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Monitoring the Coastal Environment; Part IV: Mapping, Shoreline Changes, and Bathymetric Analysis

For Cindy, I applaud your shoreline work. Regards, Laurel

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ABSTRACT

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This paper presents an overview of field methods, data collection, and analysis procedures applied to four key coastal data sets used in monitoring and baseline studies: aerial photography, satellite imagery, profile surveys, and bathymetric (hydrographic) records. Often, aerial photographs and satellite images, after rectifying and georeferencing, serve as base maps to interpret landform changes and quantify shoreline movement. Large-scale topographic and hydrographic maps are the primary sources for shoreline position and volumetric change computations. Profile surveys, available from many Federal and local agencies and universities, can also be used to evaluate shoreline changes and compute beach volume changes along and across the shore. Frequently, post-processing steps are required to normalize these data to the same coordinate system and vertical datum prior to quantifying changes for a coastal area. For example, project-specific bathymetric data in the United States is often plotted using State Plane coordinates, while hydrographic data from NOAA is supplied with latitude/longitude coordinates.

Maps, surveys, and aerial photographs are available from Federal agencies such as the USGS, NOAA, and the Corps of Engineers. These long-term data records can be used to evaluate natural and man-made changes to a coastal system. The resultant statistics and volumetric calculations should be presented in terms of the regional and local conditions, *i.e.,* storm history, seasonality, wave climate, man-made environmental and engineering changes, and large- and small-scale landforms.

ADDITIONAL INDEX WORDS: *Shoreline change, bathymetric mapping, grid models, triangular Irregular Network models, cartographic software, depth of closure, geospatial methods.*

INTRODUCTION

This paper is the fourth in a series of four that discuss techniques for measuring and analyzing coastal geologic and engineering data. The focus of this paper is on mapping technology and methods used to analyze shoreline change and offshore bathymetric changes. These techniques are often used by geologists and engineers who must evaluate the effects of coastal structures on the adjacent shorelines or decipher the morphologic history of a region based on historical maps and bathymetric data sets. Shoreline change data are critical for coastal managers tasked with establishing setback lines and guiding growth in the coastal zone, especially in low-lying areas subject to storm flooding. Volumetric analyses based on bathymetric data are used to compute amounts of sediment trapped by structures, growth of offshore shoals, migrations of channel thalwegs, and dredging volumes. Volumetric analyses are also used to monitor the performance of beach renourishment projects.

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AERIAL PHOTOGRAPHY

Aerial photographs provide invaluable information for the interpretation of geologic history. Aerial images can be obtained from Federal and state government agencies such as the United States Geological Survey (USGS), the U.S. Department of Agriculture, the EROS Data Center, and the U.S. Army Corps of Engineers (USACE) (other Government sources are listed in HEADQUARTERS, USACE, 1995). Stereographic photograph pairs with overlap of 60 percent are often available, allowing very detailed information to be obtained using photogrammetric techniques. Coverage for the United States is available since the 1930's for most locations. The types of analyses and interpretation that can be performed depend in part on the scale of the photographs, the resolution, and the percentage of cloud cover. One of the greatest advantages of aerial surveys is the ability of Federal and state agencies to rapidly mobilize photographic equipment and aircraft and document the effects of major events such as hurricanes or floods. Aircraft can cover large areas in a short time and can survey terrain that is not readily accessible from the ground. Clouds and haze are the two main factors that reduce the quality of aerial photographs.

For modern process studies, a series of aerial photographs can provide much data for examining a variety of problems. Information pertinent to environmental mapping and classification such as the nature of coastal landforms and materials, the presence of engineering structures, the effects of recent storms, the locations of rip currents, the character of wave shoaling, and the growth of spits and other coastal features can be examined on aerial photographs. For coastal morphological studies, it is generally preferable to obtain photographs during low tide so that nearshore features are exposed or partly visible through the water. However, the National Ocean Survey (NOS) prefers to map the mean high water line or high water line (mhwl/hwl) using high-tide coordinated imagery.

For studies over historical time scales, multiple sets of aerial photographs are required. Historical photographs and maps are integral components of shoreline change assessments. Water level and, therefore, shoreline locations, show great variation according to when aerial photographic missions were flown. Therefore, coastal scientists should account for such variations as potential sources of error in making or interpreting shoreline change maps.

Air photographs, which are not map projections, must be corrected by optical or computerized methods before shore positions compiled from the photos can be directly compared with those plotted on maps. The distortion correction procedures are involved because most photos do not contain defined control points such as latitude-longitude marks or triangulation stations[1]. On many images, however, secondary control points can be obtained by matching prominent features such as the corners of buildings or road intersections with their mapped counterparts (CROWELL, LEATHERMAN, and BUCKLEY, 1991). Types of distortion which must be corrected include:

- *Tilt.* Almost all vertical aerial photographs are tilted, with 1 degree being common and 3 degree not unusual (LILLESAND and KIEFER, 1987). The scale across tilted air photos is non-orthogonal, resulting in gross displacement of features depending upon the degree of tilt.
- *Variable scale.* Planes are unable to fly at a constant altitude. Therefore, each photograph in a series varies in scale. Zoom transfer scopes or cartographic software can be used to remove scale differences between photos.
- *Relief displacement.* Surfaces which rise above the average land elevation are displaced outward from the photo isocenter. Fortunately, most U.S. coastal areas, especially the Atlantic and Gulf barriers, are relatively flat and distortion caused by relief displacement is minimal. However, when digitizing cliffed shorelines, control points at about the same elevation as the feature being digitized must be selected.
- *Radial lens distortion.* With older aerial lenses, distortion varied as a function of distance from the photo isocenter. It is impossible to correct for these distortions without knowing the make and model of the lens used for the exposures (CROWELL, LEATHERMAN, and BUCKLEY, 1991). If overlapping images are available, digitizing the centers, where distortion is least, can minimize the problems.

Fortunately, most errors and inaccuracies from photographic distortion and planimetric conversion can be quantified. *Orthophotoquadrangles* and *orthophotomosaics* are photomaps made by applying differential rectification techniques (stereo plotters) to remove photographic distortions. Shoreline mapping exercises have shown that, if care is taken in all stages of filtering original data sources, digitizing data and performing distortion corrections, the resulting maps meet, and often exceed, National Map Accuracy Standards (CROWELL, LEATHERMAN, and BUCKLEY, 1991).

REMOTELY-SENSED SATELLITE DATA

Satellite imagery archives span broad areas of the globe and include regular coverage of most coastlines in all weather and seasons. Much of the existing data has a resolution of 10 m or greater. However, despite the coarse resolution (in comparison with film-based aerial photographs), satellite digital data may assist in understanding large-scale phenomena, especially processes which are indicators of geologic conditions and surface dynamics. Remote sensing data are also extensively used in wetlands research to monitor changes in flora, drainage patterns, and hazardous waste discharges (LAMPMAN, 1993). With modern processing equipment, remote sensing data can be downloaded, processed, and manipulated easily and quickly.

Satellite data are available from U.S. agencies, the French Systeme Pour L'Observation de la Terre (SPOT) satellite data network, and from Russian (Soviet) archives. In most instances, the data can be purchased either as photographic paper copy or in digital format for use in computer applications. Numerous remote sensing references are listed in LAMPMAN (1993). A listing of satellite data maintained by the National Space Center Data Center (NSCDC) is in HOROWITZ and KING (1990). This data can be accessed electronically. NELSON (1994) lists names and addresses of Government and private vendors of remote sensing imagery.

Satellite data are especially useful for assessing large-scale changes across the coastal zone. In the vicinity of deltas, estuaries, and other sediment-laden locations, spatial patterns of suspended sediment can be detected with remote sensing (Figure 1). In shallow non-turbid water bodies, some features of the offshore bottom, including the crests of submarine bars and shoals, can be imaged. The spatial extent of tidal flows may be determined using thermal infrared data, which can be helpful in distinguishing temperature differences of ebb and flood flows and freshwater discharges in estuaries. In deeper waters, satellites provide data on ocean currents and circulation (BARRICK, EVANS, and WEBER, 1977).

The Landsat satellite program was developed by the National Aeronautics and Space Administration in cooperation with the U.S. Department of the Interior. Landsat satellites

[1] For low-altitude aerial surveys, monuments and other triangulation points can be flagged with markers (triangles or plastic or cloth strips) that are large enough to be visible on the resulting photographs. This is a necessary procedure for highest accuracy photomapping, although flagging is an expensive procedure because of the many field crews that have to be on standby waiting for optimum flight conditions.

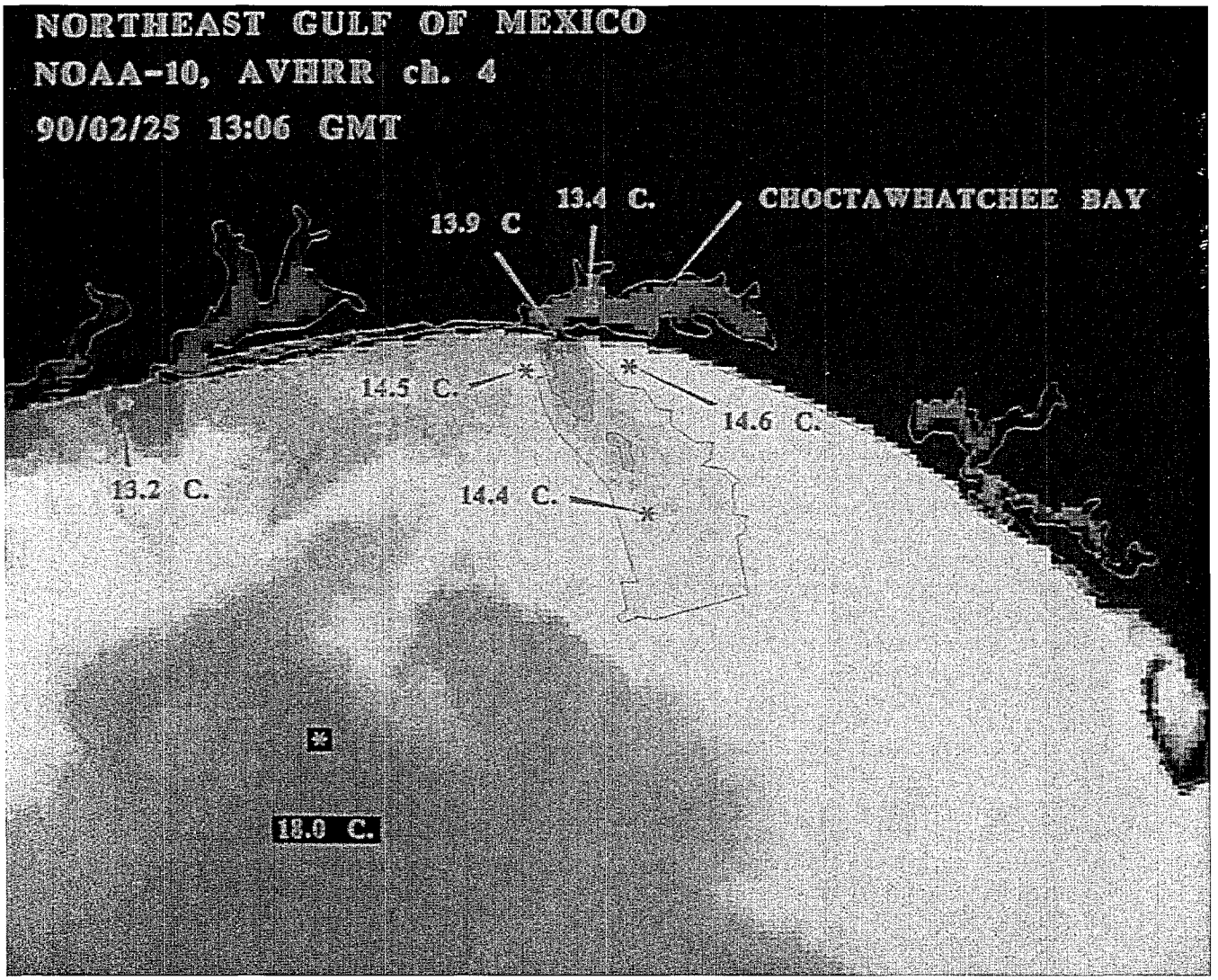

Figure 1. NOAA AVHRR satellite image from February 24, 1990, showing plume of cold water emerging from Choctawhatchee Bay, Florida (from MORANG, 1993). Image processed at the Earth Scan Laboratory, Louisiana State University, Baton Rouge.

have used a variety of sensors with different wavelength sensitivity characteristics, ranging from the visible (green) to the thermal infrared with a maximum wavelength of 12 micrometers (μm). Figure 2 shows bandwidths and spatial resolution of various satellite sensors. Of the five Landsat satellites, only Landsat 4 and Landsat 5 are currently in orbit. Both are equipped with the multispectral scanner, which has a resolution of 82 m in four visible and near-infrared bands, and the thematic mapper, which has a resolution of 30 m in six visible and near- and mid-infrared bands and a resolution of 120 m in one thermal infrared band (10.4–12.5 μm).

SPOT is a French commercial satellite program. The first satellite, SPOT 1, launched in 1986, has two identical sensors known as HRV (high-resolution-visible) imaging systems. Each HRV can function in a 10-m resolution panchromatic mode with one wide visible band (0.51–0.73 μm), or a 20-m resolution multispectral mode (two visible bands—green: 0.50–0.59 μm; red: 0.61–0.69 μm—and one near infrared band: 0.79–0.89 μm). For coastal studies, SPOT images have been used to detect suspended sediment, indicative of runoff and coastal currents (Figure 3). SPOT 1 and 2 are in sun-synchronous orbits of 832 km and orbit the earth once every 101 min. This provides full earth coverage between 72° N and 72° S every 26 days.

Several generations of satellites have flown in the National Oceanic and Atmospheric Series (NOAA) series. The most recent ones contain the Advanced Very High-Resolution Radiometer (AVHRR). This provides increased aerial coverage but at much coarser resolution than the Landsat or SPOT satellites. More information on the wide variety of satellites can be found in textbooks on remote sensing (COLWELL, 1983; LILLESAND and KIEFER, 1987; RICHARDS, 1986; SABINS, 1987; STEWART, 1985). Many defense contractors are bringing to the civilian market powerful, formerly restricted, map-

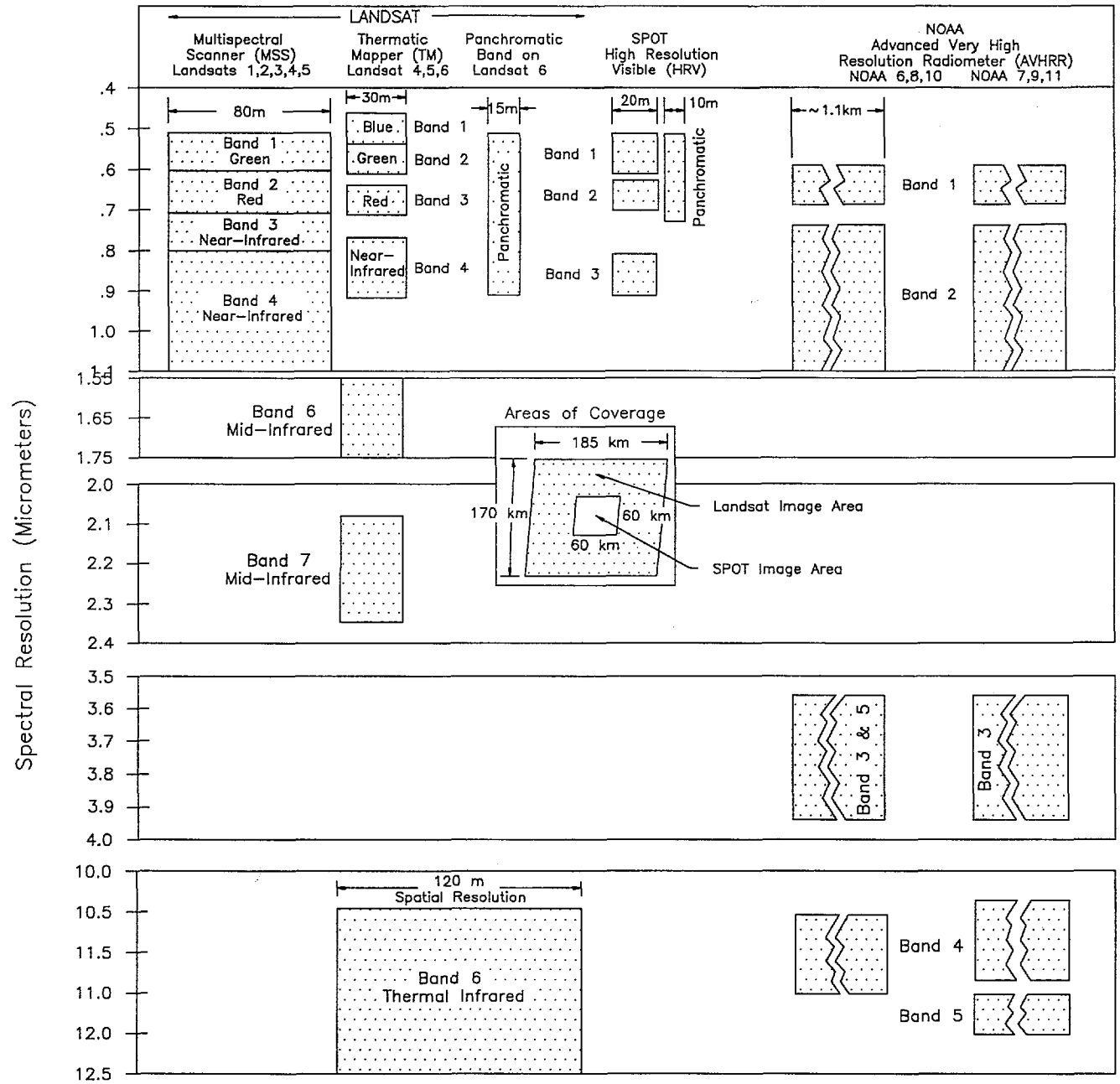

Figure 2. Spectral resolution and approximate spatial resolution of sensors on Landsat, SPOT, and NOAA satellites (from Earth Observation Satellite Company literature and HUH and LEIBOWITZ, 1986).

ping and display technologies (EOM STAFF, 1994; MCDONALD, 1995). Time will tell how many of these ventures are commercially viable, but many show tremendous potential in coastal geological and ecological studies.

Aircraft-mounted scanners, including thermal sensors and radar and microwave systems, also have applications in coastal studies. LIDAR (Light Detection and Ranging), SLAR (Side-Looking Airborne Radar), SAR (Synthetic Aperture Radar), SIR (shuttle imaging radar), and passive microwave systems have been tested for mapping the bottom topography of coastal waters.

A LIDAR system, known as SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey), is now being used by the Corps of Engineers to survey coastal areas and inlets. The system is based on the transmission and reflection of a pulsed coherent laser light from a helicopter equipped with the SHOALS instrument pod and with data processing and navigation equipment (LILLYCROP and BANIC, 1992; ES-

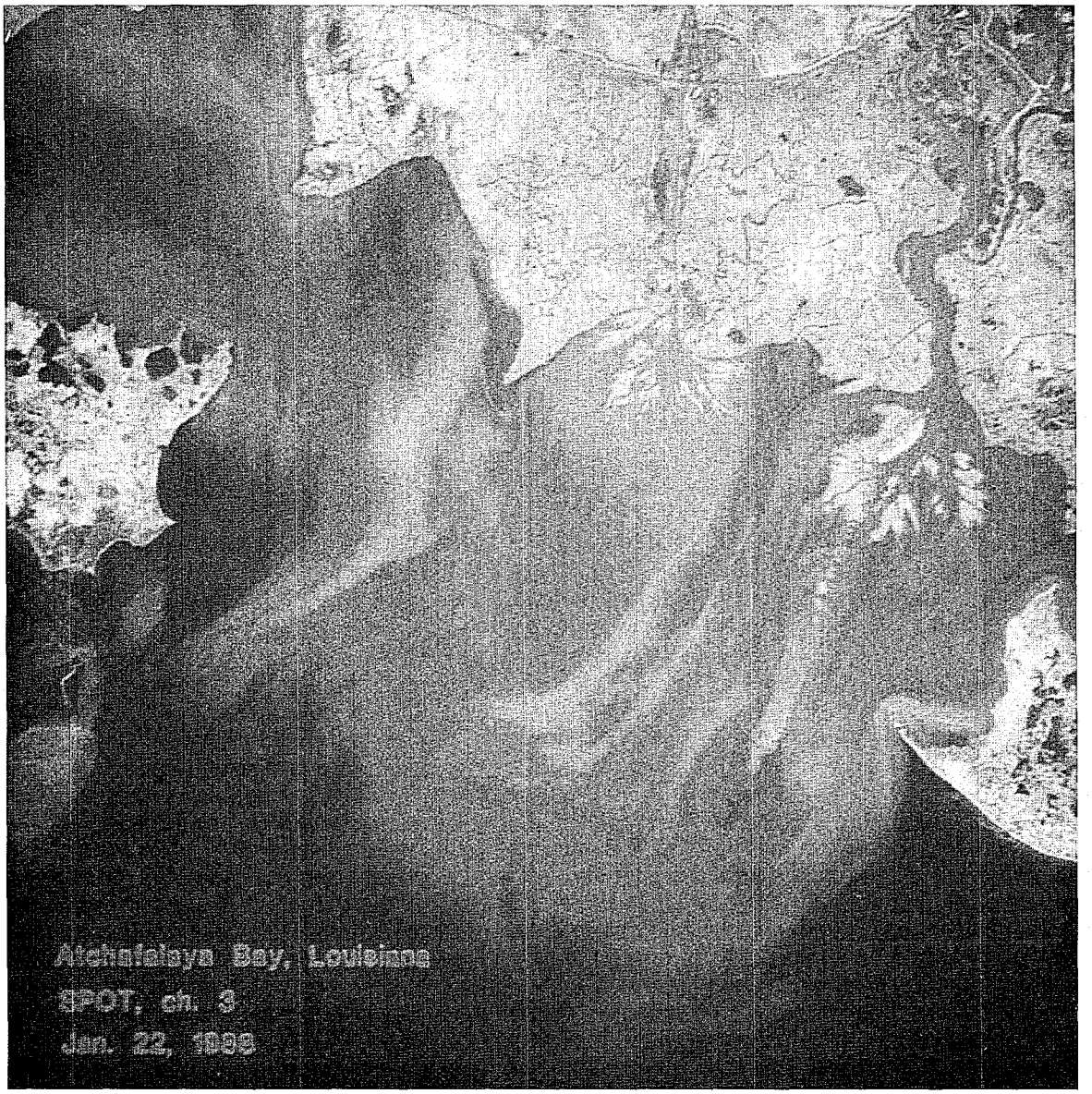

Figure 3. SPOT satellite image, Atchafalaya Bay, Louisiana. Suspended sediment from runoff is clearly visible. Data processed by the Earthscan Laboratory, School of Geosciences, Louisiana State University, Baton Rouge.

TEP, LILLYCROP, and PARSON, 1994). In operation, the SHOALS laser pulses 200 times per second and scans an arc across the helicopter's flight path, producing a survey swath equal to about half of the aircraft altitude. A strongly reflected light return is recorded from the water surface, followed closely by a weaker return from the seafloor. The difference in time of the returns corresponds to water depth. SHOALS may revolutionize hydrographic surveying in shallow water for several reasons. The most important advantage is that the system can survey up to eight square km per hour, thereby densely covering large stretches of the coast in a few days. This enables almost instantaneous data collection along shores subject to rapid changes. The system can be mobilized quickly, allowing broad-area post-storm surveys or surveys of unexpected situations such as breaches across barriers. For instance, SHOALS surveyed portions of the Florida Panhandle within a week after Hurricane Opal crossed the coast in October, 1995 (Figure 4). Finally, SHOALS can survey directly from water through the surf zone and across the beach; this allows efficient coverage of shoals, channels, or breaches that would normally be impossible or very difficult to survey using traditional methods, especially in winter. Maximum survey depth is proving to be over 30 m, depending on water clarity. Because of the immense amount of data that the SHOALS system collects, data processing, archiving, and management is proving to be a challenge.

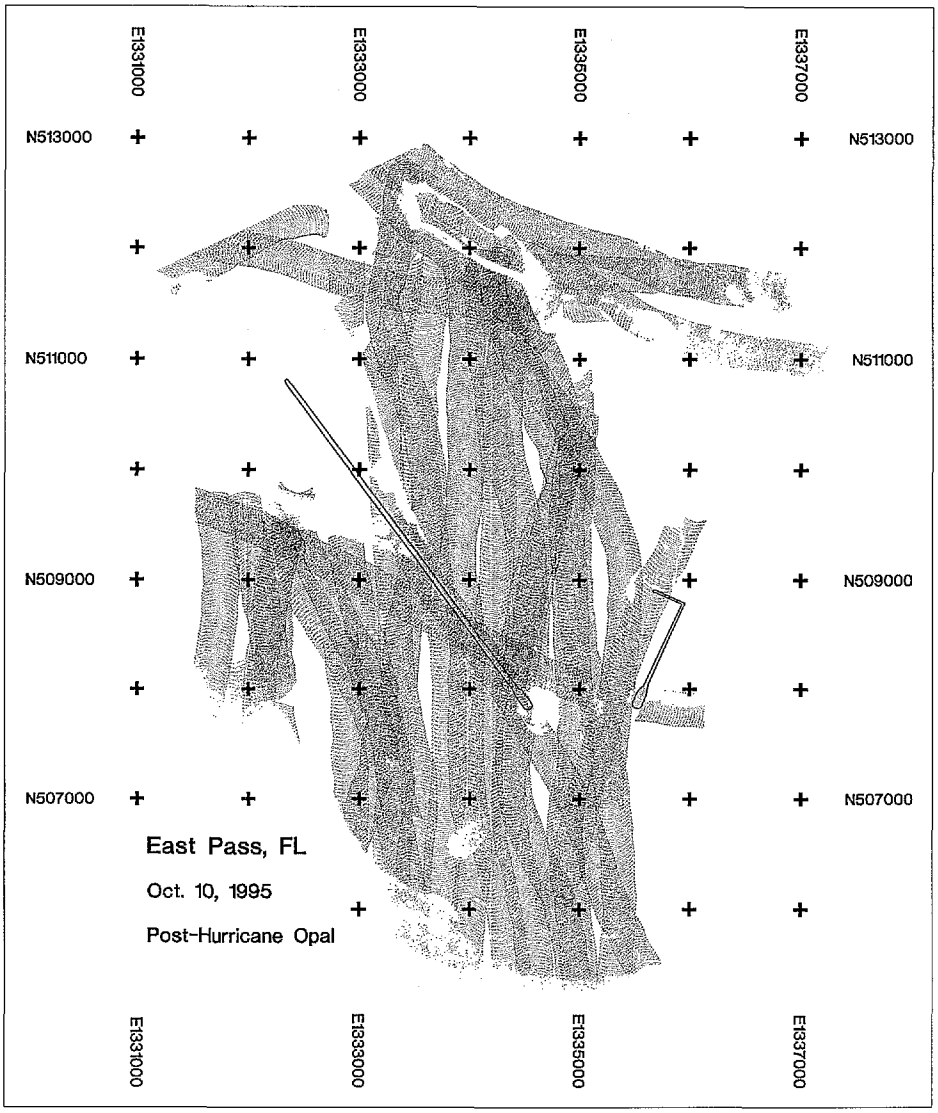

Figure 4. SHOALS helicopter LIDAR bathymetry survey tracklines at East Pass, Destin, Florida, flown on October 10, 1995, only six days the passage of Hurricane Opal. The coverage includes over 200,000 individual depth values. Arrowhead jetties mark the mouth of East Pass inlet.

TOPOGRAPHIC AND BATHYMETRIC DATA

Topographic and hydrographic[2] maps are available from the USGS, many Corps of Engineers District Offices, and the National Ocean Service (NOS), which includes the archives of the U.S. Coast and Geodetic Survey (USC&GS). U.S. Geological Survey topographic maps are generally revised every 20 to 30 years, but sometimes more often in high-priority areas. Nevertheless, the maps are sometimes outdated because of the ephemeral nature of many coastal landforms. The maps are created at a range of scales from 1:24,000 to 1:250,000 (ELLIS, 1978), with the most common being the 7½′ (minute) series (scale 1:24,000) and a 15′ series (scale 1:62,500). Their purpose is to portray the shape and elevation of the terrain above a given datum, usually the mean high water line. The resolution of these maps is typically inadequate to provide details of coastal surface features but are sufficient for examining regional landforms and pronounced local changes, particularly over long periods.

Recent and historical hydrographic survey data for the

[2] The term topographic usually refers to the shape and form of the dry land portions of the earth (from the Greek topos, "a place"). Bathymetric and hydrographic, often used interchangeably, describe the morphology of the seafloor. However, NOAA makes a subtle distinction: a bathymetric chart depicts water depths, contour lines, and gradient tints, whereas a hydrographic chart emphasizes water measurements showing submarine features and the adjacent coastal areas with respect to navigational use (BOWDITCH, 1981). The distinction between the terms map and chart are based on usage, with chart being a product constructed for use in marine navigation (SHALOWITZ, 1964).

United States marine coasts and Great Lakes are available from the NOS. Much of this data can be obtained in the form of preliminary plots that are of larger scale and contain more soundings and bottom notations than the published charts made from them. Surveys since about 1930 are available in digital form from the National Geophysical Data Center in Boulder, Colorado. For older surveys, a user must purchase photographic reproductions of T-sheets (topographic) or H-sheets (hydrographic) from the NOS and digitize them himself.

Bathymetric survey maps are sometimes out of date because geomorphic changes in many submarine areas occur rapidly. On some navigation charts, the bathymetry may be more than 50 years old and the marked depths may be quite different than actual depths. The greatest changes are likely to be in areas of strong current activity, of strong storm activity, of submarine mass movement, and of dredging near ship channels. The user must also be aware of changes in the datums used in different maps (to be discussed later in this paper). The Corps of Engineers surveys most Federal navigation projects annually to determine if the channels meet project specifications. These surveys sometimes extend over the ebb and flood shoals of inlets and along the adjacent shores.

BRIEF DISCUSSION OF DEPTH OF CLOSURE

Depth of closure is a concept that is often misinterpreted and misused. For engineering practice, depth of closure is commonly defined as the minimum water depth at which no measurable or significant change in bottom depth occurs (STAUBLE *et al.*, 1993). The word *significant* in this definition is important because it leaves considerable room for interpretation. "Closure" has erroneously been interpreted to mean the depth at which no sediment moves on- or offshore, although numerous field studies have verified that much sediment moves in deep water (WRIGHT *et al.*, 1991). Another complication is introduced by the fact that it is impossible to define a single depth of closure for a project site because "closure" moves depending on waves and other hydrodynamic forces.

For the Atlantic Coast of the United States, closure depth was often assumed to be about 9 m (30 ft) for use in engineering project design. However, at the Field Research Facility in Duck, North Carolina, BIRKEMEIER (1985) calculated closure as deep as 6.3 m relative to mean low water using surveys conducted from the Corps of Engineers' Coastal Research Amphibious Buggy (CRAB). STAUBLE *et al.* (1993) obtained 5.5 to 7.6 m at Ocean City, Maryland, from profile surveys. Obviously, it is invalid to assume that "closure" is a single fixed depth along the eastern United States.

Closure depth is used in a number of applications such as the placement of mounds of dredged material, beach fill, placement of ocean outfalls, and the calculation of sediment budgets.

Closure is related to energy factors at coastal sites. The primary assumption behind the concept of the shoreface equilibrium profile is that sediment movement and the resultant changes in bottom elevation are a function of wave properties and sediment grain size (BRUUN, 1954; DEAN, 1976, 1977, 1990; PILKEY *et al.*, 1993). Therefore, the active portion of the shoreface varies in width throughout the year depending on wave conditions. In effect, "closure" is a time-dependent quantity that may be predicted based on wave climatology or may be interpreted statistically using profile surveys.

The energy-dependent nature of the active portion of the shoreface also requires us to consider return period. The closure depth that accommodates the 100-year storm will be much deeper than one that merely needs to include the 10-year storm. Therefore, the choice of a closure depth must be made in light of a project's engineering requirements and design life. For example, if a berm is to be built in deep water where it will be immune from wave resuspension, what is the minimum depth at which it should be placed? This is an important question because of the high costs of transporting material and disposing of it at sea. It would be tempting to use a safe criteria such as the 100- or 500-year storm, but excessive costs may force the project engineer to consider a shallower site that may be stable only for shorter return period events.

Two methods are commonly used to predict closure depth. One is predictive, based on wave data collected at the site over time. HALLERMEIER (1977, 1978, 1981a, 1981b, 1981c), using laboratory tests and limited field data, introduced equations to predict the limits of extreme wave-related sediment movement. This paper is not the appropriate forum to review the formulas in detail; they are summarized in HEADQUARTERS, USACE (1995), and the reader is urged to read Hallermeier's original papers to understand his assumptions and interpretations.

When surveys covering several years are available for a project site, closure is best determined by plotting and analyzing the profiles. The closure depth computed in this manner reflects the influence of storms as well as of calmer conditions. KRAUS and HARIKAI (1983) evaluated the depth of closure as the minimum depth where the standard deviation in depth change decreased markedly to a near-constant value. Using this procedure, they interpreted the landward region where the standard deviation increased to be the active profile where the seafloor was influenced by gravity waves and storm-driven water level changes. The offshore region of smaller and nearly constant standard deviation was primarily influenced by lower frequency sediment-transporting processes such as shelf and oceanic currents (STAUBLE *et al.*, 1993). Note that the smaller standard deviation values fall within the limit of measurement accuracy. This suggests that it is not possible to specify a closure depth unambiguously because of operational limits of present offshore profiling hardware and procedures.

An example of how closure was determined empirically at Ocean City, Maryland, is shown in Figure 5. A clear reduction in standard deviation occurs at a depth of about 18 to 20 ft ($\approx$ 6 m). Above the $\approx$ 18-ft depth, the profile exhibits large variability, indicating active wave erosion, deposition, and littoral transport. Deeper (and seaward) of this zone, the lower and relatively constant deviation of about 3 to 4 inches (8 to 10 cm) is within the measurement error of the sled surveys. Nevertheless, despite the inability to precisely measure sea-

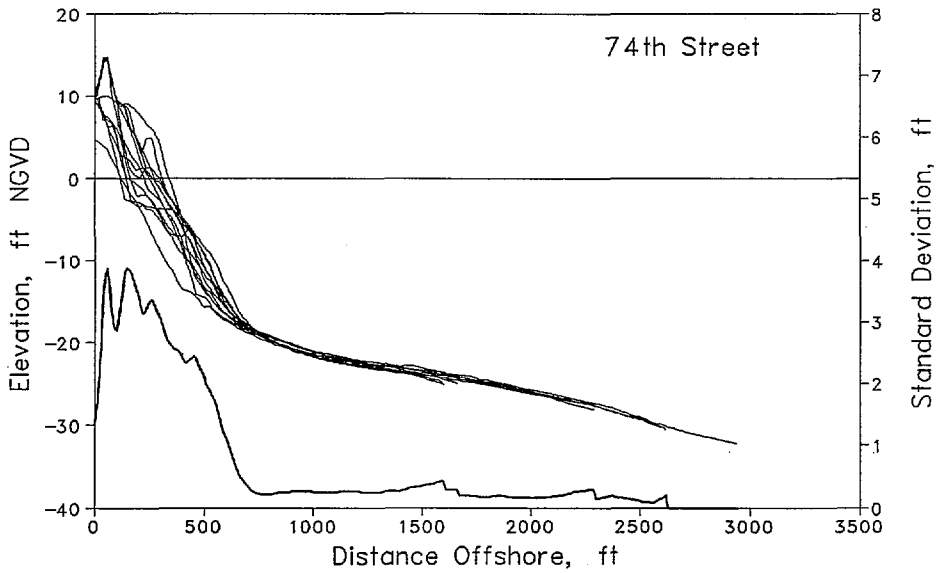

Figure 5. Profile surveys and standard deviation of seafloor elevation at Ocean City, Maryland (from STAUBLE *et al.*, 1993). Surveys conducted from 1988 to 1992. Large changes above the datum were caused by beach fill placement and storm erosion.

floor changes in this offshore region, it is apparent that less energetic erosion and sedimentation take place here than in water shallower than ≈ 18 ft. This does not mean that there is no sediment transport in deep water, just that sled surveys are unable to measure it. For the 5.6 km of shore surveyed at Ocean City, the depth of closure ranged between 18 and 25 ft (5.5 to 8.5 m). Scatter plots indicated that the average closure depth was 20 ft (6 m).

Presumably, conducting surveys over a longer time span at Ocean City would reveal seafloor changes deeper than ≈ 20 ft, depending on storms that passed the region. However, STAUBLE *et al.* (1993) noted that the "Halloween Storm" of October 29 to November 2, 1991, generated waves of peak period (T_p) 19.7 sec, extraordinarily long compared to normal conditions along the central Atlantic coast. Therefore, the profiles may already reflect the effects of an unusually severe storm.

Figure 6 is an example of profiles from St. Joseph, Michigan, on the east shore of Lake Michigan. Along Line 14, dramatic bar movement occurs as far as 2,500 ft (560 m) offshore to a depth of −25 ft (−7.6 m) with respect to International Great Lakes Datum (IGLD) 1985. This is where an abrupt decrease in standard deviation of lake floor elevation occurs and can be interpreted as closure depth. In September, 1992, the mean water surface was 1.66 ft above IGLD 85. Therefore, closure was around 26–27 ft (8 m) below *water* level.

In the Great Lakes, water levels fluctuate over multi-year cycles. This raises some fundamental difficulties in calculating closure based on profile surveys. Presumably, during a period of high lake level, the zone of active sand movement would be higher on the shoreface than during a time of low lake level (assuming similar wave conditions). Therefore, the depth where superimposed profiles converge should reflect the *deepest* limit of active shoreface sand movement. This would be a conservative value, but *only with respect to the hydrologic conditions that occurred during the survey program.* Presumably, if lake level dropped further at a later date, sediment movement might occur deeper on the shoreface. This suggests that closure on the lakes should be chosen to reflect the *lowest* likely water level that is expected to occur during the life of a project. (Note that this consideration does not arise on ocean coasts because year-to-year changes in relative sea level are minor, well within the error bounds of sled surveys. Sea level does change throughout the year because of thermal expansion, freshwater runoff, wind set-up, and other factors, but the multi-year mean is essentially stable.) In summary, determining closure depth in the Great Lakes is problematic because of changing water levels, and more research is needed to develop procedures that accommodate these non-periodic lake level fluctuations.

MAP DATUMS, CORRECTIONS, AND SOURCES OF ERROR

Definitions

A *datum* is an established reference level or position that can be used as a basis of comparison for surveying or measurement purposes (HEADQUARTERS, USACE, 1994). For coastal engineering and geologic studies, both horizontal (geographic location) and vertical (distance above sea level or other surface) datums must be established:

First, specific features of a project site must be correctly located in horizontal position on the face of the earth, especially when recent measurements are to be compared to ones collected decades ago. Several map projections are in common use. For convenience in data entry and manipulation, many Corps of Engineers project maps are plotted on rectangular grids such as the *State Plane Coordinate System.*

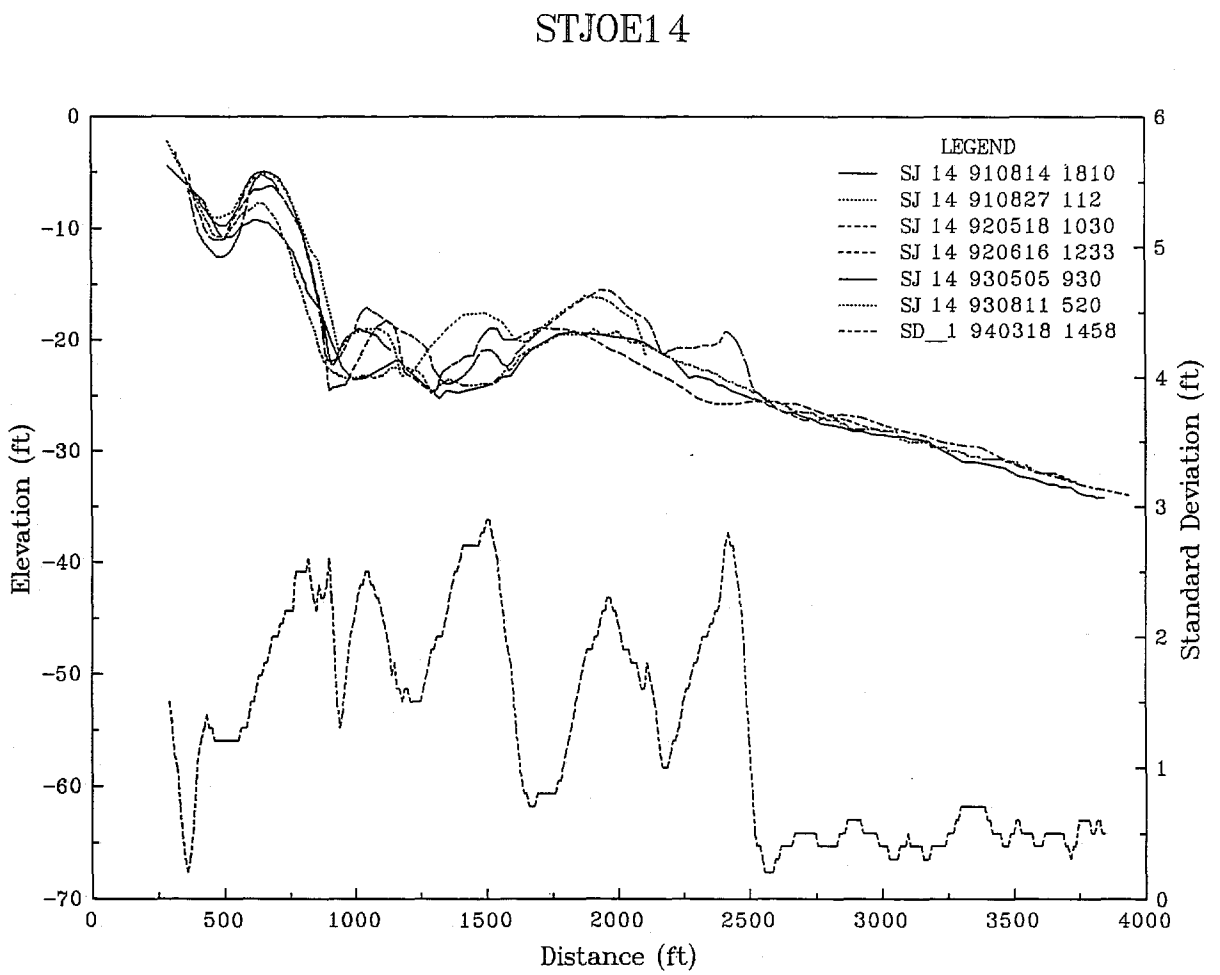

Figure 6. Profile surveys and standard deviation of lake floor elevation at St. Joseph, Michigan, on the east shore of Lake Michigan. Profiles are referenced to International Great Lakes Datum (IGLD) 1985. Surveys conducted between 1991 and 1994.

A separate grid has been established for each state, with the larger states divided into several zones. This system uses rectilinear coordinates with uniform x- and y- dimensions so that surveyors do not have to take into account the curvature of the earth in their calculations. The simplification is acceptable for local surveys because the introduced error is small (CAMPBELL, 1991). These charts are referred to either the North American Datum of 1927 (NAD27) or the North American Datum of 1983 (NAD83) (HEADQUARTERS, USACE, 1994; U.S. GEOLOGICAL SURVEY, 1989). Charts covering larger areas, particularly when they cross state boundaries, use latitude/longitude coordinates or metric dimensions based on a non-uniform projection (*e.g.*, Mercator). Mapping computer software can convert spatial data from one horizontal coordinate system to another. Note that the conversion can be difficult for old maps if they do not specifically state what coordinate system was used. Another difficulty arises when project maps use a local rectangular grid and the records that describe the relationship of the local grid to national datums have been lost. ELLIS (1978) and CAMPBELL (1991) discuss details of projections and various grid systems.

The second datum of critical importance in coastal studies is the horizontal surface to which all vertical measurements are referenced. When computing sediment volumes or examining changes in shorelines or bottom configuration, all data *must* be corrected to a common datum. For North American coastal engineering projects, normally two types of horizontal datums have been considered: those pertaining to open water, ocean coasts, and those pertaining to the Great Lakes. Studies in other lakes or in reservoirs may use local, unique datums.

Sea Level or Tidal Datums

In the 1800's, *mean sea level* (msl) was adopted as a primary datum because it was believed that msl could be accurately determined from tide gauge records. Over time, other datums became established for specific needs or for certain geographic regions. The most important for navigation-relat-

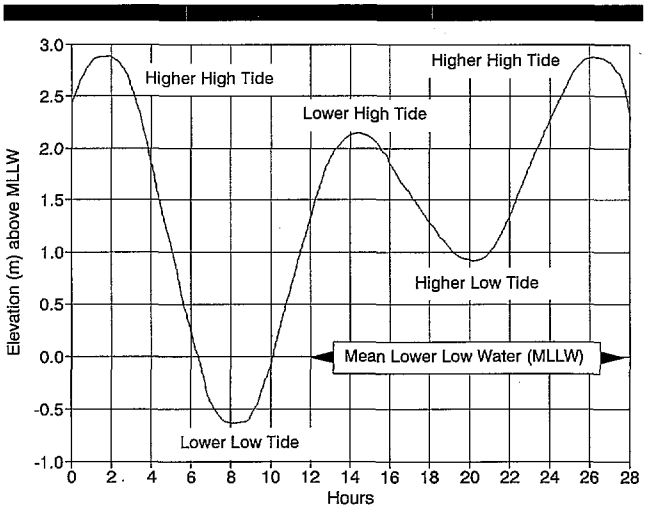

Figure 7. Tide curve for Yaquina Bay, Oregon (based on 6 years of observations). By definition, mean lower low water (mllw) is zero (from OREGON, 1973).

ed activities are *mean low water* (mlw) for the Atlantic coast and *mean lower low water* (mllw) for the Pacific coast (HEADQUARTERS, USACE, 1989). These are defined as the average height of the tide at low water (diurnal coasts: the Atlantic) or lower low water (semi-diurnal coasts: the Pacific) when all tides for a 19-year period are considered. The specific 19-year cycle is known as the National Tidal Datum Epoch. Some areas of the United States have established regional datums. These are based on combinations of other datums (*e.g., mean low gulf* (mlg) for the Gulf of Mexico), or on local measurements of water level over different periods (SWANSON, 1974). Because of varying relative sea level in many areas, tidal datums are constantly changing and require continuous monitoring and updating. Formal definitions of standard tidal datums for the United States are officially promulgated in HICKS (1984). Figure 7 and Table 1 illustrate and define terminology used to describe water levels at an Oregon bay.

The National Geodetic Vertical Datum (NGVD)

The NGVD is a national fixed datum. It was established in the 1920's because of the need to compare land elevations at sites where there were no tide gauges or at interior sites far from the ocean. Because it was desirable to have the zero of the geodetic leveling net coincide with local sea level across much of the North American continent, NGVD was adjusted in 1929 according to tide records from 26 selected United States and Canadian tide stations. The reference level defined in this manner was called the NGVD, 1929 adjustment (NGVD 29), and has been used as a primary datum for engineering design in the United States (HEADQUARTERS, USACE, 1989). Note that NGVD 29 is *not* equal to mlw or mllw. Information is available from NOAA to relate NGVD 29 to tide curves at bays, inlets, and harbors around the country. It is important to remember that two charts or two sets of hydrographic data, one based on NGVD, and another on a tidal datum, can *not* be directly compared without making the appropriate vertical correction. During the 1980's, NOS conducted a major survey and analysis effort to relevel the

Table 1. *Tidal datums and definitions, Yaquina Bay, Oregon.*[1]

Tide (m)	Datum and Definition
4.42	*Extreme high tide.* The highest projected tide that can occur. It is the sum of the highest predicted tide and the highest recorded storm surge. Such an event would be expected to have a very long recurrence interval. In some locations, the effect of a rain-induced freshet must be considered. The extreme high tide level is used for the design of harbor structures.
3.85	*Highest measured tide.* The highest tide observed on the tide staff.
3.14	*Highest predicted tide.* Highest tide predicted by the Tide Tables.
2.55	*Mean higher high water.* The average height of the higher high tides observed over a specific interval. Intervals are related to the moon's many cycles, ranging from 28 days to 18.6 years. The time length chosen depends upon the refinement required. The datum plane of mhhw is used on NOS charts to reference rocks awash and navigation clearances.
2.32	*Mean high water.* The average of all observed high tides. The average is of both the higher high and of the lower high tide recorded each day over a specific period. The datum of mhw is the boundary between upland and tideland. It is used on navigation charts to reference topographic features.
1.40	*Mean tide level.* Also called half-tide level. A level midway between mean high water and mean low water. The difference between mean tide level and local mean and sea level reflects the asymmetry between local high and low tides.
1.37	*Local mean sea level.* The average height of the water surface for all tide stages at a particular observation point. The level is usually determined from hourly height readings.
1.25	*Mean sea level.* A datum based upon observations taken over several years at various tide stations along the west coast of the United States and Canada. It is officially known as the Sea Level Datum of 1929, 1947 adj. Msl is the reference for elevations on U.S. Geological Survey Quadrangles. The difference between msl and local msl reflects many factors ranging from the location of the tide staff within an estuary to global weather patterns.
0.47	*Mean low water.* Average of all observed low tides. The average is of both the lower low and of the higher low tides recorded each day over a specific period. The mlw datum is the boundary line between tideland and submerged land.
0.00	*Mean lower low water.* Average height of the lower low tides observed over a specific interval. The datum plane is used on Pacific coast nautical charts to reference soundings.
−0.88	*Lowest predicted tide.* The lowest tide predicted by the Tide Tables.
−0.96	*Lowest measured tide.* Lowest tide actually observed on the tide staff.
−1.07	*Extreme low tide.* The lowest estimated tide that can occur. Used by navigation and harbor interests.

[1]Based on six years of observations at Oregon State University marine science center dock
From OREGON (1973)

Table 2. *Low water (chart) datum for IGLD 1955 and IGLD 1985.*

Location	Low Water Datum in Meters IGLD 1955	IGLD 1985
Lake Superior	182.9	183.2
Lake Michigan	175.8	176.0
Lake Huron	175.8	176.0
Lake St. Clair	174.2	174.4
Lake Erie	173.3	173.5
Lake Ontario	74.0	74.2
Lake St. Lawrence at Long Sault Dam, Ontario	72.4	72.5
Lake St. Francis at Summerstown, Ontario	46.1	46.2
Lake St. Louis at Pointe Claire, Québec	20.3	20.4
Montréal Harbour at Jetty Number 1	5.5	5.6

From COORDINATING COMMITTEE ON GREAT LAKES BASIC HYDRAULIC AND HYDROLOGIC DATA (1992)

first order leveling lines and establish a single, more accurate datum for North America. The result, covering Mexico, the United States, and Canada, is called the *North American Vertical Datum (NAVD) of 1988.* Maps and coastal projects are only slowly being referenced to NAVD 1988. Specific definitions of various datums and their relationship with geodetic datums are listed in HARRIS (1981).

Water Level Datums of the Great Lakes of North America (Lakes Superior, Huron, Michigan, Eerie, and Ontario)

Low water reference datums used on the Great Lakes and their connecting waterways are currently based on the International Great Lakes Datum (IGLD) 1985. This datum, established and revised by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, replaced IGLD 1955 in January, 1992. The main differences between IGLD 1955 and IGLD 1985 are corrections in the elevations assigned to water levels (Table 2). This is a result of benchmark elevation changes due to adjustments for crustal movements, more accurate measurement of elevation differences, a new reference zero point location, and an expanded geodetic network. The reference zero point of IGLD 1985 is at Rimouski, Québec (Figure 8). The new 1985 datum establishes a set of elevations consistent for surveys taken within the time span 1982–1988. IGLD 1985 is referred to NAVD 1988. Note that the IGLD's are not parallel to NGVD 29 or NAVD 1988 because the Great Lakes datums are dynamic or geopotential heights that represent the hydraulic structure of the lakes and connecting waterways (HEADQUARTERS, USACE, 1994).

On the Great Lakes, astronomic tides have little influence on water levels. Instead, atmospheric pressure changes and winds cause most of the short-term water level fluctuations. Long-term changes are caused by regional hydrographic conditions such as precipitation, runoff, temperature and evapotranspiration, snow melt, and ice cover (GREAT LAKES COMMISSION, 1986). Global climate variations, in turn, influence these factors. Crustal movements also influence levels. For example, the earth's crust at the eastern end of Lake Superior is rebounding about 25 cm/century faster than the western end, resulting in a drop of the datums (apparent higher water) at the west end at Duluth. Aquatic plant life and man-made control structures are additional factors that influence

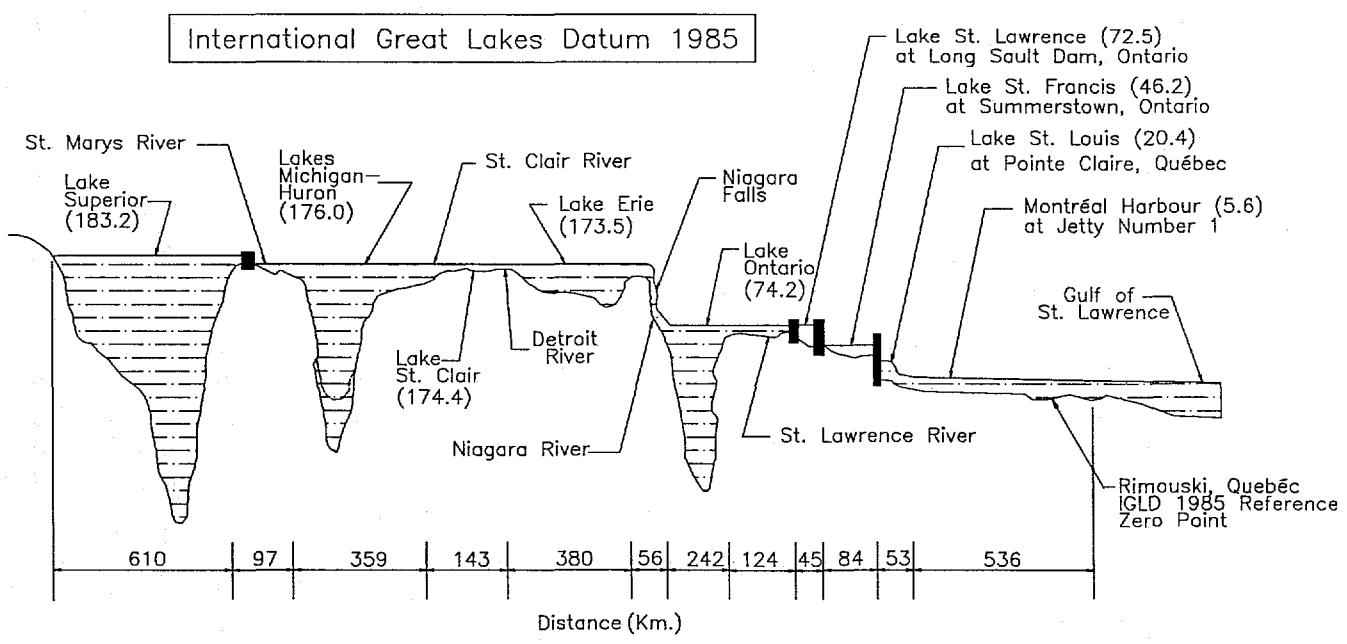

Figure 8. The reference zero point for IGLD 1985 at Rimouski, Québec is shown in its vertical and horizontal relationship to the Great Lakes-St. Lawrence River System. Low water datums for the lakes in meters (from COORDINATING COMMITTEE ON GREAT LAKES BASIC HYDRAULIC AND HYDROLOGIC DATA, 1992).

the exceedingly complex cycles of water level changes in the Great Lakes. As a result, the concept of mean water level is not applicable to these inland Great Lakes. Attempts to predict lake levels have not been entirely successful (WALTON, 1990).

SHORELINE CHANGE MAPPING

Introduction

Maps and aerial photographs provide a wealth of useful information for the interpretation of geologic coastal processes and evolution. Maps and photographs can reveal details on:

- Long-term and short-term advance or retreat of the shore
- Longshore movement of sediments
- The impact of storms, including barrier island breaches, overwash, and changes in inlets, vegetation, and dunes
- Problems of siltation associated with tidal inlets, river mouths, estuaries, and harbors
- Human impacts caused by construction or dredging
- Compliance with permits
- Biological condition of wetlands and estuaries

The use of maps and aerial photographs to determine historical changes in shoreline position is increasing rapidly. Analyzing existing maps does not require extensive field time or expensive equipment, therefore often providing valuable information at an economical price. This section summarizes the interpretation of shorelines on photographs and maps and corrections needed to convert historical maps to contemporary projections and coordinate systems.

Many possible datums can be used to monitor historical changes of the shoreline. In many situations, the high water line (hwl) has been found to be the best indicator of the land-water interface, the coastline (CROWELL, LEATHERMAN, and BUCKLEY, 1991). The hwl is easily recognizable in the field and can often be approximated from aerial photographs by a change in color or shade of the beach sand or a line of seaweed and debris. The datum printed on NOS T-sheets (topographic) is listed as "Mean High Water." Fortunately, the early NOS topographers approximated hwl during their survey procedures. Therefore, direct comparisons between historical T-sheets and modern aerial photographs are possible.

In order to calculate the genuine long-term shoreline change, seasonal beach width variations and other short-term changes should be filtered out of the record. Ideally, the best approach is to use only maps and aerial images from the same season, preferably summertime, when the beach is exposed at its maximum width. In practice, however, maps with adequate coverage of a study area are usually few in number. As a result, a researcher is typically compelled to take all the data he can find, regardless of the season (and usually he is glad to have found at least this much!).

A crucial problem underlying the analysis of all historical maps is that they must be corrected to reflect a common datum and brought to a common scale, projection, and coordinate system before data from successive maps can be compared (ANDERS and BYRNES, 1991). Maps made before 1927 have obsolete latitude-longitude coordinate systems (U.S. datum or North American (NA) datum) that must be updated to the current standards of NAD27 or the more recent NAD83. To align maps to a specific coordinate system, a number of stable and permanent points or features must be identified for which accurate and current geographic coordinates are known. These locations, called *primary control points,* are used by computer mapping programs to calculate the transformations necessary to change the map's projection and scale. The most suitable control points are triangulation stations whose current coordinates are available from the National Geodetic Survey.

Maps that were originally printed on paper have been subjected to varying amounts of shrinkage. The problem is particularly difficult to correct if the shrinkage along the paper's grain is different than across the grain. Maps with this problem have to be rectified or discarded. In addition, tears, creases, folds, and faded areas in paper maps must be corrected.

Several steps are needed to accurately quantify shoreline change. These steps include assembling data sources, entering data, digitizing coordinates, analyzing potential errors, computing shoreline change statistics, and interpreting shoreline trends. Based on shoreline change studies conducted at universities and Federal, State, and local agencies, a brief summary of the recommended techniques and procedures is given below.

Data Sources

Five potential data sources exist for assessing spatial and temporal changes in shoreline position.

USGS topographic quadrangle maps. Accurate delineation of the shoreline was not a primary concern on these land-oriented maps. However, shoreline position is routinely revised on 1:24,000 topographic maps using aerial photographic surveys. Many shoreline mapping studies have used these maps for quantifying changes in position, but more accurate and appropriate sources should be employed if available.

NOS Topographic Maps. Because the National Ocean Service is responsible for surveying and mapping topographic information along the coast, NOS topographic map products (T-sheets) have been used in the study of coastal erosion and protection, in law courts in the investigation of land ownership, and in the negotiation of international boundaries and territorial waters (SHALOWITZ, 1962). Most of these maps are planimetric in that only horizontal position of selected features is recorded; the primary mapped feature is the high-water shoreline. From 1835 to 1927, almost all topographic surveys were made by plane table; most post-1927 maps were produced using aerial photographs (SHALOWITZ, 1964). NOS shoreline position data are often used on USGS topographic quadrangles, suggesting that T-sheets are the primary source for accurate shoreline surveys. Scales of topographic surveys are generally 1:10,000 or 1:20,000. These large-scale products provide the most accurate representation of shoreline position other than direct field measurements using surveying methods.

Large-scale engineering surveys. In areas of significant human activity, engineering site maps often exist for specific projects. However, surveyed areas often are quite limited by

the scope of the project, and regional mapping at large scale (greater than 1:5,000) is sparse. If these surveys do exist, they potentially provide the most accurate estimates of high-water shoreline position and should be used. These data are valuable for rectifying aerial photographs.

Near-vertical aerial photography. Since the 1920's, aerial photography has been available for many coastal regions. However, these images cannot be used directly to produce a map. A number of graphical methods and computational routines exist for removing distortions inherent in photography (LEATHERMAN, 1984; ANDERS and BYRNES, 1991). Users are warned that conversion of photographic images to map projection is *not* a trivial procedure, despite the availability of modern cartographic software.

GPS surveys. From the late 1970's through the early 1990's, significant advances in satellite surveying were made with the development of the Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS). The GPS was developed to support military navigation and timing needs; however, many other applications are possible with the current technology. This surveying technique can be very accurate under certain conditions; however, signal degradation through selective availability causes significant positional errors if only one station is used (LEICK, 1990). BYRNES *et al.* (1994) have documented how they used GPS along with hand-held survey lasers to map the shoreline of southern Louisiana, which has experienced severe erosion and land loss. They claim that they have been able to substantially upgrade the accuracy of old aerial survey photographs by using GPS control points to rectify the photographs. In summary, differential GPS provides the capability for accurately delineating high-water shoreline position from ground surveys, but surveys must be conducted carefully by trained operators with properly calibrated equipment. Coastal researchers should be beware of unskilled contractors claiming amazing accuracy on the basis of their new GPS tools.

Data Entry

Frequently, shoreline maps have variable scales and use different datums and coordinate systems. Shoreline maps must be corrected to reflect a common datum and brought to a common scale, projection, and coordinate system before data from successive maps can accurately be compared. There are several computer cartographic systems, consisting of a high-precision digitizing table and cursor and computer interface, available. Ideally, a Geographic Information System (GIS) should be used to digitize various data sources and store the information in data layers that can be linked to a relational database. Most systems have a table or comment file associated with each data layer to document the original map source, cartographic methods, and potential errors.

Digitized shoreline points are commonly entered into an x–y data file for each shoreline source. A header or comment line should be incorporated into the digital file of the cartographic parameters such as map scale, projection, and horizontal and vertical datums.

Before the shoreline is digitized, triangulation points should be digitized for each shoreline map. These triangulation stations provide control points, which are crucial when using older maps or a multitude of different map sources (SHALOWITZ, 1964). Older maps may contain misplaced coordinate systems. If there is not enough information on the coordinate system or triangulation station, the map should not be used for quantitative data. A useful source of available United States triangulation stations is *Datum Differences* (U.S. COAST AND GEODETIC SURVEY, 1985).

Media distortion can be eliminated by using maps drawn on stable-base materials such as NOS T- and H-sheets. Most Corps of Engineers project maps have been made from linen or Mylar film. The original map or a high-quality Mylar copy should be used as opposed to black-line, blue-line, or other paper-based medium. However, if paper maps are used and distortion from shrinking and swelling is significant, the digitizer setup provides some degree of correction by distributing error uniformly across the map. In addition, rubber-sheeting and least-squares fit computer programs allow the user to define certain control points and correct for distortion errors as much as possible. It is also important to remember that data in digital form acquire no new distortions, whereas even stable-base maps can be torn, wrinkled, and folded. Scale distortion from optical methods of map reproduction are also corrected by bringing all maps to a 1:1 scale.

General Digitizing Guidelines

Cartographic methods and map handling should be consistent within a project and organization. The following shoreline digitizing guidelines are summarized from BYRNES and HILAND (1994):

All shorelines are digitized from stable-base materials. If possible use NOS T- and H-sheets on Mylar or on bromide if Mylar is not available. Shorelines mapped from rectified aerial photography are drawn onto, and digitized from, acetate film.

To prevent curling and wrinkling of maps, store cartographic and photographic materials flat or vertical. Bromide-based maps that are shipped in a map tube should be kept flat for several days before digitizing.

When attaching a map to a digitizer table, the area being digitized is always perfectly flat. Any wrinkles can cause that portion of the map to move during digitizing, creating positional errors. High-quality drafting tape or masking tape is used to attach the map. One corner is taped first, then the map is smoothed diagonally and the opposite corner is taped securely; this procedure is repeated for the other two corners. Once the corners are secured, the map is smoothed from the center to the edges and taped along each edge.

High-precision equipment must be used for accurate shoreline change mapping. Digitizer tables and cursors with a precision of 0.1 mm are recommended. This magnitude of change equates to 1 m of ground distance at a scale of 1:10,000. The center bead or crosshair should ideally be smaller than the width of the line being digitized; the smallest pen width generally used is 0.13 mm (corresponds to the size 000 Rapidograf pen). The width of the crosshair of a high-precision cursor is approximately 0.1 mm.

When digitizing, use manual point input as opposed to

Table 3. *Factors affecting potential errors associated with cartographic data sources.*

Accuracy		
Maps and Charts	Field Surveys and Aerial Photographs	Precision
Scale	Location, Quality, and Quantity of Control Points	Annotation of High-Water Line
Horizontal Datum	Interpretation of High-Water Line	Digitizing Equipment
Shrink/Stretch	Field Surveying Standards	Temporal Data Consistency
Line Thickness	Photogrammetric Standards	Media Consistency
Projection	Aircraft Tilt and Pitch	Operator Consistency
Ellipsoid	Aircraft Altitude Changes	
Publication Standards	Topographic Relief	
	Film Prints Versus Contact Prints	

After ANDERS and BYRNES (1991)

stream input. Stream input places points at a specified distance as the user traces over the line being digitized. This procedure tends to make a very uniform and smooth line. However, it could miss some curvature in the line if the specified distance is too large; likewise, it could accept more points than are needed if the specified distance is too small, resulting in extremely large files, as well as storage and display problems. In addition, if the user's hand slips during the digitizing process, stream digitizing will continue to place points in the erroneous locations. These can be difficult and time-consuming to correct. Manual digitizing allows the user to place points at non-uniform distances from each other, and therefore allows the user to represent all variations in the shoreline.

The seaward edge of the high-water shoreline and the center point of the printed bathymetric sounding should be used as the reference positions for data capture.

Potential Errors

It is important that all available procedures be used as carefully as possible to capture map data; however, no matter how cautious the approach, a certain amount of error will be generated in all measurements of horizontal position. Potential errors are introduced in two ways. *Accuracy* refers to the degree to which a recorded value conforms to a known standard. In the case of mapping, this relates to how well a position on a map is represented relative to actual ground location. *Precision,* on the other hand, refers to how well a measurement taken from a map or an aerial photograph can be reproduced. Table 3 lists the factors affecting the magnitude of error associated with data sources and measurement techniques. Both types of error should be evaluated to gauge the significance of calculated changes relative to inherent inaccuracies. The following discussion addresses these factors in terms of data sources, operator procedures, and equipment limitations.

Cartographic Sources

Shoreline measurements obtained from historical maps can only be as reliable as the original maps themselves. Accuracy depends on the standards to which each original map was made, and on changes which may have occurred to a map since its initial publication. Field and aerial surveys provided the source data used to produce shoreline maps. For T- and H-sheets at a 1:10,000 scale, national map standards allow up to 8.5 m of error for a stable point (up to 10.2 m of error at 1:20,000), but the location of these points can be more accurate (SHALOWITZ, 1964; CROWELL, LEATHERMAN, and BUCKLEY, 1991). Non-stable points are located with less accuracy; however, features critical to safe marine navigation are mapped to accuracy stricter than national standards (ELLIS, 1978). The shoreline is mapped to within 0.5 mm (at map scale) of true position, which at 1:10,000 scale is 5.0 m on the ground.

Potential error considerations related to field survey equipment and mapping of high-water shoreline position were addressed by SHALOWITZ (1964; p. 175) as follows:

> With the methods used, and assuming the normal control, it was possible to measure distances with an accuracy of 1 meter (Annual Report, U.S. Coast and Geodetic Survey 192, 1880) while the position of the plane table could be determined within 2 or 3 meters of its true position. To this must be added the error due to the identification of the actual mean high water line on the ground, which may approximate 3 to 4 meters. It may therefore be assumed that the accuracy of location of the high-water line on the early surveys is within a maximum error of 10 meters and may possibly be much more accurate than this. This is the accuracy of the actual rodded points along the shore and does not include errors resulting from sketching between points. The latter may, in some cases, amount to as much as 10 meters, particularly where small indentations are not visible to the topographer at the plane table.
>
> The accuracy of the high-water line on early topographic surveys of the Bureau was thus dependent upon a combination of factors, in addition to the personal equation of the individual topographer. But no large errors were allowed to accumulate. By means of the triangulation control, a constant check was kept on the overall accuracy of the work.

In addition to survey limitations listed by SHALOWITZ (1964), line thickness and cartographic errors (relative location of control points on a map) can be evaluated to provide an estimate of potential inaccuracy for source information. Although it can be argued that surveys conducted after 1900 were of higher quality than original mapping operations in

the 1840's, an absolute difference can not be quantified. Consequently, the parameters outlined above are assumed constant for all field surveys and provide a conservative estimate of potential errors. For the 1857/70 and 1924 T-sheets, digitizer setup recorded an average percent deviation of 0.02, or 4 m ground distance at a 1:20,000 scale. Line thickness, due to original production and photo-reproduction, was no greater than 0.3 mm, or 6 m ground distance for this same scale.

A primary consideration with aerial surveys is the interpreted high-water shoreline position. Because delineation of this feature is done remotely, the potential for error is much greater than field surveys and is a function of geologic control and coastal processes. DOLAN *et al.* (1980) indicated that average high-water line movement over a tidal cycle is about 1 to 2 m along the mid-Atlantic coast; however, accurate delineation of the line is sometimes difficult due to field conditions, human impacts, and photographic quality. Although the magnitude of error associated with locating the high-water line is unknown, on gently sloping beaches with large tidal ranges (*i.e.,* Sea Islands, Georgia/South Carolina), significant horizontal displacement can occur with a small increase in elevation.

For H-sheets, a topographical survey of the coast was often conducted before the bathymetric survey. The control points established along the shoreline were then used for positioning of the survey vessel offshore. Due to the nature of triangulating distances and angles from points on land, horizontal positions plotted for the vessel became less accurate as it moved away from shore. When the vessel was out of sight of the triangulation points along the coast, positioning was done by dead reckoning. Therefore, horizontal positions of some offshore soundings on early H-sheets may be suspect.

Digitizer Limitations

Another source of error relates to equipment and operator accuracy and precision. As stated earlier, the absolute accuracy (accuracy and precision) of the digitizing tables used for this study is 0.1 mm (0.004 in). At a scale of 1:10,000, this converts to ± 1 m. Furthermore, the precision with which an operator can visualize and move the cursor along a line can lead to much greater errors (TANNER, 1978). To evaluate the magnitude of operator error associated with digitizing shoreline position, at least three repetitive measurements should be compared.

Analysis of Shoreline Change Data

In most instances, data pairs are generated from shoreline locations relative to some arbitrary axis system. A comparison of these data pairs is used to calculate mean shoreline movements, variations in the rate and direction of movements, and maximum net movements (ANDERS, REED, and MEISBURGER, 1990). Generally the coastline is divided into segments based on the general orientation of the shoreline, as shown in Figure 9. Baselines should be chosen based on segments that are parallel to the shoreline. Usually a standard Cartesian coordinate system is assigned to each segment with the positive x-axis directed generally north to south and the positive y-axis lying orthogonally seaward. The resulting data pairs include the x-value and the y-value, which represents the perpendicular transect.

Once the shoreline data have been edited into files of equal-length segments, shoreline changes can then be computed. Shoreline change is generally reported based on three common statistical values. They include the sample mean, sample standard deviation, and maximum shoreline movement (BYRNES and HILAND, 1994; ANDERS, REED, and MEISBERGER, 1990). The *sample mean* is defined as a measure of central tendency for a set of sample observations and is expressed as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

where:

x_i = sample observations for i = 1 to n
n = total number of observations.

The *sample standard deviation s* is a measure of sample variability about the mean:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}} \tag{2}$$

The *maximum shoreline movement* represents the difference in the most landward and seaward position. It also represents the end points for shoreline change inclusive of all the data sets. Identifying areas of maximum shoreline movement is useful with beach fill projects.

Comparisons of calculated shoreline change rates are generally grouped by specific time periods or by alongshore segments (*i.e.,* geomorphic features representing spatial trends). The appropriate historical time period to use in the calculation of shoreline change rates depends on how the rates are to be applied and on the magnitude of allowable rate error. In general, the use of longer temporal spans (many decades or greater than a century) are preferred inasmuch as they act to decrease the impact of shoreline mapping and surveying error, and, at the same time, filter out short-term fluctuations (noise) from the long-term trend (signal). Shorter temporal spans (decades) are typically used in areas where recent shoreline change can be accounted for by a significant change in the beach system (such as the opening of a large and potentially long-term inlet), or where the recent construction of major coastal engineering structures has a significant impact on the beach (DOLAN, FENSTER, and HOLME, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1993). A case example, shown in Figure 9, of distinctive spatial shoreline trends is located in northern New Jersey, where the shoreline is part of a barrier spit complex including an active compound spit (Sandy Hook to Sea Bright, New Jersey), barrier peninsula (Sea Bright to Monmouth Beach), and a headland coastline (Monmouth Beach to Shark River Inlet) (GORMAN and REED, 1989).

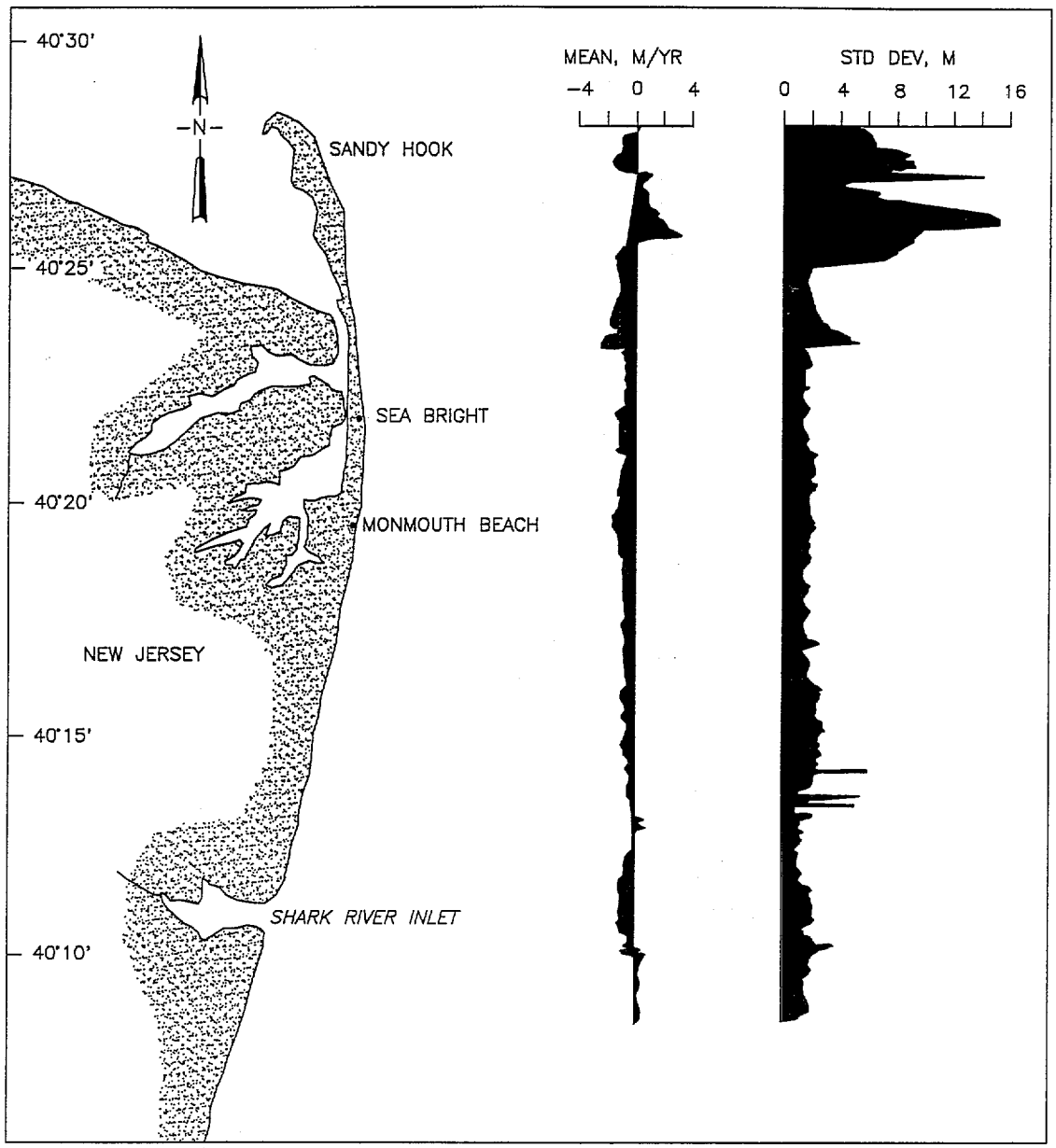

Figure 9. Distinctive spatial shoreline trends along the northern New Jersey shore.

BEACH AND NEARSHORE PROFILES

Background

Periodic topographic and nearshore profile surveys constitute one of the most direct and accurate means of assessing geologic and geomorphic changes on the shoreface to water depths of 10 or 15 m. Surveys conducted over time allow the assessment of erosion and accretion in the coastal zone. Beach profiles provide the basic data for evaluating what happens to sand placed in beach nourishment projects (WEGGEL, 1995). The most common surveying technique is the collection of shore-normal profiles. The lines must extend landward of the zone that can be inundated by storms, usually behind the frontal dunes. The lines should extend seaward deep enough to include the portion of the shoreface where most sediment moves (*i.e.,* to beyond closure—discussed below). At many projects, profiles are run to about 10 m depth, although, depending on the wave climate, this may not be deep enough to record bed elevation changes that occur during major storms.

Monuments

Permanent or semi-permanent benchmarks are required for reoccupying profile sites over successive months and

Table 4. *Example of beach fill area profile survey scheme.*

Year	Times/ Year	Number of Profiles
pre-fill	2	Collect within fill area and at control locations in summer and winter months to characterize seasonal profile envelope (beach & nearshore to closure depth).
post-fill	1	Collect all profiles immediately after fill placement at each site (beach & offshore) to document fill volume. Collect control profiles immediately after project is completed.
1	4	Four quarterly survey trips collecting all beach and offshore profiles out to depth of closure. Begin series during the quarter following the post-fill survey.
Continue year 1 schedule to time of renourishment (usually 4–6 years). If project is a single nourishment, taper surveys in subsequent years:		
2	2	6- and 12-month survey of all beach and offshore profiles.
3	2	6- and 12-month survey of all beach and offshore profiles.
4	1	12-month survey of beach and offshore profiles.

Note: If project is renourished, repeat survey schedule from post-fill immediately after each renourishment to document new fill quantity and behavior. Project-specific morphology and process requirements may modify this scheme. Monitoring fill after major storms is highly desirable to assess fill behavior and storm protection ability. Include both profile and sediment sampling. Conduct less than one week after storm conditions abate to document the beach and offshore response.
After STAUBLE (1994)

years. These benchmarks should be located at the landward end of the profile lines in order to minimize their likelihood of being damaged in storms. The locations of survey monuments must be carefully documented and referenced to other survey markers or to control points. The ability to accurately reestablish a survey monument is critical because it ensures that profile data collected over many years will be comparable (HEMSLEY, 1981). Locations that might experience dune burial should be avoided, and care should also be taken to reduce the visibility of benchmarks to minimize vandalism.[3]

The safest procedure is to establish two benchmarks or monuments. One should be at the dune line; this serves as the origin for the profiles, which are run seaward either perpendicular to the local shore or at a fixed azimuth. The second benchmark should be situated some distance inland so that it can serve as an emergency marker in case of severe coastal erosion or vandalism. Another point of importance: monuments should be referenced to geographic datums so that the profile data can used to evaluate changes in sea level or other phenomena that require reference to established regional datums. With the increasing use of Global Positioning System (GPS) receivers by surveyors, the rigorous need for duplicate survey monuments may be reduced. This is an evolving technology, and for now we still recommend that two monuments per survey line be established. U.S. Army Corps of Engineers standards for construction of monuments are discussed in HEADQUARTERS, USACE (1990).

[3] Unfortunately, damage caused by vandals is a serious and expensive problem at all coastal projects, even ones far from urban areas.

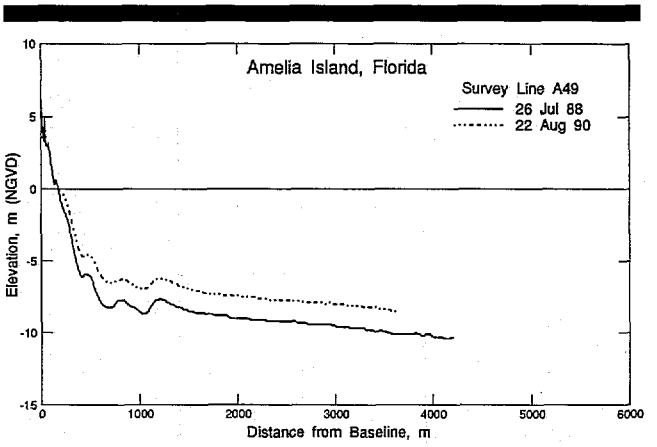

Figure 10. Example of vertical offset between two offshore profile surveys due to use of different datums. (From Gorman *et al.*, 1994)

Project Planning

When planning a beach profiling study, both the frequency of the sampling and the overall duration of a project must be considered. Morphologic changes of beaches can occur over varying time scales, and if long-term studies are to be conducted, the dynamic nature of the beach should be taken into account. Invariably, it is financially and logistically impractical to conduct frequent, repeated surveys for a sufficient length of time to obtain reliable and comprehensive information on long-term processes at the study area. Nonetheless, resurveying of profile lines over a period of more than one year can be of substantial help in understanding the prevailing seasonal changes. In addition, supplemental surveys can be made after big storms to determine their effects and measure the rate of recovery of the local beach system. At a minimum, summer and winter profiles are recommended. Unfortunately, there are no definitive guidelines for the timing and spacing of profile lines. Table 4 outlines a suggested survey schedule for monitoring beach fill projects. In summary, observations over a period of time are recommended in order to document the range of variability of morphology and bathymetry.

Spatial aspects of a field study must be carefully planned, including the spacing of profiles and the longshore and cross-shore dimensions of the study area. Profile lines should be spaced at close enough intervals to show any significant changes in lateral continuity. In a cross-shore direction, the

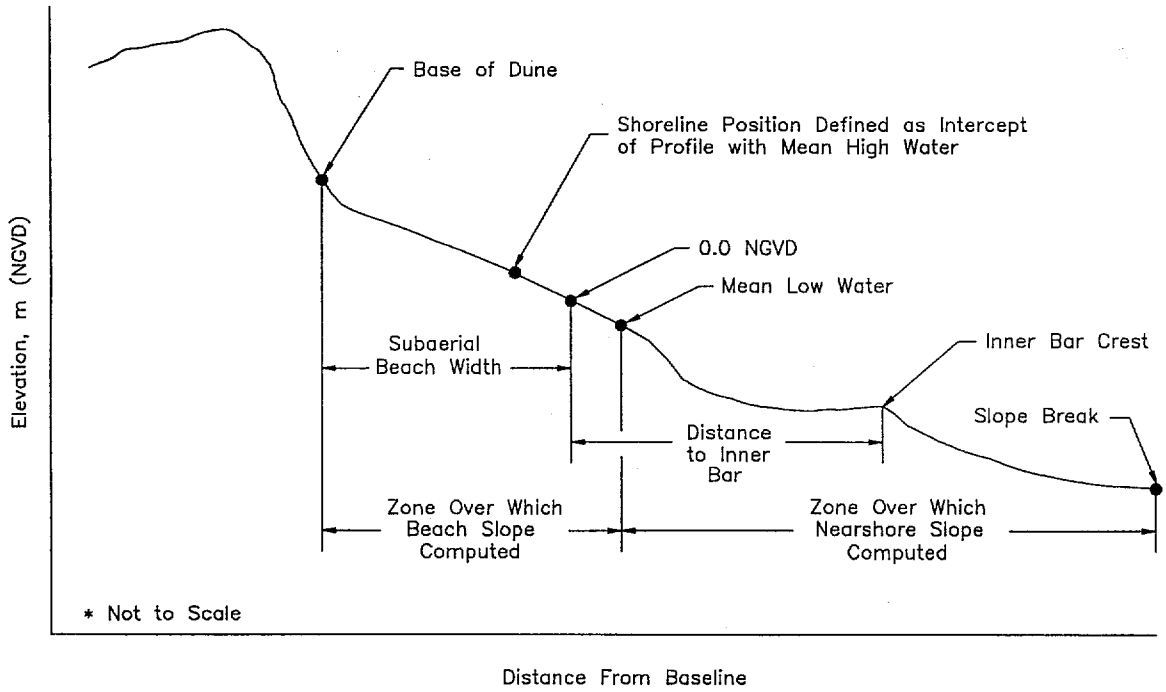

Figure 11. Features within the beach and nearshore zone used for linear profile computations.

uppermost and lower-most limits of the profiles should be located where change is unlikely to occur and should adequately cover the most active beach zones such as the foreshore and upper shoreface. Reviewing locations of historical shorelines in the study area is one way to establish the gross limits of the area that should be examined in detail during a profiling program, particularly along rapidly changing coasts. For example, shore and dune deposits that are now inland from the modern shoreline are likely to be affected by marine or lacustrine processes only during large storms. It may not be necessary to run surveys regularly across the dunes, and aerial photographs of these interior areas may be adequate for examining morphologic changes. If the shoreline has shown patterns of retreat or advance over time, the seaward extent of profiles may need to be extended far enough offshore to accommodate an advance of the shore.

Accuracy Criteria

Elevation resolution for a typical profile across the beach and extending offshore to closure depth will vary according to the survey method, sea state, reference datum, and stability of the subbottom material. It is impossible to assign a single accuracy value to cover these factors. However, under ideal conditions, the estimated vertical accuracy is the resultant mean square error of ± 0.15 ft (0.05 m) (HEADQUARTERS, USACE, 1994, Table 9–3). Most surveys do not achieve this accuracy, especially if the offshore data was collected with acoustic methods.

As described earlier, the seafloor close to shore is often surveyed by a sled which is towed by boat out into the water from about +1.5 m to closure depth. This results in overlap between onshore rod surveys and sled surveys to assure that the two systems are recording the same elevations. If offshore surveys are conducted by boat-mounted echo sounder, overlap with rod surveys is often not possible because most boats cannot survey in water shallower than about 1½ or 2 m. Also, acoustic surveys are impossible in the surf zone because bubbles in the water attenuate the acoustic pulses. DALLY, JOHNSON, and OSIECKI (1994) have described the development of a remote-operated amphibious vehicle that may allow surveys in areas where a sled cannot be maneuvered.

Comparison of sled/Zeiss systems and boat echo sounders has shown sled surveys to have a higher vertical and horizontal accuracy (CLAUSNER, BIRKEMEIER, and CLARK, 1986). Echo sounder surveys are limited by the indirect (acoustic) nature of the depth measurement, the effects of water level variations and boat motions, and the inability to survey the surf zone due to wave action and tidal range. In summary, there are quality advantages in using sled surveys offshore, but operational limitations are imposed by wave heights, water depth, seafloor obstructions, and the maneuvering needed to keep the sled on line.

All repetitively-surveyed profiles must be referenced to the same elevation datum. This can especially be a problem when echo sounder surveys are conducted by different agencies or contractors over time (Figure 10). Meticulous field notes must be kept to record datums, corrections, equipment calibrations, and other information that are needed for accurate data reduction.

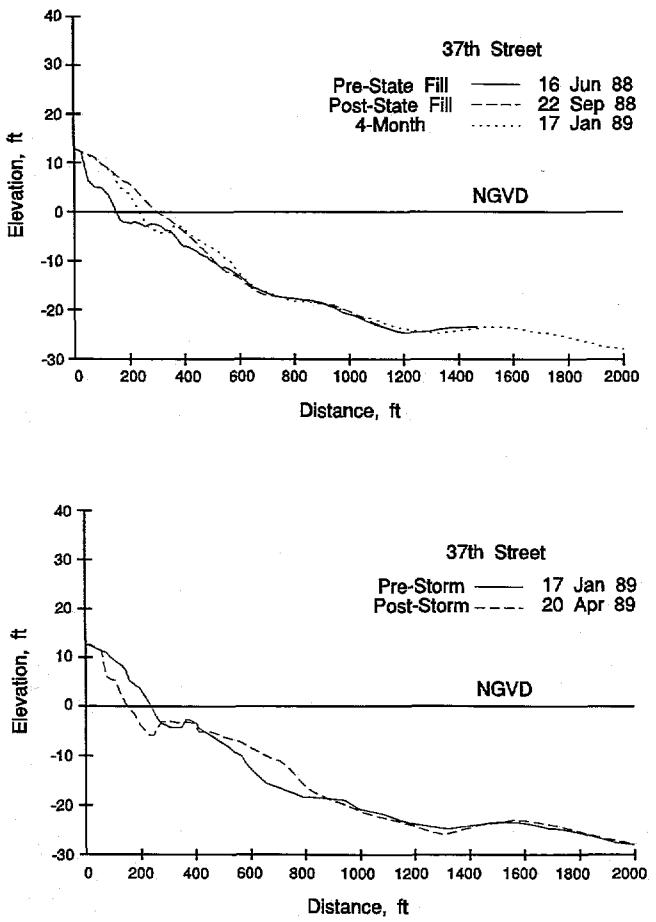

Figure 12. Analysis of the Ocean City, Maryland, beach fill project. Upper plot shows profile before beach fill and the large quantity of sand placed on the beach during the summer of 1988. Lower plot shows erosion of the upper profile during a storm in early 1989. Sand from the beach moved offshore to the region between 400 and 900 ft from the benchmark. (From Stauble *et al.,* 1992)

Analysis Techniques

Profile analysis reveals the variability in cross-shore elevation patterns and volume change that occur along a profile line. With multiple profiles, the alongshore variability in profile response is documented. With a long-term monitoring program, seasonal variations and the impact of storms can be identified.

Profile data recorded in the field are typically processed in the laboratory using computer software packages. The Coastal Engineering Research Center (CERC) Interactive Survey Reduction Program (ISRP) plots and compares both spatial and temporal profile sets (BIRKEMEIER, 1984). The program allows the plotting of field data sets at various scales and vertical exaggerations from baseline (x) and elevation (y). An unlimited number of profiles can be plotted on a single axis to compare profile change and determine profile envelopes and closure areas. The most frequent analysis uses profiles of successive dates to compare morphology and volume changes. CERC's Beach Morphology and Analysis Package (BMAP) contains many analysis tools, including generation of synthetic profiles (SOMMERFELD *et al.,* 1994).

Vertical elevations of morphologic features found on profiles are usually referenced to NGVD 29 or another datum specified for a particular project. All horizontal distances should be measured from the designated baseline monument. Survey distances offshore often vary in length due to wave conditions at the time of the sled survey. Volume change calculations can be made from the baseline to a common distance offshore (usually the shortest profile) to normalize volume change between survey dates.

Profile Survey Applications

Beach response to coastal processes can be interpreted from geometric and volumetric comparison of beach profile sets. If the profile sets cover a long period, information on both the cross-shore and alongshore evolution of a coastline can be made (*i.e.,* shoreline advance or retreat, position of the berm crest, and closure depth). Several types of beach parameters can be measured from profile data, including the width of the subaerial beach, location and depth of the inner bar, and beach and nearshore profile slope. Comparisons between successive profiles can be used to quantify shoreline position change, volumetric change, and seasonal profile response. Numerous authors (*e.g.,* BASCOM, 1964; KOMAR, 1976; HANDS, 1976; WRIGHT and SHORT, 1983) have documented the cyclic nature of beach topography and its response to seasonal shifts in wind and wave climate. In addition to normal effects, profile surveys can also be used to measure change caused by short-term episodic events (CHIU, 1977; SAVAGE and BIRKEMEIER, 1987).

Linear measurements. Selected parameters can be used to define cross-shore morphologic features within a study area. General location and limits of features in the beach and nearshore zone used for linear profile computations are shown in Figure 11.

- The most variable beach parameter is beach width, which is usually measured between the base of the dune and mean low water (mlw).
- Beach slope can be calculated between the base of the dune and mlw.
- The zone from mlw out to the nearshore slope break is generally considered as the area where the nearshore slope is computed.
- Alongshore changes of the inner bar position are a useful guide of the surf zone breaker height and bottom slope. The inner bar position is measured from 0.0 m (NGVD) to the bar crest (GORMAN *et al.,* 1994).
- If shoreline change or aerial photography maps are not available, shoreline position can be estimated from the location of a specified elevation point on a profile line. An approximate position of the high-water shoreline should be selected based on local tidal information. A common elevation referenced for this type of analysis for many engineering projects is 0.0 (NGVD) (U.S. ARMY ENGINEER DISTRICT, JACKSONVILLE, 1993). However, this position constitutes a highly variable measure due to the movement of the bar or ridge and runnel features along the lower beach.

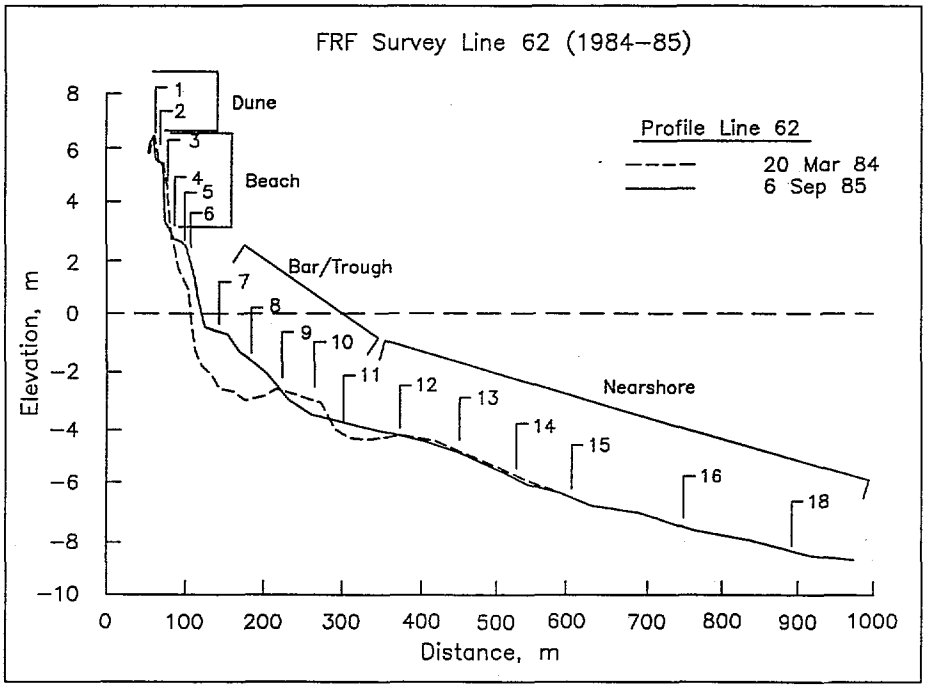

Figure 13. United States Atlantic coast profiles showing typical winter erosion and summer recovery. (Stauble 1992)

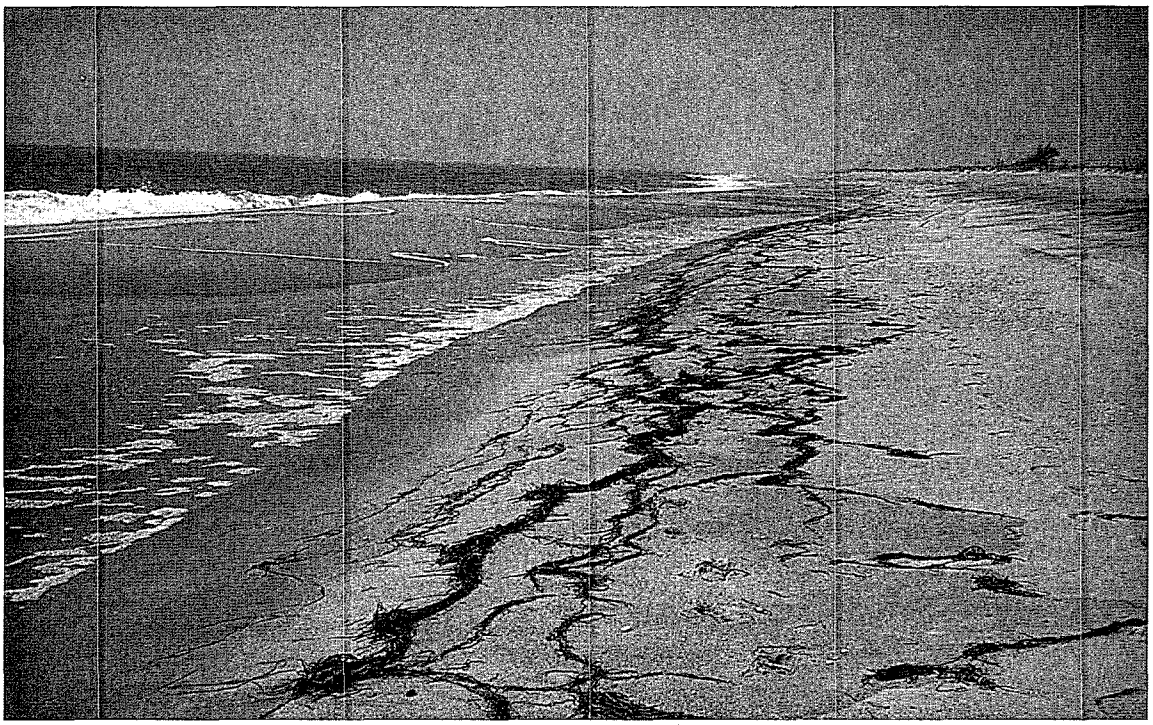

Figure 14. Ridge and runnel system, Charlestown, Rhode Island. Stranded sea grass and debris marks limit of high tide runup.

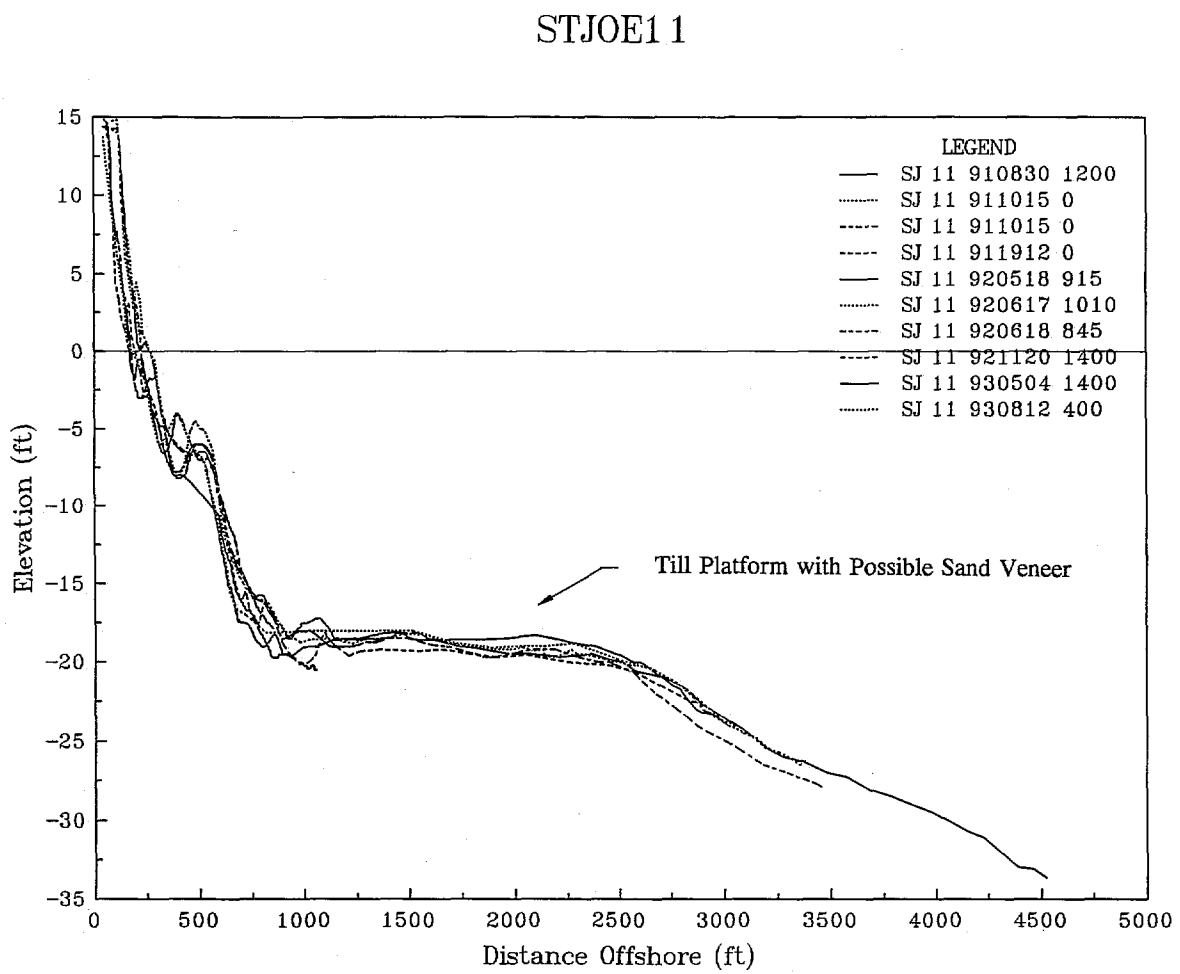

Figure 15. Profile envelope from St. Joseph, Michigan. The horizontal platform 1,000 to 2,500 ft (300 to 750 m) offshore is an exposed till surface. Most shoreface sand movement appears to be confined to the zone landward of the till platform, although it is likely that thin veneers of sand periodically cover the till (CERC project data).

Volumetric analysis. Volume analysis of most long-term profile data sets will provide temporal and spatial documentation of profile volume change due to overwash processes, storm impacts, and nearshore bar evolution. Computer programs such as ISRP can provide quantitative information on profile shape change and volume of sediment gained or lost between two or more survey dates (BIRKEMEIER, 1984). Figure 12 shows an analysis of the Ocean City, Maryland, beach fill project. Based on volume computations, this type of analysis provided a time history of fill placed on the beach and the subsequent readjustment of the fill material. Typical profile response showed erosion on the dry beach above NGVD and accretion in the nearshore area after fill placement as the shoreface adjusted to a new equilibrium profile.

Seasonality. Winter erosional beach profiles can be characterized as having concave foreshore areas and a well-developed bar/trough in the nearshore. During fair-weather summer conditions, the bar moves landward and welds onto the foreshore, producing a wider berm with a lower offshore bar and flatter trough. Profile response to the seasonal cycle is a function of storm frequency and intensity. When trying to determine the extent of the profile envelope, at least 1 year of data should be used. The profile envelope of an East Coast beach system is shown in Figure 13, with the characteristic winter and summer berm profiles. Because there are frequent local storm surges during the winter months, the berm and dune crest often retreat; however, in many areas sand recovery takes place during the summer months as littoral material moves onshore and longshore. Along a well-defined ridge and runnel system, significant sediment exchange can occur between the summer and winter months (Figure 14). Great Lakes beaches also display summer/winter patterns, often characterized by considerable bar movement (Figure 15). At some Great Lakes sites, the mobile sand layer is quite thin, and seasonal patterns can be difficult to detect.

BATHYMETRIC DATA

Introduction

In many coastal studies, the analysis of topographic and bathymetric data is one of the fundamental tools used to eval-

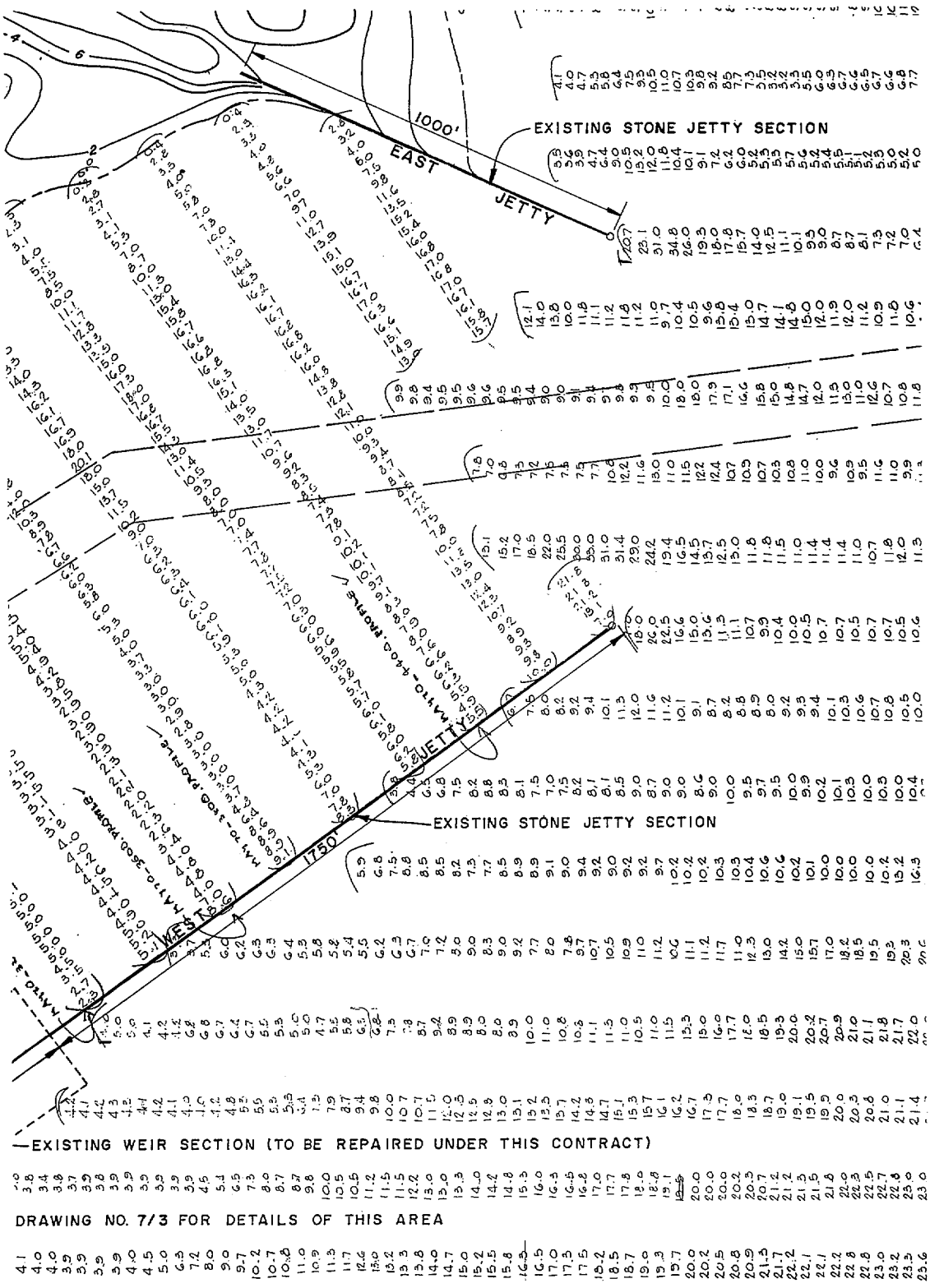

Figure 16. Hand-annotated hydrographic map from East Pass, Florida. Depths (in feet) have been corrected for tide and are referenced to mlw. (Map from U.S. Army Engineer District, Mobile.)

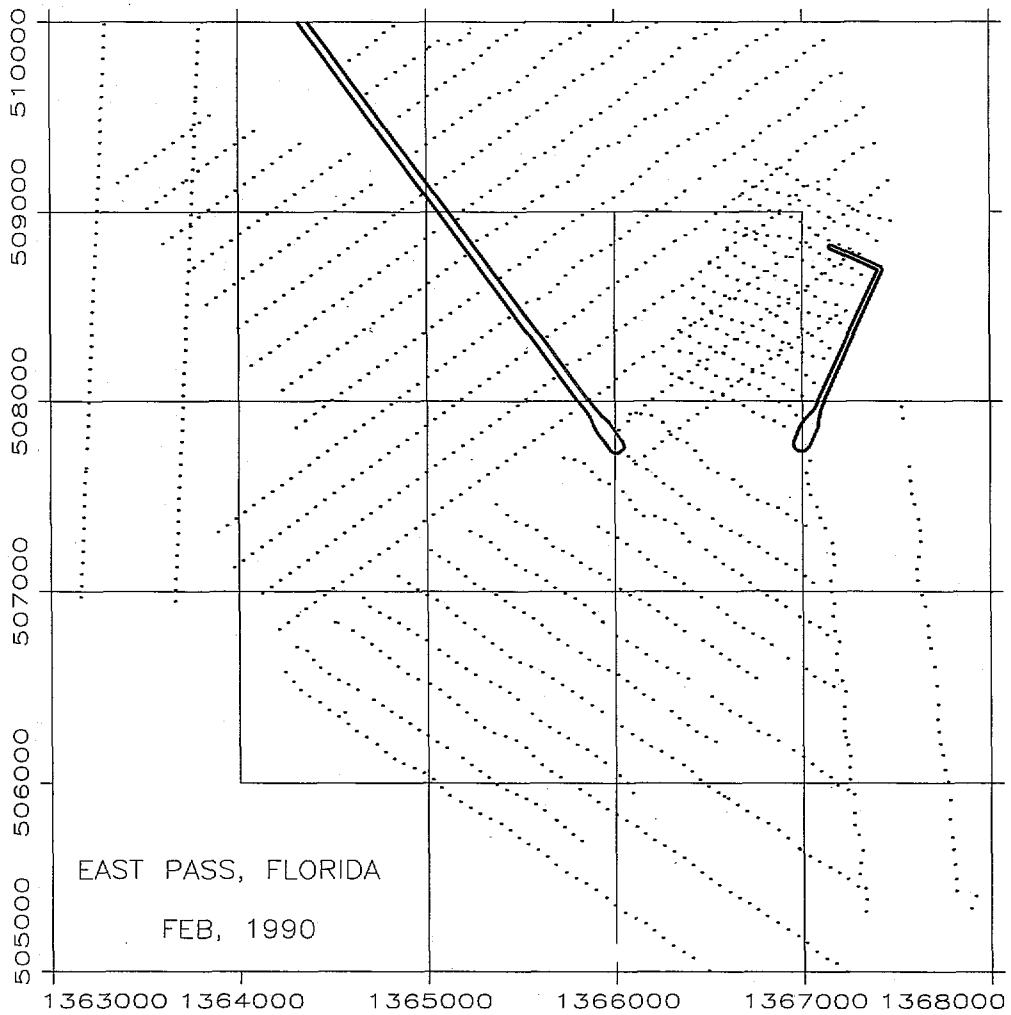

Figure 17. Digitally collected hydrographic data from a Florida project site. The track lines are obvious, as is the fact that soundings are not uniformly distributed throughout the survey area. (Data courtesy of U.S. Army Engineer District, Mobile).

uate historical morphological changes, patterns of erosion and sedimentation, and shoreline response over time. When assembling bathymetric surveys from a coastal area, a researcher is often confronted with an immense amount of data that must be sorted, checked for errors, redisplayed at a common scale, projection, and datum, and compared year by year or survey by survey in order to detect whether changes in bottom topography have occurred. This section will discuss three general aspects of geographic data analysis:

- Processing of bathymetric data using mapping software
- Applications and display of the processed results
- Error analyses

Bathymetric Data Processing—Data Preparation and Input

Most historical bathymetric data sets consist of paper maps with printed or handwritten depth notations (Figure 16). Occasionally, these data are available on magnetic media from agencies like NOAA, but often a researcher must first digitize the maps in order to be able to perform computer-based processing and plotting. If only a very limited region is being examined, it may be more expedient to contour the charts by hand. The disadvantage of hand-contouring is that it is a subjective procedure. Therefore, one person should be responsible for all of the contouring to minimize variations caused by different drawing styles or methods of smoothing topographic variations.

In order to manipulate 3-dimensional (x, y, and z) data, display and plot it at different scales, and compare different data sets, it is necessary to use one of the commercial mapping programs such as GeoQuest's Contour Plotting System 3 (CPS-3®), Golden Software's Surfer™, or Plus III Software's Terramodel™. These are comprehensive packages of file manipulation, plotting algorithms, contouring, and 2- and 3-dimensional display. Their use requires considerable training, but they are powerful analysis tools. (These and other cartographic and Geographic Information System (GIS) products are cataloged and described in GIS World (1995).)

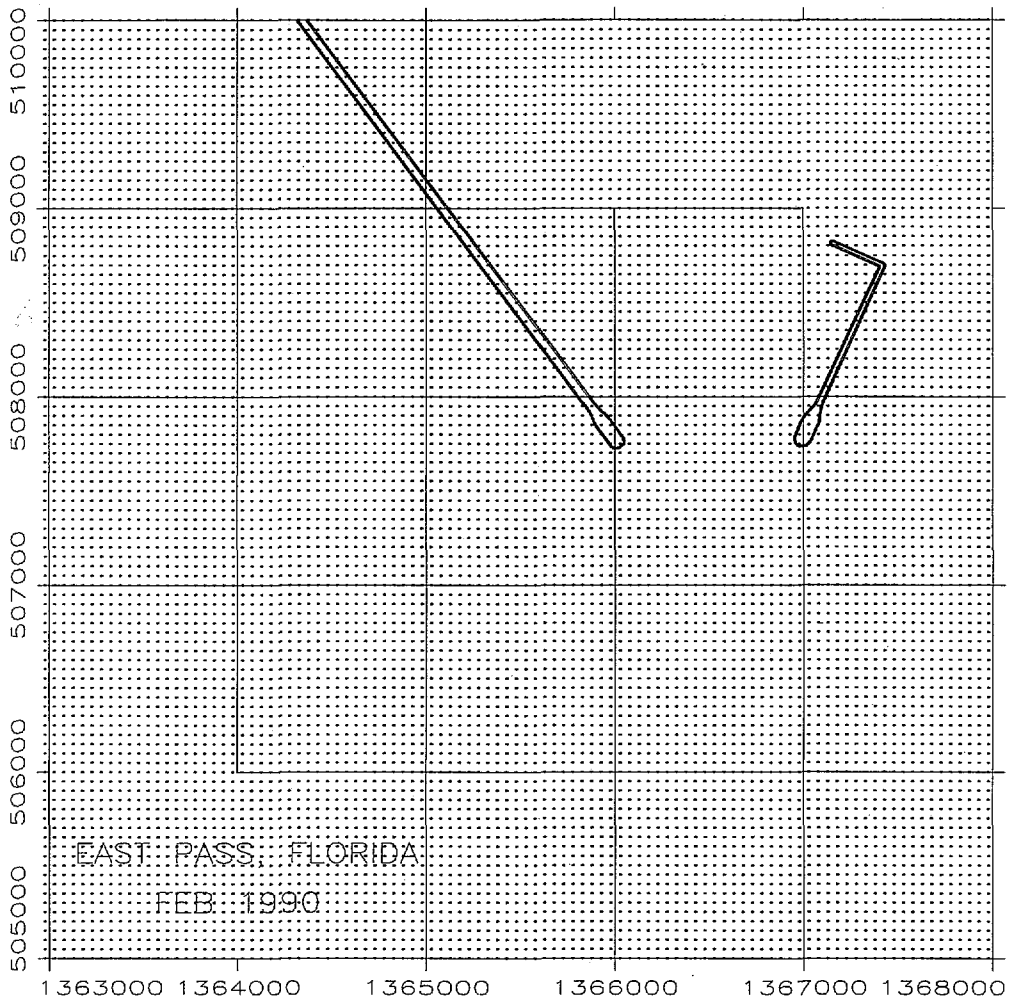

Figure 18. Surface grid computed by CPS-3 based on the data shown in Figure 17. The nodes are uniformly spaced compared with the locations of the original soundings. A grid does not necessarily have to be square, although this is common.

The raw data used by mapping programs consists of individual points in x-y-z form. As described earlier, if the data are derived from old maps, they must first be corrected to a common datum, map projection, and coordinate system. For small files, visual examination of the data may be worthwhile in order to inspect for obviously incorrect values. Because it is laborious to review thousands of data points, simple programs can be written to check the raw data. For example, if all the depths in an area are expected to be between +2.0 and −12.0 m, a checking program can tag depths that are outside this range. The analyst can then determine if questionable points are erroneous or represent genuine but unexpected topography.

Many analysis procedures display and manipulate data in Cartesian coordinates. If the original maps were based on State Plane coordinates, the x and y points will not need conversion. Points in latitude and longitude usually must be converted by the program to a rectangular projection.

Gridding Operations

Gridding (or surface modeling) is a mathematical process in which a continuous surface is computed from a set of randomly distributed x, y, and z data.[4] The result is a data structure (usually a surface) called a grid. Note that the grid is an artificial structure. It is based on the original data, but the grid points are not identical to the original survey points (Figures 17 and 18). Because the grid represents the surface that is being modeled, the accuracy of the surface model directly affects the quality of any output based on it or on comparisons with other grids generated from other data sets. Computing a grid is necessary before operations such as contouring, volume calculation, profile generation, or volume com-

[4] Most examples in this section were prepared using CPS-3® mapping software. The overall concepts and procedures discussed are general, and other software packages perform similar functions but with different mathematical algorithms.

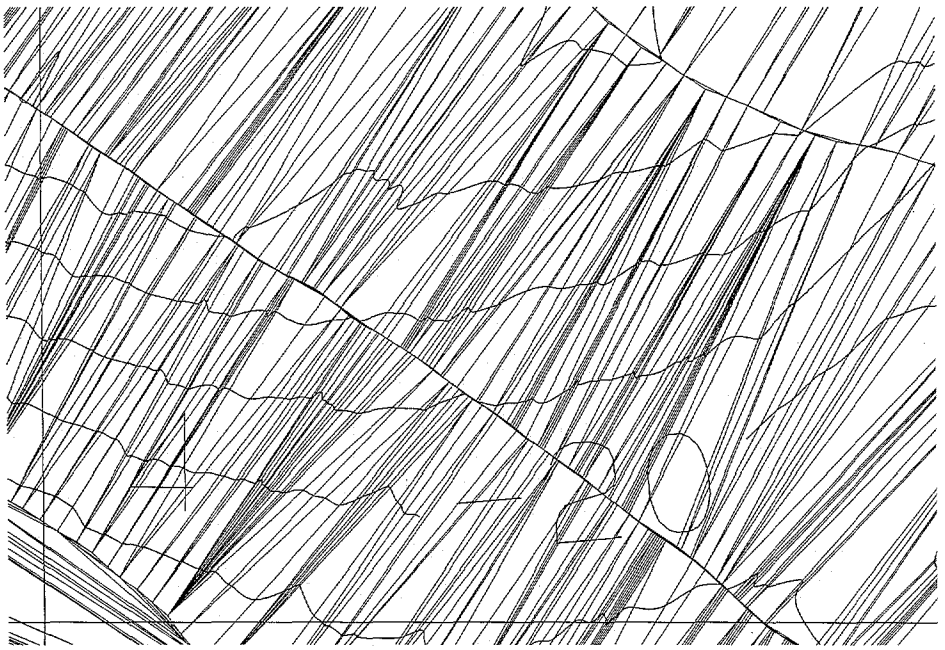

Figure 19. TIN surface model computed by Terramodel based on the data shown in Figure 17. Because of the density of the triangles, only a 200 × 300 ft section is shown. The apex of each triangle is at a depth data point.

parison can be performed. The advantage of a grid is that it allows the program to manipulate the surface at any scale or orientation. For example, profiles can be generated across a channel even if the original survey lines were not run in these directions. In addition, profiles from subsequent surveys can be directly compared, even if the survey track lines and the spacing of data points were very different.

Several steps must be considered as part of the grid generation. These include:

- Selecting a gridding algorithm
- Identifying the input data
- Specifying the limits of the grid coverage
- Specifying gridding parameters
- Specifying gridding constraints
- Computing the grid

The choice of a gridding algorithm can have a major effect on the ultimate appearance of the surface model. Software companies have proprietary algorithms which they claim are universally superior. Often, however, the type or distribution of data determines which procedure to use, and some trial and error is necessary at the beginning of a project. Because a computed grid is an artificial structure, often it is a subjective evaluation whether one grid is "better" than another. For subaerial topography, an oblique aerial photograph can be compared with a computer-generated 3-dimensional drawing oriented at the same azimuth and angle. But for a subaqueous seafloor, how can a researcher really state that one surface does not look right while another does? Even comparing a gridded surface with a hand-contoured chart is not a valid test because hand-contouring is a very subjective procedure.

The fundamental challenge of a gridding algorithm is to estimate depth values in regions of sparse data. The procedure must attempt to create a surface which follows the trend of the terrain as demonstrated in the areas where data do exist. In effect, this is similar to the trend-estimating that a human performs when he contours by hand. The other challenge occurs in complex, densely sampled terrains. The algorithm must fit the surface over many points, but genuine topographic relief must not be smoothed away! Along a rocky coast, for example, high pinnacles may indeed project above the surrounding seafloor.

Gridding algorithms include:

- Convergent (multi-snap) (CPS-3® software)
- Least squares with smoothing
- Moving average
- Trend
- Polynomial

The convergent procedure often works well for bathymetric data. It uses multiple data points as controls for calculating the values at nearby nodes. The values are blended with a distance-weighing technique such that close points have more influence over the node than distant points. Several iterations are made, with the first being crude and including many points, and the final being confined to the closest points. The least-squares method produces a plane that fits across several points near the node. Once the plane has been calculated, the z-value at the node is easily computed. The reader must consult software manuals to learn the intricacies of how these and other algorithms have been implemented.

Another important parameter that must be chosen is the

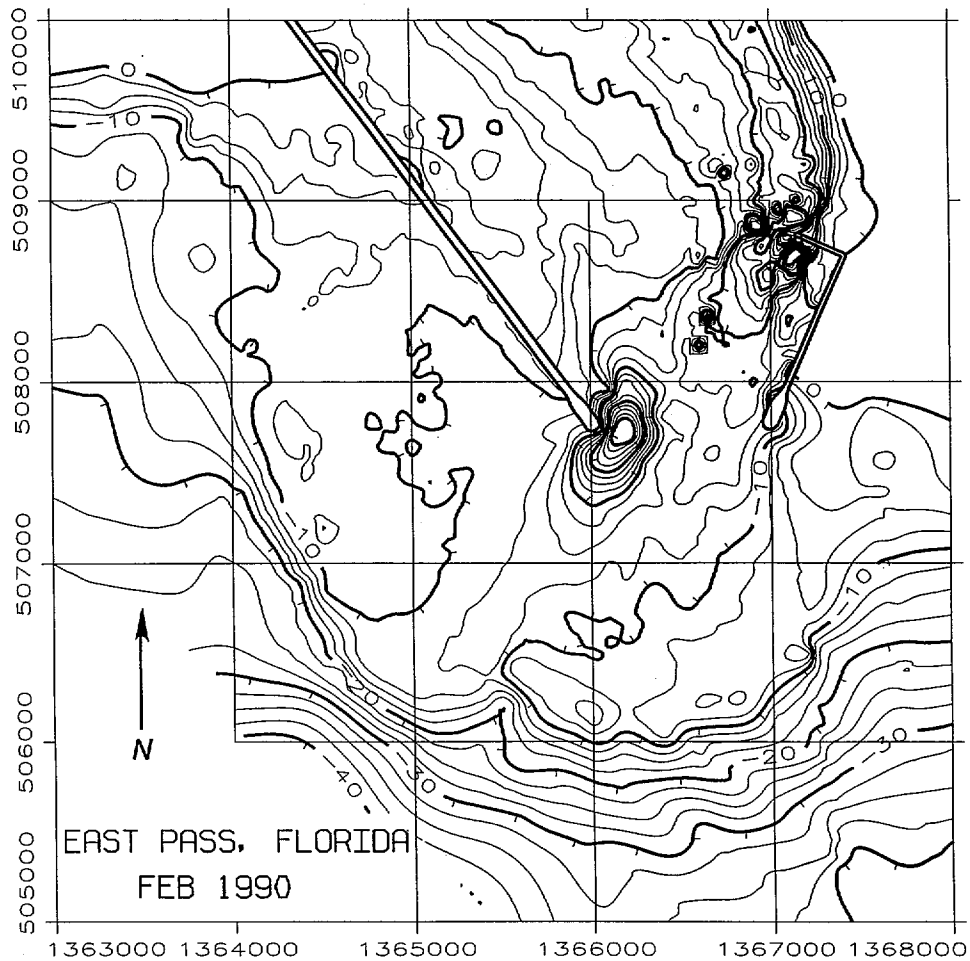

Figure 20. Contoured bathymetry of the same area shown in Figures 17 and 18. Depths in feet below mlw (English units retained to correspond with the units used for the original data collection).

gridding increment. This is partly determined by the algorithm chosen and also by the data spacing. For example, if survey lines are far apart, there is little purpose in specifying closely spaced nodes because of the low confidence that can be assigned to the nodes located far from soundings. In contrast, when the original data are closely spaced, large x- and y-increments result in an artificially smoothed surface because too many data points influence each node. Some programs can automatically calculate an increment that often produces good results.

TIN Models

Contours computed by GIS systems are frequently based on *Triangulated Irregular Network* (TIN) models (PEUCKER *et al.,* 1976). A TIN is generated from a series of irregularly shaped triangles interpolated from elevation data points forming a three-dimensional surface. A TIN model is composed of nodes, edges, triangles, and polygons (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 1994; DEFLORIANI and MAGILLO, 1994). One of the advantages of a TIN model is that it can describe a topographic surface at different levels of resolution as far as the information content is concerned (TSAI, 1993). Another advantage is that a TIN model can accurately describe more complex surfaces and use less space and computer time than grid cell models of similar resolution (MCCULLAGH, 1988). An example of a TIN surface model is shown in Figure 19 using a small portion (~ 60 × 90 m) of bathymetry data from East Pass, Florida. Additionally, TINs are used to support digital terrain modelling analyses which include contouring, calculating slope, generating cross-sectional and three-dimensional displays, analyzing cut and fill volumes, and viewing surface changes at multiple angles (BURROUGH, 1986; CLARKE, 1990; KORTE, 1994).

Once a triangulated network is computed, a grid matrix can be generated using interpolation algorithms. Topographic (or bathymetric) contours can then be computed from the grid surface. Contours are usually smoothed using various splining techniques. If survey data are sparse but the morphology complex (*i.e.,* submarine mounds, multiple bar and trough

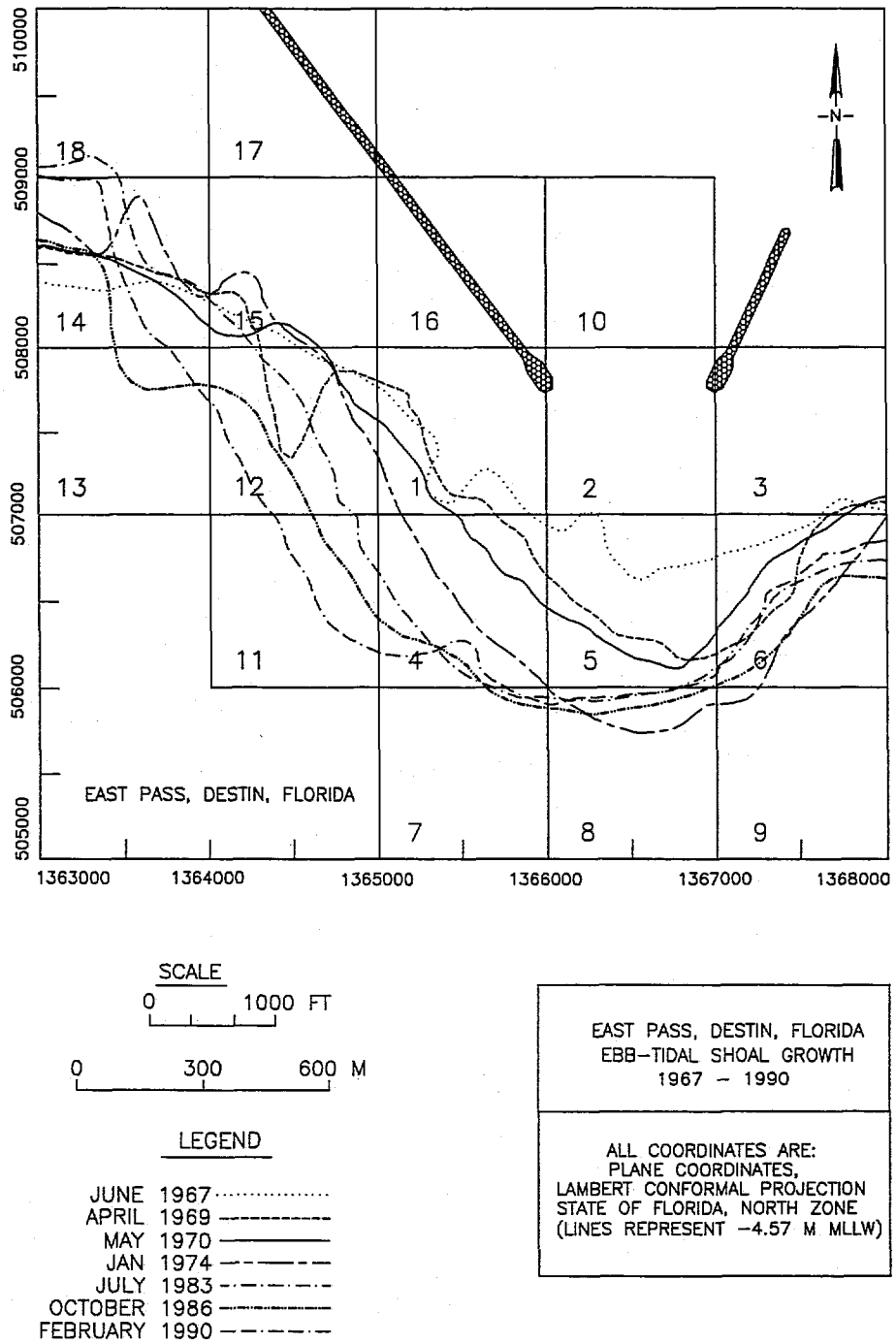

Figure 21. Overall growth of an ebb-tidal shoal over 24 years is shown by the advance of the 15-ft (4.5-m) isobath. This isobath was chosen because it represented approximately the mid-depth of the bar front. The 1000-ft (305-m) squares are polygons used for volumetric computations (MORANG, 1992).

features) or if there are structures such as jetties, groins, and breakwaters present, the resultant contours may be angular or contain spikes. When this occurs, the user needs to evaluate the original data points, line segments between data nodes, and the visible surface of the triangulated network to determine the source of error. With the use of breaklines and exclusion boundaries, TIN models can describe very complex terrain. Exclusion boundaries define explicitly the lines along which abrupt changes in surface behavior occur (for example, along jetties). Quality review is key at each procedural step to ensure that the basic trends of the bathymetric data are accurately represented.

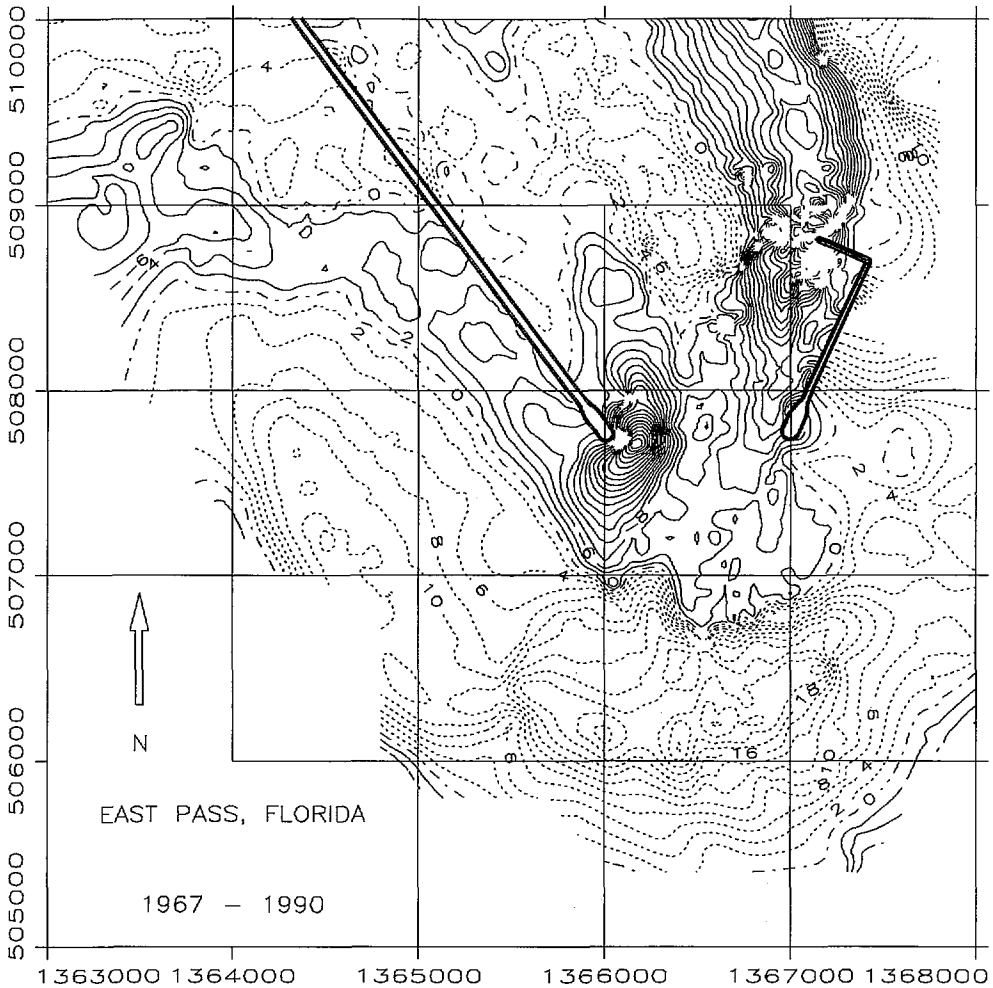

Figure 22. Isopach map showing overall changes in bottom configuration between 1967 and 1990 at East Pass, Florida. Solid contours (2-ft interval) represent erosion, while dashed represent deposition. The migration of the channel thalweg to the east is obvious, as is the growth of scour holes at the jetties. Map computed by subtracting June 1967 surface from February 1990 surface (MORANG, 1992).

Applications and Display of Gridded Data

Contouring of an area is one of the most common applications of mapping software (Figure 20). Not only is this faster than hand-contouring, but the results are uniform in style across the area and precision (*i.e.,* repeatability) is vastly superior.

The power of mapping programs is best demonstrated when analyzing different surveys. If at all possible, the different data sets should be gridded with the same algorithms and parameters in order that the results be as comparable as possible. Difficulty arises if earlier surveys contain much sparser data than later ones. Under these circumstances, it is probably best if the optimum grid is chosen for each data set. A simple application is to plot a suitable contour to demonstrate the growth over time of a feature like a shoal (Figure 21). Computation of volumetric changes over time is another application (Figure 22). This can graphically demonstrate how shoals develop or channels migrate.

Volumetric data can be used to estimate growth rates of features like shoals. As an example, using all 18 of the 1,000-ft squares shown in Figure 21, the overall change in volume of the East Pass ebb-tidal shoal between 1967 and 1990 was only 19 percent (Figure 23). Although the shoal had clearly grown to the southwest, the minor overall increase in volume suggests that considerable sand may have eroded from the inner portions of the shoal. In contrast, when plotting the change in volume of nine selected squares, the growth over time was 600 percent. This underscores how critically numerical values such as growth rates depend upon the boundaries of the areas used in the calculations. The user of secondary data beware!

Error Analysis of Gridded Bathymetry

A crucial question is how much confidence can a researcher place on growth rates that are based on bathymetric or topographic data? Unfortunately, in the past many researchers

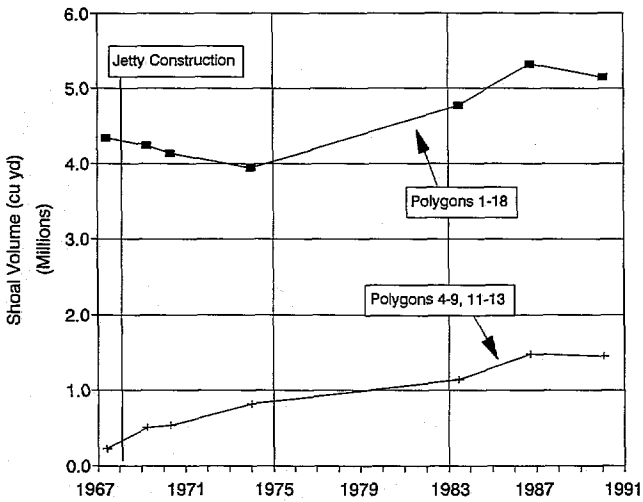

Figure 23. Growth of the ebb-tide shoal, East Pass, Florida. Areas used in the computations are shown in Figure 21. Growth rates are dramatically different depending upon which polygons are included in the computations.

ignored or conveniently overlooked the possibility that error bars may have been greater than calculated trends, particularly when volumetric computations were based on data of questionable quality.

This section outlines a basic procedure that can be used to calculate volumetric errors provided that estimates of the vertical (Δz) accuracy are available. If Δz values are unavailable for the specific surveys, standard errors of $\pm$ 0.5, $\pm$ 1.0, or $\pm$ 1.5 ft, based on the class of the survey, can be used (see discussion of hydrographic survey standards in Paper 3 of this series (MORANG, LARSON, and GORMAN, 1996) or HEADQUARTERS, USACE (1994)). For coastal surveys close to shore, this method assumes that errors in positioning (Δx and Δy) are random and have insignificant effect on the volumes compared with possible systematic errors in water depth measurements, tide correction, and data reduction. For older historical surveys, positioning error may be important, requiring a much more complicated analysis procedure. Positioning accuracy of hydrographic surveys is detailed in HEADQUARTERS, USACE (1994) and UMBACH (1976).

The error in volumetric difference between surveys can be estimated by determining how much the average depth in each polygon changes from one survey to another and then calculating an average depth change over all polygons. Maximum likely error (MLE) is:

$$\mathrm{MLE} = \frac{2 \times \Delta z}{\Delta z_{ave}} \tag{3}$$

For example, if Δz = 0.5 ft (0.15 m) and Δz_{ave} = 1.0 m, then MLE is:

$$\frac{0.30 \text{ m}}{1.00 \text{ m}} = 0.30 = 30 \text{ percent}$$

Note that this is for a Corps of Engineers Class 1 survey; many offshore reconnaissance surveys are not conducted under such tight specifications. If Δz = 1.5 ft (0.46 m) for Class 3, then MLE for the above example = 91 percent. Under these circumstances, it becomes meaningless to say that an area has changed in volume by a certain amount $\pm$ 91 percent.

The size of the polygons used in the calculation of Δz_{ave} can influence the MLE. A particular polygon that covers a large area may average Δz of only 0.3 or 0.6 m, but water depths from spot to spot within the polygon may vary considerably more. Therefore, by using smaller polygons, Δz will typically be greater and MLE correspondingly less. However, the use of smaller polygons must be balanced against the fact that positioning errors (Δx and Δy) become correspondingly more significant.

More research is needed to quantify errors associated with various types of offshore surveys and to identify how these errors are passed through computed quantities. They must *not* be neglected when analyzing geologic data, particularly if management or policy decisions will be based on perceived trends.

SUMMARY AND CONCLUSIONS

Most changes in the coastal zone are associated with inlet, beach, and nearshore zone dynamic processes. Frequently, the natural processes in coastal areas are interrupted by human development and related construction. The most useful and cost-effective methods to document and evaluate these coastal changes are to map and compare geomorphologic features, shoreline position, and offshore profiles and to use these data to quantify nearshore sediment losses and gains.

The key data sets—aerial photography, shoreline position change, and bathymetry—provide qualitative and quantitative answers to the stability and behavior of the shoreface and nearshore zone. Many classical coastal studies have used multiple and overlapping data sources to document processes and impacts on the coastal and nearshore environment. Aerial photography often serves as the foundation data set to identify small- and large-scale geomorphic features across the beach system. Additionally, with appropriate ground control, the high waterline (optimum shoreline) can be digitized from available aerial photos as part of a project's shoreline database.

There are numerous shoreline maps available through Federal, State, and local agencies that can serve as the project's data base, further supplemented by field surveys. A key step in setting up a large shoreline data base is assessing and documenting map accuracy, quantifying errors, and recording the lineage of data transformations and processing. Quantifying errors is vital to the validity of the final results. It is critical that engineering decisions or management initiatives be based on maps that have been produced from the best data available and with the most meticulous standards in digitizing and converting historical data. With the increasing use of Geographic Information Systems for coastal mapping, data sets can now be attributed and documented so that future

users will have a convenient means to evaluate how the data were prepared.

Because most of the beach is influenced by swash processes, sediments move cross-shore and alongshore. Sediment losses and gains on the lower portion of the beach are typically evaluated based on volumetric changes computed from a time series of water depths referenced to the same vertical datum. Documentation of accuracy and estimation of potential errors should be applied to all bathymetric survey data, and final shoreline change rates and volumetric calculations should be reported in the light of the maximum cumulative errors that may occur. Quality control in data collection, data preparation, conversion, and analysis, and evaluation of errors are among the most important elements to be emphasized in the technical assessment of a coastal project.

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