Geomorphology 199 (2013) 160–170

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Geomorphic and human influence on large-scale coastal change

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ARTICLE INFO

Article history:
Received 20 September 2011
Received in revised form 21 November 2012
Accepted 26 November 2012
Available online 6 December 2012

Keywords:
Coastal erosion
Shoreline change
Human development
Coastal landform

ABSTRACT

An increasing need exists for regional-scale measurements of shoreline change to aid in management and planning decisions over a broad portion of the coast and to inform assessments of coastal vulnerabilities and hazards. A recent dataset of regional shoreline change, covering a large portion of the U.S. East coast (New England and Mid-Atlantic), provides rates of shoreline change over historical (~150 years) and recent (25–30 years) time periods making it ideal for a broad assessment of the regional variation of shoreline change, and the natural and human-induced influences on coastal behavior. The variable coastal landforms of the region provide an opportunity to investigate how specific geomorphic landforms relate to the spatial variability of shoreline change. In addition to natural influences on the rates of change, we examine the effects that development and human modifications to the coastline have on the measurements of regional shoreline change.

Regional variation in the rates of shoreline change is a function of the dominant type and distribution of coastal landform as well as the relative amount of human development. Our results indicate that geomorphology has measurable influence on shoreline change rates. Anthropogenic impacts are found to be greater along the more densely developed and modified portion of the coast where jetties at engineered inlets impound large volumes of sediment resulting in extreme but discrete progradation updrift of jetties. This produces a shift in averaged values of rates that may mask the natural long-term record. Additionally, a strong correlation is found to exist between rates of shoreline change and relative level of human development. Using a geomorphic characterization of the types of coastal landform as a guide for expected relative rates of change, we found that the shoreline appears to be changing naturally only along sparsely developed coasts. Even modest amounts of development influence the rates of change and the human imprint override the geomorphic signal. The study demonstrates that human activities associated with creating and maintaining coastal infrastructure alter the natural behavior of the coast over hundreds of kilometers and time spans greater than a century. This suggests that future assessments of vulnerability, based largely on rates of change along developed coastlines, need to take the role of human alterations into account.

1. Introduction

As the demands for human uses of the coast and nearshore waters compete with coastal habitat preservation, problems facing coastal managers will become more challenging, especially with forecasts of sea level increases over the next century (e.g. Rahmstorf, 2007). To help guide management and policy decision-making, baseline scientific information on the rates and trends of regional-scale coastal change is needed. The U.S. Geological Survey (USGS) has taken the lead on addressing this need by conducting a series of investigations of shoreline change along open-ocean coasts of the U.S.

Few studies of regional-scale (hundreds to thousands of kilometers) shoreline change exist for the U.S. coast. The U.S. Army Corps of Engineers (1971) conducted a national assessment of coastal erosion which identified areas of high erosion, but did not provide rates of shoreline movement. Dolan et al. (1985, 1989) presented a national shoreline assessment based on the compilation of numerous local-scale studies (state, county, city, etc.) which resulted in a broad regional assessment. The rates were derived from a variety of sources using a number of different methods and as a result little consistency exists for comparison of rates or examining trends in a regional or national context. A Federal Emergency Management Agency (FEMA)-sponsored study of erosion (Crowell and Leatherman, 1999) highlighted the variety of approaches being utilized for measuring shoreline change in different parts of the country. In general, the contributions include a county or two in the states that are assessed, and no comprehensive and systematic assessment of regional coastal change or vulnerability was conducted.

USGS regional analyses of shoreline change have been completed for the Gulf of Mexico (Morton et al., 2004), the Southeast Atlantic (Morton and Miller, 2005), California (Hapke et al., 2006; Hapke and Reid, 2007) New England and Mid-Atlantic coasts (Hapke et al., 2011) and Hawaii (Fletcher et al., 2012). These studies are unique to the somewhat ubiquitous analyses of shoreline change, in that they have focused on measuring and presenting rates of change for thousands of kilometers of coastline using systematic and consistent methods. The approach

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0169-555X/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.geomorph.2012.11.025

and methodology developed for this scale of undertaking, especially in the more recent studies in the series (i.e. Hapke et al., 2006, 2011; Fletcher et al., 2012), have broad applicability for regional assessment of coastal vulnerability worldwide, and highlight the high variability of rates of coastal change on spatial scales not previously available.

Variations in historical and recent rates of shoreline change along a given coastline are generally attributed to some interplay of geology, sediment supply and wave climate. These combine to sustain the geomorphic form of the coastline and therefore geomorphology, or type of coastal landform, should be relatable to shoreline change. The association between coastal change and geomorphology has been generally described (May et al., 1983; Dolan et al., 1985; Komar, 1998), but not specifically quantified. This is because rarely does enough variation in the type of landform in the coverage area of more typical studies of shoreline change (ones to tens of kilometers in scale) to make the definitive linkage between rate of change and geomorphic setting. This limitation puts constraints on our understanding of how the response of the coast is linked to antecedent controls.

Another factor controlling rates of coastal change is anthropogenic in nature, associated with the protection of coastal infrastructure and the preservation and maintenance of recreational and natural coastal resources. This issue has been addressed in volumes of the literature (for example Kraus, 1987; Pilkey and Clayton, 1989; Kraus and McDougal, 1996; Pilkey and Dixon, 1996; Hobbs et al., 1999; Nordstrom, 2000; Finkl, 2002; Pstuty and Ofiara, 2002; Park et al., 2009; Slott et al., 2010; and numerous others) and has been at least topically discussed in most assessments of shoreline change for decades. The vast majority of existing studies that evaluate anthropogenic influences on shoreline change variability, however, are confined to spatial and temporal scales of individual beach nourishment projects and the effects of specific engineering structures.

The objective of this study is to gain insight into natural and anthropogenic influences on the behavior of the shoreline on scales of hundreds to over a thousand kilometers. We first provide a synthesis of the USGS regional assessment of shoreline change for one of the most populous coastlines in the U.S. — the New England and Mid-Atlantic region. We then examine how rates of change are influenced by variation in geomorphology by characterizing the coast into four types of coastal landforms. This establishes a relationship between rates of change and geomorphology (specifically coastal landform type) and allows us to explore the variability along coast.

To gain perspective of how human activities can impact assessments of coastal change, we examine the influence of large engineering structures (inlet jetties) on rates of historical and recent changes. We also develop a metric that characterizes the amount of development along the coastline and, along with the geomorphic variable, can be correlated with the regional rates of change. These correlations can help to understand how human activities influence regional patterns of shoreline change and the implications this may have, on interpretation of regional trends of shoreline change and also for understanding how the extent of human modifications to the coastal system may influence future response.

2. Regional setting

The large-scale analysis of shoreline change covers a section of the coast extending from central Maine to the Virginia/North Carolina border (Fig. 1). New England is defined as extending from Maine through Rhode Island, and the northern boundary of the Mid-Atlantic is the eastern tip of Long Island (Fig. 1).

The New England and Mid-Atlantic region is characterized by four types of beaches, each associated with a different type of coastal landform: rocky, bluffed, mainland, and barrier islands. The coastal landforms in New England are highly variable and include rocky headlands, deposits of glaciogenic origin such as moraines and drumlins, and sand and gravel beaches derived from outwash and other glacial deposits (Forbes and Syvitski, 1994). Mixed-sediment beaches comprised of glaciogenic material are dominant along ice-sheet modified coasts such as New England, and generally have a wide range of sediment sizes. Barrier beaches in New England are typically small and discontinuous (FitzGerald et al., 1994; van Heteren et al., 1998).

Rocky and bluffed portions of the New England coast comprise outcroppings of crystalline bedrock and glacial deposits, respectively. Rocky coast beaches are generally pocket beaches, bound by rocky headlands, and occur in areas that lack a substantial source of sediment and sufficient lowland area to migrate or grow as a barrier spit. Beaches that form in front of eroding bluffs are typically sourced from the eroding bluff and tend to be comprised of coarser material that remains after finer sediments are transported away (Kelley, 2004).

In the Mid-Atlantic, the most common coastal landforms are barrier islands and mainland beaches, defined here as a beach which is connected to the mainland by fronting dunes or marsh. A small stretch of bluffs occurs at the eastern end of Long Island. Rocky coast beaches are absent in the Mid-Atlantic.

Coastal change along the New England and Mid-Atlantic coasts is largely driven by tropical and extratropical ("nor'easter") cyclones (Niederoda et al., 1985; Swift et al., 1985; Morton and Sallenger, 2003). Wind-generated waves vary seasonally at a given location and spatially alongshore. Mean wave heights along the Atlantic Coast range from 0.7 to 1.3 m and mean wave periods from 6.4 to 7.4 s (U.S. Army Corps of Engineers, 2006). Extratropical storms generally are less intense (lower sustained winds) than hurricanes but may have a prolonged duration. Hurricanes occur less frequently in New England and the Mid-Atlantic than in the Southeast and Gulf Coasts of the U.S. Hurricanes that never make landfall but that track along the Eastern Seaboard, however, can generate large waves and storm surges that can cause severe erosion over a wide area. The primary source of storm waves along the New England and Mid-Atlantic coast are extratropical cyclones, which can have dramatically varying intensities and durations. Extratropical storms can occur throughout the year but are most frequent during the fall and winter months.

Tides along the New England and Mid-Atlantic coasts are semidiurnal. The range is controlled partly by the width and gradient of the continental shelf and related steepening of the tidal wave as it crosses the shelf (Redfield, 1958; Nummendal et al., 1977; Clarke, 1991). The highest tidal ranges are found where the shelf is wide and has a low gradient. Along the New England and Mid-Atlantic coast, the highest tidal range is along the coast of Maine, adjacent to the location of the widest shelf in the region (Davis and Fitzgerald, 2004). The range decreases southward as the shelf narrows. Tidal range influences beach processes and barrier-island morphologic characteristics because it determines the extent of beach exposure and inundation throughout the tidal cycle.

3. Data and methods

3.1. Shoreline compilation

The shorelines used in the change analysis are from a variety of dates and data sources. The earliest are proxy-based High Water Line (HWL) shorelines derived from historical National Ocean Service Topographic Sheets or T-sheets. Details on the years (and months, where known) of specific shorelines and the spatial coverage are available in Hapke et al. (2011) and Himmelstoss et al. (2011).

The more recent shorelines are datum-based Mean High Water (MHW) shorelines derived from lidar data, based on an operational MHW elevation contour (Weber et al., 2005) extracted from the lidar surveys using a method similar to the one developed by Stockdon et al. (2002). The operational MHW elevation represents an average of MHW elevations from individual open-ocean or near open-ocean tide gauges.

Shorelines are extracted using a regression fit through seaward-sloping foreshore points within 2 m wide cross-shore profiles spaced every 20 m along the coast (see Morton et al., 2004; Morton and