and Real-Time Networks

Real-time data are the essential driver of forecasting models; without real-time data, forecasting models are simply unreliable. When dealing with coastal floods, water-level and meteorological (mostly wind speed and direction) data are of the utmost importance; these events are also the most difficult to predict, especially on small scales, without using real data on the ground.

Having a thorough understanding of this dilemma, the USGS worked with partners, new and old, to enhance the existing interagency network of tide-monitoring locations along the Atlantic coast. As a result, an extensive network of more than 900 locations has been added to the existing monitoring network. The SWaTH network is made up of a combination of non-real-time sensors, temporary real-time gages, and permanent, long-term real-time stations.

With 32 new permanent real-time sites being installed across the SWaTH network as well as the hardening of existing permanent real-time sites, the amount of data that will be available to the forecasting and emergency management agencies and the public before, during, and after storms far surpasses the amount or the reliability of any data that were available in the past. The temporary real-time gages also will provide a better picture of what is actually happening at predetermined locations and throughout the network during an actual storm event. These data will assist the local emergency management community in making decisions regarding road closures, evacuations, and recovery operations.

The non-real-time monitor network also has been bolstered substantially in the SWaTH network. With more than 900 locations identified, presurveyed, and with infrastructure already in place, the non-real-time monitor network will provide even more data than before. These data can contribute to documenting where flooding occurred and to what extent; however, with the addition of high-resolution sensors, the data also provide detailed datasets of wave action and attenuation throughout the event.

Partnerships have been forged, many from scratch, in these coastal communities. Not only will more data be available in real-time, the preinstalled and surveyed SWaTH network infrastructure will enable USGS field crews to work more efficiently and productively while increasing their safety. The SWaTH network can provide the high-resolution datasets that are needed for the Nation to improve our ability to plan for, predict, and recover from coastal-storm impacts.

During hurricanes, the U.S. Geological Survey deploys storm-surge monitoring instruments along the coasts, sounds, and bays in areas predicted to be impacted to gage how high hurricanes push water in rivers, bays, and other areas. The sensors are important to forecasting future storms and assessing hurricane damage. They are strapped to structures expected to survive the storm, such as bridge piers, light poles, and fire hydrants. This storm surge sensor has been deployed on the Pamlico Sound in Buxton, North Carolina. Photograph by Kristen McSwain, U.S. Geological Survey.

Summary

After Hurricane Sandy made landfall along the northeastern Atlantic coast of the United States on October 29, 2012, the USGS carried out scientific investigations to assist with protecting coastal communities and resources in the future. The work included development and implementation of the Surge, Wave, and Tide Hydrodynamics (SWaTH) network consisting of more than 900 monitoring stations in order to greatly improve the collection and timely dissemination of information related to storm surge and coastal flooding. SWaTH provides a significant enhancement of USGS data-collection capabilities in the region impacted by Hurricane Sandy and represents a new strategy for observing and monitoring coastal storms that should result in improved understanding, prediction, and warning of storm-surge impacts.

Emergency management officials and the public will be able to use the data and the information provided by storm-surge forecasts driven by these newly available data to make real-time decisions on evacuation plans and the protection of property. As the data are collected and accumulated, they will feed and inform new Federal Emergency Management Agency floodplain maps, land-use decisions, and building codes, ultimately leading to more disaster-resilient coastal communities.

Acknowledgments

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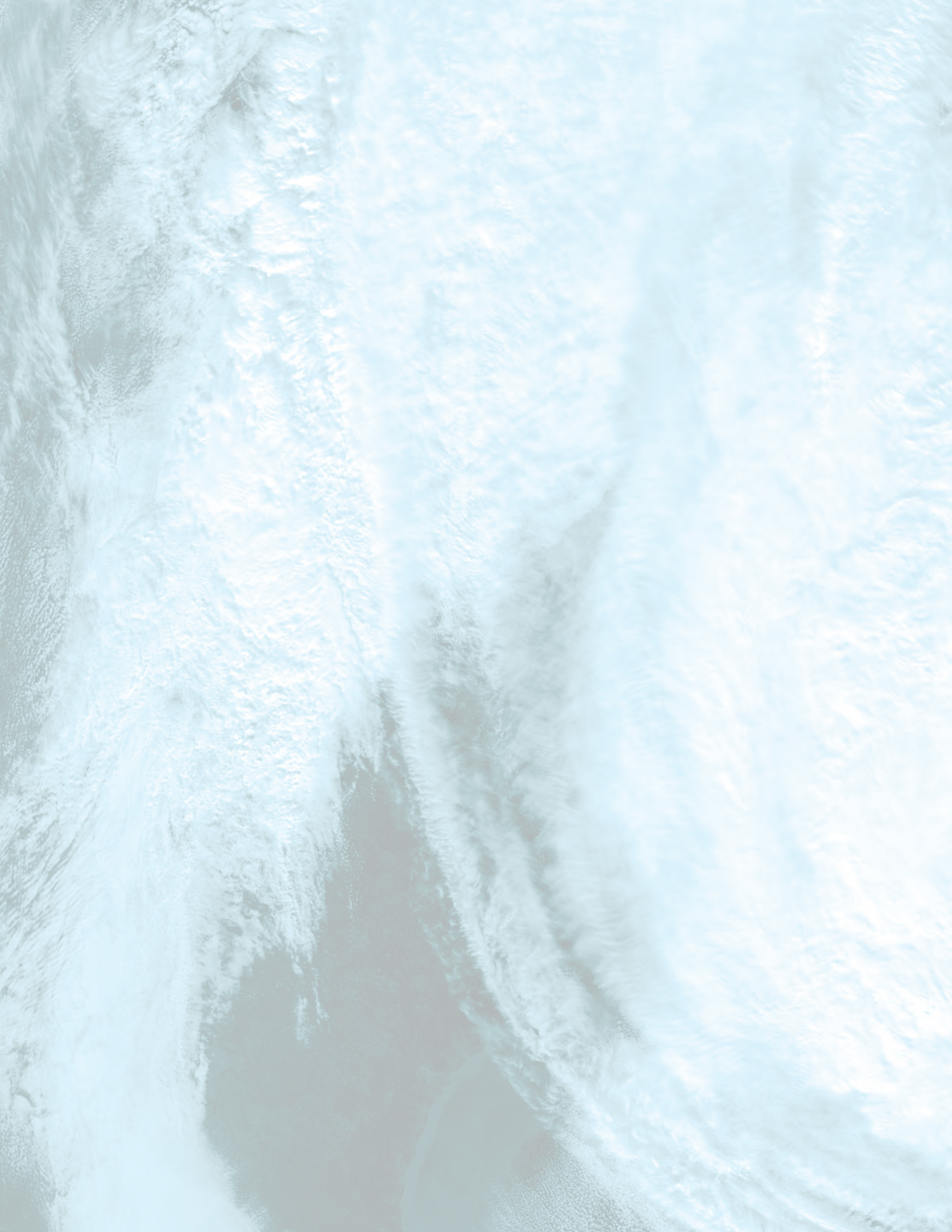

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