Shoreline Definition and Detection: A Review

Authors: Boak, Elizabeth H., and Turner, Ian L.

Source: Journal of Coastal Research, 2005(214) : 688-703

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/03-0071.1

Journal of Coastal Research	21	4	688–703	West Palm Beach, Florida	July 2005

Shoreline Definition and Detection: A Review

Elizabeth H. Boak and Ian L. Turner

Water Research Laboratory
School of Civil and Environmental Engineering
University of New South Wales
King Street, Manly Vale
NSW 2093, Australia
lboak@wrl.unsw.edu.au

ABSTRACT

BOAK, E.H. and TURNER, I.L., 2005. Shoreline Definition and Detection: A Review. *Journal of Coastal Research,* 21(4), 688–703. West Palm Beach (Florida), ISSN 0749-0208.

Analysis of shoreline variability and shoreline erosion-accretion trends is fundamental to a broad range of investigations undertaken by coastal scientists, coastal engineers, and coastal managers. Though strictly defined as the intersection of water and land surfaces, for practical purposes, the dynamic nature of this boundary and its dependence on the temporal and spatial scale at which it is being considered results in the use of a range of shoreline indicators. These proxies are generally one of two types: either a feature that is visibly discernible in coastal imagery (*e.g.,* high-water line [HWL]) or the intersection of a tidal datum with the coastal profile (*e.g.,* mean high water [MHW]). Recently, a third category of shoreline indicator has begun to be reported in the literature, based on the application of image-processing techniques to extract proxy shoreline features from digital coastal images that are not necessarily visible to the human eye.

Potential data sources for shoreline investigation include historical photographs, coastal maps and charts, aerial photography, beach surveys, *in situ* geographic positioning system shorelines, and a range of digital elevation or image data derived from remote sensing platforms. The identification of a "shoreline" involves two stages: the first requires the selection and definition of a shoreline indicator feature, and the second is the detection of the chosen shoreline feature within the available data source. To date, the most common shoreline detection technique has been subjective visual interpretation. Recent photogrammetry, topographic data collection, and digital image-processing techniques now make it possible for the coastal investigator to use objective shoreline detection methods. The remaining challenge is to improve the quantitative and process-based understanding of these shoreline indicator features and their spatial relationship relative to the physical land–water boundary.

ADDITIONAL INDEX WORDS: *Shoreline change, shoreline mapping, shoreline analysis, coastal accretion-erosion, remote sensing, geographic positioning system, GPS, image analysis.*

INTRODUCTION

The location of the shoreline (we will discuss the definition of this term shortly) and the changing position of this boundary through time are of elemental importance to coastal scientists, engineers, and managers (DOUGLAS and CROWELL, 2000; NATIONAL RESEARCH COUNCIL, 1990). Both coastal management and engineering design require information about where the shoreline is, where it has been in the past, and where it is predicted to be in the future. For example, an analysis of shoreline information is required in the design of coastal protection (*e.g.,* COASTAL ENGINEERING RESEARCH CENTER, 1984), to calibrate and verify numerical models (*e.g.,* HANSON, GRAVENS, and KRAUS, 1988), to assess sea-level rise (*e.g.,* LEATHERMAN, 2001), to develop hazard zones (*e.g.,* BELLOMO, PAJAK, and SPARKS, 1999; DOUGLAS, CROWELL, and LEATHERMAN, 1998), to formulate policies to regulate coastal development (NATIONAL RESEARCH COUNCIL, 1990), and to assist with legal property boundary definition (*e.g.,* MORTON and SPEED, 1998) and coastal research and monitoring (*e.g.,* SMITH and JACKSON, 1992). The location of the shoreline can provide information in regard to shoreline reorientation adjacent to structures (*e.g.,* KOMAR, 1998) and beach width and volume (SMITH and JACKSON, 1992), and it is used to quantify historical rates of change (*e.g.,* DOLAN, FENSTER, and HOLME, 1991; MOORE, 2000).

To analyze shoreline variability and trends, a functional definition of the "shoreline" is required. Because of the dynamic nature of this boundary, the chosen definition must consider the shoreline in both a temporal and spatial sense and must take account of the dependence of this variability on the time scale by which it is being investigated. For practical purposes, the specific definition chosen is generally of lesser importance than the ability to quantify how a chosen shoreline indicator relates in a vertical/horizontal sense to the physical land–water boundary. The challenge, then, is to develop a sufficiently robust and repeatable technique to enable the detection of the chosen "shoreline" feature within the available data source. Detection techniques vary depending on the data source and the chosen shoreline definition.

Following an introductory discussion of the importance of temporal and spatial variability to define the idealized "shoreline" boundary, we provide a compilation of the extensive range of shoreline indicators that have been reported in

DOI: 10.2112/03-0071.1 received 2 July 2003; accepted in revision 8 January 2004.

the literature. Strengths and limitations of the more common proxy shoreline features are highlighted. A summary of shoreline data sources is then provided, extending from historical photographs to contemporary digital data derived from a range of remote sensing platforms. The challenge of shoreline detection using the available data sources is then considered, along with the ability of currently available data interpretation techniques to meet the criteria of objectivity, robustness, and repeatability. We highlight recent advances that use automated image-processing techniques, which offer coastal investigators the ability to gain a better process-based understanding of the relationship between detected "shoreline" features and the physical land–water boundary.

DEFINITION OF THE "SHORELINE"

An idealized definition of *shoreline* is that it coincides with the physical interface of land and water (DOLAN *et al.,* 1980). Despite its apparent simplicity, this definition is in practice a challenge to apply. In reality, the shoreline position changes continually through time, because of cross-shore and alongshore sediment movement in the littoral zone and especially because of the dynamic nature of water levels at the coastal boundary (*e.g.,* waves, tides, groundwater, storm surge, setup, runup, *etc.*). The shoreline must therefore be considered in a temporal sense, and the time scale chosen will depend on the context of the investigation. For example, a swash zone study may require sampling of the shoreline position at a rate of 10 samples per second, whereas for the purpose of investigating long-term shoreline change, sampling every 10–20 years may be adequate.

The instantaneous shoreline is the position of the land–water interface at one instant in time. As has been noted by several authors (LIST and FARRIS, 1999; MORTON, 1991; SMITH and ZARILLO, 1990), the most significant and potentially incorrect assumption in many shoreline investigations is that the instantaneous shoreline represents "normal" or "average" conditions. A shoreline may also be considered over a slightly longer time scale, such as a tidal cycle, where the horizontal/vertical position of the shoreline could vary anywhere between centimeters and tens of meters (or more), depending on the beach slope, tidal range, and prevailing wave/weather conditions. Over a longer, engineering time scale, such as 100 years, the position of the shoreline has the potential to vary by hundreds of meters or more (KOMAR, 1998). The shoreline is a time-dependent phenomenon that may exhibit substantial short-term variability (MORTON, 1991), and this needs to be carefully considered when determining a single shoreline position.

The definition of the shoreline must also consider alongshore variation. Most studies of shoreline change consider discrete transects or points and monitor how these change through time. But this method of sampling can introduce additional uncertainty. For example, are the chosen points representative, and are morphological features, such as beach cusps, distorting the alongshore average shoreline position? The significance of alongshore variability to shoreline investigation was demonstrated by ELIOT and CLARKE (1989), who found that survey records from small segments of beach could not be used to accurately represent total beach change in their study of Scarborough and Warilla Beaches in Western Australia. Again, the context of the investigation will determine the appropriate spacings for shoreline sampling.

SHORELINE INDICATORS

Because of the dynamic nature of the idealized shoreline boundary, for practical purposes coastal investigators have typically adopted the use of shoreline indicators. A *shoreline indicator* is a feature that is used as a proxy to represent the "true" shoreline position. Figure 1 illustrates the spatial relationship between many of the commonly used shoreline indicators. Individual shoreline indicators generally fall into one of two categories. Classifications in the first group are based on a visually discernible coastal feature, whereas classifications in the second group are based on a specific tidal datum. A visually discernible indicator is a feature that can be physically seen, for example, a previous high-tide line or the wet/dry boundary (Figure 2). In contrast, a tidal datum–based shoreline indicator is determined by the intersection of the coastal profile with a specific vertical elevation, defined by the tidal constituents of a particular area, for example, mean high water (MHW) or mean sea level (Figure 3). Recently, a third category of shoreline indicator has begun to be reported in the literature, based on the application of image-processing techniques to extract proxy shoreline features from digital coastal images that are not necessarily visible to the human eye (*e.g.,* AARNINKHOF, CALJOUW, and STIVE, 2000).

Table 1 summarizes a comprehensive range of shoreline indicators identified from the shoreline analysis literature. When available, the following information has been compiled: the name of the shoreline indicator used by the study author, a description of the indicator feature as interpreted from the information provided, a generic classification of the shoreline indicator feature, additional comments, the data source, the detection technique used, and reference(s) to relevant publications.

Table 1 includes 45 examples of shoreline indicators found in the literature. Of these, there are 28 differently named shoreline indicators, as reported by their respective authors, 19 different generically named shoreline indicators, as well as a further eight shoreline indicators that are either undefined (or unknown) indicators. Four of the examples (two generic names) are tidal datum based and therefore correspond to a specific elevation at the land–ocean boundary (*e.g.,* FISHER and OVERTON, 1994; STOCKDON *et al.,* 2002). Of the remaining 41 examples, 35 are based on visually discernible features and can be grouped into three types. The first type is based on the alignment of man-made structures, *e.g.,* the landward edge of a revetment structure. The second type is based on a morphological feature, *e.g.,* an erosion scarp. The third type of visibly discernible features includes those based on the position of a selected waterline, *e.g.,* previous high-tide high-water level. A more limited number (six) of the shoreline indicators compiled in Table 1 are based upon a feature extracted from digital images by the application of image-pro-

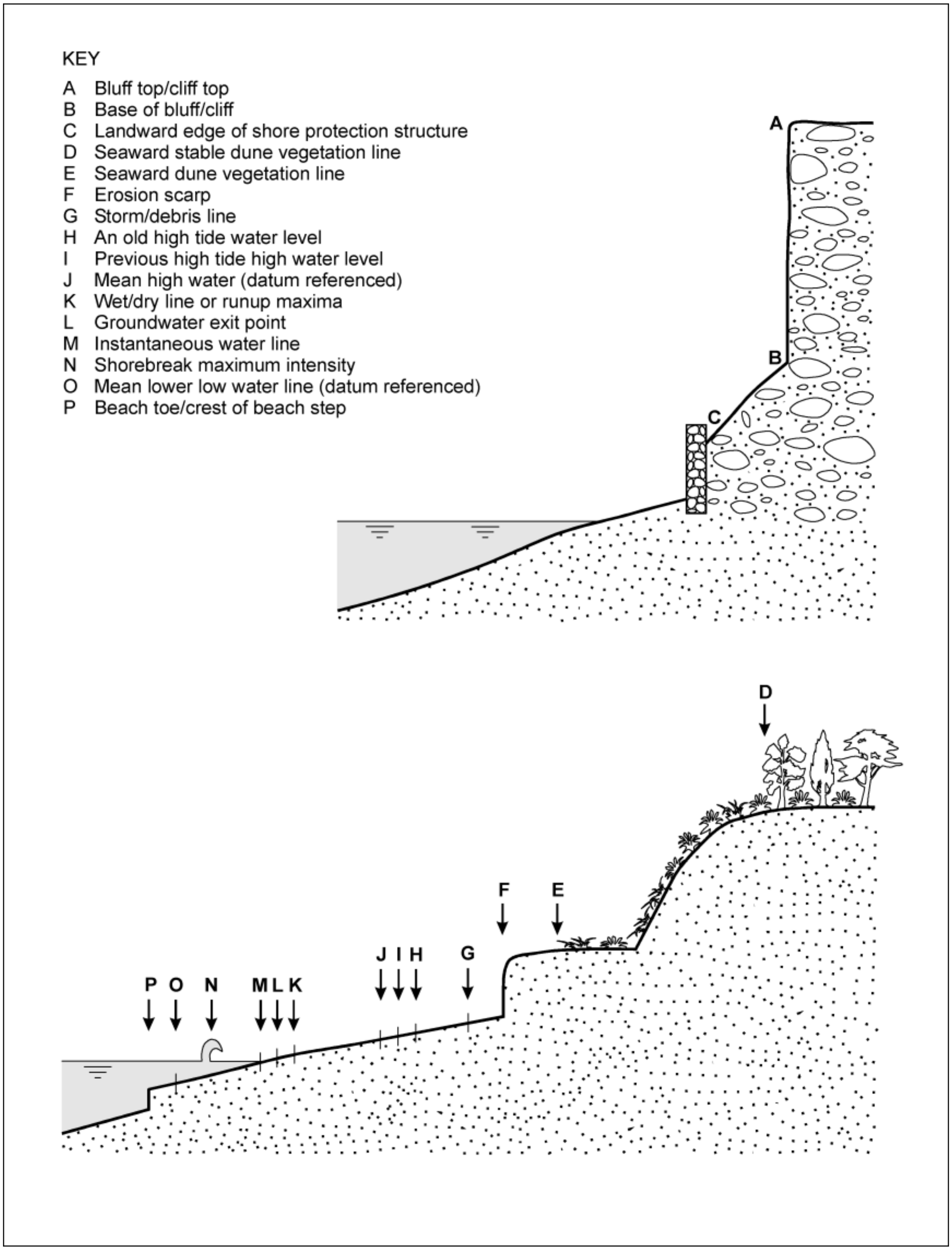

Figure 1. Sketch of the spatial relationship between many of the commonly used shoreline indicators.

cessing techniques that is not necessarily visible to the human eye.

The most common shoreline indicator reported in Table 1 is named by numerous authors as the "high-water line" (HWL). Commonly, the HWL is visually determined as a change in tone left by the maximum runup from a preceding (the last?) high tide (ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; SMITH and ZARILLO,

Figure 2. An example of a range of visibly discernible shoreline indicator features, Duranbah Beach, New South Wales, Australia. For key, see Figure 1.

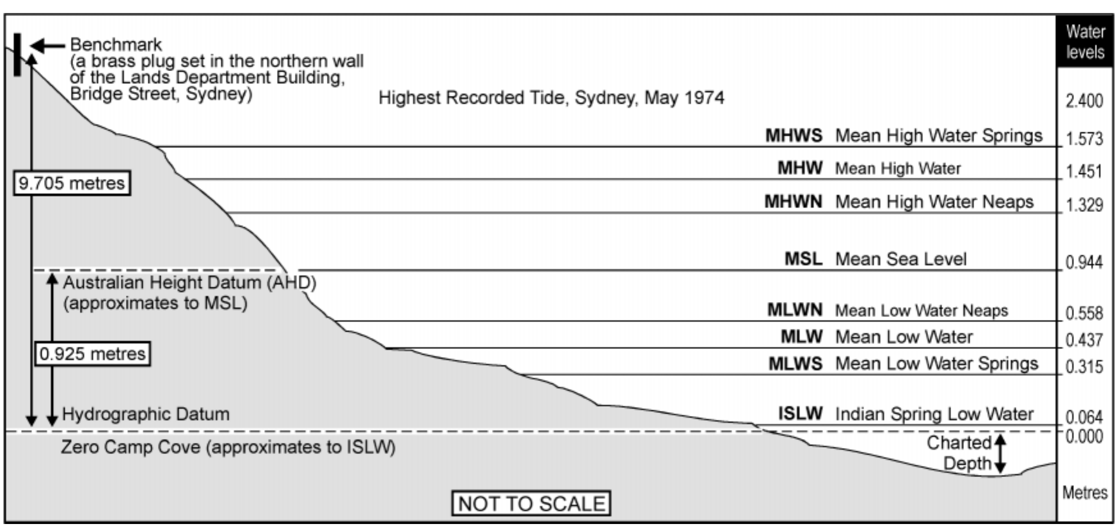

Figure 3. Tidal datums used along the New South Wales coastline, Australia (adapted from data provided by Manly Hydraulics Laboratory, New South Wales Department of Commerce).

Table 1. *A summary of some common shoreline indicators used in shoreline change literature.**

Reported Shoreline Indicator	Identification of Feature	Generic Name	Comments	Source	Detection Technique	Reference
Bluff top/cliff top	Landward edge of the bluff top or cliff top	Bluff top/cliff top	Good erosion indicator, but will not show accretion; morphology specific (hard coasts)	Aerial photographs	Manual	(Moore, Beaumof, and Griggs 1999)
Bluff top/cliff top	Break in slope resulting directly from wave erosion or from mass movements triggered by wave erosion	Bluff top/cliff top	As above	Aerial photographs	Manual	(Priest, 1999)
Bluff line/bank line/crest of slope	Undefined	Bluff top/cliff top?	As above?	Aerial photographs	Manual	(Crowell, Douglas, and Leatherman, 1997; Guy, 1999)
Landslide headwall	Top of the headwall; only used on bluffed shorelines with zones of mass movement, *e.g.,* earth flows, landslides, slumps, or transitional slide blocks	Landslide headwall	As above	Aerial photographs	Manual	(Priest, 1999)
Base of bluff/cliff	Base of bluff or cliff; used when bluff/cliff top is rounded, and it is not easy to determine the landward edge	Base of bluff/cliff	Not clearly defined; base position may be distorted due to rubble, *etc*; morphology specific (hard coasts)	Aerial photographs	Manual	(Moore, Benumof, and Griggs, 1999)
Landward edge of shore protection structure	Landward edge of shore protection structures and development	Landward edge of shore protection structure	Case specific: only where the coastline has been protected. A properly designed structure is designed not to move/fail within its design life, so the indicator is unlikely to relocate.	Aerial photographs	Manual	(Moore, Benumof, and Griggs, 1999)
Seaward edge of dune vegetation	Seaward edge of stable, long-term vegetation	Seaward stable dune vegetation line	Case specific: only where dune vegetation is present. Good erosion indicator, but may not show accretion or will show it with a significant time lag. What defines stable and long term?	Aerial photographs	Manual	(Priest, 1999; Guy 1999)
Seaward edge of dune vegetation	Seaward edge of dune vegetation	Seaward dune vegetation line	Case specific: only where dune vegetation is present. Good erosion indicator, but may not show accretion or will show it with a significant time lag. More responsive than above.	Aerial photographs	Manual	(Moore, Benumof, and Griggs, 1999)
Dune vegetation line	Seaward edge of dune vegetation	Seaward dune vegetation line	As above	Aerial photographs	Manual	(Komar, Diaz-Mendez, and Marra, 2001)
Vegetation line	Distinct edge in image based on tonal differences (brightness) between the vegetated and nonvegetated beach areas	Seaward dune vegetation line	As above	Aerial photographs	Supervised digital image analysis	(Hoeke, Zarillo, and Synder, 2001)
Dune line	Appears as a topographic break or scarp between the wind- or wave-deposited dunes and the seaward-sloping beach	Erosion scarp	Good erosion indicator, but will not show accretion. Not always present, both spatially and temporally.	Aerial photographs	Manual	(Stafford and Langfelder, 1971)

Table 1. *Continued.*

Reported Shoreline Indicator	Identification of Feature	Generic Name	Comments	Source	Detection Technique	Reference
Foredune foot	Upper level of the highest spring tide, a sharp break in slope from the gentle upper beach to the steep dune front, or a dune erosion scarp	Erosion scarp	As above	Aerial photographs, DGPS survey	Manual	(Battiau-Queney *et al.,* 2003)
Beach crest	Undefined	Berm?	Unknown	Aerial photographs	Manual	(Guy, 1999)
Berm crest	Accretionary morphologic feature interpreted as HWL	Berm	Good erosion indicator, but will not show accretion. Not always present, both spatially and temporally.	Aerial photographs	Not detailed	(Kraus and Rosati, 1997)
High-water line	Seaward line of two lines of slight discoloration. The more landward line is the storm/debris line.	Previous high-tide HWL	May not be clearly visible. Affected by wind/wave/tide conditions at the time.	Aerial photographs	Manual	(McCurdy, 1950)
High-water line	Approximation of MHW. Marking on beach from last high tide, not last storm/debris line. Visually detected in the field.	T-sheet HWL	Maximum error 10 m (Shalowitz, 1964). May not have been clearly visible. Not MHW. Affected by wind/wave/tide conditions at the time.	Field, map	Manual	(Shalowitz, 1964)
High-water line	A change in color or gray tone caused by differences in water content of the sand on either side of the high-water line	Previous high-tide HWL	May not be clearly visible. Affected by wind/wave/tide conditions at the time.	Aerial photographs	Manual	(Stafford and Langfelder, 1971; Leatherman, 1983; Smith and Zarillo 1990; Anders and Byrnes, 1991; Crowell, Leatherman, and Buckley, 1991, 1993; Crowell, Douglas, and Leatherman, 1997†; Farrell *et al.,* 1999; Leatherman and Anders, 1999; Leatherman and Eskandary, 1999; O'Connell and Leatherman, 1999; Zhang *et al.,* 2002)
High-water line	Undefined, through it is presumed to be defined similarly to the above definition, based on previous definitions by contributing authors	Previous high-tide HWL?	As above?	Aerial photographs	Manual	(Honeycutt, Crowell, and Douglas, 2001; Zhang, Douglas, and Leatherman, 2002)
High-water line	On a rising tide = maximum runup limit; on a falling tide = part of beach that is still wet, but it may be beyond the instantaneous runup limit	Wet/dry line	Clearly visible on all photos. Variation due to sand drying is not quantified. Affected by wind/wave/tide conditions at the time. Dolan, Hayden, and Heywood, (1978) infer that the wet/dry line is a stable shoreline indicator and is less sensitive to tidal stage than the instantaneous runup limit.	Aerial photographs	Manual	(Dolan, Hayden, and Heywood, 1978; Dolan *et al.,* 1979; Hayden, Dolan, and Felder, 1979; Doland *et al.,* 1980; Fenster and Dolan, 1999)
High-water line	The location of the wet and dry beach contact or the high-water debris line	Previous high-tide HWL; or storm/debris line	May not be clearly visible. Affected by wind/wave/tide conditions at the time; or represents only elevated water conditions during storms.	Aerial photographs	Manual	(McBride *et al.,* 1991)

Table 1. *Continued.*

Reported Shoreline Indicator	Identification of Feature	Generic Name	Comments	Source	Detection Technique	Reference
High-water line	Zone of high-pixel brightness variance	Unknown: near the shorebreak?	Analysis enhances the edge detection. Position Affected by wind/wave/tide conditions at the time.	Scanned aerial photographs	Supervised digital image analysis	(Shoshany and Degani, 1992)
High-water line	Change in color or shade of the beach sand, or a line of seaweed and debris	Previous high-tide HWL; or storm/debris line	May not be clearly visible. Affected by wind/wave conditions at the time; or represents only elevated water conditions during storms.	Aerial photographs	Manual	(Gorman, Morang, and Larson, 1998)
High-water line	Wet/dry boundary on a beach, recognized by an abrupt or subtle change in contrast. May be obscured by shell deposits, debris along the beach, or vegetation; or the outer limits of emergent marsh vegetation as seen in lagoons and estuaries.	Previous high-tide HWL; or seaward estuarine vegetation line	May not be clearly visible. Affected by wind/wave/tide conditions at the time; marsh vegetation may not die off rapidly in erosion or accretion conditions, so a time lag may be present.	Aerial photographs	Manual	(Byrnes, McBride, and Hiland, 1991)
High-water line	Visible in the field and can be identified by the change in gray or color tone on aerial photographs	Previous high-tide HWL	May not be clearly visible. Affected by wind/wave conditions at the time.	ARGUS video image "snapshot"	Manual	(Zhang *et al.,* 2002)
Usual (or mean) high-water line	Seaward edge of vegetation; or high-water line left by last storm. Identified by residuals such as sticks, branches, weed clumps; or water line of last high tide identified by points of darker tone, an identifiable edge after drying and receedance of the tide.	Seaward vegetation line; or storm/debris line; or previous high-tide HWL	Vegetation not always present. Good erosion indicator, but may not show accretion or will show it with a significant time lag; or only represents elevated water conditions during storms; or may not be clearly visible. Affected by wind/wave conditions at the time.	Aerial photographs	Manual	(McBeth, 1956)
Mean high-water line	The intersection of the plane of mean high water with the shore. No further information given as to how this is recognized on an aerial photograph.	Unknown	Unknown	Aerial photographs	Manual	(Everts and Gibson, 1983)
Mean high water	Tidal datum–based MHW is superimposed on a digital terrain model of the subaerial beach	Mean high water	Actual MHW	Stereo pair of aerial photographs	Digital: actual MHW	(Fisher and Overton, 1994; Parker, 2001)
Mean high water	Tidal datum–based MHW is superimposed on a digital terrain model of the subaerial beach	Mean high water	Actual MHW	Survey data	Digital: actual MHW	(List and Farris, 1999)
Mean high water	Tidal datum–based MHW is superimposed on a digital terrain model of the subaerial beach	Mean high water	Actual MHW	LIDAR	Digital: actual MHW	(Stockdon *et al.,* 2002)
Mean high water	Aerial photography taken during a tidally predicted window of time. Total absorption of infrared radiation by water greater than 1 cm deep.	Mean high water	Does not account for short-term hydrodynamic variation (waves, runup, etc.).	Aerial photographs (visual and infrared wavelengths)	Manual?	(Hess, 2003)
Mean high-water line	Changes in color or gray tone	Previous high-tide HWL	May not be clearly visible. Affected by wind/wave conditions at the time.	Aerial photographs	Manual	(Galgano and Leatherman, 1991)

Table 1. *Continued.*

Reported Shoreline Indicator	Identification of Feature	Generic Name	Comments	Source	Detection Technique	Reference
Average high-water line	Boundary between where an average high tide often reaches and where higher high water reaches less frequently. Landward of the smooth sand (high reflectance) caused by recent swash. Seaward of wind-rippled sand that represents longer aerial exposure. A line of driftwood or seaweed deposits was often the landward edge. Dewatering line also used for identification during a falling tide. Sparse seaward edge of vegetation used when changes in beach reflectivity (tonal contrast) allowed for two possible choices. If insufficient variation existed, then operator selected a point equidistant from instantaneous water line and seaward edge of vegetation.	Undefined. Between instantaneous water line and seaward edge of vegetation.	Not consistent	Aerial photographs	Manual	(KAMINSKY *et al.*, 1999)
Instantaneous high-water line	Undefined	Undefined	Unkonwn	Aerial photographs	Manual	(MORTON and MCKENNA, 1999)
PIC shoreline	Differentiates pixels based on the color difference between the "wet" and "dry" beach using H, S, and V. The "wet" and "dry" parts of the beach form well-separated clusters in HS space, and hence can be classified as "wet" or "dry." Calculates the vertical position of the shoreline based on recorded tide and wave information.	Unknown. Between instantaneous water line and maximum runup limit.	Determines an objective shoreline. Repeatable (scientifically valid). Automated (very quick). Accounts for tide and wave conditions (calculates z elevation). Actual shoreline location is unknown.	ARGUS video time-exposure image	Digital image analysis	(AARNINKHOF, CALJOUW, and STIVE, 2000; CALJOUW, 2000; DRONKERS, 2001 AARNINKHOF, 2003)
CBD shoreline	Differentiates pixels based on the reflectance properties of "wet" and "dry" regions based on a divergence of the relative intensity in the RGB spectrum	As above	Determines an objective shoreline. Repeatable (scientifically valid). Automated (very quick). Actual shoreline location is unknown. Affected by wind/wave conditions at the time, but only undertaken when significant wave height <1 m.	ARGUS video time-exposure image	Digital image analysis	(TURNER and LEYDEN, 2000; AARNINKHOF, 2003)
ANN shoreline	Differentiates pixels based on the color difference between the "wet" and "dry" beach using an artificial neural network. Inputs to ANN are the RGB values of a pixel. The output is a binary classification of either water (0) or sand (1).	As above	Determines an objective shoreline. Repeatable (scientifically valid). Automated (very quick). Affected by wind/wave conditions at the time. Actual shoreline location is unknown.	ARGUS video time-exposure image	Digital image analysis	(AARNINKHOF, 2003)

Table 1. *Continued.*

Reported Shoreline Indicator	Identification of Feature	Generic Name	Comments	Source	Detection Technique	Reference
Shoreline	Color or gray scale difference (light blue = ocean, and light yellow = beach). Detected line approximated to a reference tide level by comparing the date and time of the photo with tidal predictions.	Tide-adjusted instantaneous water line	Affected by wind/wave conditions at the time.	Aerial photographs	Manual	(Demirpolat and Tanner, 1991)
Wet/dry line	On a rising tide = maximum runup limit; on a falling tide = part of beach that is still wet, but it may be beyond the instantaneous runup limit	Wet/dry line	Clearly visible on all photos. Variation due to sand drying is not quantified. Affected by wind/wave conditions at the time. Dolan, Hayden, and Heywood, (1978) infer that the wet/dry line is a stable marker of the shore and is less sensitive to tidal stage than the instantaneous runup limit.	Aerial photographs	Manual	(Overton *et al.,* 1999)
Wet/dry line	Distinct edge in image based on tonal differences (brightness) between the dry and wet beach areas	Unknown. Between instantaneous water line and maximum runup limit.	Affected by wind/wave conditions at the time. Not specific enough. Requires operator input to detect shoreline.	Aerial photographs	Supervised digital image analysis	(Hoeke, Zarillo, and Synder, 2001)
Wetline	Undefined	Undefined	Unknown	Aerial photographs	Manual	(Douglass, Sanchez, and Jenkins, 1999)
Water line	Land/water boundary shown by a variation in color or gray tone	Instantaneous water line	As above	Aerial photographs	Manual	(Stafford and Langfelder, 1971)
Mean water level	Not clearly defined	Instantaneous water line?	Needs to be corrected for tide and wind/wave conditions.	Aerial photographs	Manual	(Jimenez *et al.,* 1997)
Shoreline intensity maxima	The maximum intensity (brightness) of the time-averaged shorebreak	Shorebreak maximum intensity	Not useful in locations with wide swash zones. Affected by wind/wave conditions at the time.	ARGUS video time-exposure image	Digital image analysis	(Plant and Holman, 1996; Plant and Holman, 1997; Aarninkhof, 2003)
Mean lower low water line (MLLW)	Tidally determined MLLW is superimposed on a three-dimensional model of the sub aerial beach	Mean lower low water line	Actual MLLW	Stereo pair of aerial photographs	Digital: actual MLLW	(Fisher and Overton, 1994)
Beach toe	Change in slope at the transition between nearshore and foreshore. Natural feature that marks the seaward edge of the beach. Crest of beach step, marked by a distinct tonal contrast by the change in water depth over the feature.	Beach toe/crest of beach step	Not visible at many locations	Aerial photographs	Manual	(Coyne, Fletcher, and Richmond, 1999; Norcross, Fletcher, and Merrifield, 2002)

* DGPS = Differential Global Positioning System, HWL = high-water line, MHW = mean high water, LIDAR = light detection and ranging, PIC = Pixel Intensity Clustering, H = hue, S = saturation, V = value, CBD = Color Band Divergence, RGB = red, blue, and green spectrum, ANN = artificial neural network, MLLW = mean lower low water.

† Crowell, Douglas, and Leatherman (1997) contains a printing error (misplaced parenthesis). The authors actually used two shorelines indicators, the HWL as defined by the wet/dry boundary and the bluff line (Crowell, personal communication, 2003).

1990). Of some concern is that the definition provided by the authors (if indeed a definition is documented) varies considerably between studies. Because of its widespread application, the definition and interpretation of the HWL has received considerable attention in the literature. A significant body of research (*e.g.,* ANDERS and BYRNES, 1991; MOORE, 2000; PAJAK and LEATHERMAN, 2002; STOCKDON *et al.,* 2002) has shown that the interpretation of the HWL from aerial photographs has the potential to be a significant source of error for shoreline mapping. For example, the HWL may not appear as a distinct line but instead may appear as a transitional zone or may not be visible at all (CROWELL, LEATHERMAN, and BUCKLEY, 1991).

MCBETH (1956) suggested that the previous high-tide HWL will appear as a static, shore-parallel band, even after the tide has receded and the shore has been exposed to drying from the sun. Some studies (*e.g.,* CROWELL, LEATHERMAN, and BUCKLEY, 1991; LEATHERMAN, 1983; STAFFORD and LANGFELDER, 1971) also use the term *wet/dry line* to describe this feature. However, this terminology introduces a further source of potential uncertainty, because other authors (*e.g.,* DOLAN, HAYDEN, and HEYWOOD, 1978; DOLAN *et al.,* 1980; OVERTON *et al.,* 1999) consider the wet/dry line to be the rising maximum runup limit on a flooding tide, and the landward extent of the falling "wetted" beach during tidal ebb.

Table 1 highlights the uncertainties inherent in the visual interpretation of proxy shoreline features. Inspection of an aerial photograph (for an example, refer to Figure 2) will often reveal multiple shore-aligned bands around the waterline (PAJAK and LEATHERMAN, 2002). These shore-aligned bands may be interpreted by different researchers as any one of several shoreline indicator features, including the previous HWL, the debris line, a prior HWL, heavy mineral lag deposits, vehicle tracks, or erosion scarps (MOORE, 2000; PAJAK and LEATHERMAN, 2002).

Many of the indicator features identified in Table 1 do not take account of the spatial and temporal influences in shoreline position; for example, they do not consider the prevailing tide and wave conditions at the time the "shoreline" was mapped. For example, on a low, sloping beach, the horizontal offset of a shoreline indicator feature (*e.g.,* the HWL) due to wave, tide, or wind effects can be on the order of several tens of meters (THIELER and DANFORTH, 1994). Seasonal influences may also significantly affect the position of the shoreline indicator relative to the land–water interface (MOORE, 2000; SMITH and ZARILLO, 1990). Storminess and short-term shoreline variability are also significant factors that need to be taken into account when assessing longer-term trends of shoreline change (CROWELL, LEATHERMAN, and BUCKLEY, 1993; FENSTER, DOLAN, and MORTON, 2001; HONEYCUTT, CROWELL, and DOUGLAS, 2001; LIST and FARRIS, 1999; MORTON, 1991; SMITH and ZARILLO, 1990; ZHANG, DOUGLAS, and LEATHERMAN, 2002).

Ideally, the selection and definition of the preferred proxy shoreline feature would be determined by the context of the specific investigation. For example, in New Zealand, "mean high-water springs" is a legal planning boundary (NEW ZEALAND GOVERNMENT, 1991) and hence is of particular interest. In practice, the decision as to which shoreline indicator to use at a specific location is almost always determined by data availability. For example, in the United States, where aerial photography is generally available and geographic positioning system (GPS) survey techniques are widely used, the HWL and the wet/dry line are among the most common shoreline indicator features used as proxies for the position of MHW. A summary of the data sources that have been used for shoreline investigation is presented next.

DATA SOURCES

A variety of data sources are available to examine the position of the shoreline. At the great majority of coastal sites, historical data is limited or nonexistent. As a result, the choice of what data to use at a specific site is generally determined by the availability of data. Sampling of past shoreline trends tends to be opportunistic, based on what is historically available for the site of interest. This often means that different sources are used in a single study (introducing additional potential uncertainty) to achieve the desired temporal coverage. A number of the common data sources that are used for shoreline analysis are briefly described in the following sections.

Historical Land-Based Photographs

Historical land-based photographs provide general background information to the coastal investigator, such as the presence of a specific morphological feature such as a sand spit or channel entrance. However, most land-based photos are by definition very oblique, with limited information available of scale or ground control points, and there is usually no information about the sea conditions (tide and waves) at the time the photograph was taken (DOLAN, HAYDEN, and MAY, 1983). For these reasons, the majority of historical photographs are of limited value for application to quantitative mapping of past shorelines.

Coastal Maps and Charts

Although often rather striking to examine, a large proportion of early historical maps and charts focused as much on decoration as they did on content, with minimal information recorded as to the mapping methods used, the specific shoreline feature selected, and assessments of accuracy (CARR, 1962). Mapping and charting techniques became more reliable in the late 18th century (CARR, 1962), and these maps and charts can be useful for shoreline change investigations. Maps and charts provide good spatial coverage, but temporal coverage can be restricted, and is most often very site specific (DOLAN, HAYDEN, and MAY, 1983).

The oldest reliable source of shoreline data in the United States is the US Coast and Geodetic Survey/National Ocean Service T-sheets, which date back to the early to mid-1800s in some areas (MORTON, 1991). The T-sheets detail the position of the HWL as estimated on site by a surveyor "by noting the vegetation, driftwood, discoloration of rocks, or other visible signs of high tides" (SHALOWITZ, 1964). This position is unlikely to be the actual vertical/horizontal position of MHW, but it is generally used as a proxy for MHW. The maximum error in the location of the HWL location on T-sheets is estimated to be on the order of 10 meters (SHALOWITZ, 1964).

In the United Kingdom, many maps and charts were inaccurate until around 1750 (BAILEY and NOWELL, 1996; CARR, 1962). In 1791, the Ordnance Survey was founded, and the accuracy of mapping began to increase and has continued to improve (BAILEY and NOWELL, 1996). The Ordnance Survey maps extended down to the high-water mark, whereas the Admiralty's Hydrographic Office charts extended seaward from the low-water mark, thus leaving a large unsurveyed area (BAILEY and NOWELL, 1996).

Potential errors associated with historical coastal maps and charts include errors in scale; datum changes; distortions from uneven shrinkage, stretching, creases, tears, and folds; different surveying standards; different publication standards; projection errors; and partial revision (ANDERS and BYRNES, 1991; CARR, 1962, 1980; CROWELL, LEATHERMAN, and BUCKLEY, 1991; MOORE, 2000). However, their advantage is being able to provide a historic record that is not available from other data sources. By necessity, the "shoreline" that is obtained from historical maps and charts is determined by the surveyor and cartographer rather than the coastal investigator, and it is generally assumed to have been associated with some type of visibly discernible feature.

Aerial Photography

Vertical aerial photographs of the coastline began to be collected around the world in the 1920s (ANDERS and BYRNES, 1991; CROWELL, HONEYCUTT, and HATHEWAY, 1999), but it was not until the late 1930s that reasonable-quality stereo aerial photos became available (ANDERS and BYRNES, 1991). Aerial photographs provide good spatial coverage of the coast (DOLAN, HAYDEN, and MAY, 1983), but temporal coverage is very site specific. Historical aerial photography may also be temporally biased toward poststorm "shorelines" (DOUGLAS, CROWELL, and HONEYCUTT, 2002). By definition, the "shoreline" obtained from aerial photography is based on a visually discernible feature.

Aerial photographs are distorted and must be corrected before they can be used to determine a shoreline. Common distortions include radial distortion, relief distortion, tilt and pitch of the aircraft, and scale variations caused by changes in altitude along a flight line (ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; MOORE, 2000; THIELER and DANFORTH, 1994).

Modern softcopy photogrammetry allows a digitally scanned pair of aerial photos to be converted into a three-dimensional digital terrain model and a georectified orthophoto (HAPKE and RICHMOND, 2000; OVERTON and FISHER, 1996). The addition of datum-referenced elevation information allows tidal datum–based shorelines to be easily and accurately determined. Where it is available, aerial photography is the most common data source for determining past shoreline positions.

Beach Surveys

Survey data can be an accurate source of shoreline information (DOLAN, HAYDEN, and MAY, 1983; GOLDSMITH and OERTEL, 1978). However, historical records tend to be limited both spatially (MORTON, 1991) and temporally (DOLAN, HAYDEN, and MAY, 1983; GOLDSMITH and OERTEL, 1978; SMITH and JACKSON, 1992). This is generally attributable to the high costs of the labor-intensive method of sending survey teams out into the field to obtain the data (DOLAN, HAYDEN, and MAY, 1983; OVERTON and FISHER, 1996). A shoreline can be compiled by interpolating between a series of discrete shore-normal beach profiles. Often the alongshore distance between adjacent profiles is relatively large, so alongshore accuracy of shoreline location is diminished accordingly (MORTON, 1991). If sufficient beach profiling data are available for a specific site, tidal datum-based shorelines, such as MHW, are easily and accurately determined.

GPS Shorelines

A more recent method of mapping the shoreline is to use a kinematic differential GPS mounted on a four-wheel-drive vehicle, which is driven at a constant speed along the visibly discernible line of interest (MORTON *et al.,* 1993). The benefits of this method are that it is relatively rapid, low cost, and highly accurate (MORTON and SPEED, 1998). With modern GPS equipment, the greatest errors associated with this method are caused by the visual determination of the line of interest by the operator, rather than error from the GPS measurements. PAJAK and LEATHERMAN (2002) concluded that the GPS method was more accurate than aerial photography to identify specific shoreline features of interest.

Remote Sensing

Over the last decade, a range of airborne, satellite, and land-based remote sensing techniques have become more generally available to the coastal scientist, coastal engineer, and coastal manager. Depending on the specific platform that is used, derived shorelines may be based on the use of visually discernible coastal features, digital image-processing analysis, or a specified tidal datum.

Multispectral/Hyperspectral Imaging

Satellites now provide near-continuous monitoring of many of the world's shorelines (MORTON, 1991). Traditional multispectral satellite-flown instruments, such as Landsat, SPOT, *etc.,* generate a discrete signal in a limited number of broadbands (CRACKNELL, 1999). Hyperspectral imaging provides wide and continuous spectral coverage (RICHARDS AND JIA, 1999). The main limitations of this data source to coastal investigations are the pixel resolution and cost (CRACKNELL, 1999). The high cost means that data are generally limited both spatially and temporally. The advantages of multispectral/hyperspectral imagery are the large areas that can be covered and the detailed spectral information provided. Shorelines may be derived from visibly discernible coastal features (using true- or false-color imagery) or by the application of digital image-processing techniques.

Airborne Light Detection and Ranging Technology

Airborne light detection and ranging technology (LIDAR) has the ability to cover hundreds of kilometers of coast in a relatively short period (STOCKDON *et al.,* 2002); LIDAR is based on the measurement of the time it takes a laser beam, from leaving the instrument, to return after reflection (CRACKNELL, 1999). Knowledge of the speed of light allows a distance to be calculated, and the use of differential GPS specifies an exact location. Tidal datum-based shorelines, such as MHW, can then be found by fitting a function to cross-shore profiles of LIDAR data (STOCKDON *et al.,* 2002). This data source is generally limited in its temporal and spatial availability because of cost. The main advantage of LIDAR data is that it can cover large areas very quickly.

Microwave Sensors

Data from the microwave range of wavelengths can be collected using airborne side-looking airborne radar or spaceborne synthetic aperture radar (CRACKNELL, 1999). Information about the point on the ground is calculated based on the return period of the signal and signal strength (RICHARDS AND JIA, 1999). Large spatial areas can be covered using radar technology, but the cost is high (RICHARDS AND JIA, 1999). Data can be easily converted into a digital terrain model (CRACKNELL, 1999), providing good determination of tidal datum-based shorelines.

Video Imaging

The advent of digital imaging technology has enabled higher-frequency and continuous images of the coast to be collected in the visible wavelengths. These systems have the capability to monitor detailed changes in the coastal system, as well as providing long-term shoreline change information (given time).

One example is the Argus coastal imaging system (HOLMAN *et al.,* 1993). An Argus station consists of one or more cameras pointed obliquely along the coastline. The cameras are connected to an automated computer, which controls the capture and preprocessing of the images. The original images are oblique and need to be corrected before they can be used to determine a shoreline. The fixed location of the sensor means that only the lens characteristics (radial distortion) and ground control points are required to create a georectified image (HOLLAND *et al.,* 1997). The Argus system has the ability to collect time-averaged images as well as instantaneous images. All other data sources discussed in prior sections collect only an instantaneous record.

These types of systems provide temporally dense but spatially limited data sets. In other words, although the coverage is limited to the discrete locations that have coastal imaging systems installed, the data collection at those locations is continuous. The density of data means that short-term fluctuations can be resolved (*i.e.,* pre- and postevent shorelines), and given time, these locations will develop detailed long-term shoreline change information.

SHORELINE DETECTION

The identification of a "shoreline" involves two stages. The first requires the selection and definition of a shoreline indicator that will act as a proxy for the land-water interface. The range of indicator features that have been used by coastal investigations (and an overview of their associated advantages and limitations) were discussed in the preceding sections. The second stage of shoreline identification involves the detection of the chosen shoreline indicator within the available data source. Both the technique for identifying the shoreline position (shoreline detection) and the assumptions made regarding the definition of the shoreline (selection of the shoreline indicator) have the potential to induce error when estimating a shoreline position (STOCKDON *et al.,* 2002).

The most common shoreline detection technique applied to visibly discernible shoreline features is manual visual interpretation, either in the field or from aerial photography (refer to Table 1). For example, with aerial photography, the image is corrected for distortions and then adjusted to the correct scale before a "shoreline" is either traced directly or scanned into a computer, corrected, adjusted for scale, and digitized. In the field, a GPS is used to digitize the visible shoreline feature *in situ,* as determined by the operator.

All but the most recent shoreline detection techniques have relied upon manual interpretation (LIST and FARRIS, 1999). These methods are by definition subjective. Manual identification relies on the individual skills of the interpreter or photogrammetrist (ANDERS and BYRNES, 1991; BYRNES, MCBRIDE, and HILAND, 1991; DOLAN, HAYDEN, and MAY, 1983; MCBETH, 1956) and often may require the operator to be familiar with the specific location, including knowledge of factors that may have affected the position of the shoreline, such as hurricanes, beach replenishment, *etc.* (BYRNES, MCBRIDE, and HILAND, 1991). PAJAK and LEATHERMAN (2002) found that scientists experienced in interpreting the shoreline position (in this case the HWL) using a data set from Assateague Island, Maryland, were unable to correctly identify this feature using an aerial print, but they realized that their interpretations were incorrect when provided with higher-resolution color slides. An adverse outcome of inherent subjectivity is that the spatial error in determining historic shoreline positions may exceed the predicted rate of shoreline change.

It has been suggested that the detection of a chosen visible shoreline indicator feature may be more subjective and less accurate when determined from aerial photographs compared with *in situ* detection in the field (CROWELL, LEATHERMAN, and BUCKLEY, 1991; PAJAK and LEATHERMAN, 2002). Unfortunately, many of the features indicating the position of the shoreline indicator, such as HWL, may be remnants of previous high-water events and may not represent the true position of the most recent maximum runup limit. An individual HWL has no reference to a tidal datum or a fixed elevation; instead, it may represent a combination of a number of factors, including preexisting beach face morphology, atmospheric (weather) conditions, and the prevailing hydrodynamic conditions. No matter which visually detected shoreline indicator is selected, by definition there can be no means of objective, quantitative control on the repeatability of this inherently subjective detection method.

Despite the significant and valuable insights that have been gained at a great many coastal locations around the world, it is a necessary criticism that the prevailing visual shoreline detection techniques are overly reliant upon opportunistic data collection and subjective interpretation. There is a recognized need by coastal investigators to improve the accuracy of shoreline mapping (MORTON, 1991). This can be achieved by the development of more objective, robust, and repeatable detection techniques.

Objectivity, Robustness, and Repeatability of Detection Techniques

Objective "shoreline" detection is now possible for tidal datum shoreline indicators, such as MHW. Techniques such as softcopy photogrammetry (HAPKE and RICHMOND, 2000; OVERTON and FISHER, 1996), the use of LIDAR topographic data (STOCKDON *et al.,* 2002), and survey data can be used to create a digital terrain model of the coastline, from which a tidal datum-based indicator can be determined (Figure 3).

Although these techniques are useful for modern data sets, their applicability to the analysis of historical trends is more limited. It is possible to generate a tidal datum-based historical shoreline using existing aerial photographs and softcopy photogrammetry if good-quality stereo pairs exist and if accurate ground control points can be identified (BROWN and ARBOGAST, 1999). Otherwise, for the purpose of shoreline change analysis, it is necessary to integrate subjective historical shorelines with modern objective analysis. The differing accuracy and potential offset between the two data sets must be carefully considered.

Objective detection methods for application to visual shoreline features have recently been developed using supervised and unsupervised classification techniques. For example, neural network classification (refer to RICHARDS AND JIA, 1999) has been used successfully to distinguish between two classes, water and sand (KINGSTON *et al.,* 2000), as has an unsupervised isodata classification method (refer to TOU and GONZALEZ, 1974) to achieve the same distinction between water and land (AARNINKHOF, CALJOUW, and STIVE, 2000). A supervised critical threshold classification technique has been applied to determine the boundary between dry sand and the inner surf zone (TURNER *et al.,* 2000), and an unsupervised intensity maxima classification technique has been used to determine the alongshore alignment of the shorebreak (PLANT and HOLMAN, 1997).

With the exception of the intensity maxima technique just mentioned, which relies on grayscale imagery, these types of objective shoreline detection techniques utilize the color information contained in digital images (*i.e.,* red, green, and blue). In a physical sense, as light penetrates a water surface, wavelengths from the red range ($\sim$0.7 μm) of the electromagnetic spectrum are attenuated more rapidly than those from the blue range ($\sim$0.4 μm). This results in a "wet" pixel being predominantly blue and green (because the red component has been absorbed), whereas a "dry" beach pixel exhibits all three components. In essence, each of these techniques manipulates this optical information in a slightly different manner to objectively define a proxy (and not necessarily visually discernible) shoreline feature.

The objective detection techniques just described, along with other comparable digital image-processing methodologies, can be used to identify a robust and repeatable shoreline indicator feature for shoreline investigation. However, a fundamental shortcoming of these new objective methods is that they still do not resolve the basic question of the relation of the specific shoreline indicator feature to the land–water interface. For example, a recent comparative study (PLANT *et al.,* in press) has shown that the four digitally processed indicator features described earlier all occur between the elevations of the shorebreak and the maximum runup limit. The four methods described were independently tested for consistency (compared with each other) and accuracy (compared with survey data) and were found to be well correlated. However, the shoreline indicators were offset from each other and, to a constant but differing degree, from the time-averaged intersection of the land and water surfaces.

Overall, it is concluded that objective detection techniques are now available to coastal researchers to map a range of objective shoreline indicator features, using either a digital terrain model combined with local tidal datum information, or a supervised/unsupervised digital image-processing classification methodology.

THE REMAINING CHALLENGE: A PROCESS-BASED DEFINITION OF DETECTED SHORELINE INDICATORS

The wider availability of image-processing technology now provides coastal investigators the ability to objectively map a range of robust and repeatable shoreline indicators using digital coastal imagery (*e.g.,* aerial photography, coastal imaging). However, the fact that the detected shoreline features are differentially but consistently offset (*i.e.,* vertical/horizontal displacement) from one another indicates that a range of physical characteristics in the vicinity of the land–water interface are being detected. What these different features are and, more critically, the quantitative relationship of these to physical parameters—such as the still-water level, runup limit, groundwater exit point, and swash exceedance levels—are questions that to date have received little attention.

It is reasonable to speculate that a number of factors could potentially influence the position of shoreline indicator features obtained by digital image analysis. The stage of the tide, beach slope, the prevailing wave energy, and the position of the groundwater exit point are likely to be of particular significance. For example, at short temporal scales comparable to the wave period, individual runup maxima and minima have the potential to affect the position of the instantaneous waterline by tens of meters across a low-slope beach. Secondary factors may include the mineralogy and grain size of the sediments, the solar zenith angle, and the sensor's viewing geometry. Together, these factors require further investigation to achieve the ultimate objective of a process-based definition of any specific shoreline indicator feature.

Some progress has been made in the area of optimizing the manner in which image data are collected for shoreline investigation. The use of time-averaged (or time-exposure) images has the effect of averaging out short-term fluctuations due to incident wave modulations (LIPPMANN and HOLMAN, 1989) and thus provides a more controlled image for shoreline detection. Although the averaging "smooths" the data and removes the effects of individual runup excursions, it also results in less wet/dry distinction in the swash zone. No longer is there a clearly visible wet/dry boundary, such as a change in tone; instead, this is replaced by a less distinct swash continuum (PAJAK and LEATHERMAN, 2002). The digital image-processing detection techniques noted earlier were indeed all developed for use with time-averaged images. Further work is required to determine the optimum sampling rate and time period over which to average the images. At the present time, collection periods on the order of 10 minutes at 1 Hz are common.

CONCLUDING REMARKS

The use by coastal researchers of the term *shoreline* is likely to remain for some time as dynamic as the feature it defines. Different data sources and a diverse range of applications of this information will continue to influence the type of shoreline indicators chosen and their method of detection. At the present time, it appears unlikely that a single shoreline indicator feature will at some time in the future suit all types of data and applications.

Temporal consideration of the "shoreline" obtained from imagery has been improved by a trend toward the analysis of time-averaged images. This approach is still to be fully optimized for shoreline change research. The temporally dense data sets that are now provided by a range of remote sensing platforms can be used for shoreline trend analysis at sampling periods of hours, days, or years (given time). In the future, these new capabilities will increasingly remove the reliance on regression, end-point, or other sparse data interpolation techniques.

Shoreline detection and definition have improved with the availability of new image capture, processing, and analysis technology. Tidal datum-based shorelines can now be determined from a number of data sources using digital terrain models.

Techniques have also been developed to detect robust and objective shoreline features using two-dimensional image data, but the physical basis of these indicator features is yet to be adequately defined. A quantitative and process-based interpretation of these shoreline indicators—and their spatial relationship relative to the physical land–water interface—is the focus of current research.

ACKNOWLEDGMENTS

The Tweed River Entrance Sand-Bypassing Project (TRESBP), a joint initiative of the New South Wales and Queensland State Governments, is acknowledged for funding the first author's postgraduate scholarship to undertake this research. The constructive comments of Mark Crowell on an earlier version of this manuscript were gratefully appreciated.

LITERATURE CITED

AARNINKHOF, S.G.J., 2003. Nearshore Bathymetry Derived from Video Imagery. Delft, The Netherlands: Delft University of Technology, Doctoral thesis, 155p.

AARNINKHOF, S.G.J.; CALJOUW, M., and STIVE, M.J.F., 2000. Video-based, quantitative assessment of intertidal beach variability. *Proceedings of the 27th International Conference on Coastal Engineering* (Sydney, Australia), pp. 3291–3304.

ANDERS, F.J. and BYRNES, M.R., 1991. Accuracy of shoreline change rates as determined from maps and aerial photographs. *Shore and Beach,* 59(1), 17–26.

BAILEY, B. and NOWELL, D., 1996. Techniques for monitoring coastal change: a review and case study. *Ocean and Coastal Management,* 32(2), 85–95.

BATTIAU-QUENEY, Y.; BILLET, J.F.; CHAVEROT, S., and LANOY-RATEL, P., 2003. Recent shoreline mobility and geomorphic evolution of macrotidal sandy beaches in the north of France. *Marine Geology,* 194, 31–45.

BELLOMO, D.; PAJAK, M.J., and SPARKS, M.J., 1999. Coastal flood hazards and the National Flood Insurance Program. *Journal of Coastal Research,* Special Issue No. 28, pp. 21–26.

BROWN, D.G. and ARBOGAST, A.F., 1999. Digital photogrammetric change analysis as applied to active coastal dunes in Michigan. *Photogrammetric Engineering and Remote Sensing,* 65(4), 467–474.

BYRNES, M.R.; MCBRIDE, R.A., and HILAND, M.W., 1991. Accuracy standards and development of a national shoreline change database. *Proceedings of the Coastal Sediments '91* (Seattle, Washington), pp. 1027–1042.

CALJOUW, M., 2000. Video-based monitoring of the Egmond beach and shoreface nourishments. Delft, The Netherlands: Delft University of Technology, Master's thesis.

CARR, A.P., 1962. Cartographic record and historical accuracy. *Geography,* 47, 135–144.

CARR, A.P., 1980. The significance of cartographic sources in determining coastal change. *In*: CULLINGFORD, R.A.; DAVIDSON, D.A., and LEWIN, J. (eds.), *Timescales in Geomorphology.* New York: John Wiley and Sons, pp. 69–78.

COASTAL ENGINEERING RESEARCH CENTER, 1984. *Shore Protection Manual,* Volumes 1 and 2. Washington, DC: US Army Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center.

COYNE, M.A.; FLETCHER, C.H., and RICHMOND, B.M., 1999. Mapping coastal erosion hazard areas in Hawaii. *Journal of Coastal Research,* Special Issue No. 28, pp. 171–184.

CRACKNELL, A.P., 1999. Remote sensing techniques in estuaries and coastal zones—an update. *International Journal of Remote Sensing,* 19(3), 485–496.

CROWELL, M.; DOUGLAS, B.C., and LEATHERMAN, S.P., 1997. On forecasting future U.S. shoreline positions: a test of algorithms. *Journal of Coastal Research,* 13(4), 1245–1255.

CROWELL, M.; HONEYCUTT, M.G., and HATHEWAY, D., 1999. Coastal erosion hazards study: phase one mapping. *Journal of Coastal Research,* Special Issue No. 28, pp. 10–20.

CROWELL, M.; LEATHERMAN, S.P., and BUCKLEY, M.K., 1991. Historical shoreline change: error analysis and mapping accuracy. *Journal of Coastal Research,* 7(3), 839–852.

CROWELL, M.; LEATHERMAN, S.P., and BUCKLEY, M.K., 1993. Shoreline change rate analysis: long term versus short term. *Shore and Beach,* 61(2), 13–20.

DEMIRPOLAT, S. and TANNER, W.F., 1991. Keys to high-accuracy mapping of shoreline changes. *Proceedings of the Coastal Sediments '91* (Seattle, Washington), pp. 1054–1068.

DOLAN, R.; FENSTER, M.S., and HOLME, S.J., 1991. Temporal analysis of shoreline recession and accretion. *Journal of Coastal Research,* 7(3), 723–744.

DOLAN, R.; HAYDEN, B.P., and HEYWOOD, J., 1978. A new photogrammetric method for determining shoreline erosion. *Coastal Engineering,* 2(1), 21–39.
DOLAN, R.; HAYDEN, B.P.; MAY, P., and MAY, S.K., 1980. The reliability of shoreline change measurements from aerial photographs. *Shore and Beach,* 48(4), 22–29.
DOLAN, R.; HAYDEN, B.P., and MAY, S., 1983. Erosion of the US shorelines. *In*: Komar, P.D. (ed.), *CRC Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, pp. 285–299.
DOLAN, R.; HAYDEN, B.P.; REA, C., and HEYWOOD, J., 1979. Shoreline erosion rates along the middle Atlantic coast of the United States. *Geology,* 7, 602–606.
DOUGLAS, B.C. and CROWELL, M., 2000. Long-term shoreline position prediction and error propagation. *Journal of Coastal Research,* 16(1), 145–152.
DOUGLAS, B.C.; CROWELL, M., and HONEYCUTT, M.G., 2002. [Discussion of FENSTER, M.S.; DOLAN, R., and MORTON, R.A., 2001.] Coastal storms and shoreline change: Signal or noise? *Journal of Coastal Research,* 17(3), 714–720.] *Journal of Coastal Research,* 18(2), 388–390.
DOUGLAS, B.C.; CROWELL, M., and LEATHERMAN, S.P., 1998. Considerations for shoreline position prediction. *Journal of Coastal Research,* 14(3), 1025–1033.
DOUGLASS, S.L.; SANCHEZ, T.A., and JENKINS, S., 1999. Mapping erosion hazard areas in Baldwin County, Alabama and the use of confidence intervals in shoreline change analysis. *Journal of Coastal Research,* Special Issue No. 28, pp. 95–105.
DRONKERS, T., 2001. Intertidal Morphodynamics at Narrowneck Reef. Delft, The Netherlands: Delft University of Technology, Master's thesis, 51p.
ELIOT, I. and CLARKE, D., 1989. Temporal and spatial bias in the estimation of shoreline rate-of-change statistics from beach survey information. *Coastal Management,* 17, 129–156.
EVERTS, C.H. and GIBSON, P.N., 1983. Shoreline change analysis—one tool for improving coastal zone decisions. *Proceedings of the Sixth Australian Conference on Coastal and Ocean Engineering* (Gold Coast, Australia), pp. 122–131.
FARRELL, S.; LEPP, T.; SPEER, B., and MAURIELLO, M., 1999. Mapping erosion hazard areas in Ocean County. *Journal of Coastal Research,* Special Issue No. 28, pp. 50–57.
FENSTER, M.S. and DOLAN, R., 1999. Mapping erosion hazard areas in the City of Virginia Beach. *Journal of Coastal Research,* Special Issue No. 28, pp. 56–68.
FENSTER, M.S.; DOLAN, R., and MORTON, R.A., 2001. Coastal storms and shoreline change: signal or noise? *Journal of Coastal Research,* 17(3), 714–720.
FISHER, J.S. and OVERTON, M.F., 1994. Interpretation of shoreline position from aerial photographs. *Proceedings of the 24th International Conference on Coastal Engineering* (Kobe, Japan), pp. 1998–2003.
GALGANO, F.A. and LEATHERMAN, S.P., 1991. Shoreline change analysis: a case study. *Proceedings of the Coastal Sediments '91* (Seattle, Washington), pp. 1043–1053.
GOLDSMITH, V. and OERTEL, G., 1978. Beach profiling. *In*: Tanner, W.F. (ed.), *Standards for Measuring Shoreline Changes: Proceedings of a Workshop.* Tallahassee, Florida: Geology Department, Florida State University, pp. 37–41.
GORMAN, L.; MORANG, A., and LARSON, R., 1998. Monitoring the coastal environment. Part IV. Mapping, shoreline changes, and bathymetric analysis. *Journal of Coastal Research,* 14(1), 61–92.
GUY, D.E., 1999. Erosion hazard area mapping, Lake County, Ohio. *Journal of Coastal Research,* Special Issue No. 28, pp. 185–196.
HANSON, H.; GRAVENS, M.B., and KRAUS, N.C., 1988. Prototype applications of a generalized shoreline change numerical model. *Proceedings of the 21st International Conference on Coastal Engineering* (Costa del Sol-Malaga, Spain), pp. 1265–1279.
HAPKE, C. and RICHMOND, B.M., 2000. Monitoring beach morphology changes using small-format aerial photography and digital softcopy photogrammetry. *Environmental Geosciences,* 7(1), 32–37.
HAYDEN, B.P.; DOLAN, R., and FELDER, W., 1979. Spatial and temporal analyses of shoreline variations. *Coastal Engineering,* 2, 351–361.
HESS, K.W., 2003. Tidal datums and tide coordination. *Journal of Coastal Research,* Special Issue NO. 38, pp. 38–43.
HOEKE, R.K.; ZARILLO, G.A., and SYNDER, M., 2001. *A GIS Based Tool for Extracting Shoreline Positions from Aerial Imagery (BEACHTOOLS)* (Coastal Engineering Technical Note IV). Washington, DC: US Army Corps of Engineers, 12p.
HOLLAND, K.T.; HOLMAN, R.A.; LIPPMANN, T.C.; STANLEY, J., and PLANT, N.G., 1997. Practical use of video imagery in nearshore oceanographic field studies. *IEEE Journal of Oceanic Engineering,* 22(1), 81–92.
HOLMAN, R.A.; SALLENGER, A.H.; LIPPMANN, T.C., and HAINES, J.W., 1993. The application of video image processing to the study of nearshore processes. *Oceanography,* 6(3), 78–85.
HONEYCUTT, M.G.; CROWELL, M., and DOUGLAS, B.C., 2001. Shoreline-position forecasting: impact of storms, rate-calculation methodologies, and temporal scales. *Journal of Coastal Research,* 17(3), 721–730.
JIMENEZ, J.A.; SANCHEZ-ARCILLA, A.; BOU, J., and ORTIZ, M.A., 1997. Analysing short-term shoreline changes along the Ebro Delta (Spain) using aerial photographs. *Journal of Coastal Research,* 13(4), 1256–1266.
KAMINSKY, G.M.; DANIELS, R.C.; HUXFORD, R.; MCCANDLESS, D., and RUGGIERO, P., 1999. Mapping erosion hazard areas in Pacific County, Washington. *Journal of Coastal Research,* Special Issue No. 28, pp. 158–170.
KINGSTON, K.S.; RUESSINK, B.G.; VAN ENCKEVORT, I.M.J., and DAVIDSON, M.A., 2000. Artificial neural network correction of remotely sensed sandbar location. *Marine Geology,* 169, 137–160.
KOMAR, P.D., 1998. *Beach Processes and Sedimentation.* Upper Saddle River, New Jersey: Prentice Hall Inc., 544p.
KOMAR, P.D.; DIAZ-MENDEZ, G.M., and MARRA, J.J., 2001. Stability of the New River Spit, and the position of Oregon's beach-zone line. *Journal of Coastal Research,* 17(3), 625–635.
KRAUS, N.C. and ROSATI, J.D., 1997. Interpretation of shoreline-position data for coastal engineering analysis. *Coastal Engineering Technical Note* (CETN II-39). Vicksburg, Mississippi: US Army Waterways Experiment Station.
LEATHERMAN, S.P., 1983. Historical and projected shoreline mapping. *Proceedings of the Coastal Zone '83* (San Diego, California), pp. 2902–2910.
LEATHERMAN, S.P., 2001. Social and economic costs of sea level rise. *In*: DOUGLAS, B.C.; KEARNEY, M.S., and LEATHERMAN, S.P. (eds.), *Sea Level Rise History and Consequences.* San Diego, California: Academic Press, p. 232.
LEATHERMAN, S.P. and ANDERS, F.J., 1999. Mapping and managing coastal erosion hazards in New York. *Journal of Coastal Research,* Special Issue No. 28, pp. 34–42.
LEATHERMAN, S.P. and ESKANDARY, L.S., 1999. Evaluation of coastal erosion hazards along Delaware's Atlantic Coast. *Journal of Coastal Research,* Special Issue No. 28, pp. 43–49.
LIPPMANN, T.C. and HOLMAN, R.A., 1989. Quantification of sand bar morphology: a video technique based on wave dissipation. *Journal of Geophysical Research,* 94(C1), 995–1011.
LIST, J.H. and FARRIS, A.S., 1999. Large-scale shoreline response to storms and fair weather. *Proceedings of the Coastal Sediments '99* (Long Island, New York), pp. 1324–1337.
MCBETH, F.H., 1956. A method of shoreline delineation. *Photogrammetric Engineering,* 22(2), 400–405.
MCBRIDE, R.A.; HILAND, M.W.; PENLAND, S.; WILLIAMS, S.J.; BYRNES, M.R.; WESTPHAL, K.A.; JAFFE, B.E., and SALLENGER, A.H., 1991. Mapping barrier island changes in Louisiana: techniques, accuracy, and results. *Proceedings of the Coastal Sediments '91* (Seattle, Washington), pp. 1011–1026.
MCCURDY, P.G., 1950. Coastal delineation from aerial photographs. *Photogrammetric Engineering,* 16(4), 550–555.
MOORE, L.J., 2000. Shoreline mapping techniques. *Journal of Coastal Research,* 16(1), 111–124.
MOORE, L.J.; BENUMOF, B.T., and GRIGGS, G.B., 1999. Coastal erosion hazards in Santa Cruz and San Diego. *Journal of Coastal Research,* Special Issue No. 28, pp. 121–139.
MORTON, R.A., 1991. Accurate shoreline mapping: past, present, and

future. *Proceedings of the Coastal Sediments '91* (Seattle, Washington), pp. 997–1010.

MORTON, R.A.; LEACH, M.P.; PAINE, J.G., and CARDOZA, M.A., 1993. Monitoring beach changes using GPS surveying techniques. *Journal of Coastal Research,* 9(3), 702–720.

MORTON, R.A. and MCKENNA, K.K., 1999. Analysis and projection of erosion hazard areas in Brazoria and Galveston Counties, Texas. *Journal of Coastal Research,* Special Issue No. 28, pp. 106–120.

MORTON, R.A. and SPEED, F.M., 1998. Evaluation of shorelines and legal boundaries controlled by water levels on sandy beaches. *Journal of Coastal Research,* 14(4), 1373–1384.

NATIONAL RESEARCH COUNCIL, 1990. *Managing Coastal Erosion.* Washington, DC: National Academy Press, 182p.

NEW ZEALAND GOVERNMENT, 1991. *Resource Management Act.* Wellington, New Zealand: New Zealand Government, 382p.

NORCROSS, Z.M.; FLETCHER, C.H., and MERRIFIELD, M., 2002. Annual and interannual changes on a reef-fringed pocket beach: Kailua Bay, Hawaii. *Marine Geology,* 190(3–4), 553–580.

O'CONNELL, J.F. and LEATHERMAN, S.P., 1999. Coastal erosion hazards and mapping along the Massachusetts Shore. *Journal of Coastal Research,* Special Issue No. 28, pp. 27–33.

OVERTON, M.F. and FISHER, J.S., 1996. Shoreline analysis using digital photogrammetry. *Proceedings of the 25th International Conference on Coastal Engineering* (Orlando, Florida), pp. 3750–3761.

OVERTON, M.F.; GRENIER, R.R.; JUDGE, E.K., and FISHER, J.S., 1999. Identification and analysis of coastal erosion hazard areas: Dare and Brunswick Counties, North Carolina. *Journal of Coastal Research,* Special Issue No. 28, pp. 69–84.

PAJAK, M.J. and LEATHERMAN, S.P., 2002. The high water line as shoreline indicator. *Journal of Coastal Research,* 18(2), 329–337.

PARKER, B., 2001. Where is the shoreline? The answer is not as simple as one might expect. *Hydro International,* 5(5), 6–9.

PLANT. N.G.; AARNINKHOF, S.C.J., TURNER, I.L., and Kingston, K.S., in press. The performance of shoreline detection models applied to video imagery. *Journal of Coastal Research,* in press.

PLANT, N.G. and HOLMAN, R.A., 1996. Interannual shoreline variations at Duck, North Carolina, USA. *Proceedings of the 25th International Conference on Coastal Engineering* (Orlando, Florida), pp. 3521–3533.

PLANT, N.G. and HOLMAN, R.A., 1997. Intertidal beach profile estimation using video images. *Marine Geology,* 140, 1–24.

PRIEST, G.R., 1999. Coastal shoreline change study: northern and central Lincoln County, Oregon. *Journal of Coastal Research,* Special Issue No. 28, pp. 140–157.

RICHARDS, J.A. and JIA, X., 1999. *Remote Sensing Digital Image Analysis.* New York: Springer, 363p.

SHALOWITZ, A.L., 1964. *Shore and Sea Boundaries with Special Reference to the Interpretation and Use of Coast and Geodetic Survey Data* (Publication 10-1). Washington, DC: US Government Printing Office, US Department of Commerce, Coast and Geodetic Survey, 484p.

SHOSHANY, M. and DEGANI, A., 1992. Shoreline detection by digital image processing of aerial photography. *Journal of Coastal Research,* 8(1), 29–34.

SMITH, A.W.S. and JACKSON, L.A., 1992. The variability in width of the visible beach. *Shore and Beach,* 60(2), 7–14.

SMITH, G.L. and ZARILLO, G.A., 1990. Calculating long-term shoreline recession rates using aerial photographic and beach profiling techniques. *Journal of Coastal Research,* 6(1), 111–120.

STAFFORD, D.B. and LANGFELDER, J., 1971. Air photo survey of coastal erosion. *Photogrammetric Engineering,* 37(6), 565–575.

STOCKDON, H.F.; SALLENGER, A.H.; LIST, J.H., and HOLMAN, R.A., 2002. Estimation of shoreline position and change using airborne topographic lidar data. *Journal of Coastal Research,* 18(3), 502–513.

THIELER, E.R. and DANFORTH, W.W., 1994. Historical shoreline mapping (I): improving techniques and reducing positioning errors. *Journal of Coastal Research,* 10(3), 549–563.

TOU, J.T. and GONZALEZ, R.C., 1974. *Pattern Recognition Principles.* Boston: Addison-Wesley, 377p.

TURNER, I.L. and LEYDEN, V.M., 2000. *System Description and Analysis of Shoreline Change: August 1999–February 2000. Report 1. Northern Gold Coast Coastal Imaging System* (Technical Report 00/12). Sydney, Australia: Water Research Laboratory, University of New South Wales.

TURNER, I.L.; LEYDEN, V.M.; SYMONDS, G.; MCGRATH, J.; JACKSON, A.; JANCAR, T.; AARNINKHOF, S.G.J., and ELSHOFF, I., 2000. Predicted and observed coastline changes at the Gold Coast artificial reef. *Proceedings of the 27th International Conference on Coastal Engineering* (Sydney, Australia), pp. 1836–1847.

ZHANG, K.; DOUGLAS, B.C., and LEATHERMAN, S.P., 2002. Do storms cause long-term beach erosion along the U.S. East Barrier Coast? *Journal of Geology,* 110, 493–502.

ZHANG, K.; HUANG, W.; DOUGLAS, B.C., and LEATHERMAN, S.P., 2002. Shoreline position variability and long-term trend analysis. *Shore and Beach,* 70(2), 31–35.