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Lines in the Sand: Geomorphic and Geospatial Characterization and Interpretation of Sandy Shorelines and Beaches

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Abstract

The world's beaches hold an appeal that draws millions of people to live and, each year, millions more to relax and play. However, in the face of this allure fly the strain and consequence of overuse. Increasingly, the imperative to find ways to effectively manage this fragile, finite resource compels science to learn more about this complex, multifaceted system. It is through such understanding that the best hope for effective management lies. In this paper, we look at ways in which researchers study the shore. Specifically, we'll examine this active corner of geomorphology as seen through the lens of the geoscientist, with particular focus on two geomorphic features: the shoreline and the beach. Further emphasis is placed on how investigators have historically, and until today, applied concepts, tools, and methods borrowed from the spatial sciences and, in more recent times, geographic information technologies to the study of the shoreline and the beach. We begin this exploration with a first principal: the definition of shoreline—the boundary where land and water meet. Next, we examine ways in which researchers over the years have worked to generate a suitable shoreline analog or proxy for study. We then follow with a look at how shoreline position is measured—an area where much recent research attention has been placed. Taking matters a step further, we explore the beach, and beach change in three dimensions, looking at how investigators are using geospatial technologies to characterize and analyze change. Finally, we look at various ways in which researchers predict shore and beach changes, by combining spatial analysis and technology with numerical and statistical models.

1. *Introduction*

Highly desirable as places to live, work, and play, coastal areas are equally so vulnerable to storm and flood, changing climate and sea-level rise, erosion and land loss, and multiple stresses imposed by a growing human population. Just how many people actually constitute this growing population has been the subject of some debate for many years (Cohen et al. 1997; Crowell et al. 2007; Crossett et al. 2004; Morrissey, 1988; Vitousek et al. 1997), but most agree that a significant portion (30% to 60% depending on the investigator's chosen definition of a coastal area or zone) of the American population lives close enough to an Atlantic, Pacific, Gulf of Mexico, or Great Lakes shoreline to influence, and be influenced by, the nearby marine/lacustrine environment (Cohen et al. 1997; Crowell et al. 2007; Graham et al. 2003; Vitousek et al. 1997, Edwards 1989). Moreover, if trends and growth estimates are any indication, populations and their attendant human-induced stresses, as well as the risks to those who choose to reside along the nation's coastlines, can only be expected to increase (Crossett et al. 2004; Culliton et al. 1990; Edwards 1989; Morrissey 1988;

Vitousek et al. 1997). The recent (2011) Japanese tsunami underscores this risk to a growing coastal-resident population to devastating effect.

Further, population growth, coupled with climate change, and an associated acceleration in regional and eustatic sea-level rise (Gutierrez et al. 2007; Intergovernmental Panel on Climate Change 2007) are expected to exacerbate risk for the world's coastal areas and their attendant human tenants. Seventy percent of the world's coastlines are already experiencing net long-term erosion (Bird 1996). If sea levels continue their ascent as predicted, the future US coastline and the whole of the US coastal zone will look much different in 25, 50, or 100 years than it does today (Riggs et al. 2011). However, in no other quarter will these changes be felt more than within the human communities that have elected, or will elect, to reside and/or place their livelihoods into the hands of these rapidly and continually changing environments. Recognizing the coastal zone's importance to society has both motivated science and driven management decisions for decades (Bartlett, in Wright and Bartlett 2000). No more so important will this motivation be than to develop viable land use and management plans to ensure a future where man and shore and sea can coexist in relative harmony. Yet, in contrast to the growing pressure being placed on the world's beaches and adjacent coastal lands, in the USA, as well as across the globe, we are not yet in a position to craft such plans. Humankind still has much to learn about these complex, dynamic environments.

In this article, we examine only a portion of the broad expanse of scientific inquiry and experiment that has gone into the study of the shoreline and beach over the past century. The focus here is purposely slanted toward the geospatial aspects of these investigations—but not entirely so. Historic work [that predating incorporation of explicit geospatial analysis tools and methods such as those found in today's digital computer-based geographic information systems (GIS)] may or may not be considered to fall under the quantitative geospatial analysis umbrella as we know it today (where we readily apply tools such as GIS in our research efforts). Its inclusion, however, is important here, for the historic work lays the groundwork for this modern work. Much emphasis is placed on the growing contributions made by GIS to beach and shoreline research. The GIS, with its wide-ranging assortment of geospatial analysis tools, robust data integration, and advanced two-dimensional (2-D) and three-dimensional (3-D) visualization systems presents an expedient environment for characterization and modeling. Moreover, the technology offers one of the more promising aides to investigators attempting to unravel some of the complexity, from the perspective of pure scientific investigation, as well as practical application, associated with these dynamic environments (Longhorn 2003).

Emphasis here is restricted to sandy ocean and lake beaches and their attendant shorelines: defining and locating these two entities within the landscape and characterizing and modeling their variations in space and through time. Marsh, mangrove, shingle, and rocky shorelines, and cliffed (naturally and/or engineered) coasts, sit beyond the scope of the present paper.

2. *The Shoreline*

2.1. DEFINING THE SHORELINE

A shoreline can be defined simply as the line delineating the location where the land meets, or intersects, a body of water. It is a simple definition. It is also one that is found in abundance within the geoscience literature (Boak and Turner 2005; Di et al. 2003; Dolan and Hayden 1983; Farris and List 2007; Gill and Schultz 2001; Graham et al. 2003; Lam and Qiu 1992; Li et al. 2002; Pajak and Leatherman 2002; Parker 2003; Shalowitz and Reed 1964). Some investigators consider the shoreline, based solely on this simple land/water interface definition, more specifically to be an instantaneous shoreline—the shoreline position marked at one instance in time (List and Farris 1999; Li et al. 2002). The instantaneous shoreline is perhaps useful qualitatively, but its value in quantitative analysis and mapping is limited (Li et al. 2002). Boak and Turner (2005) go further to state that it is incorrect, perhaps significantly so, to assume that an instantaneous shoreline will represent an average condition. Shorelines appropriate for rigorous quantitative assessment and analysis, rather, must be tied to a suitable reference frame (Boak and Turner 2005; Li et al. 2002). Typically, the reference frame selected is a readily defined and field-discernible one such as the older high-water line (HWL), or more recently tidal data such as mean low water or mean high water (MHW) (Graham et al. 2003; Li et al. 2002; Parker 2003).

When the first US shoreline survey was conducted in the early 19th century, the nascent US Coast Survey turned to the HWL as the shoreline reference for mapping and charting (Shalowitz and Reed 1964). Coastal mapping and charting during that period, which spanned the early 20th century, relied on in-the-field observation and plane table surveys (Li et al. 2002; Shalowitz and Reed 1964). The most consistently detectable and measurable shoreline indicator along the beach during that period was the HWL (Crowell et al. 1991; Morton et al. 2005; Shalowitz and Reed 1964). The HWL is qualitatively defined to be "the landward-most extent of the last high tide"—that is to say, it marks the location on the beach of the landward-most advance of the last high tide that occurred prior to conducting the survey. It is also sometimes interpreted to represent the seasonal or annual mean shoreline position for the region under study (Dolan et al. 1980; Smith and Zarillo 1990). It has been associated with strand or wrack lines, vegetation boundaries, dunes or scarps, or other artifacts on the beach surface (Leatherman 2003; Li et al. 2002). It is, however, most often identified by a change in tonal gradation of the sand along a line (often referred to as the wet/dry line) that demarcates the terminus of the previous high tide (Crowell et al. 1991; Dolan and Hayden 1983; Moore 2000). The wetted sand within that last high-tide zone is typically darker, as compared to the drier and lighter-toned sands found landward along the back beach. This wet/dry line, as seen through direct observation on the ground and, later, on aerial photographs, was considered to be the HWL (Anders and Byrnes 1991; Crowell et al. 1991; Li et al. 2002; Shalowitz and Reed 1964). The HWL wet/dry proxy is reestablished with each tidal cycle (Dolan and Hayden 1983). Today's National Oceanic and Atmospheric Administration's (NOAA's) National Geodetic Survey—the modern counterpart to the original Coast Survey—along with its sister Nautical Charting Division, has been mapping the US Coastline (including the Great Lakes) since the mid-19th century. Until recently, these manuscripts referenced the shoreline to the (field-approximated) HWL (Anders and Byrnes 1991; Crowell et al. 1991; Graham et al., 2003). The HWL remains one of the most commonly used indicators of shoreline position (Boak and Turner 2005; Leatherman 2003; Moore 2000; Moore et al. 2006; Smith and Zarillo 1990).

Dolan and Hayden (1983) and Dolan et al. (1980) investigated the reliability of the wet/dry line as representing the HWL on sandy mid-Atlantic Ocean beaches and found it to be a stable proxy for HWL shoreline determination. Displacement of the HWL mark as identified by the wet/dry sand line interface was measured at less than 1 m over the course of a single tidal cycle along shallow sloping Virginia and North Carolina beaches (Dolan et al. 1980). Crowell et al. (1991) also found the HWL indicator to be stable as well as easy to locate both on the ground and as interpreted from aerial photography.

Other investigators, however, argue that the HWL is a highly variable and often unreliable indicator of shoreline position. Zhang et al. (2002), for instance, observed the HWL position along beaches in Duck, North Carolina, and concluded that the seasonal variability from winter to summer was so high that the HWLs collected were considered to be useless for long-term shoreline trend analysis. Moore (2000) also noted significant seasonal variability in the HWL position, as did Honeycutt et al. (2001) along Delaware beaches and Smith and Zarillo (1990) on Long Island—the latter two both noting 5- to 20-m seasonal displacements in HWL. Boak and Turner (2005) further state that, because of the HWL's reliance on meteorological, tidal, and morphodynamic factors, the indicator might not accurately represent the assumed previous high tide's reach up the beach. They go on to point out that these factors can, working individually or in concert, force the HWL to vary on the order of tens of meters in position on the beach. The influence imparted by local wave conditions can have as much impact on HWL position as the local tide (Parker, 2003). Further, interpretation error, especially when the wet/dry demarcation is being identified from aerial photography, can introduce error in the HWL position, and this error can be difficult to quantify (Boak and Turner 2005; Moore 2000; Pajak and Leatherman 2002; Stockdon et al. 2002). During the fall, winter, and early spring seasons, when weather conditions tend to be stormy, the HWL can be particularly difficult to identify (Pajak and Leatherman 2002; Parker 2003; Zhang et al. 2002). Moreover, under rainy conditions, the wet/dry tonal distinction representing the HWL's visual demarcation can be reduced or even erased (Shoshany and Degani 1992). Stormy weather can shift the HWL as much as 100 m (Moore 2000). One means to reduce HWL position errors requires aerial photos captured only during late summer—those that avoid post-storm conditions (Moore 2000). Another option is to abandon the HWL all together for another, more reliable datum.

The shoreline reference that has stepped in to replace the HWL for modern high-resolution shoreline mapping is the tidally based local MHW tidal datum (Morton et al. 2005; Parker et al. 2003). The MHW datum, shown schematically relative to other tidal data in Figure 1, is defined as the average value for all high tides as measured at a given tide recording station for the period spanning a single National Tidal Datum Epoch—an

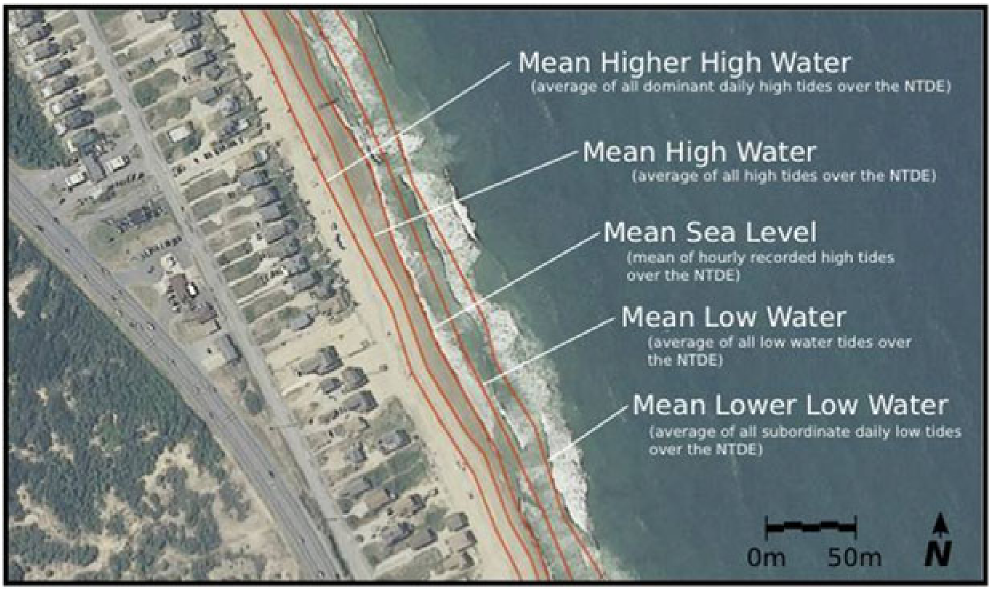


Fig. 1. Schematic representation of most common tidal data defined and recognized by the National Ocean and Atmospheric Administration for use in navigation charting and for explicit definition of the USA's MHW shore line (Woolard et al. 2003). Photography courtesy of the US Department of Agriculture, Farm Service Agency, Aerial Photography Field Office—National Aerial Imagery Program (NAIP 2009). http://www.apfo.usda.gov/FSA.

NOAA-specified 18.6-year period (Brisco 1983; Crowell et al. 1991; Hess 2003; Hicks, 1985; NOAA Office of Coast Survey, 1995; Parker 2003). The epoch defines a period that takes into consideration select variations in the Earth's and Moon's orbital dynamics, variations that influence tidal high and low water levels (Morton and Speed 1998; Parker 2003). The tidal water MHW shoreline is defined as the intersection of the water surface with the land where the water level is at an elevation equal to the elevation of the MHW datum (Hicks 1985; NOAA Office of Coast Survey, 1995). MHW reduces or removes the interpretation errors associated with ground-based or aerial photography HWL determination (Moore et al. 2006).

The HWL reference has not been entirely abandoned for MHW, however, for there exists a wealth of historic data in the form of ground surveys, maps, and charts whose shoreline positions are based on this datum. Further, little of the older aerial photography is tide coordinated (flown precisely at some known stage of the local tide), making it difficult to link the interpreted wet/dry line seen on the photograph with a specific tidal datum such as MHW (Dolan et al. 1991; Liu et al. 2007; Pajak and Leatherman 2002). The MHW shoreline is almost always found lower down the beach (to seaward) than the interpreted HWL, a distance which can approach 50 m on gently sloping beaches with high wave run-up (Moore et al. 2006; Ruggiero et al. 2003). This complicates matters when comparisons are necessary, for the offset is not always obvious or easy to ascertain (Moore et al. 2006). Nevertheless, when investigators incorporate older, HWL-based data sources into their current research, the differences between HWL and MHW must be quantified and appropriate adjustments applied if the results are to be valid (Ruggiero et al. 2003).

In the USA, the individual coastal states have legal authority to determine their own shoreline. These are used to define property ownership, usage rights, and other associated concerns (Brisco 1983; Graham et al. 2003; Hicks 1985). Most of these shorelines are referenced to one of NOAA's tidal data (Brisco 1983; Hicks 1985; Graham et al. 2003; Li et al. 2002). For the US overall, the NOAA has the mandate to establish the national shoreline (Parker 2003), and this is a tidal datum (MHW) and its associated MHW shoreline that define this national shoreline that separates the land and sea on NOAA charting products (Graham et al. 2003; Parker 2003; Woolard et al. 2003).

Formal definitions and descriptions aside, our ability to define, and ultimately locate, the shoreline with reasonable accuracy and precision at any given time is important if we're to interpret the past and, more importantly, develop spatial models that extrapolate accurate and reliable positions into the future. Over the last few decades, much effort has been directed toward collecting the data and developing the technologies necessary to identify and reliably extract from that data a viable shoreline, or suitable representative proxy—one that is both geographically (positionally) accurate and readily, and repeatedly, extracted (Boak and Turner 2005 and Figure 2).

2.2. LOCATING THE SHORELINE

Numerous studies (e.g., Anfuso and Martinez Del Pozo 2008; Bartlett et al. 1997; Cleary et al. 2001; Dar and Dar 2009; Gares et al. 2006; Gilman et al. 2007; Hapke et al. 2004; Karpilo and Sadd 2001; Langley et al. 2003; Martínez del Pozo and Anfuso 2009; Moore and Griggs 2002; Moran 2003; Rodríguez et al. 2009; Shaw and Allen 1995; Zhang 2000; Zink 2002), describing a process to capture shoreline positions into a GIS, that begins with one or more historic maps or aerial photographs exist. The shoreline from map sources is readily available. The cartographer has already made a determination as to where the shoreline was to be located; all that remains for the investigator to do is to digitize the line directly from the document and georeference the digitized data for use in GIS. The principal

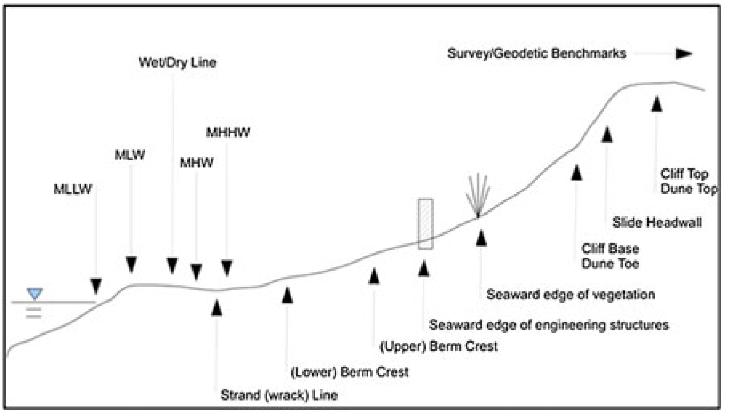


Fig. 2. Some of the many shoreline proxies and baselines employed by investigators in studying coastal change. Note that the positions of proxies portrayed in this cartoon are not meant to imply that all such features will be found on all beaches, nor should the reader assume that the relative positions are the only possible juxtaposition. For instance, engineered structures can occur on the beach, offshore, or not be present at all. Vegetation can occur seaward and/ or landward of the dune or be absent altogether. Wrack lines and debris may not be present. Dunes may or may not be present, be smaller, and be less well defined or be found farther inland relative to the shoreline than is shown here. The berm surface may also occur without a crest during stormy conditions. Adapted from information in Boak and Turner (2005).

challenge presented by these older maps and charts today, however, is in association with the undocumented and/or unquantifiable surveying and cartographic errors that surround locating the HWL (Crowell et al. 1991; Moore 2000; Shalowitz and Reed 1964). For many 19th and early 20th century manuscripts, the error attendant with HWL survey interpolation can potentially be large (Shalowitz and Reed 1964). Moreover, physical manuscript damage due to handling and age, obsolete mapping data/ellipsoids, cartographic mistakes, and the approximate methods sometimes employed to compile the mapped shoreline data are other sources and contributors to the overall error tied to the mapped HWL shoreline (Crowell et al. 1991; Shalowitz and Reed 1964). Shalowitz and Reed (1964) discuss shoreline position accuracy found on early Coast and Geodetic Survey T-sheet manuscripts, stating that in spite of the dearth of accuracy standards in play at the time (mid-19th to early 20th centuries) much care was taken to ensure that the derived HWL shoreline survey was conducted with as much accuracy as was feasible. Shalowitz and Reed (1964) go on to estimate that shoreline positional errors reflected on the highest-resolution sheets (1:5000 scale) likely do not exceed 3 to 4 m. As part of NOAA's T-sheet rescue project, an effort aimed at digitizing historical T-sheets, Daniels and Huxford (2001) reported that T-sheets for the Oregon and Washington coasts exhibited errors on the order of ±3 m for 1:10,000 sheets and ±6 m at 1:20,000 scale, both exceeding the National Map Accuracy standards by a large degree. There are others, however, who report that T-sheet error magnitudes may approach 20 m for smaller-scale (1:40,000) manuscripts (Crowell et al. 1991).

The capture of shorelines from aerial photographs is less straightforward than that from map sources. With photography, it is left to the investigator to make a judgement as to what visible feature on the image should represent the shoreline. This freedom of judgement does, however, leaves the investigator with greater control over the conversion than if presented with extant mapped data. Historically, the common demarcation has been the HWL (Boak and Turner 2005; Crowell et al. 1991; Dolan et al. 1978; Leatherman 2003; Moore 2000; Moore et al. 2006; Shoshany and Degani 1992; Smith and Zarillo 1990; Stockdon et al. 2002). As discussed in Section 2.1, the HWL (Figure 3) is qualitatively defined to be the

Fig. 3. The visually identified wet/dry line along shore, as seen here, is a commonly employed shoreline reference. Coupled with tide-coordinated aerial photography, the line is considered to be a good surrogate for the tidal high-water line (HWL) shoreline (Dolan et al. 1978). Photography courtesy of the US Department of Agriculture, Farm Service Agency, Aerial Photography Field Office—National Aerial Imagery Program (NAIP 2009). http://www.apfo.usda.gov/FSA.

landward reach of the last high tide as marked by the change in tonal gradation (wet/dry line) terminating the high-tide swash zone as depicted on an aerial photo (Anders and Byrnes 1991; Crowell et al. 1991; Shalowitz and Reed, 1964). The HWL satisfies the criteria proposed by Dolan et al. (1978) as a suitable shoreline proxy, though, as was also pointed out in Section 2.1, the proxy has its detractors, who question, in whole or part, its fidelity in representing a mean or HWL shoreline (Boak and Turner 2005; Honeycutt et al. 2001; Moore 2000; Pajak and Leatherman 2002; Parker 2003; Smith and Zarillo 1990; Stockdon et al. 2002; Zhang et al. 2002). Dolan et al. (1983) report a typical error for aerial photographs to be approximately 2.5 m.

Through aerial photography, the shoreline position can also be extracted photogrammetrically using GIS or specific-purpose photogrammetric software (Figure 4a). In fact, photogrammetry is currently the most common method for extracting shoreline positions from aerial photo products (Li et al. 2003). From the associated stereo-elevation model, an elevation contour is selected as the representative shoreline, identified on the model, and extracted (Judge and Overton 2001; Stockdon et al. 2002). This approach eliminates some of the subjectivity associated with visual (e.g., tonal gradation/wet–dry lines) shoreline identification. Moreover, the elevation selected can be based on one of the established orthometric, elliptical, or tidal data, a geomorphic feature, an engineered structure, or other identifiable entity as deemed appropriate by the investigator (Boak and Turner 2005). Though more costly, aerial photographs can also be tide coordinated—the photo is captured during a particular period in the tidal cycle (e.g., MHW) (Li et al. 2003).

Satellite and aircraft-based active sensor technologies such as the Earth observation satellites IKONOS and QuickBird, radar, and lidar present other options for extraction of the shoreline using a GIS (Campbell 2007; Dellepiane et al. 2004; Di et al. 2003; Gares et al. 2006; Geological

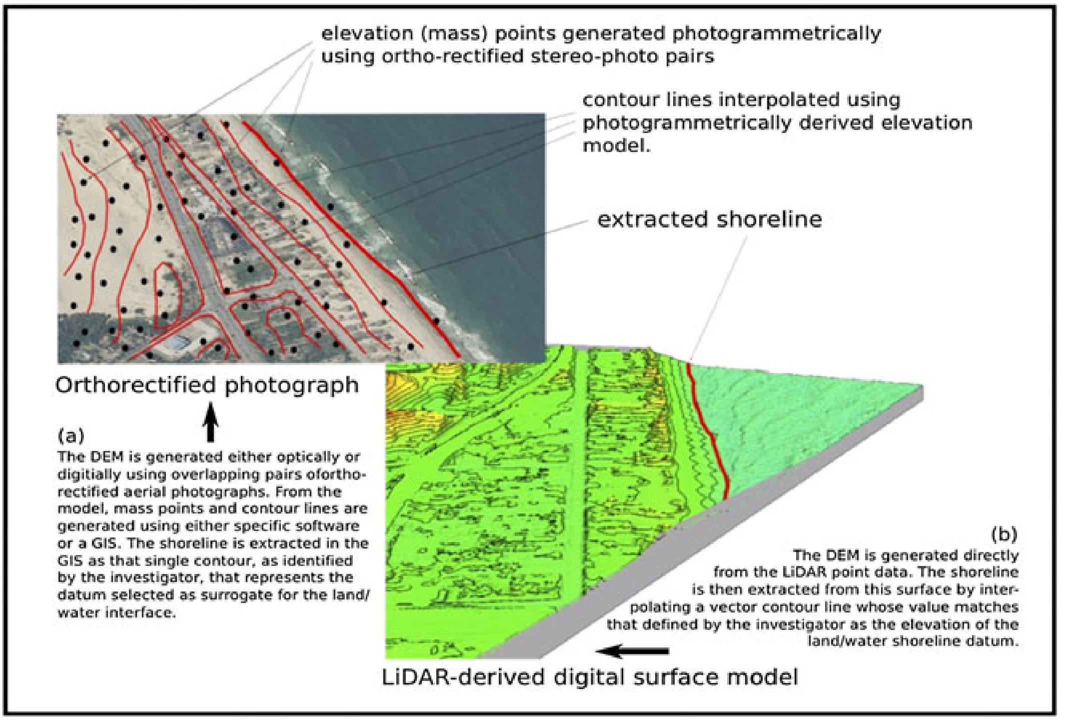


Fig. 4. The shoreline contour along the beach as extracted using optical or digital photogrammetric techniques and orthorectified aerial photography (a) and contour interpolation from a LiDAR-derived elevation surface (b). Both methods rely on finding the position of a contour line on the original DEM that (best) meets the investigator's specified shoreline definition criteria. Photography courtesy of the US Department of Agriculture, Farm Service Agency, Aerial Photography Field Office—National Aerial Imagery Program (NAIP 2009). http://www.apfo.usda.gov/FSA. GIS, geographic information system.

Survey 2007; Liu et al. 2007; Mitasova et al. 2002, 2003, 2004, 2009b; Moore 2000; Rodríguez et al. 2009; Sallenger et al. 2003 Schwaebisch et al. 1997; Shu et al. 2010; Stockdon et al. 2002; Woolard et al. 2003; Zhang et al. 2005). Di et al. (2003) developed a rational function model that coupled GIS and GPS with IKONOS imagery to semiautomatically extract shorelines along the US Great Lakes. Li et al. (2002, 2003) used GIS to develop methods for extracting a tide-coordinated (MHW) shoreline using IKONOS imagery for a section of the Ohio coast along Lake Erie. Horizontal accuracies associated with the results were estimated at 2 to 4 m (Li et al. 2003; Zhou and Li 2000).

Though less frequently employed in the past, due in part to higher costs, low noise rejection, and lower resolution (2.5 to 25 m) (Boak and Turner 2005; Cracknell 1999; Graham et al. 2003) relative to other active sensors such as lidar, radar is also a potential source for shoreline extraction (Figure 4b) and demarcation (Dellepiane et al. 2004; Niedermeier et al. 2000; Schwaebisch et al. 1997; Shu et al. 2010; Takewaka 2005). Radar is sensitive to the stability of the surface upon which it interacts (Schwaebisch et al. 1997). The wave phasing, or coherence, associated with the reflected return signal from an interferometric synthetic aperture radar is effective at discriminating land and water (Dellepiane et al. 2004). This difference is exploited to isolate land and water, from which a shoreline can be derived. NOAA is exploring radar (2.5-m interferometric synthetic aperture radar) as a potential means for remote-area shoreline mapping in Alaska (Graham et al. 2003).

Lidar generates spatially dense datasets using a pulsed laser to bounce light off ground surface features. This reflected light signal is captured and used to generate a surface model of those features. The high-density data collected by the lidar system makes possible the generation of high-resolution topographic surface models more in accord with actual ground morphology than similar surface/elevation models based on photogrammetric interpretation (Cracknell and Hayes 2007). By using a lidar-based digital elevation model (DEM), a shoreline can be identified and extracted by first locating the elevation contour whose *z*-value matches a specified sea-level (orthometric) height or tidally derived datum (Figure 4b). One such technique is described in Figure 5.

Ground-based systems such as land surveyor tools (e.g., theodolites, electronic distance-measuring equipment, and total stations), handheld and vehicle-mounted real-time kinematic (RTK) GPS, still and video cameras, and terrestrial laser scanners are also employed to locate and capture the shoreline (Aarninkhof et al. 1997, 2003; Baptista et al. 2008; Davidson et al. 1997; Dolan et al. 1983; Ingham 1992; Madsen and Plant 2001; Pajak and Leatherman 2002; Pearre 2006; Pearre and Puleo 2009; Pietro et al. 2008; Plant and Holman 1997; Shaw and Allen 1995). Though limited in range relative to airborne and satellite-platformed systems, for smaller surveys, these technologies are a means toward shoreline

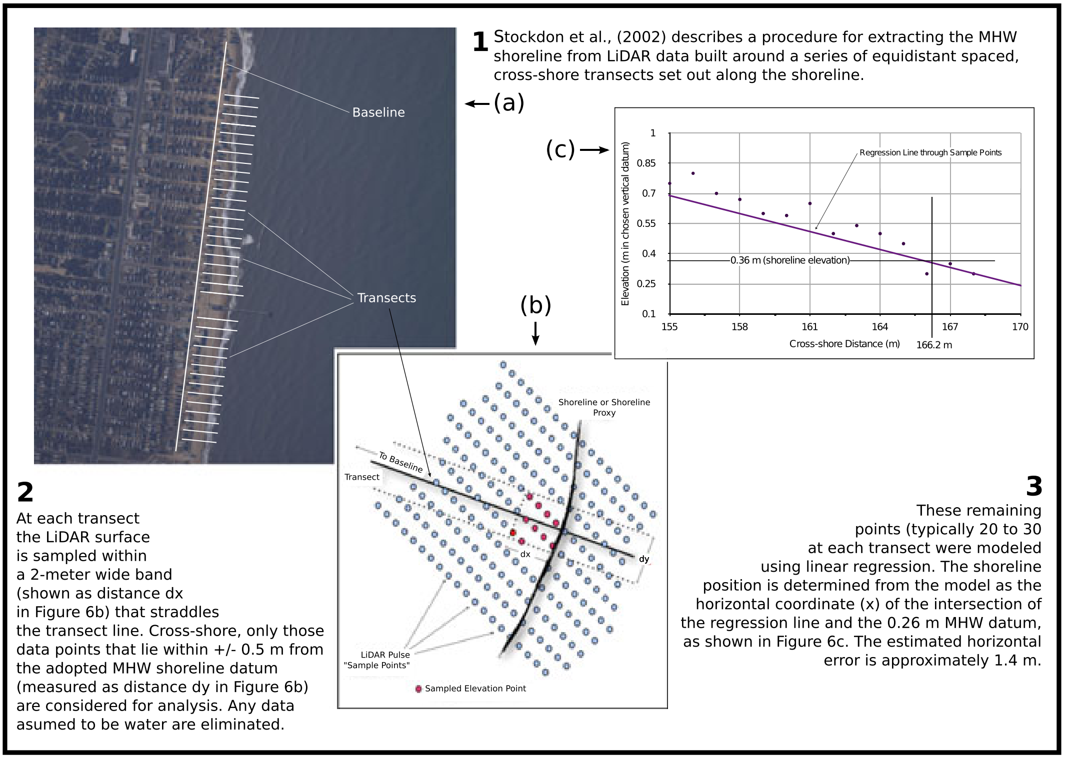


Fig. 5. A process for extracting the MHW shoreline based on methods proposed by Stockdon et al. (2003), where transects are draped across a digital elevation model (DEM) surface (a). At each transect site, a selection of elevation values are captured from the position inside or out of a defined sampling region (b). Stockdon et al. (2002) defined the distance d*x* as spanning the ±0.5-m contours, and d*y* as 1 m alongshore on each side of the transect profile. The elevation points from the sampled DEM that fall in the region defined by d*x* – d*y* are then plotted against their cross-shore positions and a linear regression fit to the data (c). The shoreline crossing along that transect is next extracted as the intersection of the NOAA-defined local MHW (0.26 m off of NAVD88) and that regression line.

mapping. GPS, in particular, is enjoying broad application in its use for shoreline and beach surveys in the USA (Baptista et al. 2008; Boak and Turner 2005; Freeman et al. 2004; Lentz and Hapke 2011; Morton et al. 1993; Pajak and Leatherman 2002), as are video-image-based systems (Aarninkhof et al. 1997, 2003; Davidson et al. 1997; Madsen and Plant 2001; Pearre 2006; Pearre and Puleo 2009; Plant and Holman 1997). With GPS, the shoreline is often captured by mounting the device on an all-terrain vehicle and driving this vehicle along the wet/dry line or other visible shoreline proxy (Baptista et al. 2008; Morton et al. 1993) with shoreline position coordinates captured automatically along the way. RTK-GPS accuracy is such that the greatest survey errors originate not from the GPS device itself, but from the operator's tracking of the visible shoreline proxy on the ground (Morton and Speed 1998; Morton et al. 1993; Pajak and Leatherman 2002). GPS also supplies the horizontal positions (x and y) in space for radar and lidar surveys (Boak and Turner 2005; Lentz and Hapke 2011).

Prior to aerial photography's advent in the 1920s for use in shoreline delineation and mapping (Graham et al. 2003), plane table surveys were the principal means used by the Coast and Geodetic Survey surveyors to locate and capture the HWL shoreline (Graham et al. 2003; Parker 2003; Shalowitz and Reed 1964). Today, ground-level studies using land surveyor tools and techniques continue to offer the most accurate survey results attainable—0.01 m or better accuracy is typical—however, the costs rise quickly in accord with the survey's geographic extent (Dolan et al. 1983). For larger survey areas, the time required and high man-hour costs make ground surveys cost prohibitive (Baptista et al. 2008; Dolan et al. 1983).

2.3. MEASURING SHORELINE CHANGE

Shoreline position changes through time are often determined by juxtaposing a series of historic shorelines, measuring the distances between adjacent pairs and dividing these distances by the difference in time represented by the pair (Dolan et al. 1978). Such measurements are often made at discrete locations using a series of equidistant-spaced, cross-shore transects (Figure 6). Spacing varies depending upon the scope and purpose of the paper, available resources, and the experimental design (Dolan et al. 1991, Phillips 1985). Transects typically extend out perpendicular to the shore, from an established shore-parallel baseline or other similar reference. The shoreline position is located on that point where the land/water interface, or its proxy, as defined by the investigator, intersects the transect. The position is recorded as that distance measured along the transect out from the established baseline to the intersection point.

The GIS offers investigators options for detecting, tracking, and assessing shoreline change. GIS editing and analysis environments are amply robust to support data capture from many analog and digital sources. Further, source data can be rectified and georeferenced, measured (linear, areal, and volume metrics) on a single layer or across multiple data layers, and analyzed in space and through time. As a step further, researchers have now developed automated software systems such as the US Geological Survey's Digital Shoreline Assessment System (DSAS) within and around existing GIS software that streamline the shoreline position, change analysis, and tracking process (US Geological Survey, 2007).

In compiling a nationwide clearinghouse for recordation and dissemination of erosion/accretion rates for all of the conterminous US sandy ocean shorelines, the US Geological Survey has assembled the National Assessment of Shoreline Change. The National Assessment of Shoreline Change is built around the agency's GIS-based DSAS (Thieler et al. 2003, 2009), a collective of tools and services specifically designed to process and record shoreline erosion rates. To locate and extract the digital shorelines compiled in the database, the US Geological Survey

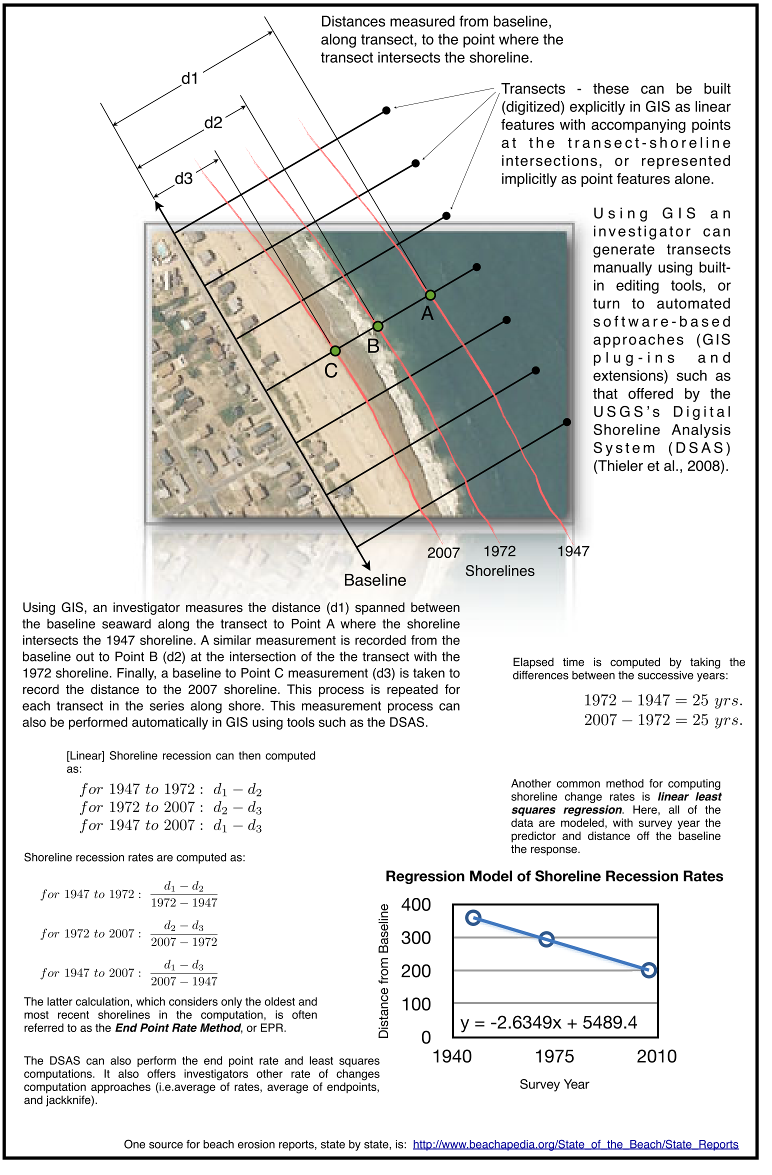


Fig. 6. Some common methods for detecting and quantifying shoreline change and rates of change. Photography courtesy of the US Department of Agriculture, Farm Service Agency, Aerial Photography Field Office—National Aerial Imagery Program (NAIP 2009). http://www.apfo.usda.gov/FSA

has adopted the method described by Stockdon et al. (2002). The DSAS uses both the end point rate and linear regression methods to compute change rates for the database.

In addition to the US Geological Survey's DSAS, other systems have been developed, both around GIS and other analysis toolsets for shoreline extraction, inventory, monitoring, and analysis. One example is BeachTools (Hoeke et al. 2001; Zarillo et al. 2008). BeachTools was developed by the US Army Corps of Engineers (as an ArcGIS ArcView 3.x/9.x extension) to aid with shoreline extractions from aerial photographs. Another toolset, this one built around the open-source R Environment for Statistical Computing system

(R Core Team, 2012), is Analyzing Moving Boundaries Using R (AMBUR) (Jackson et al. 2012). AMBUR was developed by researchers at three Georgia universities and the Skidaway Oceanographic Institute to inventory and monitor shoreline positions and displacement rates and forecast shoreline change. AMBUR is unique for its lack of dependence on GIS but instead leverages R's large statistical and spatial library collection.

Most recently, Olsen et al. (2012) introduced the Topographical Compartment Analysis Tool. The Topographical Compartment Analysis Tool is designed around a GIS (Economic and Social Research Institute's ArcGIS) with a purpose to provide statistical and other quantitative analytical tools for quantifying and analyzing linear geomorphic features. Such features include unconsolidated, sandy shores, for which the tools are particularly well suited.

Numerous examples to illustrate the use of the baseline/transect and various other methods for capturing shoreline positions into a GIS and/or in using GIS for subsequent change analysis can be found. Martínez del Pozo and Anfuso (2008) examined 32 years of GIS "integrated" historic maps and aerial photos covering 60 km of Sicilian coastline, to identify shoreline change and assess the contribution of local shoreline engineering (groins, breakwaters, and re-nourishment) to that change. Langley et al. (2003) digitized and georeferenced a series of National Ocean Service T-Sheets into GIS and computed a historical average erosion rate for Georgia's Wassaw and St. Catherine's Islands. Comparable studies examined shoreline recession along the Yellow River Delta in China (Zhang 2000), the shoreline at Point Mugu Naval Air Station in California (Karpilo and Sadd 2001), and coastal terraces on the big island of Hawaii (Hapke et al. 2004), shoreline geomorphology along India's Rameswaram Island (Nobi et al. 2010), Lake Erie lakeshore mapping (Di et al. 2003; Li et al. 2001), US Gulf Coast regional shoreline changes (Morton et al. 2005), mapping shoreline position along the North and South Carolina coasts (Robertson et al., 2004), historic shorelines, shoreline change, the role of antecedent geology on change (Harris et al. 2003), and the shoreline metric mapping method (Leatherman 2003). Cleary et al. (2001) used shorelines extracted from aerial photography, with GIS, to characterize the migration of Rich Inlet along the North Carolina coast. Rodríguez et al. (2009), working along the Catalonian Ebro Delta, computed shoreline change and constructed a companion GIS-based assessment of coastal risk. Dar and Dar (2009) used GIS to compute historic shoreline change for the Chennai Coast in southeast India.

3. The Beach

3.1. DEFINING THE BEACH

Most of the studies thus far discussed have considered the shoreline only, a one-dimensional (1-D) feature, a line that exists in planform only—literally, a line drawn in the sand. Migration over time is described solely as the line's translation in position, landward or seaward, across a horizontal plane. The shoreline is, however, only a part of a larger dynamic system, one that exists not in one or even two dimensions, but three. This added dimension leads us to consider volumetric changes and the concept of the landward subaerial beach and dunes, and its adjacent subaqueous counterpart, the shoreface, as geomorphic provinces that encompass not only the 1-D shoreline but also a much larger volume of sedimentary materials to both landward and seaward. The shoreface, which will not be discussed in this article, extends from the low-water line seaward to that point beyond the surf zone where slopes transition onto the continental shelf (US Army Corps of Engineers 2008). The beach, whose province is central to this discussion, is defined as that area from the low-water line inland to the reach of storm wave effects (US Army Corps of Engineers 2008). Changes through time in these zones can be better characterized as bulk redistributions of sediments. Thus, we are no longer just considering changes in shoreline position across the plane, but instead, changes in sedimentary distributions through 3-D space.

3.2. MEASURING, CHARACTERIZING, AND ANALYZING THE BEACH

Volumetric approaches that rely on empirical relationships between planform beach width/area and volume exist (Miller and Fletcher 2003; Norcross et al. 2002; Robertson et al. 2007) and have met with limited success but are not widely embraced as the results produced are considered to be inferior to those generated using other sources (Gares et al. 2006; Pietro et al. 2008). Instead, 3-D topographic models—DEMs—are often employed to evaluate volume and surface character. Such representations have been assembled within GIS using data from on-ground surveys, air-photo-derived DEMs, and more recently lidar (Gares et al. 2006).

For short-term, small-geographic-area surveys, ground-based methods employing land surveying tools and methods can be used effectively to capture and quantify volume-oriented beach and shoreface change (Dolan et al. 1978; Smith and Zarillo 1990). By using total station instruments and/or GPS, data can be collected along fixed transects or at randomized positions. RTK-GPS systems in particular are playing an increasingly greater role in these studies. By using GIS, profiles or elevation surface models can then be generated for analysis (Andrews et al. 2002). Ground surveys can also play a supporting role in beach, shoreline, and shoreface studies involving remotely sensed data (Mitasova et al. 2003). The high relative accuracy of survey instrument (e.g., total station) in ground surveys, moreover, offer the investigator a means to detect and rectify error in aerial photography, lidar, and GPS-captured data (Mitasova et al. 2003; Ojeda Zújar et al. 2002). Though mitigated somewhat by mobile GPS systems, the principal disadvantage to the ground-based approach remains their relative expense and associated logistical difficulties when applied over increasingly larger study areas (Dolan et al. 1978; Gares et al. 2006).

The DEMs generated in concert with, and in support of, aerial photography missions, coupled with GIS, offer an alternative that is often more cost effective than on-ground acquisition (Moore and Griggs 2002; Zhang et al. 2005). This advantage grows in accord with study area size (Dolan et al. 1978; Gares et al. 2006; Smith and Zarillo 1990). Air-photo-derived photogrammetric DEMs are typically sampled using the older, well-established baseline transect method. Here, surface elevations and/or bathymetric depths are collected along a series of parallel, equidistant-spaced, shoreline-normal transects. These elevations are then used to generate a profile under the transect, whose cross-sectional area, as defined by the surface profile, the horizontal reference datum, and the landward and seaward survey limits, is used to extrapolate a beach volume. This process is repeated for all transects in the survey, and the individual volumes added to produce a total beach volume. Figure 7 describes this process in greater detail.

The DEMs generated using active sensor technologies such as radar, and more commonly lidar, in concert with GIS present another option for studying beach volume and change (Betenbaugh and Dumars 2007; Gares et al. 2006; Mitasova et al. 2002, 2003, 2004, 2005, 2009a, 2009b; Revell et al. 2002; Sallenger et al. 2003; Stockdon et al. 2002; White and Wang 2003; Zhang et al. 2005). Resolutions (a measure of the capacity of data to resolve specific detail on a surface) needed to detect subtle changes along the beach are often not easily attainable with transect-based methods. By using suitably interpolated lidar-derived surfaces, DEMs that reveal much subtle detail to the researcher can be generated (Sallenger et al. 2003; Woolard and Colby 2002). One means of computing beach volume using a lidar-constructed DEM is shown in Figure 8. Most lidar data are captured from airborne

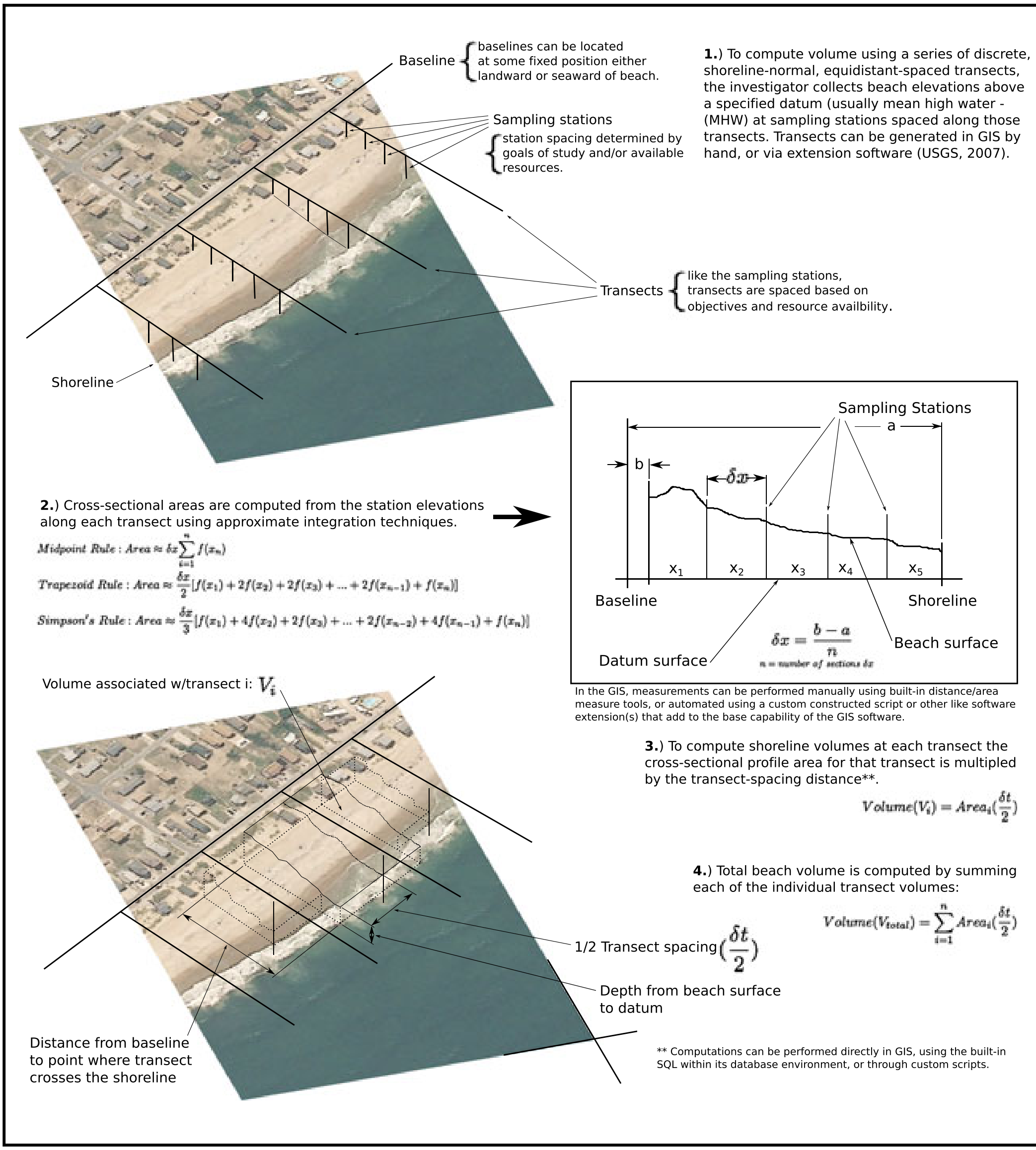


Fig. 7. Computation of beach volume using shoreline-normal transects. Profiles measured for the shore along each transect in a survey (the number of transects is determined by the scope of the investigation, along with the available resources) are used to compute cross-sectional areas bounded by the surface profile above, the vertical datum below, and the proximal (to the baseline) and distal (seaward) measurement points. These areas are extrapolated in both alongshore directions to a point ≤1/2 the transect spacing and with those distances being used to compute a per-transect volume. The total volume is computed as the accumulation of these individual transect volumes. Photography courtesy of the US Department of Agriculture, Farm Service Agency, Aerial Photography Field Office—National Aerial Imagery Program (NAIP 2009). http://www.apfo.usda.gov/FSA

platforms; however, very-high-resolution ground-based laser scanning systems can also be used (Pietro et al. 2008).

A growing body of lidar-generated data is inspiring new and innovative ways to quantify beach change. Whereas the more established DEM differencing approach (subtracting DEMs of differing vintages from one another to isolate change through time) is still commonly

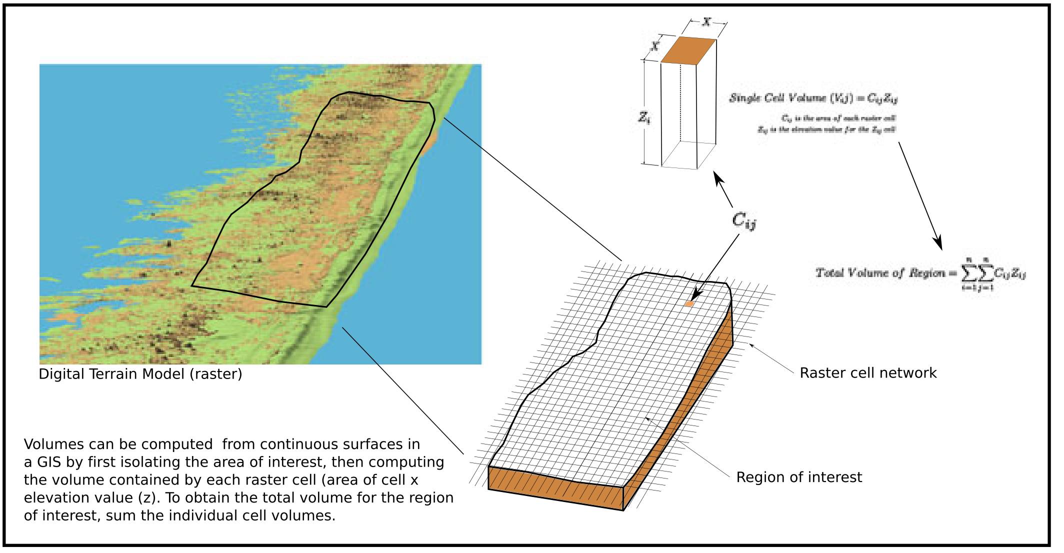


Fig. 8. Computation of shore volume using continuous (raster) surfaces. For an area of interest, the elevation associated with each included raster cell (*z*-value) is multiplied by the cell's surface area—this yields a per-cell shore volume. The total volume is determined in a straightforward manner by simply summing all of the individual cell volumes included in the region. The raster surface shown here was generated from airborne lidar data. GIS, geographic information system.

employed (James et al. 2012), newer methods of spatial–temporal characterization are gaining a foothold in the research community. Conspicuous among these is the novel coupling of descriptive (mean and variance) and predictive (correlation and regression) statistics and GIS to illustrate change in the coastal landscape (Mitasova et al. 2009a, 2009b; Neteler and Mitasova 2002). Moreover, new tools are now available in GIS to compute a host of statistics where time is accounted for by computing across DEMs (inter-surface computations) in the series (Figure 9). Three fundamental metrics, the topographic core and envelope and the derivative dynamic layer, have emerged in the literature from this merger, concepts based on identification of per-cell minimum and maximum elevation/bathymetric values through time (Mitasova et al. 2009a, 2009b).

The core surface, as shown in Figures 10 and 11, is defined as that surface depicting, for each raster cell, the minimum elevation recorded across all datasets for a given time period. The envelope surface, also shown in Figures 10 and 11, is the core's maximum elevation counterpart. Taken together, the core can be thought of as the stratigraphic contact at and below which sediment has remained stationary over the course of the study period. The envelope surface, on the other hand, represents the upper contact of a layer of material of varying thickness at and below which some degree of horizontal and/or vertical sediment displacement has occurred. The volume of material between the core and envelope surfaces is the dynamic layer, that zone where all morphological evolution has taken place during the study period represented by the given data. Dynamic contour bands depicting the maximal landward and seaward excursions of the shoreline, shown in Figure 11, can be derived by extracting specific elevation contours from both the core and envelope surfaces—where these surfaces intersect the shoreline datum—and computing the horizontal area for the region bounded by the two resulting isolines. The core and envelope surfaces quantify both the amount and spatial distribution of change through time (Figure 11).

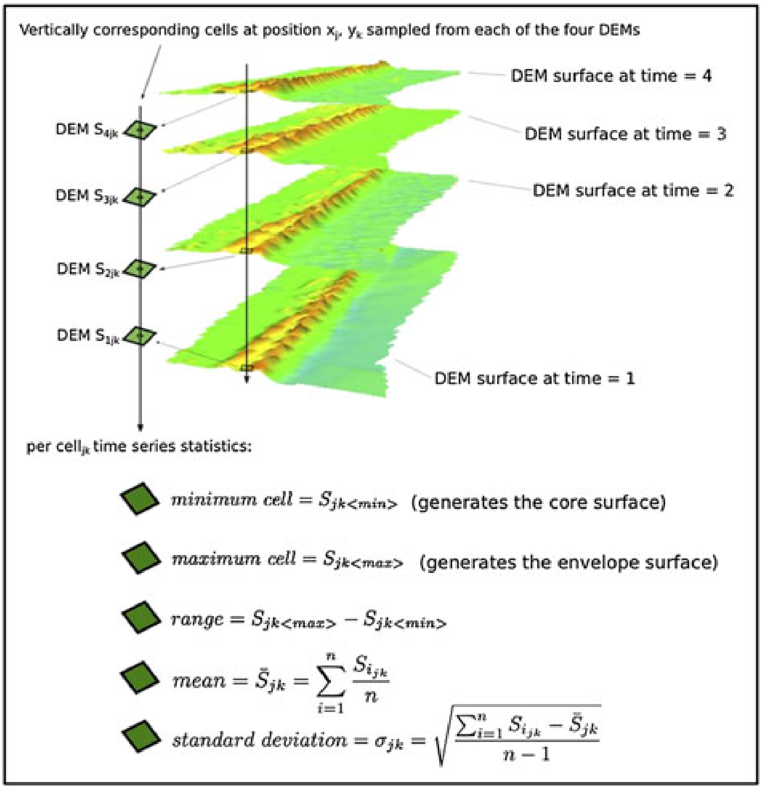


Fig. 9. The concepts behind a time series of digital surface models. Each surface shown represents the spatial distribution of values (e.g., elevations) that existed at the time the surface was captured. Corresponding raster cells are compared between the included surfaces (four are shown here) to generate various statistical surface models (e.g., mean, variance, range, mode, and regression) and time-of-event surfaces (i.e., at which time in the sequence did the minimum or maximum value occur?). Some example by-cell computations are shown. DEM, digital elevation model.

Two additional raster maps, similar to the core and envelope, that show at what time, per raster cell, the minimum and maximum elevation occurred over the time spanned by the study can be derived (Neteler and Mitasova 2008; Wegmann and Clements 2004). Examples of per-cell year of minimum and maximum elevation surfaces are shown in Figure 12. These data are used to assist in isolating long-term trends (e.g., sea-level rise). Short-term events can also be identified, manifested typically as transients, such as storms, which act to create short-lived anomalies, followed by subsequent-year restoration. These are seen as minima and/or maxima on the surfaces whose dates are in accord with geomorphic, meteorological, or other events in the historic record. One example would be erosional impacts from a storm event (e.g., a hurricane), recorded as an elevation minima, that occurred during the time period spanned by the study.

Recent work evaluating changes along the beach, dunes, and back island sections along North Carolina's Outer Banks highlights the use of these new tools. One such study (Mitasova et al. 2010) considered two areas along Hatteras Island, one north of Cape Hatteras and the other south, with an objective to evaluate and quantify beach variability and change over a study period spanning more than a decade. Results were interesting. At both sites, the core accounted for less than 50% of the sediment volume, leaving the majority share to the mutable envelope. While most of this dynamic behavior is interpreted here as due to natural processes, numerous building construction and demolition sites are also identified along the back island, dune, and beach sections.

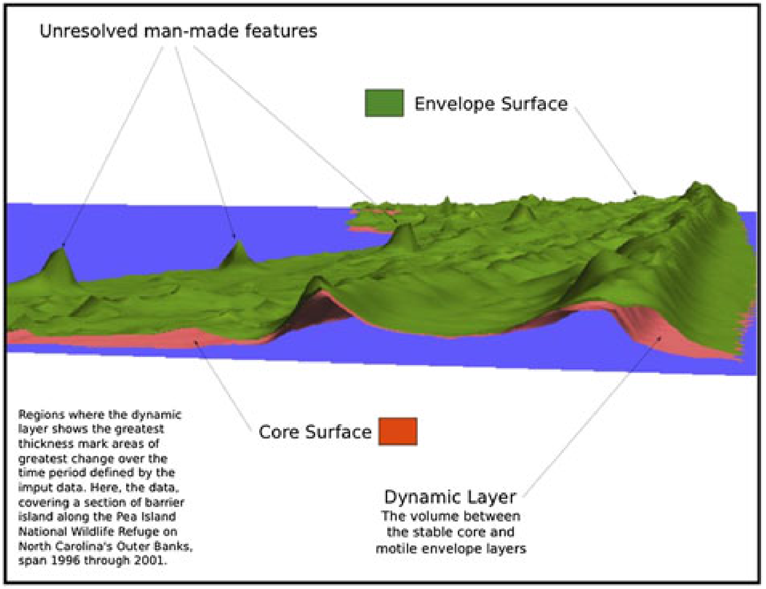


Fig. 10. Schematic of the core and envelope surfaces and dynamic layer. The core surface represents the stratigraphic upper surface, or contact, as measured through the time series of digital surface models included for consideration, at and below which no change has occurred for the time span of the data as represented. The envelope is the core's counterpart, representing, for each raster cell, the uppermost excursion of the value (e.g., elevation) observed over the course of the time series. The dynamic layer is the volume bounded by the core surface (below) and envelope surface (above). The dynamic layer constitutes volume of the shore where all change (erosion and accretion) occurred over the course of the time period represented by the data included in the investigation.

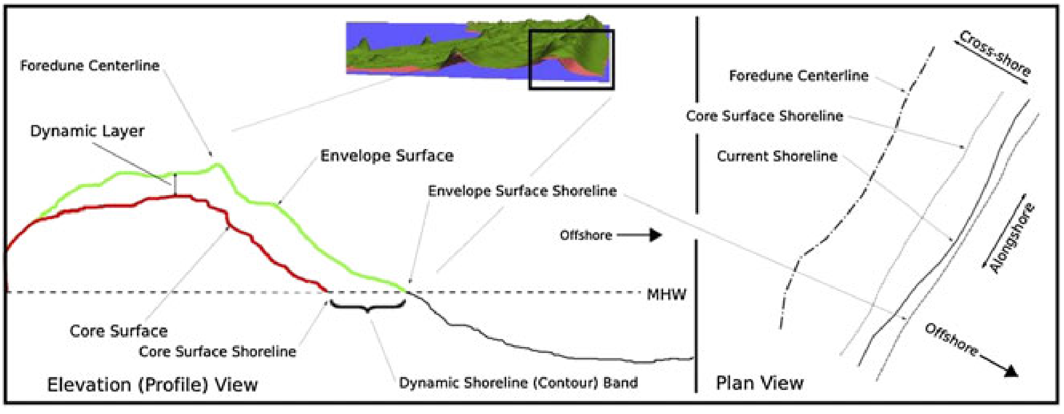


Fig. 11. Another perspective on the concept of a core and envelope surfaces—the core is shown in red, the envelope in green on the elevation view (left) and in plane on the right. The former is the portion of the volume measured above vertical datum surface (often a tidally coordinated sea-level surrogate), the upper contact of which delineates the region where no change was observed during the course spanned by the data (in this illustration for example, from 1999 through 2008). The latter envelope defines the maximal extent of a volume referred to as the dynamic layer, below which, down to its contact with the core, all changes where observed. An additional measure is the dynamic shoreline band. The dynamic shoreline band is defined as the area bounded by the lines created where the core and envelope surfaces intersect the vertical datum surface. This defines the extent of shoreline position change (landward and seaward extremes) that occurred during the period represented by the data.

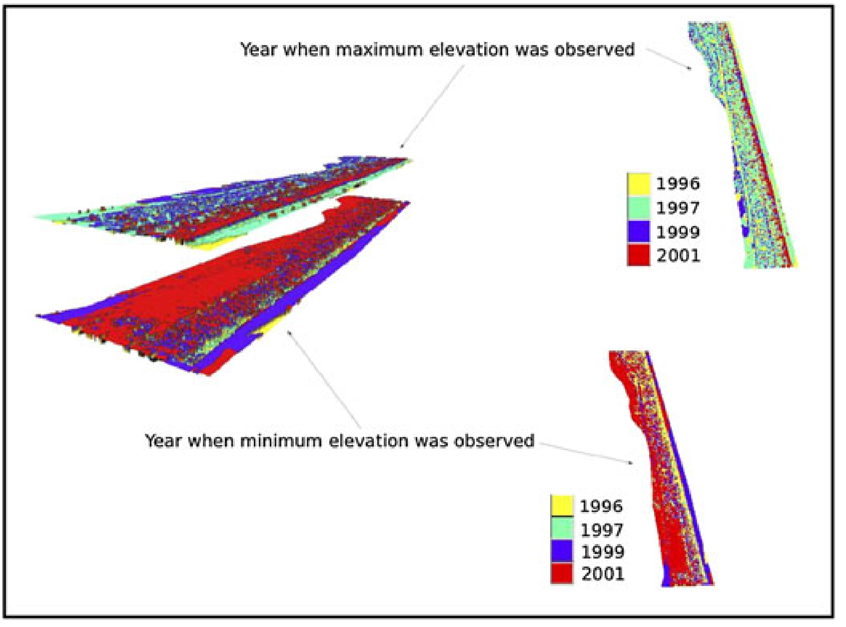
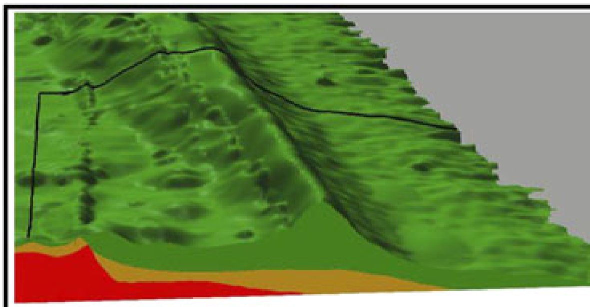


Fig. 12. Raster maps depicting the year when the minimum elevation (bottom right) and maximum elevation (upper right) occurred over the time period as represented by the data. Minimum and maximum value determinations are performed on a per-raster-cell basis. For each cell, all of the surfaces are interrogated as well as the minimum and maximum elevations, along with a reference to the layer(s) associated with these extremes. The date(s) associated with these representing layer(s) are conveyed to the output surfaces. In this example, the time unit is the year when the lidar data, used to generate the source surfaces, were captured.

Hardin et al. (2011) considers the entirety of Hatteras Island from Oregon Inlet in the north to Hatteras Inlet south, a span of some 80.5 km (50 miles) for a large-scale beach erosion/accretion characterization study. For these investigations, core and envelope surfaces were computed, and dynamic layers derived to analyze shoreline position and beach sediment volume evolution. However, in a departure from prior work, the investigators here computed a normalized dynamic layer volume. They did this by first subtracting the material below the core surface from the envelope volume and then dividing the difference by the elevation range; this result is shown in Figure 13. Through normalization, changes reflected in the beach's dynamic layer are further elucidated. The investigators also introduce an additional pair of new techniques: one for beach evolution and the other tackling dune ridge height and along/cross-shore motion.

The former involves measuring the cross-shore position of a series of elevation contours for a time series of DEMs. By using regression analysis, the evolution of the beach can be modeled to track complex sediment transport in the longshore direction as well as between the lower and upper beach and foredune. The latter technique employs a novel use of least-cost path optimization to isolate from the data, dune ridge crest lines. Here, the model seeks not the minimum but instead "inverts" the algorithm to locate the most costly path across the dune field (Figure 14a and b). The resulting trace should represent the crest line.

These studies demonstrate the utility of these newer GIS-based spatiotemporal analysis tools in identifying and quantifying shoreline/beach change. As techniques such as these further evolve and data quality improves, studies such as this will become more common. Further, as the ability to collect nearshore bathymetric data is refined, investigators will have at their disposal a more complete picture of the coast. The subaqueous shoreface, in many coastal locations, remains poorly, or not at all, surveyed.



	Volume [10^3m^3]	Normalized Volume
Envelope	38.5	1.00
2008	16.2	0.26
Core	8.3	0.00

Fig. 13. Normalized volume. Normalization helps to emphasize the changes that have occurred through time, as represented by the dynamic (envelope–core surface) layer. Figure courtesy of Hardin et al. (2010).

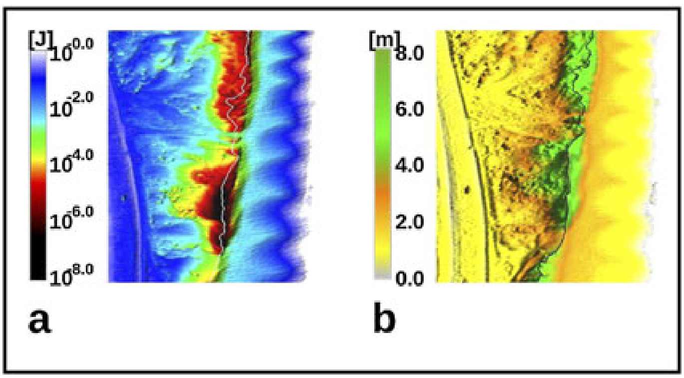


Fig. 14. (a, b) Shown here are traces of the extracted foredune crest line extracted using the technique described by Hardin et al. (2010, 2012). Figure courtesy of Hardin et al. (2010).

4. Modeling Shoreline and Beach Change

The coupling of numerical deterministic and stochastic models with GIS within the research community has been slow (Wright and Bartlett 2000). Natural systems modeling is difficult; often, we simply do not know enough about the processes we wish to model to be able to formulate the complex analogs needed to model them. This knowledge gap has been further compounded by a dearth of data at spatial and temporal scales that offer the resolutions needed to craft such models. Nevertheless, work continues toward this integration. In the two sections to follow, we explore some of these efforts.

4.1. NUMERICAL MODELING

Historically, most combined GIS/numerical modeling efforts have been vector-based attempts to forecast shoreline changes in response to rising sea level (Daniels 1996; Granger 1995; Hennecke and Cowell 2000; Lee et al. 1992; Li et al. 1998). These approach modeling as a two-step process: inundation at the hand of a rising sea and shoreline retreat through erosion in reply. Models can employ complex mathematics (Li et al. 2001), but in most instances, simplicity makes the adoption of empirical methods an appealing, and often preferred, option (Fenster et al. 1993). Such approaches demand no knowledge of the underlying physical processes (Li et al. 2001). Here, shoreline change is quantified by first computing a historically based rate and then using this historical rate to extrapolate future change. Linear process response models from the coastal engineering community such as the Bruun Rule and its variants (Bruun 1962; Dean and Maurmeyer 1983; Dubois 1990), GENESIS (Hanson 1989), SBEACH (Larson and Kraus 1989), XBEACH (Roelvink et al. 2006), and the European LITPACK and UNIBEST (Cooper and Pilkey 2004) are popular. Most are well known and represented in the literature (Fenster et al. 1993) and have been combined with GIS in research (Cowell and Zeng 2003; Daniels 1996; Hennecke and Cowell 2000). Many other models are in use within the scientific and engineering communities, though ties with GIS vary (Vafeidis et al. 2008). However, these models, and numerical modeling in general, are not without their detractors who cite various shortcomings in their use, in their ability to both describe and predict (Cooper and Pilkey 2004; Thieler et al. 2000; Young et al. 1995).

Daniels (1996) integrated a simple inundation model with the Bruun and modified Brunn (Dean and Maurmeyer 1983) rules into GIS to forecast shoreline change out to 2100. Results indicate that the Nags Head, North Carolina, study site would surrender more than 40% of its 1983 land to the sea by the target date but further predicted that the barrier island should be able to withstand the anticipated sea-level rise, provided no large-scale stabilization efforts are undertaken to inhibit natural processes. Li et al. (2001) presents an alternative to simple "bathtub" inundation (where flooding is based on filling to existing contours) for shoreline response to sea-level rise, by combining a numerical water level model with GIS to generate a time series of Lake Erie shorelines. These shorelines were then used to generate longshore recession predictions.

Hennecke and Cowell (2000) used GIS to model inlet shorelines responding to rising sea levels. The study grouped the modified Bruun Rule and two lesser-known transport models into a GIS-based model (Curray 1964; Van Straaten 1954). These latter two transport models generate long-term predictions for shoreline and shoal variations, describing vertical change in depth and lateral position across an inlet flood tide delta. Cowell et al. (1996) proposed a GIS-based probabilistic model for predicting coastline response to sea-level rise. Cowell and Zeng (2003) would take this 1996 probability model a step further by introducing a multiphase GIS-based methodology designed to account for uncertainties associated with the sea-level rise estimation. Their four-component model expands on other, more common deterministic approaches, with stages that employ fuzzy set theory and randomized inputs. Ekebom et al. (2003) used GIS to model open-water wind fetch and predict wave heights as a proxy for coastal wave exposure. Wave exposure was then used to predict shoreline response. Further, GIS-based models have been developed around differing climatic scenarios to forecast flood risk due to sea-level rise (Thumerer et al. 2000). GIS was also used to assess the impact of a rising sea level on coastal bluff erosion along the Maine coastline (Keblinsky and Kelley 2002). Clark and Befus (2009) incorporated a geophysical deformation model with GIS to generate paleo-Great Lakes shorelines, and the geographic extent of the lakes themselves, for the past 20,000 years BP. Researchers working along the Andalusia coast in southwestern Spain (Guisado and Malvarez 2009) combined GIS with Delft University's Simulating WAves Nearshore water-wave prediction model, high-resolution DEMs (including topography and bathymetry), and several additional physical, biological, and socioeconomic datasets, to generate

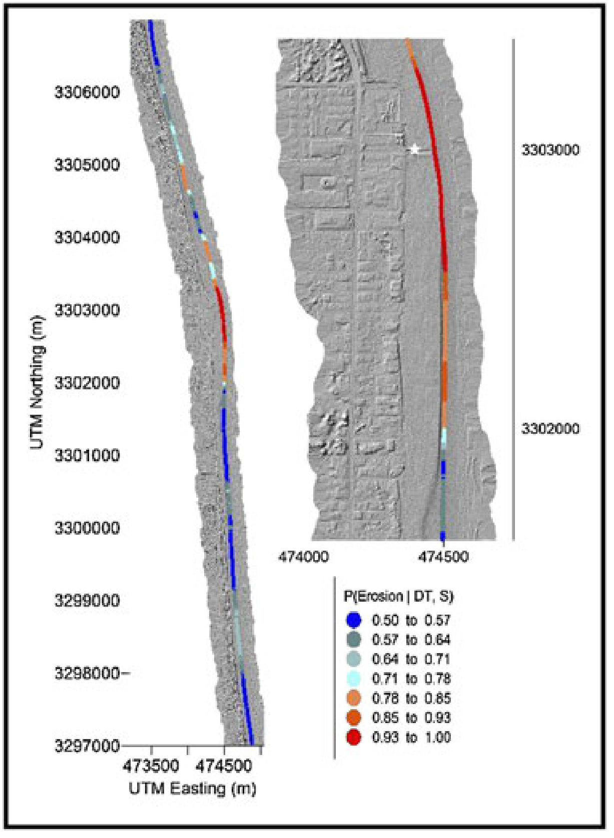


Fig. 15. Alongshore map for a section of St. Augustine Beach, FL coast, showing the relative likelihood of erosion based on a probability-based parameterization scheme. See Starek et al. (2007, 2009) for a complete description. Figure courtesy of Stare et al. (2009).

shoreline vulnerability predictions for their study area coastline. Results were published to the GIS-based Coastal Atlas of Andalusia, with additional access provided through the Internet.

4.2. STOCHASTIC MODELING

Starek et al. (2009) presents an approach that uses multi-temporal lidar data to extract and detect subtle morphologies indicative of shoreline change patterns observed along a section of beach in St. Augustine, Florida. A parameterization scheme compresses the subaerial beach surface into a series of single-dimension morphologic features (e.g., beach slope, width, and deviation from the shoreline trend) using cross-shore profiles that are then partitioned into either erosional or accretionary groups. These features are then ranked for their ability to segment erosion and accretion tending zones along the beach using full probability density information estimated non-parametrically from the lidar data (Starek et al. 2007). The greater the interclass separation exhibited by a feature, the higher is its ranking as a shoreline change indicator. Those metrics exhibiting the highest ranks were then implemented within a Bayesian classifier to map probability of erosion vulnerability (Figure 15). As the findings here are dependent on the data, the applicability of this approach must be considered on a case-by-case basis (parameters found to be significant in this study may not be so at another location) and not as a general model/tool for shoreline change prediction. The investigators did, however, stress the value of the idea as a framework for "data driven learning" that could be applied in a more general sense toward isolating and discerning patterns of change in shoreline morphologies from lidar datasets.

5. Conclusion

The beach is a complex geomorphic entity, and the processes that shape it are equally so complex, and arguably little understood. It is this complexity that makes any effort at quantification challenging. However, with evidence supporting an accelerated eustatic sea-level rise mounting (IPCC 2007), our ability to understand and predict the beach's response, when viewed as a potential hazard to life and property, is vital (Cowell and Zeng 2003).

Spatial data and spatial analysis have been an implicit part of the shoreline mapping and beach characterization process since NOAA's predecessor, the Coast Survey, mapped its first shoreline early in the 19th century. From plane tables and levels carried into the field by skilled surveyors, through the development of aerial photography, to modern laser, video, and satellite systems, and the advent of digital technologies such as GIS, the science behind locating, mapping, monitoring, and predicting change along the shore and beach has made great strides in two centuries. We've reached a point where accurate, reproducible 2-D and 3-D models for the shoreline and beach, respectively, are within reach of expert and non-expert alike. This expands opportunity not only for scientists who seek to understand but also for planners and managers who seek to protect and preserve these important regions and resources.

The GIS as a tool in the study of the world's changing beaches/shorelines offers many advantages for the coastal scientist or planner. As research continues to demonstrate, the modern GIS provides the means to capture data at almost any density and scale. Coupled with high-quality, high-resolution, remotely sensed data, GIS makes the sampling, characterization, and analyses of the beach over large areas relatively easy (Dolan et al. 1992). It offers a ready means for exploratory study, along with raster and vector processing tools that support sophisticated modeling. More recent developments have expanded GIS's reach to include both numerical and physical models that can address both the elements of space and time. GIS is thus proving itself to be not only a useful mapping tool but also one that can contribute in significant ways to quantitative analyses and prediction (Rodríguez et al. 2009).

Still, in spite of the many advantages that GIS technology offers the investigator and the myriad uses so far in evidence, adoption within the overall coastal research community has been slow (Boots 2000; Rodríguez et al. 2009). The full embrace of these technologies thus awaits future researchers willing to apply these tools in new and creative ways to shed light on the physical processes that govern a complex, poorly understood, yet vitally important system, where the land and water meet.

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Short Biographies

Paul came to coastal research after more than two decades as a professional in the private sector and government. His work combined ocean and estuarine management, inventory, and assessment with geospatial technologies and GIS. While a member of NOAA's National Ocean Service (NOS), he led the Digital Shoreline Development team, a group which ultimately generated the agency's first nationwide digital shoreline product. He was the technical coordinator for the NOS T-Sheet Recovery and Archive and National Shellfish Register digitalization projects. During his professional career, he was also a technical advisor and analyst to the Florida Keys and Monterey Bay National Marine Sanctuary Management Plan, the NOAA Coastal Assessment Framework Data Base and East Coast of North America Marine Data Atlas, the NOAA/EPA TRI (Toxic Release Inventory) Program, the Florida Keys Benthic Habitat Survey, and the EPA's Commencement Bay Nearshore Tidal Flats Superfund cleanup. His interests include beach, shore, and nearshore geomorphology, coastal quaternary geology, and sediment transport. Paul holds a bachelor's degree in Geography from Virginia Tech and a master's degree in Marine Science from the Louisiana State University. He is currently pursuing a PhD in the Marine, Earth, and Atmospheric Sciences from the North Carolina State University.

Michael J. Starek received an MS degree in Computer Science from the Texas A&M University, Corpus Christi (2000–2002) and a PhD degree in Civil Engineering with an emphasis in Geosensing Systems Engineering from the University of Florida, Gainesville (2004–2008). From 2009 to 2011, he was a National Research Council Postdoctoral Fellow of the US Army Research Office in affiliation with the North Carolina State University. He is currently an associate research professor at the Harte Research Institute for Gulf of Mexico Studies. Michael's current research thrusts include emergent light detection and ranging (lidar) systems and applications, sensor characterization, statistical learning, and nearshore coastal hazards assessment.

Eric Hardin is a doctoral candidate in the Department of Physics at North Carolina State University. His research is in smoothed particle hydrodynamics simulations of wind-driven sand saltation for geomorphological applications. His most recent publication in *Journal of Coastal Research* describes a least-cost path approach to extracting a coastal dune ridge from airborne lidar data and its application to high-resolution storm hazard mapping.

Onur Kurum is a PhD candidate in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. His research focus is directed toward numerical modeling of coastal systems, wave–sediment interactions, beach morphology, storm impacts, sea-level rise, and inlet dynamics.

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