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Shoreline Mapping Techniques

Laura J. Moore

Earth Sciences Department
University of California
Santa Cruz, CA 95064

ABSTRACT

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Numerous coastal mapping techniques have been developed over the last twenty-seven years (STAFFORD, 1971; DOLAN *et al.,* 1978; FISHER and SIMPSON, 1979; LEATHERMAN, 1983; MCBRIDE *et al.,* 1991; THIELER and DANFORTH, 1994a, OVERTON *et al.,* 1996). These techniques, used to measure shoreline erosion, barrier island migration, and dune erosion, vary in approach, accuracy, expense and training/time requirements.

Some of the more recent coastal mapping techniques apply advances in cartography and photogrammetry providing high-resolution measurements with less error than manual methods that use a photographic comparator or stereo zoom transfer scope. However, such techniques are expensive, require extensive training, and may take longer than manual methods. While many coastal mapping studies would benefit from these advanced techniques, not all studies require the high resolution these more recent techniques offer.

When beginning a coastal mapping project or choosing to upgrade laboratory facilities, researching established coastal mapping techniques before choosing from among them requires extensive literature review. To assist researchers, engineers and planners who wish to undertake a coastal mapping project, this paper provides an overview of the errors associated with shoreline mapping, and a discussion of factors to be considered when selecting a coastal mapping technique.

ADDITIONAL INDEX WORDS: *Aerial photography, cartography, photogrammetry, shoreline change, erosion rates, coastal mapping.*

INTRODUCTION

With increasing population in coastal areas, the study of changing shorelines has become more than a topic of scientific curiosity. Coastal areas are dynamic in nature with changes occurring over many time scales. When shoreline retreat occurs on a human time scale, quantification of erosion rates becomes important for many reasons. Erosion rates are not only used by scientists to study sediment budgets or the role of natural processes in shoreline alteration, they are also used to determine safe construction setbacks, settle property ownership disputes, study the effectiveness of shoreline protection structures and to make land use decisions.

The range of purposes for which coastal erosion is studied, the variety of equipment and funding available to scientists, engineers or planners, and the varying expertise of professionals studying the coastal zone, has lead to the lack of a standard method for analyzing shoreline change. This lack of a standard method has made comparison of coastal change at regional and national scales difficult (MAY *et al.,* 1982; DOLAN *et al.,* 1980).

Existing shoreline mapping techniques vary from simple measurements made directly from uncorrected aerial photographs to precise measurements made from computer rectified aerial orthophotographs in digital format. In an ideal world of unlimited time, money and expertise, the standard technique for calculating shoreline change would be the latter of these two. In the real world, not all studies of the changing coastal zone require the highest resolution possible.

Numerous papers have been published on the topic of shoreline mapping and erosion rate determination (see bibliography). In most cases, the authors have included a discussion of errors involved in shoreline mapping, an analysis of data sources, an introduction to a new technique and/or a description of existing techniques. The objective of this paper is to synthesize the existing information into a comprehensive guide to shoreline mapping. I accomplish this by providing 1) a discussion of all potential errors associated with shoreline mapping, 2) an overview of shoreline mapping techniques and 3) a summary of considerations to be made prior to technique selection. Since it is impossible to include details from all publications relevant to shoreline mapping, sources of additional or more specific information have been carefully referenced throughout this paper.

Sources of Error in Shoreline Mapping

Erosion rates can only be as accurate as the data from which they are derived and the methods by which they are calculated. Since there are many potential sources of error involved in the process of measuring shoreline erosion rates, a thorough understanding of these errors is vital to the successful completion of a project. For the purpose of the following discussion, errors are divided into two categories: 1) er-

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Present Address: Laura J. Moore, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Mail Stop #22, Woods Hole, MA 02543, USA.

rors introduced by data sources and 2) errors introduced by measurement methods. See Table 1 for a summary of these errors and their approximate magnitudes on a map or photo at a scale of 1:20,000.

Potential Data Source Errors

Historical Maps

If a study requires reconstruction of shoreline position before the aerial photographic record begins, or if a particular location has poor photographic coverage, the use of historical maps in conjunction with aerial photography is necessary. The maps most commonly used for shoreline mapping are United States Geological Survey (USGS) quadrangles and National Ocean Service (NOS) Topographic (T) sheets. NOS T-sheets date back to the 1830s while USGS quadrangles date back to the formation of the USGS in 1879 (Ellis, 1978). The use of historical maps introduces several potential errors to the coastal mapping process. The severity of these errors depends on the accuracy standards met by each map and on physical changes in each map since publication (Anders and Byrnes, 1991).

Both USGS quadrangles and NOS T-sheets produced after 1941 meet or exceed the National Map Accuracy Standards (NMAS) of 1941 (Ellis, 1978, p. 60). Under these standards, the maximum allowable error for 90 percent of points on a 1:24,000 USGS quadrangle is 12.2 m while the maximum allowable error for 90 percent of points on a 1:10,000 and 1:20,000 NOS T-sheet, is 8.5 m and 10.2 m, respectively. Since NOS T-sheets are used to construct nautical charts, the location of features which can be critical to safe navigation are held to stricter standards. Thus, while USGS maps barely meet NMAS, NOS T-sheets generally significantly exceed NMAS. Under these stricter standards as outlined in Ellis, 1978 (p. 61), the shoreline must be mapped within 0.5 mm (at map scale) of its true position (within 10 m at 1:20,000) while fixed navigation aids and objects charted as landmarks are plotted even more accurately and must be within 0.3 mm at map scale (within 6.0 m at a scale of 1:20,000). Galgano (1989) found T-sheet errors to be even smaller, within 3 m at 1:20,000.

When dealing with maps constructed prior to the first T-sheets in the 1830s, reliability is a serious issue. In these cases, map accuracy depends on the standards set forth by the chief surveyor of each individual survey party (Anders and Byrnes, 1991). Shalowitz (1964) evaluated the accuracy of early surveys from which T-sheets were constructed and found that the intention of NOS surveyors was to determine the location of the high water line (HWL) for delineation on maps. Therefore, despite the lack of general accuracy standards, surveys of the HWL were taken seriously (Shalowitz, 1964).

The accuracy of older surveys was also limited by the quality of available ground control. Assuming standard control, Shalowitz (1964) estimates that the distance to rodded points could be measured within 1.0 m and the true position of the plane table could be determined within 2.0–3.0 m. He also estimates that the HWL could be identified within 3.0–4.0 m. Assuming these potential errors, Shalowitz (1964)

Table 1. *Summary of potential errors involved in the shoreline mapping process.*

Potential Source of Error	Error at Map Scale	Error at 1:20,000	Citations
Maps			
USGS Quadrangles	*90% of points within ±0.61 mm	*90% of points within ± 12.2 m	National Map Accuracy Standards, 1941 (Ellis, 1978)
NOS T-Sheets	90% of points within ±0.51 mm	90% of points within ± 10.2 m	same as above
Shoreline on NOS T sheet	±0.5 mm	±10 m	same as above
Landmarks on NOS T sheet	±0.3 mm	±6 m	same as above
Maps prior to 1941	±1 mm	±20 m	Shalowitz, 1964
Map shrinkage	±0.03–0.25 mm	±0.6–5 m	Knowles and Gorman, 1991
Photos			
Radial distortion	up to ±0.110 mm	±2.0 m	Slama, 1980
Photo shrink/stretch	±1–2 mm	±20–40 m	Thieler and Danforth, 1994a
Diapositive shrink/stretch	±0.005 mm	±0.1 m	Slama, 1980
Tilt 1°, point 10 cm from isocenter	±0.68 mm	±13.6 m	Anders and Byrnes, 1991
Proxy Variability and Interpretation			
Seasonal variations of HWL	±0.05 mm	up to ±10 m	Smith and Zarillo, 1990; for Mecox Bay
Tidal cycle variations of HWL	±0.025–0.05 mm	±0.5–1 m	Dolan, et al., 1980; for med. grained beach, slope = 3–6°
Interpretation of HWL	±0.5 mm	±10 m	U.S. Coast and Geodetic Survey, 1944
Annotation			
Annotation (pen line 0.13 mm)	±0.13 mm	±2.6 m	Anders and Byrnes, 1991
Annotation (pen line 0.30 mm)	±0.3 mm	±6 m	Anders and Byrnes, 1991
Digitizer	up to ±0.25 mm	up to ±5 m	Anders and Byrnes, 1991; Crowell et al., 1991
Digitizer + operator error	±0.225 mm	±4.5 m	Theiler and Danforth, 1994b

* USGS Quadrangle at scale 1:24,000

suggests that the overall accuracy of early surveys is within a maximum total error of ± 10 m. However, this estimate does not include sketching between surveyed points, which is an important consideration for irregular shorelines. Sketching between points may account for up to 10 additional meters of uncertainty (SHALOWITZ, 1964). As long as errors are considered, the use of older maps seems reasonable, but only to obtain estimates of general shoreline trends (ANDERS and BYRNES, 1991). For studies requiring a high degree of accuracy, it is prudent to assess the accuracy of each map used. CROWELL *et al.* (1991) discuss the assessment of map accuracy and present a detailed accuracy analysis of 232 T-sheets from the state of Massachusetts.

Map accuracy is also influenced by displacements of feature position resulting from changes in the horizontal reference datum. Before shorelines from maps with different projections, ellipsoids and datums can be compared, they must be converted to a common projection, ellipsoid and datum. Depending on the shoreline mapping technique used, shoreline coordinates can be converted using a series of equations (CLOW and LEATHERMAN, 1984; THIELER and DANFORTH, 1994a), digitized coordinates can be converted to an intermediate coordinate system and then projected into a map projection as in EVENDEN (1990 and 1991), or Geographic Information System (GIS) software can be employed to convert map data to a common coordinate system (MCBRIDE, 1989).

Finally, map shrinkage, stretch and other defects also add error to shoreline change analysis. For example, typical map paper can expand by greater than 1 percent with a humidity increase of 60 percent (SNYDER, 1987). To complicate matters further, the magnitude of shrinkage and stretch can vary with direction on the same map sheet (SNYDER, 1987). Estimates by KNOWLES and GORMAN (1991) of potential change in map paper range from 0.03 to 0.25 mm. At a scale of 1:20,000 this is a ground distance of ±0.6 to 5.0 m. Errors may also result from tears, folds and creases in paper maps. The replacement of paper maps with maps printed on mylar (a stable medium, which does not shrink, stretch, crease, or tear as easily as paper) will significantly reduce these errors. When using historical T-sheets, creases and tears in the original map may appear in the mylar reproductions obtained from NOS archives (CROWELL *et al.*, 1991). In such instances, the magnitude of distortion should be determined by digitizing control points on either side of the defect. CROWELL *et al.* (1991) suggest that each segment of the "defect-divided" map should be dealt with separately if excessive distortion is discovered.

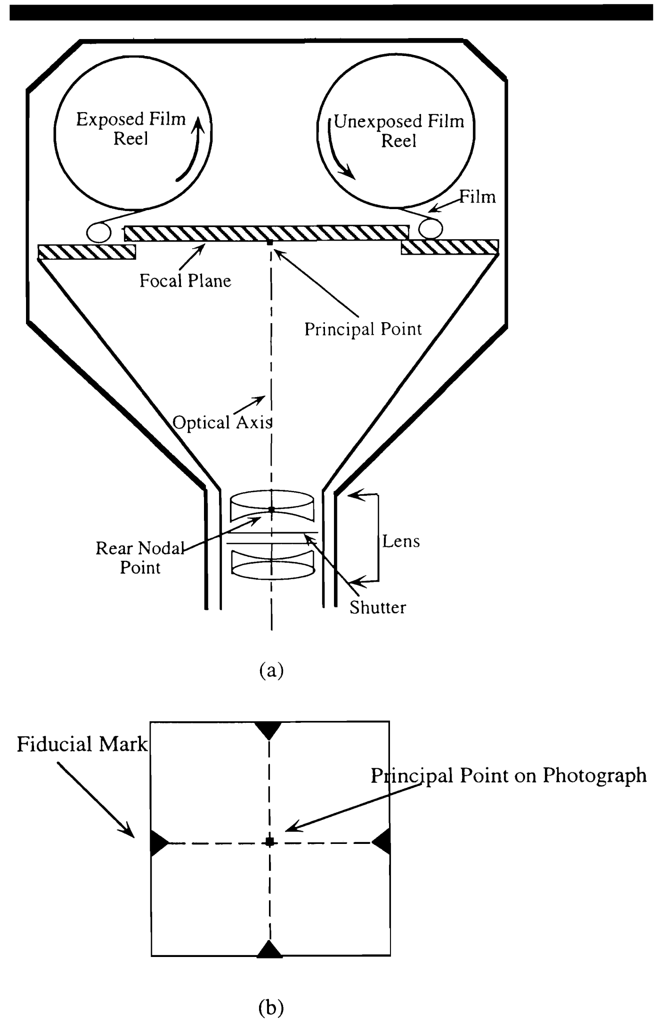

Figure 1. (a) The principal point as shown in the generalized cross section above, is the point in the focal plane intersected by a perpendicular line from the rear nodal point (after WOLF, 1983). (b) The principal point also lies at the intersection of lines joining opposite fiducial marks on an aerial photograph.

Aerial Photography

Aerial photographs are the most commonly used data source in shoreline mapping. Because many coastal areas of the United States have extensive aerial photo coverage and because aerial photographs are taken fairly often, they provide a valuable record of shoreline position. Black and white vertical aerial photographs date back to the late 1920s but quality stereo aerial photographs were not available until the late 1930s and early 1940s (ANDERS and BYRNES, 1991).

Accurate measurements cannot be made on uncorrected vertical aerial photographs because various distortions and displacements are introduced at different stages in the photographic process. These distortions and displacements are perturbations of the geometric relationship between image space and object space (SLAMA, 1980). Image space refers to a three dimensional, rectangular Cartesian coordinate system defined inside the camera with the principal point as the origin. The principal point, shown in Figure 1a, is the point in the focal plane intersected by a perpendicular line from the rear nodal point of the camera lens. On an exposed photograph, the principal point lies at the intersection of lines between opposing fiducial marks (Figure 1b). In this coordinate system, the z axis corresponds to the optical axis and the x axis typically corresponds to the flight direction. Object space refers to the real-world geographic coordinates of the photographed area outside the camera. Image space and object space are related by the collinearity condition. Under this

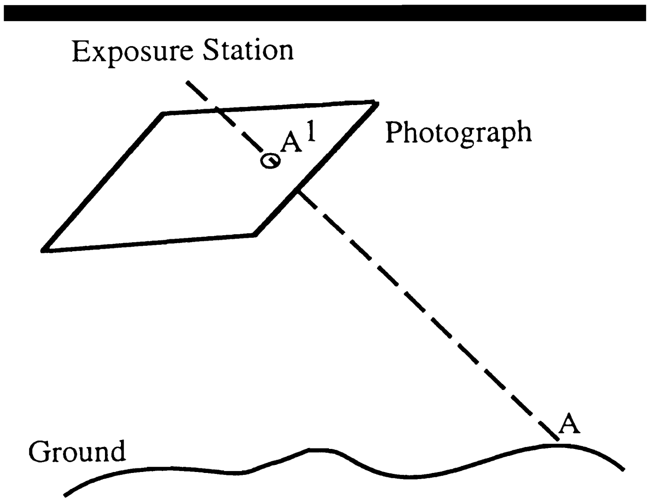

Figure 2. In an undistorted photograph the collinearity condition exists in which a point on the ground, its representation on the photograph, and the exposure station (camera) all lie on a straight line.

condition, the exposure station (camera), any ground point, and its corresponding photo image, lie on a straight line (Figure 2). In an ideal, undistorted photograph, this condition would hold and all image points would correctly correspond to their respective ground points. Unfortunately the geometric perturbations described in the following sections prevent the capture of such an ideal photograph.

Most shoreline mapping methods involve techniques to minimize the effect of geometric perturbations on measurements. A few methods even utilize photogrammetric techniques to iteratively solve for the collinearity condition. In these cases, the camera parameters necessary to meet the condition are determined and the image is reprojected with most displacements and distortions removed. Since the magnitude of perturbations, and thus the magnitude of displacements and distortions, are greater in smaller scale photographs (*e.g.* 1:100,000 = "small scale" and 1:10,000 = "large scale"), it is advisable to use the largest scale photography available. In fact, 1:20,000 is considered the smallest scale usable for shoreline mapping (TANNER, 1978; BYRNES *et al.*, 1991; CROWELL *et al.*, 1991; THIELER and DANFORTH, 1994a). For a discussion of photogrammetry as it relates to coastal mapping, beyond what appears below, see THIELER and DANFORTH (1994a) and for detailed explanations of photogrammetric principles refer to WOLF (1983) or SLAMA (1980).

Image Space Distortions

Image space perturbations are the result of lens distortion and film deformation. As an image passes through a camera lens, two types of distortion, radial and tangential, can occur. Radial distortion, caused by imperfections in the lens elements, distorts image points along radial lines from the principal point. Tangential distortion, caused by faulty centering of the camera lens, distorts image points at right angles to radial lines from the principal point. In most modern well-adjusted cameras, only radial distortion, on the order of 0.010 mm or less (THIELER and DANFORTH, 1994a), is present. However, some lenses may have up to 0.110 mm of radial distortion (SLAMA, 1980), which at a photographic scale of 1:20,000, is equivalent to a ground distance of over 2 m.

Film deformation, the second cause of image space distortion, may occur at any or all of three stages in the photographic process. Deformation may occur during an aerial survey due to buckling of film in the camera with changes in humidity, temperature and/or film spool tension. Film may also become further deformed by buckling, shrinking or stretching during processing of original negatives or in subsequent processing of each generation of prints. Finally, deformation may occur due to the instability of photographic media once the image has been printed. In their study of coastal changes in Puerto Rico, THIELER and DANFORTH (1994a) report observation of 1–2 mm of shrinkage and expansion in some standard paper prints due to differences in age, paper quality and changes in laboratory conditions. At a photo scale of 1:20,000 these errors are equivalent to 20–40 m on the ground and are significant. Standard dispositive (transparency) film is stable within 0.005 mm (SLAMA, 1980) and for this reason will have a minimal response to temperature and humidity conditions.

If film deformation and camera lens distortion are present in a photograph, measurements made directly from that photograph will be significantly in error. In some cases, making measurements only at the center of a photograph may reduce the effect of these errors to a tolerable level. For more recent photography, camera calibration test results can be obtained or in the case of older photography, initial camera parameters can be estimated. Modern photogrammetric techniques utilize this information to remove most image space distortions by either correcting the image itself or by applying a correction to data (*e.g.* shoreline position) collected from an image.

Object Space Displacements

Conditions outside of the camera, such as ground relief, aerial camera tilt and atmospheric refraction, cause objects on the photo image to be displaced from their true ground positions. Relief displacement, for example, causes objects above ground level to be displaced outward from the center of the photograph and objects below ground level to be displaced inward toward the center of the photograph (Figure 3). The severity of relief displacement increases with decreases in flight altitude, increases in elevation or depression of objects relative to ground level, and increases with radial distance from the center of the photograph (WOLF, 1983).

When the camera axis is unintentionally tilted from vertical at the time of exposure, a nearly vertical, instead of a truly vertical photograph results (Figure 4). The scale of this image will be larger on the upward side of the tilt axis and smaller on the downward side of the tilt axis (Figure 5). Tilts of up to 3 degrees are common (LEATHERMAN, 1983) and a tilt of even 1 degree generates significant displacement. For example, a point 10.0 cm from the isocenter and 40 degrees from the principal line on a 1:20,000 scale photograph, which is tilted one degree, would be displaced 13.6 m (ANDERS and

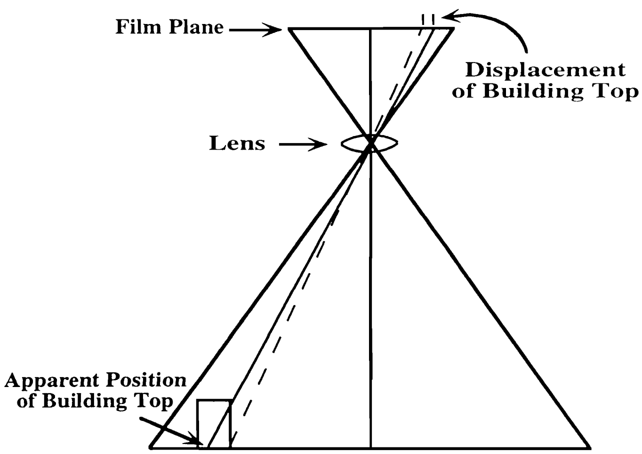

Figure 3. Relief displacement causes objects above the ground to be displaced toward the edges of an aerial photograph (after STAFFORD, 1971).

BYRNES, 1991). Many coastal researchers have not realized the severity of this error and thus have not considered tilt in their methods (*e.g.* DOLAN *et al.,* 1978).

Atmospheric refraction is the bending of light rays as they pass through the atmosphere. The exact magnitude of displacement due to atmospheric refraction depends on flight altitude, camera focal length and direction of the optical axis relative to the ground. However, atmospheric refraction is generally responsible for less than 0.006 mm of displacement on photos commonly used for coastal mapping (SLAMA, 1980). At a photographic scale of 1:20,000, this displacement is approximately 10 cm. Because the displacements are so small, errors due to atmospheric refraction are negligible for the purposes of coastal mapping.

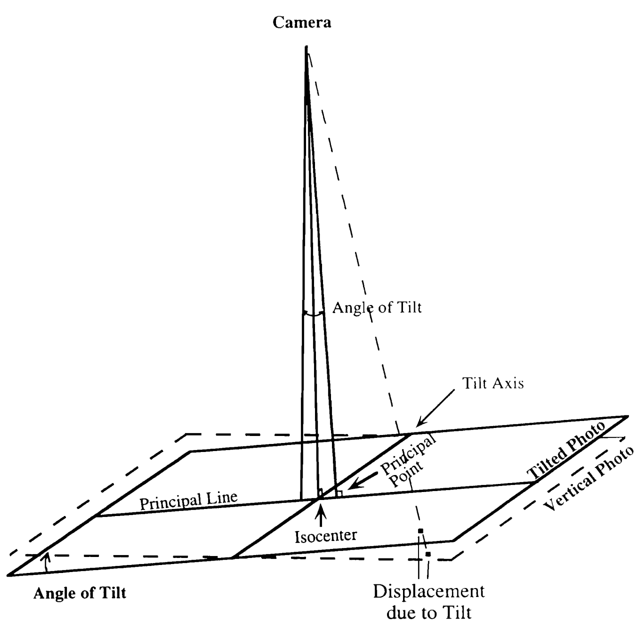

Figure 4. When a photograph is nearly vertical, as opposed to truly vertical, objects will be displaced from their true positions (after WOLF, 1974; and LEATHERMAN, 1983).

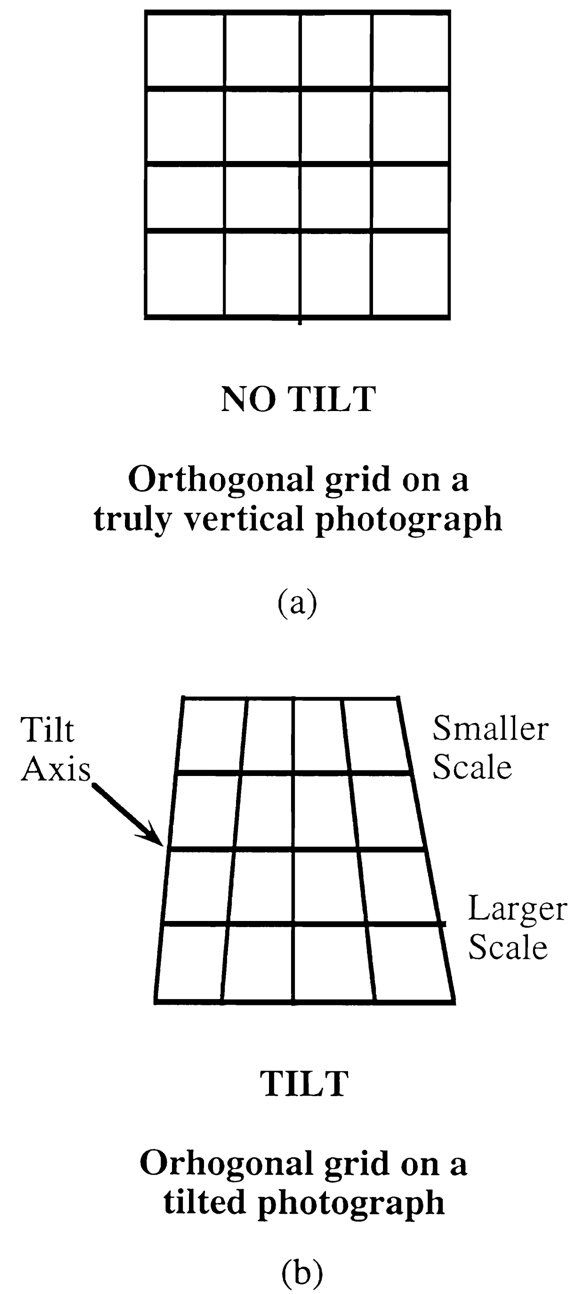

Figure 5. On an untilted photograph, the scale will be uniform across the image. On a tilted aerial photograph the scale is larger on the upward side of the tilt axis and smaller on the downward side (after LEATHERMAN, 1983).

Ground Control

Ground control points are used to rectify aerial photographs and to transfer older maps from obsolete to currently used datums. Depending on the application used, photorectification (removal of the previously discussed distortions and displacements) typically requires 4 to preferably 6 or 9 control points evenly distributed throughout each photograph (CLOW and LEATHERMAN, 1984) or approximately 6–10 control points for every 10 photographs (THIELER and DANFORTH, 1994a and MOORE *et al., In Press*). Control is gathered in one of three ways: 1) by locating stable points on current NOS T-sheets (USGS quadrangles are not accurate enough for this purpose), 2) by locating triangulation stations with updated coordinates obtained from the National Geodetic Survey (CROWELL *et al.,* 1991), or 3) by locating the latitude and longitude of stable points by field survey, for example, using Global Positioning System (GPS) technology. GPS field surveys undoubtedly provide the most reliable control. However, unless GPS equipment is available, this method of gathering control is not only more labor intensive, but also more expensive than gathering control from maps. If GPS equipment must be purchased, an economical option is to use hand-held GPS equipment capable of sub-meter accuracy if post-processed.

The accuracy of shoreline mapping is not only affected by the quality of ground control but also by the availability of ground control. Availability will depend on the time period being studied and on the extent to which the study site has been developed. The best control points are road intersections or low-relief building corners (geodetic markers, such as bench marks, are easy to obtain coordinates for but are rarely visible at photo scale). Where stable control is difficult to establish, less reliable points, such as river meanders, can be used but will substantially affect mapping accuracy. Additionally, if control is established using USGS or NOS maps, care should be taken to choose points that are not spaced too closely to other objects. For example, if a road and a railroad run parallel and are adjacent to one another, one of the routes will be offset at map scale in order for both features to be displayed.

Finally, regardless of how accurately control point locations are known, some error will remain due to the difficulty of precisely locating each control point on a photograph. For example, the geographic coordinates of the corner of a road intersection may be very accurately known, but the precision with which the corner of an intersection can be identified on a photograph is more limited. Additionally, roads are widened or repaved and buildings are sometimes renovated or reconstructed. Such changes should be watched for in a series of aerial photographs so that alternative control points can be selected if necessary.

Potential Measurement Errors

Interpretation

The line between wet sand and dry sand, which can usually be clearly seen as a significant tonal change on aerial photographs, is the most commonly used proxy for shoreline position (DOLAN *et al.,* 1980; SMITH and ZARILLO, 1990; ANDERS and BYRNES, 1991; and SHOSHANY and DEGANI, 1992). The wet/dry line closely approximates the high water line (HWL) which in turn approximates the mean HWL (DOLAN, 1980). There are, however, many errors associated with using the wet/dry line to represent the shoreline. These errors result from the short-term natural migration of the HWL, interpretation of the wet/dry line on a photograph and measurement of the interpreted line position. In some areas, where beach morphology permits, the bluff/cliff edge, bluff/cliff toe or a vegetation line may be a better choice for shoreline analysis (MORTON, 1991).

Since the wet/dry boundary has been the most commonly used proxy for shoreline position, several researchers have investigated the errors associated with using this boundary. The greatest error occurs due to the natural migration of the HWL with seasonal and tidal changes. SMITH and ZARILLO (1990) found that the HWL at Mecox Bay on the south shore of Long Island with a mean tidal range of 0.9 m and a beach slope of 5.5 degrees, migrated within a 20 m range over a 13-month period (due to seasonal and tidal changes). In addition, on the Atlantic Coast, storms can cause the HWL to migrate up to 100 m (LEATHERMAN, *Personal Communication*). For locations with good aerial photo coverage, errors due to seasonal and post-storm variability can be minimized by using only spring or summer photographs and by completely avoiding the use of post-storm photography when investigating long-term changes. If photo availability makes this impractical, then it is necessary to investigate the local seasonal variability of the HWL, and the variability of the HWL during storms, in order to include these errors in erosion rate calculations.

The HWL may also migrate according to tidal cycle, tidal range, beach slope, beach sediment size, wind, and wave height (DOLAN *et al.,* 1980). DOLAN *et al.* (1980) found the HWL on a medium grained beach with a slope of 3–6 degrees, to migrate within an average of 1–2 m over one tidal cycle. Shoreline position measured on an aerial photograph may be corrected for tidal stage if the time of photography and the variability of the HWL with tidal changes are known, but the effects of other local factors are difficult to assess.

In addition to errors arising from natural variations in the HWL, interpretative errors may be made if the tonal change between wet and dry sand on an aerial photograph is unclear. This may be the case if photo contrast is poor, or if other shore-parallel lines, such as the flotsam line at the upper swash limit, erosional scarps or tire tracks are present and may be confused with the HWL (CROWELL *et al.,* 1991). The U.S. COAST and GEODETIC SURVEY (1944) found that the wet/dry line could be interpreted within 0.5 mm at map scale. At a scale of 1:20,000 this is within 10 m. This error estimate is likely high for modern photographs, which tend to be of much higher quality than historical photographs. Limiting data sources to photographs on which the HWL can be discerned with confidence can lessen errors due to interpretation.

Annotation

Finally, errors arise due to the difficulty of measuring a single line on a photograph. The magnitude of these errors will vary according to the shoreline mapping technique used. For example, if using the finest pen commonly available to annotate the HWL, the pen line will be 0.13 mm thick at photoscale, which is 2.6 m of ground distance for a 1:20,000 scale photograph (ANDERS and BYRNES, 1991). If using a pen of thickness 0.3 mm, the annotated line at 1:20,000 will cover a strip of ground 6.0 m wide (ANDERS and BYRNES, 1991). When digitizing the wet/dry line instead of annotating with a drafting pen, an investigator must account for digitizer and digitizer operator error. Most modern high-quality digitizers are fairly accurate, and an accuracy of ± 0.25 mm (ANDERS and BYRNES, 1991; CROWELL *et al.,* 1991) is considered acceptable for mapping shoreline position. At a scale of 1:20,000, this is a potential ground error of ± 5.0 m. Operator error may also be significant and will vary according to working conditions, steadiness of hand and the operator's level of experience. The extent of digitizer and operator error should be quantified for each study. For example, THIELER and DANFORTH (1994b) found a combined digitizer and operator error of ± 0.225 mm for their study.

DESCRIPTION OF MAPPING TECHNIQUES

Numerous shoreline mapping techniques have been developed throughout the last 27 years. The progression of techniques from manual, to partially automated, to fully automated is consistent with decreases in the cost of personal computers and workstations as well as improvements in data processing and storage capabilities. With such quickly changing technology, it is not surprising that a standard technique for shoreline analysis has not emerged. Below, the methods and capabilities of several techniques are briefly described. A more complete description of each technique can be obtained from the cited material. For a summary of the capabilities and requirements of each technique refer to Table 2.

Point Measurements

Point measurement, a widely used method to measure shoreline change, can be performed fairly inexpensively, quickly and simply. This technique, developed by STAFFORD (1971) to study erosion on the Outer Banks of North Carolina, involves computing the scale of each individual photograph and then measuring the distance between a fixed reference object and the shoreline. This procedure is repeated for as many sets of photographs as desired. An erosion rate for each point is then calculated by dividing the difference between distances to the shoreline from a reference point by the time interval between photographs.

Errors due to radial distortion, tilt displacement, and relief displacement cannot be eliminated using the point measurement method, but they can be minimized by working only at the center of each photograph. A thorough accuracy assessment of this technique has not been conducted, however, LEATHERMAN (1983) states that this method probably meets National Map Accuracy Standards when "good judgment and care are exercised" (p. 28). One drawback to using this method is that a continuous representation of the shoreline cannot be generated.

Orthogonal Grid Mapping System (OGMS)

Drawing upon Stafford's work, DOLAN *et al.* (1978) (also DOLAN *et al.,* 1979; DOLAN *et al.,* 1980) developed a method which, unlike Stafford's method, can produce a continuous representation of the shoreline. The first step in this procedure is the generation of 1:5,000 scale base maps (each covering an area 3500 m by 2100 m) of the study site by photo enlargement of a series of 7.5 minute USGS maps (scale 1:24,000). The long axis of each base map is oriented parallel to the shoreline and the oceanward map edge serves as the baseline from which all measurements are made. Historical aerial photographs are then enlarged to the exact scale of the base map and superimposed onto the base map using a projecting light table. Once the high water lines from several sets of aerial photography have been superimposed and traced onto an overlay, shoreline position change is determined using a rectilinear grid to take measurements at 100 meter intervals along the shoreline. These measurements are then manually entered into a computer and shoreline maps are generated.

Since a projecting light table can only enlarge or reduce an image, this method does not allow correction for radial distortion, tilt distortion, or relief displacement (LEATHERMAN, 1983). In addition, LEATHERMAN (1983) points out that the apparent goal of this technique, to create an accurate and continuous shoreline map, is not truly realized since the final map product is actually based on closely spaced point data. LEATHERMAN (1983) also points out that in addition to air photo procedure errors, considerable errors are introduced when using USGS quadrangles as base maps. Although these maps meet National Map Accuracy Standards, the location of a stable point may be in error by as much as 12 m and the potential error in shoreline position is even greater (LEATHERMAN, 1983).

Stereo Zoom Transfer Scope

For a period of time, the stereo zoom transfer scope (ZTS) was considered state-of-the-art in coastal mapping (FISHER and SIMPSON, 1979). This technique, or a variation of it, is still used in coastal mapping today (SMITH and ZARILLO, 1990; MCBRIDE *et al.,* 1991). The ZTS can be used to bring photography of different scales to the same scale by superimposition onto a base map and rectification to ground control points. Once a photograph has been rectified and adjusted in scale, shoreline features can be traced. By tracing shoreline features, such as the HWL, from several sets of aerial photography, shoreline changes can be recognized and quantified.

Two major benefits of the ZTS over point measurements and the OGMS are: 1) the ZTS can produce a continuous (though hand-traced) record of shoreline position and 2) the ZTS is efficient at removing scale differences inherent in each photograph (LEATHERMAN, 1983). However, like the point measurement and the OGMS methods, the ZTS cannot correct for relief displacement and since the ZTS is a linear adjustment device (*i.e.* it cannot simultaneously stretch an image on one side while shrinking it on the other), it cannot completely eliminate tilt displacement. When using a ZTS for coastal mapping, care should be taken to choose stable con-

Table 2. *Summary and comparison of shoreline mapping techniques.*

Technique	Corrections Possible					Output	Time Requirement	Cost	Equipment and Software Needed
	Film Deformation	Radial Lens Distortion	Tilt Displacement	Relief Displacement	Incorporates Map Shorelines				
Softcopy Photogrammetry IGIS (Overton *et al.*, 1996; Moore *et al.*, 1999)	X	X	X	X	X	Computer Plotted Map or Photo Backdrop	High	High	Scanner, Sun Workstation, Softcopy Photogrammetric Software, Geographic Information System, Significant Storage, Plotter
Digital Shoreline Mapping and Analysis System (DSMS/DSAS) (Thieler and Danforth, 1994a,b)	X	X	X		X	Computer Plotted Map	Moderate–High	Moderate	Digitizer, Workstation, Plotter, DSMS/DSAS Software, Access to GIANT
GIS Strategy (Hilland et al., 1994; Brynes and Hilland, 1994)	X	X	X		X	Computer Plotted Map	Moderate–High	Moderate–High	Computer, Photo Rectification Software, Geographic Information System
Zoom Transfer Scope and GIS (McBride et al., 1991)	⟵	Minimized	⟶		X	Computer Plotted Map	Moderate	Moderate	Zoom Transfer Scope, Computer, Plotter, GIS Software Package
Metric Mapping (Leatherman, 1983; Clow and Leatherman, 1984)	X	X	X			Computer Plotted Map	Moderate	Moderate	Digitizer, Computer, Plotter, Clow and Leatherman Fortran IV Program
Zoom Transfer Scope (Fisher, 1979)	⟵	Minimized	⟶			Hand-Traced Map	Moderate	Moderate	Zoom Transfer Scope
Orthogonal Grid Mapping System (OGMS) (Dolan et al., 1978)						Hand-Traced Map	Moderate	Moderate	Projecting Light Table
Point Measurements (Stafford, 1971)	⟵	Minimized	⟶			Point Data	Low	Low	Photo Comparator

trol close to mapping areas, to work from one side of the photograph to the other (Leatherman, 1983) and to choose photographs which center on the study area (Smith and Zarillo, 1990). Although these efforts make the process tedious and time-consuming, they keep errors to a minimum (Leatherman, 1983).

Metric Mapping

Metric Mapping, a semi-automated technique introduced by Leatherman (1983) and developed by Clow and Leatherman (1984), was the first shoreline mapping technique developed to utilize a computer to apply an analytical treatment of photogrammetry based on mathematical models and numerical solutions. Since its initial development, this technique has also been combined with ArcInfo Geographic Information System (GIS) (Leatherman, *Personal Communication*). Clow and Leatherman (1984) used NOS T-sheets as a source of both primary control points (geographic coordinates of labeled grid marks on maps) and secondary control points (features on photos which can be identified on a map and assigned geographic coordinates using primary control points). Once control has been selected, the shoreline and control points are annotated on the aerial photographs. Primary and secondary control points on the NOS T-sheets are then digitized and primary control coordinates are used to obtain the state plane coordinates of the secondary control points. The annotated shoreline and secondary control points are then digitized from the air photos and run through a Fortran IV space resection program. This program removes radial distortion and tilt displacement from each individual photograph and adjusts all of the photos to the same scale. A MESH program adjusts the junctions between adjacent photographs, and a shoreline map is plotted as the final product.

Metric Mapping was developed to allow the production of accurate shoreline maps utilizing less expensive equipment and less effort than more advanced photogrammetric techniques (*e.g.* the stereoplotter) (Leatherman, 1983). The Metric Mapping technique successfully meets this objective. However, because photographs are rectified individually, several control points are required per photograph (*e.g.* minimum of 30 points for a set of 10 photos depending on overlap) and although not a problem for Clow and Leatherman (1984), there exists the potential for errors in shoreline position at the boundaries between two adjoining images.

Zoom Transfer Scope and GIS

This technique, developed by McBride *et al.* (1991) to map barrier island changes in Louisiana, combines ZTS, computer-aided design and drafting (CADD), computer cartography and geographic information system (GIS) technology in an attempt to improve accuracy. McBride *et al.* (1991) used both aerial photographs and NOS T-sheets as sources of shoreline information, while McBride (1989) used the same technique solely for cartographic data.

First, aerial photographs are registered to USGS 7.5 minute quadrangles using a ZTS and the shoreline is annotated using a drafting pen. Following photoregistration, aerial photo and NOS T-sheet shoreline data are digitized in original projection, ellipsoid and datum using computer mapping hardware (large format, high precision digitizer and cursor) and software. Data are then converted (McBride *et al.* (1991) used Intergraph's World Mapping System and Projection Manager software) to a common projection, coordinate system, horizontal datum and ellipsoid. After conversion, shore-normal transects are established and average erosion rates are determined by dividing measurements by elapsed time. Finally, shoreline change data, collected by McBride *et al.* (1991) at 15 second intervals, are converted to Universal Transverse Mercator projection and can be output as a continuous shoreline map.

This method simplifies the mapping process when using a combination of photos and maps but does not improve upon the accuracy of previously developed techniques since: 1) photos are rectified with a ZTS and 2) USGS quadrangles are used as base maps. The errors involved with the use of a ZTS and USGS quadrangles have already been discussed and apply here. In addition, shoreline maps generated from aerial photographs using a zoom transfer scope in combination with GIS technology are similar to those generated by the OGMS and point measurement techniques in that they are generated from closely spaced point data. This method is recommended for projects which require only, or primarily, the use of cartographic data (McBride, 1989). For such projects, this method will be advantageous since a GIS allows maps to be converted to a common projection, coordinate system, datum and ellipsoid.

GIS Strategy

This technique, presented by Hilland *et al.* (1993) and Byrnes and Hilland (1994), is similar to the one described above. Both techniques use CADD, computer cartography and GIS software packages, begin with compiling and evaluating the data sources, and use similar procedures for map digitization and transformation. However, in addition to using the ZTS to rectify photographs, Hilland *et al.* (1993) present a second method which involves scanning a photograph, rectifying it using computer software and control points from a previously digitized map, and then digitizing the shoreline as it appears on the computer screen. An Automated Shoreline Analysis Program (ASAP) is then used to quantify change in the digitized shoreline at 50 m intervals and to perform statistical analyses such as standard deviations and 95% confidence intervals. The GIS strategy also has other benefits such as the ability to perform area change analyses, create a spatial index of maps and photographs, and to record attributes such as map condition, date, and projection or aerial photograph flight altitude, scale and quality.

Hilland *et al.* (1993) used a combination of maps, aerial photographs and GPS field surveys. Since GIS simplifies the integration of a variety of data types by allowing transformation to a common projection, coordinate system, datum, and ellipsoid, the GIS strategy worked well for their purposes. However, there are still errors that must be accounted for in the analysis of aerial photography when using the GIS strategy. For example, the method of scanning and on-screen digitizing used by HILLAND *et al.* (1993) is likely to produce more accurate results, yet a 400 dpi (dots per inch) graphic scanner of unknown accuracy was used. In addition, this technique utilizes control from maps and this can introduce considerable error during photorectification. Regardless of these potential sources of error, the capability to convert an image to digital format has provided access to powerful methods, such as the GIS strategy, which have the potential to significantly reduce errors.

Digital Shoreline Mapping System (DSMS) and Digital Shoreline Analysis System (DSAS)

The DSMS/DSAS method is based on the General Integrated Analytical Triangulation Program (GIANT) written by the National Ocean Service. THIELER and DANFORTH (1994a and 1994b) designed the DSMS/DSAS to provide a highly accurate coastal mapping solution that can be carried out by one person in a small laboratory using a digitizing tablet, workstation, GIANT, DSMS/DSAS software written by THIELER and DANFORTH (1994a), GIS software and a plotting device. The first step in this process is to establish a network of fully known control points and secondary or supplemental control points (or pass points). Second, the control points, pass points, shoreline and fiducials (camera position markers in each corner and/or the center of each side of the photograph) are digitized using the Digital Shoreline Mapping System. Camera calibration data are then used to correct for errors in the image space coordinate system. The digitized photo information, tied together by the ground control network, is then operated on by a simultaneous adjustment program, called the General Integrated Analytical Triangulation (GIANT) program (ELASSAL and MALHOTRA, 1987; see THIELER and DANFORTH, 1994a). This program performs an absolute orientation to solve for the six elements of camera position, *i.e.* latitude, longitude, elevation, roll, pitch and yaw.

Once the photographs and maps have been digitized and oriented with respect to the ground, the DSMS uses the camera position and image space coordinates of the digitized shoreline to compute the geographic position of the shoreline. The digital shoreline analysis program can then be used to determine shoreline rates-of-change. Final presentation-quality shoreline maps can be generated by importing shoreline position data from the DSAS to a GIS system for output on a plotting device.

For a lab equipped with the necessary hardware, the Digital Shoreline Mapping and Analysis Systems are inexpensive to run. These systems are reported to offer a high level of accuracy, allow error quantification and are more flexible than other techniques since digitized data from the aerial photographs are rectified as a group and thus require fewer fully known control points. Perhaps the only drawback to using this method is the time investment necessary to learn how to operate all aspects of the DSMS/DSAS software and General Integrated Analytical Triangulation (GIANT) program. These programs are available from THIELER and DANFORTH (1994a). So far, no U.S. coastal state has adopted this methodology with all tests run to date in Puerto Rico.

Softcopy Photogrammetry/GIS Methodology

Softcopy photogrammetry is the newest method to be used in the measurement of shoreline change. It utilizes photogrammetric techniques of the traditional stereoplotter (a manual instrument typically used to generate topographic maps), but is automated and can be performed by non-photogrammetrists who have been trained to use a softcopy system. Softcopy technology (called such because the process is carried out on the computer screen) has been successfully applied to coastal mapping by OVERTON *et al.* (1996) and MOORE *et al.* (1999).

This technique is the most automated and thorough but is by far the most expensive of the techniques currently applied to the study of shoreline change. Most softcopy systems on the market, varying in user-friendliness and capabilities, range in price from $25,000 to $100,000+ (SALEH and SCARPACE, 1994). However, a few recently developed softcopy software packages can be purchased for less, especially with academic and government discounts. A lab equipped to use this technique will contain the following software and hardware: softcopy photogrammetric software and the corresponding computer platform, a GIS system or specialized computer program to measure distance between shorelines, a photogrammetric scanner, storage devices and a large-format printer. If a photogrammetric scanner is not available and cannot be purchased, a high-quality graphic scanner may be used for some projects, or photogrammetric scanning services may be employed. A service bureau may also be used for printing. Although the specifics of the softcopy process will vary depending on the software used, a generalized softcopy procedure is outlined below.

The first step in the mapping process is to transfer the photographic image to digital format by obtaining an accurate, high-resolution scan of the image (most likely at least 35 microns which is equivalent to 725 dpi [dots per inch] for recent photography) from a diapositive (transparency print) or if necessary, a contact print. Once the scans have been obtained, the group of images, called a block is imported to the softcopy system and block triangulation is performed. During block triangulation, camera calibration information, fiducial point locations, ground control points, and tie points (points appearing on more than one photo that serve to "tie" the photos together), are used to solve for camera position at the time each photograph was taken. Once triangulation is complete, digital stereo pairs are created for each overlapping pair of photographs in the block. After stereo pairs are generated, a digital elevation model or DEM is created, edited, mosaicked and then combined with the triangulated images to generate an orthophoto mosaic (an existing DEM may also be used). From this orthophoto mosaic, the shoreline is digitized on-screen (most likely in a GIS) to create a vector file of shoreline position. Once these steps have been repeated for one or more sets of photographs, a GIS or stand-alone program, takes measurements between the historical and recent shorelines at specified intervals and from this information, calculates erosion/accretion rates.

The application of softcopy photogrammetry to the study of shoreline change requires extensive training and is quite ex-

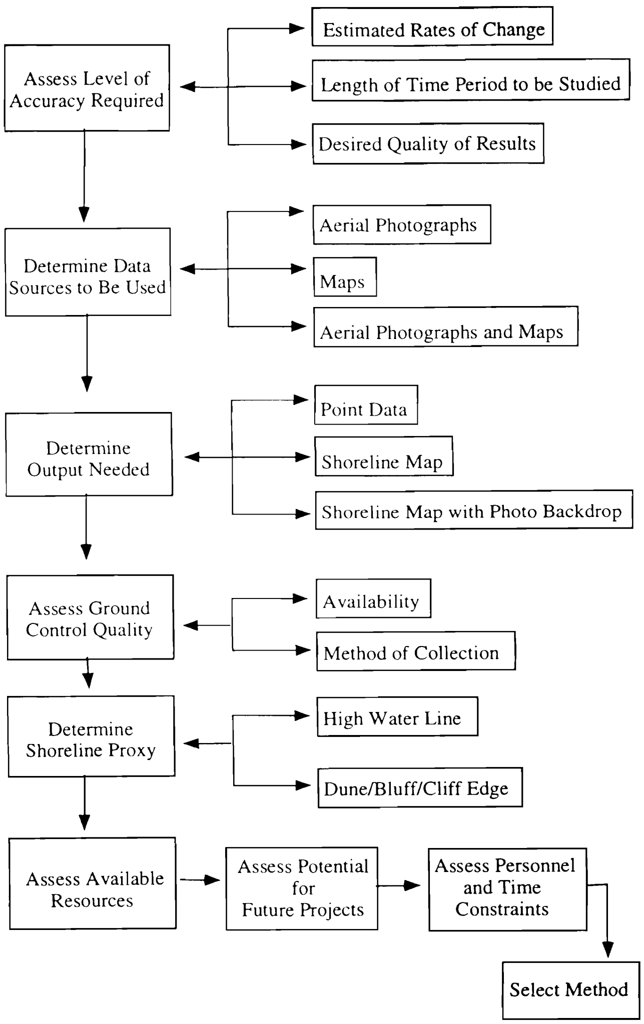

Figure 6. There are many factors to consider before selecting a shoreline mapping technique. This flow chart summarizes the discussion provided in the text.

pensive. Realistically, a project must require the highest accuracy possible and/or a laboratory must be planning many future projects in order to justify such an investment of equipment and time. However, in addition to offering a high level of accuracy, this technique does have a few other major advantages. For example, since tie points can be selected, few ground control points are needed, *e.g.* for a group of 10 stereo photographs only 6–10 known points are needed. The other major advantages are the capability to generate a corrected photographic image as output and the capability to remove relief displacement by incorporating digital elevation models in the photo correction process.

TECHNIQUE SELECTION

Selecting from among the established techniques can pose a significant challenge. Throughout the following discussion, several factors are recommended for consideration including:

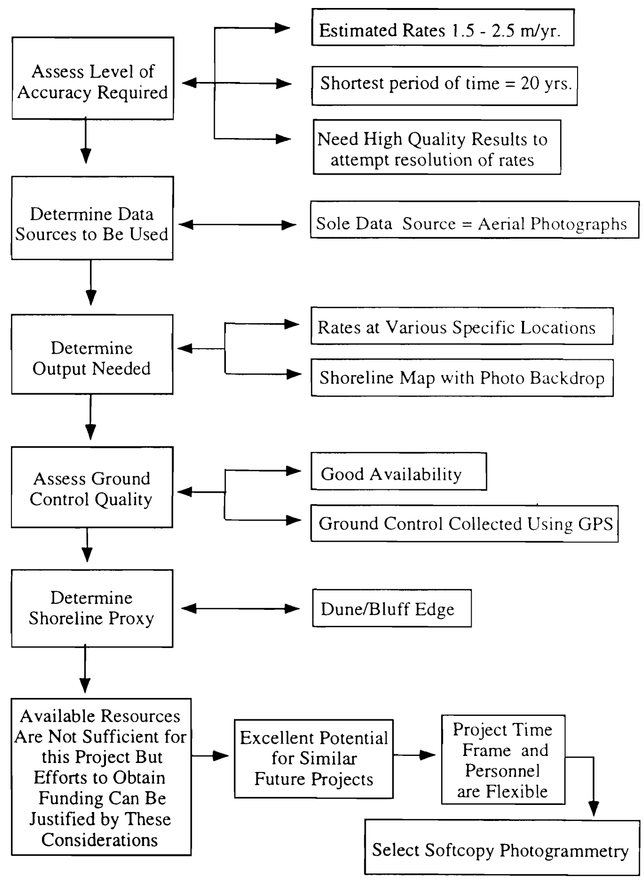

Figure 7. This flow chart has been completed to provide an example of how these considerations might assist with technique selection. For this particular project the use of Softcopy Photogrammetry can be justified.

the level of accuracy required, type of output desired, method of ground control point collection, availability of funding and/or equipment, and the potential for similar future projects (MOORE, 1994). Consideration of these factors will aid in preventing selection of a technique which will ultimately not meet project needs or which unnecessarily (and perhaps wastefully) goes *beyond* project needs. Figure 6 is a generalized flowchart that illustrates how consideration of the factors discussed below may affect technique selection. Figure 7 provides an example of how the flowchart may be put to use when selecting a technique. The example given involves a project for which the use of Softcopy Photogrammetry can be justified.

Determining Accuracy Requirements

When determining which technique will be best suited for a particular project, the first step is to assess the resolution needed. This assessment will then assist in determining the error reduction capabilities required to achieve the desired resolution. For example, the following questions should be addressed: 1) What are the estimated/suspected erosion or accretion rates for the study site?, 2) Over what length of time will changes in shoreline position be assessed?, and 3) How precisely do erosion or accretion rates need to be known, *i.e.* is the project goal simply to identify whether or not change has occurred, or is the goal to provide the most accurate rates-of-change possible?

Figure 6 is a generalized flow chart designed to serve as a starting point for determining the accuracy requirements of a particular project. Some projects may unrealistically require a level of accuracy that cannot be achieved. For example, it may be difficult to resolve an average annual erosion/accretion rate for a very slowly changing coast over a 20 year time span, especially since HWL migration alone could account for enough error to prevent resolution of rates under these circumstances. If, however, rates of change are expected to be high, the time period of study is long, and only a qualitative analysis is required, it would be difficult to justify the use of a more time consuming method since point measurements would likely satisfy project requirements.

Data Input and Desired Output

Before undertaking a project, it is wise to consider the data sources to be used. If the only source of shoreline and control point information is aerial photography, technique selection will not be limited by this factor. If however, the project requires the use of historical maps in addition to aerial photography, it would be most prudent to choose from among the methods that allow for map transformation.

In addition to considering the inputs, the output to be generated should also be taken into account. If the project goal is to generate average annual erosion/accretion rates for selected points along the shoreline, technique selection will not be limited by output requirements because all of the methods discussed can generate data in this format. However, if the project goal is to provide a computer plotted shoreline map or to provide a photo backdrop for use in a GIS, selection will be limited to methods with the corresponding capabilities.

Ground Control Considerations

Once the level of accuracy and type of input/output required have been determined, the availability of ground control points and the method of control point collection must be considered. In undeveloped areas, it may be difficult to establish a control network with a sufficient number of points to use an approach such as Metric Mapping. In such cases, it may only be possible to achieve results using Softcopy Photogrammetry or the DSMS/DSAS since 6 to 10 high-quality, fully known points are generally sufficient to control a group of 10 aerial photographs. In situations where development has only occurred recently, recent digital orthophotos created using softcopy photogrammetry can be used to rectify older photography (MOORE *et al.*, 1999).

Since USGS quadrangles are not of sufficient accuracy to provide usable control points, it is not justifiable to use an automated method of shoreline analysis for projects in which control cannot be collected from NOS T-sheets or by GPS survey. To benefit from the error reduction capabilities of the more automated methods of shoreline analysis, high-quality control is essential. For this reason, although results may be achieved using control from NOS T-sheets, the time and monetary commitments required to generate results using the more recently developed methods, can only be justified when using control collected by GPS survey.

Shoreline Proxy

The feature or features chosen as proxy for shoreline position may also affect technique selection. As discussed in earlier sections, migration and interpretation of the HWL alone can be a source of considerable error. Depending on the level of accuracy required, if the HWL must be used as a proxy for shoreline position, it may be prudent to select a method that significantly reduces error from other potential sources. On the other hand, if the potential error due to the migration of the HWL is too great, it may not be worth the extra time involved to utilize the techniques which significantly reduce error since errors due to image distortions and displacements will likely be insignificant when compared to errors in HWL position. When using a proxy such as the edge of a high-relief dune, bluff or cliff, a method that allows the removal of relief displacement should be considered. Especially in high relief environments, this error due to relief displacement can be significant (MOORE and HAPKE, *In Preparation*).

Monetary and Time Constraints

The following questions summarize additional critical factors to consider when selecting a shoreline mapping technique: 1) What equipment, or hardware and software is already available?, 2) How much funding is designated for this project?, 3) How many future projects of a similar nature will be conducted, *i.e.* can the cost of a more expensive method be justified?, 4) What is the expertise of personnel responsible for completing the project?, and 5) Are there time constraints on completion of the project?

RECOMMENDATIONS FOR SUCCESSFUL COMPLETION OF A SHORELINE MAPPING PROJECT:

(1) Using the considerations discussed above, select the shoreline mapping technique most suitable for the project.

(2) Whenever possible use GPS over NOS T-sheets or NOS T-sheets over USGS quadrangles to establish control.

(3) If historical maps are to be used, assess their accuracy.

(4) Use the highest quality vertical aerial photographs available.

(5) Use photography of the largest scale possible and avoid using photographs of a scale smaller than 1:20,000.

(6) When possible, use the top edge of a bluff, cliff, or dune as a proxy for shoreline position. If the selected proxy is of high relief, use a method, which can correct for relief displacement.

(7) If using the HWL as a proxy, only use photographs taken during the spring or summer to reduce error in HWL position and avoid post-storm photographs when investigating long-term trends.

(8) If using the HWL as a proxy, determine the daily var-

iation in the HWL at the study site to provide an estimate of potential errors in HWL position.

(9) Perform an overall error assessment and quantify total error.

CONCLUSIONS

In response to an increasing need to quantify changes in shoreline position, numerous techniques have been developed to provide a more accurate means for determining rates of shoreline erosion and accretion. Though project results are ultimately limited by the quality of available inputs, each of the techniques developed over the last 27 years was created in an attempt to improve upon previous methods by reducing the potential for error. These techniques range from ruler measurements on uncorrected photographs to high-tech generation of orthophotos and measurement in a GIS. With advances in computer technology and decreases in the cost of hardware, the more recently developed methods of shoreline mapping are not only quite successful at reducing error, they are also becoming more accessible. This has made the process of selecting a shoreline mapping technique ever more challenging.

This paper provides a general review of the errors involved in shoreline mapping, a survey of existing methods, and a summary of considerations to be made when selecting a shoreline mapping technique. Although some of the latest shoreline mapping methods are extremely successful at reducing the error involved in measuring shoreline position, not all projects require the use of such high-end techniques. Additionally, regardless of the method used, some amount of error, which should be quantified, will always remain. Before selecting a mapping method, it is important to consider many factors including: accuracy required, characteristics of data inputs, necessary output, monetary constraints, time constraints and the potential applicability to future projects. For information and details beyond the scope of this manuscript refer to the extensive bibliography which contains at least a representative sampling of articles and reports on the topic of shoreline mapping.

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