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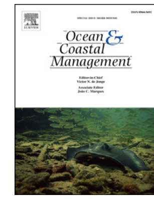

Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane

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ABSTRACT

Acting on the perception that they perform better for longer, most property owners in the United States choose hard engineered structures, such as bulkheads or riprap revetments, to protect estuarine shorelines from erosion. Less intrusive alternatives, specifically marsh plantings with and without sills, have the potential to better sustain marsh habitat and support its ecosystem services, yet their shoreline protection capabilities during storms have not been evaluated. In this study, the performances of alternative shoreline protection approaches during Hurricane Irene (Category 1 storm) were compared by 1) classifying resultant damage to shorelines with different types of shoreline protection in three NC coastal regions after Irene; and 2) quantifying shoreline erosion at marshes with and without sills in one NC region by using repeated measurements of marsh surface elevation and marsh vegetation stem density before and after Irene. In the central Outer Banks, NC, where the strongest sustained winds blew across the longest fetch; Irene damaged 76% of bulkheads surveyed, while no damage to other shoreline protection options was detected. Across marsh sites within 25 km of its landfall, Hurricane Irene had no effect on marsh surface elevations behind sills or along marsh shorelines without sills. Although Irene temporarily reduced marsh vegetation density at sites with and without sills, vegetation recovered to pre-hurricane levels within a year. Storm responses suggest that marshes with and without sills are more durable and may protect shorelines from erosion better than the bulkheads in a Category 1 storm. This study is the first to provide data on the shoreline protection capabilities of marshes with and without sills relative to bulkheads during a substantial storm event, and to articulate a research framework to assist in the development of comprehensive policies for climate change adaptation and sustainable management of estuarine shorelines and resources in U.S. and globally.

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1. Introduction

Global climate change, resulting largely from anthropogenic greenhouse gas emissions, is causing the oceans to expand as waters warm and receive additional freshwater from melting glaciers and ice caps, producing rising sea levels. The global rate of sea-level rise is accelerating (Church et al., 2008), and will likely continue to accelerate as the climate continues to warm (Nicholls and Cazenave, 2010). Sea-level rise will require shoreline ecosystems, such as coastal marshes, either to accrete vertically or to transgress landward to higher elevations to persist. Additionally, climate change may result in an increase in the frequency of intense storm events, particularly hurricanes (Grinsted et al., 2013), and cause significant damage to coastal structures and erosion of shorelines (Thieler and Young, 1991). Coastal marshes act as natural buffers to wave energy and inhibit erosion of coastal lands (Barbier et al., 2008; Meyer and Townsend, 1997; Shepard et al., 2011). Nevertheless, these marshes are at great risk from degradation and loss as sea-level rise and increased storminess interact with coastal development and associated shoreline hardening (Grinsted et al., 2013; Nicholls and Cazenave, 2010; Peterson et al., 2008a,b; Rahmstorf, 2010; Titus et al., 2009).

Shoreline hardening, the installation of man-made shoreline protection structures, is intended to protect coastal property from erosion caused by ambient winds, boat wakes, and storm events (Titus, 1998). On the U.S. Atlantic coast, vertical asbestos, treated wood, composite plastic, or steel bulkheads (Fig. 1A), sloping stone, marl, or concrete riprap revetments (Fig. 1B), or a combination of riprap revetment and bulkhead (referred to as hybrid herein) are constructed at or above the observed high-water mark (OHWM),

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Fig. 1. Photographs of shoreline types: A) a bulkhead: a vertical structure typically constructed of vinyl composite, concrete, asbestos, or treated wood placed at or above the observed high water mark; B) a riprap revetment: a sloped structure typically constructed of granite, marl, or concrete placed at or above OHWM; and C) a sill: a structure typically constructed of granite, marl, or oyster shell, seaward of marsh.

which is typically landward of regularly inundated, coastal marshes (United States Army Corps of Engineers [USACE], 2004). Because of their fixed position relative to coastal marshes, bulkheads and riprap revetments have the potential to inhibit upslope transgression of marshes as sea level rises (Peterson et al., 2008b; Titus, 1988). This may ultimately lead to the loss of coastal marsh habitats and their ecosystem services, including nutrient and pollutant filtration, habitat provision for fishes and crustaceans, and erosion prevention (Peterson et al., 2008a). For coastal policies to be comprehensive in providing storm protection for estuarine land owners, while also preventing or minimizing degradation and loss of coastal habitats, the following scientific and engineering information on each shoreline protection approach is needed and is currently lacking or incomplete: (1) relative shoreline protection capabilities; (2) cost effectiveness; (3) ecological effects; and (4) reversibility and adaptability if the approach results in the eventual violation of applicable laws (e.g., Clean Water Act [CWA]) as sea-level rise threatens to drown tidal marshes (Titus, 1998).

Bulkheads and riprap revetments are the dominant method of shoreline protection in North Carolina and many other coastal states (National Research Council [NRC], 2007). Many property owners assume that bulkheads provide superior shoreline protection from erosion and storm damage compared to other methods (Fear and Currin, 2012; Scyphers et al., 2014). However, studies comparing the shoreline protection provided by marshes and marshes with sills to traditional shoreline protection methods are lacking, particularly during storms (see Shepard et al., 2011). A sill is a shoreline protection structure typically constructed of low-rising granite, marl, or oyster shell placed well below OHWM and 1–2 m seaward of regularly inundated marsh macrophytes (Fig. 1C). Incomplete knowledge of the ecosystem effects and adaptability of each alternative shoreline protection approach has resulted in conflicting permitting policies for shoreline protection among the individual districts of the United States Army Corps of Engineers (USACE) and between states. For example, in North Carolina, bulkheads can be exempt from USACE review, via use of Nationwide Permit (NWP) 13, and are often permitted in fewer than two days by the North Carolina Division of Coastal Management (NC DCM). Sills, because of their position relative to OHWM, are not exempt from USACE review. Hence, permitting in North Carolina can take 30–120 days or longer (NC DCM, 2012). However, the Baltimore, Maryland, USACE District does not recognize NWP 13 and the Maryland Department of Natural Resources (MD DENR) requires that marsh planting with or without sills be used in lieu of bulkheads (Titus et al., 2009). To produce estuarine shoreline protection policies within states and nations that maximize benefits and minimizes losses, new studies are needed that address the relative shoreline protection capabilities, costs, ecological effects, and reversibility and adaptability of various shoreline protection approaches.

The hypothesis that bulkheads, riprap revetments, marshes with sills, and marshes without sills, differ in their ability to protect the shoreline from erosion during a storm event was tested during Hurricane Irene. Coastal North Carolina is a relevant location in which to test this hypothesis because the NC coast has been affected by nearly 100 tropical storms or hurricanes since 1851 and as much as 5900 km^2 of the coastal land in North Carolina is expected to be inundated by 2100 under a projected sea level rise of 1.1 m (NC State Climate Office, 2014; Poulter et al., 2009). Our study included: 1) visual classification of the extent of shoreline damage as a function of shoreline protection type over long extents of the back-barrier shorelines of Bogue Banks and the Outer Banks, NC, immediately after passage of Hurricane Irene; and 2) erosion analysis of marshes with and without sills along Bogue Sound, NC, before and after Hurricane Irene. The resulting shoreline-protection evaluation data represent the first empirical progress within a larger framework of information necessary for developing comprehensive and sustainable coastal management policies for estuarine shorelines.

2. Methods

2.1. Description of study sites

Visually apparent damage to bulkheads, riprap revetments, and marshes with sills was recorded within one month of landfall of Hurricane Irene in North Carolina (Fig. 2A). Landfall occurred at Cape Lookout, NC, on August 27, 2011 as a Category 1 Hurricane, with a sustained wind-speed of 38 m/s. The strongest winds were primarily to the east of the eye over Pamlico Sound and the Outer Banks (Avila and Cangialosi, 2011). Approximately 14 km of back-barrier shoreline on the Outer Banks were surveyed within the towns of Rodanthe, Waves, and Salvo on the north end of Hatteras Island (Fig. 2B), as well as approximately 38 km of shoreline within Frisco and Hatteras Village on the southern end of Hatteras Island, NC (Fig. 2C, D). Hatteras Island is a barrier island approximately 320 km in length, bordered by Pamlico Sound to the west and the Atlantic Ocean to the east. Approximately 25 km of back-barrier estuarine shoreline on Bogue Banks (Fig. 2E) were also surveyed. Bogue Banks is a south-facing barrier island approximately 34 km in length, bordered by Bogue Sound to the north and the Atlantic Ocean to the south and the surveyed shoreline on Bogue Banks is situated within 25 km of the Irene landfall.

To determine if marsh with sills or marshes without sills would protect coastal property from erosion during a storm event, three marshes with sills and three unmodified marshes were evaluated in Pine Knoll Shores, NC, bordering Bogue Sound (Fig. 2E). At each sill site, a sill consisting of piled granite boulders (diameter of 20 cm–50 cm) had been constructed between the years of 2002 and 2007. The elevation of the top of each sill was between 0.14 and