Chapter 10

Short-Term Barrier Evolution:
Overwash at Onslow Beach Through Assessment
of Training Activities and Model Predictions

SERDP Project Number: RC-1413

Coastal Barrier Module

Research Project CB-1

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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADCIRC</td>
<td>Advanced Circulation (model)</td>
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<tr>
<td>CLARIS</td>
<td>Coastal Lidar and Radar Imaging System</td>
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<tr>
<td>Cm</td>
<td>centimeter</td>
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<tr>
<td>d&lt;sub&gt;c&lt;/sub&gt;</td>
<td>primary dune</td>
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<tr>
<td>DoD</td>
<td>U.S. Department of Defense</td>
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<td>FRF</td>
<td>Field Research Facility</td>
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<td>GHz</td>
<td>gigahertz</td>
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<tr>
<td>GIS</td>
<td>geographic information systems</td>
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<tr>
<td>HWL</td>
<td>high water line</td>
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<td>ICW</td>
<td>Intracoastal Waterway</td>
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<tr>
<td>kHz</td>
<td>kilohertz</td>
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<tr>
<td>km</td>
<td>kilometer</td>
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<tr>
<td>km/hr</td>
<td>kilometer per hour</td>
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<tr>
<td>km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>square kilometer</td>
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<tr>
<td>kW</td>
<td>kilowatt</td>
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<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
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<tr>
<td>m</td>
<td>meter</td>
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<tr>
<td>m/y</td>
<td>meters per year</td>
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<tr>
<td>m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>square meter</td>
</tr>
<tr>
<td>MCBCL</td>
<td>Marine Corps Base Camp Lejeune</td>
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<tr>
<td>MHz</td>
<td>megahertz</td>
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<tr>
<td>NAD83</td>
<td>North American Datum of 1983</td>
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<tr>
<td>NAVD88</td>
<td>North American Vertical Datum of 1988</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>POS-LV</td>
<td>Position and Orientation System for Land Vehicles</td>
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<td>R</td>
<td>wave-driven runup</td>
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<td>ROM</td>
<td>Runup and Overwash Model</td>
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<td>RTK-GPS</td>
<td>real-time kinematic global positioning system</td>
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<td>S</td>
<td>regional surge water level</td>
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<td>SERDP</td>
<td>Strategic Environmental Research and Development Program</td>
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<td>STWAVE-FP</td>
<td>steady-state spectral WAVE model full plane</td>
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<td>USACE</td>
<td>U.S. Army Corps of Engineers</td>
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Abstract

Research Project CB-1 investigated overwash processes, defined here as ocean breaching of the primary dune, along the southern half of Onslow Beach, NC. Overwash processes and the resulting transport of sand from the beach to the backbarrier environments can dramatically change the topography of barrier islands, create and destroy habitat for birds and sea turtles, and change the geotechnical properties (i.e. vehicle use) of the beach. Amphibious training at Marine Corps Base Camp Lejeune (MCBCL) has been active on the southern half of Onslow Beach since the late 1940s, and sustaining this environment for continued expeditionary training is of high importance. Our objectives were two-fold: (1) to assess whether training activities on Onslow Beach have measurably changed the occurrence of overwash, and (2) to develop an analytical model that can accurately predict the location of overwash during storm events at Onslow Beach. Changes in the spatial extent of washover deposits created by overwash since 1938, prior to MCBCL use, were measured for each decade (1930–2010) from aerial photographs and field mapping. Results suggest a relationship between the amount of overwash and the number of tropical cyclones that impacted the region in a given decade. Neither an increase nor a decrease in washover deposits were discernable as a linear trend, suggesting that MCBCL training activities did not measurably influence overwash processes. Observed boundary conditions required for overwash modeling included high-resolution beach and dune topography, nearshore bathymetry, and surf-zone waves and water level. New observational techniques, namely Coastal Lidar and Radar Imaging System (CLARIS), were developed to measure these conditions and refine model equations. Modeled wave runup, defined as the elevation reached by the upper 2% of wave swash on the beach foreshore, and projected locations of overwash (where runup exceeded the elevation of the primary dune crest) demonstrated strong skill during Hurricane Irene. Our Runup and Overwash Model (ROM) simulations correctly predicted all four overwash locations along Onslow Beach. Model results imply that runup elevations vary along Onslow Beach as a function of beach slope and nearshore bathymetry such that overwash and inundation predictions based solely on regional tides and surge would likely have poor skill except for the most extreme storm events. Furthermore, outcropping hardbottom in the surf zone in the central portion of the region (near the old Riseley Pier) will likely continue to induce higher elevations of runup. Best management practices designed to minimize lowering of the primary dune crest and anticipating likely inundation of sea turtle nest in this region should be considered.

Keywords: Onslow Beach, overwash, washover, barrier island, Light Detection and Ranging (LIDAR), X-band radar, runup, Hurricane Irene, steady-state spectral WAVE model full plane (STWAVE-FP), real-time kinematic global positioning system (RTK-GPS), MCBCL

Objectives

1. Assess whether amphibious training activities have influenced overwash processes on Onslow Beach.

2. Develop a numerical model that predicts the location of overwash during storms at Onslow Beach. Model skill was assessed during a severe storm event (i.e., Hurricane Irene) in August 2011.
Hypotheses

1. The number and spatial area of washover deposits did not change significantly prior to or after training operations began at Marine Corps Base Camp Lejeune (MCBCL).

2. The location of overwash can be predicted using high-resolution bathymetry and wave runup simulations at Onslow Beach.

Background

Overwash

Barrier islands are dynamic features that migrate in response to both natural forcings (e.g., storms, sea level rise) and anthropogenic activities through a combination of mechanisms including aeolian transport and overwash. Overwash occurs when either wave runup or storm surge exceeds dune height, generating a unidirectional flow of sediment-laden water from the nearshore over the beach crest and towards the back of the island (e.g., Davis, 1994; Donnelly et al., 2006; Leatherman, 1979; Schwartz, 1975), resulting in permanent changes to island morphology (Figure 10-1). This transport of sand onto and/or behind the barrier surface supports backbarrier marsh habitats while also providing a mechanism for barrier island stability in regions with rising sea level (e.g., Godfrey, 1970; Kochel and Dolan, 1986 and 1989; Leatherman, 1983). Overwash processes may also result in a thin veneer of sand on the beach which could impact training exercises with respect to geotechnical (e.g. beach stability, etc.) requirements for military vehicles, as well as potentially influencing suitable habitat for nesting sea turtles. The likelihood of overwash penetration and potential island breaching is significantly higher where dune fields are lower than the relevant storm tide elevation (or are absent altogether) compared to regions of the beach characterized by higher and/or broader dune fields (Houser et al., 2007 and 2008; Morton, 2002; Sallenger, 2000; Thieler and Young, 1991).

Figure 10-1. Overwash and washover.

Panel A: The process of dune overtopping from the sea causing overwash; Panel B: Overwash leaving a fan-shaped deposit of beach sediment, known as washover (after Donnell et al., 2004; and Schwartz, 1975).

Recent work (Donnelly et al., 2006; Morton et al., 2000; Sallenger, 2000) has refined the definition of overwash into the following two regimes: (1) runup overwash, and (2) inundation overwash. Runup overwash occurs under conditions of excess wave runup, usually associated with lower magnitude storm events and/or barrier islands with high, well-developed dune fields.
During runup overwash, water and sediment are funneled through existing lows of the dune crest and spread laterally on the backbarrier. In contrast, inundation overwash occurs when the mean water level exceeds the dune crest, usually during extreme storms and/or on low-lying barrier islands with poorly developed dune fields (Figure 10-1; Panel B). In addition, although the terms “overwash and washover” are occasionally used interchangeably, “overwash” is the mass of water or the physical process by which water and sediment are carried over a dune crest, and “washover” refers to the actual geologic deposit of sediment created by the action of overwash (Donnelly et al., 2006).

![Figure 10-2. Runup overwash.](image)

Breaching the crest of the primary dune ($d_c$) by wave-driven runup ($R$) well above the regional surge water level ($S$) (after Donnelly et al., 2004).

Washover can extend landward from the shoreline up to hundreds of meters and ranges in thickness from a few tens of centimeters (Davis, 1994) up to a meter (McCubbin, 1982). Washover is distinguished from other barrier deposits by specific sedimentological characteristics such as grain size and mineralogy (Buynevich et al., 2004; Davis, 1994; Donnelly et al., 2004; Heron et al., 1984; Hippensteel and Martin, 1999). Multiple overwash episodes may result in a composite fan that is meters thick (Davis, 1994) and, in undeveloped settings, washover sequences are likely superimposed upon vegetated backbarrier surfaces, dunes, or previously deposited washover deposits.

**Predicting wave runup and dune overwash**

Accurate model predictions of overwash during storms necessitate a correct parameterization of wave runup, a principal driver of elevated water levels on beaches. Observations at the Field Research Facility (FRF) in Duck, NC, for example, revealed that wave runup accounted for 78% of the elevated water level whereas astronomical tides and surge were responsible for 9% and 13%, respectively, during Hurricane Irene. Wave runup certainly does not always dwarf storm surge or tidal forcing, but it can be an important driver in settings such as Onslow Beach and cannot be ignored when predicting overwash.

Measuring wave runup, however, is challenging because the interface between water and beach is spatially dynamic and extremely energetic. Previous studies aimed at measuring wave runup, defined here as the time-varying motion of wave swash on the beach foreshore, have been
restricted to analyzing water-elevation time series of the shoreward-most swash excursion using video imaging or near-bed resistance wires (e.g., Aagard and Holm, 1989; Holland et al., 1995; Holman and Guza, 1984), or measurement of water elevation at a particular location using pressure sensors (e.g., Guza and Thornton, 1982). These data are then compared with wave forcing parameters in deeper water, as well as with beach topography observed at finite intervals throughout the time series (e.g., Holland and Puleo, 2001). These approaches have led to numerous parameterizations and empirical equations for wave runup (e.g., Stockdon et al., 2006), but have so far been ineffective at providing data that are spatially and temporally dense enough to accurately understand the complex physical processes that govern wave runup during both storm and quiescent times. As a result, model skill (a measure of a physical model's ability to accurately reproduce observations) is often poor with respect to beach response and overwash during storms.

Study area

Onslow Beach, located on the North Carolina coast midway between Cape Lookout to the north and Cape Fear to the south, is a 12-km long barrier island with a nearshore region (shoreline to approximately 10-m depth) that spans 20 km² (Figure 10-3). The southern portion of the island is characterized by a low-gradient beach that varies greatly in width and contains numerous washover fans (Figure 10-3A). With increasing distance to the north, beach width stabilizes and is characterized by a high primary dune field with little to no evidence of overwash (Figure 10-3B). Onslow Beach is bordered on the northeast by Browns Inlet, on the southwest by the New River Inlet, and on the landward side by the linear channel of the Intracoastal Waterway (ICW), which was dredged in 1932 through a marshy habitat previously characterized by numerous, sinuous channels (Cleary and Riggs, 1999). The ICW currently averages 130 m in width and is maintained to a depth of approximately 4 m by the U.S. Army Corps of Engineers (USACE; available at http://www.saw.usace.army.mil/nav/aiww.htm). The island and surrounding lands were purchased by the U.S. Department of the Navy in 1941, and are part of Marine Corps Base Camp Lejeune (MCBCL), serving as the largest U.S. Marine Corps amphibious training facility in the world.

Onslow Beach is microtidal, with a mean tidal range of approximately 1 m (Cleary and Riggs, 1999). Both a 20-year hindcast model generated by the USACE (available at http://www.frf.usace.army.mil/cgi-bin/wis/atl/atl_main.html) and hourly wave data from an offshore National Oceanic and Atmospheric Administration (NOAA) buoy indicate the region experiences mean significant wave heights of approximately 1 m, with an average wave period of 4.6 seconds. Dominant wave direction is from the southeast in the summer and northeast during the winter, but the sheltering effects of northern Cape Lookout shadow the beach from much of the winter wave energy, thus minimizing the effect of winter storms (nor’easters) on the shoreline and beach morphology (Cleary and Riggs, 1999). Tropical cyclones (hurricanes) are episodic in North Carolina, with a predicted recurrence interval of about once in a 4-year period (Barnes, 2001). Although during-storm tropical storm wave heights have not historically been measured on Onslow Beach, predicted tropical storm wave heights for adjacent Topsail Island range from 3.3 m for a 50-year storm to 3.8 m for a 100-year storm (Cleary and Riggs, 1999) and provide an accurate representation of general tropical conditions for the overall region.
Onslow Beach, NC, is a microtidal barrier island that experiences frequent overwash events in the southern half of the island. A = Numerous washover fans on the south portion of the island (aerial view), and B = high primary dune field on the northern end of the island with no evidence of overwash.

**Methods and Methods**

**Mapping overwash deposits**

Changes in overwash processes along the southern half of Onslow Beach, a portion of which includes the amphibious training zone, were evaluated by mapping the spatial extent of washover deposits through time. A series of aerial photographs and satellite images depicting six time periods between 1938 and 2008 were used to track how the shoreline and vegetation line, which marked the landward extent of recent overwash events, has changed along Onslow Beach before and after amphibious exercises commenced (Foxgrover, 2009). An IKONOS satellite image collected in September 2006 was used as the basis by which all other imagery was georeferenced to a common projection and horizontal datum (UTM Zone 18, North American Datum of 1983 [NAD83]). The 2006 imagery has a resolution error of 80 cm and a reported horizontal circular error of 2.2 m at the 90% confidence interval. We used a National Map Accuracy Standards application factor of 2.146, which equates to a horizontal positioning root-mean squared error (RMSE) of 1 m (FGDC, 1998).
Additional aerial imagery was georeferenced to the 2006 image using a minimum of four secondary, or supplemental, control points (Thieler and Danforth, 1994). A first-degree polynomial transformation was performed on each image to estimate the best fit between all control points. Unfortunately, in the absence of primary control points providing accurate coordinate and elevation data, and without camera calibration reports, it was not possible to assess errors introduced through the distortion of the camera lens and/or film or any tilt in the aircraft at the time of exposure. The majority of images used, however, did have adjacent overlap of approximately 30% and, whenever possible, data from the center of the photo were used to limit the effects of radial or tilt distortion (Foxgrover, 2009).

A geographic information systems (GIS)–based tool (i.e., Beach Tools), developed by USACE for the purpose of delineating features on aerial imagery, was used to automate digitization of features. Software details and a description are available at the following link: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA490237. The wet/dry line was used as a proxy for the high water line (HWL). Potential errors associated with shoreline change assessment based upon aerial imagery include the following: (1) seasonal and tidal fluctuation of the wet/dry line, (2) errors in delineating features, and (3) errors in the original source data. The excursion of the HWL ranges from 1 m to 2 m over a tidal cycle on medium-sized, sandy North Carolina and Virginia beaches (Dolan et al., 1980; Moore, 2000). Larger variations on the order of ±10 m are estimated for seasonal fluctuations of HWL (Smith and Zarillo, 1990), but offset of the wet/dry line due to seasonal variability was minimized by selecting imagery collected between January and May (with the exception of the November 1989 digital orthophoto quadrangles), and that did not immediately proceed or follow large storm events (Foxgrover, 2009). User error associated with pixel identification and digitization of features from aerial imagery was assessed by performing a repetitive measurement of the wet/dry line three times over a 600-m long stretch of beach, as well as comparisons to field mapping of recent washovers using a real-time kinematic global positioning system (RTK-GPS; Figure 10-4). A different set of pixels was highlighted in each repetition to perform the classification analyses, and the difference in positioning between the three lines suggests a potential digitization error of ±5.6 m.

Due to the fragmentation of the dunes in all post-1938 imagery, the vegetation line cannot be accurately represented by a single line in all of the images. Rather, the vegetation line was augmented by a number of “vegetation islands” that occur landward of a shore-parallel beach access road. Because the aim of this research is to evaluate naturally forced vegetation change, the vegetation line that coincides with the landward side of the road was not traced. The pockets of dune vegetation seaward of the road were considered a better representation of a natural vegetation line and, despite occasionally being difficult to distinguish due to their limited size, vegetation clusters with an area of 20 m² or more were encircled using BeachTools.

The position of both the shoreline and the vegetation line was extracted at a 50-m alongshore interval from each aerial photograph using the Digital Shoreline Analysis System (Thieler et al., 2005), yielding a time-series of shoreline and vegetation line positions. The average and standard deviation of the shoreline and vegetation line positions at each transect were then derived using MATLAB.
The spatial area of recent washover deposits was digitized from aerial photographs spanning six decades using vegetation and open sandy areas as a delineation of washover deposits. Digitizing error was assessed through RTK-GPS field mapping of the digitized features.

**Nearshore bathymetry**

Accurate nearshore and surf zone bathymetry is a critical boundary condition for correctly modeling wave dissipation, runup and, ultimately, overwash. These data are often very sparse and questionable in quality when derived from traditional sources such as NOAA bathymetric charts because depths are infrequently measured in the shallow nearshore. Accordingly, high-resolution, interferometric swath bathymetry (Sea SwathPlus, 234 kHz) was collected over approximately 18 km² of the Onslow Beach nearshore (**Figure 10-5**). Line spacing ranged from 25–75 m, depending upon water depth, and the position of each data point was related to NAD83 using RTK-GPS. Vessel heave, pitch, and roll were corrected in real-time using an IXSEA Octans motion sensor. Seafloor depths were corrected for tides by using the real-time, motion-corrected vertical movement of the vessel throughout the survey as recorded with Hypack Oceanographics software. Similar studies using identical methodology in other nearshore regions indicate an average horizontal and vertical elevation error of ±10 cm and ±12 cm, respectively. Data were initially gridded using line averaging at a 1m resolution and subsequently despiked, filtered, and smoothed. Cleaned data were re-gridded at 5-m resolution in IVS Fledermaus Professional (version 7.0d), using a weighted moving average interpolation algorithm at a spacing of 5 m and a search diameter of 7 m.
Figure 10-5. Nearshore bathymetry.

Multibeam (interferometric) bathymetry of the nearshore, southern half of Onslow Beach, shown with 5-m grid spacing. Note presence of outcropping hardbottom in the surf zone in the central region of the nearshore.

Beach and dune topography: Coastal Lidar and Radar Imaging System (CLARIS)

High-resolution topography of the upper beach, primary dune face, and dune crest are critical boundary conditions for modeling wave runup and overwash. Traditional topographic data sources, such as U.S. Geological Survey topographic maps and airborne Light Detection and Ranging (LIDAR), are often limited for predicting overwash because the data are typically dated (rarely more frequent than annual), and the resolution of the dune crest and shape of the dune face are reduced by data density and vegetation. The Coastal Lidar and Radar Imaging System (CLARIS) is a fully mobile mapping system that integrates two state of the art remote sensing technologies, a terrestrial laser scanner (Riegl LMS-z390i; vz1000) and X-Band radar (4 kW, X-band 9.4 GHz), with precise motion (Position and Orientation System for Land Vehicles [POS-LV]) and location (RTK-GPS) information (Figure 10-6).

CLARIS, developed in-house at the FRF (Brodie and McNinch, 2011), is a robust system capable of rapidly (10 km/hr) and quantitatively measuring beach and dune topography (accuracy of 10 cm) with terrestrial LIDAR, and nearshore bathymetry from radar-derived wave velocity measurements (to within 10% of the actual depth). Vehicle motion is removed from both radar and laser data using the POS-LV observations in real-time and post-processed using Applanix PosPAC software for increased accuracy. The heading angle of each radar pulse is recorded using an Applanix POS-LV motion system with a less than 0.05 degree accuracy, and the location of
the center of each radar collection is recorded using RTK-GPS to 10 cm to 15 cm accuracy. The radar range is 1.2 km and at 10 km/hr, every location across the surf zone has at least a 10-minute time series of radar observations. Range resolution is 3 m, a function of analog to digital sampling using a 50-MHz card, and temporal resolution is 1.2 seconds. Radar observations are rectified through a polar transformation from azimuth-range space using heading and position information, to Cartesian coordinates (e.g., North Carolina State Plane Easting and Northing, Horizontal Datum: NAD83). The laser scanner simultaneously scans the topography starboard of the vehicle during transit along the beach. Terrestrial laser scanner survey precision is on the order of 1.3 cm and accuracy is ±5–10 cm. Point-cloud density averages 30 to 40 points per m², with higher density in the near range. Mobile, ground-based LIDAR provides complete spatial coverage and high data density, enabling three-dimensional features such as the beach cusps, primary dunes, and the berm (exemplified in Figure 10-7) to be robustly mapped without the data aliasing errors common in traditional survey methods (Plant et al., 2002). Once the LIDAR data are edited, they are typically gridded at 0.25- to 0.5-m spacing, and pertinent elevations such as dune crest are contoured.

**Figure 10-7. Beach and dune topography.**

CLARIS–measured beach and dune topography at Onslow Beach showing the high resolution of geomorphic features that are critical to improving model skill (perspective view looking south).

**Modeling nearshore waves**

CLARIS provides a quasi-instantaneous measure of waves in the surf zone providing a powerful tool for inferring bathymetry and showing the complexity of breaking wave parameters in the shallow surf zone. These data are useful for establishing boundary conditions and assessing the skill of wave model results but a continuous time series of wave conditions near the beach.
throughout storm events are needed to force the Runup and Overwash (ROM) model. The
STeady-state spectral WAVE model Full Plane (STWAVE-FP) version was used to model wave
transformation over nearshore bathymetry during the storm event to assess spatial variations in
wave height and direction (and subsequently radiation stress), the dominant hydrodynamic
forcing mechanisms in the surf zone. STWAVE-FP solves the steady-state conservation of
spectral wave action along wave rays enabling the modeling of wave transformation (refraction,
shoaling, and breaking) and wind-wave generation in the nearshore (Smith and Sherlock, 2007;
Smith et al., 2001). STWAVE-FP assumes a mild bottom slope with no wave reflection, a
spatially homogeneous offshore wave field, steady-state waves and winds (i.e., wave-generation
from winds assumes fetch-limited or fully developed conditions), and linear refraction and
shoaling. STWAVE-FP is used in this study because it was recently calibrated for an optimal
bottom friction coefficient using the cross-shore wave array at the FRF in Duck, NC (Hanson et
al., 2009). Though STWAVE-FP attempts to improve wave modeling within the surf zone
through the use of a wave-steepness breaking criterion, as opposed to a simple depth-dependence
breaking criterion, the non-linear nature of breaking waves in the surf zone makes them difficult
to model using linear wave theory, and thus wave heights predicted by STWAVE-FP within the
surf zone are neglected in this study.

Nearshore bathymetric survey data were used to generate an inner nested bathymetric grid (15-m
× 15-m resolution) from the shoreline to 10-m depths, and a courser (25 m × 25 m) grid was used
to characterize the region from 10- to 17-m depth. The model was forced hourly at the offshore
boundary with spectral wave and wind data from a suite of NOAA nearshore wave buoys and
run for 10 directional sweeps to ensure maximum accuracy. Water level data may be input from
either local tide stations or water level surge models such as the Advanced Circulation
(ADCIRC) model (Luettich et al., 1992). Bottom friction is also held spatially constant, with
Manning’s coefficient set to 0.073, as calibrated by Hanson et al. (2009). Given the
heterogeneity in sediment found at Onslow Beach (e.g., hardbottom, peat, gravel), the
assumption of spatially constant bottom friction may be a source of error in the model results;
however, defining spatially variable bottom friction coefficients given gross sediment parameters
is beyond the scope of this study.

Figure 10-8. Topographic and bathymetric model grid.
A portion of the model grid showing nearshore bathymetry and island topography with the shoreline
(0 m, North American Vertical Datum of 1988 [NAVD88]), black line, and the crest
of the primary dune defined by the white line.
Significant wave height and peak period is extracted along the 5- and 10-m contours (approximate edge of the surf zone) hourly, every 10 m alongshore and input to the Stockdon et al. (2006) overwash equation (Equation 10-1).

$$R_2 = 1.1 \left[ 0.35 \beta_f \left( H_o L_o \right)^{\frac{1}{2}} + \frac{H_o L_o \left( 0.563 \beta_f^2 + 0.004 \right)^{\frac{1}{2}}}{2} \right]$$

Eq. 10-1

Stockdon et al. (2006) defines the 2% exceedence elevation of runup ($R_2$) and foreshore beach slope ($\beta_f$), local wave height (e.g., 10-m water depth) reverse-shoaled to its deep-water equivalent ($H_0$), and deep-water wavelength ($L_0$). Peak wave period ($T_p$) is converted to deep-water wavelength ($L_\infty$) in Eq. 10-1 using the deep water approximation of the linear dispersion equation. Wave parameters are available at every 15 m alongshore throughout the study site and every hour during the modeled events. Beach foreshore slope was extracted from CLARIS LIDAR topographic data by fitting an average linear trend of the topography between the dune toe and the water line every 15 m alongshore. Runup elevations were added to observed and modeled tide and surge water level to determine a total dune cresting potential. If dune crest elevations were exceeded by modeled dune cresting potential (total water level height), overwash is predicted to occur.

Results and Discussion

Overwash

To test the hypothesis that the number and spatial extent of washover deposits did not change significantly prior to and after training operations began at MCBCL, an estimate of washover area per decade was determined starting in 1938. We compared decadal-scale changes in washover area due to tropical storm activity since the mid-1930s. Changes in washover area per decade were quantified using aerial photographs. On each image, both the wet/dry line and the farthest landward vegetation line were digitized, and the distance between the two lines was calculated every 50 m along Onslow Beach. The wet/dry line is a standard estimate of shoreline position in aerial photography and the location of an island’s vegetation line reflects the extent of the sandy washover deposit extending from the beach to the backbarrier. A large distance between the shoreline and vegetation lines on any one image indicates a large washover deposit and thus represents significant overwash breaching the barrier and dune during that period of time. The overall extent of washover deposits, based on the average distance between the shoreline and vegetation lines, was averaged from aerial photographs for each of the six decades (1930–2010) and is plotted on the left $y$-axis on Figure 10-9 as a proxy for washover extent. From these data, it is evident that the highest extent of washover deposits occurred in 1950, and again in 1990. The lowest extent of washover deposits, as reflected by the smallest average distance between shoreline and vegetation lines, was found in 1980. Overwash processes thus peaked both in 1950 and again in 1990, but a clear linear trend (either increase or decrease) was not evident suggesting that MCBCL amphibious training activities did not have a measurable effect on overwash processes at Onslow Beach.
Overwash is a result of inundation from wave runup or storm surge, or both, exceeding dune height during storms. The orientation of Onslow Beach protects it from the worst of the energy from winter nor’easters due to the partial sheltering provided by Cape Lookout, but not from storm systems approaching from the southeast. Along the North Carolina coast, most southeastern storms are tropical in nature and impact some portion of the coastline on average once every 4 years, with the result that most of the significant, overwash-generating storms impacting Onslow Beach are tropical in origin (Barnes, 2001; Cleary and Riggs, 1999). Tropical cyclone data for the region of Onslow Beach was obtained from NOAA’s Atlantic basin hurricane database called HURDAT (available on NOAA’s Web site at http://www.csc.noaa.gov/hurricanes) and included all hurricanes or tropical storms passing near Onslow Beach and the southern North Carolina Outer Banks. Storms were summed per decade (1930–2010) and plotted on the right y-axis of Figure 10-9. The highest numbers of tropical storms impacting the greater Onslow Beach region were found both in 1950 and 1990, mirroring the greatest extent of washover deposits. The lowest number of storms was noted in 1980, comparable to the lowest digitized extent of washover deposits.

**Predicting Overwash**

Overwash was modeled at Onslow Beach during Hurricane Irene using a combination of observational data (i.e., CLARIS topography, nearshore bathymetry, regional surge, and offshore wave spectra) and modeled nearshore waves (i.e., STWAVE-FP). Model and observational techniques were developed at both Onslow Beach and at the FRF over several years but Hurricane Irene was the only severe storm (with respect to wind and wave energy) to impact the study site during the DCERP1. **Figure 10-10**, top panel, shows primary dune crest elevation (purple) and predicted water level along the ocean beach which includes runup, surge, and
astronomical tides. The bottom two panels of Figure 10-10 present before and after aerial photographs of the study site and exhibit clear evidence of washover deposits at the predicted locations. Locations where the ROM model predicted water levels to exceed dune crest elevations (highlighted by vertical red bars) and thus overwash to occur were consistent with aerial photographs and visual observations (Rodriguez, personal communication) as exemplified in Figure 10-11. The two most substantial washover deposits generated by Hurricane Irene (two located farthest west; highlighted red bars) had not been overwashed, at least since 1938, and thus are not just a reoccurrence of overwash at a previously breached dune (as occurred at the two eastern locations).

Figure 10-10. Modeled water level and overwash prediction.

Dune crest elevation (purple line; top panel) and predicted water level (runup+surge+tide) along Onslow Beach during Hurricane Irene. Bottom two panels show washover deposits before and after Hurricane Irene.
ROM results also indicate the importance of spatial variations in nearshore bathymetry and wave runup. In particular, these varying runup elevations highlight the disadvantages and poor skill of simply flooding a beach with predicted tide and surge, except for the most extreme storms when surge levels completely inundate the primary dune. The differences in water level elevation reached across Onslow Beach during Hurricane Irene varied by almost 1 m, exemplified by the arrows in top panel of Figure 10-10, and can only be explained by differences in wave runup. Recent experiments at the FRF (Brodie and McNinch, 2011) reveal the sensitivity of wave runup to the amount of wave dissipation (breaking) across the surf zone which, in turn, is partly controlled by surf zone sand bars and foreshore slope. Simply put, spatial differences in the nearshore bathymetry of Onslow Beach due to sandbars and outcropping hard-bottom (Figure 10-5) drives differences in runup and may ultimately dictate the location of overwash. The region marked by the arrow (eastern; farthest to the right in top panel of Figure 10-10) shows the highest runup elevations, almost 3 m (North American Vertical Datum of 1988 [NAVD88]),
during Hurricane Irene. The nearshore bathymetry in that region has pronounced outcrops of hardbottom (Figure 10-5) elevated above the surrounding sandy seabed that likely leads to greater wave dissipation and steeper beach slopes which, in turn, force higher runup. Fortunately, the crest of the primary dune is relatively high in that region and did not overwash extensively during Hurricane Irene. Over longer time periods, however, this region will likely continue to experience elevated runup during storm events and remain prone to overwash should the primary dune become further degraded by repeated dune scarping during storms or anthropogenic activities.

Conclusions and Implications

- Overwash and its resulting washover deposits provides a means to accumulate sediment on and behind Onslow Beach, and thus is an important mechanism by which island morphology changes in response to changes in storm frequency and sea level rise over seasonal to decadal timescales. Overwash, however, may also reduce sand thickness on the beach, possibly affecting vehicle-related training exercises, and destroy habitat for nesting sea turtles.

- A comparison of washover extent, as obtained from aerial photographs from 1938–2010, suggest that the primary forcing mechanism generating overwash processes on Onslow Beach was tropical storm activity. Despite MCBCL using Onslow Beach as a training area since the late 1940s, no significant increases or decreases in overwash extent were observed post-MCBCL that were not also directly comparable to changes in tropical storm frequency. In short, MCBCL training activities on Onslow Beach have not measurably influenced the number of overwash events.

- Wave runup is an important component of elevated water levels during storm events at Onslow Beach. Maximum runup elevations vary spatially along Onslow Beach depending on the surf zone geology and bathymetry, which influences wave height, wave dissipation, and beach slope. In all but the most severe storm events, when storm surge far exceeds the elevation of the primary dune crest, runup may determine the location of overwash. Overwash predictions during Hurricane Irene demonstrated strong skill, correctly predicting all four overwash locations.

- The more central region of Onslow Beach, where outcropping rock in the surf zone influences wave energy and creates steeper beach slopes, will likely continue to experience increased runup elevations during storm events as compared to surrounding areas. Management strategies that help maintain dune crest elevations and care for sea turtle nest, with respect to minimizing inundation, should be closely followed in this region.


Appendix 10-A

Supporting Data
Supporting Data


Summary: In addition to the nearshore interferometric bathymetry data presented in this report, greater than 330 km of co-registered side-scan sonar reflection data (234 kHz), greater than 120 km of high-resolution seismic reflection data, and detailed sedimentological analysis (wet-pipette grain-size analysis) performed on nine marine vibracores (4–6 m in length) were used to characterize the bottom geology and nearshore sediment volume at Onslow Beach. These data were coupled with the aerial photography and shorelines change data presented in this report, as well as the data collected for Ms. Foxgrover’s master’s thesis, to: (1) test the skill of previously developed metrics for predicting shoreline change along Onslow Beach, and (2) develop metrics to reliably predict potential amphibious coastal landing and staging hazards (i.e., littoral penetration points).

1. Specific results pertinent to predicting shoreline change include the following:

- The northern region of Onslow Beach is characterized by stable to accreting short- and long-term erosion rates. In contrast, erosion rates increase with increasing distance south along the study site.
- The previously described spatial relationship of high alongshore steepness values with regions of elevated shoreline erosion (McNinch, 2004) held true for only the portion of varying nearshore gradients controlled by sedimentary features, suggesting that bottom type has an unquantified influence on the alongshore steepness metric.
- The previously described spatial relationship of low nearshore sediment volumes with regions of elevated shoreline erosion (Miselis and McNinch, 2006) held true only when transport-relevant (i.e., unconsolidated sand) sediment was considered.
- Combining both nearshore and subaerial volumes of transport-relevant sediment improved the sediment volume metric’s skill at predicting regions of elevated shoreline erosion.

2. Specific results pertinent to predicting amphibious coastal landing and staging hazards include the following:

- Even up-to-date topographic maps and bathymetric charts are often insufficient for predicting hazards relevant to transporting and/or staging personnel and equipment in the dynamic coastal zone (i.e., identifying littoral penetration points) because most maps and charts are based on sparse and static datasets.
- Several easily measurable environmental metrics can be identified, including gradients in nearshore bathymetry and nearshore sediment volume, and variation in shoreline and vegetation line positions as derived from aerial photograph, that allow for rapid and accurate evaluation of the suitability of various coastal regions for potential military applications.
These metrics were integrated with high-resolution bathymetric and isopach maps, and adjacent aerial photography, to generate a map of suggested littoral penetration points as well as coastal hazards for Onslow Beach.

(2) Heidi Wadman, Postdoctoral Research Associate, Virginia Institute of Marine Science, College of William and Mary, Williamsburg, VA. May 2008.

Summary: Geophysical, geospatial, and sedimentological data indicate that: (1) the relevant-sand prism of Onslow Beach is severely limited; (2) approximately 11% of the prism is comprised of sedimentologically distinct washover deposits; (3) the southern portion of Onslow Beach is actively undergoing barrier-island rollover; and (4) natural forcings have predominately shaped the evolution of Onslow Beach over the past 80 years. These conclusions are based not only on the overwash and aerial imagery data presented in this final report, but also on data from the collection of RTK-GPS transects of modern overwash fans, nine short (less than 2 m) and 12 long (up to 4 m) vibracores from the beach and backbarrier of Onslow Beach, and the collection of approximately 80 km of ground-penetrating radar (GPR) data collected throughout southern Onslow Beach. Sediment analysis included full Rapid-Sediment-Analyzer (sand-size, fractional-phi, grain-size analysis) of hundreds of core samples to distinguish overwash-transported sediment from aeolian-transported sediment. Overwash locations and beach volumes were compared to a multitude of previously defined proxies for predicting shoreline erosional hotspots, including long- and short-term shoreline change rates, and cross-island sediment volume (normalized to transect area). Specific findings include:

- The volume of the relevant-sand prism south of the former Riseley Pier is $1.8 \pm 1.1 \times 10^6$ m$^3$ and averages approximately 90 cm in thickness.
- Sedimentologically distinct washover deposits make up approximately $199 \pm 88 \times 10^3$ m$^3$ of sediment, which equals 29% of the active overwash complex or 11% of the entire study area’s relevant sand-prism.
- Large overwash events are a mechanism by which sediments can accumulate on and behind the island, thereby increasing the relevant-sand prism and decreasing susceptibility to future erosion.
- Although a simple linear relationship between spatial and temporal variability in shoreline behavior and volume of the relevant-sand prism did not exist, a positive correlation does exist between both rates of change and net movement of the shorelines and vegetation lines.
- The region of Onslow Beach experiencing the highest rate of erosion from 1938–2008 (3.85 m/y) is not the region used for military amphibious training activities.
Appendix 10-B

List of Scientific Publications
**List of Scientific Publications**

**Peer-Reviewed Publications**


**Thesis**


**Presentations**


Association of Geological Societies with the Gulf Coast Section of the Society for Sedimentary Geology (SEPM) 40(6).
Appendix 10-C

List of Students


- Amy Foxgrover, M.S., Virginia Institute of Marine Science, College of William and Mary, Williamsburg, VA. May 2010.