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Storm-driven cyclic beach morphodynamics of a mixed sand and gravel beach along the Mid-Atlantic Coast, USA

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ABSTRACT

The morphodynamics of a mixed sand and gravel beach in Delaware were investigated based on 18 almost monthly beach-profile surveys at 46 locations from 2009 to 2011, 60 sediment cores, and 550 surface sediment samples collected at various alongshore and cross-shore transects. Three different atmospheric disturbances occurred within a 3-month window during the study period: 1) a distal hurricane, 2) an energetic winter storm, and 3) "Nor'Ida", a long-lasting and extremely energetic event resulting from the collision of a hurricane and winter storm. The storm-induced beach changes and post-storm recovery following each of the three storms are evaluated. A distinctive beach cycle was identified consisting of a built-up berm profile and depleted nearly-planar storm profile. The time-scale of the beach cycle relates to the frequency and intensity of storm impact and duration of inter-storm recovery instead of simple seasonality. The initiation of post-storm recovery occurs during the subsiding phase of the storm, attributable to the reduction in wave height and steepness transitioning to accretionary swells. The sediment characteristics of the storm deposit associated with Nor'Ida demonstrated substantial cross-shore variation ranging from sandy-gravel and gravelly-sand within the storm swash zone (near the pre-storm dune edge) to well-sorted medium to coarse sand seaward of the storm swash zone. Storm deposits along mixed sand and gravel beaches demonstrate a variety of sedimentological characteristics. In addition, the studied beaches lacked a sandbar under all wave conditions. A new beach cycle model is proposed for the non-barred mixed sand and gravel beach.

1. Introduction

Understanding beach morphodynamics at myriad temporal and spatial scales is important for both scientific inquiry and beach management practices. Although geographically variable and influenced by regionally-specific geologic and oceanographic processes, site-specific beach change studies at multiple temporal and spatial scales aid in the understanding and generalization of beach morphodynamics (Dean, 1977; Bodge, 1992; Inman et al., 1993; Larson and Kraus, 1994; Larson et al., 1999; Ruggiero et al., 2005). Often, the generalization of beach morphodynamics is placed into the context of beach cycles, typically with a seasonal periodicity. Shepard (1950) and Bascom (1953) were among the first to document different beach profile shapes during the winter and summer seasons. The varying profile shapes are interpreted to be controlled by the generalized seasonality in wave climate. During the winter season, frequent winter storms tend to erode the subaerial beach and transport the sediment offshore, depositing in the form of a sandbar. During the summer season, the frequent swell-type waves tend to move the sandbar onshore, subsequently attaching to and widening the subaerial beach (Komar, 1998).

Numerous studies have been conducted on the morphodynamics of nearshore bars on sandy beaches (Wright and Short, 1984; Kraus and Larson, 1988; Larson et al., 1988; Kraus et al., 1992; Ruessink and Kroon, 1994; Lee et al., 1998; Plant et al., 1999; Morton and Sallenger, 2003). One of the well-documented mechanisms for bar formation is related to high, steep storm waves. The cross-shore profile responds to storms by forming a sandbar from eroded berm sediment or the offshore migration of an already existent sandbar (Holman and Bowen, 1982; Sallenger et al., 1985; Boczar-Karakiewicz and Davidson-Arnott, 1987; Larson and Kraus, 1989; Holman and Sallenger, 1993; Kriebel and Dean, 1993; Gallagher et al., 1998; Hoefel and Elgar, 2003). Hoefel and Elgar (2003) showed one mechanism for offshore sandbar migration is the breaking of large storm waves over the sandbar driving a strong offshore-directed undertow reaching a maximum just over the bar crest. Gallagher et al. (1998) modeled offshore sandbar migration using an energetics-type sediment transport formulation. In the summer season, the common occurrence of long-period swells tends to cause the sandbar to migrate onshore, attach to the beach, and build-up the berm.

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The process of onshore bar migration tends to happen over a period of weeks to months, occurring slower as compared to the often single event-driven (i.e., storm induced) offshore migration (Greenwood, 2005). The process driving onshore bar migration is not as well-quantified as offshore migration.

The above studies were mostly focused on sandy beaches. Although the influence of cross-shore grain size variations on the beach profile is acknowledged, little is known about the morphodynamic influence of the large grain-size variation associated with a mixed sand-gravel (MSG) beach. The morphodynamics of MSG beaches exhibit somewhat different transport mechanisms and morphologic characteristics compared to sandy beaches (Mason and Coates, 2001; Pontee et al., 2004; Horn and Li, 2006; Horn and Walton, 2007; Karunaathna et al., 2012). Due to the permeable nature of gravel-sized sediment, infiltration and interaction with groundwater can influence sediment transport processes on MSG beaches (Turner and Masselink, 1998; Mason and Coates, 2001: Horn and Li, 2006). Depending on the spatial distribution of sediment at varying temporal scales, the content ratio of gravel and sand will also affect sediment transport processes and the resulting morphology (Pontee et al., 2004; Austin and Masselink, 2006; Masselink and Puleo, 2006).

The morphology of MSG beaches tends to vary due to the broad range of processes influencing transport, as well as the large variations of sand/gravel ratio. For example, in New Zealand, the primary morphologic characteristic of a MSG beach was a steep migratory break-point step modulated by tidal water level fluctuations and the absence of an offshore sandbar (Ivamy and Kench, 2006). Horn and Walton (2007) identified another type of MSG beach in the UK, where the reflective upper beach is composed of mixed sand and gravel, with a flat dissipative sandy low-tide terrace. Horn and Walton (2007) examined temporal changes in sand and gravel distribution patterns associated with a beach nourishment consisting of bi-modal sediment. Most of the MSG beach studies focus primarily on the intertidal and supratidal beach regions, whereas corresponding morphology in the direct offshore regions is less well-documented (Carter and Orford, 1993; Jennings and Shulmeister, 2002; Neal et al., 2002).

Morphological and sedimentological impacts of storms have been the topic of numerous studies on sandy beaches, typically along barrier islands (Morton et al., 1994; Forbes et al., 2004; Hill et al., 2004; Stone et al., 2004; Ruggiero et al., 2005; Wang et al., 2006; Claudino-Sales et al., 2008, 2010). Most of these studies focus primarily on large storm-induced cross-shore profile changes with less attention focused on the immediate post-storm recovery (Morton et al., 1994; Stone et al., 2004; Ruggiero et al., 2005; Wang et al., 2006; Houser and Hamilton, 2009). Wang et al. (2006) found that the berm crest elevation and foreshore slope recovered rapidly (within a month) following the impact of Hurricane Ivan along the northwest coast of Florida. Short-term recovery (1–2 years) of the beach width and dune field was minimal. Ruggiero et al. (2005) emphasized the importance of improved understanding of beach behavior associated with storms on multiple scales, including inter-annual (e.g., seasonality), decadal (e.g., El Nino and La Nina cycles), and long-term scales associated with climate change (e.g., sea-level changes). Some studies conducted along MSG beaches have documented morphodynamic responses both similar to and different from sandy beaches (Neal et al., 2002; Pontee et al., 2004; Orford and Anthony, 2011). Pontee et al. (2004) identified that although the profile response to tidal fluctuations, wave conditions, and accretion via ridge welding of MSG beaches is similar to sandy beaches, the morphology of the lower foreshore often differs between the two. Pontee et al. (2004) emphasized that rapid changes in sediment texture and short term variability of profiles in response to storms are different for MSG beaches as compared to sandy beaches.

The morphodynamics and sedimentary characteristics of a MSG beach in Delaware, USA are investigated based on 18 beach profile surveys at 46 locations (total of 740 beach profiles) extending to over 10 m water depth surveyed almost monthly from 2009 to 2011, 550 surface sediment samples, and 60 sediment cores. Three different atmospheric disturbances occurred within a 3-month window during the study period: 1) a distal hurricane, 2) an energetic winter storm, and 3) "Nor'Ida", a long-lasting and extremely energetic event resulting from the collision of a hurricane and winter storm. These energetic events provided a unique opportunity to study the morphodynamics of a MSG beach, including: 1) beach–nearshore profile response to storms with different oceanographic and initial-profile characteristics; 2) sedimentological characteristics of storm deposits; and 3) post-storm recovery. It is hypothesized that selective transport and deposition associated with a wide range in sediment grain size and under various wave energy conditions provide a specific set of morphological and sedimentological characteristics of MSG beaches. Specifically, this study aims at documenting a large range of parameters associated with a MSG beach, including the beach–nearshore profile evolution and associated spatiotemporal scales as well as the horizontal and vertical distribution of sediment characteristics controlled by selective transport under storm and calm-weather conditions.

2. Study area

Delaware is located on the United States mid-Atlantic seaboard (Fig. 1), just south of the southern-most extent of the Laurentide icesheet that covered much of North America 17,000 years ago (Lemcke and Nelson, 2004). Delaware's coastal geology reflects the post-Wisconsinan transgression and glacial outwash that resulted in landward shoreline migration from its location on the edge of the continental shelf 120 km east of the present-day location. The post-glacial transgression resulted in the infilling of valleys with swamp, stream, marsh, and lagoonal deposits, later overlain by nearshore and offshore sediments, and the formation of barrier islands (UDel/DE SGP, 2004). Offshore sediments are primarily composed of fine to coarse sand and sandy gravel to gravel, characteristic of glacial outwash (Ramsey, 1999). Using over 55 years of data from beach sand samples, Ramsey (1999) determined the native composite of sediment in Delaware to be between 1.5 and 0.5 ϕ (0.35 to 0.71 mm) in mean grain size with a standard deviation of 0.5 ϕ, classified as well-sorted medium sand (Wentworth, 1922). Considerable variation in surface and subsurface sediments results from post-transgression sediment reworking, with lagoonal deposits overlain by silt to very coarse sand-gravel in the offshore and fine sand to pebbles in the nearshore (McKenna and Ramsey, 2002). Recent large-scale beach nourishments using sand borrowed from the offshore glacial outwash deposits has resulted in a gradual coarsening of beach sediment, towards a more mixed sand and gravel beach (McKenna and Ramsey, 2002).

The roughly north–south trending 40 km-long Delaware coast is bound to the north by Delaware Bay, terminating as a northward accreting spit known as Cape Henlopen (Fig. 1A). No specific geographic feature bounds Delaware to the south, although the state border terminates at roughly the eastern-most apex of the large broad headland of the Delmarva Peninsula (comprised of Delaware, Maryland, and Virginia) that has been identified as a nodal point in longshore sediment transport (Dalrymple and Mann, 1986; Puleo, 2010). The littoral drift along Delaware is interrupted by the structured Indian River Inlet. Based on sediment volume change on the ebb delta, Lanan and Dalrymple (1977) determined the net northward longshore sediment transport rate at Indian River Inlet to be approximately 100,000 m^3/yr. Based on hindcast wave data, Puleo (2010) estimated the potential net northward longshore sediment transport to be 370,000 m^3/yr. Gross transport rates reportedly vary between 535,000 and 688,000 m^3/yr (USACE, 1996). Large seasonal shifts in Delaware beach morphology occur, with cyclical changes in berm shape and elevation (Dubois, 1988) and shoreline position changes of 75 m (Ozkan-Haller and Brundidge, 2007).

Winds vary seasonally, with prevailing northwesterly winds during the winter and southwesterly winds during the summer. The strongest winds tend to coincide with the passage of winter northeasters (nor'easters), with the easterly component of wind directed onshore.