Rapid Response 3D Survey Techniques for Seamless Topo/Bathy Modeling: 2003 Hatteras Breach, North Carolina

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ABSTRACT

On 18 September 2003, Hurricane Isabel made landfall along the Outer Banks of North Carolina and created a breach in the barrier island chain south of Cape Hatteras. The breach isolated the community of Hatteras Village by washing out a 500-m section of North Carolina State Highway 12 (NC12). To rapidly assess breach geomorphology, document short-term morphological evolution, and to collect data in support of coastal modeling efforts, a series of high-density topographic and bathymetric surveys were performed. The unique three-dimensional (3D) survey design utilizes real-time kinematic GPS and ultra shallow-water singlebeam and multibeam sonar technologies. The integration of these technologies with specialized acquisition and processing techniques allows for a seamless merger of high-resolution beach and nearshore data within the surf zone. Processing the approximately 1.5 million data points into accurate 3D digital elevation models (DEMs), representing shoreline topography and nearshore bathymetry with strong anisotropy, provides a unique challenge that is handled with specialized interpolation algorithms used in both proprietary and open source GIS. Rapid 3D processing and GIS integration provided the U.S. Army Corps of Engineers (USACE) Wilmington District office with information to assess and engineer the breach closure and provided researchers of coastal processes with information that could not be adequately captured with traditional 2D techniques.

Additional Keywords: RTK-GPS, digital elevation models, shallow-water sonar, GIS, Hurricane Isabel

INTRODUCTION

On 18 September 2003, Hurricane Isabel made landfall along the Outer Banks of North Carolina and created a breach in the barrier island chain south of Cape Hatteras, NC (Figure 1). To rapidly assess breach geomorphology, document short-term morphological evolution, and collect data in support of engineering and research efforts, a series of high-density topographic and bathymetric (topo/bathy) surveys were performed. The first topo/bathy survey was completed over the period of 3-5 October and the second survey from 13-16 October 2003. Mapping the breach and surrounding areas presented many challenges due to the logistics of working in a severely storm-damaged environment. To overcome challenges such as submerged and floating debris, high-velocity tidal and wind-driven currents, and loss of infrastructure required a coordinated survey design and strategy. Specific objectives of this paper are to: (1) detail the rapid response 3D acquisition systems and methodology implemented at the site of the Hatteras breach, (2) highlight the unique and flexible survey strategy employed for the collection of detailed topo/bathy data at the site of a natural disaster, and (3) illustrate how specific 3D topo/bathy processing routines within various GIS platforms helped produce accurate morphological information that could assist in the design of the breach closure.

ACQUISITION METHODS

The goals of the field surveys were to assess the breach and surrounding morphology quickly and with as much detail as possible. The collection of high-resolution topo/bathy data in the vicinity of the Hatteras breach required a mode of data collection that could span the beach, surf zone, and extremely shallow reaches of the breach shoals rapidly and accurately. To accomplish this goal, several flexible and highly mobile instrument platforms were deployed that utilize real-time kinematic (RTK) GPS systems for high-resolution topography coupled with motion-compensated shallow-water singlebeam and multibeam sonar technologies for 3D seafloor mapping acquisition (Figure 2).

A detailed GPS site calibration was performed prior to the collection of any survey data at the breach. National Geodetic Survey (NGS) benchmark designated C193 was recovered along with three North Carolina Department of Transportation (NCDOT) marks in the center of NC12. NGS C193 was the best available control that could be found in the hurricane debris and overwash for establishing the land-based station. Results of the site calibration showed an average deviation in the Northing of 4.1 cm, Easting of 1.5 cm and an average of 2.0 cm in the vertical component. To quantify daily environmental and/or operator error, NCDOT mark PT207 was checked each day prior to the collection of field data. Results of daily benchmark checks over the entire survey period showed a maximum vertical deviation of 1.8 cm and a minimum deviation of 0.07 cm.

Topography

RTK-GPS has quickly gained acceptance as a leading tool for ground-based 2D and 3D beach (Morton et al. 1993) and nearshore (Wong, et al. 2000) mapping applications and is the foundation of Geodynamics' *Shoreline and Nearshore Digital Mapping and Analysis Program* (*SANDMAP*). Geodetic GPS systems have been employed in 2D beach mapping studies for several years, including the collection of the traditional beach profile. However, a more advanced 2D application of GPS is the introduction of a vehicle-assisted instrument platform for the collection of accurate datum-derived shorelines or elevation contours by the U.S. Geologic Survey and others (List and Farris 1999; Freeman et al. 2003; Bernstein et al. 2004; Ruggiero, Kaminsky, and Gelfenbaum 2004). A modification of this vehicle-based method is the application of geodetic GPS to acquire both 2D datum-based shorelines and 3D topographic data simultaneously by inclusion of an all terrain vehicle (ATV) and backpack mounted system (Bernstein et al. 2003; Freeman et al. 2003, Mitasova et al. 2003).

Collection of 2D and 3D topographic data at the site of the Hatteras breach applied both vehicle- and backpack-assisted acquisition techniques (Figure 2a and 2b) using low latency Trimble 5700 GPS receivers collecting at 10 Hz. The northeast side of the breach was the only access location and served as the staging area for both topographic and bathymetric surveys. Along this side of the breach, detailed topographic data were acquired using the ATV system. This allowed collection of approximately 11,000 data points over the course of the two surveys. The inaccessibility of the southwest shoreline and subaerial portions within the middle of the breach required the use of the backpack system. Although this is not the most efficient means of collecting 3D elevation data, the portability of the backpack system allowed for the collection of over 15,000 topographic data points along the southwest side of the breach in less than 7 hr.

To accurately model topographic data in three dimensions and to extract datum-derived shorelines requires the collection of elevation data along breaks in morphology (Bernstein et al. 2003; Freeman et al. 2003). Along the beachface adjacent to the breach, this requires the systematic collection of data from the base of the dune to the lowest tide line (Figure 3). Morphological features such as scarps, cusps, and berms were bracketed to provide accurate calculations of volume and change between the two surveys. Isolated portions of land within the center of the breach were surveyed in a circular pattern from the lowest tide perimeter to the center. Walking the morphology breaks in this area became challenging due to the dense debris field, including building materials and destroyed portions of NC12 (Figure 4).

Bathymetry

Due to the extremely shallow nature of the site surrounding the breach, the bulk of bathymetric data could best be collected with a personal watercraft outfitted for shallow water surveying (Beach, Holman and Stanley 1996; MacMahan 2001; Wamsley and Edge 2001). The *Surfzone Explorer* (Figure 2c) is a Yamaha four-stroke Wave Runner equipped with an Odom HT 100 ultra-shallow water singlebeam sonar system compensated for motion (with a VT TSS DMS-05 sensor) and sound velocity (with an Odom Digibar Pro). This combination of instruments and jet-propelled survey platform allowed for the collection of accurate hydrographic data at speeds of up to 10 knots in a variety of extreme physical conditions across the breach, flood tidal delta, and surf zone.

Swath bathymetry surveys at the breach were performed for submerged object detection, for detailed bathymetry within the main breach channel, and to measure the offshore gradient outside the quickly forming ebb tidal delta. Multibeam sonar data was collected aboard the *R/V 4-Points*; a custom Carolina-built 8 m research vessel specifically designed for shallow water multibeam sonar operations (Figure 2d). The *R/V 4-Points* draws less than 30 cm of water and is outfitted with twin four-stoke outboard engines to provide superior maneuverability in shallow or constricted bodies of water like the Hatteras breach. The vessel is equipped with a Simrad EM3000 multibeam sonar system combined with a VT TSS Meridian Surveyor gyrocompass and

DMS-05 motion reference unit. Critical sound velocity data is collected with an Odom Digibar Pro. Raw multibeam sonar data is acquired and processed in Triton Elics International software. To quantify and limit error in the hydrographic survey, a number of hydrographic calibration procedures were performed, including the collection of sound velocity profiles spatially across the survey area, a detailed multibeam patch test, crosscheck error analysis, and daily “bar checks” of the singlebeam. In addition to the “bar check”, the singlebeam system was calibrated with a direct seafloor elevation measurement derived from an RTK-GPS rover.

SURVEY STRATEGY

In order to accurately document the morphology and bathymetry change at the site of the Hatteras breach, a comprehensive survey strategy was developed to provide the most flexible and cautious means of collecting these data within the disaster area. Upon arrival to the survey site, a pre-survey logistics meeting at the USACE Field Research Facility was conducted in order to detail the project goals and resolve possible logistical problems such as lodging, food, power, and outside support. Once these details were finalized, reconnaissance of the survey area began in order to determine site-specific complications that might be encountered, locate survey control, begin the RTK-GPS site calibration, and identify a staging area. Field reconnaissance at the survey site revealed high-velocity tidal currents in the main breach channel, submerged and exposed roadbed and wood pilings, cut power and cable lines freely drifting in the main channel, and a large amount of floating and partially submerged debris.

These natural and storm-induced obstacles at the survey location required a survey strategy that was governed by stages of the tide. Bathymetric surveys within the main breach were conducted around and during the time of slack high tide due to the tremendous tidal and wind-driven currents in the channel (Figure 5) and the presence of submerged roadbed and pilings. Hydrographic surveys within the backbarrier, along the flood tidal delta and in the surf zone were accomplished during a higher tide stage to avoid breaking waves in the nearshore and exposed tidal flats in the backbarrier. Although the *Surfzone Explorer* is able to map in less than 30 cm of water, the shallowest regions of the flood delta and backbarrier required additional RTK elevation surveys. Complete survey coverage was obtained in these regions with the backpack system during peak low tides. All topographic data collection occurred around the times of low to peak low tide in order to capture the maximum amount of subaerial exposure, ensure complete overlap with bathymetric surveys and to navigate the dangerous debris field in the center of the breach. The flexible topo/bathy surveying strategy proved highly efficient, greater than 80 line kilometers of singlebeam and multibeam sonar data, and approximately 65 line kilometers of topographic data were collected in a total of about 5 days.

3D TOPO/BATHY PROCESSING & ANALYSIS

Quality assurance and quality control (QA/QC) of the approximately 1.5 million data points (Figure 6) begin with a first order procedure to ensure data quality and general consistency. This included correcting sonar data for motion and tides and inspecting topographic information to ensure all data meet specific RTK-GPS thresholds. After these basic procedures were completed, the data was filtered in a customized MATLAB routine called the Beach-profile Analysis MATLAB-tool or BAM (Park 2002). BAM was specifically designed for QA/QC, and to process and analyze large amounts of marine and terrestrial data collected through methods similar to those described in this paper. The BAM module applied for this project was designed to analyze and delete redundant points and sonar spikes, correct any draft errors, and merge the data into one topo/bathy file. Once the files were "clean" and merged, the data was ready to process into 3D elevation models.

Processing massive and sometimes oversampled datasets into accurate DEMs, representing shoreline topography and nearshore bathymetry with strong anisotropy, provides a unique challenge (Mitasova et al. 2003). An adequate gridding method is important in order to produce a temporal series of coastal elevation and bathymetric surfaces, with a minimum of distortion in the output geometry. While a TIN (Triangular Irregular Network) is most commonly used in elevation modeling, it becomes problematic when a series of surfaces, each based on a different set of measured points, needs to be compared (Mitasova et al. 2003). The comparison is greatly simplified if all data are gridded at the same resolution and map algebra is applied for computing differences between elevation surfaces and other measures. The selection of a gridding method strongly depends on the spatial distribution of input data, resolution of the output grid, and the anticipated properties of the modeled terrain.

To preserve most of the detail captured from these high-density surveys and minimize artifacts commonly created by standard interpolation algorithms such as a TIN, a Universal Krigging method (Bernstein et al. 2003) was applied. The parameters were specifically tuned to the spatial pattern and along-track density of the survey data and modeled topo/bathy output (Bernstein et al. 2003; Mitasova et al. 2004). One of the challenges in modeling elevation data derived from RTK-GPS and singlebeam sonar is that the density of points along the survey line is high (1-2 m apart) while the distance between survey lines is typically 10-150 m apart. By incorporating an anisotropy factor and other tunable parameters into the gridding procedure, the accuracy and repeatability of the resulting DEM is substantially improved (Bernstein et al. 2003; Mitasova et al. 2004). Figure 7 illustrates a detailed 3D elevation model of the breach calculated from the high-resolution topographic and bathymetric data merged at the land/water interface. Wamsley and Hathaway (2004) give a complete discussion of the breach morphology.

To rapidly generate these high-resolution surfaces, produce detailed grid statistics, and manage and integrate the large datasets from the Hatteras breach, a combination of proprietary and Open Source GIS applications were applied. The efficiency of GIS in processing and visualizing these spatial data provided the USACE Wilmington District design team with an immediate and simple means to assess and aid in the ultimate closure of the breach (Wutkowski 2004). Figure 8 demonstrates the integration of contour-based shorelines extracted from the topo/bathy DEM of the Hatteras breach draped on a 1 m resolution NCDOT digital orthographic quarter quadrangle using GIS.

CONCLUSIONS

Morphological assessment at the site of the Hatteras breach with *SANDMAP* illustrates the utility of combining modern mapping instrumentation, detailed 3D spatial data collection techniques, and a managed and flexible survey strategy. These methods provide an accurate and cost-effective means of collecting spatial and temporal information previously unattainable with traditional 2D techniques. The superior mobility of the *SANDMAP* surveying systems deployed at the site of the Hatteras breach illustrates the rapid-response technology necessary to collect data following a natural disaster such as Hurricane Isabel. Processing and analyzing these massive datasets is significantly aided with proprietary and Open Source GIS applications. These data analysis tools allowed the coastal management community to easily assess the breach geomorphology and appropriately engineer closure of the Hatteras breach.

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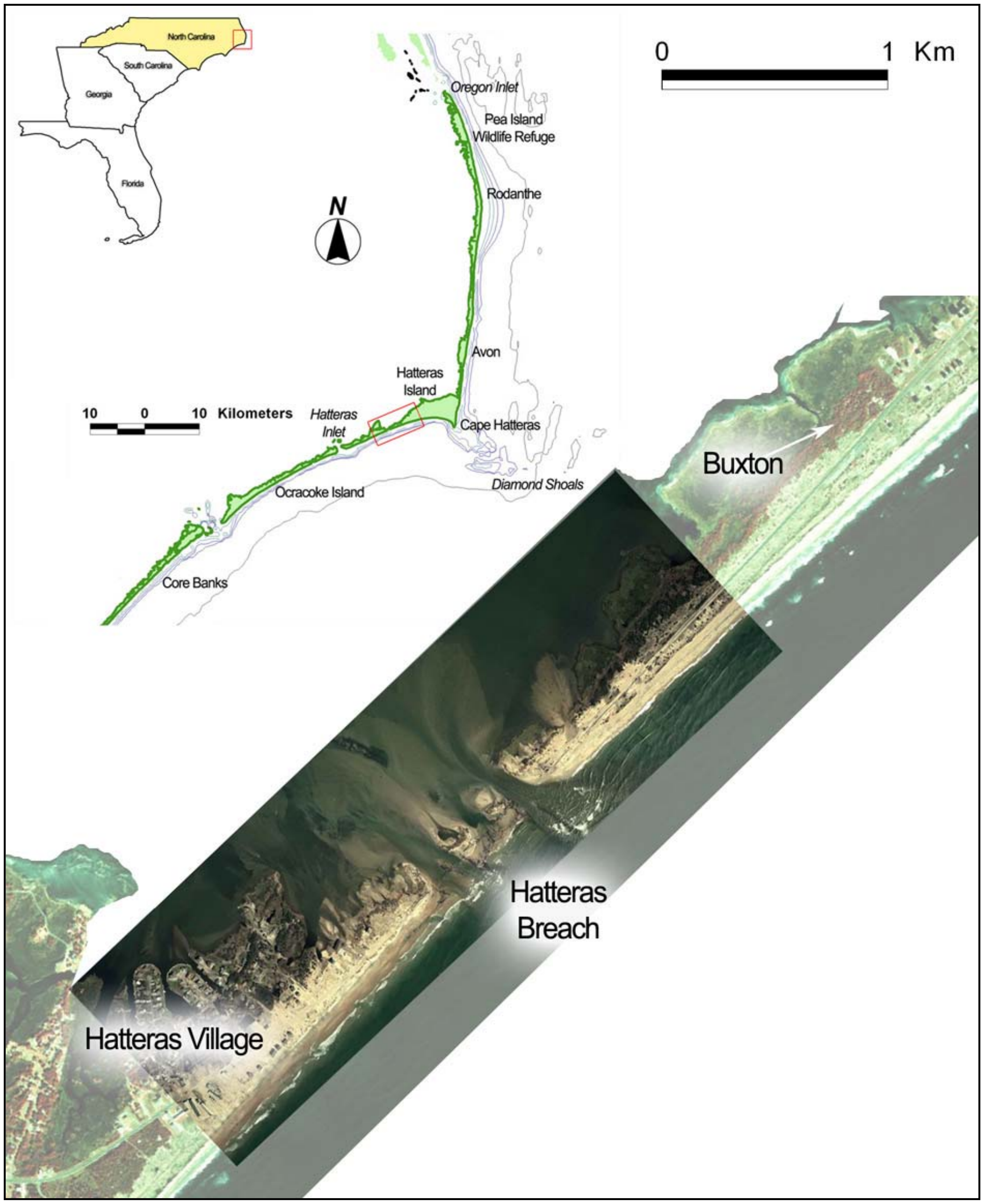

Figure 1. **Study location.**

Figure 2. **(a) Topographic mapping of dunes and inaccessible areas with the RTK-GPS rover backpack system, (b) topographic mapping of the subaerial beach from the dune-base to the low-tide region with RTK-GPS mounted on all-terrain vehicles, (c) singlebeam bathymetric mapping of the Hatteras breach with the *Surfzone Explorer*, and (d) multibeam bathymetric mapping of the Hatteras breach with the *RV 4-points*.**

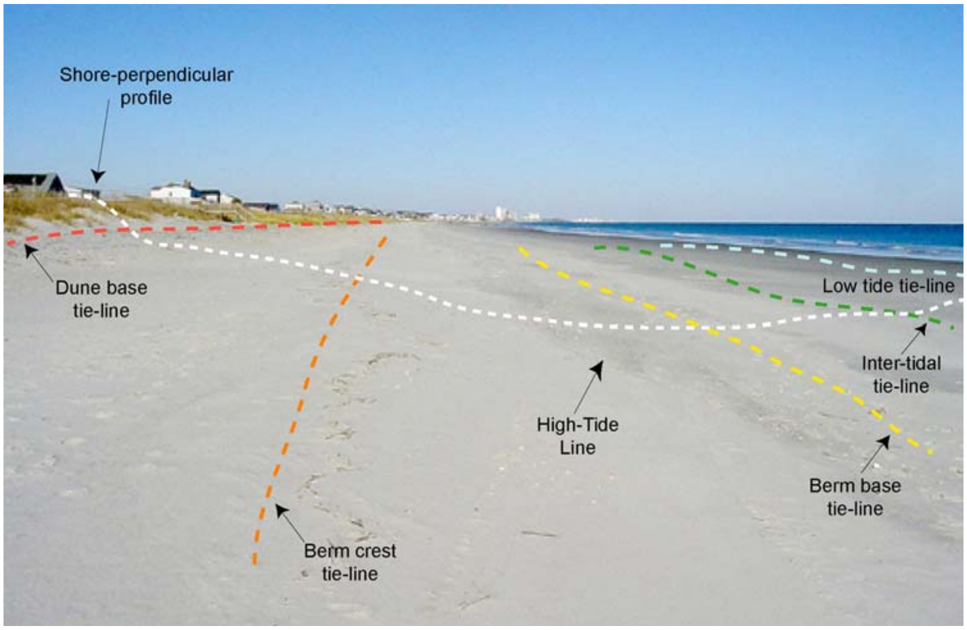

Figure 3. Photograph illustrating the survey design by which the subaerial beach was mapped. Morphologically derived survey paths were driven to collect critical data between standard beach profiles.

Figure 4. Photograph illustrating the debris within the central portion of the breach. Asphalt from NC12 and broken utility lines covered extensive areas (looking northeast).

Figure 5. Photograph illustrating high velocity tidal currents, wind-driven currents, and waves within the main breach channel.

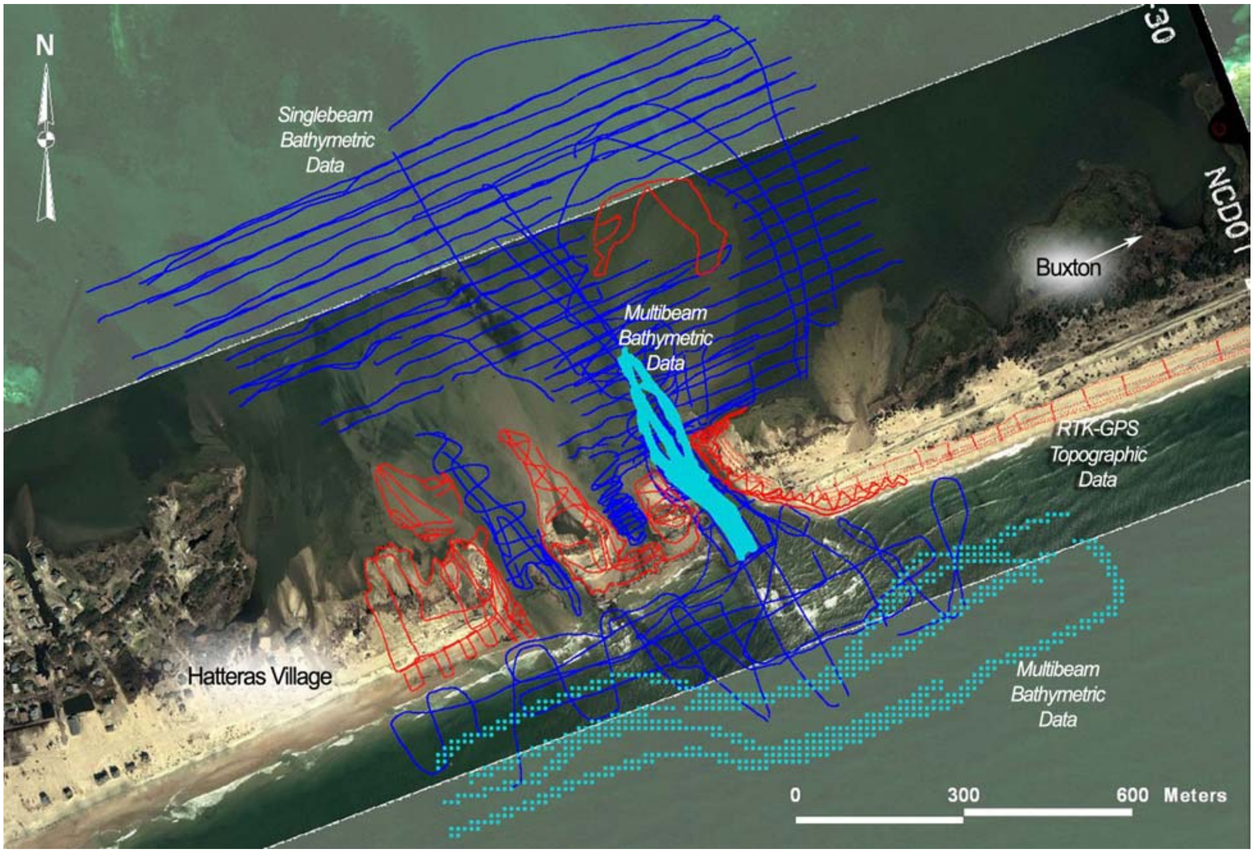

Figure 6. **Survey coverage map.**

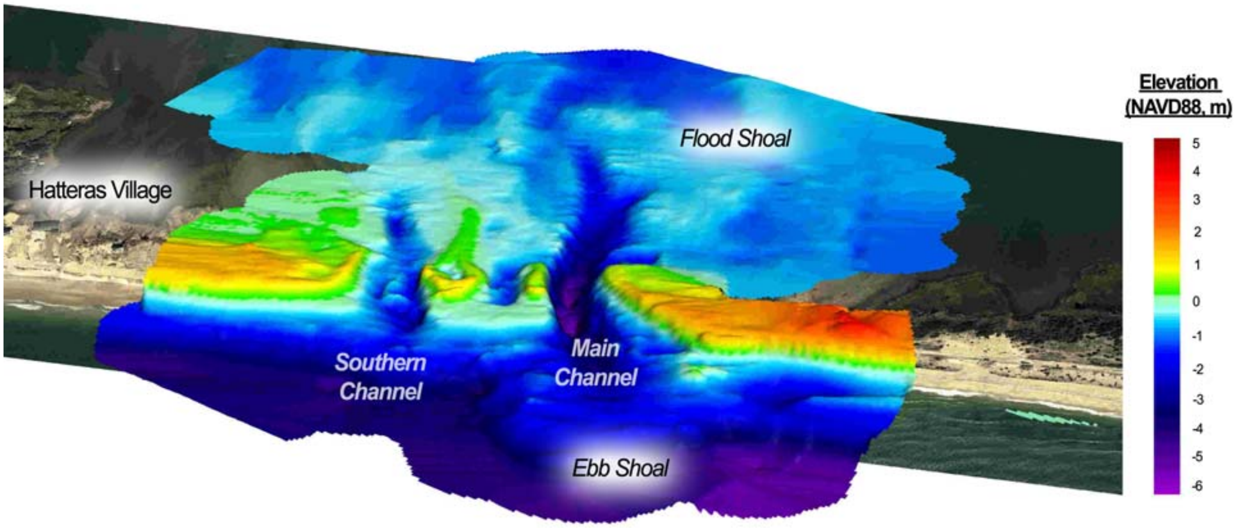

Figure 7. Detailed 3D DEM of the Hatteras Breach.

Figure 8. **Contour change map.**