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GEO-SPATIAL TECHNOLOGIES IN SHORELINE ANALYSIS, VARIABILITY AND EROSION

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ABSTRACT

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.

Key words: Shoreline Change, Shoreline E Mapping, Shoreline Analysis, Coastal Accretion-Erosion, Remote Sensing, Geographic Information System, GPS, Image Analysis.

1. INTRODUCTION

The location of the shoreline and the changing position of this boundary through time are of elemental importance to coastal scientists, engineers, and managers. 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 to calibrate and verify numerical models, to assess sea-level rise, to develop hazard zones, to formulate policies to regulate coastal development, and to assist with legal property boundary definition and coastal research and monitoring. The location of the shoreline can provide information in regard to shoreline reorientation adjacent to structures and beach width and volume, and it is used to quantify historical rates of change.

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 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.

2. DEFINITION OF THE "SHORELINE

An idealized definition of shoreline is that it coincides with the physical interface of land and water. 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, 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. 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, is the chosen point's representative, and are morphological features, such as beach cusps, distorting the alongshore average shoreline position.

3. 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[Source: Journal of Coastal Research] 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
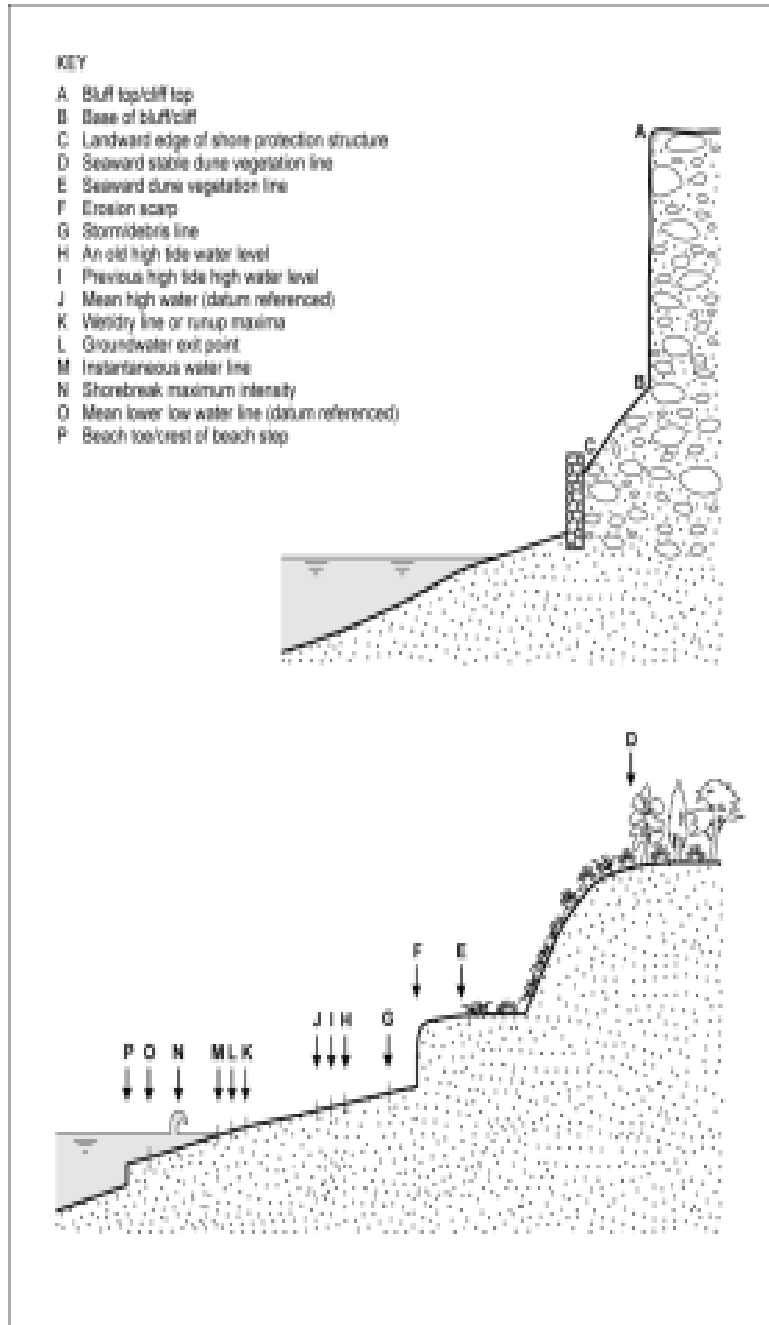
KEY

A Bluff top/cliff top
B Base of bluff/cliff
C Landward edge of shore protection structure
D Seaward stable dune vegetation line
E Seaward dune vegetation line
F Erosion scarp
G Storm/debris line
H An old high tide water level
I Previous high tide high water level
J Mean high water (datum referenced)
K Wet/dry line or runup maxima
L Groundwater exit point
M Instantaneous water line
N Shorebreak maximum intensity
O Mean lower low water line (datum referenced)
P Beach toe/crest of beach step

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

Figure 2 [Source: Journal of Coastal Research]

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.

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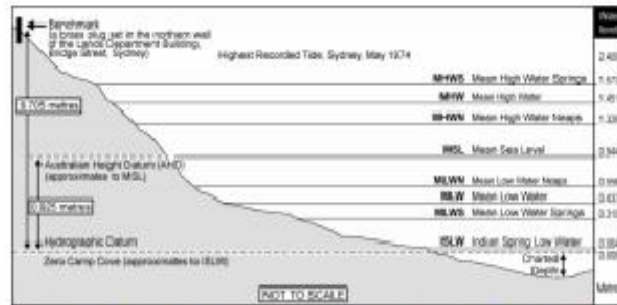

Figure 3. Tidal datums used along the New South Wales coastline, Australia (adapted from data provided by Manly Hydraulics Laboratory, New South Wales Department of Commerce).

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.

4. 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.

4.1. 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.

4.2. 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. 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". 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.

In the United Kingdom, many maps and charts were inaccurate until around 1750. In 1791, the Ordnance Survey was founded, and the accuracy of mapping began to increase and has continued to improve. 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.

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.

4.3. Aerial Photography

Vertical aerial photographs of the coastline began to be collected around the world in the 1920s, but it was not until the late 1930s that reasonable-quality stereo aerial photos became available. Aerial photographs provide good spatial coverage of the coast, but temporal coverage is very site specific. Historical aerial photography may also be temporally biased toward post storm "shorelines" 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.

Modern softcopy photogrammetry allows a digitally scanned pair of aerial photos to be converted into a three-dimensional digital terrain model and a georectified ortho-photo. 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.

4.4. Beach Surveys

Survey data can be an accurate source of shoreline information. However, historical records tend to be limited both spatially and temporally. 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. 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. If sufficient beach profiling data are available for a specific site, tidal datum-based shorelines, such as MHW, are easily and accurately determined.

4.5. 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. 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.

4.6. 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.

4.7. Multispectral/Hyperspectral Imaging

Satellites now provide near-continuous monitoring of many of the world's shorelines. Traditional multispectral satellite-flown instruments, such as Landsat, SPOT, etc., generate a discrete signal in a limited number of broad bands. Hyperspectral imaging provides wide and continuous spectral coverage. The main limitations of this data source to coastal investigations are the pixel resolution and cost. 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.

4.8. Airborne Light Detection and Ranging Technology [LiDAR]

Airborne light detection and ranging technology (LIDAR) has the ability to cover hundreds of kilometers of coast in a relatively short period; LIDAR is based on the measurement of the time it takes a laser beam, from leaving the instrument, to return after reflection. 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. 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.

4.9. Microwave Sensors

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

4.10. 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. 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. 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 post event shorelines), and given time, these locations will develop detailed long-term shoreline change information.

5. 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 have the potential to induce error when estimating a shoreline position.

The most common shoreline detection technique applied to visibly discernible shoreline features is manual visual interpretation, either in the field or from aerial photography. For example, with aerial photography, the image is corrected for distortions and then adjusted to the correct scale before a "shoreline" is 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 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. 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 . 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.

5.1. 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, the use of LIDAR topographic data, 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.

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. 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 has been used successfully to distinguish between two classes, water and sand (Kingston et al., 2000), as has an unsupervised isodata classification method to achieve the same distinction between water and land. A supervised critical threshold classification technique has been applied to determine the boundary between dry sand and the inner surf zone , and an unsupervised intensity maxima classification technique has been used to determine the alongshore alignment of the shore-break .

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 (~0.7 μm) of the electromagnetic spectrum are attenuated more rapidly than those from the blue range (~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 shore break 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.

6. 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. 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.

7. EXCEPTED OUTPUT

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.

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