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BARNEGAT BAY STORM SURGE ELEVATIONS DURING HURRICANE SANDY
And
SOURCES OF SURGE FLOODING WITHIN THE BAY

Hurricane Sandy came ashore in New Jersey Sunday evening, October 29, 2012 as a hybrid hurricane and northeaster which moved westward from the Atlantic Ocean crossing the coastline in northern Atlantic County. This path proved particularly devastating for NJ bayfront and oceanfront communities north of Little Egg Inlet in Ocean and Monmouth Counties, with extensive tidal flooding also recorded in Cape May and Atlantic Counties.

A critical impact was the cutting of one major and two minor breaches in the barrier extending between Manasquan Inlet and Barnegat Inlet coupled with extensive cross-island flow at many streets perpendicular to the shoreline between Twilight Lake in Bay Head and Holgate on the southern end of Long Beach Island. This added flow volume exacerbated water levels achieved within Barnegat Bay due to tidal flow in from the Manasquan Canal, Barnegat Inlet, direct rain and uplands runoff surrounding the bay and tidal impacts from Little Egg Inlet at the south end of Barnegat Bay.

This paper is an attempt to quantify the sources of tidal flooding and water volumes associated with these potential sources in relation to the ultimate flood levels seen during Sandy. The analysis is based on gathering together the United States Geologic Survey's monitoring data for tide levels and tidal flow discharge rates for 7 locations within Barnegat Bay immediately prior to, during and following Hurricane Sandy's NJ landfall late October 29, 2012. In addition an animation (in Excel VBA) of this data was put together by John Yagecic (Delaware River Basin Commission) and Jeffrey Gebert, Chief of Coastal Planning, Philadelphia District Corps of Engineers. This analysis is not a model, but a compilation of all the hydrographic data collected during the storm and subjected to rapid review to allow this paper's presentation on the subject of Barnegat Bay tidal flooding due to Hurricane Sandy. The animation can be viewed on You Tube at https://www.youtube.com/watch?v=bN0o_bt-bwo Several screen captures have been included at important moments in the unfolding disaster (Figures 5 & 6).

Barnegat Bay:

Barnegat Bay is an elongated "lagoon" positioned between a barrier spit and barrier island comprising the NJ coastline between Bay Head and Holgate on Long Beach Island and the Ocean County mainland. Its average depth is between 4 and 6 feet at high tide with abundant natural and man-made channels permitting vessel navigation. The Point Pleasant Canal, built in the first half of the 20th Century supplies tidal flow to the northern end of the bay, while Barnegat Inlet supplies a considerable tidal prism volume of flow to the middle section of the bay. Little Egg Inlet in the south feeds both Great Bay and Barnegat Bay along the southern 60% of Long Beach Island. Fresh water streams supply modest quantities of fresh water, but heavy rains produce greater runoff from all the developed surfaces that drain directly to the bay.

The water surface area of Barnegat Bay from Bay Head, including the Metedeconk and Toms River south to Holgate comprises 68,599 acres. This multiplied by 43,500 square feet per acre yields a water surface area of 2,984,073,900 square feet (NJDEP 2007 LAND USE geo-database). The area of the bay found to be salt marsh is 24,847.34 acres (NJDEP Ocean County wetland delineations). This multiplied by 43,500 square feet per acres yields a marsh surface area of 1,080,859,290 square feet. Summing both areas, the entire Barnegat Bay capable of storm surge flooding equals 4,064,933,190 sq. ft.

Since the impact on the water elevations within the bay varied from south to north, a subdivision of the area was made between the entire bay and marsh surface area to the marsh and water surface area lying north of the Route 37 Bridge into Seaside Park. This portion of the bay consists of 12,182 acres or 529,932,225 square feet. This part of the bay is about one eighth the area of the entire bay and subject to far greater levels of flooding impacts from the same water volume as compared to the entire bay area.

Under normal tidal flow conditions, the marsh area is not subjected to tidal flooding except for spring tide cycles. Hurricane Sandy added at least 5.0 feet of water on the marsh surface area making the entire bay surface area above the reservoir of water volume. Therefore, once the in-flow of water reached the surface elevation of the salt marsh (approximately +1.5 feet NAVD88), each additional foot of water level rise would require 4 billion cubic feet of added in-flow to Barnegat Bay.

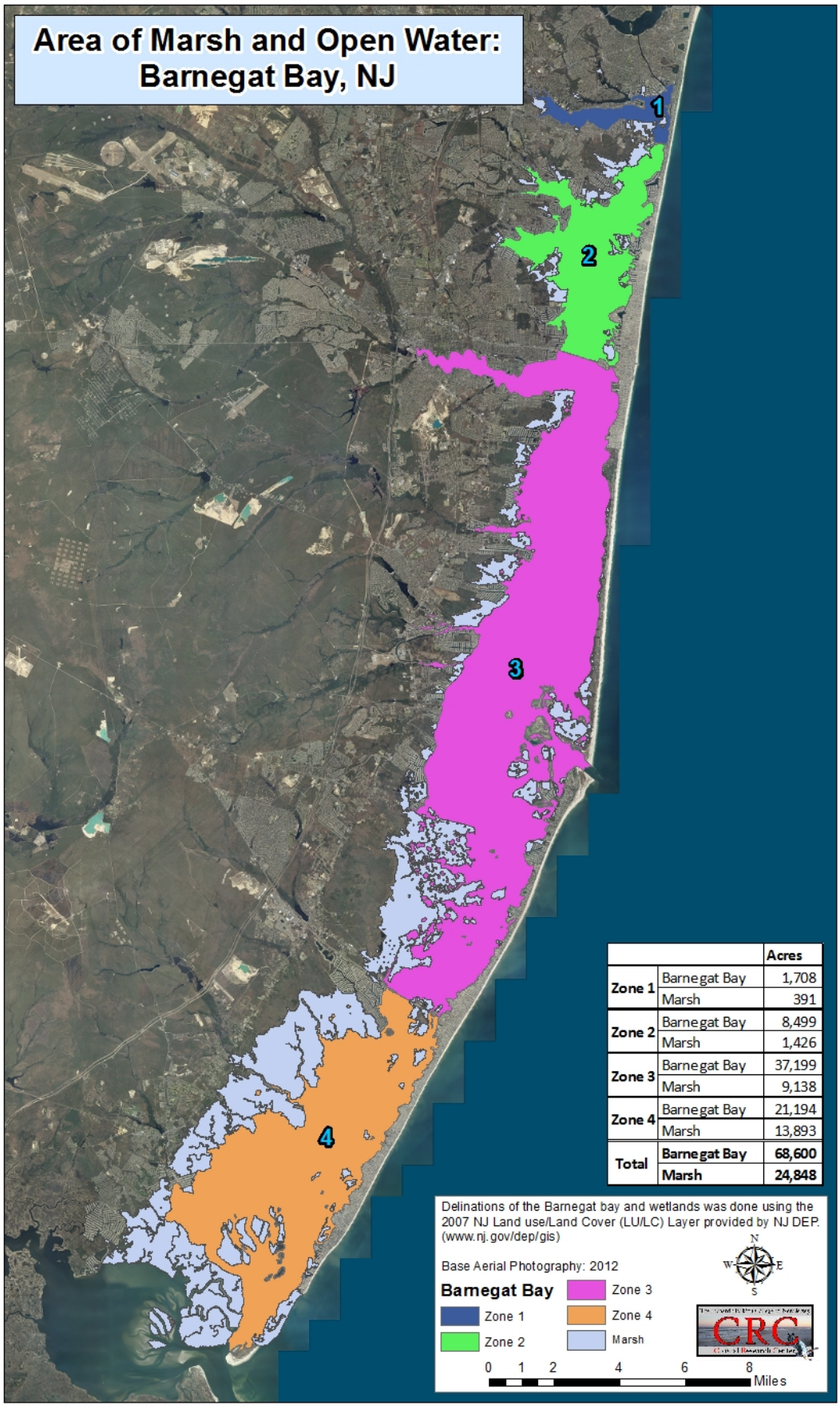

Figure 1. Map of the delineated areas of salt marsh, and open water within four zones in Barnegat Bay, Ocean County, NJ. These data were part of the NJDEP 2007 NJ Land Use/Land Cover Arc-GIS layers.

The Point Pleasant Canal:

Tidal flow into Barnegat Bay is partially achieved through the manmade canal connecting the Manasquan Estuary with the upper part of Barnegat Bay. As fate would have it there is a USGS flow gage on the canal which was functional during the days surrounding Hurricane Sandy. The data is displayed graphically below.

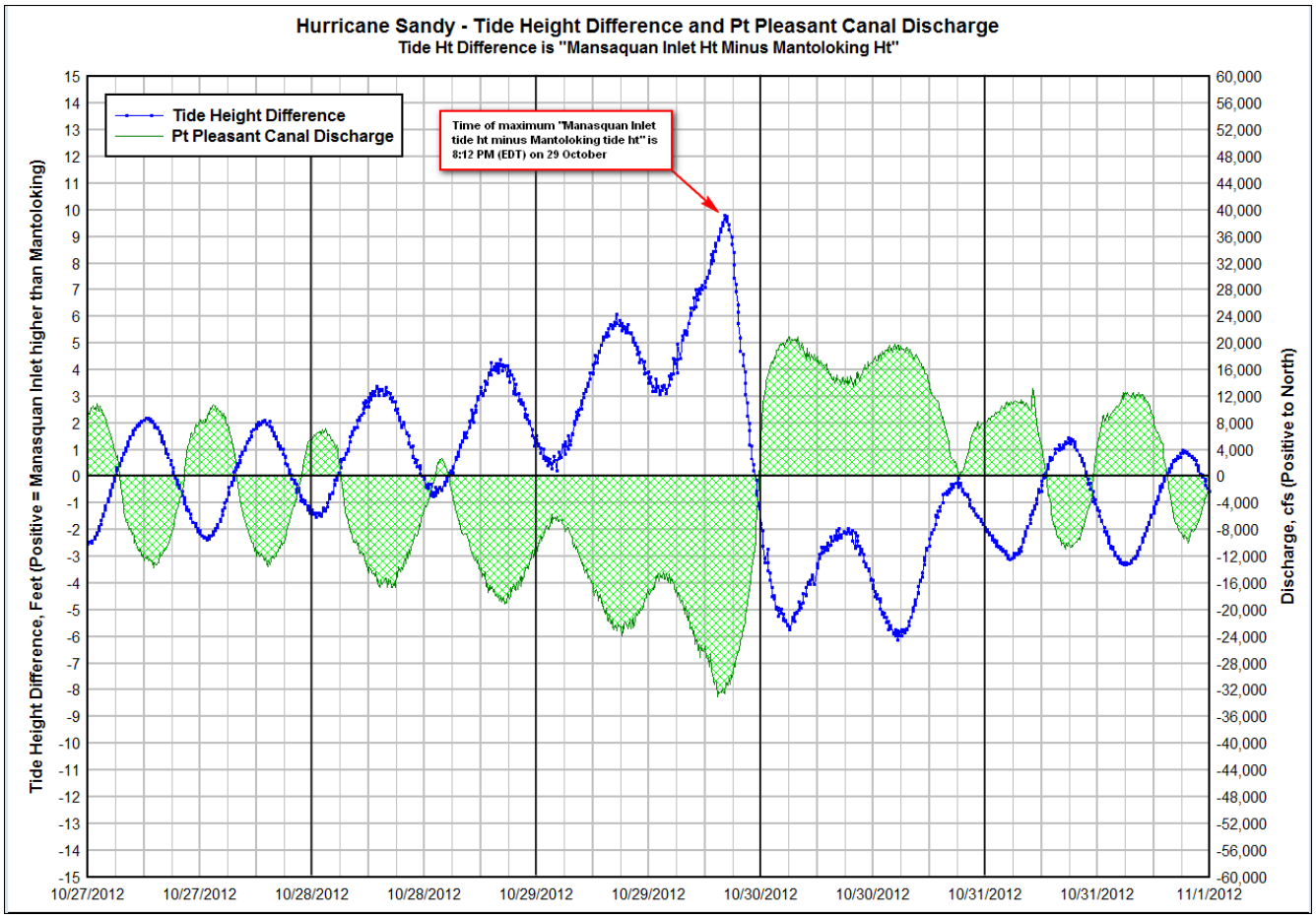

Figure 2. The graph shows two things. The green line is the flow rate as generated by the water velocity past the gage times the cross sectional area of the canal channel at the gage with southward as negative numbers and northward flow as positive numbers. Note that the last ebb-tidal (northward) flow from Barnegat Bay prior to breaching occurred about 1:30 pm on October 28th. The next three flood-tidal cycles produced ever-increasing southward flow volumes until approximately 7:30 pm October 29th. Between that time and Midnight on October 30th the flow dramatically reversed to ebb-tidal (northward) velocities in the canal for the next 30 hours. The blue line is the difference in tidal water surface elevation between the Mantoloking tide gage at Herbert Street Bridge and the gage at Manasquan Inlet. The maximum elevation difference occurred at 8:12 pm October 29th with a value of 9.8 feet. Over the next six hours this value reverses to a point where the Mantoloking tide height exceeds that at the Manasquan Inlet by 5.7 feet repeated again 12.5 hours later before slowly returning to normal (10/31/2012).

The tidal inflow (southward) values at the Point Pleasant Canal peak at 32,000 cubic feet per second. Taking an average inflow rate of 22,000 cu. ft. per second from 9pm October 28th until 9pm October 29th one gets a total water volume inflow of 79,200,000 cubic feet per hour times 24 hours is 1,900,800,000 cubic feet of water volume. This IS APPROXIMATELY HALF the water volume needed to raise the entire flooded bay and marsh surface area by one foot. BUT, if confined to the upper bay above the Route 37 Bridge, this impact represents a 4.0-foot water level rise (starting from -1.2 feet NAVD88 in Mantoloking taking the level to +2.8 feet).

Tide Levels at the Mantoloking Bridge to the Ocean County Mainland:

The USGS maintains a tide gage at the Herbert Avenue Bridge between Ocean County mainland and the barrier spit. This gage recorded tide elevations leading through the Hurricane Sandy interval. A graphic table below shows the resulting data.

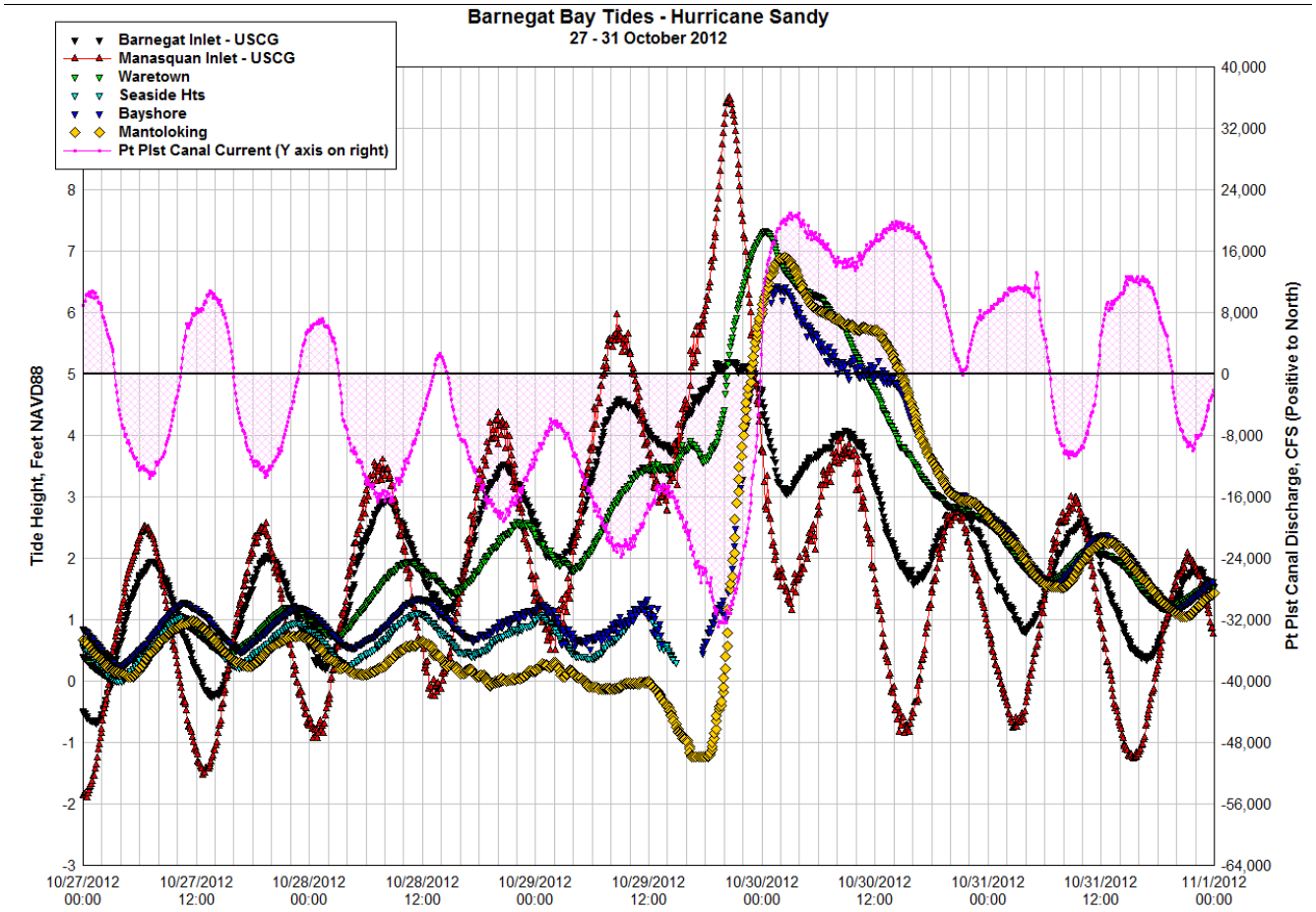

Figure 3. A compilation of tide gage records within Barnegat Bay providing insights into tidal elevations and the timing of maximum elevations. The Mantoloking Bridge graph represents the northernmost Barnegat Bay gage in this record. Important issues to note are the dramatic contrasts between the tide elevation within the bay and at the Manasquan Inlet (red). The Manasquan Inlet gage has by far the highest elevation (9.5 feet NAVD88) while climbing steadily higher each high tide prior to the storm's shoreline crossing, then dropping off, returning to normal. The Mantoloking gage (gold diamonds) steadily drops in both average water level elevation and in total range between high and low tide until noon on October 29th as Sandy's final approach was occurring. Then the water level drops about 1.2 feet below the zero NAVD88 datum for almost two hours. This action is attributable to the 80 MPH northeast winds blowing down the axis of Barnegat Bay pushing the shallow water column south leaving the Herbert Avenue tide gage far below the water elevation at Manasquan Inlet. The spectacular rise in water level commences after 6:30 pm on October 29th and peaks by 2 am October 30th 8.2 feet higher. Therefore, the northern section of Barnegat Bay rises 8.2 feet in 7.5 hours. Since water is strongly flowing into the bay through the Manasquan Canal, the dramatic reversal in both elevation of the Herbert Street tide gage and the reversal in tidal flow in the canal points to overwhelming water influx via the Mantoloking Borough breaches and all the other dune failures where each street perpendicular to the shoreline became a conduit for flood waters entering the bay and the influx from Barnegat Inlet.

This graph corroborates the information shown in Figure 1 explaining how the process was set up by the storm's approach and landfall, but then explodes into the final situation following multiple breaching of the barrier and a multiplicity of alternative sources down countless streets and across many lots and blocks (Ortley Beach for example). Water entered Barnegat Bay from the sea as far north as Twilight

Lake in Bay Head, all the way south to Holgate where total overwash covered the final 3 miles of the Long Beach Island shoreline.

Tidal Flow at the Route 37 Bridge at Bayshore, NJ:

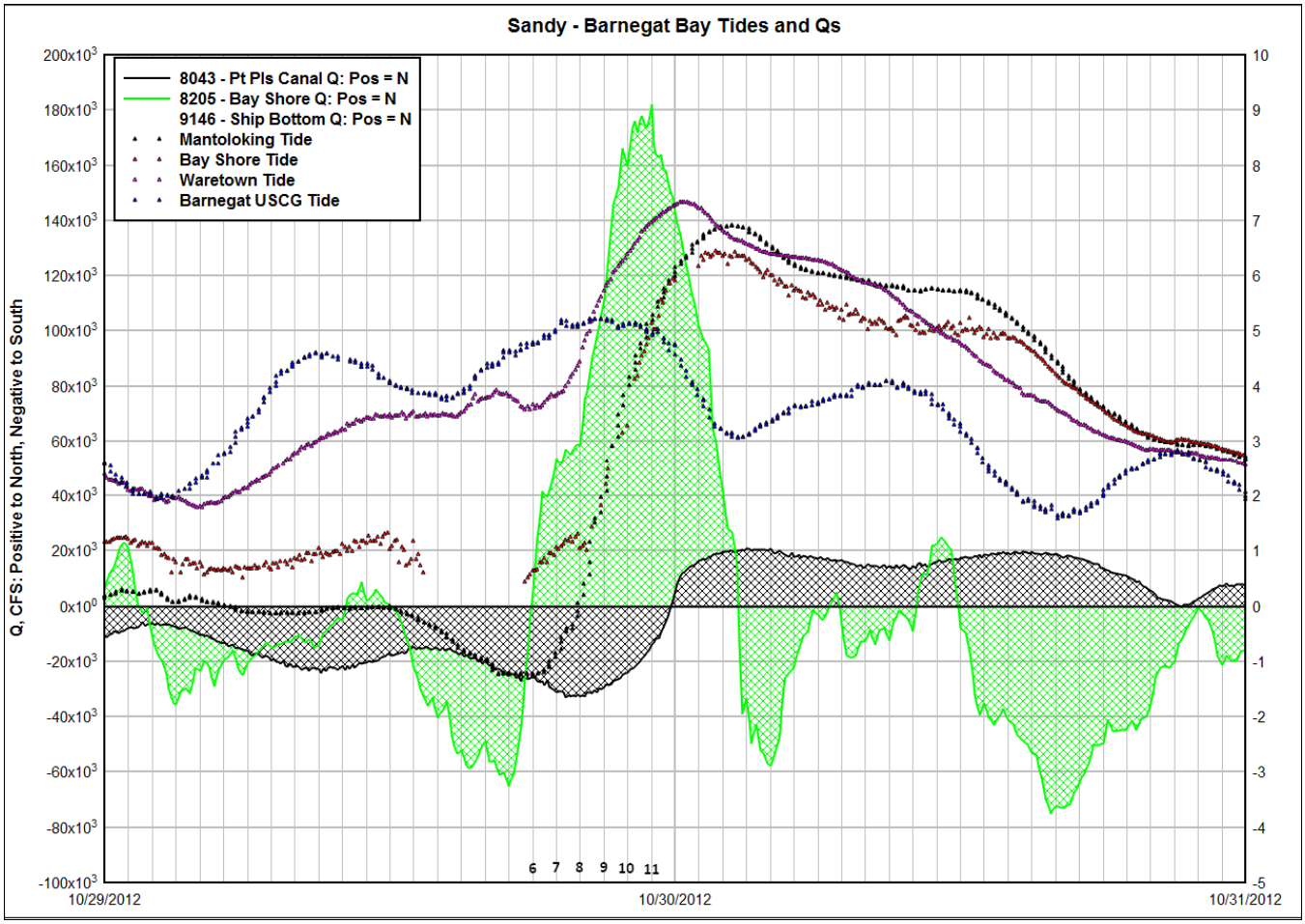

Figure 4. Tidal data and flow rates for the USGS gage located on the bridge span for NJ Route 37 between Toms River and Seaside Park just north of Island Beach State Park. The green-shaded graphic shows the flow at the bridge computed as cubic feet per second passing the gage. Normally, the flows to the north (positive) are in the range of 20,000 cu. ft/sec. Between 6pm on October 29 and 3am on October 30th the flow reversed at the bridge and reached a peak of 180,000 cu. ft/sec to the north toward the upper bay. Remember that Barnegat Inlet is south of this point as is Island Beach State Park. However, Ortley Beach lies to the east, just north of the bridge.

The peak in the flow rate graph resembles a "normal distribution" curve so that a mean flow would amount to 64% of the peak flow if the values range from zero up to the peak, then back down to zero (to the north). A mean flow is then 115,200 cu ft/sec. The nine hour flow time would have produced a total water influx of 115,200 x 60 x 60 x 9 = 3,732,480,000 cubic feet. This volume represents just under a foot of water level rise for the entire Barnegat Bay. It does include the Barnegat Inlet component of the Hurricane Sandy tidal prism volume moving north into the mid- and upper bay area. However, since this volume is added to the inflow from the Manasquan Canal, this adds 7.04 feet of added elevation to the northern section of Barnegat Bay taking the theoretical tide elevation to 9.84 feet NAVD88 when combined with the Manasquan Canal inflow.

Tidal Flow at the Route 72 Bridge at Ship Bottom, NJ:

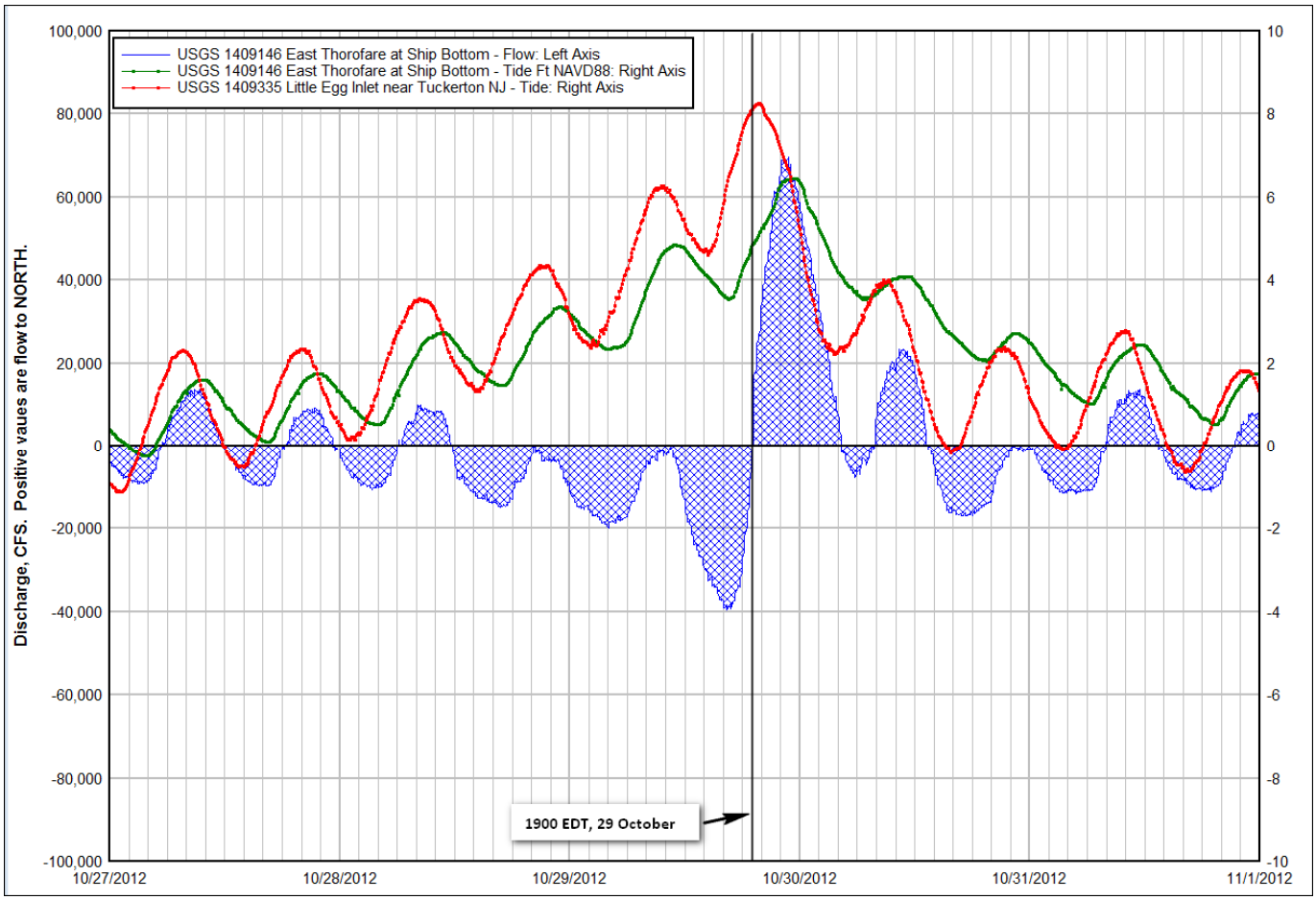

Figure 5. The southernmost tidal flow gage is positioned at the Route 72 Bridge to Ship Bottom on Long Beach Island, is south of Barnegat Inlet and influenced by tidal flow up from Little Egg Inlet at the south end of Long Beach Island. Here the tidal flow switches to the north (positive values) at 7pm October 29th from a peak flow south of 40,000 cu. ft/sec. at 4:30pm, reaching a peak flow to the north by 10:30pm, and then falling to zero flow by 4:15am on the 30th. Normal flows resume by the pm ebb tide on October 30th at less than 18,000 cu. ft/sec. The highest storm surge tidal elevation was 8.2 feet NAVD88 at Tuckerton gage at 8pm on the 29th.

The graph above illustrates a more normal storm surge process where alternative influences other than tidal inlet flows are absent in spite of wholesale overwash in Holgate and across the southern two miles of the Forsythe Wildlife Refuge section of Long Beach Island. These flows simply added to the water flow seen up at the Route 72 Bridge because these were all well south of the bridge.

Barnegat Inlet Tidal Prism During Sandy:

Barnegat Inlet supplies tidal water to the middle segment of Barnegat Bay opposite Waretown on the Ocean County mainland. Powerful tidal currents move large volumes of water in a cycle of ebb- and flood-tidal flow normally. Sandy was far from normal. The Waretown tide gage in the bay showed a peak water elevation of 7.3 feet NAVD88. This was the highest bay gage elevation observed and is expected since it is located opposite Barnegat Inlet. Work following jetty realignment by 1992 reflected a flood-tidal prism volume of 1,458,550,800 cu. feet of water volume (Seabergh, et. al 1998). This is a normal flood-tidal flow water volume given by Seabergh as 41.3 x 10^6 meters cubed. The USGS tidal flow gage at Route 37 Bridge shows that the inlet tidal prism was at least tripled during Hurricane Sandy.

Fresh Water Influx into Barnegat Bay:

Work by the Barnegat Bay Partnership and published by Stanton Hales, indicated that all fresh water influx amounted to less than 3% of the Barnegat Inlet tidal prism volume. If one assumes that the Hurricane rainfall amounted to three time's the normal influx, this would result in 1,312,696 cubic feet of runoff entering Barnegat Bay during a 6.25 hour cycle. It does appear that fresh water influx is marginal in elevating Barnegat Bay surface elevations.

Shore-Normal Street Flow into Barnegat Bay:

Using related observations among both Northern Ocean County and Long Beach Island residents, the average street flow was 50 wide x 2 feet deep flowing at 4 feet per second. This yields 400 x 60 x 60 x 2 hours = 2,880,000 cubic feet of water added to Barnegat Bay per street flowing. If it requires 4 billion cubic feet to raise the water level by a foot in a marsh-flooded Barnegat Bay, then 1,389 streets between Bay Head and Holgate need to flow at that rate to produce the 1-foot rise in water surface elevation.

Island Beach State Park Overwash Events:

A careful review of the entire length of the Island Beach State Park as covered by the immediate post-Sandy aerial photography shows that one overwash element moved sand into Barnegat Bay, but all others the alluvial fan of overwash sand deposited died out at the highway or prior to reaching it. Debris on the road appears to consist of tall reeds and other marsh materials found in mega-abundance following Sandy throughout the NJ coastal lagoon system. Everything floatable including decades of dead grass mats on the marshes were mobilized by the waves and elevated water levels and transported onto the mainland or back into the bayshore of the barrier islands after the wind switched directions but prior to the receding of the water levels.

If each of four overwash events crossed the park with a 4 foot per second average flow rate similar to that seen in the streets crossing the barrier beaches, and the narrowest width of flow was 200 feet with a depth of 3 feet (the 6-foot highway elevation subtracted from the 9-foot maximum storm surge elevation, the same computation for all four IBSP overwash events is 600 x 4 x 60 x 60 x 2 hrs. x 4 overwash sites = 69,120,000 cubic feet. This calculation makes the flow depth 3 feet, the narrowest part of a "channel" 200 feet wide and keeps the 4.0 ft/second flow rate seen on paved streets, not through vegetation. The 69.1 million cubic feet represents all four overwash sites observed in the post-Sandy aerial photographs. This is 0.01728 foot of added water elevation addition to Barnegat Bay. If one only considers the bay surface area north of the Route 37 Bridge, and all this water turned north and flowed under the bridge, the rise in the northern bay section would be 0.13 feet of surface elevation increase.

The Mantoloking Breaches:

Surveys at Mant-3, located at 1117 Ocean Avenue in Mantoloking November 5, 2012 by the Coastal Research Center staff found that in the middle of the major breach the elevation of the Route 35 highway surface concrete slabs was -1.8 feet NAVD88. This gap was 450 feet wide at approximately this elevation, so would have had a flow cross sectional area of 450 x 8.8 vertical feet = 3,960 square feet. The flow was anything but steady state, so a guess as to average flow rates would be 4.5 feet per second based on northeast storm flows in various inlets. This produces a flow volume in 4 hours of 3960 x 4.5 x 60 x 60 x 4 = 256,608,000 cubic feet. This is 6.4% of the flow volume necessary to raise the entire salt marsh flooded Barnegat Bay by one foot. However, since this inflow is concentrated in the northern segment of the bay, its impact is far larger (about 50% of the volume needed to raise this portion of the bay by an additional foot) due to a smaller total area. The massive inflow seen at the Route 37 bridge reversed dramatically by 3am October 30th, rising rapidly to a peak southerly flow of 60,000 cu. ft/sec. by

4am on the 30th. The breaching, overwash and continued inflow from the Manasquan Canal (until midnight 10/30) dominated the situation after midnight on October 30th. This speedy reversal in flow directions for both the Canal and the Route 37 bridge gages emphasize the significance of the overwash and Mantoloking breaches as driving forces impacting upper Barnegat Bay flooding.

The Barnegat Bay Tidal Animation:

This animated graph of water surface elevations and discharges in the vicinity of Barnegat Bay, NJ during Hurricane Sandy was programmed in Excel VBA by John Yagecic and Jeff Gebert. All tidal elevation and discharge data are from the US Geological Survey. The Hurricane Sandy track is from NOAA. The URL above on page 1 will take you to the site so you can watch the animation process. You will probably need to pause and restart the flow simply because the highly relevant details occur in the last few hours on October 29th and early on the 30th. Below are screen capture pictures of the key points in time showing the combination of all the USGS tidal elevation and flow data for Barnegat Bay.

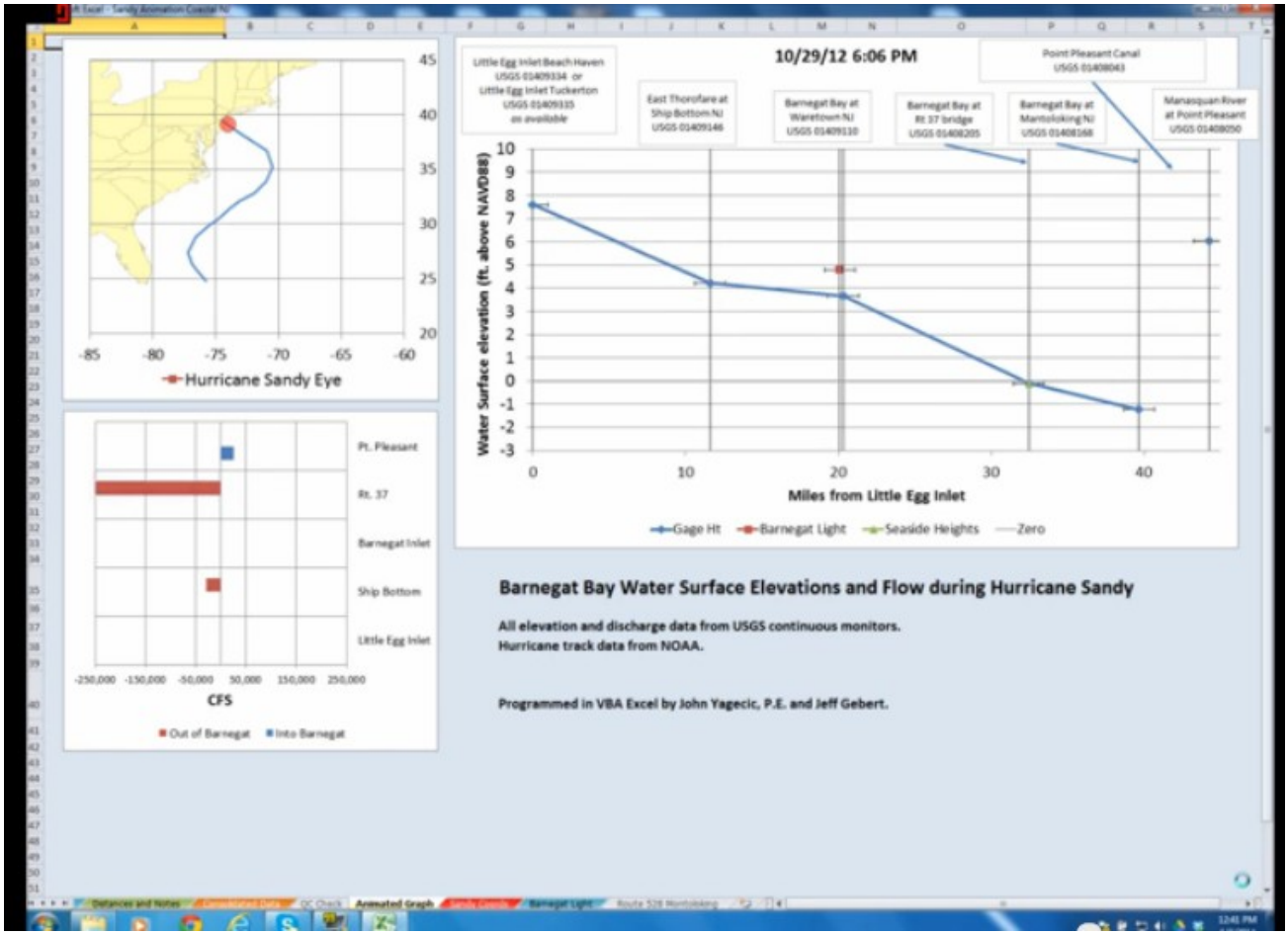

Figure 6. Digital animation graph showing Barnegat Bay tide elevations at 6:06 pm on October 29, 2012. The tide gages range from Tuckerton on the left to the Manasquan Inlet on the extreme right. The water elevations range from 7.6 feet at Tuckerton dropping steadily to -1.2 feet NAVD88 at the Borough of Mantoloking just prior to the overwash and breaching. The tide elevation at Manasquan Inlet was 6.0 feet, therefore representative of a 7.2-foot hydraulic head difference between the inlet and Mantoloking that was generating the 32,000 cu. ft/sec flow rates into Barnegat Bay through the Manasquan Canal (Figure 1). This also explains the huge northerly flow under the Route 37 bridge that commenced at 9pm and ended at 3am on the 30th.

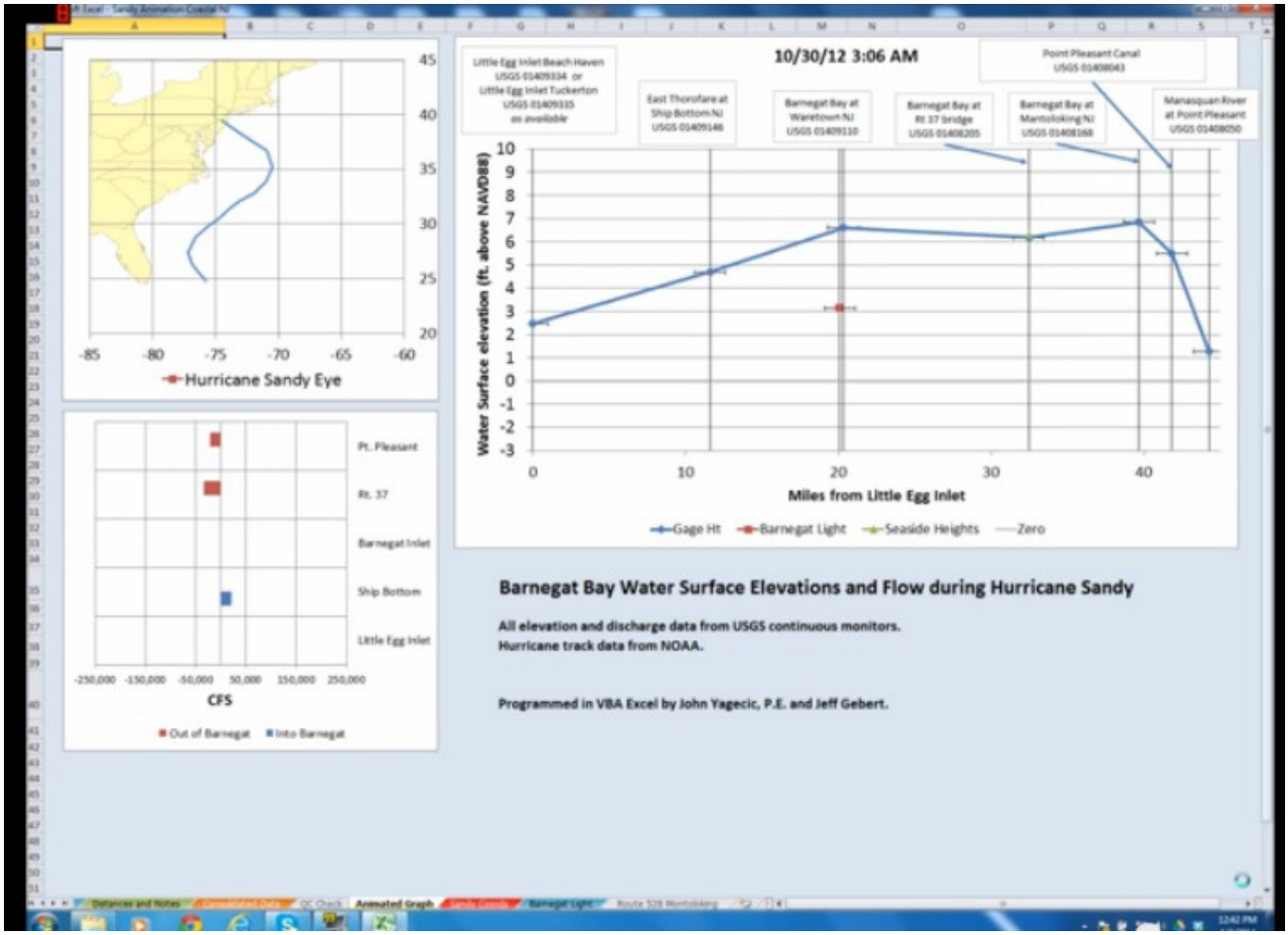

Figure 7. Digital animation graph showing Barnegat Bay tide elevations at 3:06 am on October 30, 2012. The tide gages range from Tuckerton on the left to the Manasquan Inlet on the extreme right. This data is nine hours later, now the highest elevations are between Waretown (directly opposite Barnegat Inlet) and Mantoloking at 6.6 to 7.0 feet NAVD88. By 3am the tide elevation at Manasquan Inlet had dropped to +1.2 feet now generating a reverse hydraulic head driving high flow rates out of Barnegat Bay via the Manasquan Canal (Figure 1). At Tuckerton to the south the tide elevation has dropped to 2.5 feet likewise generating the 60,000 cu. ft/sec. flow rates back south under the Route 37 Bridge.

Conclusions:

This work owes a great debt of gratitude to Mr. Jeffery Gebert, Philadelphia District Corps of Engineers who compiled and produced the graphs showing the actual data collected by the gages monitored by the USGS throughout Barnegat Bay and the two tidal inlets. The combinations of tide heights and flow rates and direction plotted versus time have given insight into the hydrographic scenario that unfolded within Barnegat Bay during Hurricane Sandy late in October 2012. The animation compiled by John Yagecic, Delaware River Basin Commission, adds a dimension to the data showing that the massive inflows from the existing tidal inlets were only altered by overwash and inlet breaching during the 6-9 hours between 6pm on the 29th and 3am on October 30th.

1. The Manasquan Canal and Barnegat Inlet tidal flow dominate the Barnegat Bay flooding scenario for Hurricane Sandy. Both together provide enough water to raise the normal high tide elevation of +1.2 feet NAVD88 to 6.0 feet elevation (excluding the precursor increase of 1.5 feet added to the 1.2-foot normal High Tide elevation) during the prior 18 hours (see figure 1) due to the decrease in barometric pressure effect on the water level related to the storm's arrival.

2. The entire ocean to bay flooding across the barrier islands approximates an additional added foot of water elevation rise in the bay.
3. Prior to breaching, the northeast wind was driving the northern bay surface water south as a shallow lagoonal seiche leaving the Mantoloking Herbert Street tide gage sitting on the bay floor until overwash and breaching occurred.
4. The inlet breaches in Mantoloking account for at most 50% of an additional foot of regional bay surface elevation rise. Massive overwash between Bay Head and Ortley Beach added another 0.6 foot to the total rise based on estimated flow rates across the island where dunes failed.
5. The contribution from 3 or 4 overwash events across Island Beach State Park could not and did not produce any form of significant additional Barnegat Bay water elevation rise during Hurricane Sandy (in a high range of 0.017 feet). Dunes on Island Beach State Park did allow water to flow to Barnegat Bay, but in general the dune system in the park was much more of a barrier to storm surge flooding than a pathway for flood-tidal flow.

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