Shoreline Change in the New River Estuary, North Carolina: Rates and Consequences

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Shoreline Change in the New River Estuary, North Carolina: Rates and Consequences

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ABSTRACT

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Aerial photography was used to determine rates of shoreline change in the New River Estuary (NRE), North Carolina, from 1956 to 2004. The NRE shoreline was digitized from aerial photographs taken in 1956, 1989, and 2004, and shoreline type was determined by ground-truthing the entire shoreline by small boat in 2009. Major shoreline type categories included swamp forest (6% of total), salt marsh (21%), sediment bank (53%), and modified/hardened (19%). Ground-truthing provided additional details on relief, marsh species composition, and structure type. A point-based, end-point rate approach was used to measure shoreline change rate (*SCR*) at 50 m intervals for the periods 1956–89, 1989–2004, and 1956–2004. Representative wave energy (*RWE*) was modeled for each interval using local bathymetry and wind data. Average *SCR* across all shoreline types for the entire time period ranged from –2.3 to +1.0 m y^{-1}, with a mean *SCR* of –0.3 m y^{-1}. This translates to an average loss of ~13 m for any given point over the 48-year period covered by this study. The most negative average *SCR* (greatest erosion) occurred along unvegetated sediment bank shorelines (–0.39 m y^{-1}). Change along marsh shorelines (–0.18 m y^{-1}) was lower than along sediment banks, and narrow fringing marsh associated with sediment bank shorelines significantly reduced bank erosion. Modeled *RWE* values were positively correlated with erosion only in the highest wave-energy settings. Erosion of sediment bank shorelines provides a conservative estimate of 17,660 m^3 of sediment each year to the estuary, with marsh erosion contributing up to an additional 1900 m^3 y^{-1}. Based on analysis of the sediment volume required to maintain marsh surface elevation with respect to sea level, we hypothesize that shoreline erosion plays a vital role in supporting growth and maintenance of downstream marshes.

ADDITIONAL INDEX WORDS: *Estuarine shoreline, coastal erosion, sheltered coast, salt marsh, sediment supply*.

INTRODUCTION

The land-water interface is a dynamic boundary. Shorelines change position regularly as a result of seasonal and annual changes in water levels and weather patterns, biological activity, episodic storm events, and scouring by nearshore currents (Curtiss, Osborne, and Horner-Devine, 2009; Quartel, Kroon, and Ruessink, 2008; Ruddy, Turley, and Jones, 1998). Thus, present shoreline position reflects the balance between erosion and accretion over recent history. In the past several decades, booming coastal populations (NOAA, 2013) and increased per capita land consumption have resulted in increased shoreline development (Beach, 2002; Douglas and Pickel, 1999), fueling an interest on the part of coastal landowners and resource managers in predictions of future shoreline position (NRC, 2007). Estuarine shorelines are a dominant component of the landscape in coastal regions of the U.S. Gulf and Southeast coasts (Dame *et al*., 2000). A recent analysis based on aerial imagery identified >12,000 miles (19,312 km) of estuarine shoreline in North Carolina alone (McVerry, 2012). While many previous investigations of shoreline change have focused on oceanfront beaches, there are fewer reports of change rates along estuarine coasts. The sheer magnitude of estuarine-shoreline extent, combined with the fact that many oceanfront regions are already heavily developed, makes these regions desirable for developers of waterfront property. Understanding change along estuarine coasts is therefore of increased urgency.

Wave energy has obvious importance in interpreting a given shoreline's likelihood of change. All other things being equal, if one shoreline is battered by waves, and the other is impacted by gently lapping seas, the shoreline being battered will erode at a faster rate. Although some investigators have found significant correlations between estuarine shoreline erosion and wave energy (Marani *et al*., 2011; Roland and Douglas, 2005; Schwimmer, 2001), others have not (Cowart, Walsh, and Corbett, 2010; Ravens *et al*., 2009). Shoreline elevation, type (natural *vs*. altered, vegetated *vs*. bare, *etc*.), underlying lithology, sediment supply, and human modification have all been identified as potential predictors of shoreline change (Cowart, Walsh, and Corbett, 2010; Gunnell, Rodriguez, and McKee, 2013; Mattheus *et al*., 2010; Riggs and Ames, 2003; Sunamura, 1992). Spatial and temporal variability in these factors combine with interactions between factors to render it difficult to predict erosion rates for a specific location with any degree of certainty. This is particularly true of estuarine or

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sheltered coast shorelines, which tend to be highly sinuous and spatially variable with respect to shoreline type.

Compounding the impacts of shoreline erosion by physical scouring, many regions are experiencing an increase in relative sea level (Boon, 2012; Fitzgerald *et al.*, 2008). To keep up with rising sea level, coastal lands must grow vertically through *in situ* production of new organic matter or deposition of mineral sediments carried by flood tides (Mariotti and Carr, 2014; Morris *et al.*, 2002; Nyman *et al.*, 2006). Deposition of mineral sediments along the seaward margin can also result in progradation, particularly when vegetation takes hold quickly enough to trap sediments in place (Allen, 2000; Gunnell, Rodriguez, and McKee, 2013; Kirwan *et al.*, 2011; Mudd, 2011). If an estuary's sediment supply is reduced (e.g., through damming of upstream waters, for example), shoreline retreat is a common result (Day *et al.*, 2007; Tweel and Turner, 2012). Thus, supply of mineral sediments is likely to be a key determinant of estuarine shoreline change rates (Chauhan, 2009; Mariotti and Carr, 2014; Mariotti and Fagherazzi, 2013).

In the current study, we used a time-series analysis to investigate recent (1956–2004) rates of shoreline change in the New River Estuary (NRE), North Carolina. We compared rates of change at discrete points within the estuary based on both shoreline type (vegetated, nonvegetated, hardened) and modeled values of wind-driven wave energy. This comparison allowed us to assess the interaction among shoreline characteristics, wave exposure, and erosion rates. Additionally, we combined measured shoreline change rates with field observations of sediment and marsh bank height to estimate sediment loading from shoreline erosion within the NRE.

METHODS

The NRE is a shallow (< 3 m) estuary extending approximately 30 km from the city of Jacksonville, North Carolina, to Onslow Bay. The highly serpentine NRE shoreline encompasses a linear distance of ~150 km. While the northernmost portion is urbanized, approximately 80% of the NRE shoreline falls within Marine Corps Base Camp Lejeune (MCBCL). The estuary is composed of a series of smaller lagoons, which range in salinity from full-strength seawater near the mouth of the estuary to freshwater at the head. Barrier islands at the mouth of NRE restrict exchange with the ocean, resulting in long flushing times and low tidal amplitudes throughout the estuary (Mallin *et al.*, 2005; Peierls, Hall, and Paerl, 2012). The microtidal (<0.5 m daily tidal amplitude) nature of this system suggests that wind-driven waves likely provide the major erosional force on NRE shorelines.

Shoreline Characterizations

The NRE shoreline was digitized from aerial photographs taken in 1956, 1989, and 2004 to provide three time points for analysis. The 2004 images were natural color digital orthophotography with 0.3 m resolution. The 1989 and 1956 images were color infrared and black and white photographic prints, respectively, that were digitally scanned and georeferenced. All aerial images were provided by MCBCL. For all three time points, the wet-dry line on sediment shorelines and the vegetation-water boundary on vegetated shorelines were manually on-screen digitized in ArcGIS (Boak and Turner, 2005; Cowart, Walsh, and Corbett, 2010). Shoreline habitat type was initially characterized using 2004 true color imagery (with a 1:12,500 scale) obtained from U.S. Geological Survey (USGS). All shoreline segments were assigned to one of five categories (swamp forest, salt marsh, sediment bank, modified, or miscellaneous), and a shapefile of shoreline habitat type was created in ArcGIS. Modified shorelines were those that were visibly (in the imagery) altered by human action, such as bulkheads, while miscellaneous shorelines were those for which shoreline type could not be determined from aerial photography. In 2009, preliminary ground-truthing revealed a number of discrepancies between actual shoreline type and that determined from aerial photos as described here. Following this discovery, the entire shoreline was explored by small boat, and shoreline type designations were mapped with the use of a Trimble Pro XH with Zephyr antenna GPS connected to a laptop using the GPS extension in ArcGIS, with subsequent postprocessing. Surveying the entire shoreline by small boat also allowed us to supplement the shoreline type designations with detailed information about the type of vegetation present, including the presence of narrow (<2 m) bands of vegetation associated with sediment banks, shoreline relief, and in the case of modified shores, the type of modification (bulkhead, sill, *etc.*). All shorelines designated as modified were hardened with the addition of nonnative material.

Ground control points (GCPs) were collected to determine the rectification error associated with each imagery data set. Sixteen GCPs were located at road intersections, building corners, or other infrastructure that was identifiable at all three time points. Rectification error (*Er*) was calculated as the root mean square (RMS) of the differences between the GCPs and their locations on each photo. The rectification error associated with comparisons made over the entire time period (1956–2004) was 3.48 m.

Shoreline Change Rates

A point-based, end-point rate approach (Cowart, Walsh, and Corbett, 2010) was used to measure shoreline change rate (*SCR*) at 50 m intervals for the periods 1956–89 (early period), 1989–2004 (recent period), and 1956–2004 (total period). A few shoreline segments within MCBCL could not be ground-truthed due to their "restricted access" designation (Figure 1). Those points were excluded from the analysis, as were any regions for which there was not useable aerial photography for one or more of the time periods. Overall, 2182 discreet points (representing 109 km or 88% of the mapped shoreline) are included in the following analysis. Error in *SCR* was estimated as described in Fletcher *et al.* (2003) and adapted for estuarine shorelines by Cowart, Walsh, and Corbett (2010). The RMS of rectified aerial imagery was 3.48 m, and we estimated tidal stage uncertainty at 1 m. As a single individual conducted the heads-up digitizing, we do not have an estimate for digitization error, but we utilize a reported digitization error of 0.55 m from a similar study (Cowart, Walsh, and Corbett, 2010), which results in an estimated total uncertainty (U_t) of 3.66 m. Annualized over the study period, uncertainty in the *SCR* equals 0.08 m.

Wave Energy

The impact of wind-driven waves on shoreline change rates within the NRE was evaluated with the National Oceanic and

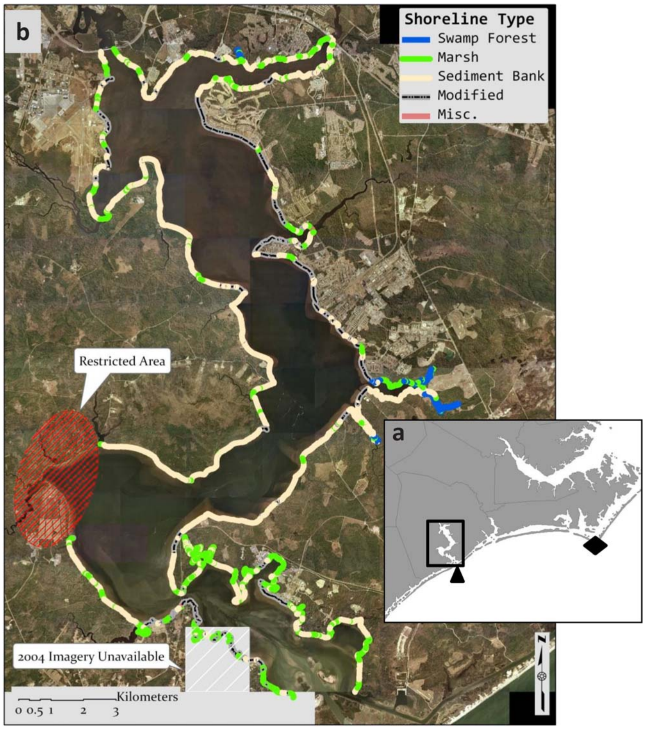

Figure 1. (a) Central North Carolina coastline, showing location of New River Estuary study area (rectangle). Buoy 41035 (triangle), and Cape Lookout, North Carolina, weather station (diamond) were sources of wind data. (b) Results of 2009 field survey of New River Estuary shoreline type displayed over 2004 aerial photography. Restricted area was inaccessible and excluded from data set. (Color for this figure is available in the online version of the paper.)

Atmospheric Administration's (NOAA) Wave Exposure Model (WEMo; Malhotra and Fonseca, 2007). WEMo is a GIS-based hydrodynamic model and was used to calculate representative wave energy (*RWE*), which represents the total wave energy in one wavelength per unit wave crest length, in units of $J\ m^{-1}$ or $kg\ m^{-1}\ s^{-2}$. *RWE* is based on linear wave theory, and wave height is calculated with a wave ray technique, calculating wave energy along each of up to 56 fetch rays. For our purposes, WEMo was used to create *RWE* chart products over a spatially registered GIS grid (200 m on center) based on NOAA shoreline shapefiles, bathymetry data, and wind data covering the 3-year period 2008–10 from National Data Buoy Center (NDBC), buoy 41035 (Figure 1). By convention, only exceedance wind events (average of top 5% of wind speeds measured during 2008–10) were used to run the model because these events are most likely to produce significant shoreline changes (Keddy, 1982; Kelly, Fonseca, and Whitfield, 2001). WEMo output also provided an estimate of wind-generated wave energy at the 50 m intervals used to estimate *SCR* along the NRE shoreline.

Sediment Loading

Shoreline characterization results were combined with calculated average shoreline change rates over the total period (1956–2004) to estimate the annual volume of sediment liberated by erosion of sediment bank and marsh shorelines.

Table 1. *Comparison of New River Estuary shoreline types as determined by analysis of aerial imagery and ground field surveys.*

	Aerial (2004)		Field (2009)	
Description	Length (km)	%	Length (km)	%
Miscellaneous	3.6	3	0.0	0
Swamp Forest	0	0	7.3	6
Marsh	15.9	13	26.5	21
Sediment Bank	91.6	73	66.3	53
Modified	13.1	10	24.3	19

Sediment bank shorelines were subdivided into three categories based on visual estimation of bank height during the shoreline field surveys: (1) high relief (greater than 3 m), (2) medium relief (1–3 m), and (3) low relief (less than 1 m). A fourth category was dedicated to salt marsh shorelines. Annual estimates of sediment release were calculated using the equation:

$$V = R \times SCR_{\mathrm{R}} \times L$$

where V = annual sediment volume ($m^3\ y^{-1}$), R = relief height (m), SCR_{R} = average *SCR* by relief category ($m\ y^{-1}$), and L = total length of sediment bank shoreline by relief category (m). We used assumed R values of 3 m for all high-relief, 2 m for medium-relief, and 0.5 m for low-relief banks. We assumed an R value of 0.4 m for marsh shorelines. This approach assumes a vertical profile and a user-defined relief height that is constant across the expanse of each sediment bank.

Statistical Analyses

Statistical tests were conducted with R version 2.14.0 (R Core Team, 2012). Factorial analysis of variance was used to determine the impact of shoreline type and *RWE* on erosion rates.

RESULTS

Initial ground-truthing expeditions to compare shoreline classifications made from the 2004 aerial imagery with field conditions revealed frequent errors. The resultant field survey of the entire shoreline conducted in 2009 significantly reduced the uncertainty surrounding the accuracy of characterizations, though this approach does not capture changes that occurred between 2004 and 2009. A comparison of the data from the two methods of characterization indicates that salt marsh and hardened shorelines were frequently incorrectly categorized as sediment bank based on their appearance in aerial photos (Table 1). Swamp forest was not classified from aerial photos because these regions were indistinguishable from dry forests that overhang the shoreline. In fact, the majority of incorrectly characterized sections of shoreline were populated with upland forest that obstructed views of the shoreline from aerial imagery. Because shoreline type could not be defined from aerial photography with a high degree of confidence, we applied the 2009 survey-based shoreline type categories to all shoreline points, even back to 1956. This presents a challenge when interpreting dynamics of the modified shoreline segments in that we do not know at what time a particular segment may have been hardened.

Results of the ground survey revealed that over half of the current NRE shoreline (~61 km) is sediment bank (Table 1;

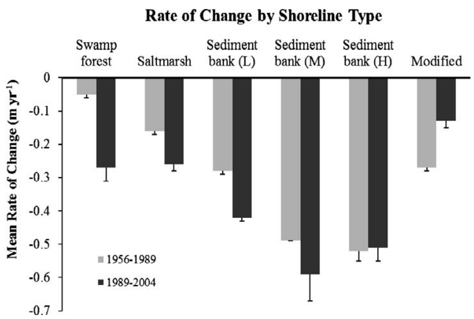

Figure 2. Average rates (and standard errors) of shoreline change by shoreline type and time period. Shoreline type characterizations were made in 2009 only; thus, measured erosion along modified (hardened) shorelines is likely the result of changes that occurred before the shoreline was modified.

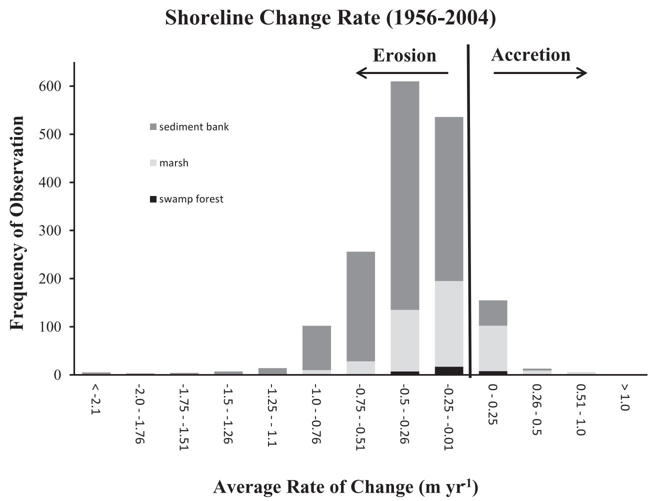

Figure 3. Histogram of shoreline change rates by shoreline type. Most sediment bank shorelines eroded over this time period. Change along marsh shorelines ranged from low rates of erosion to accretion. Overall, marsh shorelines appear to be more stable.

Figure 1). Most of the sediment bank shoreline in the NRE (68%) is low relief (<1 m), roughly 5 km (8%) falls into the medium-relief category (1–3 m), and 15 km (24%) is high relief (>3 m). Field surveys indicated that ~27% of sediment bank shorelines are bordered by a narrow (<2 m width) marsh. A large portion (~19%) of the entire NRE shoreline has been modified, or hardened. The majority of the modified areas are armored with rip rap. Vertical bulkheads and stone sills made minor contributions (<3%) to the total modified area. Vegetated shoreline, including salt marsh and swamp forest, contributed 21% and 1.5%, respectively, with marsh occurring primarily in the lower estuary and along tributaries (Figure 1). Salt marsh shorelines near the mouth of the estuary were dominated by *Spartina alterniflora*. A transition to marshes dominated by *Juncus roemerianus* and *Spartina cynosuroides* occurred along a transect from the mouth to head regions of the NRE.

Shoreline Change

Over the entire period (1956–2004), shoreline change rates averaged –0.30 m y^{-1}, for an average loss of 12.9 m. However, rates of change were variable, with some shorelines receding at >2× the average, while other areas experienced measurable accretion over the same time period. In total, 1947 points (89% of the shoreline) exhibited net erosion, 205 points (9%) exhibited net accretion, and the remaining 30 (2%) demonstrated no net change over the total time period. Analysis of the average rates of change by shoreline type and time period (Figure 2) indicated considerable variability in *SCR*s. High- and medium-relief sediment bank shoreline exhibited the largest rates of change over both time periods (early and recent), with mean change rates of approximately –0.50 m y^{-1}. Swamp forest, salt marsh, and low-relief sediment bank all experienced increased rates of change during the recent time period, while hardened shorelines exhibited the opposite trend, with decreased shoreline change rates during the recent period. The fact that hardened shorelines experienced any net erosion is an artifact of the application of 2009 shoreline type across the entire time period as described earlier. The decrease in rates of erosion between the early and recent time period for current hardened shorelines demonstrates that these features are fulfilling their intended purpose.

A frequency plot of average *SCR* over the total time period for all points showed that sediment banks experienced the most substantial losses (Figure 3). *SCR* values <–1 m y^{-1} were detected exclusively on sediment bank shorelines. Regions that experienced lower loss rates (*SCR*s closer to 0) were still dominated by sediment bank, but many marsh shorelines also fell into this category. Regions with *SCR* > 0 were dominated by marshes. Whether swamp forests exhibited erosion or accretion varied by location, but in all cases, *SCR*s within swamp forest shorelines were comparatively small.

Wind Wave Energy

RWE maps were created from WEMo using local bathymetry and wind data. The wind data used to generate these products consisted of the average wind speed produced during the top 5% of all wind events measured over the period 2008–10. Use of these data to analyze patterns of shoreline change over the entire study period (1956–2004) assumed that exceedance values, or top 5%, of wind events occurring in the 2008–10 period were representative of historical exceedance wind events. We validated this assumption by analyzing long-term (1985–present) hourly wind data from the closest available station at Cape Lookout, North Carolina (Figure 1; hourly records are not available at the buoy 41035 before 2005). Visual comparison of 2005–10 data from Cape Lookout and buoy 41035 showed no major differences between sites. Further, a visual analysis of the long-term trend of Cape Lookout wind data indicated that while there was an increase in the number of extreme events (number of hurricanes per decade), the average wind trends (directions and speeds) of extreme events in 2008–10 were not anomalous with respect to those of previous decades. Thus, our wave maps based on recent buoy

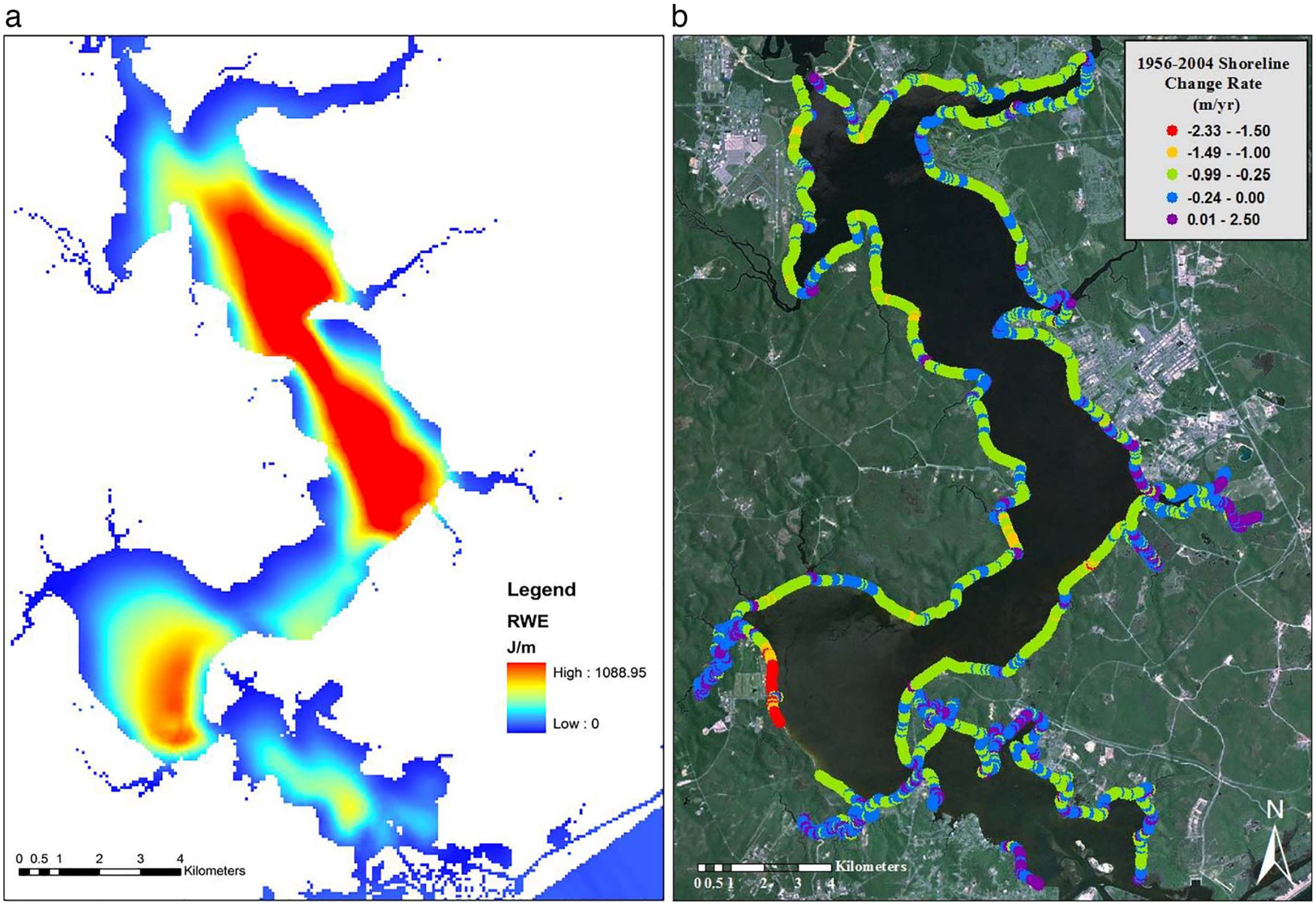

Figure 4. (a) Representative wave energy determined by the Wave Exposure Model (WEMo). (b) Average shoreline change rate for total time period in the New River Estuary, North Carolina. Note that shorelines that experience the greatest wave energy are not those with the greatest erosion rates. (Color for this figure is available in the online version of this paper.)

41035 wind data are a reasonable basis for evaluating long-term trends in NRE shoreline change.

Map products indicated a strong northerly component to exceedance wind events in the NRE, rendering south-facing shores relatively protected (Figure 4a). The median wave height predicted by WEMo was 0.22 m, with maximum wave heights approaching 0.5 m for the most exposed shorelines. To evaluate the influence of waves impacting the shoreline, *RWE* (J m^{-1}) values adjacent to each 50 m shoreline interval (calculated using WEMo) were compared with *SCR*s calculated for the same shoreline segment (Figure 4b). Calculated shoreline *RWE* values ranged between 0.04 and 983 J m^{-1} and were spatially variable. In general, south-facing shorelines and those that occur in small tributaries where fetch is minimal experienced much lower wave energy than north-northwest–facing shorelines along the main trunk of the estuary (Figure 4b). To investigate the relationship between wave energy and *SCR*, we created a four-level *RWE* classification scheme. The boundaries for each level were determined from a cumulative frequency plot of all calculated *RWE* values (Table 2) with wave class 0 representing the lowest values and class 3 representing the top 5% of all *RWE* values.

Table 2. *Wave class designations for New River Estuary shorelines as determined from cumulative frequency plot*. RWE = *representative wave energy*.

RWE Class	*RWE* (J m^{-1})	Percentiles
3	>583	>95
2	337–583	75–95
1	184–336	50–75
0	<184	<50

The relative distribution of shoreline type was surprisingly consistent with respect to wave class (Figure 5). Sediment bank was the dominant shoreline type regardless of wave-energy setting. Salt marshes were slightly more abundant in regions with lower wave energy (wave class 0 and 1) but were present at all wave-energy settings. Swamp forest was completely absent from regions of wave class 1 and 3 and made only a minor contribution to shoreline type in regions of wave class 0 and 2. Hardened shorelines contributed 15–26% of the total shoreline across all wave classes.

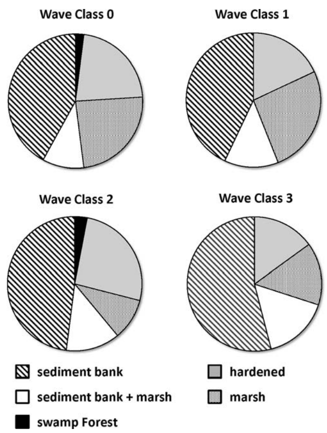

Figure 5. Distribution of shoreline type by wave-energy regime. Note that shoreline types are distributed fairly evenly among wave-energy classes. Representative wave energy (*RWE*) classes 0–3 are in increasing order as determined from a cumulative frequency plot (see Table 2). *RWE* class 0 < 184 J m^{-1}; class 1 = 184–336 J m^{-1}; class 2 = 337–583 J m^{-1}; class 3 > 583 J m^{-1}.

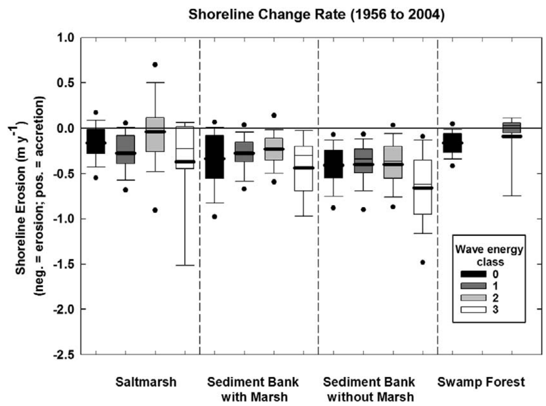

Figure 6. Shoreline change rates by shoreline type and wave-energy class (whiskers indicate 5th and 95th percentiles). Average rates of erosion are similar across all shoreline types in regions of wave class 0–2. Elevated erosion occurs in all shoreline types in regions of the highest wave energy (wave class 3).

Erosion rates for each shoreline point were analyzed in terms of both shoreline type and wave class. A two-way analysis of variance indicated a significant effect of shoreline type ($F = 68.72$, $p < 0.001$) and wave class ($F = 7.65$, $p < 0.01$) with no significant interaction between factors. There were no significant differences in *SCR* among shorelines of wave class 0–2, but those exposed to wave class 3 showed consistently higher erosion rates. Salt marshes and sediment banks with marsh borders exhibited lower average erosion rates than did sediment banks without marsh under the same wave regime (Figure 6), indicating that marsh vegetation plays an important role in reducing erosion rates. Analysis of the average *SCR* of sediment banks with fringing marsh *vs*. those without indicates a highly significant ($P < 0.001$) average difference of 0.11 m y^{-1}. Extrapolated over the 48 years covered by this data set, this would result in 5.28 m greater loss in sediment bank shorelines without marsh borders. Accretion occurred along roughly 10% of shoreline segments, irrespective of wave energy category, and was most commonly associated with vegetated shorelines.

Sediment Loading Rates

Our rough calculation suggests that the average annual volume of sediment available *via* shoreline erosion is 37,236 m^3 y^{-1} (Table 3), assuming a vertical shoreline profile. A more conservative estimate, assuming a 45° angle of repose, would be half that amount, or ~18,600 m^3 y^{-1}. We have high confidence in the total extent of NRE sediment bank shoreline and the long-term average erosion rates, and we feel that the conservative approach represents a reasonable first-order estimate of erosion-related sediment loading.

DISCUSSION

A previous analysis of estuarine shoreline change rates in northeastern North Carolina indicated an average *SCR* of –0.82 m y^{-1} across all nonhardened shoreline types (Riggs and Ames, 2003). This average includes shorelines spread throughout the Albemarle-Pamlico Sounds (APES) and upper and lower reaches of the Pamlico River. An average shoreline change rate of –0.58 m y^{-1} was calculated for the nearby Neuse River Estuary using methodology similar to this study (Cowart, Corbett, and Walsh, 2011). The average *SCR* determined here across all nonhardened shorelines of the NRE (–0.30 m y^{-1}) is substantially lower. The Albemarle-Pamlico Sound shoreline is dominated by marsh (>55%), the Neuse River Estuary shoreline is 46% marsh, while marsh comprises a much smaller fraction of the NRE shoreline (~20%). The most abundant shoreline type in the NRE is low-relief sediment bank.

We observed that unconsolidated sediment bank shoreline that was not bordered by marsh was highly susceptible to erosion. Within the NRE, erosion rates >1.0 m y^{-1} occurred exclusively along sediment bank shorelines (Figure 3). In the current study, the average *SCR* among marsh shorelines (–0.18 m y^{-1}) was substantially lower than that for sediment bank shorelines (–0.36 m y^{-1}). Cowart, Corbett, and Walsh (2011), and Riggs and Ames (2003) reported similar patterns of elevated erosion rates on sediment bank relative to marsh shorelines. Given this trend, and the dominance of vulnerable sediment bank shorelines within the NRE, one might predict greater overall erosion in this system relative to that of the APES and Neuse River Estuary. However, estuarine morphology is one likely reason we do not see greater erosion rates in the NRE. While the APES has wide expanses of open water, the NRE is long and narrow with shorter fetch lengths that limit the maximum potential wave energy of this system relative to that of the APES. In the Neuse River Estuary, Cowart, Corbett, and Walsh (2011) found an inverse relationship between *SCR* and mean fetch, with low *SCR* values in the narrow upper reaches of the estuary, and steadily increasing (more negative) *SCR*s in the downstream, more exposed regions.

Wind Wave Energy, Shoreline Change, and Shoreline Type

While many factors have been implicated as potential predictors of future shoreline erosion, the most intuitive and

Table 3. *Calculated annual sediment volume released* via *erosion for shoreline types of the New River Estuary, using shoreline change rates determined from aerial photography and assuming either a vertical or more conservative 45° shoreline profile. Bank heights for each category are based on field observations. Total time period is 1956–2004.*

Shoreline Type	Bank Height (m)	Length (m)	Mean *SCR* (m y^{-1})	Vertical/45° Profile Sediment Volume (m^3 y^{-1})
High Bank	3	15,050	−0.51	23,027/11,513
Medium Bank	2	4950	−0.52	5148/2574
Low Bank	0.5	43,350	−0.32	7153/3576
Marsh	0.4	26,500	−0.18	1908/954
Sum				37,236/18,618

often cited is wave energy. Because most waves are wind driven, previous authors have attempted (with varying success) to relate *SCR* and either fetch or some metric of wave energy or power calculated utilizing fetch. In a study of marsh shorelines in Rehoboth Bay, Delaware, Schwimmer (2001) found wave power to be a strong predictor of shoreline erosion rates. Similarly, Roland and Douglas (2005) used wave hind casts to explain the presence of eroding *vs*. noneroding shorelines in Alabama *S. alterniflora* marshes. In contrast, we did not find a strong relationship between wave energy and *SCR*.

Comparison of our results to these earlier works provides important insight into the processes controlling *SCR* on estuarine shorelines. In Rehoboth Bay, calculated wave energy flux, or wave power, for individual sites ranged from ~660 to 9200 W m^{-1} (Schwimmer, 2001). *RWE* can be converted to wave power by dividing by average wave period, which ranged from 0.98 to 1.85 in the NRE study, yielding a range in wave power of 0.1 to 567 W m^{-1}. While Roland and Douglas (2005) did not report values of wave energy, their work indicates that significant wave heights of >0.3 m occurred 40% of the time along eroding shorelines, representing the average wind conditions over a 14-year period. In the NRE, using only data from the top 5% of all wind events, we found significant wave heights >0.3 m less than 25% of the time. Further, our results suggest that in the NRE, significant wave heights >0.1 m are rare. Thus, NRE is a much lower-energy system than those examined by Schwimmer (2001) and Roland and Douglas (2005), a characteristic which likely explains the lack of a strong relationship between *RWE* and *SCR*. In an analysis of the cause of marsh erosion in West Galveston Bay, Texas, Ravens *et al*. (2009) found a tenuous link between wave-energy hind casts and marsh shoreline erosion rates. Their system, like the NRE, was characterized by relatively low wave energy.

Previous works have demonstrated the importance of episodic large-scale events in driving shoreline erosion (Doran *et al*., 2013; Morton, 2002, and references therein). Hurricanes are arguably the most significant erosion-causing phenomena that occur in the NRE. The influence of hurricanes on shoreline change in the NRE is supported by the concomitant increase in both erosion rate and hurricane frequency and strength in the recent time period, which saw a total of 21 tropical storms or hurricanes in 15 years, four of which were greater than category 1 (NOAA Coastal Services Center, 2014). The *SCR*s presented here are averages over 15- (recent), 33- (early), or 48-year (total) periods, and the full impact of major storm events is likely lost within the long-term averages. We suspect that a stronger correlation between *RWE* and *SCR* would be detected if it were possible to analyze change in shoreline position over much shorter time intervals.

Vegetated shorelines occurred in all wave classes in the NRE. Swamp forest shorelines were limited to the three lower wave classes, which experienced maximum wave energy of <583 J m^{-1}. However, salt marsh shorelines and sediment banks with narrow bands of marsh occurred in settings exposed to wave energies of up to 700 J m^{-1}. Further, vegetated shorelines in the highest wave class exhibited lower erosion rates than unvegetated shorelines. These data further support the utilization of marsh vegetation as a shoreline stabilization strategy (Gedan *et al*., 2011), and they provide guidance on the physical settings in which they can be effective.

Shoreline Erosion as a Sediment Source

Inadequate sediment supply due to damming and other human-induced changes in stream flow has been cited as a primary driver of decreases in areal expanse of marshes from the Gulf Coast to the mid-Atlantic (Kirwan *et al*., 2011; Mariotti and Fagherazzi, 2013; Ravens *et al*., 2009; White, Morton, and Holmes, 2002). While the New River that empties into the NRE is not impacted by damming, it is a slow-flowing river with low suspended sediment loads, and, thus, there appears to be no significant source of extrinsic sediments available to marshes of the NRE. The material that is liberated from sediment banks through erosion may ultimately be deposited in deeper regions of the estuary, may remain in suspension and be carried out of the system, or may be resuspended and deposited on the marsh surface during flood tides (Mariotti and Carr, 2014). We hypothesize that much of the measured marsh accretion (lateral and vertical) in the NRE was fueled by recycling of sediments eroded from sediment banks. Approximately 130 ha of tidal-fringing salt marsh are present within the main stem of the NRE, and roughly 275 ha of back barrier lagoon marsh surround the mouth of the estuary, based on existing wetland inventories (North Carolina Division of Coastal Management, 2014). Presumably, all of these regions are candidates for receiving material liberated from sediment banks within the NRE. At the current average rate of relative sea-level rise in North Carolina (2.7 mm y^{-1}; Zervas, 2004), approximately 12,000 m^3 of sediment would be needed annually for these marshes to maintain their present relative surface elevation in the face of rising sea level. Compositional analysis of soils in marshes near the mouth of the estuary indicates that the percent by weight of the sand fraction varies from 20% to >80% (Currin, unpublished data). Thus, sand is a major component of the soils in these marshes, and while some portion of this material likely comes from other sources (Rodriguez *et al*., 2013), material eroded from NRE sediment banks may represent a quantitatively significant source of sediment to NRE marshes. Our calculations of total volume of sediment liberated annually (~18,600 m^3) *vs*. total amount necessary to sustain measured rates of lateral (3510 m^3) and vertical (~12,000 m^3) accretion suggest that redistribution of material within the NRE may play a significant role in the observed patterns of shoreline change. Under this scenario, continued erosion of these shorelines may be vital to the persistence of NRE fringing salt marshes. This is similar to Mariotti and Carr's (2014) conclusion that allowing marsh retreat in high-energy areas will support local vertical marsh accretion, thereby increasing marsh resilience to sea-level rise.

We found that roughly 20% of the NRE shoreline is currently hardened, mostly with loose rubble or rip-rap. Increases in coastal population that are predicted in the coming decades will undoubtedly result in increased building along estuarine shorelines. Previous investigators have shown that the extent of anthropogenically modified (hardened) shoreline increases proportionally with population size (Douglas and Pickel, 1999). In the NRE and regions like it, increases in coastal population size and associated development-related efforts to stabilize sediment bank shoreline may have the unintended negative consequence of starving remaining marshes of their sediment source.

CONCLUSIONS

Ever-increasing development pressure along U.S. estuarine shorelines necessitates an understanding of the rates and causes of estuarine erosion to help develop sustainable shoreline management policies. In low-energy settings like the NRE, wind is generally not well correlated with shoreline change rates. Rather, shoreline type is a stronger predictor of long-term change. The data presented here illustrate the importance of shoreline vegetation and understanding sediment budgets in ameliorating erosion. Marsh and swamp forest shorelines exhibited lower erosion rates than unvegetated shoreline, particularly at higher wave classes (Figure 6). Sediment banks bordered by even a narrow strip of vegetation exhibited lower erosion rates than unvegetated sediment banks, and a higher percentage of salt marsh shorelines prograded, even in the highest-energy regions of the estuary.

In estuaries like the NRE that do not have a significant source of extrinsic sediments, erosion of sediment bank shorelines likely plays a major role in sustaining marsh growth. However, sediment bank shorelines exhibit the greatest rates of erosion and are therefore the most likely candidates for stabilization. As more and more of these shorelines are stabilized in efforts to stave off losses of coastal property, it is likely that less material will be available for sustaining the platforms of nearby marshes, ultimately reducing the ability of marshes to keep up with sea-level rise. Thus, the amount of shoreline armoring should be limited and shoreline type should be considered when developing comprehensive plans aimed at regulating development of estuarine shorelines.

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