# Hurricane Irene and the Pea Island Breach: Pre-storm site characterization and storm surge estimation using geospatial technologies

*By*

Adam S. Clinch[1], Emily R. Russ[2], Ross C. Oliver[1],
Helena Mitasova[2], and Margery F. Overton[1]

*(1) North Carolina State University*
*Department of Civil, Construction, and Environmental Engineering*
*Raleigh, NC 27695-7908*
*asclinch@ncsu.edu*

*(2) North Carolina State University*
*Department of Marine, Earth, and Atmospheric Sciences*
*Raleigh, NC 27695-8208*

## ABSTRACT

Hurricane Irene crossed into Pamlico Sound and tracked north in August 2011, forcing water to the west that rebounded in a significant storm surge to the backside of the barrier islands known as the Outer Banks of North Carolina. Pea Island from Oregon Inlet to Rodanthe, with its narrow barrier islands and exposure to waves and surge, has always been highly vulnerable to storm impact, but the severity of the damage from Irene was unexpected given the Category 1 status of the storm on landfall. This paper reviews similar historic storms with soundside flooding on the Outer Banks. Several techniques based on orthophoto imagery and pre-storm LiDAR topography are used to analyze the formation of this breach. A temporal dune profile assessment shows the vulnerability of the breach site due to previous storms. An alongshore dune ridge analysis reveals low dune elevations at the site of the breach before the Hurricane Irene event. Remote sensing is used to estimate the soundside surge elevations from a distinguishable wrack line left on Pea Island after the storm. An inundation visualization simulates the effects of a significant soundside surge by flooding the barrier island in the locations of the two channels of the breach.

**ADDITIONAL KEYWORDS:** Wrack line, soundside flooding, barrier island breaching, digital elevation models, aerial photography

*Manuscript submitted 20 January 2012, revised and accepted 22 March 2012.*

On 27 August 2011, Hurricane Irene made landfall near Cape Lookout and traveled north across Pamlico Sound and the Pamlico-Albemarle peninsula, creating a large surge on the sound side of the North Carolina Outer Banks. The barrier islands south of Oregon Inlet were breached in two places, one just south of a series of fresh water ponds and two at Mirlo Beach. The one at Mirlo Beach (or the Rodanthe Breach) closed, but the breach just south of the ponds (or the Pea Island Breach, as it is called) remains open. The North Carolina Department of Transportation (NCDOT) has, at the time of the writing of this article, repaired NC 12 and installed a temporary bridge over the Pea Island Breach. Figure 1 shows a location map indicating the Pea Island Breach study site and other key locations referenced in this paper. Figure 2 below shows two orthophoto images taken at dates before and after Hurricane Irene at the Pea Island Breach.

This paper intends to provide a review of four historic soundside events (including Hurricane Irene) that had a significant impact on the Outer Banks. To better understand the vulnerability of the Pea Island Breach location just prior to the storm, remote sensing of LiDAR data and orthophoto imagery will be used to investigate the site using four approaches:

1) Dune evolution will be observed through a temporal analysis of two dimensional profiles.

2) Maximum dune elevations will be estimated from a dune ridge extraction technique, to identify areas that are susceptible to inundation.

3) Identification and mapping of the deposition vegetative debris, or wrack lines, will be used in combination with elevation models to estimate the maximum water level during the storm at this site.

4) Visualizations of the maximum water level over topographic data will illustrate the vulnerability of the site to soundside surge due to Hurricane Irene.

## HISTORIC SOUND SURGE EVENTS

Of the four soundside events that we discuss in this paper, three events have had a significant effect on the morphology of the Outer Banks and one (Hurricane Emily) has caused heavy soundside flooding. These events are the 1846 storm, the 1932 nor'easter, Hurricane Emily, and Hurricane Irene. For each of these storms, a high surge level in the sound flooded the bay side of the Outer Banks. Table 1 shows the soundside surge data reported for these events. Each storm event is briefly reviewed in the section below.

### THE 1846 STORM

Although the 1846 storm was extremely influential to the shape of the Outer Banks,

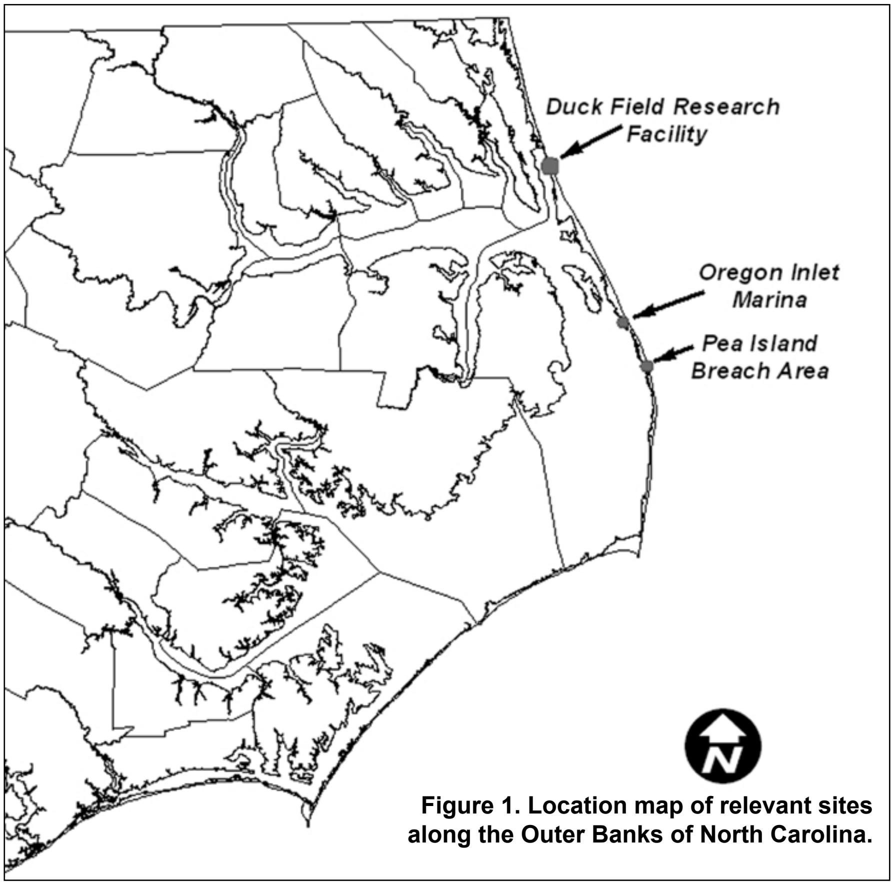

**Figure 1. Location map of relevant sites along the Outer Banks of North Carolina.**

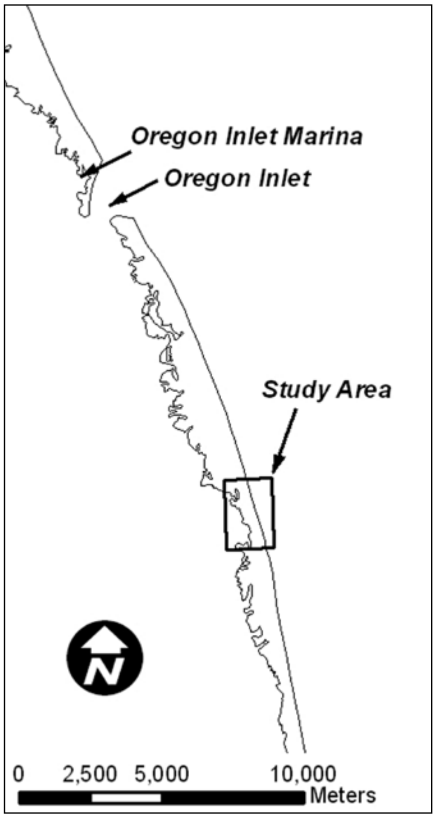

**Figure 2. Study area location on Pea Island on the Outer Banks of North Carolina.**

very little information on the storm exists. One account of the storm documents, "A remarkable surge of water, driven by continuous northeast winds, pushed far into the Pamlico and Albemarle Sounds, flooding rivers and creeks for miles inland. Then, as the hurricane passed and its winds rotated to the southwest, this massive expanse of water rushed back toward the sea, overwashing the Outer Banks from west to east. On the night of September 7, a new inlet was created by these events, known today as Hatteras Inlet. The next day, a second inlet was formed just south of Roanoke Island. This inlet soon became navigable and was named Oregon Inlet…" (Barnes 1995). Both Oregon Inlet and Hatteras Inlet remain major inlets in the Outer Banks to this day.

### THE 1932 STORM

The 1932 storm was a nor'easter, occurring on 6 March 1932 (Markham 1935). This storm event opened New Inlet approximately one kilometer south of the location of the recent Pea Island Breach. A 1935 report based on the observations of the officer in charge of the Pea Island Coast Guard Station who witnessed the event, states that "with a 55 mile per hour wind blowing from the southwest, following a severe easterly storm of the previous day, the wind tide in Pamlico Sound reached a height of about 12 feet and broke over the barrier beach from the sound to the ocean." In 1932, New Inlet consisted of five channels at opening, the northernmost channel nearly identical in location to the 2011 Pea Island Breach. This channel was only 75 feet wide and subsequently closed. The second channel (moving south) was the largest at about 1,000 feet wide. The three southern channels varied between 50 and 100 feet wide. By 1935, the four smaller inlets had closed naturally, leaving only the main channel. This main channel of the inlet shifted southward and narrowed, eventually closing in 1945. Prior to the 1932 storm, another inlet in this location had opened and closed and had been mapped in the 1800s. There is no documentation of the storm that initially caused a breach in this area.

### HURRICANE EMILY (1993)

In 1993, Hurricane Emily caused a significant inland surge to flood the soundside shoreline between Hatteras and Avon (USACE and FEMA 1994). Although this storm did not cause a breach on the Outer Banks, the magnitude of the wind driven surge in the sound is noteworthy for this study. Several field investigations of wrack lines near Buxton were done to determine the surge elevations given in Table 1 (Bush *et al.* 1996). These wrack line studies will be reviewed in the methodology for the wrack line analysis conducted for this research.

### HURRICANE IRENE

Similarly, Hurricane Irene was characterized by a large storm surge in the sound. Local accounts describe heavy flooding inland of the Pamlico Sound and low water elevations on the sound side of the Outer Banks during the beginning of the storm as the winds pushed the waters to the west. Alternately, a rapid increase in water elevation and wave action was reported on the sound side of the Outer Banks during the second half of the storm.

Gage data documents the storm surge on the sound as compared to the oceanfront. The U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck recorded 0.92 meters of surge from the ocean side and 1.9 meters of surge from the sound (USACE 2011). The soundside surge elevation was the highest soundside water level elevation measured at the

**Figure 3. Pea Island breach site before and after Hurricane Irene. (A) was taken on 2 August 2011 before Hurricane Irene reached the Outer Banks on 27 August 2011. (B) was taken after Hurricane Irene on 28 August 2011 (NCDOT imagery).**

FRF since measurements began in 1979. Farther south along the coast, Tide Station 8652587 at the Oregon Inlet Marina recorded an even higher maximum water elevation of 2.1 meters (NOAA NOS 2011). The locations of the USACE FRF site and the Oregon Inlet tide station are presented in Figure 1.

South of Oregon Inlet, Pea Island and Rodanthe suffered the most damage from Hurricane Irene, including breaching of the barrier island in two places: Pea Island and the north side of Rodanthe known as Mirlo Beach. Soon after the storm, the Rodanthe Breach closed naturally and the NCDOT repaired the dunes and the roadbed in the area. After the immediate post-storm monitoring of the breach at Pea Island, the NCDOT also acted to install a temporary bridge to restore the NC 12 transportation corridor.

## PEA ISLAND STUDY SITE

The Pea Island Breach site provides an opportunity to consider the pre-storm conditions that contributed to vulnerability as well as the cumulative impact of multiple storms. The study site chosen for this paper encompasses the Pea Island Breach site as well as the immediate surrounding area to the north and south. Figure 2 shows the location of the study area.

**Figure 4. Orthophotos taken before and after Nor'Ida struck the Outer Banks of North Carolina in November 2009. Figure 4A, on the left, was taken on 8 October 2009. Figure 4B, on the right, was taken on 21 December 2009.**

**Figure 5. Figure 5A shows the study area with the project transects 1 through 45 at the Pea Island Breach. Figures 5B and 5C show a close view of the Hurricane Irene wrack line just south of the Pea Island Breach. The top-right image is without the digitized wrack line. The bottom-right image contains part of the digitized wrack line used in this study.**

There are very few structures on this part of the island; however, this study area includes three buildings belonging the U.S. Fish and Wildlife Service. NC 12 is approximately shore parallel and access to the U.S. Fish and Wildlife facility consists of shore perpendicular paved road and parking areas.

## METHODOLOGY

In order to better understand the vulnerability of the Pea Island Breach location, certain site characteristics must be analyzed. The multi-temporal pre-storm topographic data for the study site can provide valuable information on the dynamics of the site. Storm data, such as the peak water elevation in the sound behind the study site quantifies the flooding. For these reasons, the Pea Island Breach site was studied using four methods: temporal dune cross section analysis, dune ridge analysis, wrack line surge estimation, and inundation visualization.

## Table 1. Storm event surge data.

| Storm event | Date | Surge height (m) | Affected areas |
|---|---|---|---|
| 1846 storm | 9/7/1846 | unknown | Hatteras and Oregon Inlet |
| 1932 storm | 3/6/1932 | 3.67 max (unknown datum) | Pea Island |
| Hurricane Emily | 8/31/1993 | 3.2 max, 1.9 average (NAVD88) | Buxton |
| Hurricane Irene | 8/27/2011 | 2.57 average (NAVD88) | Pea Island |

### Temporal Dune Cross Section Analysis

In November 2009, Nor'Ida, which was a combination of Hurricane Ida and a nor'easter, brought offshore storm conditions to the Outer Banks. Nor'Ida produced storm waves (those defined as larger than 2 meters) for 99 hours at the USACE's Field Research Facility in Duck (USACE 2012). Figure 4 shows how the study area changed before and after Nor'Ida. Figure 4A, was taken on 8 October 2009 and Figure 4B was taken on 21 December 2009. In both figures, the location of the future Hurricane Irene breach is indicated by the dashed black and white line. Although some previous dune degradation can be seen in Figure 4A, Figure 4B shows a new overwash fan, situated directly where the breach later broke through in Hurricane Irene.

The position of the breach directly in the path of one of the overwash fans sug-

## Table 2. 2009 dune ridge elevations for transects in Figure 5A.

| 2009 Dune Ridge | | | | | | | |
|---|---|---|---|---|---|---|---|
| Transects | Northing (SPM) | Easting (SPM) | Pre-Irene dune ridge elevations (m, NAVD88) | Transects | Northing (SPM) | Easting (SPM) | Pre-Irene dune ridge elevations (m, NAVD88) |
| 1 | 927800 | 220761 | 5.3 | 24 | 928138 | 219661 | 3.8 |
| 2 | 927802 | 220710 | 3.8 | 25 | 928153 | 219614 | 3.1 |
| 3 | 927821 | 220663 | 4.7 | 26 | 928166 | 219565 | 3.7 |
| 4 | 927839 | 220616 | 5.0 | 27 | 928180 | 219517 | 5.6 |
| 5 | 927855 | 220569 | 5.5 | 28 | 928194 | 219469 | 5.2 |
| 6 | 927866 | 220520 | 4.3 | 29 | 928208 | 219421 | 5.6 |
| 7 | 927878 | 220472 | 5.7 | 30 | 928221 | 219373 | 6.9 |
| 8 | 927889 | 220423 | 6.2 | 31 | 928232 | 219324 | 7.2 |
| 9 | 927900 | 220374 | 4.2 | 32 | 928246 | 219276 | 6.2 |
| 10 | 927914 | 220326 | 3.7 | 33 | 928260 | 219228 | 7.2 |
| 11 | 927916 | 220274 | 3.4 | 34 | 928269 | 219179 | 5.5 |
| 12 | 927919 | 220223 | 2.0 | 35 | 928282 | 219130 | 5.7 |
| 13 | 927946 | 220179 | 3.4 | 36 | 928292 | 219081 | 6.0 |
| 14 | 927961 | 220131 | 3.4 | 37 | 928313 | 219035 | 4.6 |
| 15 | 927984 | 220086 | 2.5 | 38 | 928309 | 218982 | 5.5 |
| 16 | 927990 | 220035 | 2.4 | 39 | 928332 | 218937 | 5.2 |
| 17 | 928007 | 219988 | 2.6 | 40 | 928330 | 218884 | 5.1 |
| 18 | 928020 | 219940 | 2.6 | 41 | 928358 | 218840 | 7.3 |
| 19 | 928045 | 219895 | 2.9 | 42 | 928373 | 218792 | 5.5 |
| 20 | 928067 | 219849 | 3.5 | 43 | 928382 | 218743 | 6.1 |
| 21 | 928085 | 219802 | 4.4 | 44 | 928400 | 218696 | 5.0 |
| 22 | 928103 | 219755 | 3.9 | 45 | 928408 | 218646 | 5.1 |
| 23 | 928123 | 219709 | 3.4 | | | | |

gests that weakening of the dune system from Nor'Ida may have contributed to the size and location of the Pea Island Breach. To visualize the extent of the damage, a cross section at the breach site was extracted from pre and post Nor'Ida LiDAR data. The pre-Nor'Ida DEM was created from LiDAR points collected in March 2008 as part of the Integrated Ocean and Coastal Mapping (IOCM) project conducted by the National Oceanic and Atmospheric Administration (NOAA). The post-Nor'Ida DEM was constructed using LiDAR points from the NASA/USGS Experimental Advanced Airborne Research LiDAR (EAARL) program (Hardin *et al.* 2012). This LiDAR data was collected in December 2009 as a post storm reconnaissance for the Nor'Ida storm. Both dates of LiDAR data have a horizontal accuracy of two meters and a vertical accuracy of 0.15 meters. Using this data in GRASS GIS, a transect in the breach area was draped over the 2008 and the 2009 DEMs and the elevations were extracted and plotted to show the effects of the Nor'Ida event.

## Table 3. Wrack line elevations for transects shown in Figure 5A.

| Wrack line elevations | | | | | | | |
|---|---|---|---|---|---|---|---|
| Transects | Northing (SPM) | Easting (SPM) | Elevation (m, NAVD88) | Transects | Northing (SPM) | Easting (SPM) | Elevation (m, NAVD88) |
| 1 | 927782 | 220756 | 1.9 | 27 | 928156 | 219511 | 2.1 |
| 2 | - | - | - | 28-31 | - | - | - |
| 3 | 927795 | 220656 | 2.4 | 32 | 928227 | 219271 | 2.7 |
| 4 | 927821 | 220611 | 2.5 | 33 | 928238 | 219222 | 2.8 |
| 5 | 927844 | 220566 | 3.3 | 34 | - | - | - |
| 6 | 927854 | 220517 | 2.5 | 35 | 928267 | 219126 | 2.7 |
| 7 | 927864 | 220467 | 2.4 | 36-38 | - | - | - |
| 8 | 927871 | 220418 | 2.3 | 39 | 928310 | 218931 | 2.7 |
| 9-20 | - | - | - | 40 | 928320 | 218881 | 3.1 |
| 21 | 928051 | 219793 | 2.5 | 41 | 928328 | 218831 | 2.6 |
| 22 | 928064 | 219745 | 2.2 | 42 | - | - | - |
| 23 | - | - | - | 43 | 928344 | 218732 | 2.8 |
| 24 | 928089 | 219648 | 3.0 | 44 | 928354 | 218683 | 3.1 |
| 25 | - | - | - | 45 | 928362 | 218633 | 3.0 |
| 26 | 928151 | 219561 | 2.2 | | | | |

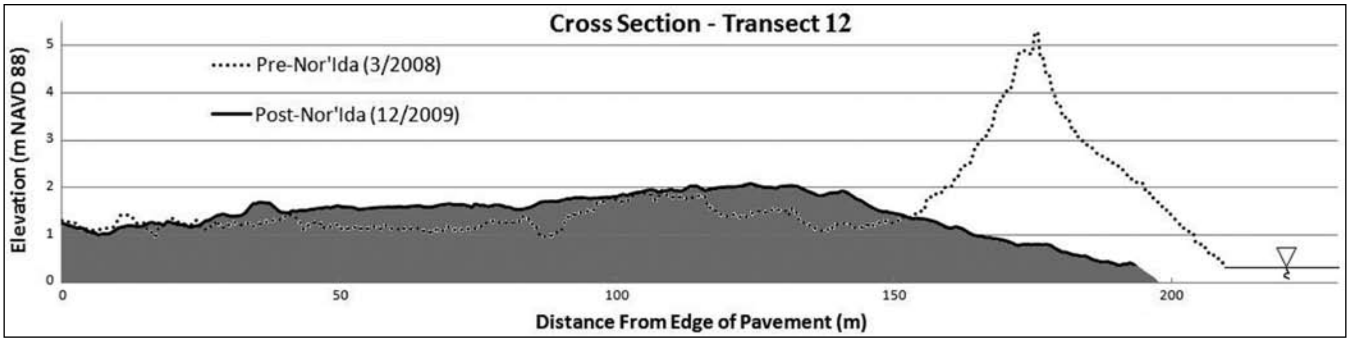

**Figure 6. Pre-Nor'Ida and post-Nor'Ida profile at the Pea Island Breach, displayed from the edge of pavement to the oceanside mean high water level.**

### Dune Ridge Analysis

A more robust way to evaluate the vulnerability of the study site is to examine elevations of the dune ridge. Extracting the elevations of a dune crest will provide an estimate for what the maximum dune elevations are at each transect. Although the maximum elevations could be extracted for each profile, the benefit of a dune ridge analysis is its ability to map a continuous dune field across the study site. In this way, a maximum dune elevation and location can be observed with the same resolution as the elevation points along the DEM used. In the absence of modeling, comparing dune elevations with surge levels can determine where flooding is likely to occur, or explain the location of existing overwash areas. For this study, the dune crest before the effects of Hurricane Irene will be examined.

The 2009 EAARL DEM used in the temporal cross section analysis was also used for this method as pre-Irene topography. Although this data was collected in 2009, it is the most recent LiDAR data in existence for this site. Since the study site is undeveloped and no significant storm activity has affected the site since Nor'Ida, the 2009 DEM is assumed to be a valid estimate of the pre-Irene topography. Dune elevations for this study were obtained using a least cost path extraction method in GIS software. Through this process, a cost surface is created by inverting and exaggerating the topographic elevations such that minimum cost reflects the highest elevations (Hardin *et al.* 2012). By creating a cost surface and selecting a beginning and ending point along a dune peak, the least cost path will create a vector that traces the peaks of the dune line and runs along a high elevation path for a dune overwash site. Once the dune ridge location is established, the vector is draped over the original 2009 topography to extract the dune elevations. Maximum elevations along the dune ridge can be extracted from the DEM with an average root-mean-squared vertical error of 0.02 m due to interpolation, which is less than the LiDAR measurement error of 0.15 m. Thus, the dominant source of error with this method is from the input LiDAR and would require on-site surveys to verify the accuracy. The error to the extracted dune ridge location can be attributed to two factors: DEM uncertainty and dune geometry. The dune geometry can influence dune ridge extraction for locations that have a degraded dune, such as the overwash sites near the breach (Figure 4). For these areas, the least cost path method extracts an optimized high elevation path to approximate the dune ridge. Thus, the dune ridge elevation can be approximated for areas with little or no dune, where consideration for vulnerability is particularly significant. For some site specific locations, a profile analysis is a more accurate method for extracting the maximum elevations. Due to the low error for this analysis, however, the least cost path analysis for a dune crest provides a good estimate of the maximum dune elevation for a beach profile.

To better illustrate the distribution of elevations along Pea Island dune ridge, 45 parallel transects were constructed along the entire study site. From each transect the locations and elevations of the dune crest were identified. Figure 5A illustrates the transects spaced at 50 meters along the Pea Island study site.

### Wrack Line Analysis

As Hurricane Irene moved north of the Pamlico Sound, flooding on the backside of Pea Island deposited a debris line, or wrack line, along landward side of the dunes and against vegetation. Because of the lack of tide gages in this region, the water level in the vicinity of the study site is not documented. While the U.S. Geological Survey installed a number of rapid deployment tide and wave gages prior to the arrival of Hurricane Irene (USGS 2011), these devices were not immediately available after the storm event. Also, none of these gages were located directly in the location of the breach. In cases where surge levels are uncertain, field investigations of vegetated debris can be used to estimate the peak water level. Because on-site surveys can be costly, dangerous, and time consuming, remote sensing could provide an effective alternative to field investigation. The methodology described below explains how a) wrack lines are typically identified, and b) orthophoto imagery and LiDAR data can be used to estimate the elevation of the wrack line.

Several cases exist in which the debris line has been used to estimate the high water elevation from surge and wave effects of a storm. The Federal Emergency Management Agency (FEMA) reports using debris lines in Texas to identify the maximum water level after Hurricane Alice (USACE undated report). After Hurricane Katrina, emergency management representatives identified high water marks using wrack lines as well (FEMA 2006). In these cases, the surveyor's best judgment of the high water mark was used when identifying and marking wrack. Research also exists for cyclones in Western Australia, where debris line elevations were surveyed to determine the surge elevations and then verified using numerical models (Nott and Hubbert 2005). The closest wrack line study to Pea Island occurred about 30 miles south of the Pea Island Breach in Buxton after Hurricane Emily in 1993 (Bush *et al.* 1996).

Similar to the effects of Hurricane Irene, the large soundside surge from

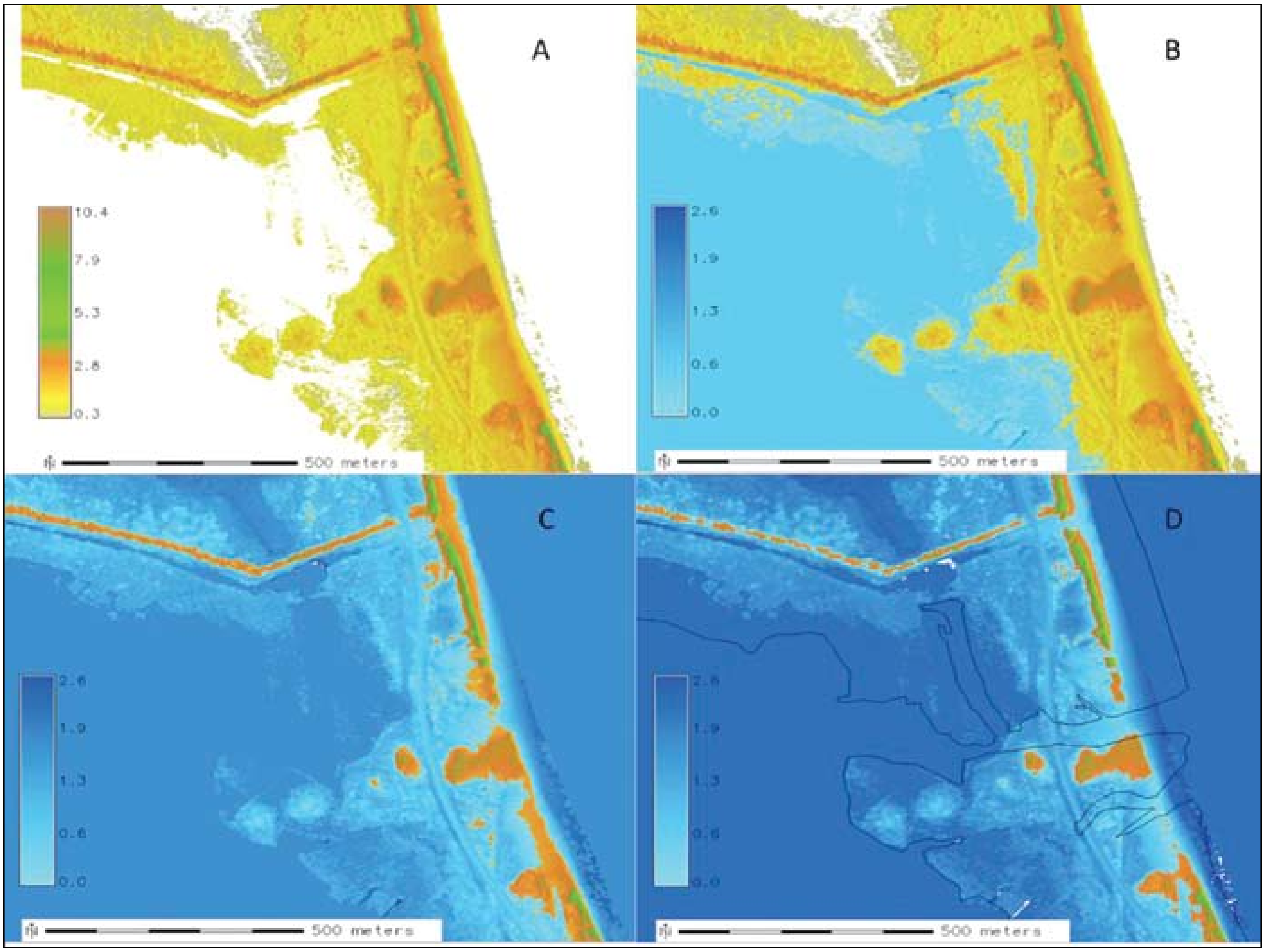

**Figure 7. Inundation models over 2009 topography of the northern portion of the study site are shown above. Flood levels are given as (A) 0.3 m, (B) 1.0 m, (C) 2.1 m, and (D) 2.57 m NAVD 88. Topographic elevations are given in meters in map A. An outline of the post-Irene breach site is included in map D.**

Hurricane Emily pushed ashore a wrack line, primarily containing salt marsh grass from the Pamlico Sound (Bush *et al.* 1996). Images and reports detail a semi-continuous line of vegetated debris that looks identical to the wrack line formed by Hurricane Irene on Pea Island. Elevations for the Buxton wrack line were surveyed on site using a Jacob Staff and leveling rod, and were then utilized to estimate storm surge. The study sites between Avon and Hatteras were segmented into three areas: Avon, the Buxton/Frisco area, and Hatteras Village. These sites produced average wrack line elevations of 2.4 m, 1.8 m, and 1.5 m, with standard deviation values of 0.2 m, 0.7 m, and 0.2 m. The maximum surge value obtained in this study was 2.9 m. This compares closely with a U.S. Army Corps of Engineers field investigation in that area after the storm event, which found a maximum water level from the wrack line in Buxton to be 3.2 m (USACE 1994).

These field investigations have shown that some site characteristics tend to have an effect on the distribution of storm debris along a site and must be considered in this analysis. According to Bush *et al.* (1996), salt march grasses could get snagged or stopped by thick or high vegetation as water levels continue to rise, leaving debris below the maximum water level. Also, houses, docks, and other structures can trap wrack before the maximum water elevation is reached. It is even possible, through multiple rising and lowering of the water level, to produce multiple debris lines.

Using the wrack line dynamics suggested in previous reports, post-Irene debris was only examined on minimally vegetated areas of the Pea Island Breach site to assure that there was no obstruction to the debris line due to thick vegetation. Wrack was only analyzed within the region of the designated study site. Because the study site has very few man-made structures such as buildings or docks, heavy vegetation was the only major obstruction to debris. Most wrack that was not obstructed by vegetation was deposited on the heel side of beachfront dunes. In the case of multiple wrack lines, the most eastern wrack line was analyzed to capture the highest elevation of debris. Figures 5B and 5C show examples of the wrack line identified on the Pea Island study site. The image shows that although a portion of this wrack line was influenced by a footpath and high vegetation, only parts of the wrack line that were not impeded by natural or man-made structures were digitized for this study. Some wrack lines near the breach area were also omitted due to the likelihood of morphological change from the storm. Since the wrack line elevations were extracted from pre-storm topography, analysis directly at the breach could be inaccurate due to sediment transport induced by the storm.

**Figure 8. Three dimensional orthogrametric image of the Pea Island Breach, overlaid with 2.57 m (NAVD 88) storm inundation. The red vector along the heel of the dunes shows the digitized wrack line used in this study.**

dune ridge extraction due to the degraded dune at this site. Nevertheless, 2.1 m is still the lowest maximum elevation for the study site, and thus, vulnerable to inundation. The second lowest maximum elevation occurs at transect 16 (2.4 m NAVD88). This area is the site of the second, smaller channel of the breach, which has also shown evidence of dune overwash damage prior to the storm.

### Wrack Line Analysis

The wrack line digitized at the study site is presented in Figure 5A. Some of the fluctuation between wrack line elevations is apparent in Table 3. Note that since the vegetated debris is not a continuous line, not every transect has a representative wrack line elevation. Clearly for this case, the typical wrack line elevations shown in Table 3 exceed the maximum elevations for some transects in Table 2. The average elevation of nearly 1,300 digitized wrack line points was 2.57 meters (NAVD88) with a standard deviation of about 0.32 meters. Considering that the on-site investigations after Hurricane Emily produced standard deviations between 0.2 m and 0.7 m, the values determined using geospatial data seem relatively precise. Comparing data to a rapid deployment gage, the wrack line elevation analysis agrees to better than 0.3 m with direct measurements of water levels during Irene near the Rodanthe Breach (S. Rogers and A. Kennedy, pers. comm. 2012).

The distribution of high water elevations can be explained by geomorphic funneling of surge water, vegetation, and varying runup heights due to different bathymetric slopes (Bush *et al.* 1996). Other sources of error could be attributed to any erosion or accretion that may have occurred after the 2009 DEM, which would have altered the elevations in some locations. A more accurate high water elevation could be obtained using post-storm LiDAR data, if available.

### Inundation Visualization

Figure 7 shows four stages of inundation (0.3 m, 1.0 m, 2.1 m, and 2.57 m NAVD88) on the breach region of the study site. The final inundation map of elevation of 2.57 m also shows the shore outline of the breach directly after the storm. When the Pea Island area is flooded to the average high water elevation determined from the wrack line analysis, the flooded area corresponds to the location of the breach. Inundating the sound behind Pea Island to an elevation slightly smaller than the average wrack line (2.1 m) shows that flooding in this area occurred primarily at both channels first, before expanding and inundating surrounding areas. Figure 8 displays a three dimensional post-Irene orthogrametric image, inundated to the average wrack line elevation. Although the wrack line elevation represents wave setup and run-up in addition to surge, this figure gives a good representation of what areas of Pea Island were inundated at the highest water level of the storm.

## CONCLUSION

Investigation of the Pea Island Breach site conditions prior to the effects of Hurricane Irene has shown that the dunes in this area had been eroded due to the effects from Nor'Ida. At that time, the dune directly at the site of the breach was degraded, which clearly impacted the location of the breach. This was observed both in the pre and post-storm orthophotos as well as in the cross-section analysis at the breach site.

Utilizing the least cost dune extraction method, the dune crest along the study site provided a valuable assessment of dune elevations along the study site, prior to the effects of Hurricane Irene. The lowest dune elevations before the storm were situated at the location of the two channels formed during the storm. These low elevation dune sites had a high vulnerability to flooding from sound to ocean during the storm.

The average wrack line elevation estimated for this study site was greater than some of the maximum dune ridge elevations shown in Table 2. This is particularly significant in areas within the channels of the breach. The successful inundation visualization of both channels created during Hurricane Irene shows that extracting elevations from a wrack line can provide a valid estimate of surge elevations on low-vegetation barrier islands without the need for costly and unsafe on-site investigation. Wrack lines can be identified in high resolution imagery quickly and over a large study site, but caution must be used to selectively choose debris areas that accurately represent the highest water elevation. The accuracy of current LiDAR data can provide favorable topographic elevations at these debris sites. In upcoming research, further remote sensing, and on-site analysis should be attempted and compared to surge models and tide gauges.

Inundation visualization using these elevations can also be helpful to illustrate storm impacts, such as the Pea Island Breach. Although this form of flooding does not account for changes in morphology, it can provide a good representation of storm surge and wave effects as an initial hazards assessment. For future studies, more accurate measurements of wrack line elevations could be interpolated from post-storm LiDAR data. Since this type of data may be unavailable immediately after the storm event, wrack line elevations determined from pre-storm conditions still provide a valid estimate and an immediate assessment of a hazardous area. Eventually, larger wrack lines could be mapped using the least cost path extraction technique on detailed post-storm LiDAR data. The ridge and trough of a large pile of wrack could be mapped and give a more accurate, three dimensional view of the storm debris.

## ACKNOWLEDGEMENTS

The authors would like to recognize the collaborative efforts of the Coastal and Geospatial Lab group. M. Onur Kurum and Eric Hardin assisted by offering advice on technical aspects of geospatial modeling for this project while Brandon Grant and Nicholas Spore provided insightful comments on the preparation of the manuscript. This material is based upon work supported by the U.S. Department of Homeland Security under Award Number: 2008-ST-061-ND 0001.

## REFERENCES

Barnes, C., H. Fritz, and Y. Jeseon 2007. "Hurricane disaster assessments with image-driven data mining in high-resolution satellite imagery." *IEEE Transactions on Geoscience and Remote Sensing*, 45(6), 1631-1640. doi: 10.1109/TGRS.2007.890808.

Barnes, J., 1995. *North Carolina's Hurricane History*. Chapel Hill: UNC Press. Retrieved from website created by Berry, M.: http://www.ncgenweb.us/hyde/maps/HURICANE.HTM

Bush, D., R. Young, C. Webb, and R. Thieler 1996. "Soundside impacts of a northward tracking tropical cyclone: Hurricane Emily (31AUG93)." *J. Coastal Res.*, 12(1), 229-239.

Hardin, E., O. Kurum, H. Mitasova, and M.

Overton 2012. "Least cost path extraction of topographic features for storm impact scale mapping." *J. Coastal Res.* DOI:10.2112/JCOASTRES-D-11-00126.1 – accepted.

Federal Emergency Management Agency (FEMA) 2006. "High Water Mark Collection for Hurricane Katrina in Alabama." FEMA-1605-DR-AL, Task Orders 414 and 421. Federal Emergency Management Agency, Atlanta, Georgia. 9-16.

Lane, S., T. James, H. Pritchard, and M. Saunders 2003. "Photogrammetric and laser altimetric reconstruction of water levels for extreme flood event analysis." *Photogrammetric Record*, 18(104), 293-307. doi: 10.1046/j.0031-868X.2003.00022.x

Markham, E.M., 1935. "Beach Erosion at Kitty Hawk, Nags Head, and Oregon Inlet, NC." Office of the Chief of Engineers, Beach Erosion Board, United States Army. 1-40.

National Oceanic and Atmospheric Administration (NOAA) 2011. "NOAA NOS Hurricane Irene Water Level & Meteorological Data Report." U.S. Dept. of Commerce, National Ocean Service, MA. Retrieved from website: http://tidesandcurrents.noaa.gov/publications/Hurricane_Irene_Water_Level_and_Meteorological_Data_Report.pdf

Neteler, M., and H. Mitasova 2008, *Open Source GIS: A GRASS GIS Approach*. Third Edition. The International Series in Engineering and Computer Science: Volume 773. Springer New York Inc, 406 p.

Nott, J., and G. Hubbert 2005. "Comparisons between topographically surveyed debris lines and modelled inundation levels from severe tropical cyclones Vance and Chris, and their geomorphic impact on the sand coast." *Australian Meteorological Magazine*, 54, 187-196. Retrieved from http://www.bom.gov.au/amm/docs/2005/nott.pdf.

U.S. Army Corps of Engineers and Federal Emergency Management Agency 1994. *Hurricane Emily Assessment: Review of Hurricane Evacuation Studies Utilization and Information Dissemination* Retrieved from website: http://chps.sam.usace.army.mil/USHESdata/Assessments/Emily/hurricane_emily_assessment.htm.

U.S. Army Corps of Engineers Field Research Facility 2012. *Storms*. Retrieved from website: http://www.frf.usace.army.mil/storms.shtml.

U.S. Army Corps of Engineers Field Research Facility 2011. *Hurricane Irene Observations at the Field Research Facility*. Retrieved from website: http://www.frf.usace.army.mil/irene/irene_obs.pdf.

U.S. Army Corps of Engineers (n.d.). *Storm Surges and Shore Processes: Hurricane Alicia Investigation*. Retrieved from website: http://chps.sam.usace.army.mil/USHESdata/Assessments/alicia/storm_surges.htm.

U.S. Geological Survey (USGS) 2011. Hurricane Irene Rapid Deployment Gauges, http://water.usgs.gov/osw/floods/2011_HIrene/SurgeAndRDG.html.