Chapter 5
Coastal Geological Investigations[1]

5-1. Introduction

a. Three principal time scales are important in assessing the geologic and geomorphic[2] changes of coasts. These include: (1) modern studies, which are based largely on field data or laboratory and office experiments of environmental processes; (2) historic studies, which are based largely on information from maps, photography, archives, and other sources; and (3) studies of paleoenvironments, which are based largely on stratigraphy and associated geological principles (Figure 5-1). These general categories overlap. Furthermore, within each of the categories, certain time scales may be of particular importance for influencing coastal changes. For example, tidal and seasonal changes are significant in modern studies, and Holocene sea level history is important in paleoenvironmental studies. Tidal fluctuations are difficult to detect in studies of paleoenvironmental changes, and sea level typically changes too slowly to be an important factor in modern process studies.

b. Several lines of inquiry are available to assess the geologic and geomorphic history of coasts. One means of acquiring coastal data is through field data collection and observation. These data may be numerical or non-numerical, and may be analyzed in the field, laboratory, or office. Laboratory studies are used to collect data through physical model experiments, such as in wave tanks, or to analyze geological properties of field data, such as grain size or mineralogy. Office studies include interpretation of historic maps, photographs, and references as well as analyses and numerical simulation of field, laboratory, and office data. Typically, the best overall understanding of environmental processes and the geologic history of coasts is acquired through a broad-based combination of techniques and lines of inquiry.

c. Quality of results depends on several factors, including the use of existing data. If secondary data sources (i.e. existing maps, photography, and literature sources) are limited or unavailable, assessing the geologic history will be more difficult, more costly, and typically more inaccurate. Consequently, before initiating detailed field, laboratory, or office studies, thorough literature review and search for secondary data sources should be conducted. Appendices E and F list sources and agencies that can be consulted in searches for secondary data.

d. Quality of research equipment, techniques, and facilities also influences the quality of the evaluation of geologic and geomorphic history. For example, echo-sounding and navigation instruments used to conduct bathymetric surveys have recently been improved. Using these tools, the mapping of geologic and geomorphic features can be extended further seaward to a higher degree of accuracy than was previously possible. It is important that coastal researchers stay abreast of new techniques and methods, such as remote sensing and geophysical surveys, computer software and hardware developments, and new laboratory methods. For example, recent developments in Geographical Information Systems (GIS) enable the coastal scientist to analyze and interpret highly complex spatial data sets. This report describes some recent developments and techniques that are used in the analysis of coastal data sets.

e. Scientists must recognize certain problems and assumptions involved in data collection and analyses and make adjustments for them before attempting an interpretation. It is critical to account for various sources of error in preparing estimates of coastal changes and acknowledge the limitations of interpretations and conclusions when these are based on data covering a short time period or a small area.

f. Many of the techniques used to monitor processes and structures in the coastal zone are exceedingly complex. This chapter outlines some of the many errors that can occur when the inexperienced user deploys instruments or accepts, without critical appraisal, data from secondary sources. The text is not intended to be so pessimistic that it dissuades coastal researchers from continuing their investigations, but rather is intended to guide them to other references or to specialists where expert advice can be obtained.

5-2. Sources of Existing Coastal Information

a. Literature sources.

(1) University and college departments and libraries. In many instances, books, periodicals, dissertations, theses, and faculty research project reports contain data.

[1] Chapter 5 is an adaptation of Morang, Mossa, and Larson (1993), with new material added.

[2] Geomorphic refers to the description and evolution of the earth's topographic features - surficial landforms shaped by winds, waves, ice, flowing water, and chemical processes.

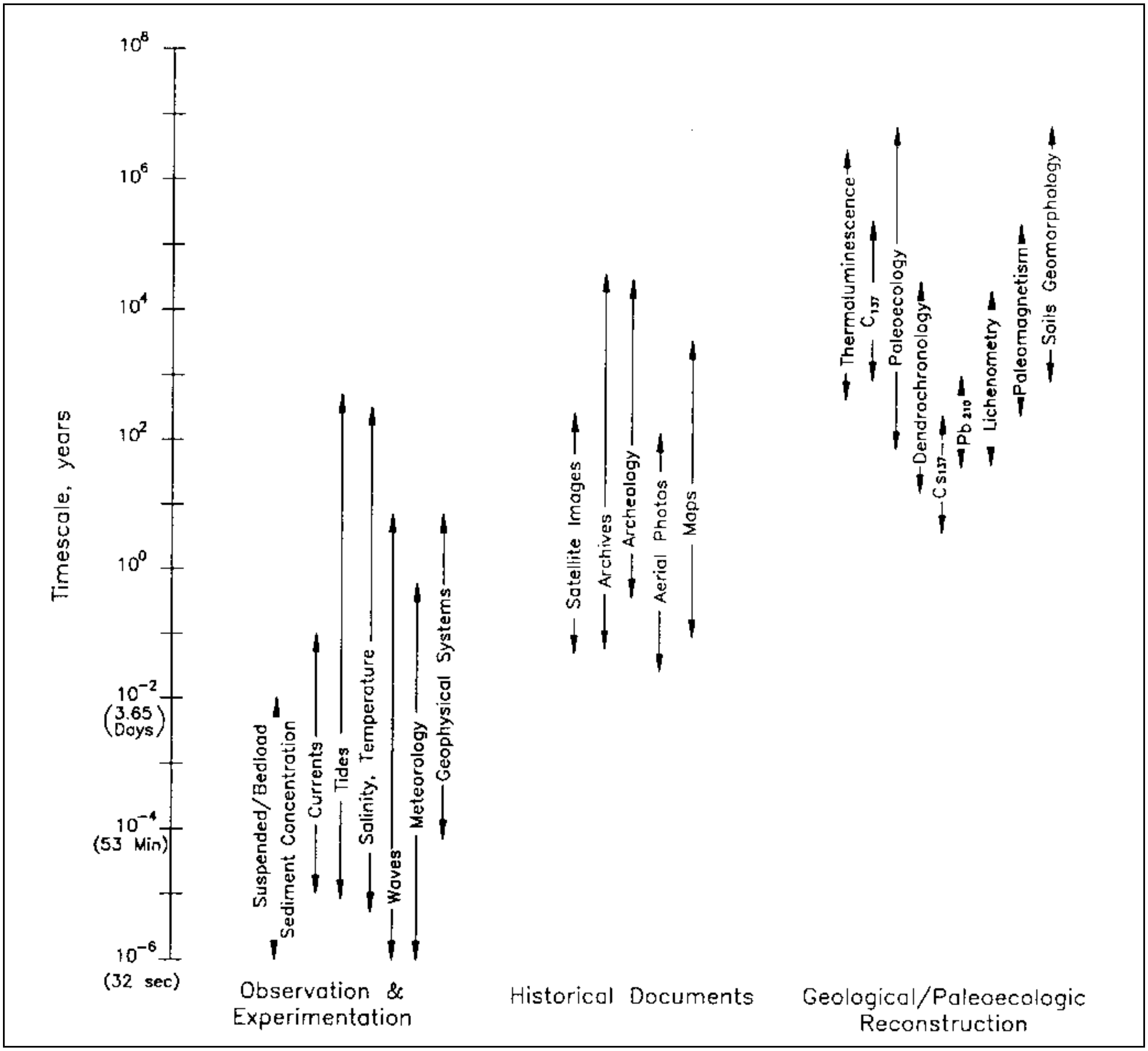

Figure 5-1. Techniques for studying geomorphic changes of coasts over various time scales. Arrows indicate approximate time span during which a particular study technique can be used. X-axis is unitless; width of outlines represent relative importance of general methods for studying coastal changes

This especially occurs when the institutions are in coastal areas, where research is funded by Federal or state government agencies (i.e. Sea Grant), where the university has graduate programs and faculty active in research in appropriate fields. Major universities also have government document repositories where Federal and state government publications are housed.

(2) Local sources. These can provide detailed and sometimes unique data pertinent to the locale. Such sources include the local newspaper, courthouse records, historical diaries, lighthouse records, local journals, engineering contract records, land transactions, and museums.

(3) Government agencies. Geologic coastal data may be available from government agencies at the Federal, state, and local level (Appendices E and F). Federal agencies with data archives include the U.S. Geological Survey (USGS), the U.S. Coast and Geodetic Survey (USCGS), the National Oceanographic and Atmospheric

Agency (NOAA), the U.S. Army Corps of Engineers (USACE), (including the Waterways Experiment Station, and USACE District and Division offices), the Department of Transportation, the Environmental Protection Agency, the U.S. Fish and Wildlife Service, and the Naval Research Laboratory (NRL). A geographic list of CERC coastal geologic and monitoring reports is provided in Appendix G. State agencies with relevant coastal information include state geological surveys (or bureaus of geology), departments of transportation, departments of environmental resources and/or water resources, and state planning departments. Some state health departments archive well logs.

(4) Industry. Energy (oil and gas) companies often keep records, which may be accessible to scientists, of coastal processes in conjunction with their offshore drilling operations. Construction companies have records in files on their construction projects. Environmental and engineering firms may also have data from projects that were performed for government. Some of these data are in the public domain. Environmental impact reports from nuclear power plants built in coastal areas contain extensive coastal process and geologic data.

(5) Journals and conference proceedings. Most large university libraries have holdings of national and international scientific journals. Most of the scientific literature associated with the geologic history of coasts is in the realm of geology, oceanography, marine science, physical geography, atmospheric science, earth science and polar studies.

(6) Computerized literature searches. Most major university and government agency libraries have access to computerized literature databases. The databases contain information that may be acquired by key terms, subjects, titles, and author names.

b. Meteorological and climatic data.

(1) Meteorological and climatic data are often useful for characterizing significant environmental processes and for revealing the characteristics of severe storms. Major storms or long-term variations in storminess strongly affect coastal morphology (Carter 1988). This is manifested, for example, by the changes on barrier beaches associated with winds, waves, and high water levels, which may cause overtopping and overwashing during storms.

(2) Meteorological and climatic data can be compiled from secondary sources or through an original data collection program in the field using instruments and observations. As with most of the important environmental factors, most existing information pertains to studies over historic and modern time scales. The National Climatic Data Center and the National Hurricane Center within NOAA are important sources of meteorological and climatic data.

c. Wave data.

(1) Wave data are required to characterize the process-response framework of the coastal zone. Important wave parameters include wave height, period, steepness and direction, and breaker type. Of special interest is the character of waves inside the breaker zone, where it is estimated that 50 percent of sediment movement takes place, mostly as bed load (Ingle 1966). Wave data can be: (a) collected from existing sources; (b) estimated in the office using hindcast techniques from weather maps, shipboard observations, and littoral environment observations; or (c) measured in the field using instrumented wave gauges.

(2) Wave gauge data are collected by Federal and state agencies and by private companies. For research projects that require wave data, analyzed wave statistics may be available if instrumented buoys, offshore structures, and piers are located near the study site. Published data, which are geographically spotty, include statistics from wave gauges, wave hindcasting, and visual observations from shipboard or the littoral zone.

(3) Wave hindcasting is a technique widely used for estimating wave statistics by analysis of weather maps using techniques developed from theoretical considerations and empirical data. A coastal scientist can use published hindcast data or may choose to compute original estimates for a study area. Appendix D is a list of the USACE Wave Information Studies reports, which cover the Atlantic, Pacific, Gulf of Mexico, and Great Lakes coasts. Advantages of hindcasting include the long-term database associated with weather maps and the comparatively economic means of obtaining useful information. Disadvantages involve the transformation of waves into shallow water, especially in areas of complex bathymetry.

(4) Visual wave observations from ships at sea and from shore stations along the coasts of the United States are also published in several references. Although observations are less accurate than measured data, experienced persons can achieve reasonably accurate results and the great amount of observations available make it a valuable resource. Offshore, shipboard wave observations have

been compiled by the U.S. Navy Oceanographic Research and Development Activity, (now the Naval Research Laboratory (NRL)), in the form of sea and swell charts and data summaries such as the Summary of Shipboard Meteorological Observations. While geographic coverage by these sources is extensive, the greatest amount of observations come from shipping lanes and other areas frequented by ship traffic.

(5) At the shore, a program sponsored by HQUSACE for data collection is the Littoral Environmental Observation (LEO) program (Schneider 1981; Sherlock and Szuwalski 1987). The program, initiated in 1966, makes use of volunteer observers who make daily reports on conditions at specific sites along the coasts of the United States. Data from over 200 observation sites are available from CERC (Figure 5-2). As shown, LEO data not only include wave parameters, but also information on winds, currents, and some morphologic features. LEO is best applied to a specific site, and does not provide direct information on deepwater statistics. The biggest disadvantage is the subjective nature of the wave height estimates. LEO data should only be used as indicators of long-term trends, not as a database of absolute values.

d. Sources of water level data. The NOS of the NOAA is responsible for monitoring sea level variations at 115 station locations nationwide (Hicks 1972). Coastal USACE District offices collect tidal elevation data at additional locations. Daily readings are published in reports that are titled "Stages and Discharges of the (location of district office) District." Predicted water levels and tidal current information for each day can be obtained from the annual "Tide Tables: High and Low Water Predictions" and "Tidal Current Tables" published by the NOS. A convenient way to obtain daily tides is from commercial personal computer (PC) programs. Many of these programs are updated quarterly or yearly. Background information concerning tidal datums and tide stations can be found in NOS publications titled "Index of Tide Stations: United States of America and Miscellaneous Other Stations," and "National Ocean Service Products and Services Handbook."

e. Geologic and sediment data.

It is often important in studies of the geologic and geomorphic history of coasts to evaluate existing geologic and sediment data. This type of information is dispersed among numerous agencies and sources and includes a variety of materials such as geologic maps, soil surveys, highway borings, and process data such as the concentrations and fluxes of suspended sediment from nearby rivers. Published data are available from agencies such as the USGS, the U.S. Soil Conservation Service, the American Geological Institute, and CERC. Differences in geology and soil type may provide clues toward understanding erosion and accretion patterns. Geologic and sedimentologic data are often useful for characterizing significant environmental processes and responses, such as the effects of severe storms on coastlines.

f. Aerial photography.

(1) Historic and recent aerial photographs provide invaluable data for the interpretation of geologic and geomorphic history. The photographs can be obtained from Federal and state government agencies such as the USGS, the U.S. Department of Agriculture, the EROS Data Center, and others listed in the Appendices E and F. Stereographic pairs with overlap of 60 percent are often available, allowing very detailed information to be obtained using photogrammetric techniques. Temporal coverage for the United States is available from the 1930's to present for most locations. The types of analysis and interpretation that can be performed depend in part on the scale of the photographs, the resolution, and the percentage of cloud cover. The effects of major events can be documented by aerial photography because the photographic equipment and airplane can be rapidly mobilized. By such means, the capability exists for extensive coverage in a short time and for surveillance of areas that are not readily accessible from the ground.

(2) For modern process studies, a series of aerial photographs provides significant 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 the assessment of some morphologic features, photogrammetric techniques may be helpful. It is generally preferable to obtain photography acquired during low tide so that nearshore features are exposed or partly visible through the water.

(3) For studies over historical time scales, multiple time series of aerial photographs are required. Historical photography 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.

LITTORAL ENVIRONMENT OBSERVATIONS

RECORD ALL DATA CAREFULLY AND LEGIBLY

SITE NUMBERS ☐☐☐☐☐ 1 2 3 4 5

YEAR ☐☐ 6 7

MONTH ☐☐ 8 9

DAY ☐☐ 10 11

TIME ☐☐☐☐ 12 13 14 15

WAVE PERIOD

Record the time in seconds for eleven (11) wave crests to pass a stationary point. If calm record 0.

☐☐☐ 16 17 18

BREAKER HEIGHT

Record the best estimate of the average wave height to the nearest length of a foot.

☐☐ ☐ 19 20 21

WAVE ANGLE AT BREAKER

Record to the nearest degree the direction the waves are coming from using the protractor on the following page. 0 if calm

☐☐☐ 22 23 24

WAVE TYPE

0-Calm 3-Surging
1-Spilling 4-Spill/Plunge
2-Plunging

☐ 25

WIND SPEED

Record wind speed to the nearest mph. If calm record 0.

☐☐ 26 27

WIND DIRECTION

Direction the wind is coming.

1-N 3-E 5-S 7-W 0-Calm
2-NE 4-SE 6-SW 8-NW

☐ 28

FORESHORE SLOPE

Record foreshore slope to the nearest degree.

☐☐ 29 30

WIDTH OF SURF ZONE

Estimate in feet the distance from shore to breakers, if calm record 0.

☐☐☐☐ 31 32 33 34

LONGSHORE CURRENT

DYE

Estimate distance in feet from shoreline to point of dye injection.

☐☐☐ 36 37 38

CURRENT SPEED

Measure in feet the distance the dye patch is observed to move during minute period; if no longshore movement record 0.

☐☐☐ 43 44 45

CURRENT DIRECTION

0 No longshore movement
+1 Dye moves toward right
-1 Dye moves toward left

☐☐ 46 47

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Figure 5-2. Littoral Environmental Observation forms used by volunteer observers participating in the LEO program (draft) (Continued)

RIP CURRENTS

If rip currents are present, indicate spacing (feet). If spacing is irregular estimate average spacing. If no rips record 0.

49 50 51 52

BEACH CUSPS

If cusps are present, indicate spacing (feet). If spacing is irregular estimate average spacing. If no cusps record 0.

54 55 56

BEACH WIDTH

Measure the distance of the most seaward Beach Berm crest from a reference point to the nearest foot.

57 58 59 60

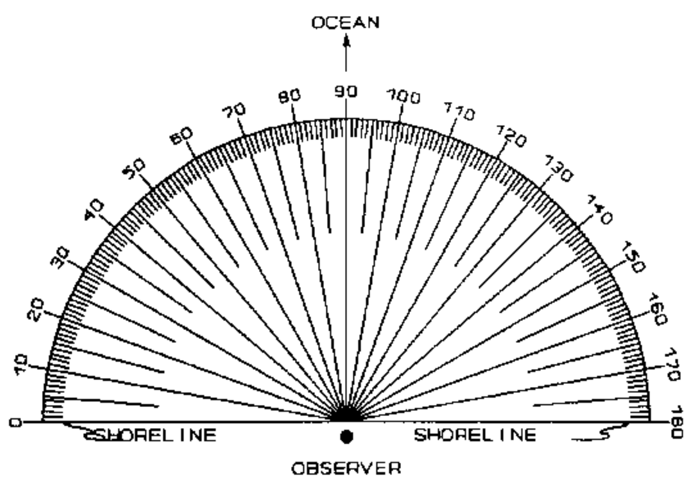
PLEASE PRINT:

SITE NAME

OBSERVER

Please Check The Form For Completeness

REMARKS:



NOTE: If a pier is used for an observation platform: place 0-180 line on the rail parallel to the centerline of the pier, sight along the crest of the breaking waves and record the angle observed

Figure 5-2. (Concluded)

Therefore, the coastal scientist should account for such variations as potential sources of error in making or interpreting shoreline change maps. Section 5-5 contains a more detailed discussion of aerial photograph analysis.

g. Satellite remotely sensed data.

(1) Satellite data are available from U.S. agencies, the French Systeme Pour L'Observation de la Terre (SPOT) satellite data network, and from Russian coverage.[1] In most instances, the data can be purchased either as photographic copy or as digital data tapes for use in computer applications. Imagery and digital data may assist in understanding large-scale phenomena, especially processes which are indicators of geologic conditions and surface dynamics. Agencies that collect and distribute satellite data are listed in Appendix E. Numerous remote sensing references are listed in Lampman (1993). A listing of satellite data maintained by the National Space Science Data Center (NSSDC) is printed in Horowitz and King (1990). This data can be accessed electronically.

(2) Satellite data are especially useful for assessing large-scale changes of the surface of 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 5-3). 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 can also provide data on ocean currents and circulation (Barrick, Evans, and Weber 1977). Aircraft-mounted radar data also show considerable promise in the analysis of sea state.

(3) The Landsat satellite program was developed by the National Aeronautics and Space Administration in cooperation with the U.S. Department of the Interior. When it began in 1972, it was primarily designed as an experimental system to test the feasibility of collecting earth resource data from unmanned satellites. Landsat satellites 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 5-4 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).

(4) SPOT is a commercial satellite program. The first satellite, which was sponsored primarily by the French government, was launched in 1986. The SPOT-1 satellite 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, or a 20-m resolution multispectral (visible and near infrared) mode with three bands (Figure 5-3).

(5) Several generations of satellites have flown in the 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 (i.e. Colwell 1983, Lillesand and Kiefer 1987, Richards 1986, Sabins 1987, Siegal and Gillespie 1980, Stewart 1985).

(6) Aircraft-mounted scanners, including thermal sensors and radar and microwave systems, may 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 applications including mapping of bottom contours of coastal waters. A LIDAR system, known as SHOALS (Scanning Hydrographic Operational Airborne Lidar System), is now being used by the U.S. Army Corps of Engineers to profile 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 istrument pod and with data processing and navigation equipment (Lillycrop and Banic 1992). In operation, the SHOALS laser scans an arc across the helicopter's flight path, producing a survey swath equal to about half of the aircraft altitude. A strongly reflected return is recorded from the water surface, followed closely by a weaker return from the seafloor. The difference in time of the returns is converted to water depth. SHOALS may revolutionize hydrographic surveying in shallow water for several

[1]Russian Sojuzkarta satellite photographs are available from Spot Image Corporation (Appendix E). Almaz synthetic aperture radar data are available from Hughes STX Corporation.

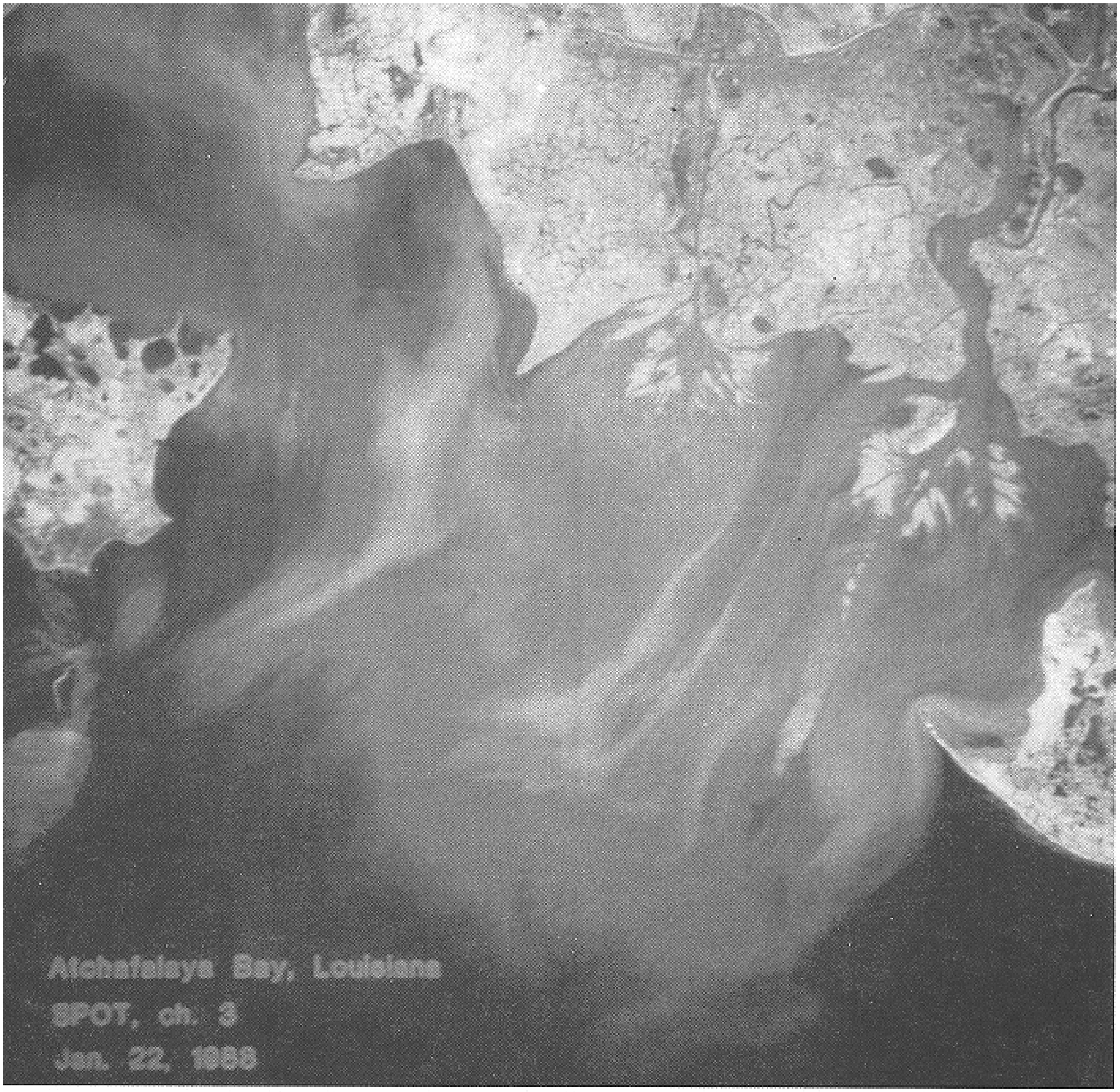


Figure 5-3. SPOT satellite image, Atchafalaya Bay, LA. Suspended sediment from runoff is clearly visible. Data processed by the Earthscan Laboratory, School of Geosciences, Louisiana State University, Baton Rouge, LA

reasons. The most important advantage is that the system can survey up to 8 square km per hour, thereby 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 large-scale post-storm surveys or surveys of unexpected situations such as breaches across barriers. Finally, minimum survey water depth is only 1 m; 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 about 10 m, depending on water clarity.

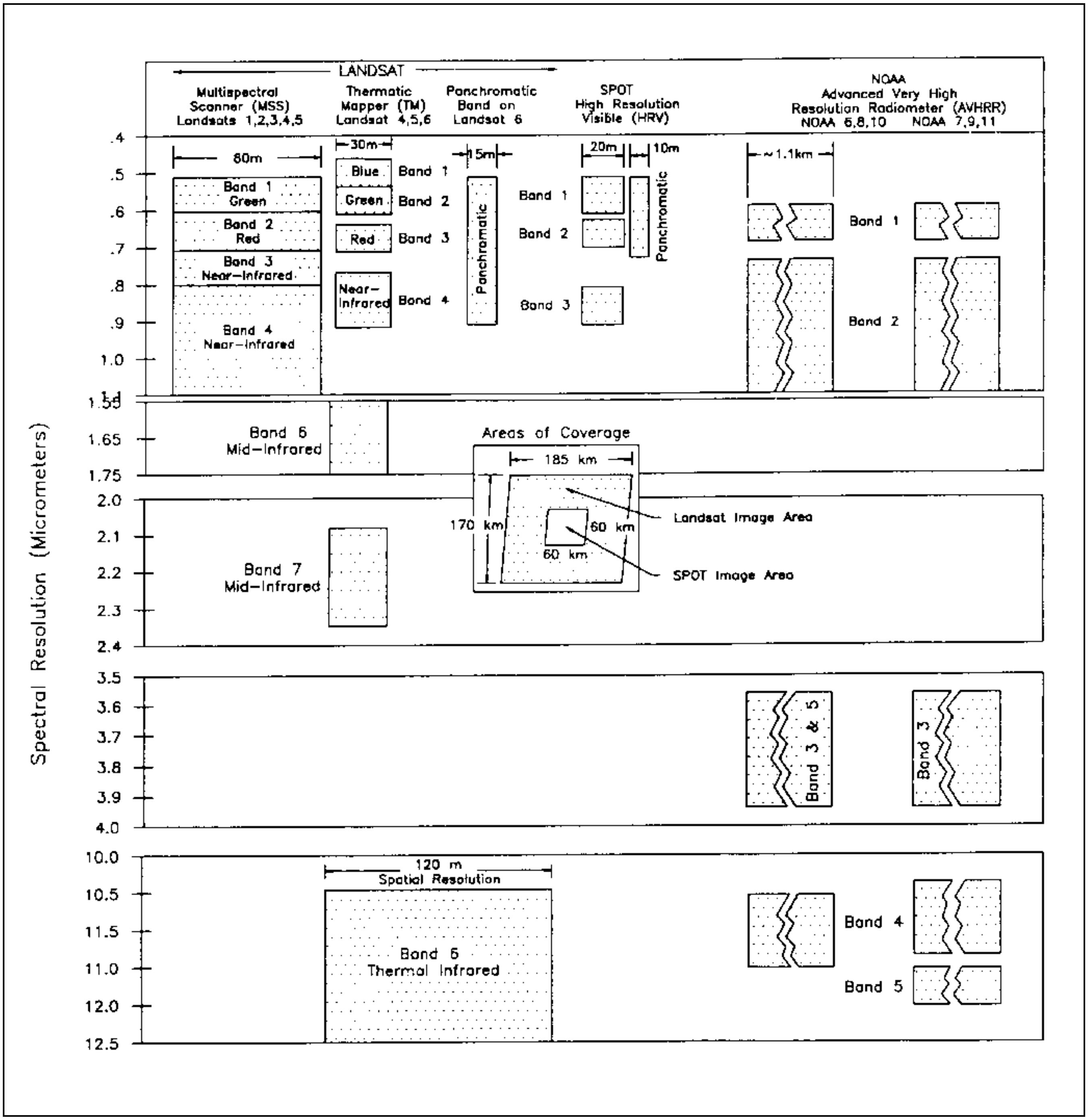


Figure 5-4. Spectral resolution and approximate spatial resolution of sensors on Landsat, SPOT, and NOAA satellites (from Earth Observation Satellite Company literature and Huh and Leibowitz (1986))

h. Topographic and bathymetric data.

(1) Topographic and bathymetric maps are available from the USGS, many USACE District Offices, and the USCGS. USGS topographic maps are generally revised every 20 to 30 years, and sometimes more often in areas determined to be of high priority. Nevertheless, the maps may be outdated for some studies because of the ephemeral nature of many coastlines. The USGS quadrangles are available in a 7.5' series (scale 1:24,000) and a 15' series (scale 1:62,500). The resolution of these maps is typically inadequate to provide details of surface

features, but may be sufficient for examining large landforms and pronounced changes, particularly over long periods.

(2) Recent and historic hydrographic survey data are available from the National Ocean Survey (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.

(3) 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 from actual depths. The greatest changes can be 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 datum used in different maps. Annual or more frequent hydrographic surveys are available at most Federal navigation projects.

i. Shoreline change maps.

(1) Shoreline changes may be interpreted from navigation maps, topographic maps, aerial photographs, and property records. In some areas, maps showing shoreline changes and land loss may have been produced by state and federal agencies, universities, or engineering firms. However, the user should be aware of potential sources of error which may not have been adequately corrected when these maps were prepared.

(2) Shoreline and coastal change maps that are constructed from historic maps and photographs are subject to numerous sources of error. For example, maps may not have common datums, may have different scales, may have variable accuracy due to age or loss of accuracy in publication procedures, and may be based on different projections which in turn cause geometric distortions. Ideally, shoreline change maps constructed from aerial photographs should be corrected for distortions caused by pitch, tilt, and yaw of the aircraft. Difficulties in identifying common points over time, problems in rectifying scale, and distortions near margins and corners are common. Additional problems include the unavailability of photographs of the desired vintage, scale, clarity, or resolution. Haze, fog, and cloud cover may obscure ground features. Finally, the water level at the time that the photographs were taken can greatly influence the position of the shorelines. Specific data sources and procedures for analyzing shoreline change maps are presented in section 5-5.

5-3. Field Data Collection and Observation

a. Background.

(1) In order to apply appropriate technologies to a field study, the coastal scientist should know something about the nature of the problem and the expected outcome. For example, if a community is being threatened by erosion, measurements of processes, topography, and bathymetry are needed to determine storm-induced and long-term erosion trends. Also, studies of historical data may be required to determine the rates and spatial variability of shoreline change over time. Studies involving stratigraphy may be required if the purpose is to find local sources of borrow material for beach nourishment. Design of a research study must include thorough planning of objectives and sampling strategies, given time, logistic, and budget constraints. Much time and effort can be wasted during a field study if the research objectives are not well-defined and the sampling plan is inappropriate.

(2) Before undertaking detailed field studies, it is important to review all available coastal data pertinent to the study area and problems. The existing information is critical to the effective design of field studies and can result in more cost-effective field work. Often, time and budget constraints may severely limit data collection, making available data even more important.

(3) While in the field, relevant data and information should be meticulously recorded in water-resistant field books. Details can also be recorded on a tape recorder. Photographs serve as valuable records of field conditions, sampling equipment, and procedures. Video recorders are being increasingly used during field reconnaissance.

(4) The type of work conducted in the field may fall into several categories. It may range from a simple visual site inspection to a detailed collection of process measurements, sediment samples, stratigraphic samples, topographic and bathymetric data, and geophysical data. Studies may include exploring the acting forces, rates of activity, interactions of forces and sediments, and variations in activity over time. If the field work will involve extensive data collection, a preliminary site visit is highly recommended to help determine site conditions and to develop a sampling plan.

(5) Spatial and temporal aspects of site inspection are important considerations. The spatial dimensions of the sampling plan should have adequate longshore and cross-shore extent and an adequate grid or sample spacing with which to meet study objectives. Temporal considerations include the frequency of sampling and the duration over which samples will be collected. Sampling frequency and duration are most important in modern process studies, such as monitoring the topographic and bathymetric changes associated with storms. Studies of paleoenvironmental or geologic time scales usually do not require repetitive visits, but thorough spatial sampling is critical.

(6) A conceptual model is essential before designing a field data collection program. This "model" is a set of working hypotheses which use existing knowledge to organize missing information. As information is acquired, the conceptual model is revised and validated. Additional observations may be required to test a wider variety of conditions, and conceptual models may need to be revised depending on the results of the study.

b. Site inspection and local resources.

(1) A general site inspection can provide insights toward identifying significant research problems at a study area, in verifying and enhancing data from aerial photographs and remote sensing sources, and in developing sampling strategies for more rigorous field work. Even for a brief site visit, thorough preparation is strongly recommended. Preparation should include reviewing the pertinent geologic, oceanographic, and engineering literature, compiling maps and photographs, and understanding the scope of the problem or situation. The field inspection should include observations by all members to be involved in the project, if at all possible.

(2) The duration of the field examination must be sufficient to assess the major objectives of the study. Local residents, existing data records, and field monitoring equipment may need to be used. A site inspection should include observation of marine forces and processes, assessment of geomorphic indicators, visits to neighboring sites, and interviews with residents and other local or knowledgeable individuals. Questions to be asked might include what, why, when, where, and how come? Why does this section of the shore look as it does? How do humans influence the local environment? Is the problem geologic (natural) or man-made? Do catastrophic events, such as hurricanes, appear to have much impact on the region? A checklist of data to be collected at a coastal site visit is presented in Appendix H. A handy field notebook of geologic data sheets is published by the American Geologic Institute (Dietrich, Durto, and Foose 1982).

c. Photographs and time sequences. Photography is often an important tool for initial reconnaissance work as well as for more detailed assessments of the study area. One special application of cameras involves the use of time-lapse or time interval photography, which may be helpful in studies of geomorphic variability to observe shoreline conditions, sand transport (Cook and Gorsline 1972), and wave characteristics. If the camera is set to record short-term processes, relatively frequent photographs are typically obtained. If historic ground photographs are available, additional pictures can be acquired from the same perspective. Changes in an area over time, applicable to both short- and long-term studies, can also be recorded with video photography. It is important that pertinent photographic information be recorded in a field log:

- Date.
- Time.
- Camera location.
- Direction of each photograph.
- Prominent landmarks, if any.

Date, location, and direction should be marked on slide mounts for each exposure.

d. Wave measurements and observations. It is often relevant in studies of historic and process time scales to obtain data regarding wave conditions at the site. Instrumented wave gauges typically provide the most accurate wave data. Unfortunately, wave gauges are expensive to purchase, deploy, maintain, and analyze. Often, they are operated for a short term to validate data collected by visual observation or hindcasting methods. Multiple gauges, set across the shore zone in shallow and deep water, can be used to determine the accuracy of wave transformation calculations for a specific locale.

(1) Types of wave gauges.

(a) Wave gauges can be separated into two general groups: directional and non-directional. In general, directional gauges and gauge arrays are more expensive to build, deploy, and maintain than non-directional gauges. Nevertheless, for many applications, directional instruments are vital because the directional distribution of wave energy is an important parameter in many applications, such as sediment transport analysis and calculation of wave transformation. Wave gauges can be installed in buoys, placed directly on the sea or lake bottom, or mounted on existing structures, such as piers, jetties, or offshore platforms.

(b) Of the non-directional wave gauges, buoy-mounted systems such as the Datawell Waverider are accurate and relatively easy to deploy and maintain. Data are usually transmitted by radio between the buoy and an onshore receiver and recorder. Bottom-mounted pressure gauges measure water level changes by sensing pressure variations with the passage of each wave. The gauges are either self-recording or are connected to onshore recording devices with cables. Bottom-mounted gauges must be maintained by divers unless the mount can be retrieved by hoisting from a workboat. Internal-recording gauges usually need more frequent maintenance because the data tapes must be changed or the internal memory downloaded. Advantages and disadvantages of self-contained and cable-telemetered gauges are listed in Table 5-1. Structure-mounted wave gauges are the most economical and most accessible of the non-directional gauges, although their placement is confined to locations where structures exist. The recording devices and transmitters can be safely mounted above water level in a protected location.

(c) Directional wave gauges are also mounted in buoys or on the seafloor (Figure 5-5). Arrays of non-directional gauges can be used for directional wave analyses. Directional buoy-type wave gauges are often designed to collect other parameters such as meteorology.

(2) Placement of wave gauges. The siting of wave gauges along the coast depends on the goals of the monitoring project, funds and time available, environmental hazards, and availability of previously collected data. There are no firm guidelines for placing gauges at a site, and each project is unique. There are two approaches to wave gauging: one is to deploy instruments near a project site in order to measure the wave and sea conditions that directly affect a structure or must be accounted for in designing a project. The second approach is to deploy a gauge further out to sea to measure regional, incident waves. In the past, when wave gauges were exceedingly expensive, researchers often opted to collect regional data with a single instrument. Now, with lower costs for hardware and software, we recommend that several gauges be deployed near the coast flanking the project area. A priori knowledge of a site or practical considerations may dictate gauge placement. The user must usually compromise between collecting large amounts of data for a short, intensive experiment, and maintaining the gauges at sea for a longer period in order to try to observe seasonal changes. Table 5-2 summarizes some suggested practices based on budget and study goals. Suggestions on data sampling intervals are discussed in Section 5-5.

(3) Seismic wave gauge. Wave estimates based on microseismic measurements are an alternative means to obtain wave data in high-energy environments. Microseisms are very small ground motions which can be detected by seismographs within a few kilometers of the coast. It is generally accepted that microseisms are caused by ocean waves and that the amplitudes and periods of the motions correspond to the regional wave climate. Comparisons of seismic wave gauges in Oregon with in situ gauges have been favorable (Howell and Rhee 1990; Thompson, Howell, and Smith 1985). The seismic system has inherent limitations, but deficiencies in wave period estimates can probably be solved with more sophisticated processing. Use of a seismometer for wave purposes is a long-term commitment, requiring time to calibrate and compare the data. The advantage of a seismograph is that it can be placed on land in a protected building.

e. Water level measurements and observations.

(1) To collect continuous water level data for site-specific, modern process studies, tide gauges must be deployed near the project site. Three types of instruments are commonly used to measure water level:

(a) *Pressure transducer gauges.* These instruments are usually mounted on the seafloor or attached to structures. They record hydrostatic pressure, which is converted to water level during data processing. A major advantage of these gauges is that they are underwater and somewhat inaccessable to vandals. In addition, ones like the Sea Data Temperature Depth Recorder are compact and easy to deploy.

(b) *Stilling-well, float gauges.* These instruments, which have been in use since the 1930's, consist of a float which is attached to a stylus assembly. A clockwork or electric motor advances chart paper past the stylus, producing a continuous water level record. The float is within a stilling well, which dampens waves and boat wakes. The main disadvantage of these gauges is that they must be protected from vandals. They are usually used in estuaries and inland waterways where piles or

Table 5-1
Self-Contained and Cable-Telemetry Wave Gauges; Advantages and Disadvantages

I. Self-contained gauges

A. Advantages

1. Deployment is often simple because compact instrument can be handled by a small dive team.
2. Gauge can be easily attached to piles, structural members, or tripods.
3. Field equipment can be carried by airplane to remote sites.
4. Gauges will continue to function in severe storms as long as the mounts survive.
5. Usually easy to obtain permits to deploy instruments (typically, notification to mariners must be posted).

B. Disadvantages

1. Gauge must be periodically recovered to retrieve data or replace storage media.
2. Data collection time is limited by the capacity of the internal memory or data tapes. Researcher must compromise between sampling density and length of time the gauge can be gathering data between scheduled maintenance visits.
3. Battery capacity may be a limiting factor for long deployments.
4. If bad weather forces delay of scheduled maintenance, gauge may reach the limit of its storage capacity. This will result in unsampled intervals.
5. While under water, gauge's performance cannot be monitored. If it fails electronically or leaks, data are usually lost forever.
6. Gauge may be struck by anchors or fishing vessels. The resulting damage or total loss may not be detected until the next maintenance visit.

C. Notes

1. Data compression techniques, onboard data processing, and advances in low-energy memory have dramatically increased the storage capacity of underwater instruments. Some can remain onsite as long as 12 months.

II. Data transmission by cable

A. Advantages

1. Data can be continuously monitored. If a failure is detected (by human analysts or error-checking computer programs), a repair team can be sent to the site immediately.
2. Because of the ability to monitor the gauge's performance, infrequent inspection visits may be adequate to maintain systems.
3. Frequency and density of sampling are only limited by the storage capacity of the shore-based computers.
4. Gauge can be reprogrammed in situ to change sampling program.
5. Electrical energy is supplied from shore.

B. Disadvantages

1. Permitting is difficult and often requires considerable effort.
2. Lightning is a major cause of damage and loss of data.
3. Cable to shore is vulnerable to damage from anchors or fishing vessels.
4. Shore station may be damaged in severe storms, resulting in loss of valuable storm data.
5. Shore station and data cable are vulnerable to vandalism.
6. Backup power supply necessary in case of blackouts.
7. Installation of cable can be difficult, especially in harbors and across rough surf zones.
8. Installation often requires a major field effort, with vehicles on beach and one or two boats. Heavy cable must be carried to the site.
9. Cable eventually deteriorates in the field and must be replaced.
10. Cable may have to be removed after experiment has ended.

C. Notes

1. Some cable-based gauges have internal memory and batteries so that they can continue to collect data even if cable is severed.
2. Ability to constantly monitor gauge's performance is a major advantage in conducting field experiments.

bridges are available for mounting the well and recording box. Figure 5-6 is an example of tide data from Choctawhatchee Bay, Florida.

(c) *Staff gauges.* Water levels are either recorded manually by an observer or calculated from electric resistance measurements. The resistance staff gauges require frequent maintenance because of corrosion and biological fouling. The manual ones are difficult to use at night and during storms, when it is hazardous for the observer to be at the site.

Typically, water level measurements recorded by gauges are related to an established datum, such as mean sea level. This requires that the gauge elevations be accurately measured using surveying methods. The maximum water level elevations during extreme events can also be

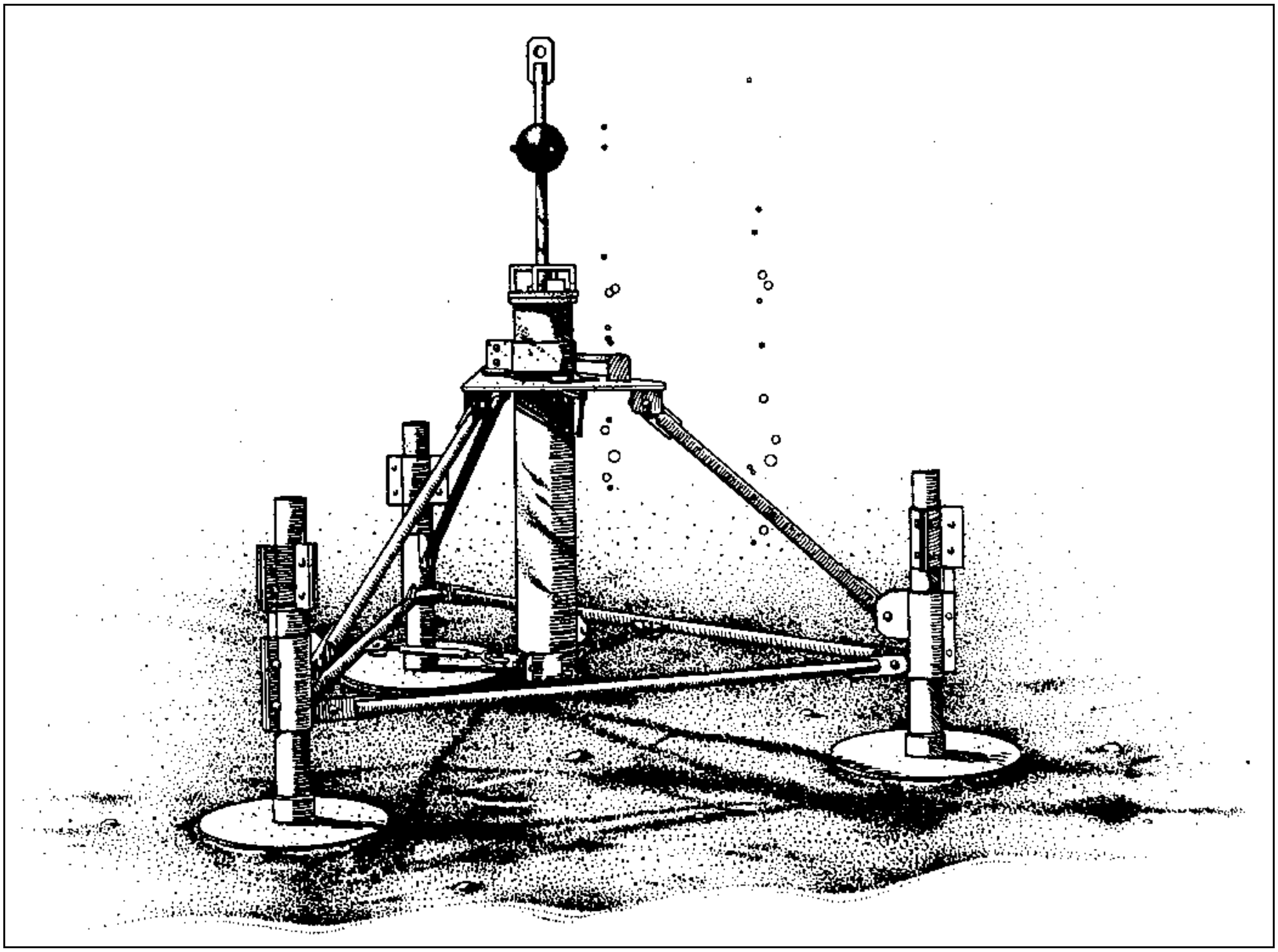


Figure 5-5. Bottom-mounted Sea Data™ 635-12 directional wave gauge mounted in tripod using railroad wheels as corner weights

determined by examining water marks on structures or other elevated features.

(2) Water level information over paleoenvironmental time scales has been investigated by researchers using stratigraphic coring, seismic techniques, and radiometric dating. Petroleum geologists have used seismic stratigraphy to reconstruct ancient sea levels (Payton 1977, Sheriff 1980).

f. Current measurements and observations.

(1) General techniques of current measurement.

(a) The observation of hydraulic phenomena can be accomplished by two general approaches. One of these, Lagrangian, follows the motion of an element of matter in its spatial and temporal evolution. The other, Eulerian, defines the motion of the water at a fixed point and determines its temporal evolution. Lagrangian current measuring devices are often used in sediment transport studies, in pollution monitoring, and for tracking ice drift. Eulerian, or fixed, current measurements are important for determining the variations in flow over time at a fixed location. Recently developed instruments combine aspects of both approaches.

(b) Four general classes of current measuring technology are presently in use (Appell and Curtin 1990):

- Radar and Lagrangian methods.

- Spatially integrating methods.

Table 5-2
Suggested Wave Gauge Placement for Coastal Project Monitoring

I. High-budget project (major harbor; highly populated area)

A. Recommended placement:

1. One (or more) wave gauge(s) close to shore near the most critical features being monitored (example, near an inlet). Although near-shore, gauges should be in intermediate or deep water based on expected most common wave period. Depth can be calculated from formulas in *Shore Protection Manual* (1984).
2. In addition, one wave gauge in deep water if needed for establishing boundary conditions of models.

B. Schedule:

1. Minimum: 1 year. Monitor winter/summer wave patterns (critical for Indian Ocean projects).
2. Optimum: 5 years or at least long enough to determine if there are noticeable changes in climatology over time. Try to include one El Niño season during coverage for North American projects.

C. Notes:

1. Concurrent physical or numerical modeling: Placement of a gauge may need to take into account modellers' requirements for input or model calibration.
2. Preexisting wave data may indicate that gauges should be placed in particular locations. As an alternative, gauges may be placed in locations identical to the previous deployment in order to make the new data as compatible as possible with the older data. **Long, continuous data sets are extremely valuable!**
3. Hazardous conditions: If there is a danger of gauges being damaged by anchors or fishing boats, the gauges must be protected, mounted on structures (if available), or deployed in a location which appears to be the least hazardous.

II. Medium-budget project

A. Recommended placement:

1. One wave gauge close to shore near project site.
2. Obtain data from nearest NOAA National Data Buoy Center (NDBC) buoy for deepwater climatology.

B. Schedule: minimum 1 year deployment; longer if possible

C. Notes: same as IC above. Compatibility with existing data sets is very valuable.

III. Low budget, short-term project

A. Recommended placement: gauge close to project site.

B. Schedule: if 1-year deployment is not possible, try to monitor the season when the highest waves are expected (usually winter, although this may not be true in areas where ice pack occurs).

C. Notes: same as IC above. It is critical to use any and all data from the vicinity, anything to provide additional information on the wave climatology of the region.

- Point source and related technology.
- Acoustic Doppler Current Profilers (ADCP) and related technology.

The large number of instruments and methods used to measure currents underscores that detection and analysis of fluid motion in the oceans is an exceedingly complex process. The difficulty arises from the large continuous scales of motion in the water. As stated by McCullough (1980), "There is no single velocity in the water, but many, which are characterized by their temporal and spatial spectra. Implicit then in the concept of *a* fluid 'velocity' is knowledge of the temporal and spatial averaging processes used in measuring it. Imprecise, or worse, inappropriate modes of averaging in time and/or space now represent the most prominent source of error in near-surface flow measurements." McCullough's comments were addressed to the measurement of currents in the ocean. In shallow water, particularly in the surf zone, additional difficulties are created by turbulence and air entrainment caused by breaking waves, by suspension of large concentrations of sediment, and by the physical violence of the environment. Trustworthy current measurement under these conditions becomes a daunting task.

(2) Lagrangian.

(a) Dye, drogues, ship drift, bottles, temperature structures, oil slicks, radioactive materials, paper, wood chips, ice, trees, flora, and fauna have all been used to study the surface motion of the oceans (McCullough 1980). Some of these techniques, along with the use of

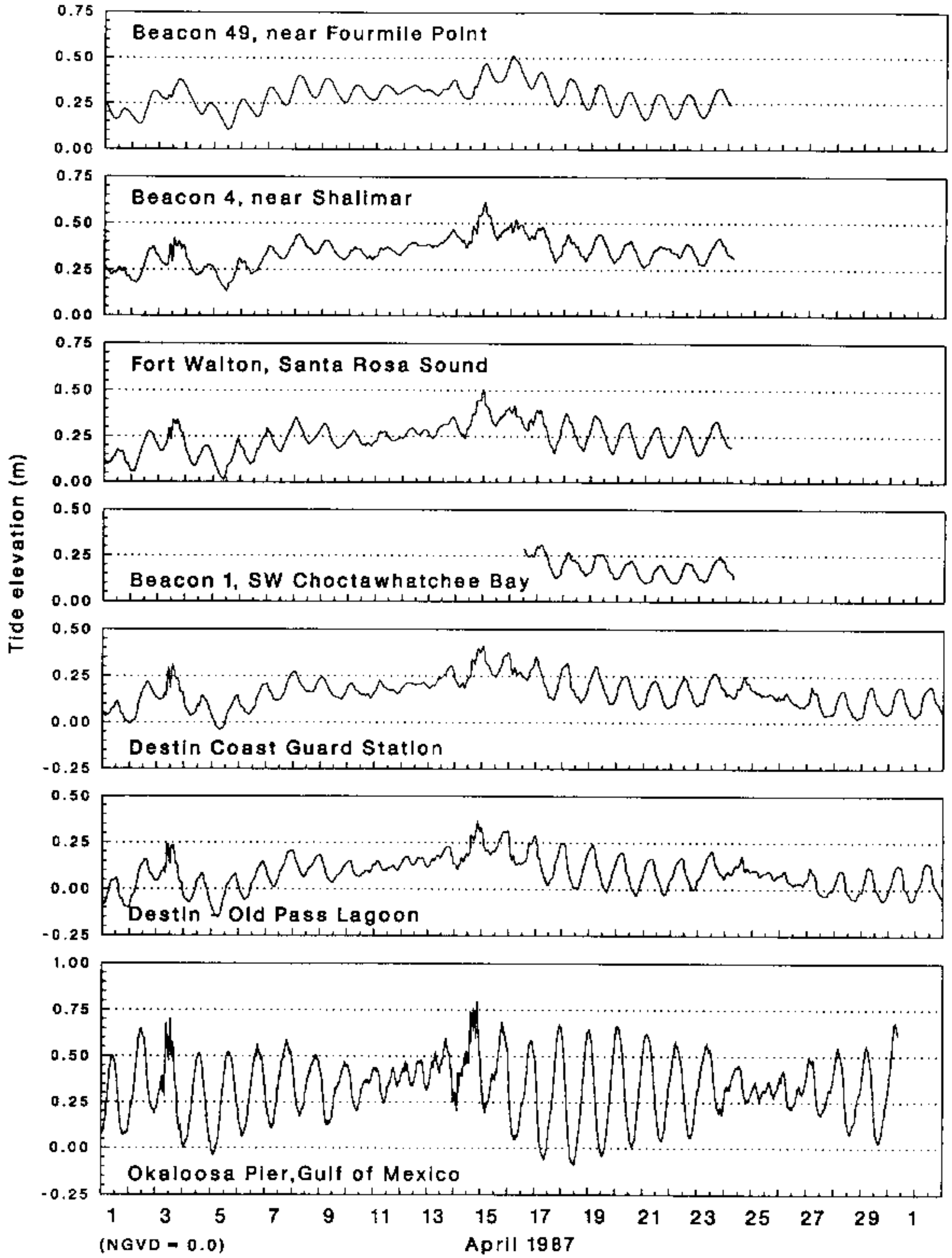


Figure 5-6. Tidal elevations from seven stations in Choctawhatchee Bay, FL, and the Gulf of Mexico. The overall envelope of the seven curves is similar, but individual peaks are shifted in phase from station to station. Original tide records courtesy of U.S. Army Engineer (USAE) District, Mobile

mid-depth drogues and seabed drifters, have been widely used in coastal studies. A disadvantage of all drifters is that they are only quasi-Lagrangian sensors because, regardless of their design or mass, they cannot exactly follow the movement of the water (Vachon 1980). Nevertheless, they are particularly effective at revealing surface flow patterns if they are photographed or video recorded on a time-lapse basis. Simple drifter experiments can also be helpful in developing a sampling strategy for more sophisticated subsequent field investigations. Floats, bottom drifters, drogues, and dye are used especially in the littoral zone where fixed current meters are adversely affected by turbulence. Resio and Hands (1994) analyze the use of seabed drifters and comment on their value in conjunction with other instruments.

(b) High frequency (HF) radar surface-current mapping systems have been tested since the 1970's. The advantage of using the upper high radar frequencies is that these frequencies accurately assess horizontal currents in a mean water depth of only 1 m (total layer thickness about 2 m). Hence, HF radar accurately senses horizontal currents in the uppermost layers of the oceans, where other instruments such as moored current meters and ADCP's become inoperable (Barrick, Lipa, and Lilleboe 1990). Nevertheless, HF radar has had limited success in the oceanography community because of the difficulty in proving measurement accuracy and because of relatively high system costs (Appell and Curtin 1990).

(c) Large-scale coastal circulation can be observed in satellite images, as seen in Figure 5-3.

(3) Spatially integrating methods. To date, experiments in spatially averaging velocity by observing induced electrical fields have been conducted by towing electrodes from ships or by sending voltages in abandoned underwater telephone cables. Some of these experiments have been for the purpose of measuring barotropic flow in the North Pacific (Chave, Luther, and Filloux 1990; Spain 1990 - these two papers provide a substantial summary of the mathematics and methods). This author is unaware of whether these techniques have been tested in shallow water or in restricted waterways such as channels. At this time, therefore, spatially integrating methods appear to have no immediate application to coastal engineering studies.

(4) Point source (Eulerian) and related technology.

(a) In channels, bays, and offshore, direct measurements of the velocity and direction of current flow can be made by instruments deployed on the bottom or at various levels in the water column. Two general classes of current meters are available: mechanical (impeller-type) and electronic. Several types of electronic current meters are in common use, including electromagnetic, inclinometer, and acoustic travel-time (Fredette et al. 1990, McCullough 1980; Pinkel 1980).

(b) Impeller current meters measure currents by means of a propeller device which is rotated by the current flow. They serve as approximate velocity component sensors because they are primarily sensitive to the flow component in a direction parallel to their axle. Various types of propeller design have been used to measure currents, but experience and theoretical studies have shown that the ducted propellers are more satisfactory in measuring upper ocean currents than rotor/vane meters (Davis and Weller 1980). Impeller/propeller meters are considered to be the most reliable in the surf zone (Teleki, Musialowski, and Prins 1976), as well as the least expensive. One model, the Endeco 174, has been widely used by CERC for many years throughout the country. Impeller gauges are subject to snarling, biofouling, and bearing failures, but are more easily repaired in the field and are more easily calibrated than other types (Fredette et al. 1990).

(c) Electronic current meters have many features in common, although they operate on different principles. Their greatest common advantages are rapid response and self-contained design with no external moving parts. They can be used in real-time systems and can be used to measure at least two velocity components. The degree of experience of the persons working with the instruments probably has more influence on the quality of data acquired than does the type of meter used (Fredette et al. 1990). The InterOcean Systems S4 electromagnetic meter has been successfully used by CERC at field experiments.

(5) ADCPS. These profilers operate on the principle of Doppler shift in the backscattered acoustic energy caused by moving particles suspended in the water. Assuming that the particles have the same velocity as the ambient water, the Doppler shift is proportional to the velocity components of the water within the path of the instrument's acoustic pulse (Bos 1990). The backscattered acoustic signal is divided into parts corresponding to specific depth cells, often termed "bins." The bins can be various sizes, depending upon the depth of water in which the instrument has been deployed, the frequency of the signal pulse, the time that each bin is sampled, and the acceptable accuracy of the estimated current velocity. Much excitement has been generated by ADCP's, both among scientists working in shallow water and in the

deep ocean (a comprehensive bibliography is listed in Gordon et al. (1990)). A great advantage of using ADCP's in shallow water is that they provide profiles of the velocities in the entire water column, providing more comprehensive views of water motions than do strings of multiple point source meters. ADCP data are inherently noisy, and signal processing and averaging are critical to the successful performance of the gauges (Trump 1990).

(6) Indirect estimates of currents. Indirect estimates of current speed and direction can be made from the orientation, size, and shape of bed forms, particularly in shallow water. Widespread use of side-scan sonar has made this type of research possible in bays, inlets, and offshore. Sedimentary structures on the seafloor are caused by the hydrodynamic drag of moving water acting on sediment particles. The form and shape of bottom structures reflect the effects and interaction among tidal currents, waves, riverine flow, and longshore currents. These complex interactions especially affect bedforms in tidal channels and other restricted waterways. Bedforms reflect flow velocity, but are generally independent of depth (Clifton and Dingler 1984; Boothroyd 1985). Their shape varies in response to increasing flow strength (Hayes and Kana 1976). Bedform orientation and associated slipfaces also provide clues to flow direction (Morang and McMaster 1980; Wright, Sonu, and Kielhorn 1972).

g. Grab sampling and samplers.

(1) Seafloor sediments in coastal areas can show great spatial and temporal variation. The surface sediments may provide information about the energy of the environment as well as the long-term processes and movement of materials, such as sediment transport pathways, sources and sinks. Bed surface sediments are typically collected with grab samplers and then analyzed using standard laboratory procedures. These tests are described in detail in other sources (Fredette et al. 1990; Buller and McManus 1979).

(2) There are a variety of grab type samplers of different sizes and design that are used for collecting surface sediment samples (described in detail in Bouma (1969)). Most consist of a set of opposing, articulated scoop-shaped jaws that are lowered to the bottom in an open position and are then closed by various trip mechanisms to retrieve a sample. Many grab samplers are small enough to be deployed and retrieved by hand; others require some type of lifting gear. If there is gravel in the sample, at least 2 to 3 litres of sample are needed for reliable grain size distribution testing.

(3) A simple and inexpensive dredge sampler can be made of a section of pipe that is closed at one end. It is dragged a short distance across the bottom to collect a sample. Unlike grab samples, the dredged samples are not representative of a single point and may have lost finer material during recovery. However, dredge samplers are useful in areas where shells or gravel which prevent complete closure of the jaws are present.

(4) Although obtaining surficial samples is helpful for assessing recent processes, it is typically of limited value in stratigraphic study because grab samplers usually recover less than 15 cm of the sediment. Generally, the expense of running tracklines in coastal waters for the sole purpose of sampling surficial sediments is not economically justified unless particularly inexpensive boats can be used. Occasionally, grab and dredge samples are taken during geophysical surveys, but the sampling operations require the vessel to stop at each station, thus losing survey time and creating interrupted data coverage. Precise offshore positioning now allows grab samples to be collected at specific locations along the boat's track after the survey has been run and the data examined.

h. Stratigraphic sampling.

(1) Sediments and sedimentary rock sequences are a record of the history of the earth and its changing environments, including sea-level changes, paleoclimates, ocean circulation, atmospheric and ocean geochemical changes, and the history of the earth's magnetic field. By analyzing stratigraphic data, age relations of the rock strata, rock form and distribution, lithologies, fossil record, biopaleogeography, and episodes of erosion and deposition at a coastal site can be determined. Erosion removes part of the physical record, resulting in unconformities. Often, evidence of erosion can be interpreted using physical evidence or dating techniques.

(2) Sediment deposits located across a zone that ranges from the maximum water level elevation to the depth of the wave base are largely indicative of recent processes. Within this zone in unconsolidated sediments, simple reconnaissance field techniques are available for collecting data. The techniques often use ordinary construction equipment or hand tools. Smaller efforts require shovels, hand augers, posthole diggers, or similar hand-operated devices. Larger-scale efforts may include trenches, pits or other large openings created for visual inspection, sample collection, and photography (Figure 5-7). A sedimentary peel can be taken from the exposed surface. The peel retains the original

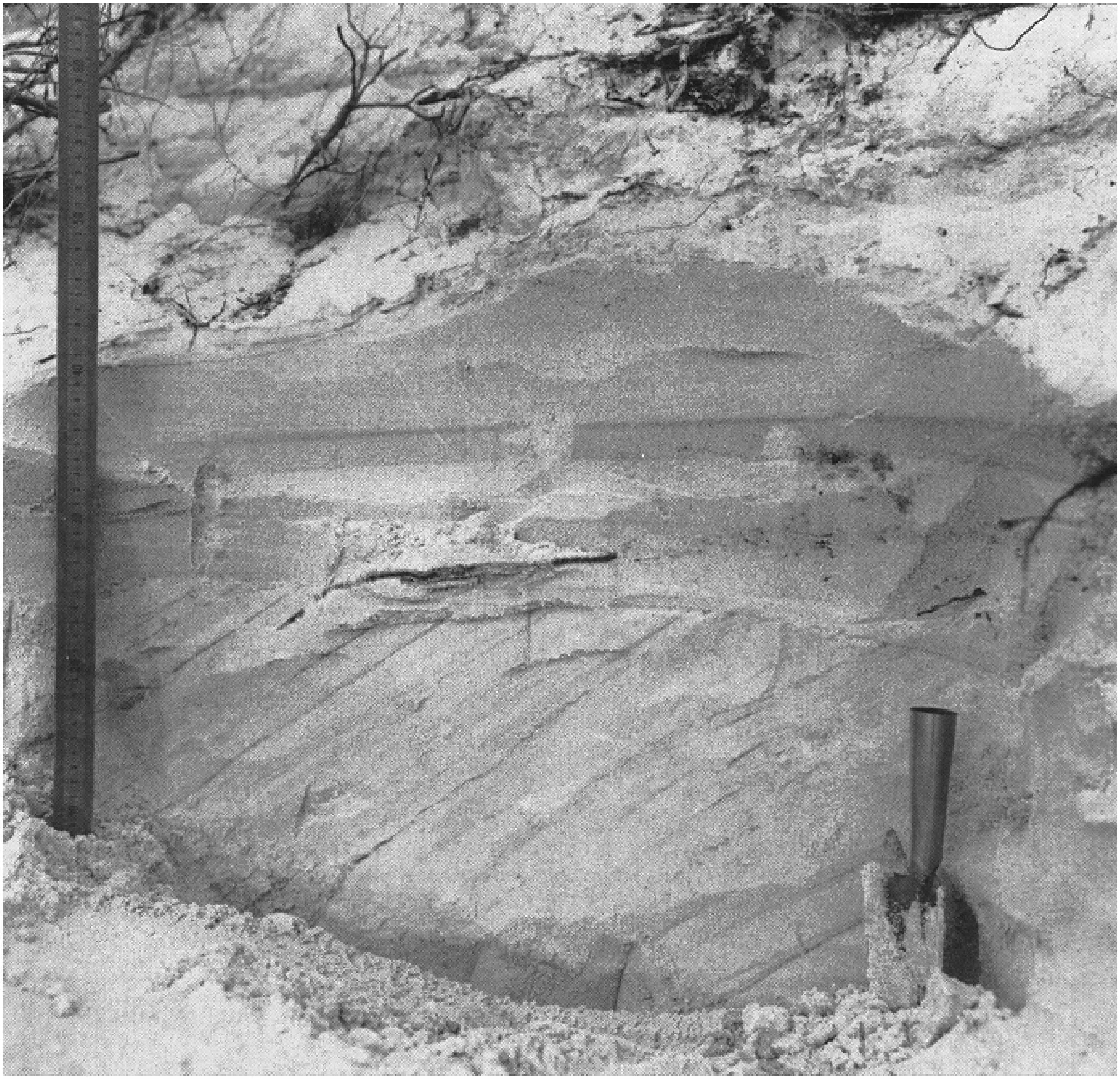


Figure 5-7. Trench excavated in the edge of a sand dune, eastern Alabama near Alabama/Florida state line

arrangement of sedimentary properties (Bouma 1969). Often, undisturbed chunk or block samples and disturbed jar or bag samples are carved from these excavations and taken back to the laboratory.

(3) Rates and patterns of sedimentation can be determined using marker horizons. Marker horizons may occur in relation to natural events and unintentional human activities or they may be directly emplaced for the express purpose of determining rates and patterns of sedimentation. Recently, several studies have estimated rates of sedimentation in marshes by spreading feldspar markers and later measuring the thicknesses of materials deposited on the feldspar with cryogenic coring devices.

(4) The petrology and mineralogy of rock samples can be used to identify the source of the sediment. This can indicate if river flow has changed or if coastal currents have changed directions. Mineralogy as it pertains to sediment budgets is discussed in Meisburger (1993) and Wilde and Case (1977).

(5) Direct sampling of subbottom materials is often essential for stratigraphic studies that extend beyond historic time scales. Table 5-3 lists details on a number of subaqueous sediment sampling systems that do not require drill rigs. One system listed in Table 5-3, the vibracorer, is commonly used by geologists to obtain samples in the marine and coastal environment. Vibratory corers consist of three main components: a frame, coring tube or barrel, and a drive head with a vibrator (Figure 5-8). The frame consists of a quadrapod or tripod arrangement, with legs connected to a vertical beam. The beam supports and guides the core barrel and vibrator and allows the corer to be free-standing on the land surface or seafloor. The core may be up to 3 or 4 m long, which is adequate for borrow site investigations and many other coastal studies.

(6) While common vibratory corers are capable of penetrating up to 5 m or more of unconsolidated sediment, actual performance depends on the nature of the subbottom material. Under unfavorable conditions, very little sediment may be recovered. Limited recovery occurs for several reasons, chief among these being lack of penetration of the core barrel. In general, stiff clays, gravel and hard-packed fine to very fine sands are usually most difficult to penetrate. Compaction and loss of material during recovery can also cause a discrepancy between penetration and recovery. In comparison with rotary soil boring operations, vibratory coring setup, deployment, operation, and recovery are rapid. Usually a 3-m core can be obtained in a manner of minutes. Longer cores require a crane or some other means of hoisting the equipment, a procedure that consumes more time, but is still comparatively rapid. Success with vibracoring depends on some prior knowledge of sediment type in the region.

(7) Cores can be invaluable because they allow a direct, detailed examination of the layering and sequences of the subsurface sediment in the study area. The sequences provide information regarding the history of the depositional environment and the physical processes during the time of sedimentation. Depending upon the information required, the types of analysis that can be performed on the core include grain size, sedimentary structures, identification of shells and minerals, organic content, microfaunal identification, (pollen counts) x-ray radiographs, radiometric dating, and engineering tests. If only information regarding recent processes is necessary, then a box corer, which samples up to 0.6-m depths, can provide sufficient sediment. Because of its greater width, a box corer can recover undisturbed sediment from immediately below the seafloor, allowing the examination of microstructure and lamination. These structures are usually destroyed by traditional vibratory or rotary coring.

(8) If it is necessary to obtain deep cores, or if there are cemented or very hard sediments in the subsurface, rotary coring is necessary. Truck- or skid-mounted drilling rigs can be conveniently used on beaches or on barges in lagoons and shallow water. Offshore, rotary drilling becomes more complex and expensive, usually requiring jack-up drilling barges or four-point anchored drill ships (Figure 5-9). An experienced drilling crew can sample 100 m of the subsurface in about 24 hr. Information on drilling and sampling practice is presented in EM 1110-1-1906 and Hunt (1984).

i. Sediment movement and surface forms. Of great importance in investigations of geologic history is tracing sediment movement. This includes identifying the locations of sediment sources and sinks, quantifying sediment transport rates, and discovering the pathways. Sediment transportation is influenced by grain properties such as size, shape, and density, with grain size being most important. Differential transport of coarse and fine, angular and rounded, and light and heavy grains leads to grading. Field visits to a locality are often repeated to assess temporal variability of these phenomena. Simultaneous measurements of energy processes, such as current and waves, are often required to understand the rates and mechanisms of movement.

(1) Measurement of sediment movement.

(a) The measurement of suspended and bed load sediment movement in the surf zone is an exceedingly difficult process. There are a variety of sampling devices available for measuring suspended and bed load transport in the field (Dugdale 1981; Seymour 1989), but these devices have not performed properly under some conditions or have been expensive and difficult to use. For these reasons, new sampling procedures are being developed and tested at CERC and other laboratories. Point measurements of sediment movement can be performed by two general procedures:

- Direct sampling and weighing of a quantity of material.

Table 5-3
Subaqueous Soil Sampling Without Drill Rigs and Casing

Device	Application	Description	Penetration depth	Comments
Petersen dredge	Large, relatively intact "grab" samples of seafloor.	Clam-shell type grab weighing about 1,000 lb with capacity about 0.4 ft^3	To about 4 in.	Effective in water depths to 200 ft. More with additional weight.
Harpoon-type gravity corer	Cores 1.5- to 6-in.-dia. in soft to firm soils.	Vaned weight connected to coring tube dropped directly from boat. Tube contains liners and core retainer.	To about 30 ft.	Maximum water depth depends only on weight. Undisturbed (UD) sampling possible with short, large-diameter barrels.
Free-fall gravity corer	Cores 1.5- to 6-in. dia. in soft to firm soils.	Device suspended on wire rope over vessel side at height above seafloor about 15 ft and then released.	Soft soils to about 17 ft. Firm soils to about 10 ft.	As above for harpoon type.
Piston gravity corer (Ewing gravity corer)	2.5-in. sample in soft to firm soils.	Similar to free-fall corer except that coring tube contains a piston that remains stationary on the seafloor during sampling.	Standard core barrel 10 ft; additional 10-ft sections can be added.	Can obtain high-quality UD samples.
Piggott explosive coring tube	Cores of soft to hard bottom sediments.	Similar to gravity corer. Drive weight serves as gun barrel and coring tube as projectile. When tube meets resistance of seafloor, weighted gun barrel slides over trigger mechanism to fire a cartridge. The exploding gas drives tube into bottom sediments.	Cores to 1-7/8 in. and to 10-ft lengths have been recovered in stiff to hard materials.	Has been used successfully in 20,000 ft of water.
Norwegian Geotechnical Institute gas-operated piston	Good-quality samples in soft clays.	Similar to the Osterberg piston sampler except that the piston on the sampling tube is activated by gas pressure.	About 35 ft.	
Vibracorer	High-quality samples in soft to firm sediments. Dia. 3-1/2 in.	Apparatus is set on seafloor. Air pressure from the vessel activates an air-powered mechanical vibrator to cause penetration of the tube, which contains a plastic liner to retain the core.	Length of 20 and 40 ft. Rate of penetration varies with material strength. Samples a 20-ft core in soft soils in 2 min.	Maximum water depth about 200 ft.
Box corer	Large, intact slice of seafloor.	Weighted box with closure of bottom for benthic biological sampling.	To about 1 ft.	Central part of sample is undisturbed.

(Adapted from Hunt (1984))

- Detection of the fluid flow by electro-optical or acoustic instruments deployed in the water.

(b) Two general methods are available to directly sample the sediment in suspension and in bed load. First, water can be collected in hand-held bottles or can be remotely sucked into containers with siphons or pump apparatus. The samples are then dried and weighed. The second method is to trap a representative quantity of the sediment with a mesh or screen trap through which the water is allowed to flow for a fixed time. A fundamental problem shared by both methods is the question of whether the samples are truly representative of the sediment in transport. For example, how close to the seabed must the orifice be to sample bed load? If it is high enough to avoid moving bed forms, will it miss some of the bed load? Streamer traps made from mesh are inexpensive to build but difficult to use. The mesh must be small enough to trap most of the sediment but must allow water to flow freely. Kraus (1987) deployed streamers at Duck, NC, from stainless steel wire frames (Figure 5-10). Kraus and Dean (1987) obtained the distribution of longshore sand transport using sediment traps. At this time, sediment traps are still research tools and are not

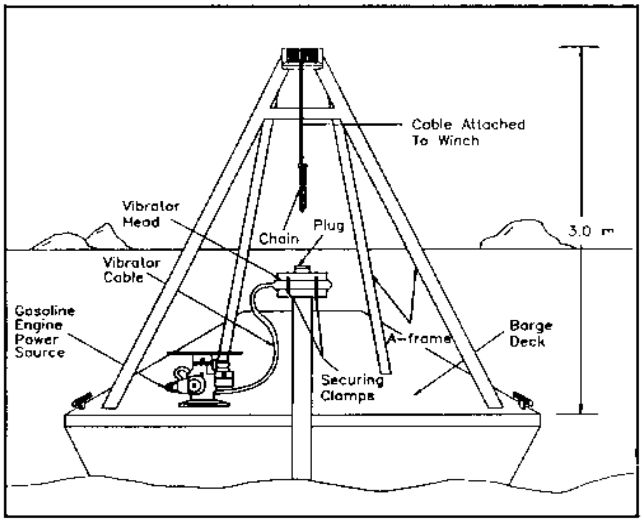


Figure 5-8. Front view of lightweight vibracorer mounted on a barge

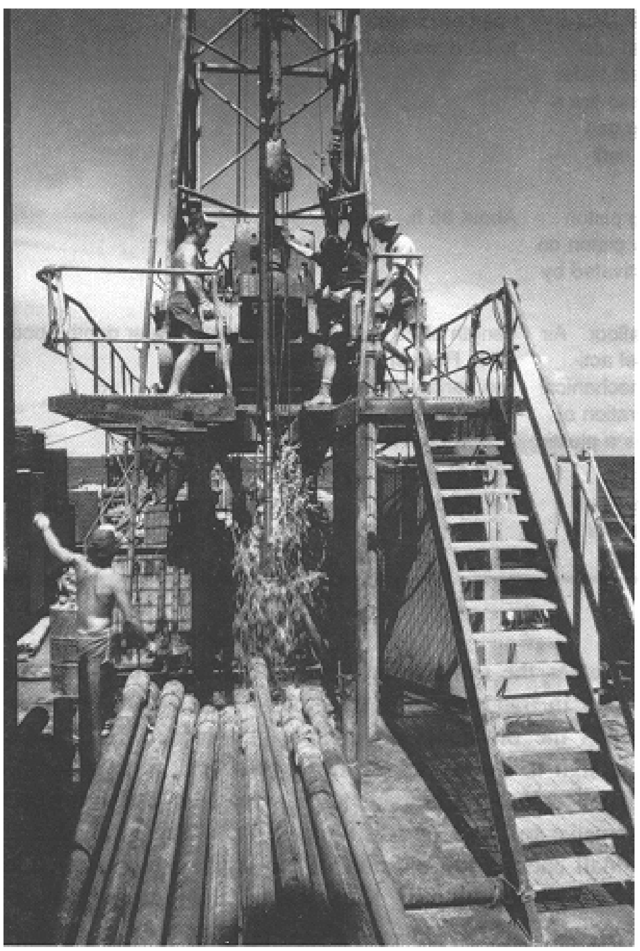


Figure 5-9. Rotary drilling operations underway from a 4-point anchored drill ship. Drilling is conducted 24 hr using two crews

commonly used. A fundamental limitation of traps is that they can usually only be used in mild conditions. In winter and during storms it is too hazardous for the field technicians to maintain the equipment. Perversely, it is under these harsher conditions when the greatest sediment movement occurs. Another fundamental problem is relating the instantaneous measured suspended and bedload transport to long-term sediment movement. Because of the extreme difficulty of conducting research in the surf zone, answers to these questions remain elusive.

(c) Electronic instruments are being developed to detect or estimate sediment transport. They have some advantages over direct sampling procedures. These include the ability to measure the temporal variations of suspended or bed load sediment and the ability to be used in cold water or in harsh conditions. (Note, however, that in severe storms, essentially no man-made devices have survived in the surf zone.) Their disadvantages include the difficulty of calibrating the sensors and testing their use with different types of sand and under different temperatures. In addition, many of these instruments are expensive and not yet commonly available. Sternberg (1989) and Seymour (1989) discuss ongoing research to develop and test new instruments for use in sediment transport studies in estuarine and coastal areas.

(d) Sediment movement, both bed load or total load, can also be measured with the use of natural and artificial tracers (Dugdale 1981). Heavy minerals are natural tracers which have been used in studies of sediment movement (McMaster 1960; Wilde and Case 1977). Natural sand can also be labelled using radioactive isotopes and fluorescent coatings (Arlman, Santema, and Svaŝek 1958; Duane 1970; Inman and Chamberlain 1959; Teleki 1966). Radioactive tracers are no longer used because of health and safety concerns. When fluorescent dyes are used, different colors can be used simultaneously on different size fractions to differentiate between successive experiments at one locality (Ingle 1966). Artificial grains, which have the same density and hydraulic response of natural grains, can also be used in tracer studies. Aluminum cobble has been used by Nicholls and Webber (1987) on rocky beaches in England. The aluminum rocks were located on the beaches using metal detectors. Nelson and Coakley (1974) review artificial tracer methods and concepts.

(e) As with other phenomena, the experimental design for tracer studies may be Eulerian or Lagrangian. For the time integration or Eulerian method, the tracer grains are injected at a constant rate over a given interval

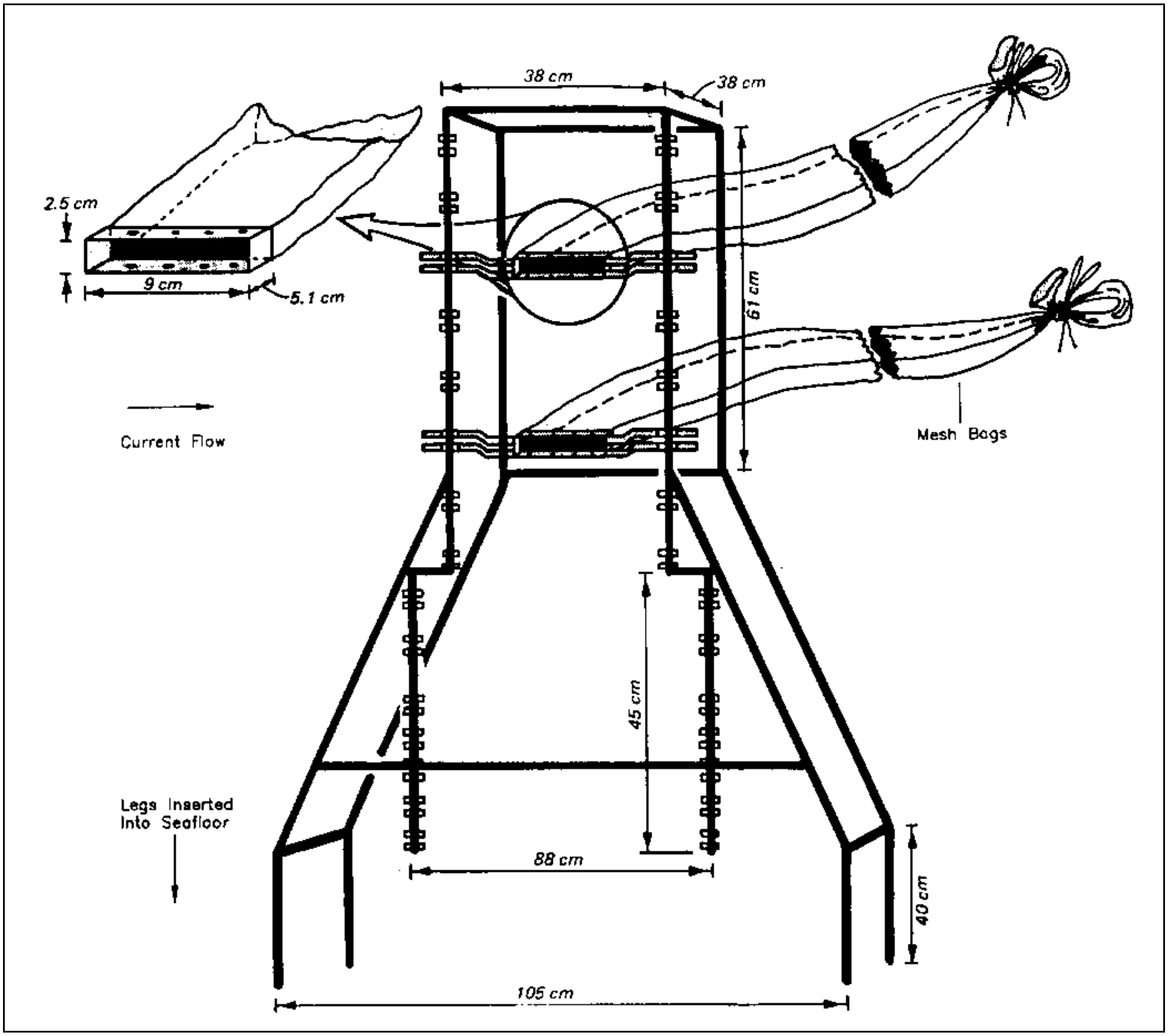


Figure 5-10. Side view of steel frame and polyester mesh sediment trap used at Duck, NC, by Kraus (1987) during CERC's DUCK-85 field experiments

of time. For the space integration or Langrangian method, the tracers are released over an area at the same time. The choice of the method depends upon the nature of the problem. Field experiments must be designed carefully to isolate the parameter of interest that is to be measured or traced. For example, if the purpose of the study is to assess bed-load transport, then care must be taken not to introduce tracers into the suspended load in the water column.

(2) Use of subsurface structure to estimate flow regime. An introduction to bed form shape and nomenclature has been presented in Chapter 4.

(a) Several useful indices of foreset laminae, which may assist in making qualitative estimates of the strength of currents in modern and ancient sediments, are given by Jopling (1966). These include: (1) maximum angle of dip of foreset laminae (at low velocities the angle may exceed the static angle of repose whereas at high velocities the angle is less than the static angle); (2) character of contact between foreset and bottomset (the contact changes from angular to tangential to sigmoidal with increasing velocity); (3) laminae frequency measured at right angles to bedding (there are more laminae per unit area with increasing velocity); (4) sharpness or textural contrast between adjacent laminae (at higher velocities laminae become less distinct); and (5) occurrence of regressive ripples (regressive ripples indicate relatively higher velocities).

(b) Measurements of bed forms can be accomplished on exposed sand banks at low water using surveying techniques or large-scale aerial photographs. Dimensionless parameters of ripples and other bedforms can indicate depositional environment (Tanner 1967). The flow directions can be assessed in terms of the trace of the crestline (Allen 1968). Wave-formed structures reflect the velocity and direction of the oscillatory currents as well as the length of the horizontal component of orbital motion and the presence of velocity asymmetry within the flow (Clifton and Dingler 1984). The flow strength for intertidal estuarine bed forms can also be estimated for a given flow depth by the velocity-depth sequence of bed forms (Boothroyd 1985).

j. Navigation and positioning equipment.

(1) Accurate positioning is essential for most geological monitoring studies. Several types of positioning and navigation systems are available for coastal studies, with the most common being Loran-C and Global Positioning Systems (GPS). Other technologies, such as short-range microwave and optical systems, are also in common use (Fredette et al. 1990).

(2) Loran-C computes microsecond time differences using pulsed low-frequency radio waves between networks and receivers. The differences are then computed as lines of position. The receivers can be used up to about 2,000 km from the networks with reasonable accuracy. The absolute accuracy of Loran-C varies from 180 to 450 m, while the repeatable accuracy varies from 15 to 90 m.

(3) *Global Positioning System* (GPS) is a revolution in electronic navigation for the military because of its unmatched ability to provide rapid and extremely accurate position fixes around the world under all weather conditions. The system is not yet fully operational and some of the satellites have not yet been launched. Unfortunately for civilian users, the Department of Defense has implemented a national security program called *Selective Availability* (SA), which deliberately degrades GPS accuracy by distorting the satellite signals. There are two types of GPS receivers:

- *Precise Positioning Systems* (PPS), which are available only to the military and "approved civilians," contain electronic chips which recognize and correct the SA distortion.

- *Standard Positioning Systems* (SPS) are available commercially for boaters and civilians. The SA distortion makes these units accurate to 100 m 95 percent of the time and 300 m for the remaining 5 percent. The problem with SPS is that civilian users do not know the extent of the SA distortion or when it is in effect, therefore making it impossible to determine the level of accuracy of the GPS readings at any given time.

In an effort to provide accuracy of 12-20 m in harbors and harbor approaches, the U.S. Coast Guard has been developing *Differential GPS* (DGPS) for coastal waters. This procedure attempts to cancel the error which SA imposes. Using land-based receivers at specific, known locations (Coast Guard stations, lighthouses), the Coast Guard receives simultaneous signals from 12 satellites, determines the difference between the exact and GPS-reported locations, calculates a correction, and transmits the correction over local radio frequencies to nearby vessels. Boats must be equipped with special receivers to demodulate the signal and apply it to the GPS signal that the boat is receiving.

As of 1994, only 10 of the planned 47 U.S. DGPS stations have been installed, and the operating stations are still in the prototype stage. Several more years of adjusting and tuning are anticipated. Users can contact the Coast Guard's GPS Information Center (Alexandria, VA; tel 703/313 5900) for up-to-date information on the status of the system. In light of the developmental stage of DGPS technology, **users are cautioned against relying on manufacturers' claims of pinpoint accuracy.** The technology is simply not yet developed to this level. Use of GPS for USACE surveys is discussed in EM 1110-1-1003.

(4) Navigation (positioning) error standards have been established for USACE hydrographic surveys. Three general classes of surveys have been defined (EM 1110-2-1003):

- Class 1 - Contract payment surveys.
- Class 2 - Project condition surveys.
- Class 3 - Reconnaissance surveys.

Although the requirements of geologic site surveys may not be the same as those of USACE hydrographic surveys, the accuracy standards are useful criteria when specifying quality control requirements in contractual documents. The frequency of calibration is the major distinguishing factor between the classes of survey, and directly affects the accuracy and adequacy of the final results. With the increasing use of Geographic Information Systems (GIS) for analysis and manipulation of data, high standards of accuracy are imperative. Calibrations are time-consuming and reduce actual data collection time. Nevertheless, this must be countered with the economic impact that low quality data may be useless or may even lead to erroneous conclusions (leading, in turn, to incorrectly designed projects and possible litigation).

(5) The maximum allowable tolerances for each class of survey are shown in Table 5-4.

(6) Table 5-5 depicts positioning systems which are considered suitable for each class of survey. The table presumes that the typical project is located within 40 km (25 miles) of a coastline or shoreline reference point. Surveys further offshore should conform to the standards in the NOAA Hydrographic Manual (NOAA 1976). Planning and successful implementation of offshore surveys are sophisticated activities and should be carried out by personnel or contractors with considerable experience and a successful record in achieving the accuracies specified for the particular surveys.

k. Geophysical techniques.

(1) Geophysical survey techniques, involving the use of sound waves and high quality positioning systems on ocean vessels, are widely used for gathering subsurface geological and geotechnical data in coastal environments. Geophysical procedures provide indirect subsurface data as opposed to the direct methods such as coring and trenching. The use of geophysical methods can assist in locating and correlating geologic materials and features by determining acoustic transparency, diffraction patterns, configuration and continuity of reflectors, and apparent bedding patterns. Inferences can often be made using these measures of stratigraphic and lithologic characteristics and important discontinuities. Table 5-6 lists frequencies of common geophysical tools.

(2) Fathometers or depth-sounders, side-scan sonar, and subbottom profilers are three major types of equipment used to collect geophysical data in marine exploration programs. All three systems are acoustic devices that function by propagating acoustic pulses in the water and measuring the lapsed time between pulse initiation and the arrival of return signals reflected from various features on or beneath the bottom. These systems are used to obtain information on seafloor geomorphology, bottom features such as ripple marks and rock outcrops, and the underlying rock and sediment units. Acoustic depth-sounders are used for conducting bathymetric surveys. Side-scan sonar provides an image of the aerial distribution of sediment and surface bed forms and larger features such as shoals and channels. It can thus be helpful in mapping directions of sediment motion. Subbottom profilers are used to examine the near-surface stratigraphy of features below the seafloor.

(3) A single geophysical method rarely provides enough information about subsurface conditions to be used without actual sediment samples or additional data from other geophysical methods. Each geophysical technique typically responds to several different physical characteristics of earth materials, and correlation of data from several methods provides the most meaningful results. **All geophysical methods rely heavily on experienced operators and analysts.**

Table 5-4
Maximum Allowable Errors for Hydrographic Surveys

	Survey Classification		
Type of Error	**1 Contract Payment**	**2 Project Condition**	**3 Reconnaissance**
Resultant two-dimensional one-sigma RMS positional error not to exceed	3 m	6 m	100 m
Resultant vertical depth measurement one-sigma standard error not to exceed	± .152 m (± 0.5 ft)	± .305 m (± 1.0 ft)	± .457 m (± 1.5 ft)

(From EM 1110-2-1003)

Table 5-5
Allowable Horizontal Positioning System Criteria

Positioning System	Estimated Positional Accuracy (meters, RMS)	Allowable for Survey Class 1	2	3
Visual Range Intersection	3 to 20	No	No	Yes
Sextant Angle Resection	2 to 10	No	Yes	Yes
Transit/Theodolite Angle Intersection	1 to 5	Yes	Yes	Yes
Range Azimuth Intersection	0.5 to 3	Yes	Yes	Yes
Tag Line (Static Measurements from Bank)				
< 457 m (1,500 ft) from baseline	0.3 to 1	Yes	Yes	Yes
> 457 m (1,500 ft) but < 914 m (3,000 ft)	1 to 5	No	Yes	Yes
> 914 m (3,000 ft) from baseline	5 to 50+	No	No	Yes
Tag Line (Dynamic)				
< 305 m (1,000 ft) from baseline	1 to 3	Yes	Yes	Yes
> 305 m (1,000 ft) but < 610 m (2,000 ft)	3 to 6	No	Yes	Yes
> 610 m (2,000 ft) from baseline	6 to 50+	No	No	Yes
Tag Line (Baseline Boat)	5 to 50+	No	No	Yes
High-Frequency EPS* (Microwave or UHF)	1 to 4	Yes	Yes	Yes
Medium-Frequency EPS	3 to 10	No	Yes	Yes
Low-Frequency EPS (Loran)	50 to 2000	No	No	Yes
Satellite Positioning:				
Doppler	100 to 300	No	No	No
STARFIX	5	No	Yes	Yes
NAVSTAR GPS:**				
Absolute Point Positioning (No SA)	15	No	No	Yes
Absolute Point Positioning (w/SA)	50 to 100	No	No	Yes
Differential Pseudo Ranging	2 to 5	Yes	Yes	Yes
Differential Kinematic (future)	0.1 to 1.0	Yes	Yes	Yes

* Electronic Positioning System
** Global Positioning System

(From EM 1110-2-1003)

(4) Bathymetric surveys are required for many studies of geology and geomorphology in coastal waters. Echo sounders are most often used to measure water depths offshore. Errors in acoustic depth determination are caused by several factors:

(a) Velocity of sound in water. The velocity in near-surface water is about 1,500 m/sec but varies with water density, which is a function of temperature, depth, and salinity. For high- precision surveys, the acoustic velocity should be measured onsite.

(b) Boat-specific corrections. As the survey progresses, the vessel's draft changes as fuel and water are used. Depth checks should be performed several times per day to calibrate the echo sounders.

(c) Survey vessel location with respect to known datums. An echo sounder on a boat simply measures the depth of the water as the boat moves over the seafloor. However, the boat is a platform that moves vertically depending on oceanographic conditions such as tides and surges. To obtain water depths that are referenced to a

Table 5-6
Summary of Acoustic Survey Systems

Acoustic System	Frequency (kHz)	Purpose
Sea floor and water column		
Echosounder	12 - 80	Measure water depth for bathymetric mapping
Water column bubble detector (tuned transducer)	3 - 12	Detect bubble clusters, fish, flora, debris in water column
Side-scan sonar	38 - 250	Map sea floor topography, texture, outcrops, man-made debris, structures
Sub-bottom profilers		
Tuned transducers	3.5 - 7.0	High resolution sub-bottom penetration
Electromechanical:		
Acoustipulse®	0.8 - 5.0	Bottom penetration to ~30 m
Uniboom®	0.4 - 14	15 - 30 cm resolution with 30 - 60 m penetration
Bubble Pulser	~ 0.4	Similar to Uniboom®
Sparker:		
Standard	50 - 5,000 Hz	Use in salt water (minimum 20 ‰), penetration to 1,000 m
Optically stacked	(same)	Improved horizontal resolution
Fast-firing 4 KJ & 10 KJ	(same)	Improved horizontal and vertical resolution
De-bubbled, de-reverberated	(same)	Superior resolution, gas-charged sediment detection
Multichannel digital	(same)	Computer processing to improve resolution, reduce noise

(From Sieck and Self (1977), EG&G®, Datasonics®, and other literature)

known datum, echo sounder data must be adjusted in one of two ways. First, tides can be measured at a nearby station and the echo sounder data adjusted accordingly. Second, the vertical position of the boat can be constantly surveyed with respect to a known land datum and these results added to the water depths. For a class 1 survey, either method of data correction requires meticulous atten tion to quality control.

(d) Waves. As the survey boat pitches up and down, the seafloor is recorded as a wavey surface. To obtain the true seafloor for the highest quality surveys, transducers and receivers are now installed on heave-compensating mounts. These allow the boat to move vertically while the instruments remain fixed. The most common means of removing the wave signal is by processing the data after the survey. Both methods are effective, although some contractors claim one method is superior to the other.

Even with the best efforts at equipment calibration and data processing, the maximum practicable achievable accuracy for nearshore depth surveys using echosounders is about ± 0.15 m (EM 1110-2-1003). The evaluation of these errors in volumetric calculations is discussed in Section 5-5. Survey lines are typically run parallel to one another, with spacing depending on the survey's purpose and the scale of the features to be examined.

(5) In geophysical surveys, the distance between the sound source and reflector is computed as velocity of sound in that medium (rock, sediment, or water) divided by one half of the two-way travel time. This measurement is converted to an equivalent depth and recorded digitally or on a strip chart.

(6) The principles of subbottom seismic profiling are fundamentally the same as those of acoustic depth sounding. Subbottom seismic devices employ a lower

frequency, higher power signal to penetrate the seafloor (Figure 5-11). Transmission of the waves through earth materials depends upon the earth material properties, such as density and composition. The signal is reflected from interfaces between sediment layers of different acoustical impedance (Sheriff 1980). Coarse sand and gravel, glacial till and highly organic sediments are often difficult to penetrate with conventional subbottom profilers, resulting in poor records with data gaps. Digital signal processing of multi-channel data can sometimes provide useful data despite poor signal penetration. Spacing and grid dimensions again depend upon the nature of the investigation and the desired resolution.

(7) Acoustic characteristics are usually related to lithology so that seismic reflection profiles can be considered roughly analogous to a geological cross section of the subbottom material. However, because of subtle changes in acoustic impedence, reflections can appear on the record where there are minor differences in the lithology of underlying and overlying material. Also, significant lithologic differences may go unrecorded due to similarity of acoustic impedance between bounding units, minimal thickness of the units, or masking by gas (Sheriff 1980). Because of this, seismic stratigraphy should always be considered tentative until supported by direct lithologic evidence from core samples. Signal processing procedures are being developed by the USACE to analyze waveform characteristics of outgoing and reflected pulses. With appropriate field checks, the seafloor sediment type and hardness can be modeled, reducing the need for extensive coring at a project site.

In shallow coastal areas, it is common practice to use jet probing to accompany subbottom seismic surveys. This is especially important when there is a thin veneer of sand over more resistant substrate.

(8) The two most important parameters of a subbottom seismic reflection system are its vertical resolution, or the ability to differentiate closely spaced reflectors, and penetration. As the dominant frequency of

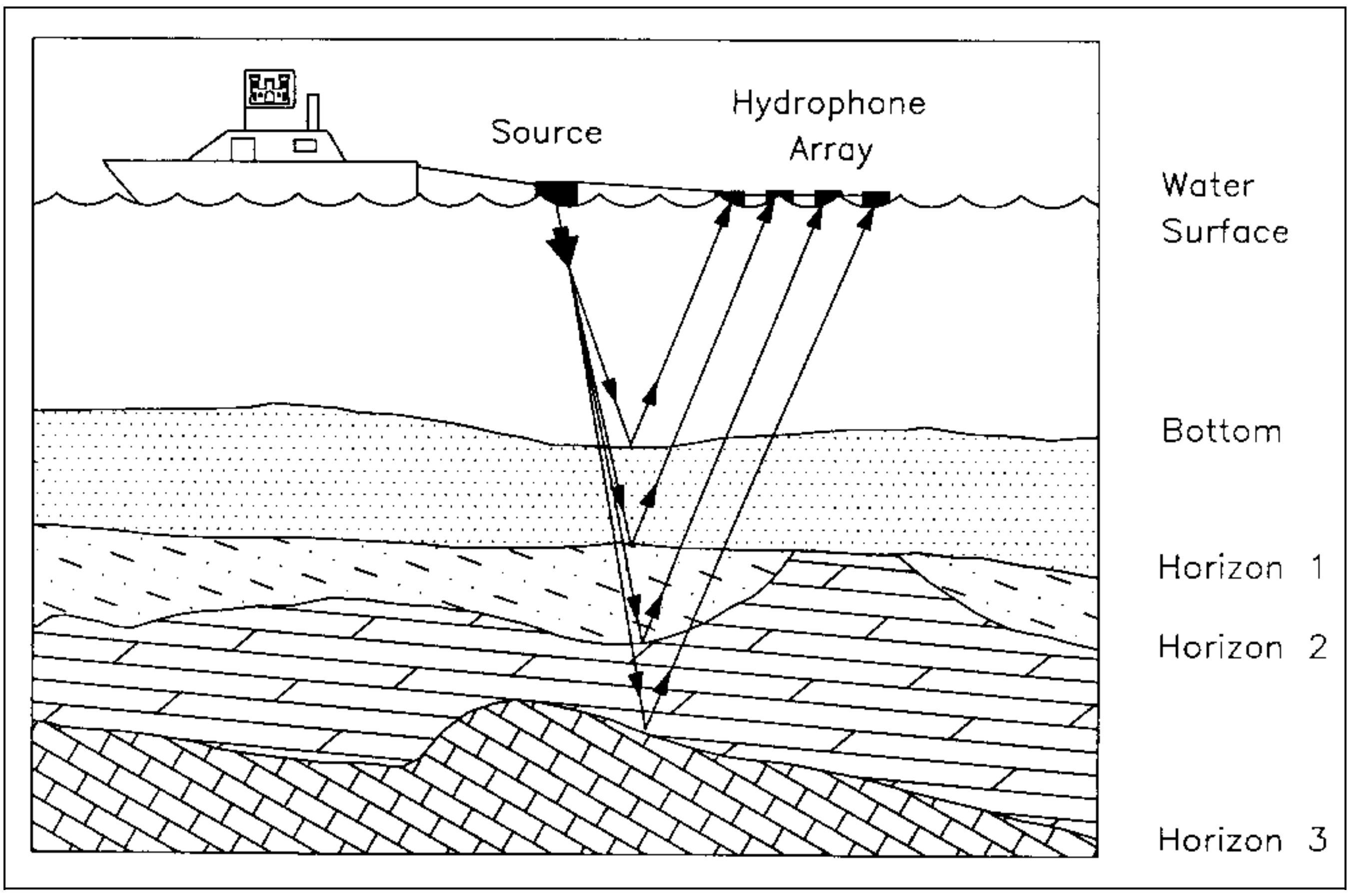


Figure 5-11. Principles of obtaining subbottom seismic data

the output signal increases, the resolution becomes finer. Unfortunately, raising the frequency of the acoustic pulses increases attenuation of the signal and consequently decreases the effective penetration. Thus, it is a common practice to use two seismic reflection systems simultaneously during a survey; one having high resolution capabilities and the other capable of greater penetration.

(9) Side-scan sonar is used to distinguish topography of the seafloor. Acoustic signals from a source towed below the water surface are directed at a low angle to either or both sides of a trackline, in contrast with the downward-directed Fathometer and seismic reflection signals (Figure 5-12). The resulting image of the bottom is similar to a continuous aerial photograph. Detailed information such as spacing and orientation of bed forms and broad differences of seafloor sediments, as well as features such as rock outcrops, boulders, bed forms, and man-made objects, can be distinguished on side-scan. It is generally recommended that bathymetry be run in conjunction with side-scan to aid in identifying objects with subtle vertical relief. The side-scan system is sensitive to vessel motion and is most suitable for use during calm conditions.

(10) Commonly available side-scan sonar equipment, at a frequency of 100 khz, is capable of surveying the seafloor to over 500 m to either side of the vessel trackline; thus, a total swath of 1 km or more can be covered at each pass. To provide higher resolution output at close range, some systems are capable of dual operation using both 500-khz and 100-khz frequency signals. The data are simultaneously recorded on separate channels of a four-channel recorder. Digital side-scan sonar systems are available that perform signal processing to correct for slant range to seafloor targets and correct for survey vessel speed. The resulting records show the true x-y location of seafloor objects, analagous to maps or aerial photographs. The digital data can be recorded on magnetic media, allowing additional signal processing or reproduction at a later date.

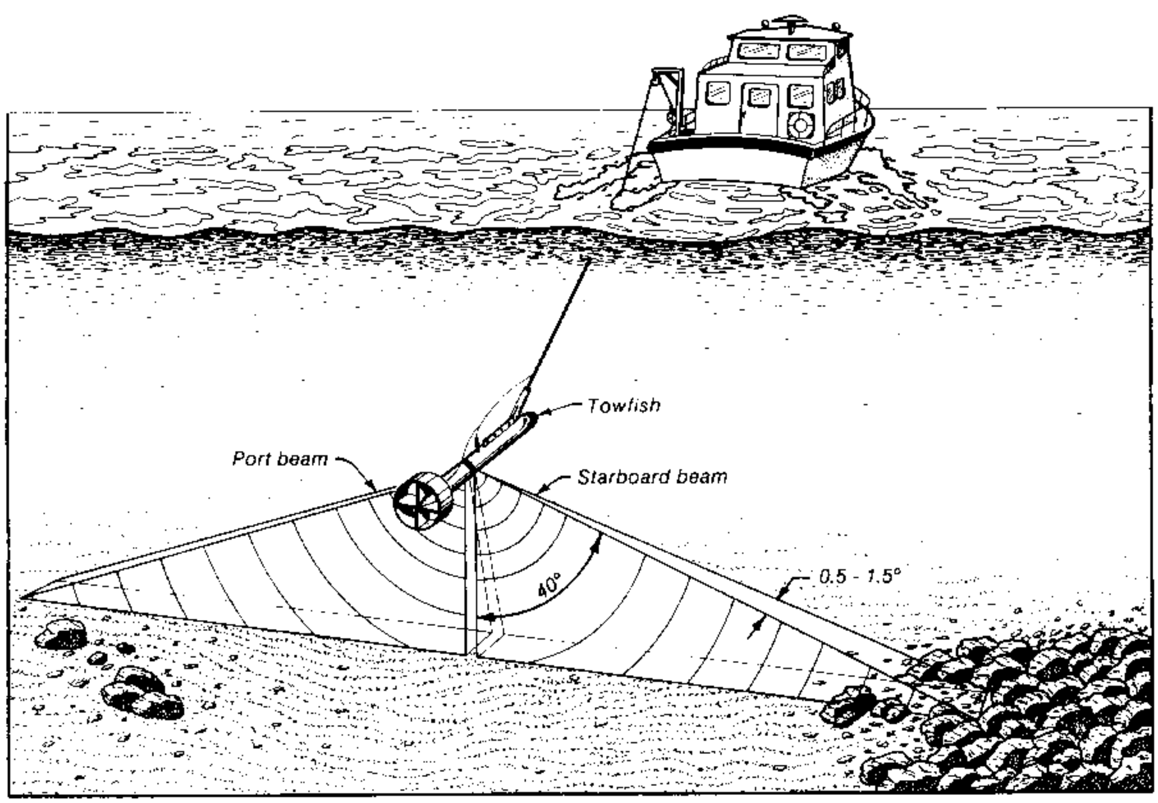


Figure 5-12. Side-scan sonar in operation

(11) The identification of potential sand borrow sites for beach renourishment has become an increasingly important economic and environmental issue in recent years. Reconnaissance surveys to identify potential sites are made using high-resolution seismic profilers, side-scan sonar, and echo sounders. Suggested survey procedures are discussed in Appendix I.

(12) Ground-penetrating radar (GPR) is a relatively new technique for subsurface exploration. In contrast to the acoustic systems described above, GPR is used subaerially. The radio portion of the electromagnetic spectrum is emitted from the source and reflected back to the sensors. The transparency of geologic materials varies. Sands and limestones are typically reasonably transparent. The use of GPR in marine environments is limited because salt water is non-transparent to electromagnetic radiation in the radio frequencies. Fitzgerald et al. (1992) used GPR as a tool to study beach ridge barriers in Buzzards Bay, Massachusetts. GPR has been very useful in the Great Lakes to detect buried channels and till outcrops.

l. Morphologic and bathymetric profiles.

(1) Periodic topographic and nearshore bathymetric surveys constitute the most direct and accurate means of assessing geologic and geomorphic changes over modern time scales. Time series data, such as repeated beach profiles, allow the assessment of erosion and accretion in the coastal zone. The preferred surveying technique involves collecting a series of shore-normal profile lines. These 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, as defined in Chapter 4).

(2) Permanent or semi-permanent benchmarks are required for reoccupying profile sites over successive months or years. On rapidly transgressing coasts, these benchmarks should be located at the landward end of the profile line 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 control points. The ability to accurately reestablish a survey monument is very important because it ensures that profile data collected over many years will be comparable (Hemsley 1981). Locations which might experience dune burial should be avoided, and care should also be taken to reduce the visibility of benchmarks to minimize damage by vandals.

(3) Both the frequency of the sampling and the overall duration of the project must be considered when planning a beach profiling study. 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. Often, it is financially or 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. Resurveying of control profile lines at selected time intervals can reveal seasonal patterns. In addition, special surveys can be made after significant 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 5-7 outlines a suggested survey schedule for monitoring beach fill projects. In summary, observation over a period of time is recommended in order to document the range of variability of morphology and bathymetry.

(4) Some issues concerning the spatial aspects of study include the spacing of profiles, longshore dimensions, and cross-shore dimensions. Profile lines should be spaced at close enough intervals to show any significant changes in lateral continuity. In a cross-shore direction, the uppermost and lowermost limits of the profiles should be located where change is unlikely to occur, and should adequately cover the most active zones such as the shore and upper shoreface. The preferred closure depth is at the toe of the shoreface, although a selected depth contour where variability becomes minimal is acceptable. Historical shorelines are an important component of where these uppermost and lowermost limits are located, particularly along rapidly changing coastlines. 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. Large-scale aerial photographs or maps of these interior areas are usually adequate for examining these more stable features. Appropriate longshore dimensions of the survey grid depend upon the nature of the problem. Profile lines should be connected with a shore-parallel survey to determine positions and elevations of each profile relative to one another.

Table 5-7
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 & offshore).
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.

(5) Onshore (beach) profiles.

(a) Onshore portions of profiles are surveyed using standard land survey techniques and equipment. Equipment commonly used in surveys includes transits, levels, or theodolites, which are used for siting survey rods. Detailed information concerning techniques and equipment can be found in textbooks (i.e. Brinker and Wolf (1984)).

(b) Surveys are preferably conducted during low tide, when the profile line can be extended as far seaward as possible. A typical cross-shore profile survey can consist of around 25 to 50 points over a total length of 600 to 1,000 m. Data point spacing is variable, with more points taken over areas with complex elevation change such as a berm scarp or the nearshore bar trough and crest. Measurements are usually made every 5 to 10 m along the subaerial profile, or at a shorter interval to define major morphologic features. Standard procedure places the survey instrument at the baseline and proceeds seaward.

(6) Extending profile lines offshore beyond wading depths requires boats or amphibious vehicles. Amphibious vehicles are better-suited to this task because they can traverse the sea-land boundary and maintain the continuity of profile lines. Acoustic echo sounders can be used for continuous profiling seaward of the breaker zone, but the signals are usually disrupted by breaking waves, and boats suitable for offshore use cannot approach the shore close enough to connect directly with a land profile. High-precision electronic navigation is recommended if the surveys extend offshore more than a few hundred meters.

(7) Sea sleds.

(a) During calm weather conditions, sea sleds have been successfully used to obtain shoreface profiles close to shore. A sea sled consists of a long, upright stadia rod mounted vertically on a base frame with sledlike runners (Clausner, Birkemeier, and Clark 1986) or a sled-mounted mast with a prism for use by total station survey system (Fredette et al. 1990). The sled is towed, winched, or otherwise propelled along the profile lines while frequent depth and position data are determined using onshore instruments. Because the sea sled does not float, elevations are not subject to wave or tide variations, thus providing a more accurate comparison between repeated surveys. At present, it is not possible to obtain bottom samples with a sea sled; these must be obtained from a boat or amphibious vehicle working in conjunction with the sled. Sleds are currently limited to use within 4 km of the coast and water depths of 12 m, less than the height of the sled masts. A limitation of sleds is that they normally must be used at sites with road access to the beach. It is very difficult to use them if the shore is revetted or armored. Also, sleds cannot be used if the offshore topography is rough (i.e., till or coral outcrops, glacial boulders).

(b) When conducting a sled survey, the tow boat is navigated based upon a continuous report of the sled's coordinates transmitted from the shore station. The sled should be kept to within 2 to 3 m of the shore-normal profile line 95 percent of the time. Measurements of the sled position are usually read at approximately 10-m intervals along the profile line close to shore to resolve bar/trough features, and increased to 15- to 20-m intervals further offshore (Birkemeier et al. 1985, Stauble et al. 1993). The positioning measurements are automatically recorded by a data logger and copied to a computer for processing or editing at the end of each survey day.

(8) A helicopter bathymetric surveying system has been in use at USAE District, Portland, since the 1960's. The big advantage of this procedure is that land-accuracy surveys can be conducted offshore in high waves and near structures, conditions under which a boat could not perform (Pollock 1995). A helicopter is fitted with a weighted, calibrated cable and prisms. A total station survey system is set up onshore to measure the location of the cable. Soundings are commonly taken at 8-m intervals along profile lines up to 2,500 m offshore. Operations are limited by poor visibility or winds over 15-20 m/sec (30-40 knots).

(9) The Coastal Research Amphibious Buggy (CRAB), a self-propelled vehicle, was developed to make continuous onshore-offshore profiles and obtain bottom samples. The CRAB is a tripod mounted on wheels and is propelled by hydraulic motors. It can move under its own power across the beach and shoreface to a depth of about 8 m. It has been widely used at the CERC Field Research Facility at Duck, North Carolina. Both the CRAB and sea sled are important tools for characterizing submarine bars and the overall morphology of offshore profiles (Stauble 1992).

m. Prototype monitoring.

Prototype testing and monitoring involve bringing together multiple means of investigating and measuring the processes and responses of a coastal site. Prototype studies often involve physical experiments, conducted under ideal or well-monitored conditions in the field. The purpose of many prototype studies is to test and evaluate theoretical formulae or conceptual asssumptions. Prototype studies, in other instances, are conducted to assess the status and variations of environmental conditions at a site and to develop information for guidance in construction of structures.

5-4. Laboratory Techniques and Approaches

a. Laboratory observation and experiment. The characteristics of samples obtained in the field can be further analyzed in the laboratory. Some properties that are commonly examined include: (1) sediment properties, such as grain size, shape, and density, mineralogy, and heavy mineral type and content; (2) stratigraphic properties, which can be characterized using core description, preservation, and analysis techniques; and (3) geochronological history, obtained from radiometric dating and a variety of relative dating approaches. In order to achieve maximum benefit from laboratory analyses, the coastal scientist must be cognizant of the limitations and variance of precision and accuracy of each test and procedure.

(1) Laboratory analysis of sediment.

(a) Sediments can be classifed into size range classes. Ranked from largest to smallest, these include boulders, cobbles, gravel, sand, silt, and clay (Table 5-8). Particle size is often expressed as D, or the diameter in millimeters, and sometimes includes a subscript, such as D_{84}, to indicate the diameter corresponding to the listed percentile. As an alternative, grain size is often expressed in phi (ϕ) units, where $\phi = -\log_2 D$ (Hobson 1979). This procedure normalizes the grain size distribution and allows computation of other size statistics based on the normal distribution.

(b) Grain-size analysis involves a series of procedures to determine the distribution of sediment sizes in a given sample. An important aspect of the laboratory analysis program, which must be designed into the field sampling scheme, is to obtain sufficient sediment to adequately determine the sediment population characteristics (Table 5-9). Large samples should be divided using a sample splitter to prevent clogging of sieves. Particle aggregates, especially those in the silt-clay range which show cohesive properties, should be separated and dispersed by gentle grinding and use of a chemical dispersant (sodium hexametaphospate) before analysis. Note that depending on the purpose of the study, it may be important to preserve the hydraulic characteristics of sediment aggregates (i.e., clay balls, cemented sand, or shell fragments). In these circumstances, it is best to not split or mechanically grind the samples.

Table 5-8
Sediment Particle Sizes

ASTM (Unified) Classification[1]	U.S. Std. Sieve[2]	Phi Size in mm	PHI Size	Wentworth Classification[3]
Boulder		4096.	-12.0	
		1024.	-10.0	Boulder
	12 in (300 mm)	256.	-8.0	
		128.	-7.0	Large Cobble
Cobble		107.64	-6.75	
		90.51	-6.5	Small Cobble
	3 in (75mm)	76.11	-6.25	
		64.00	-6.0	
		53.82	-5.75	
		45.26	-5.5	Very Large Pebble
Coarse Gravel		38.05	-5.25	
		32.00	-5.0	
		26.91	-4.75	
		22.63	-4.5	Large Pebble
	3/4 in (19 mm)	19.03	-4.25	
		16.00	-4.0	
		13.45	-3.75	
		11.31	-3.5	Medium Pebble
Fine Gravel		9.51	-3.25	
	2.5	8.00	-3.0	
	3	6.73	-2.75	
	3.5	5.66	-2.5	Small Pebble
	4 (4.75 mm)	4.76	-2.25	
	5	4.00	-2.0	
Coarse Sand	6	3.36	-1.75	
	7	2.83	-1.5	Granule
	8	2.38	-1.25	
	10 (2.0 mm)	2.00	-1.0	
	12	1.68	-0.75	
	14	1.41	-0.5	Very Coarse Sand
	16	1.19	-0.25	
Medium Sand	18	1.00	0.0	
	20	0.84	0.25	
	25	0.71	0.5	Coarse Sand
	30	0.59	0.75	
	35	0.50	1.0	
	40 (0.425 mm)	0.420	1.25	
	45	0.354	1.5	Medium Sand
	50	0.297	1.75	
	60	0.250	2.0	
	70	0.210	2.25	
Fine Sand	80	0.177	2.5	Fine Sand
	100	0.149	2.75	
	120	0.125	3.0	
	140	0.105	3.25	
	170	0.088	3.5	Very Fine Sand
	200 (0.075 mm)	0.074	3.75	
	230	0.0625	4.0	
Fine-grained Soil:	270	0.0526	4.25	
	325	0.0442	4.5	Coarse Silt
Clay if PI ≥ 4 and plot of PI vs.	400	0.0372	4.75	
LL is on or above "A" line*		0.0312	5.0	
Silt if PI < 4 and plot of PI vs.		0.0156	6.0	Medium Silt
LL is below "A" line*		0.0078	7.0	Fine Silt
		0.0039	8.0	Very Fine Silt
		0.00195	9.0	Coarse Clay
*and the presence of organic		0.00098	10.0	Medium Clay
matter does not influence LL.		0.00049	11.0	Fine Clay
		0.00024	12.0	
		0.00012	13.0	
		0.000061	14.0	

1. ASTM Standard D 2487-92. This is the ASTM version of the Unified Soil Classification System. Both systems are similar (from ASTM (1993)).
2. Note that British Standard, French, and German DIN mesh sizes and classifications are different.
3. Wentworth sizes (in inches) cited in Krumbein and Sloss (1963).

Table 5-9
Minimum Weight of Sample Required for Sieving

Maximum Particle Size Present in Substantial Proportion (> 10%)		Weight of Sample
in.	mm	kg
2.5	64	50
2.0	50	35
1.5	40	15
1.0	25	5
0.75	20	2
0.50	12.5	1
0.38	10	0.5
0.25	6.3	0.2
	2.4	0.1

British Standards Institution (1975). Note: quantities specified in ASTM Standard D2487-92 are similar.

(c) Laboratory techniques used to estimate sediment diameter depend in part on the grain size. Pebbles and coarser sediments can be directly measured with calipers or by coarse sieves. The grain-size distribution of sand is determined directly by sieve analysis, sedimentation tubes, or Coulter counter. Silt and clay-sized material is determined indirectly by hydrometer or pipette analysis, or the use of a Coulter counter. The size distribution of mixed sediments is determined by using a combination of sieve and hydrometer or pipette analyses. Practical procedures for conducting laboratory grain size and mineralogical tests on sediment samples are covered by Folk (1980) and Lewis (1984). Laboratory manuals more oriented towards engineering applications include EM 1110-2-1906 and those produced by the American Society for Testing and Materials (1964) and Bowles (1986).

(d) Coastal sediments reflect the relative importance of various source areas, and transport processes. Some sources of coastal sediments include river basins that empty into the coastal zone, nearshore cliffs and uplands that are denuded by waves, wind, transported material mass wasting and slope wash, and sediments transported by longshore currents. Because gravel and larger particles require more energy to be transported, they are typically found close to their source. In contrast, silt and clay may be transported long distances. The size fraction distribution is determined by the composition of the source rocks and weathering conditions. The mineralogy of sediments, especially clays, shows that variations are controlled by source rocks and weathering conditions. Resistant minerals, such as quartz and feldspars, comprise most coastal deposits (Table 3-2). However, as tracers, the least common minerals are generally the best indicators of source.

(e) Heavy minerals can provide information regarding source and process and other aspects of geomorphic variability in the coastal zone (Brenninkmeyer 1978; Judge 1970; McMaster 1960; Neiheisel 1962). Pronounced seasonal variations in heavy minerals may occur in beach and nearshore samples. Lag deposits of heavy minerals are often seen on the beach after storms.

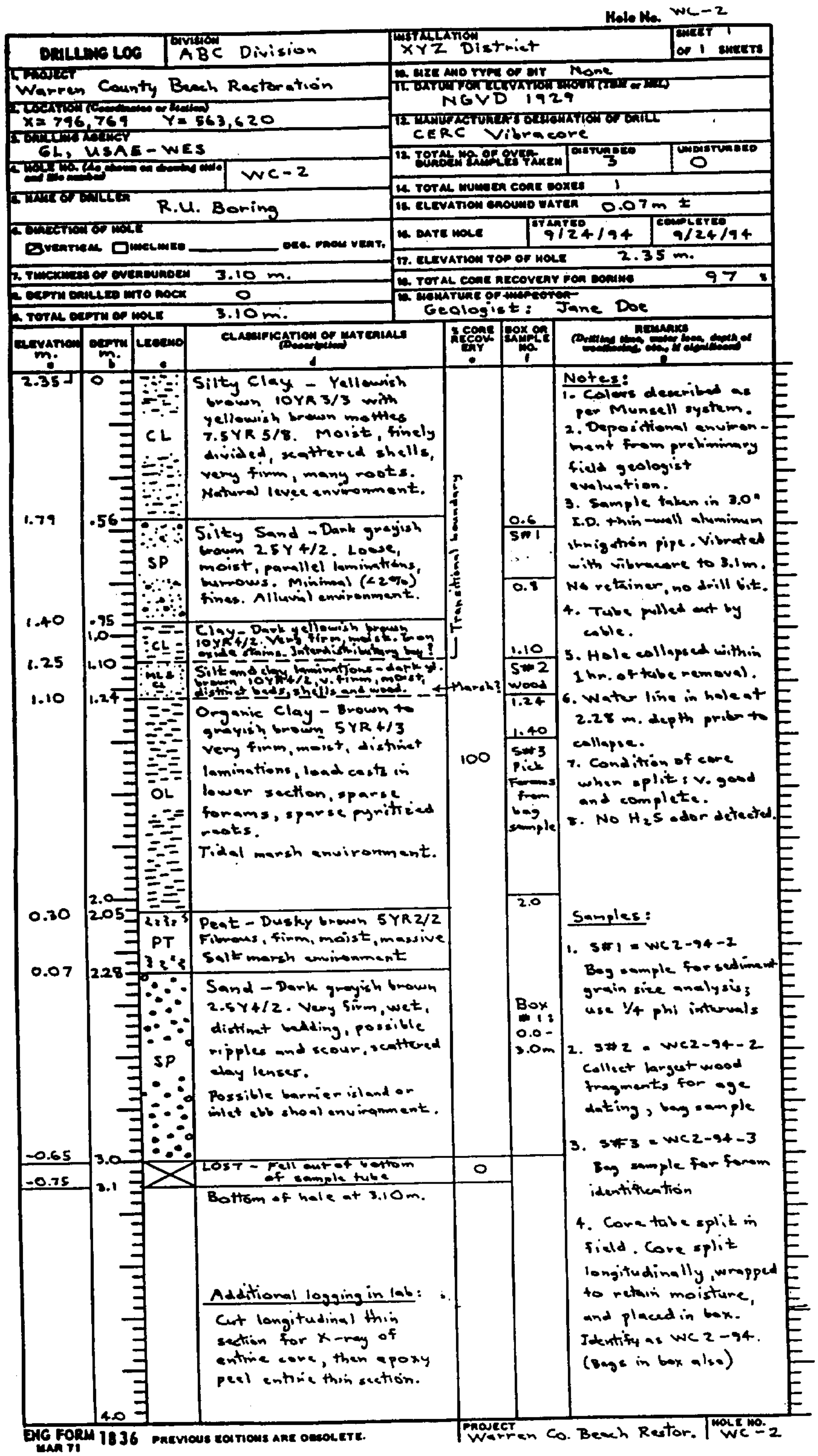
(f) Analysis of size and texture can also be used to distinguish among sediments that may have come from the same original source area. As an example, Mason and Folk (1958) used size analysis to differentiate dune and beach sediments on Mustang Island, Texas.

(g) A variety of techniques are used to identify the mineralogy of coastal sediments. Mineralogy of coarse sediments and rocks is typically assessed using laboratory microscopes. Clay mineralogy is usually assessed with X-ray diffraction methods or electron microscopy. Heavy minerals are separated from light minerals using bromoform (specific gravity of 2.87) after washing and sieving. In unconsolidated sediments, heavy mineral samples are examined under a microscope to determine approximations or percentages of mineral types.

(2) Core description and analysis.

(a) Core description is widely used to characterize the features and depositional environments of sediments. After being collected in the field, core barrels are sealed to retain moisture. In the laboratory, they are cut in half lengthwise. One side of the core is used for description and the other for radiography, peels, and subsampling for grain size analysis, palynology, and organic materials. Cores are often photographed soon after splitting, while the exposed surfaces are still fresh.

(b) A hypothetical USACE core drilling log is shown in Figure 5-13 completed in the level of detail necessary for coastal geologic studies. An alternate sheet used at some universities is shown in Figure 5-14. Important characteristics of the sedimentary sequence that need to be described include grain size variations, sedimentary structures and directions, and occurrences of cyclic bedding, such as varves. Evidence of plant roots and features such as color changes, mottling, discontinuities, and other variations in physical characteristics may be indicators of key changes. Roots, for example, often correspond to marshes in coastal sequences. Fossils and pollen in stratigraphic sequences are indicative of paleoenvironmental characteristics and changes. Techniques for



Hole No. WC-2

DRILLING LOG	DIVISION: ABC Division	INSTALLATION: XYZ District	SHEET 1 OF 1 SHEETS

1. PROJECT: Warren County Beach Restoration
2. LOCATION (Coordinates or Station): X= 796,769 Y= 563,620
3. DRILLING AGENCY: GL, USAE-WES
4. HOLE NO. (As shown on drawing title and file number): WC-2
5. NAME OF DRILLER: R.U. Boring
6. DIRECTION OF HOLE: [x] VERTICAL [ ] INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN: 3.10 m.
8. DEPTH DRILLED INTO ROCK: 0
9. TOTAL DEPTH OF HOLE: 3.10 m.
10. SIZE AND TYPE OF BIT: None
11. DATUM FOR ELEVATION SHOWN (TBM or MSL): NGVD 1929
12. MANUFACTURER'S DESIGNATION OF DRILL: CERC Vibracore
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 3; UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES: 1
15. ELEVATION GROUND WATER: 0.07 m ±
16. DATE HOLE: STARTED 9/24/94; COMPLETED 9/24/94
17. ELEVATION TOP OF HOLE: 2.35 m.
18. TOTAL CORE RECOVERY FOR BORING: 97 %
19. SIGNATURE OF ~~INSPECTOR~~: Geologist: Jane Doe

ELEVATION m. (a)	DEPTH m. (b)	LEGEND (c)	CLASSIFICATION OF MATERIALS (Description) (d)	% CORE RECOVERY (e)	BOX OR SAMPLE NO. (f)
2.35	0	CL	Silty Clay – Yellowish brown 10YR 3/3 with yellowish brown mottles 7.5YR 5/8. Moist, finely divided, scattered shells, very firm, many roots. Natural levee environment.		
1.79	.56	SP	Silty Sand – Dark grayish brown 2.5Y 4/2. Loose, moist, parallel laminations, burrows. Minimal (<2%) fines. Alluvial environment.		0.6; S#1; 0.8
1.40	.95	CL	Clay – Dark yellowish brown 10YR 4/2. Very firm, moist. Iron oxide stains. Interdistributary bay?		1.10
1.25	1.10	ML & CL	Silt and clay laminations – dark yl. brown 10YR 4/2, v. firm, moist, distinct beds, shells and wood.		S#2 wood
1.10	1.24	OL	Organic Clay – Brown to grayish brown 5YR 4/3 very firm, moist, distinct laminations, load casts in lower section, sparse forams, sparse pyritized roots. Tidal marsh environment.	100	1.24; 1.40; S#3 Pick Forams from bag sample; 2.0
0.30	2.05	PT	Peat – Dusky brown 5YR 2/2 Fibrous, firm, moist, massive Salt marsh environment		
0.07	2.28	SP	Sand – Dark grayish brown 2.5Y 4/2. Very firm, wet, distinct bedding, possible ripples and scour, scattered clay lenses. Possible barrier island or inlet ebb shoal environment.		Box #1: 0.0 - 3.0m
-0.65	3.0		LOST – Fell out of bottom of sample tube	0	
-0.75	3.1		Bottom of hole at 3.10 m.		
	4.0		Additional logging in lab: Cut longitudinal thin section for X-ray of entire core, then epoxy peel entire thin section.		

Transitional boundary (1.79–1.25); ← Marsh?

REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) (g)

Notes:
1. Colors described as per Munsell system.
2. Depositional environment from preliminary field geologist evaluation.
3. Sample taken in 3.0" I.D. thin-wall aluminum irrigation pipe. Vibrated with vibracore to 3.1 m. No retainer, no drill bit.
4. Tube pulled out by cable.
5. Hole collapsed within 1 hr. of tube removal.
6. Water line in hole at 2.28 m. depth prior to collapse.
7. Condition of core when split: v. good and complete.
8. No H_2S odor detected.

Samples:
1. S#1 = WC2-94-1 Bag sample for sediment grain size analysis; use 1/4 phi intervals
2. S#2 = WC2-94-2 Collect largest wood fragments for age dating, bag sample
3. S#3 = WC2-94-3 Bag sample for foram identification
4. Core tube split in field. Core split longitudinally, wrapped to retain moisture, and placed in box. Identify as WC 2-94. (Bags in box also)

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT: Warren Co. Beach Restor. HOLE NO.: WC-2

Figure 5-13. Example of hypothetical USACE drilling log. Descriptions and notations by field geologist should be sufficiently complete to allow an interpretation of depositional environment and other factors indicating paleoenvironmental characteristics

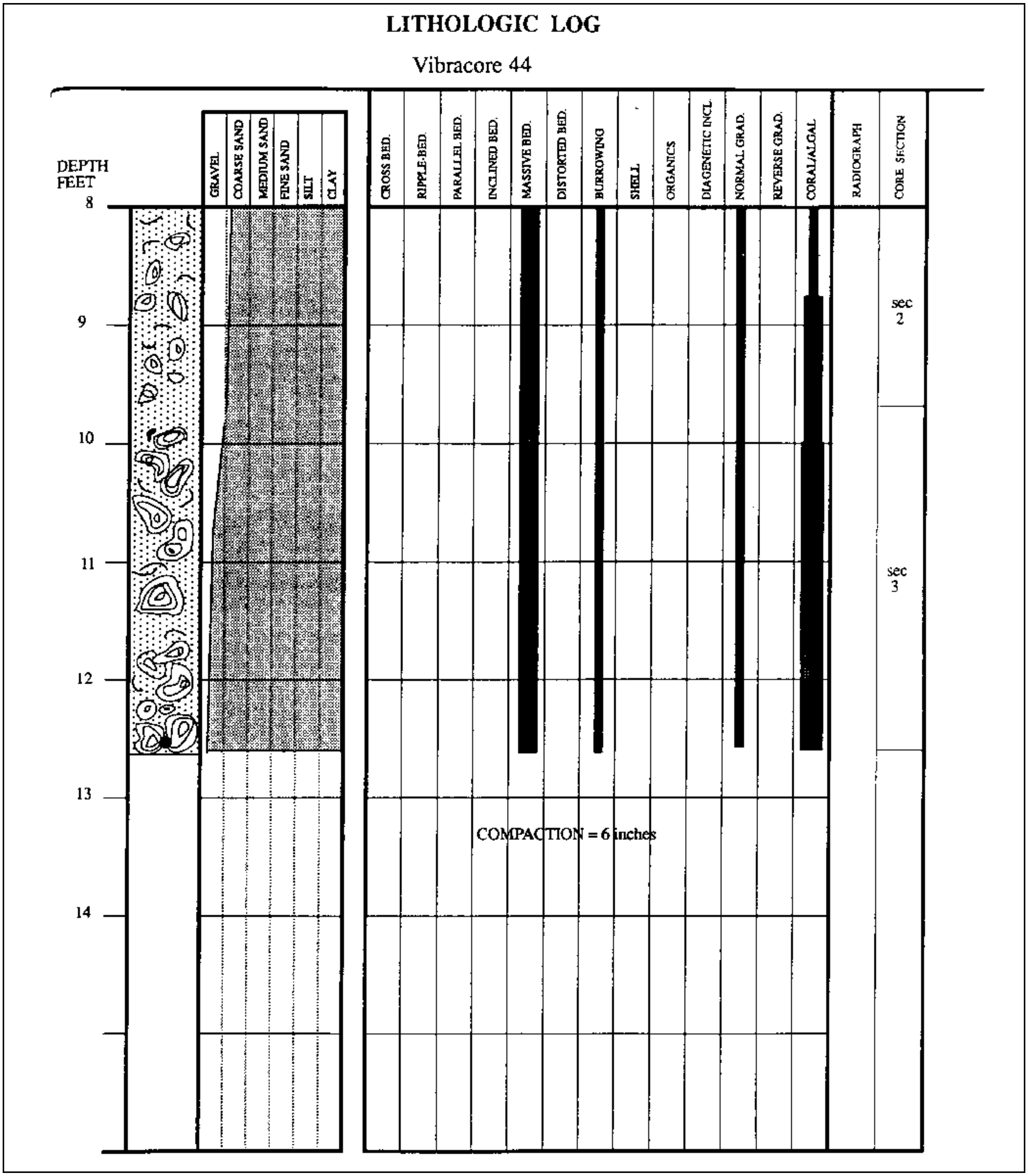


Figure 5-14. Example core description form used for sedimentary environments (courtesy of Dr. Harry Roberts, Louisiana State University)

analysis and interpretation of such evidence can be found in Faegri and Iverson (1975) and Kapp (1969).

(c) Grain size variation in cores can yield much information about the sedimentary environments and thus the geologic history of the region. Coarser fractions settle first, followed by silts and clays. This separation is a function of particle settling velocities, which vary depending upon particle size, density, shape, and the nature of the transport media. Changes in the environment of deposition can result in the clay fraction being separated from granular material both spatially and temporally. For example, silt and clay are usually deposited further from shore than granular material.

(d) X-ray radiography is an imaging method that amplifies contrasts in grain size, mineralogical composition, packing density, water content, diagenetic products, sedimentary structures and geochemical inclusions in cores that otherwise appear homogeneous (Roberts 1981). Being able to distinguish these features may assist in understanding the sequence of geomorphic changes that occurred at that site. For example, the scale and direction of bed forms can be used to estimate paleocurrents. Marker horizons are related to a date or a significant event. Peat indicates stability and growth at or near sea level. Radiography is based on the differential transmission of X-ray radiation through a sample onto sensitized X-ray photographic film. Variations in texture as well as chemical composition throughout the sediment result in differential attenuation of the incident X-ray radiation before it reaches the underlying film. Samples of uniform thickness (about 1 cm) that are cut lengthwise with a wire knife provide the best results in radiography (Roberts 1981).

(e) The occurrence of paleosols in cores may also provide important information toward assessing the geologic history of coasts. In terrestrial coastal environments, there may be prolonged periods of minimal sedimentation during which soil development may occur, followed by periods of relatively rapid sedimentation without soil development.[1] This scenario is characteristic of recent sea level changes during the Quaternary. As alternative scenarios, such cycles could occur in a semi-protected salt marsh subject to sedimentation during a severe storm or in a soil which subsided as a result of rapid burial by other sediments. As with modern soils, horizon color and horizon assemblages based on color permit an initial identification. Important paleosols, which may reflect only limited pedogenesis, are represented only by thin, dark, organic horizons. Less apparent chemical and physical changes in sediments which were exposed to atmospheric and meteorological processes may also occur. Soils that are uniform over a wide area can sometimes be used as approximate marker horizons and thus are valuable for relative dating purposes. In some circumstances, soils may also contain enough organic material to be suitable for radiocarbon dating.

(3) Geochronology. Geochronology is the study of time in relationship to the history of the earth. Geochronology encompasses a variety of radiometric and non-radiometric techniques, which collectively can date materials whose ages extend from near-present through the Pleistocene and earlier. Radiometric techniques vary in precision, in time range, in the types of materials that can be analyzed, and the type of information that results are capable of providing. Non-radiometric techniques that may be useful in coastal areas include archives, archeology, dendrochronology, thermoluminescence dating, magnetostratigraphy or paleomagnetic dating, paleoecology, the use of weathering and coating indices. Use of multiple techniques typically provides the best results for assessing the geologic history of coasts.

(4) Radiometric dating and isotopes.

(a) Radiometric dating techniques have been used since the 1950's. Many natural elements are a mixture of several isotopes, which have the same chemical properties and atomic numbers but different numbers of neutrons and hence atomic masses. Radiometric methods of dating are based on radioactive decay of unstable isotopes. The duration of time leading to the state where half the original concentration remains is known as the half-life. In general, the useful dating range of individual isotopic methods is about ten times their half-life. The radiometric isotopes Carbon-14, Potassium-Argon 40, Caesium-137, Lead-210, and Thorium-230 are the most commonly used in standard geologic investigations (Faure 1977; Friedlander, Kennedy, and Miller 1955).

(b) Radiocarbon (Carbon-14 or ^{14}C) dating is perhaps the most widely used technique for assessing the age of Holocene and late Pleistocene organic materials. Once an organism or plant dies, its radiocarbon (^{14}C) content is no longer replenished and begins to decrease exponentially, achieving a half-life after some 5,730 years.

[1] The term "soil" in this context refers to unconsolidated surficial sediment which supports plant life. This is a more restrictive definition than the one typically used in engineering texts, which refers to soil as any unconsolidated material, even if barren of plant life.

Substances that are often examined with ^{14}C dating include wood, charcoal, peat, shells, bones, aqueous carbonates, rope, and soil organics. Recent developments using mass spectrometers allow detection of absolute amounts of ^{14}C content in samples as small as 5 mg. To be comparable, radiocarbon dates are adjusted to a zero age at AD 1950. Analytical error factors are given as one or two standard deviations about the mean. Other errors, associated with sample contamination, changes in atmospheric or oceanic ^{14}C content, and fractionation, are more difficult to estimate. Absolute dates of samples less than 150 years old or greater than 50,000 years old are currently considered to be ambiguous.

(c) Potassium:argon dating (Potassium-Argon-40 or K:Ar) can be applied to a wide range of intrusive and extrusive igneous rocks that contain suitable minerals. In addition to constraints on rock type, it is necessary for the sample to be unaltered by weathering or other geological processes that may allow diffusion of radiogenic argon from the sample. The occurrence of such rocks along coasts is generally restricted to regions adjacent to plate boundaries and regions of active tectonics. Potassium-argon dating of Holocene deposits is generally imprecise, with errors of ± 15 to 30 percent. Only certain minerals, particularly those with a high K and low atmospheric Ar content, are suitable for extending the K:Ar dates into the late Pleistocene. For these reasons, it has limited applications in studies of the geologic history of coasts.

(d) Fission-track dating was developed as a complementary technique to potassium:argon (K:Ar) dating. Most applications to Quaternary deposits have involved dating airfall volcanic ash or glass deposits, a field known as tephrochronology. This material usually has wide distribution and geologically speaking has infinitely narrow depositional time duration. However, it is often absent or quickly removed in many coastal settings. If present, the rapid deposition and large aerial extent of ash make it an excellent tool for correlation of rock strata, which can provide radiometric age dates. A listing of some of the important volcanic ash layers in North America, which include very recent to Pleistocene dates, can be found in Sarna-Wojcicki, Champion, and Davis (1983).

(e) Cesium-137 (^{137}Cs) is an artificial isotope, primarily produced during the atmospheric testing of nuclear weapons. These tests began in the 1940's, peaked in the early 1960's, and have declined since the advent of nuclear test ban treaties (Wise 1980). ^{137}Cs is strongly absorbed onto sediment or soil and has been used in studies of soil erosion and sediment accumulation in wetlands, lakes, and floodplains. The timing of very recent events (post-1954) and human impacts on coastal ecosystems can be improved using such techniques.

(f) Lead-210 (^{210}Pb) is an unstable, naturally occurring isotope with a half-life of just over 22 years and a dating range of 100 to 200 years (Oldfield and Appleby 1984, Wise 1980). It forms as part of a decay chain from Radium-226, which escapes into the atmosphere as the inert gas Radon-222. The excess or unsupported ^{210}Pb returns to the earth as rainfall or dry fallout, and can be separated from that produced by in situ decay. Applications in coastal environments are limited but show good potential. This technique would be of greatest value in low-energy environments and would allow documentation of the timing of recent events and human impacts on coastal ecosystems.

(g) Thorium-230/Uranium-234 ($^{230}Th/^{234}U$), a useful dating technique that complements other methods, is applicable for dating coral sediments. The technique involves comparing the relative amounts of the radioactive isotope of thorium, ^{230}Th, with that of uranium, ^{234}U. Thorium-230 increases in coral carbonate from zero at the death of the organism to an equilibrium with Uranium-234 at 0.5 million years, allowing samples as old as middle Pleistocene to be dated.

(5) Non-radiometric methods of dating and relative dating.

(a) Archival and archeological documentation can assist in understanding the geologic history of coasts. Historical and social documents may contain detailed descriptions of major storms, of ice movements, of shoreline changes, and of other catastrophic events. Historical records are most useful if they correspond to a particular date or specified range of time, as do newspaper reports. Archeological evidence can provide important clues for assessing Holocene environmental changes. Pottery, stone tools, coins, and other artifacts can be assigned ages and thus may be of assistance in dating surface and subsurface deposits. If discovered in a stratigraphic sequence, cultural artifacts provide a minimum age for deposits beneath and maximum age for deposits above. Archeological evidence, such as buried middens, inland ports, or submerged buildings, may also indicate shoreline changes and sometimes can be used to estimate rates of deposition in coastal areas. For example, the Holocene Mississippi River deltaic chronology was revised using artifacts as indicators of the age of the deltaic surfaces (McIntire 1958).

(b) Thermoluminescence (TL), a technique that is commonly practiced in archeology for dating pottery, has been extended for use in geological studies. It has been used for dating a variety of Pleistocene sediments, including loess. For geological purposes, TL needs further refinement because most results to date are considered in error, generally being too young. It does, however, generally provide a good estimate of stratigraphic order. Thermoluminescence dating has the best potential where clay-fired artifacts are present and has promise for dating a variety of deposits of Quaternary age.

(c) Magnetostratigraphy or paleomagnetic dating is a geochronologic technique that is used in conjunction with correlations of regional radiometric dates and paleomagnetic characteristics. Because the earth's magnetic field changes constantly, the magnetic characteristics of rock and sediments can be used to determine an age for materials. The most dramatic changes are reversals, in which the earth's polarity switches from the north to the south pole. The reversals are relatively infrequent occurrences, with the most recent one occurring 700,000 years ago. Less dramatic secular variations of the geomagnetic field, however, can also be important in helping to provide a time scale useful for dating over hundreds or thousands of years by linking magnetic properties with time scales established by radiometric techniques. The combination of declination (the angle between true and magnetic north), inclination (the dip of the earth's magnetic field), and magnetic intensity produces a characteristic paleomagnetic signature for a particular location and time. The magnetic alignments can be incorporated and preserved in baked materials, in sediment particles which settle out in standing water, and in cooled magma. The technique is most-suited to lake sediments containing homogeneous particle sizes and organics. This technique can be used in places where the magnetostratigraphy has been linked with radiometric dates and can be extended to over 200 million years before present.

(d) Dendrochronology or tree ring dating can provide precise data regarding minimum age of a geomorphic surface. It can also provide proxy data concerning environmental stresses, including climatic conditions such as cold temperatures and droughts. In some parts of the world, overlapping sets of rings on trees have been used to construct a comprehensive environmental history of the region.

(e) Lichenometry is the study of the establishment and development of lichen to determine a relative chronology (Worsley 1981). Although used most extensively for studies of glacier fluctuations, this technique also has application in shoreline dating. The method involves the measurement of thallus size, with increasing diameter representing increasing age. It is valid from about ten years to a few centuries before present. This measurement is often conducted in the field with a ruler or with calipers. Field techniques differ, although normally the largest diameters are measured. Although there has been a lack of critical assessment of the technique, the majority of research shows that the technique gives reasonable dates when applied to a variety of environments.

(f) Paleoecology is the study of fossil organisms in order to reconstruct past environments. Pollen analysis, or palynology, is the single most important branch of paleoecology for the late Pleistocene and Holocene. Uses of paleoecological tools include: (a) the establishment of relative chronologies and indirect dating by means of correlation with other dated sequences; (b) characterization of depositional environments at or near the sampling site, since certain species and combinations of species are adapted to certain conditions; (c) reconstruction of the paleoenvironmental and paleoclimatic conditions; (d) establishment of human-induced transformations of the vegetation and land use regime (Oldfield 1981).

(g) The use of weathering and coating indices for relative age dating in geomorphology is rapidly increasing. Using laboratory microscopes, samples are calibrated with those of known age and similar chemistry for each geographic area. One such method, obsidian hydration dating, is based on the reaction of the surface of obsidian with water from the air or soil, which produces a rind whose thickness increases with time (Pierce, Obradovich, and Friedman 1976). Rock varnish-cation ratio dating is used primarily in deserts, where rocks develop a coating (Dorn 1983). Emery (1941) used dated graffiti to determine the rates of erosion and weathering in sandstone cliffs.

(h) Varve chronology may be useful in quiescent or low-energy basins where thin laminae of clay and silt are deposited. In glaciated coastal areas, the thin layers or varves are usually annual deposits. The sequences of successive graded layers can be discerned visually. Color variations occur because usually the winter season deposits have a higher organic material content. The result is alternating light-colored, gray-brown sediment layers and dark-colored organic layers.[1] Varve chronology rarely extends beyond about 7,000 years.

[1] In freshwater lakes, varves are caused by clay-silt deposition cycles. The silt settles out in spring and summer, and the clay in fall and winter.

(i) A major limitation of varve chronology is the fact that in the marine environment, annual varves are usually only preserved in anoxic basins, where a lack of oxygen causes a dearth of bottom-dwelling animals. Otherwise, mollusks, worms, fish, and crustaceans thoroughly rework the seafloor. This reworking, known as bioturbation, thoroughly destroys near-surface microstructure in most of the shallow-water portions of the world's oceans. Examples of anoxic basins include portions of the Black Sea (Anderson, Lyons, and Cowie 1994) and Saanich Inlet in British Columbia. The latter receives an annual input of clays from the Fraser River. Yearly variations in the discharge of the Fraser River's spring freshet cause changes in varve thicknesses.

b. Physical models.

(1) The use of physical models can be invaluable in understanding how geomorphic variability occurs in coastal areas. Physical modelling provides an opportunity for reducing the complexity of natural systems, for scaling down dimensions, and for accelerating change over time so that detailed interactions can be identified. Physical models can be applied in studies of hydrodynamics, sediments, and structures. In studies of coastal processes and responses, the wave tank is both the simplest and the most utilized physical model.

(2) Physical models are typically either two- or three-dimensional. A wave tank is considered to be a two-dimensional model because changes over length and over depth can be examined. Where variations over width are also investigated, the model is considered to be three-dimensional. A three-dimensional model or basin may have a variety of types of bottoms, including beds that are fixed, fixed with tracers, or moveable. Physical models require precise scaling and calibration, and much design and construction expertise must be devoted to their initial construction. Once set up, however, they allow for direct measurement of process elements, repeated experiments over a variety of conditions, and the study and isolation of variables that are difficult to assess in the field.

(3) Some examples of physical model experiments (conducted principally in wave tanks) that helped elucidate geomorphologic variability of coasts include studies of littoral drift blockage by jetties (Seabergh and McCoy 1982), breaker type classification (Galvin 1968), experiments of cliff erosion (Sunamura 1983), relationships of storm surge or short-term water level changes to beach and dune erosion, and studies of suspended sediment concentration under waves (Hughes 1988).

(4) Large-scale physical models of harbors, rivers, and estuaries have been built and tested at the Waterways Experiment Station in order to examine the effects of jetties, weirs, channel relocations, and harbor construction on hydrodynamics and shoreline changes in these complex systems. Measurements made by gauges at prototype (i.e. field) sites have sometimes been used to help calibrate the physical models. In turn, the results of tests run in the physical models have identified locations where gauges needed to be placed in the field to measure unusual conditions. An example is provided by the Los Angeles/Long Beach Harbor model (Figure 5-15). In operation since the early 1970's, it has been used to predict the effects of harbor construction on hydrodynamics and water quality. As part of this project, wave gauges were deployed in the two harbors at selected sites. Figure 5-16 is an example of wave data from Long Beach Harbor. Although the two gauge stations were only a few hundred meters apart, the instrument at sta 2 occasionally measured unusually high energy compared to sta 1. The cause of these energy events is unknown but is hypothesized to be related to long-period harbor oscillations. The lesson is that a user must discard data without considering the siting of the instruments.

5-5. Analysis and Interpretation of Coastal Data

a. Background.

(1) All geologic and engineering project data, whether obtained from existing sources, field prototype collection, laboratory analyses, or physical models, must be analyzed and interpreted to ultimately be useful in geologic and geomorphic studies. The analysis procedures depend upon the type of data collected. Some analyses require subjectivity or interpolation, such as constructing geologic cross sections or making seismic interpretations. Others are highly objective involving computer probabilistic models. A coastal scientist or engineer should be aware of the assumptions, limitations, and errors involved, and should attempt to provide sufficient information so that his data can be replicated, analyses tested, and the interpretation supported.

(2) Computers play an important role in analysis and interpretation of data from various sources. Statistical techniques are applied to a variety of data, including: (a) spectral analysis of wave characteristics; (b) wave refraction analysis; (c) time series analysis of water level data; (d) Fourier analysis of current data; (e) moment measures of grain size; (f) eigenvectors of shoreline change; and (g) the use of fractals in shoreline geometry.

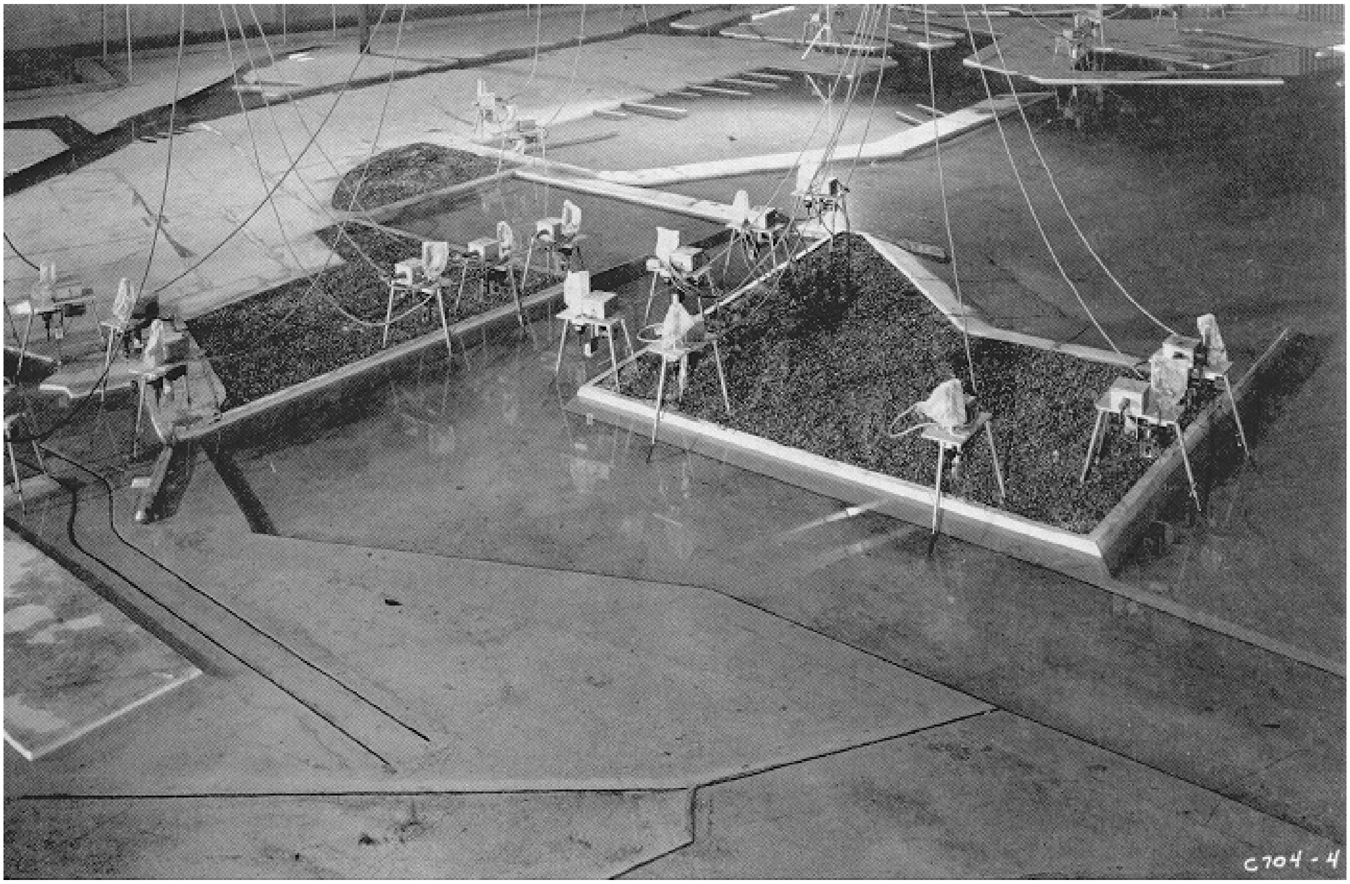


Figure 5-15. Physical model of Los Angeles/Long Beach Harbor. Instruments on tripods are water level gauges

Computers are also used for numerous types of calculations, such as volumetric changes in beach profiles, as well as two-and three-dimensional plotting of these changes. If numerous types of spatial data exist for a location, they may be entered into a Geographic Information System (GIS) so that important questions can be addressed involving spatial changes. Computer software and hardware are also used for analysis, classification, and interpretation of digital remotely sensed data from satellites and aircraft.

(3) The following sections briefly outline some concepts and procedures pertinent to analyses of coastal data. The reader is referred to specialized texts for detailed descriptions of the underlying mathematics and data processing methods.

b. Wave records.

(1) General procedures.

(a) To an observer on the shore or on a boat, the sea surface usually appears as a chaotic jumble of waves of various heights and periods, moving in many different directions. Wave gauges measure and record the changing elevation of the water surface. Unfortunately, these data, when simply plotted against time, reflect the complexities of the sea's surface and provide little initial information about the characteristics of the individual waves which were present at the time the record was being made (Figure 5-17). Once the water elevation data are acquired, further processing is necessary in order to obtain wave statistics that can be used by coastal scientists or engineers to infer what wave forces have influenced their study area.

(b) Wave data analysis typically consists of a series of steps:

- Data transfer from gauge to computer.

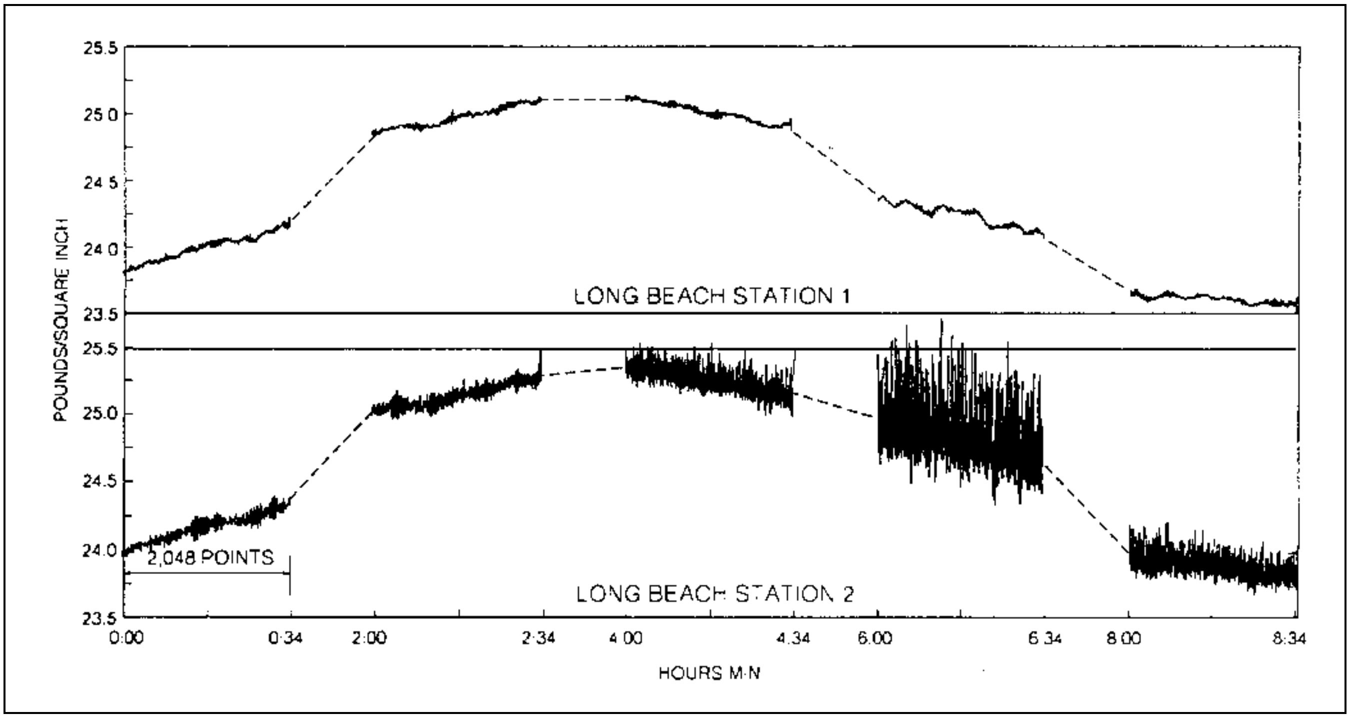


Figure 5-16. Comparison of wave gauge pressure measurements recorded at Long Beach Harbor sta 1 and 2. Although the two stations were only a few hundred meters apart, unusual energy events were recorded at sta 2 which did not appear at sta 1. The abrupt shifts in the curve at each 2-hr interval represent changes in tide height. Each 2048-point record is 34.13 min long and each new wave burst is recorded at a 2-hr interval

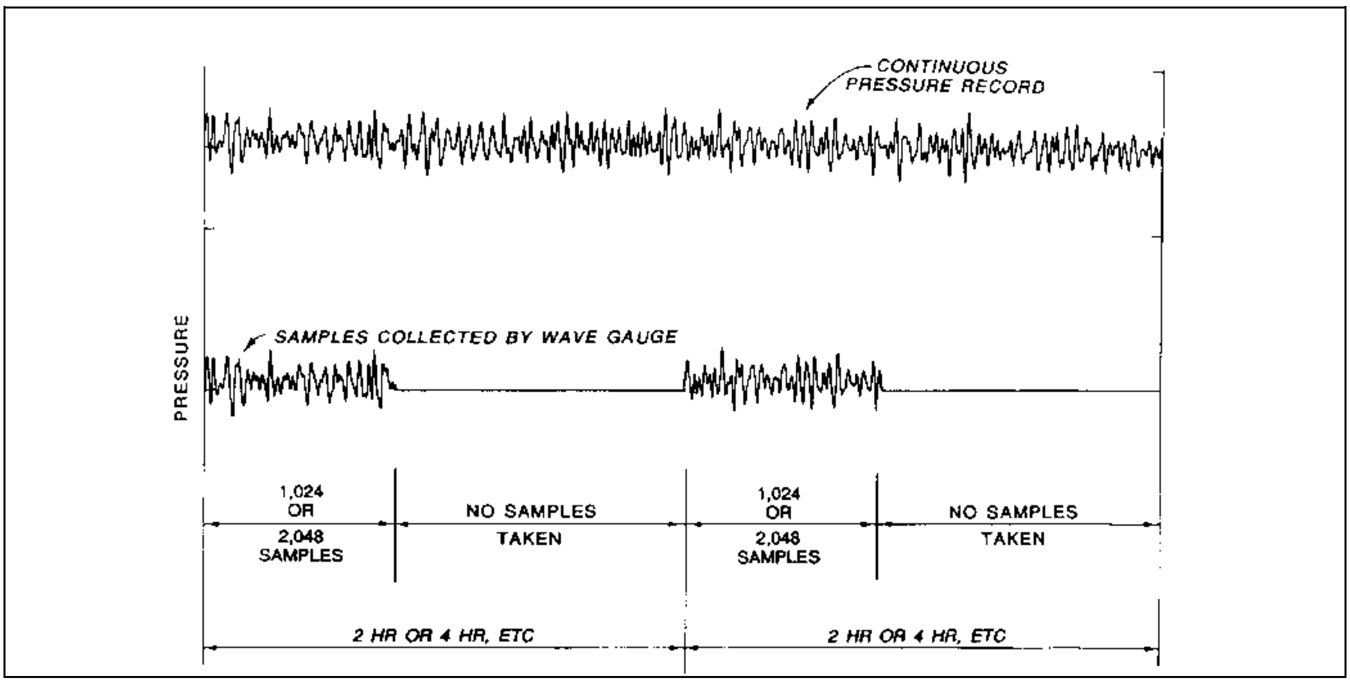


Figure 5-17. Example of continuous wave pressure record and wave burst sampling of pressure data

- Conversion of data from voltage readings to engineering units.
- Initial quality control inspection.
- Spectral analysis.
- Additional quality control (if necessary).
- Summary statistics in table and plot form.
- Plots of individual wave bursts or special processing.

It is beyond the scope of this manual to discuss details of the above procedures. This section will summarize some aspects of data collection, quality control, analysis, and terminology. Because of the complexity of the subject, the reader is referred to Bendat and Piersol (1986), Horikawa (1988), and Weaver (1983) for additional references.

(2) Data collection planning.

A continuous time series of raw pressure values plotted with time along the x-axis is shown in Figure 5-17. Because it is impractical and too expensive to collect data continuously throughout the day, discrete time series or "bursts" are collected at predetermined intervals (often every 2, 4, or 6 hr; Figure 5-17). Wave bursts typically consist of 1,024 or 2,048 consecutive pressure, U-velocity, and V-velocity[1] samples. At a sampling frequency of 1 Hz, these produce time series of 17.07 min and 34.13 min, respectively. Clearly, it would be desirable to acquire wave bursts frequently, but the sheer amount of data would soon overwhelm an analyst's ability to organize, interpret, and store the records. A researcher who plans a data acquisition program must balance the need to collect data frequently versus the need to maintain gauges in the field for an extended period. There is a temptation to assume that as long as the gauges are at sea, they should be programmed to collect absolutely as much data as possible. However, data management, analysis, and archiving can cost at least as much as the deployment and maintenance of the gauges. It is essential that these analysis costs be factored into the project budget. Typical sampling schemes used at CERC projects are listed in Table 5-10.

(3) Quality control of wave data.

[1] Orthogonal horizontal water velocity measurements.

Table 5-10
Wave Data Sampling Intervals, Typical CERC Projects

Instrument	Location	Sample interval hr
Sea Data self-contained wave gauge	Ocean coastlines	4 or 6
Sea Data self-contained wave gauge	Great lakes	2 or 3
CERC Directional Wave Gauge	Ocean coastlines	1
NOAA wave and meteorology buoys	Oceans and lakes	1

(a) One aspect of wave analysis, which is absolutely critical to the validity of the overall results, is the quality control procedures used to ensure that the raw data collected by the gauges are truly representative of the wave climate at the site. Wave gauges are subject to mechanical and electrical failures. The pressure sensors may be plugged or may be covered with growths while underwater. Nevertheless, even while malfunctioning, gauges may continue to collect data which, on cursory examination, may appear to be reasonable. As an example, Figure 5-18 shows pressure records from two instruments mounted on the same tripod off the mouth of Mobile Bay, Alabama. The upper record in the figure is from a gauge with a plugged pressure orifice. The curve reflects the overall change in water level caused by the tide, but high frequency fluctuations caused by the passing of waves have been severely damped. The damping is more obvious when a single wave burst of 1,024 points is plotted (Figure 5-19). Without the record from the second gauge, would an analyst have been able to conclude that the first instrument was not performing properly? This type of determination can be especially problematic in a low-energy environment like the Gulf of Mexico, where calm weather can occur for long periods.

(b) Another difficult condition to diagnose occurs when the wave energy fluctuates rapidly. Many computerized analysis procedures contain user-specified thresholds to reject records that contain too many noise spikes. Occasionally, however, violent increases in energy do occur over a short time, and it is important that the analysis procedures do not reject these records without verification. As an example, one of two gauges in Long Beach harbor (the lower curve in Figure 5-16) may have malfunctioned and written many noise spikes on the tape. In reality, the gauge recorded unusual energy events within the harbor. Another example, from Burns Harbor, Indiana, is shown in Figure 5-20. When wave height was plotted against time, numerous spikes appeared. In this

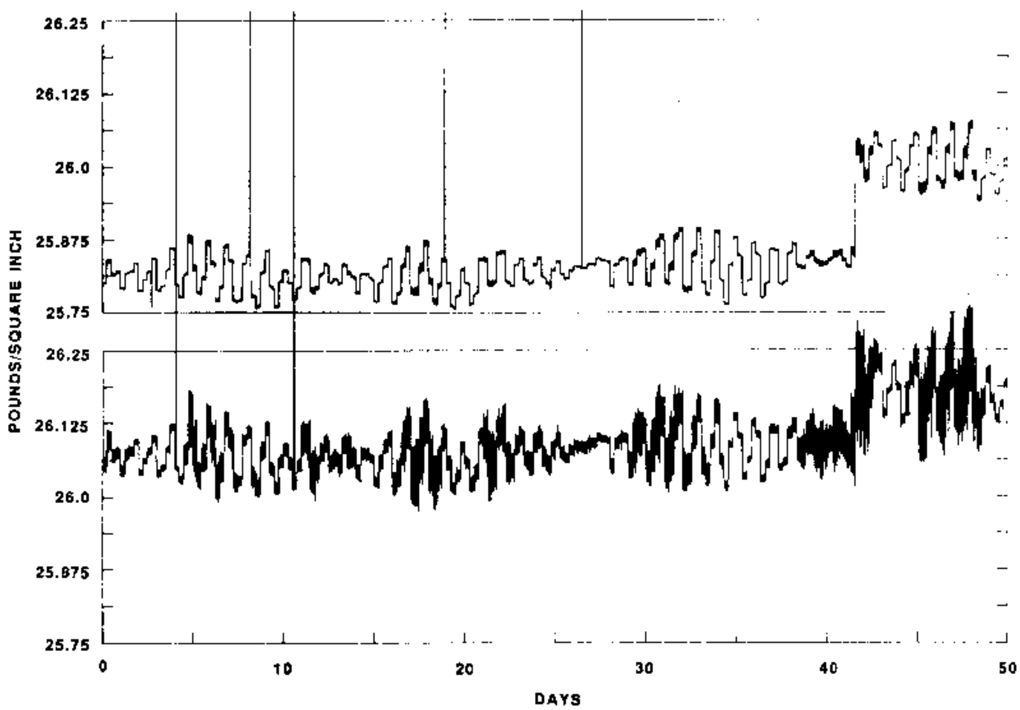


Figure 5-18. Pressure data collected by two gauges mounted on a tripod off Mobile Bay, Alabama. The upper record is from a gauge with a plugged pressure orifice. The abrupt increase in pressures near day 43 was caused when a fishing boat struck and overturned the tripod

case, the rapid increase in energy was genuine, and the spikey appearance was caused by the plotting of many weeks of data on one plot. An examination of the individual pressure records (Figure 5-21) reveals how rapidly the energy increased in only a few hours (a characteristic of Great Lakes storms). This example demonstrates that the method of displaying wave statistics can have a major influence on the way the data are perceived by an analyst. Additional examples and quality control procedures for validating wave data are discussed in Morang (1990).

(4) Analysis procedures and terminology.

(a) Wave data analysis can be broadly subdivided into non-directional and directional procedures. Although the latter are considerably more complex, the importance of delineating wave direction in coastal areas is usually great enough to justify the extra cost and complexity of trying to obtain directional wave spectra. The types of wave statistics needed vary depending on the application. For example, a geologist might want to know what the average wave period, height, and peak direction are along a stretch of the shoreline. This information could then be used to estimate wave refraction and longshore drift. An engineer who is building a structure along the shore would be interested in the height, period, and approach direction of storm waves. He would use these values to calculate stone size for his structure. Table 5-11 lists common statistical wave parameters.

(b) Table 5-11 is intended to underscore that wave analysis is a complex procedure and should be undertaken by coastal researchers with knowledge of wave mechanics and oceanography. In addition, researchers are urged to be cautious of wave statistics from secondary sources and to be aware of how terms have been defined and statistics calculated. For example, "significant wave height" is defined as the average height of the highest one-third of the waves in a record. How long should this record be? Are the waves measured in the time domain by counting the wave upcrossings or downcrossings? The two methods may not produce the same value of H_s. Might it not be better to estimate significant wave height by performing spectral analysis of a wave time series in the frequency domain and equating $H_s = H_{m0}$? This is the procedure commonly used in experiments where large amounts of data are processed. The latter equivalency is

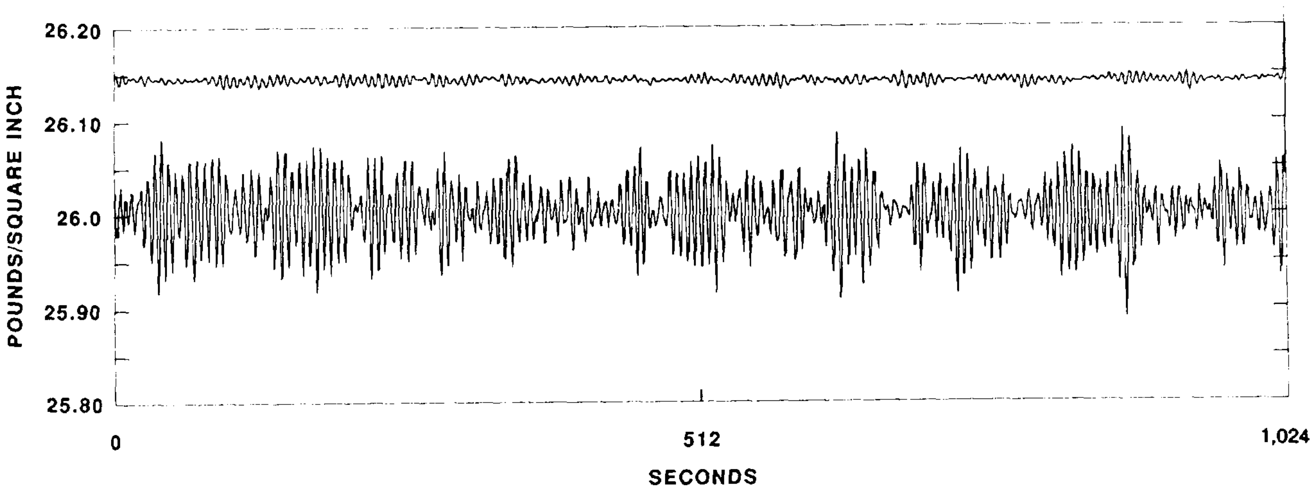


Figure 5-19. Example of a single wave burst of 1,024 pressure points from the same gauges which produced the records in Figure 5-18. The data from the plugged gauge (the upper curve) is not only reduced in amplitude but also shifted in phase. It is essentially impossible to correct the plugged data and recreate even an approximation of the original

usually considered valid in deep and intermediate water but may not be satisfactory in shallow water (Horikawa 1988).

(c) Directional wave statistics are also subject to misinterpretations depending upon the computation method. At sea, very rarely do the waves come from only one direction. More typically, swell, generated by distant storms, may approach from one or more directions, while the local wind waves may have a totally different orientation. Researchers need to distinguish how the wave energy is distributed with respect to both direction and period (i.e., the directional spectral density, $S(f,\Theta)$). The directional distribution of wave energy is often computed by a method developed by Longuet-Higgins, Cartwright, and Smith (1963) for use with floating buoys in deep water. Other distribution functions have been proposed and used by various researchers since the 1970's (Horikawa 1988). Although the various methods do not produce the same directional wave statistics under some circumstances, it is not possible to state that one method is superior to another.

(d) The user of environmental data must be aware of the convention used to report directions. Table 5-12 lists the definitions used at CERC; other institutions may not conform to these standards.

(e) Some oceanographic instruments are sold with software that performs semi-automatic processing of the data, often in the field on personal computers. In some instruments, the raw data are discarded and only the Fourier coefficients saved and recorded. The user of these instruments is urged to obtain as much information as possible on the mathematical algorithms used by the gauge's manufacturer. If these procedures are not the same as those used to analyze other data sets from the area, the summary statistics may not be directly comparable. Even more serious, this author has encountered commercial processing software which was seriously flawed with respect to the calculation of directional spectra. In one field experiment, because the original raw data had not been archived in the gauge, the data could not be reprocessed or the errors corrected. As a result, the multi-month gauge deployment was rendered useless.

(f) In summary, it is vital that the user of wave data be aware of how wave statistics have been calculated and thoroughly understand the limitations and strengths of the computational methods that were employed.

(5) Display of wave data and statistics.

(a) In order to manage the tremendous amount of data that are typically acquired in a field experiment,

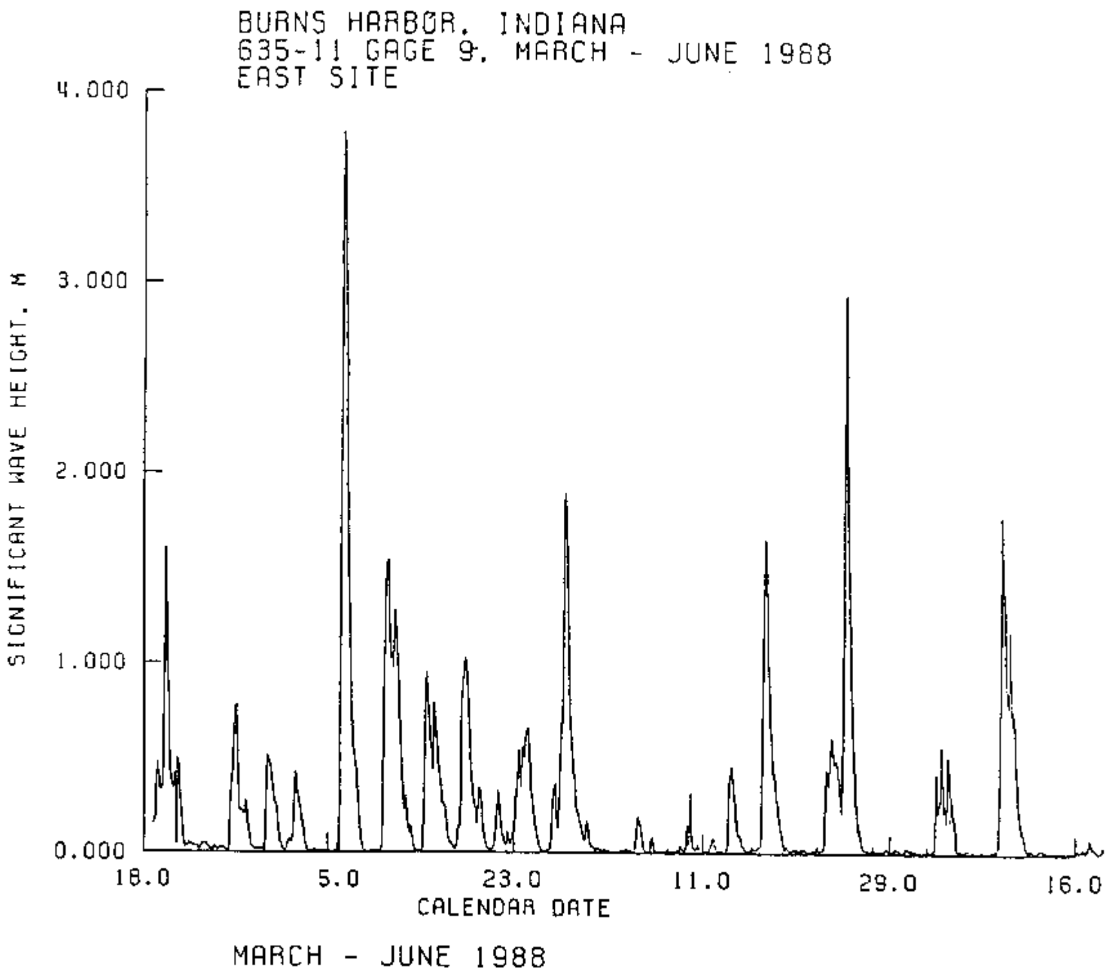


Figure 5-20. Analyzed wave data from Burns Harbor, Indiana. Spikey appearance is caused by plotting almost 3 months of data on one plot

perform quality control, and interpret the results, wave data should be analyzed as soon as possible. In addition, there is often an urgent need to examine the raw data to ascertain whether the gauges can be redeployed or must be repaired.

(b) Figures 5-17 and 5-19 are examples of pressure plotted against time. The value of this form of display for quality control purposes has been demonstrated, but these plots are of limited value in revealing information about the overall nature of the wave climate in the study area.

(c) To review the data from an extended deployment, the summary statistics must be tabulated or plotted. Figure 5-22 is an example of tabulated directional wave data from a Florida project site. These same data are graphically displayed in Figure 5-23. The upper plot shows H_{m0} wave height, the center peak period, and the lower peak direction. Although other statistics could have been plotted on the same page, there is a danger of making a display too confusing. The advantage of the tabulation is that values from individual wave bursts can be examined. The disadvantage is that it is difficult to detect overall trends, especially if the records extend over many months. As data collection and processing procedures improve, and as more and more data are acquired at field projects, it will be increasingly difficult to display the

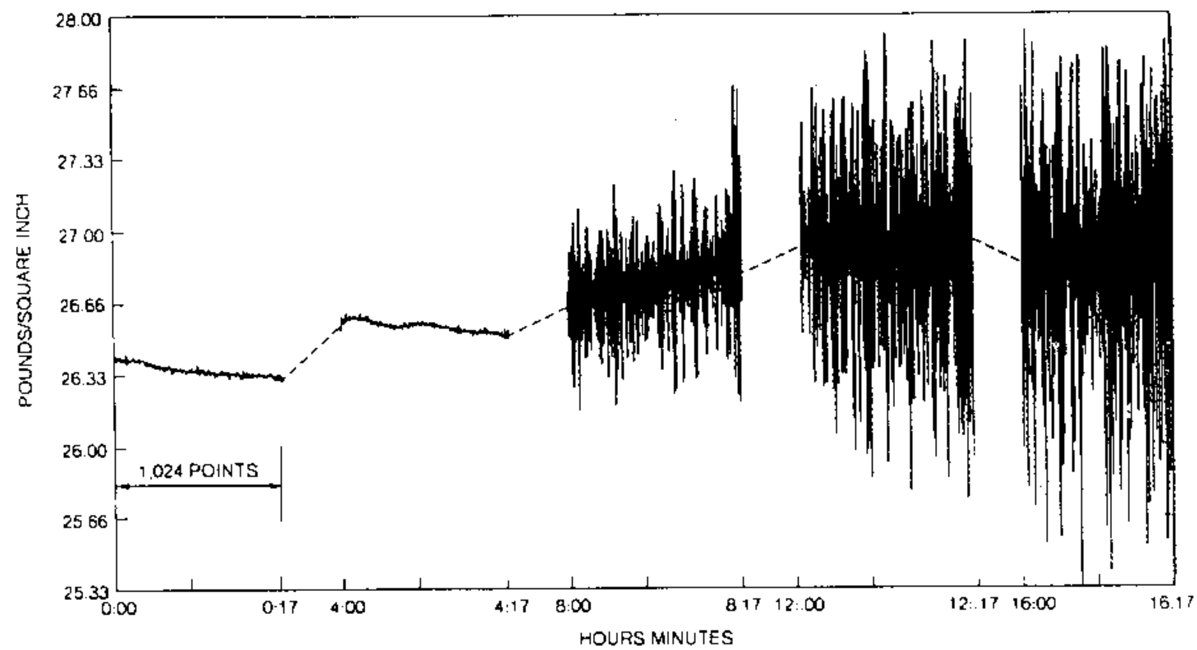


Figure 5-21. Pressure data from Burns Harbor, Indiana, April 6, 1988. This plot shows how dramatically the energy can increase in only a few hours

results in a useful and flexible format that does not overwhelm the end user but yet also does not over-simplify the situation.

(6) Applications of wave data. One important use of wave climate data in coastal engineering is in the construction of wave refraction diagrams. These demonstrate how nearshore bathymetry influences the direction of waves approaching the shoreline. This information can be used to estimate mass transport and longshore transport of sediment, which, in turn, can be used to predict morphologic changes under both natural and structurally influenced coasts. Wave refraction analyses can also be used for hypothetical scenarios, such as predicting the effects on incident waves of dredging an offshore shoal or dumping dredged materials offshore.

c. Water level records.

(1) Changes in water levels along coastlines have profound influence on the geology, the natural ecology, and human habitation in these regions. Predicting and understanding these changes can guide coastal planners in developing rational plans for coastal development and in the design, construction, and operation of coastal structures and waterways. Causes of sea level changes along open coasts have been discussed in Chapter 2.

(2) Tide gauge records may be analyzed for spatial interpolation and for assessing temporal variations such as surges, tides, seasonal changes, and long-term trends. Discrepancies between the predicted tide at one site and the actual tide measured only a short distance away may be considerable. A method for adjusting between predicted tides at a station and those at a nearby study area using only limited field measurements is discussed by Glen (1979). Other analysis methods are discussed in EM 1110-2-1414.

(3) For engineering projects, assessments of short-term water level changes range from simple plotting of data to more sophisticated mathematical analyses. In some cases, some of the components that drive water level changes can be isolated. To assess longer (multiyear) trends, it is important to dampen or separate the effects of yearly variability so that the nature of the secular trends becomes more pronounced. Least-squares regression methods are typically inadequate because the secular trends often show pronounced nonlinearity (Hicks 1972). It may also be important to examine long-term periodic effects in a long data record such as the 18.6-year nodal period, which Wells and Coleman (1981) concluded was important for mudflat stabilization in Surinam.

Table 5-11
Sea State Parameters

Symbol	Description	Units
	Basic Terms	
a	Amplitude	m
c	Phase velocity or celerity	m/sec
c_g	Group velocity	m/sec
f	Frequency	Hz
H	Wave height	m
L	Wave length measured in the direction of wave propagation	m
T	Wave period $1/f$	sec
Θ	Direction of wave propagation as used in directional spectra	deg
Δf	Basic frequency increment in discrete Fourier analysis	Hz
σ	Standard deviation	m
	General Parameters	
f_p	Spectral peak frequency $1/T_p$	Hz
H_s	Significant wave height defined as the highest one-third of the wave heights calculated as $H_{1/3,\ downcrossing}$; or $H_{1/3,\ upcrossing}$	m
T_p	Spectral peak period $1/f_p$	sec
	Time Domain Analysis Functions	
$H_{1/3,d}$	Zero-downcrossing significant wave height. Average of the highest one-third zero-downcrossing wave heights	m
$H_{1/3,u}$	Zero-upcrossing significant wave height	m
	Frequency Domain Analysis Parameters	
f_p	Spectral peak frequency. This frequency may be estimated by different methods, such as: (1) Frequency at which $S_n(f)$ is a maximum; (2) Fitting a theoretical spectral model to the spectral estimates	Hz
H_{mo}	Estimate of significant wave height, $4\sqrt{m_o}$	m^2/Hz
m_n	nth moment of spectral density	m^2/sec^n
$S(f)$	Spectral density	m^2/Hz
T_p	Spectral peak period $1/f_p$	sec
	Directional Parameters and Functions	
k	Wave vector	rad/m
$d(f,\Theta)$	Directional spreading function	deg
$S(f,\Theta)$	Directional spectral density	(m^2/Hz)/deg
a	Wave direction. This is the commonly used wave-direction parameter, representing the angle between true north and the direction from which the waves are coming. Clockwise is positive in this definition	deg
Θ	Direction of wave propagation describing the direction of k. Counterclockwise is positive	deg
$\Theta_m(f)$	Mean wave direction as a function of frequency. The mean of all $\Theta_m(f)$ is known as the overall wave direction	deg

(Condensed from IAHR Working Group on Wave Generation and Analysis (1989))

Table 5-12
Reporting Conventions for Directional Environmental Measurements

Type	Convention	Example
Wind	FROM WHICH wind is blowing	North wind blows from 0 deg
Waves	FROM WHICH waves come	West waves come from 270 deg
Unidirectional currents	TO WHICH currents are flowing	East current flowing to 90 deg

(4) Historic water levels have been used by Hands (1979, 1980) to examine the changes in rates of shore retreat in Lake Michigan and to predict beach/nearshore profile adjustments to rising water levels. Additional research is being sponsored by the International Joint Commission to model how changing water levels affect erosion of various bluff stratigraphies and the nearshore profile.

d. Current records. Current data are often critical for evaluating longshore and cross-shore sediment transport and for evaluating hydraulic processes in inlets and other restricted waterways. Currents, which are generated by a variety of mechanisms, vary greatly spatially and temporally in both magnitude and direction. Four general classes of unidirectional flow affect coastal environments and produce geologic changes. These include:

- Nearshore wave-induced currents, including longshore and rip currents.
- Flow in tidal channels and inlets, which typically changes direction diurnally or semi-diurnally, depending on the type of tide along the adjacent coast.
- River discharge.
- Oceanic currents, which flow along continental land masses.

This section will briefly discuss the first two of these topics and present data examples. The third and fourth are beyond the scope of this manual, and the reader is referred to outside references for additional information.

(1) Nearshore wave-induced currents.

(a) In theory, one of the main purposes for measuring nearshore, wave-induced currents is to estimate longshore transport of sediments. At the present level of technology and mathematical knowledge of the physics of sediment transport, the direct long-term measurement of longshore currents by gauges is impractical. Two main reasons account for this situation. First, deployment, use, and maintenance of instruments in the nearshore and the surf zone are difficult and costly. Second, the mechanics of sediment transport are still little-understood, and no one mathematical procedure is yet accepted as the definitive method to calculate sediment transport, even when currents, grain size, topography, and other parameters are known. An additional consideration is how to monitor the variation of current flow across and along the surf zone. Because of the extreme difficulty of obtaining data from the surf zone, neither the cross-shore variations of currents nor the temporal changes in longshore currents are well known.

(b) Longshore (or littoral) drift is defined as: “Material (such as shingle, gravel, sand, and shell fragments) that is moved along the shore by a littoral current” (Bates and Jackson 1984). Net longshore drift refers to the difference between the volume of material moving in one direction along the coast and that moving in the opposite direction (Bascom 1964). Along most coasts, longshore currents change directions throughout the year. In some areas, changes occur in cycles of a few days, while in others the cycles may be seasonal. Therefore, one difficulty in determining net drift is defining a pertinent time frame. Net drift averaged over years or decades may conceal the fact that significant amounts of material may also flow in the opposite direction.

(c) Because net longshore currents may vary greatly from year to year along a stretch of coastline, it would be desirable to deploy current meters at a site for several years in order to obtain the greatest amount of data possible. Unfortunately, the cost of a multi-year deployment could be prohibitive. Even a long deployment might not detect patterns that vary on decade-long scales, such as the climatic changes associated with El Niño. At a minimum, near-shore currents should be monitored at a field site for at least a year in order to assess the changes associated with the passing seasons. Coastal scientists and engineers must be aware of the limitations of field current data and recognize that long-term changes in circulation patterns may remain undetected despite the best field monitoring efforts.

(2) Flow in tidal channels and inlets.

(a) An inlet is “a small, narrow opening in a shoreline, through which water penetrates into the land” (Bates

EAST PASS, DESTIN, FLORIDA
635-9 GAGE 03
APRIL - JUNE 1989
(OFF OKALOOSA PIER, FT. WALTON BEACH)

ANALYSIS SUMMARY
PUV Version 3.5
20-JAN-90
CEWES-CD-P

MM	DY	YR	HRMN	HmO (M)	Tp (SEC)	Dp (DEG)	AVE.CUR (M/SEC)	C.DIR. (DEG)	DEPTH (M)
6	6	89	1230	0.64	5.4	182	0.34	296	9.8
6	6	89	1830	1.02	6.2	209	0.36	273	9.3
6	7	89	30	1.29	6.6	203	0.39	275	9.3
6	7	89	630	0.98	6.6	200	0.36	310	9.5
6	7	89	1230	0.91	6.6	204	0.24	301	9.8
6	7	89	1830	0.75	6.9	201	0.20	273	9.4
6	8	89	30	0.65	5.4	207	0.17	240	9.4
6	8	89	630	1.24	5.2	192	0.28	287	9.7
6	8	89	1230	2.21	7.3	200	0.60	297	10.0
6	8	89	1830	2.56	8.8	193	0.64	209	9.5
6	9	89	30	2.40	9.5	194	0.59	187	9.4
6	9	89	630	1.71	8.8	206	0.48	352	9.5
6	9	89	1230	1.45	7.8	202	0.40	203	9.7
6	9	89	1830	1.49	8.8	200	0.42	292	9.5
6	10	89	30	1.16	7.8	204	0.35	281	9.4
6	10	89	630	0.83	6.6	206	0.26	272	9.5
6	10	89	1230	0.83	7.3	198	0.25	279	9.6
6	10	89	1830	0.73	6.9	203	0.20	250	9.4
6	11	89	30	0.58	7.3	201	0.18	269	9.4
6	11	89	630	0.56	6.9	205	0.15	144	9.5
6	11	89	1230	0.56	6.6	203	0.15	15	9.5
6	11	89	1830	0.54	6.6	211	0.13	138	9.4
6	12	89	30	0.43	6.6	213	0.12	111	9.4
6	12	89	630	0.48	5.4	209	0.12	118	9.5
6	12	89	1230	0.49	4.5	224	0.10	109	9.4
6	12	89	1830	0.50	5.2	216	0.12	246	9.4
6	13	89	30	0.47	4.2	233	0.12	129	9.5
6	13	89	630	0.68	4.7	219	0.12	265	9.6
6	13	89	1230	0.67	5.0	225	0.17	271	9.4
6	13	89	1830	0.56	4.7	213	0.20	274	9.3
6	14	89	30	0.68	4.7	215	0.24	282	9.5
6	14	89	630	0.70	5.0	220	0.14	203	9.6
6	14	89	1230	0.67	5.2	212	0.14	254	9.4
6	14	89	1830	1.12	5.7	213	0.24	209	9.3
6	15	89	30	1.32	6.9	218	0.34	267	9.5
6	15	89	630	1.87	6.9	213	0.46	267	9.8
6	15	89	1230	1.97	8.3	201	0.51	269	9.5
6	15	89	1830	1.56	8.8	201	0.43	337	9.3
6	16	89	30	1.25	7.3	212	0.34	305	9.5
6	16	89	630	1.45	5.2	206	0.31	248	9.8
6	16	89	1230	1.91	7.8	203	0.48	3	9.4
6	16	89	1830	1.06	7.8	214	0.34	280	9.2
6	17	89	30	1.07	6.6	203	0.31	298	9.5
6	17	89	630	0.94	6.2	206	0.33	289	9.8
6	17	89	1230	0.77	6.0	198	0.21	260	9.5
6	17	89	1830	0.60	6.6	199	0.20	278	9.2
6	18	89	30	0.47	6.9	197	0.17	289	9.4
6	18	89	630	0.50	5.2	185	0.19	290	9.8
6	18	89	1230	0.49	6.0	180	0.22	270	9.6

Figure 5-22. Example of tabular summary of wave data from offshore Fort Walton Beach, Florida

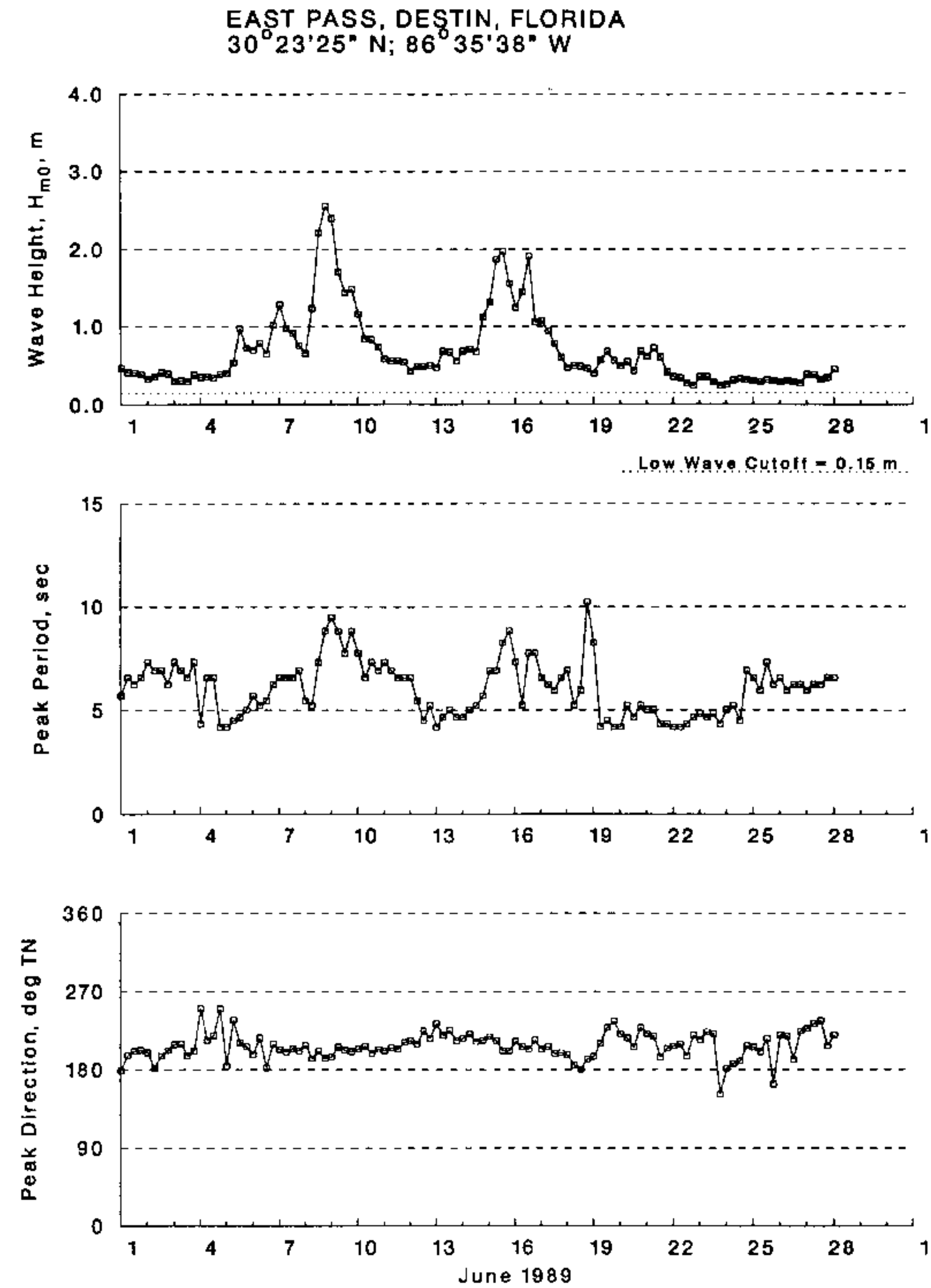


Figure 5-23. Plots of wave height, peak period, and peak direction from offshore Fort Walton Beach, Florida

and Jackson 1984). Inlets range in size from short, narrow breaches in barrier islands to wide entrances of major estuaries like Chesapeake Bay. Many geologic and engineering studies concern flow through tidal inlets in sand-dominated barriers, particularly when the inlets serve as navigation channels connecting harbors to the open sea.

(b) Inlets allow for the exchange of water between the sea and the bay during each tidal cycle. Therefore, currents in tidal inlets are typically unidirectional, changing direction diurnally or semidiurnally, depending upon the tides along the adjacent open coast. Flow through the inlets can be complicated by the hydrodynamics of the inland bay, especially if there are other openings to the sea.

(c) Various numerical and conceptual models have been developed to describe flow through inlets and allow researchers to predict the effects of changing inlet dimensions, lengths, and orientations (Aubrey and Weishar 1988; Escoffier 1977; Seelig, Harris, and Herchenroder 1977; *Shore Protection Manual* 1984). Most models, however, benefit from or require calibration with physical measurements made within the inlet and the general vicinity. The required field measurements are usually either tidal elevations from the open sea and within the adjacent bay or actual current velocities from within the inlet's throat.

(d) Display of tidal elevation data is relatively straightforward, usually consisting of date or time on the x-axis and elevation on the y-axis. Examples of tidal elevations from a bay and an inlet in the Florida Panhandle are shown in Figure 5-6. Although the overall envelope of the curves is similar, each one is unique with respect to the heights of the peaks and the time lags. The curves could be superimposed to allow direct comparison, but, at least at this 1-month-long time scale, the result would be too complicated to be useful.

(e) Display of current meter measurements is more difficult because of the large quantity of data usually collected. An added difficulty is posed by the changing currents within an inlet, which require a three-dimensional representation of the flow which varies with time. Current measurements from East Pass, Florida, collected during three field experiments in the mid-1980's are presented as examples. Currents were measured with manual Price type AA meters deployed from boats and with tethered Endeco 174 current meters. The manual measurements were made hourly for 24 hr in order to observe a complete tidal cycle. The measurements were made across the inlet at four stations, each one consisting of a near-surface, a mid-depth, and a near-bottom observation (Figure 5-24). Therefore, 12 direction and velocity data values were obtained at each hour (Figure 5-25). One way to graphically display these values is to plot the velocities on a plan view of the physical setting, as shown in Figure 5-24. This type of image clearly shows the directions and relative magnitudes of the currents. In this example, the data reveal that the currents flow in opposite directions in the opposite halves of the inlet. The disadvantage of the plan view is that it is an instantaneous snapshot of the currents, and the viewer cannot follow the changes in current directions and magnitudes over time unless the figure is redrawn for each time increment. Temporal changes of the currents can be shown on dual plots of magnitude and direction (Figure 5-26). Unfortunately, to avoid complexity, it is not reasonable to plot the data from all 12 measurement locations on a single page.

Therefore, measurements from the same depth are plotted together, as in Figure 5-26, or all measurements from one site can be plotted together (top, middle, and bottom).

(f) In summary, current data can be displayed in the form of instantaneous snapshots of the current vectors or as time series curves of individual stations. Many plots are usually needed to display the data collected from even short field projects. It may be advantageous to present these plots in a data appendix rather than within the text of a report.

(3) Error analysis of current data.

(a) Error analysis of current records can be broadly divided into two categories. The first concerns calibrations of the actual current sensing instruments. A user needs to know how closely the numbers reported by a particular instrument represent the water motions that it is purported to be measuring. This information is important for both evaluation of existing data sets and for planning of new field experiments, where some instruments may be more suitable than others.

(b) The second broad question pertains to whether the measurements which have been gathered adequately represent the flow field in the inlet or channel that is being examined. This second problem is exceedingly difficult to evaluate because it raises the fundamental questions of "How much data do I need?" and, "Can I afford to collect the data that will really answer my questions?" The user is typically tempted to respond that he wants just as much data as possible, but this may prove to be counterproductive. For example, if the

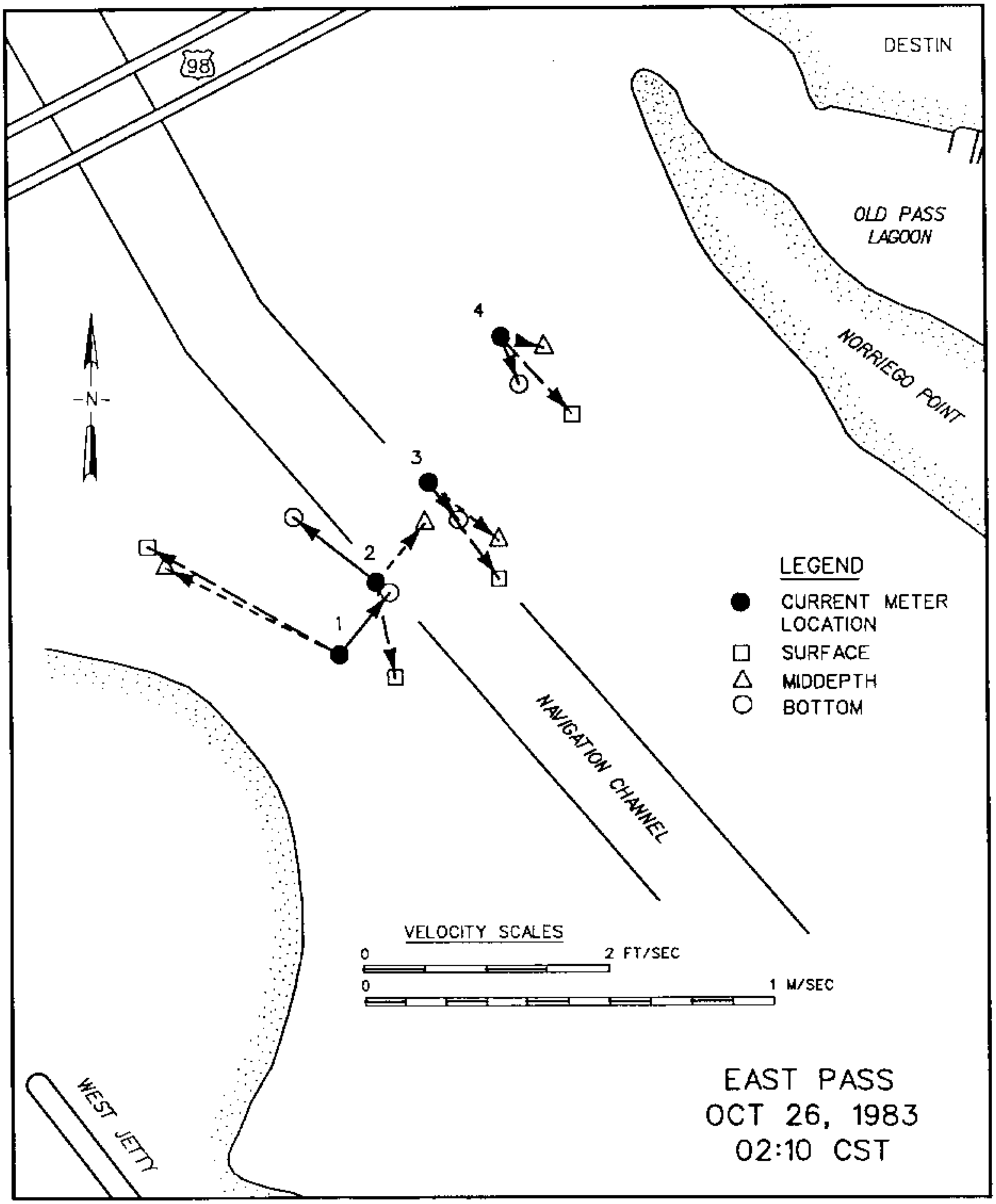


Figure 5-24. Current measurement stations in East Pass Inlet, Destin, Florida, during October, 1983. Measurements were made hourly from small boats. At 02:10 CST, currents were flowing to the northwest along the west side of the inlet and to the southeast along the center and east sides of the inlet. Station 2 was in the mixing zone

DESTIN (EAST PASS) TIDE STUDY

U.S. ARMY ENGINEER DISTRICT, MOBILE

Project: DESTIN TIDE STUDY | Date: 26OCT83 | Page 7 of 12 Pages

Boat: SKI BARGE | Meter No. PRICE TYPE AA STANDARD | Dir. Ind. No. WES 23

Observers: JAB | JHL | JTM

Range: EAST PASS SOUTH OF US 98 BRIDGE
STARTED @ STATION # 1 @ BEACON # 9 (WEST TO EAST)

* DST = DAYLIGHT SAVING TIME / SUBTRACT ONE HOUR FOR STANDARD TIME

Sta No.	* Military Time	Feet Below Surface		Current Dir Mag	Current Rev / Time	Current Velocity Ft/Sec	Remarks	Sta No.	* Military Time	Feet Below Surface		Current Dir Mag	Current Rev / Time	Current Velocity Ft/Sec
1	0200	.2 S	4.16	135	20/49	.910	ANCHOR WINDY	1	0302	S	3.80	EBB? 122	40/48	1.84
		.5 M	10.4	150	20/50	.892	CHOPPY SEAS			M	9.56	EBB? 120	40/49	1.80
		.8 B	16.6 / 20.8	128	20/64	.701	FLOOD TIDE			B	15.4 / 19.2	EBB 220	20/45	.989
2	0206	S	4.16	128	30/50	1.33	ANCHOR WINDY	2	0307	S	3.62	EBB 350	20/51	.815
		M	10.4	125	20/42	1.06	CHOPPY SEAS			M	9.20	EBB 230	20/51	.875
		B	16.6 / 20.8	150	20/42	1.06	FLOOD TIDE			B	14.8 / 18.4	FLOOD? 130	20/42	1.06
3	0211	S	2.44	120	30/42	1.58	ANCHOR WINDY	3	0321	S	2.40	EBB 325	20/47	.948
		M	6.10	120	30/42	1.58	CHOPPY SEAS			M	6.00	EBB 310	20/50	.892
		B	8.9 / 12.2	118	30/41	1.62	FLOOD TIDE			B	9.2 / 12.1	EBB 320	20/64	.701
4	0216	S	2.92	122	30/50	1.33	ANCHOR WINDY	4	0326	S	2.92	EBB 320	20/49	.910
		M	7.30	125	30/51	1.30	CHOPPY SEAS			M	7.30	EBB 295	10/41	.552
		B	11.1 / 14.6	122	20/43	1.03	FLOOD TIDE			B	11.1 / 14.6	EBB 340	20/62	.723
		S								S				
		M								M				
		B								B				
		S								S				
		M								M				
		B								B				

Figure 5-25. Example of handwritten field notes listing times and data values of East Pass current measurements. The data are efficiently presented but difficult to visualize

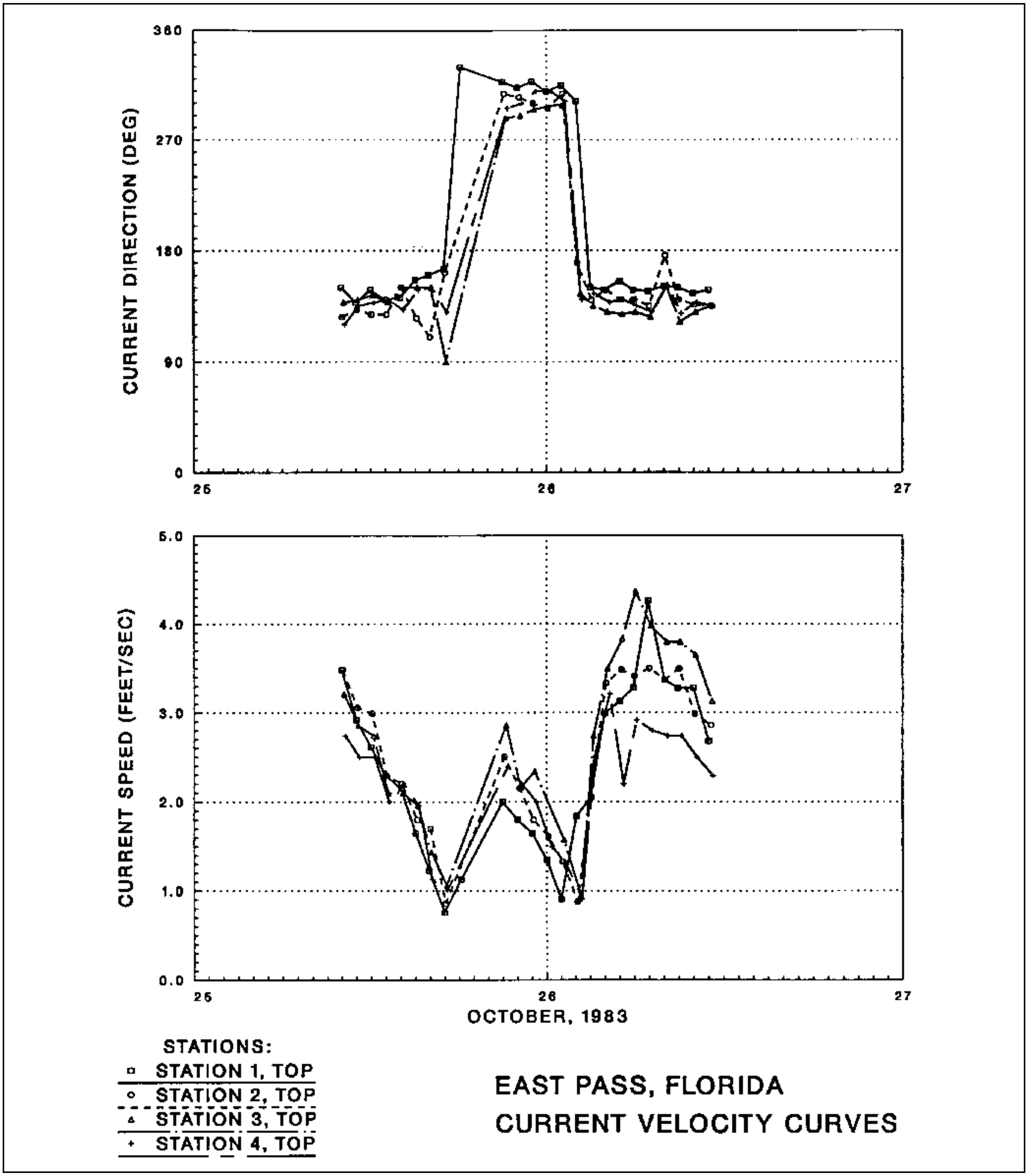


Figure 5-26. Time series plots of East Pass current speed (bottom) and direction (top)

currents in an inlet are being measured to determine variations in the tidal prism over time, will a dense gridwork of sampling stations in an inlet provide more useful data? Or might the excess data reveal unnecessary details about turbulence and mixing in the inlet? These are intrinsically interesting questions, but may not be germane to the engineering problems that must be addressed. Although the dense grid pattern of data can be used to evaluate overall flow, the collection, analysis, and management of the excess data can be costly and time-consuming. The money used on management of this data might be better spent extending a simpler sampling program for a longer period at the site. Unfortunately, there are no firm guidelines to planning current studies and placing instruments.

(c) Analysis of error from various types of current sensors has been the subject of extensive study in the last 30 years. Numerous types of error can occur, both during field deployment of the instrument and during data processing. These can result from instrument calibration, clock time errors, and data recording and playback. In addition, the user is cautioned that each of the many types and brands of current meters is capable of recording accurately only a segment of the spectrum of water motions because of the influence of the mooring assembly, type of velocity sensor used, and recording scheme of the instrument (Halpern 1980). Halpern's (1980) paper lists many references pertaining to the results of tests of moored current meters.

(d) Manufacturers of current meters publish accuracy standards in their literature. These standards may be optimistic, especially under the adverse conditions encountered in many coastal settings. In addition, the type of mooring used for the instrument affects the quality of the measured data (Halpern 1978). For these reasons, the user of existing data is urged to obtain as much information as possible regarding the specifics of the deployment and the type of mooring in order to try to assess the accuracy of the results. Ultimately, successful use of current gauges is critically dependent upon the planning of the experiment and upon the care and skill of the technicians who maintain and deploy the instruments.

(4) River discharge.

(a) River outflow has a major effect on some coastlines, particularly where massive deltas have formed (e.g. Mississippi Delta). Even if a study area is not located on a delta, coastal researchers must be aware of the potential impact of rivers on coastal processes, especially if the study region is affected by freshwater runoff at certain seasons or if longshore currents carry river-derived sediment along the shore.

(b) River discharge data are available for many coastal rivers. A cursory examination of the annual hydrograph will reveal the seasonal extremes. Because of the episodic nature of coastal flooding, annual disharge figures may be misleading. A useful parameter to estimate river influence on the coast is the hydrographic ratio (H_R), which compares tidal prism volume with fluvial discharge volume (Peterson et al. 1984).

(5) Oceanic currents.

(a) Major oceanic currents intrude onto some continental shelves with enough bottom velocity to transport sandy sediments. The currents operate most effectively on the outer shelf, where they may transport significant volumes of fine-grained sediments but presumably contribute little if any new sediment (Boggs 1987). Along most coastlines, ocean currents have little direct effect on shoreline sedimentation or erosion. Even off southeast Florida, where the continental shelf is narrow, the western edge of the Gulf Stream flows at least 1/2 km offshore. However, in some locations where currents approach the coastal zone, sediment discharged from rivers is transported and dispersed along the adjacent coastline. This process may arrest the seaward progradation of the delta front, while causing extensive accumulations of riverine-derived clastics downdrift of the river mouth (Wright 1985).

(b) In shallow carbonate environments, reefs thrive where currents supply clean, fresh ocean water. Reefs stabilize the bottom, provide habitat for marine life, produce carbonate sediment, and sometimes protect the adjoining shore from direct wave attack (i.e., the Great Barrier reef of Australia). In the United States, live reefs are found in the Gulf of Mexico off Texas and west Florida and in the Atlantic off Florida. Coral islands are found in the Pacific in the United States Trust Territories. For geologic or engineering studies in these environments, there may be occasional need to monitor currents. Procedures of deepwater current measurement are presented in Appell and Curtin (1990) and McCullough (1980).

(c) In summary, the effect of tide or wave-induced currents is likely to be much more important to most coastal processes than ocean currents. Measurement of ocean currents may occasionally be necessary for geologic studies in deltaic or carbonate environments.

e. Shoreline change mapping[1].

(1) Introduction.

(a) Maps and aerial photographs can 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.

(b) 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 historic maps to contemporary projections and coordinate systems.

(c) 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 usually be approximated from aerial photographs by a change in color or shade of the beach sand. The datum printed on the NOS T-sheets 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. 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.

(d) 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 standard of NAD 1927 or the more recent NAD 1983. 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.

(e) 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.

(f) 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 photos do not contain defined control points like latitude-longitude marks or triangulation stations. 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 deg being common and 3 deg not unusual (Lillesand and Kiefer 1987). The scale across tilted air photos is non-orthogonal,

[1] Material in this section adapted from Byrnes and Hiland (1994) and other sources.

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. A zoom transfer scope 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. 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).

(g) In order to accurately document shoreline position and generate shoreline position maps, several steps are needed to 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.

(2) Data sources. Five potential data sources exist for assessing spatial and temporal changes in shoreline position. These include United States Geological Survey (USGS) topographic quadrangles, National Ocean Service (NOS) topographic sheets, local engineering surveys, near-vertical aerial photographs, and GPS surveys. Each data source addresses a specific mapping purpose, as described below.

(a) USGS topographic maps. The most common maps used for documenting changes along the coast are USGS topographic quadrangle maps. These maps are created at a range of scales from 1:24,000 to 1:250,000 (Ellis 1978). The primary purpose of these maps is to portray the shape and elevation of the terrain above a given datum, usually the mean high water line. Accurate delineation of the shoreline was not a primary concern on these land-oriented maps. However, shoreline position routinely is 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.

(b) NOS Topographic Maps. Another type of topographic map is that produced by the U.S. Coast and Geodetic Survey (USC&GS) (now National Ocean Survey - NOS). Because this agency is responsible for surveying and mapping topographic information along the coast, topographic map products (T-sheets) have been used in the study of coastal erosion and protection, and frequently in law courts in the investigation of land ownership (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 and photogrammetric methods (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.

(c) Large-scale engineering surveys. In areas of significant human activity, engineering site maps often exist for specific coastal regions. However, surveyed areas often are quite limited by the scope of the project; regional mapping at large scale (greater than 1:5,000) is sparse. If these data 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 photography for mapping shoreline position.

(d) Near-vertical aerial photography. Since the 1920's, aerial photography has been used to record shoreline characteristics in many coastal regions. However, these data cannot be used directly to produce a map. Aircraft tilt and relief may cause serious distortions that have to be removed by rectification. A number of graphical methods and computational routines exist for removing distortions inherent in photography (Leatherman 1984; Anders and Byrnes 1991). Orthophotoquadrangles and orthophotomosaics are photomaps made by applying differential rectification techniques (stereo plotters) to remove photographic distortions. Users are warned that conversion of photographic images to map projections is not a trivial procedure, despite the availability of modern cartographic software. Ease of data collection and the synoptic nature of this data source provide a significant advantage over most standard surveying techniques.

(e) GPS surveys. During the late 1970's through the 1980'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 level of 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 being used (Leick 1990). Differential GPS provides the capability for accurately delineating high-water shoreline position from ground surveys.

(3) Data entry.

(a) Frequently, shoreline maps have variable scales and use different datums and coordinate systems. Shoreline maps should 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 GIS system 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.

(b) Digitized shoreline points are commonly entered into an X-Y data file for each shoreline source. Data transformation to a common surface can be converted using standard mapping software packages. A header or comment line should be incorporated into the digital record of the cartographic parameters, i.e., map scale, projection, and horizontal and vertical datums. Datum shifts can account for significant changes in historical maps generated in the 1800's.

(c) Another transformation is the projection of the earth's spherical shape onto a two-dimensional map. The method by which the earth's coordinates are transferred to a map is referred to as the map projection. Commonly used projections include:

- Lambert projection - scaled to correct along two standard parallels; base for state plane coordinates.
- Mercator projection - scaled along uniformly spaced straight parallel lines; used for NOS T- and H-sheets.
- Transverse Mercator projection - essentially the standard Mercator rotated through 90 deg; used for all large scale maps such as USGS 7½′ quadrangles.

Additional projections are described in Ellis (1978).

(d) Before the shoreline is digitized, triangulation points should be digitized for each shoreline map. The 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 U.S. triangulation stations is *Datum Differences* (USC&GS 1985).

(e) Media distortion can be eliminated by using maps drawn on stable-base materials such as NOS T- and H-sheets. Most USACE District project maps are made from 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.

(4) General digitizing guidelines. Cartographic methods and map handling should be consistent within a project and organization. Shoreline digitizing guidelines (summarized by Byrnes and Hiland, in preparation) include:

(a) 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 for a particular map. Shorelines mapped from rectified aerial photography are drawn onto, and digitized from, acetate film.

(b) 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.

(c) 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.

(d) 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 available is 0.13 mm. The width of the crosshair of a high-precision cursor is approximately 0.1 mm.

(e) When digitizing, use manual point input as opposed to 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.

(f) 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.

(5) 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 digitized 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 5-13 lists the factors affecting the magnitude of error associated with data sources and measurement techniques. Both types of error should be evaluated to gage 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.

(6) Cartographic sources.

(a) 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 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.

(b) Potential error considerations related to field survey equipment and mapping of high-water shoreline

Table 5-13
Factors Affecting Potential Errors Associated with Cartographic Data Sources

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

(After Anders and Byrnes (1991))

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 planetable.
>
> 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.

(c) 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.

(d) 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, knowledge of 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.

(e) 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.

(7) 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.

(8) Analysis of shoreline change data.

(a) 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 5-27. 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.

(b) Three primary statistics are generally used for shoreline change computations. They include the sample mean, sample standard deviation, and maximum shoreline movement. The sample mean is defined as a measure of central tendency for a set of sample observations and is expressed as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{5-1}$$

where x_i = sample observations for i = 1 to n and n = total number of observations. The sample standard deviation s is a measure of sample variability about the mean.

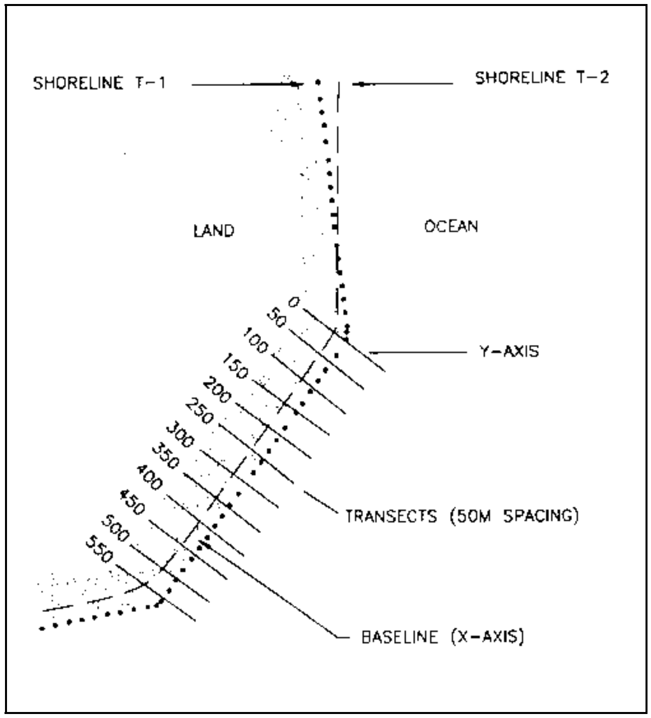


Figure 5-27. Coastline is divided into segments based on the general orientation of the shoreline

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}} \tag{5-2}$$

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.

(c) Comparisons of calculated shoreline change rates are generally grouped by specific time periods or by alongshore segments (i.e. geomorphic features representing spatial trends). A case example, shown in Figure 5-28, 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, New Jersey to Sea Bright), barrier peninsula (Sea Bright to Monmouth Beach), and a headland coastline (Monmouth Beach to Shark River Inlet) (Gorman and Reed 1989).

(9) Interpretation of shoreline change.

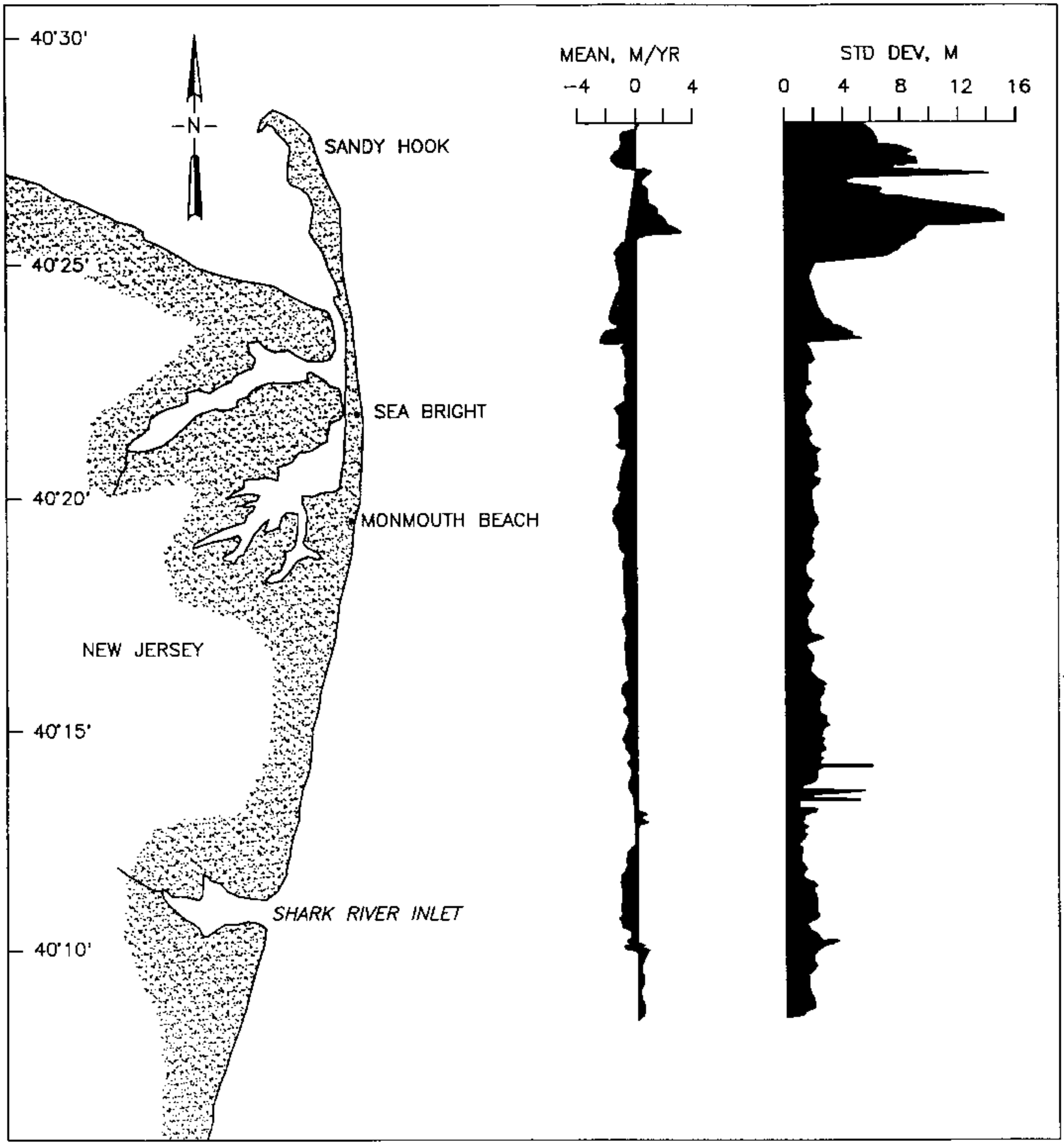


Figure 5-28. Distinctive spatial shoreline trends along the northern New Jersey shore

(a) Historical shoreline positions have been recognized as a primary data source for quantifying rates of erosion and accretion. Coastal scientists, engineers, and planners often use this information for computing rates of shoreline movement for shore protection projects, determining a project rate of retreat for shore protection, estimating the magnitude and direction of sediment transport, monitoring engineering modifications to a beach, examining geomorphic variations in the coastal zone, establishing coastal erosion set-back lines, and verifying numerical shoreline change models.

(b) Relevant published studies that quantify shoreline movement for key U.S. coastlines are listed in Table 5-14. Usually, the alongshore shoreline is subdivided based on geomorphic features or human modifications (Anders, Reed, and Meisburger 1990; Gorman and Reed 1989). Another criterion used is to identify end points of shoreline segments where little or no net change was measured (Knowles and Gorman 1991). Recently, a blocking technique was used by Byrnes and Hiland (1994) to evaluate the spatial shoreline trends based on areas with similar direction of change producing variable-length shoreline cells.

f. Beach and nearshore profiles.

(1) Background. Evaluation of continuous and repeated beach and nearshore profiles documents the entire active profile envelope and provides a complete picture of the response of the profile to coastal processes. Because storms are an important factor in coastal sedimentary processes, it is important to assess profile changes after major storm events. Collecting field data as soon as possible after storms and comparing these profiles to the most recent pre-storm ones provides a measure of areas of erosion and accretion and the volume changes that have occurred.

(2) Accuracy criteria.

(a) Elevation resolution for a typical project profile is estimated to be about 0.012 m at a maximum range.

(b) As described in section 5-3, water bodies are 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 the onshore rod survey and the sled survey to assure that the two systems are recording the same elevations. If offshore surveys are conducted by boat-mounted echosounder, overlap with the rod survey is usually not possible.

(c) Comparison of sled/Zeiss systems and boat echosounder systems has shown sled surveys to have a higher vertical and horizontal accuracy (Clausner, Birkemeier, and Clark 1986). Echosounder 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.

(d) All profile surveys must be referenced to the same elevation datum. This can especially be a problem when echosounder surveys are conducted by different agencies or contractors over time (Figure 5-29). Meticulous field notes must be kept to record datums, corrections, equipment calibrations, and other information that is needed for accurate data reduction.

(3) Analysis techniques.

Table 5-14
Selected Shoreline Movement Studies

Author	Location	Method
Byrnes and Hiland 1994	Cumberland-Amelia Islands, Georgia/Florida	Georeferenced in GIS
Gorman and Reed 1989	Northern New Jersey	Cartographic techniques, map overlays
Anders, Reed, and Meisburger 1990	South Carolina	Cartographic techniques, map overlays
McBride et al. 1991	Louisiana	Georeferenced in GIS
Morton 1979	Texas	Map overlays
Everts, Battley, and Gibson 1983	Cape Henry - Cape Hatteras	Map overlays
Leatherman 1984	Maryland	Metric mapping

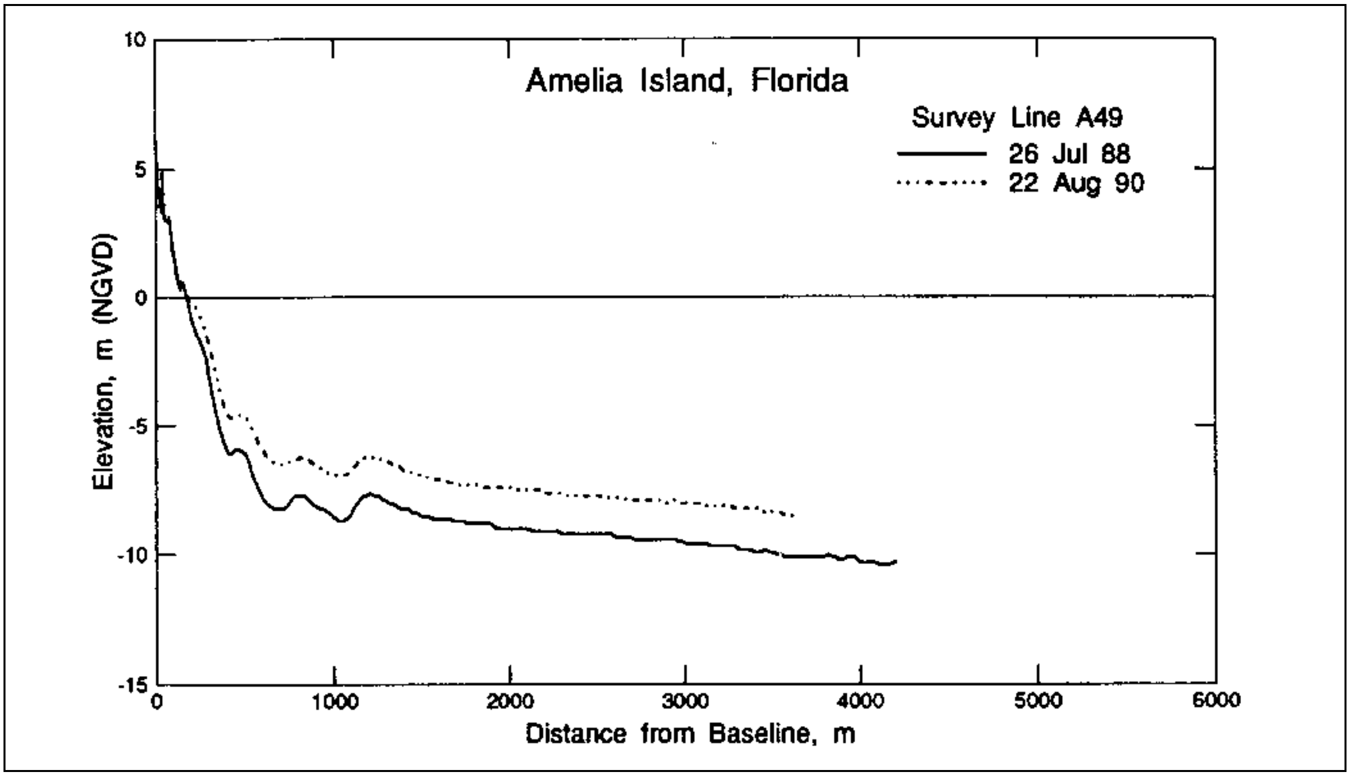


Figure 5-29. Example of vertical offset between two offshore profile surveys due to use of different datums

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

(b) Profile data recorded in the field are typically processed in the laboratory using computer software packages. The 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).

(c) Vertical elevations of important morphologic features found on profiles are usually referenced to NGVD or another datum specified for a particular project. All horizontal distances should be measured from the designated baseline position, preferably located behind the primary dunes for safety (i.e., survival during major storms). 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 volume calculations should be based on the minimum distance value. Survey distances off-shore often vary in length due to the wave conditions at the time of the sled survey.

(4) Profile survey applications.

(a) General. Interpretation of beach response to coastal processes can be done with 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., dunes versus seawalls, 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 studies (Hands 1976, Wright and Short 1983) have documented the cyclic nature of beach topography in response to seasonal shifts in the local 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).

(b) 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 5-30.

- 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 (Hands 1976; 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 is 0.0 (NGVD) (USAE 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.

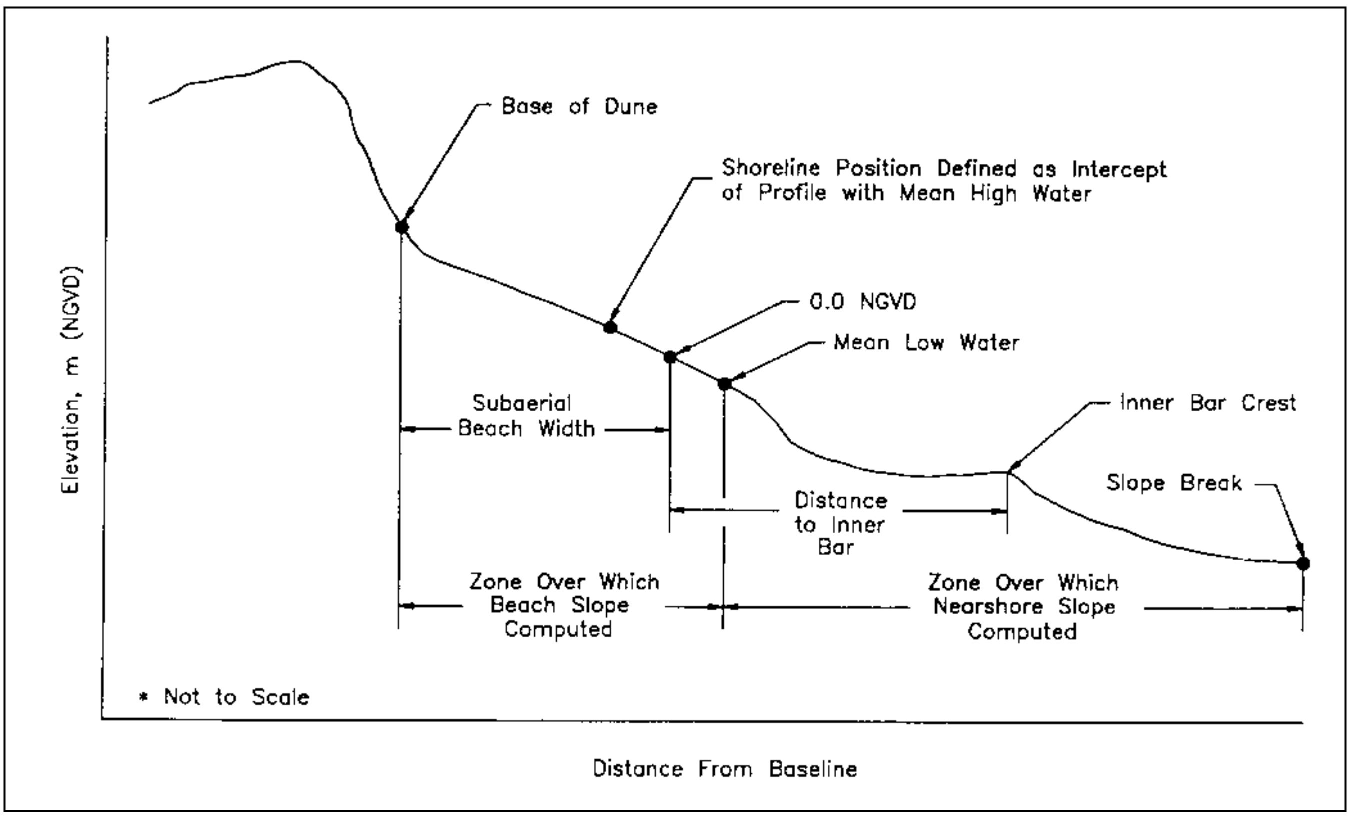


Figure 5-30. Features within the beach and nearshore zone used for linear profile computations

(c) 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 5-31 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.

(d) 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 4-29, 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 most 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 3-21).

Great Lakes beaches also display summer/winter patterns, often characterized by considerable bar movement (Figure 4-30). At some Great Lakes sites, the mobile sand layer is quite thin and seasonal patterns can be difficult to detect (Figure 5-32).

g. Bathymetric data.

(1) Introduction. Analysis and examination of topographic and bathymetric data are fundamental in many studies of coastal engineering and geology. When assembling bathymetric surveys from a coastal area, a researcher is often confronted with an immense amount of data which must be sorted, checked for errors, redisplayed at a common scale, 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.

(2) Bathymetric data processing - data preparation and input.

(a) Most historical bathymetric data sets consist of paper maps with printed or handwritten depth notations (Figure 5-33). Occasionally, these data are available on magnetic media from agencies like NOAA, but often a reseacher 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.

(b) In order to be able 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 Corporation's Contour Plotting System 3 (CPS-3) or Golden Software's Surfer. These are comprehensive packages of file manipulation, mapping algorithms, contouring, and 2- and 3-dimensional display. Their use requires considerable training, but they are powerful analysis tools.

(c) The raw data used by mapping programs consists of data in X-Y-Z form. As described in the previous section, 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, the 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. The X and Y points should typically

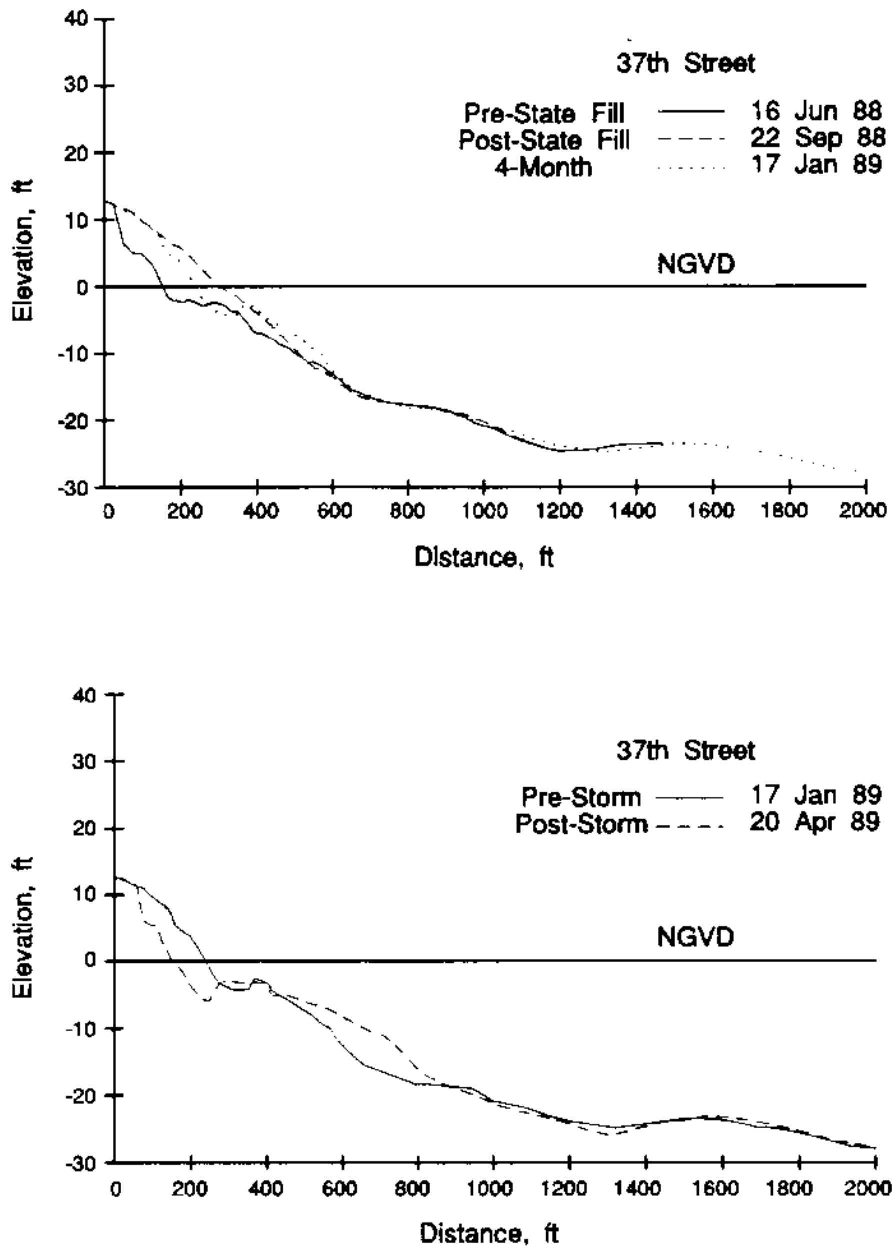


Figure 5-31. Analysis of the Ocean City, MD, beach fill project. Upper plot shows profile before beach fill and the large quantity of sand placed on the beach during the summer of 1988. Lower plot shows erosion of the upper profile during a storm in early 1989. Sand from the beach moved offshore to the region between 400 and 900 ft from the benchmark

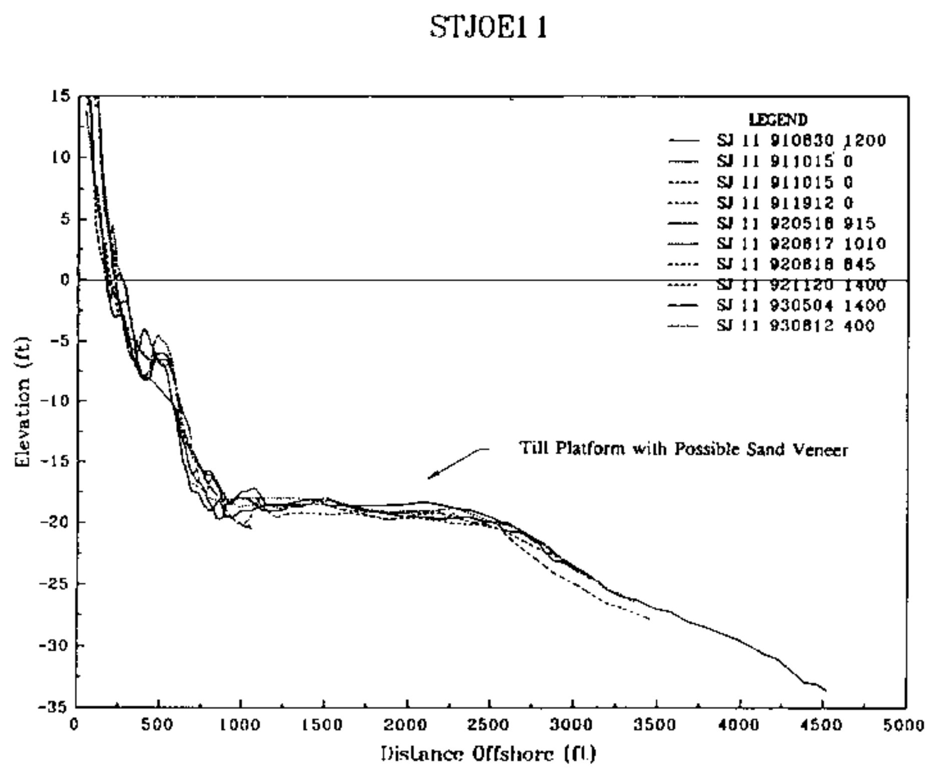


Figure 5-32. Profile envelope from St. Joseph, Michigan. The horizontal platform from 1,000 to 2,500 ft offshore is an exposed till surface. Most shoreface sand movement appears to be confined to the zone landward of the till platform, although it is likely that thin veneers of sand periodically cover the till (previously unpublished CERC data)

represent Cartesian coordinates, which is the case if the original maps were based on State Plane coordinates. X and Y points which are latitude and longitude must be converted by the program.

(3) Gridding operations.

(a) Gridding is a mathematical process in which a continuous surface is computed from a set of randomly distributed X, Y, and Z data.[1] 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 5-34 and 5-35). Because the grid represents the surface that is being modeled, the accuracy of the grid 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 comparison 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 were very different.

(b) 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.

[1] Examples in this section were prepared using CPS-3 mapping software from GeoQuest Corporation. However, the overall concepts and procedures discussed are general, and other software packages perform similar functions.

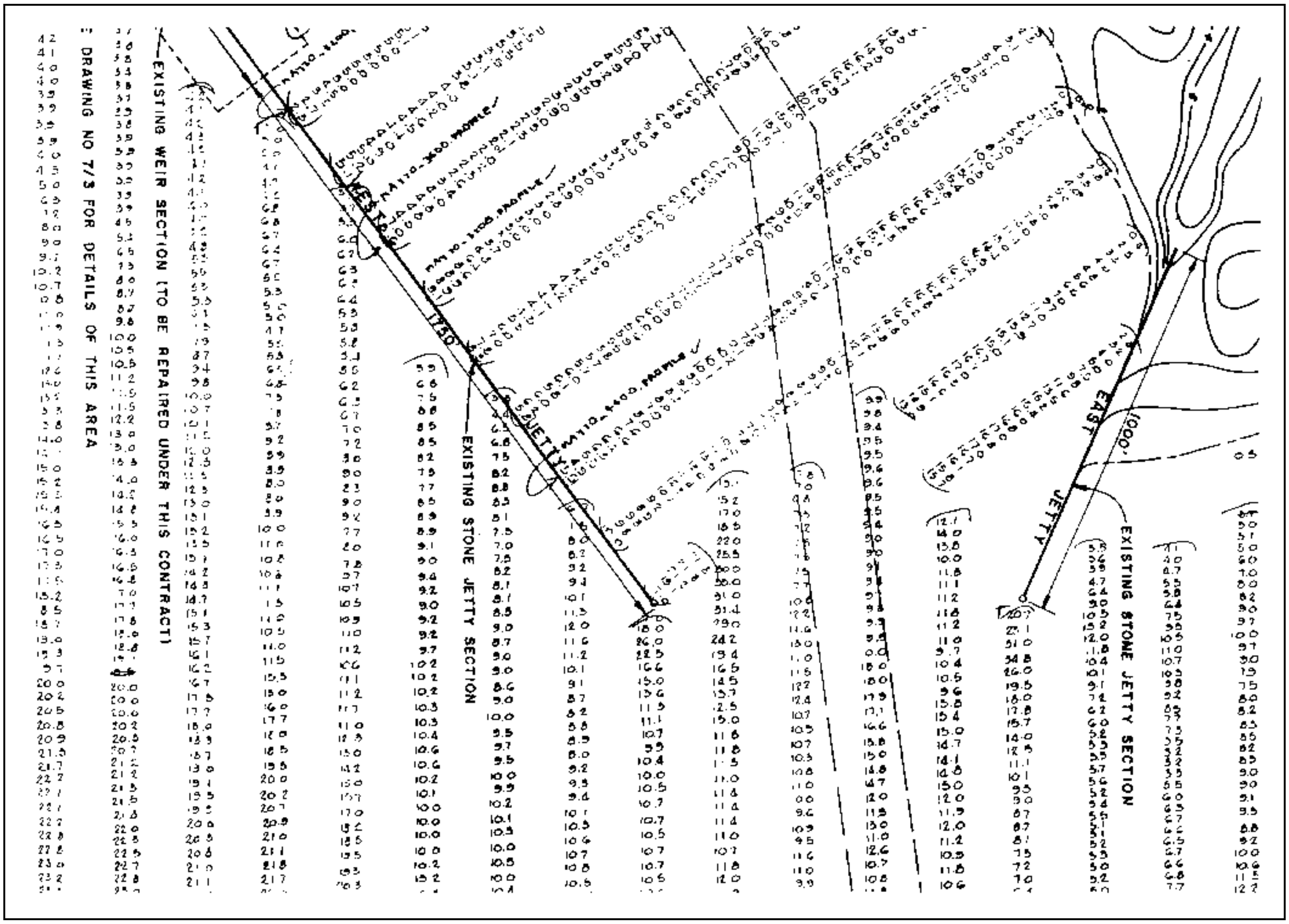


Figure 5-33. Example of a hand-annotated hydrographic map from a Florida project site. The depths have been corrected for tide and are referenced to mlw. (Map courtesy of USAE District, Mobile)

- 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 grid. 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-contured chart is not a valid test because hand-contouring is a very subjective procedure.

(4) 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 bathymetric data 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.

(a) Gridding algorithms include:

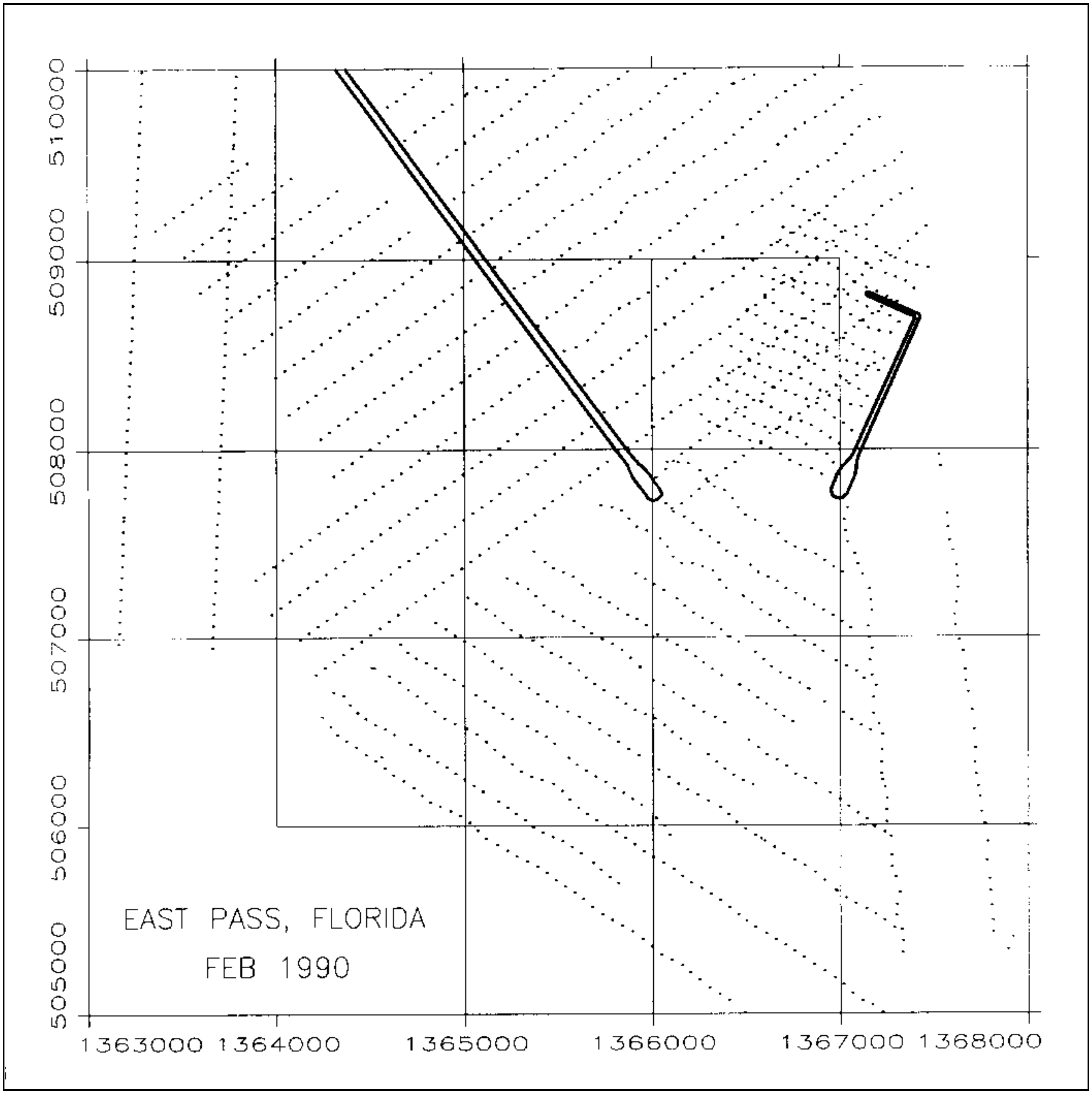


Figure 5-34. Digitally collected hydrographic data from a Florida project site. The track lines are obvious, as is the fact that the soundings are not uniformly distributed throughout the survey area. (Data courtesy of USAE District, Mobile)

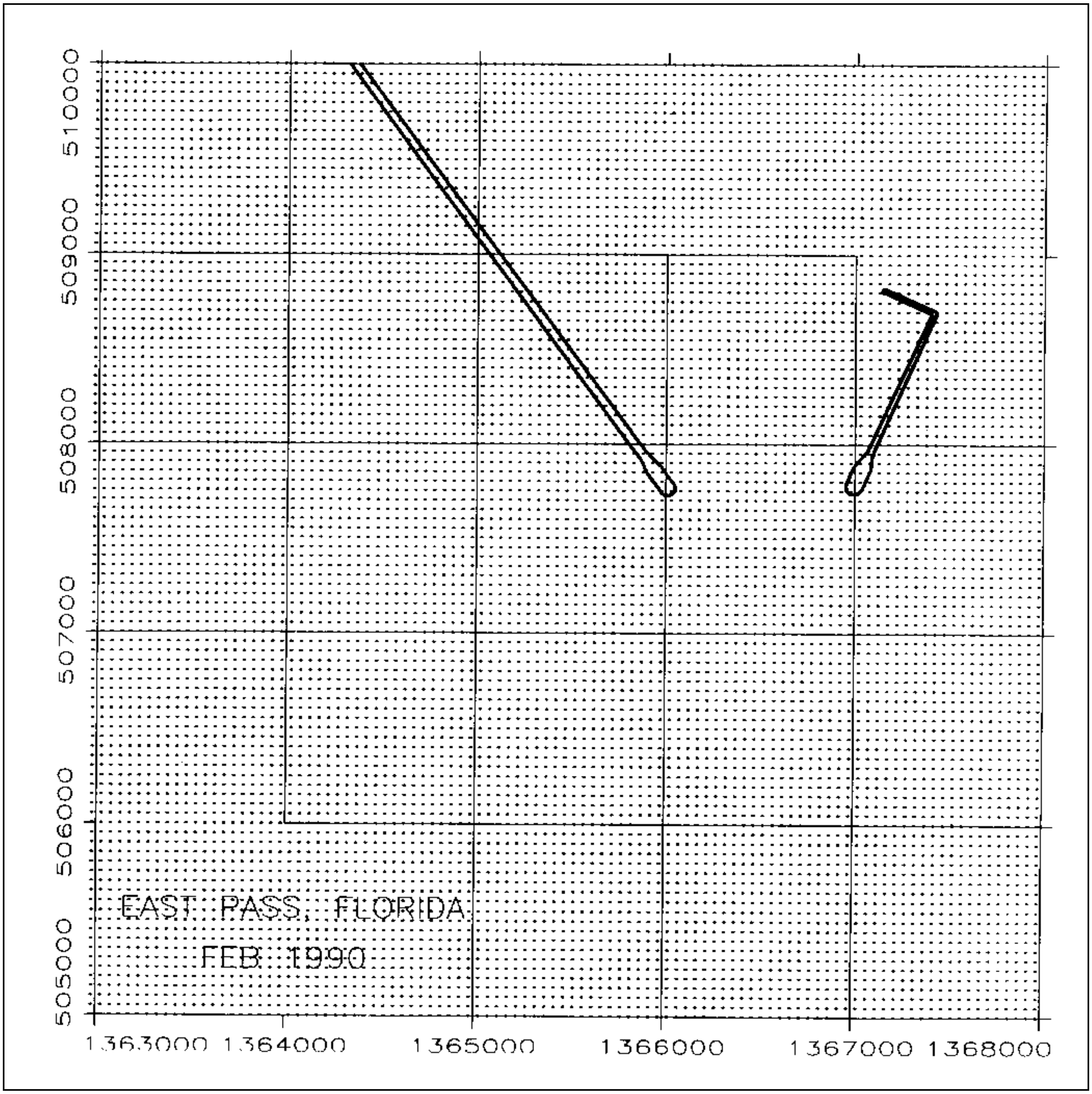


Figure 5-35. Surface grid computed by CPS-3 based on the data shown in Figure 5-31. The nodes are uniformly spaced compared with the locations of the original soundings. A grid does not necessarily have to be square, although this is common

- 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-weighting 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.

(b) Another important parameter that must be chosen is the 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.

(4) Applications and display of gridded data.

(a) Contouring of an area is one of the most common applications of mapping software (Figure 5-36). 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.

(b) 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 5-37). Computation of volumetric changes over time is another application (Figure 5-38). This can graphically demonstrate how shoals develop or channels migrate.

(c) 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 5-37, the overall change in volume of the East Pass ebb-tidal shoal between 1967 and 1990 was only 19 percent (Figure 5-39). 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!

(5) Error analysis of gridded bathymetry.

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

(b) 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 ± 0.5, ± 1.0, or ± 1.5 ft, based on the class of the survey, can be used (Table 5-4). 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 historic surveys, positioning error may be important, requiring a much more complicated analysis procedure. Positioning accuracy of hydrographic surveys is discussed in EM 1110-2-1003 and NOAA (1976).

(c) 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:

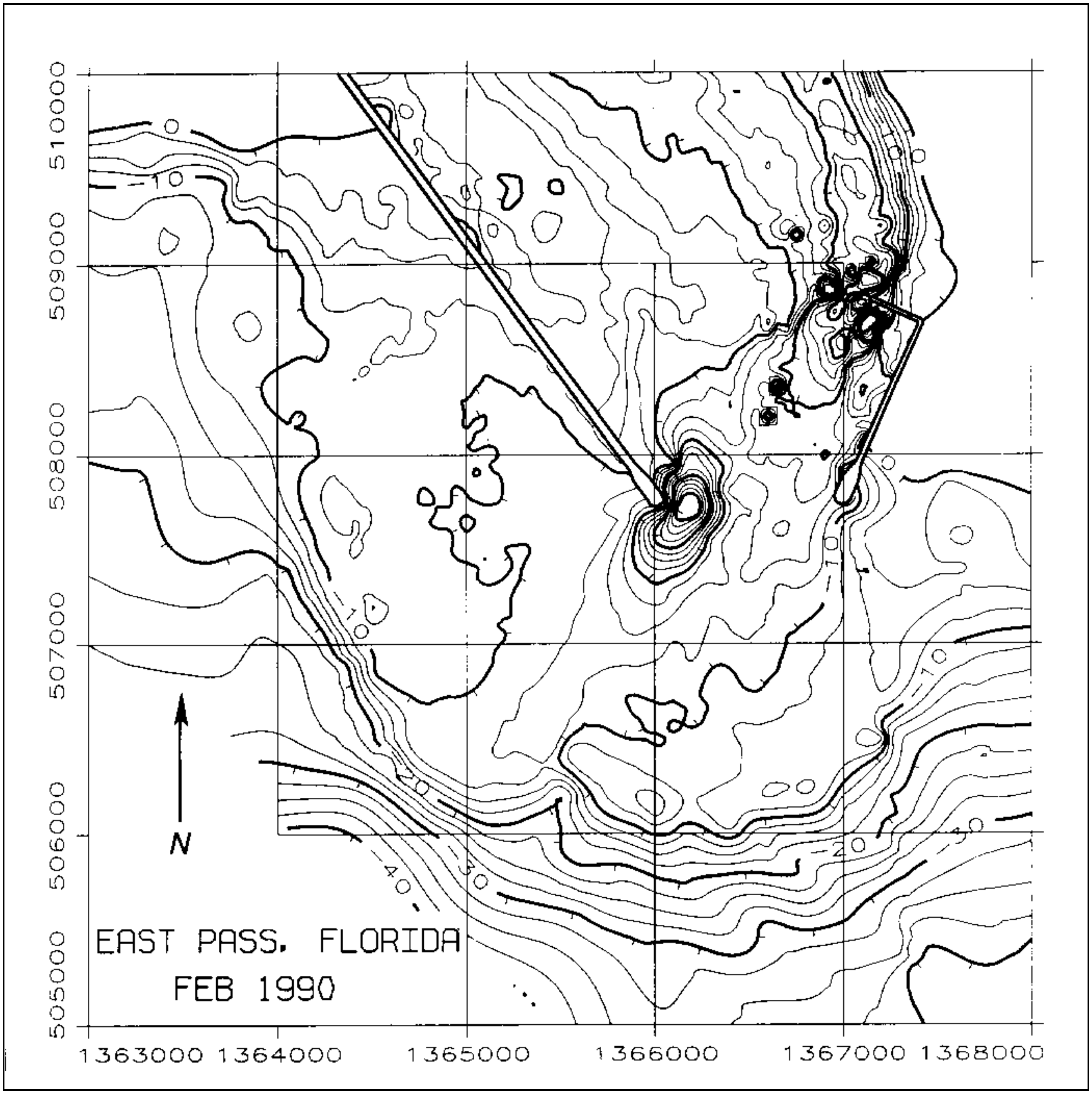


Figure 5-36. Contoured bathymetry of the same area shown in Figures 5-34 and 5-35. Depths in feet below mlw

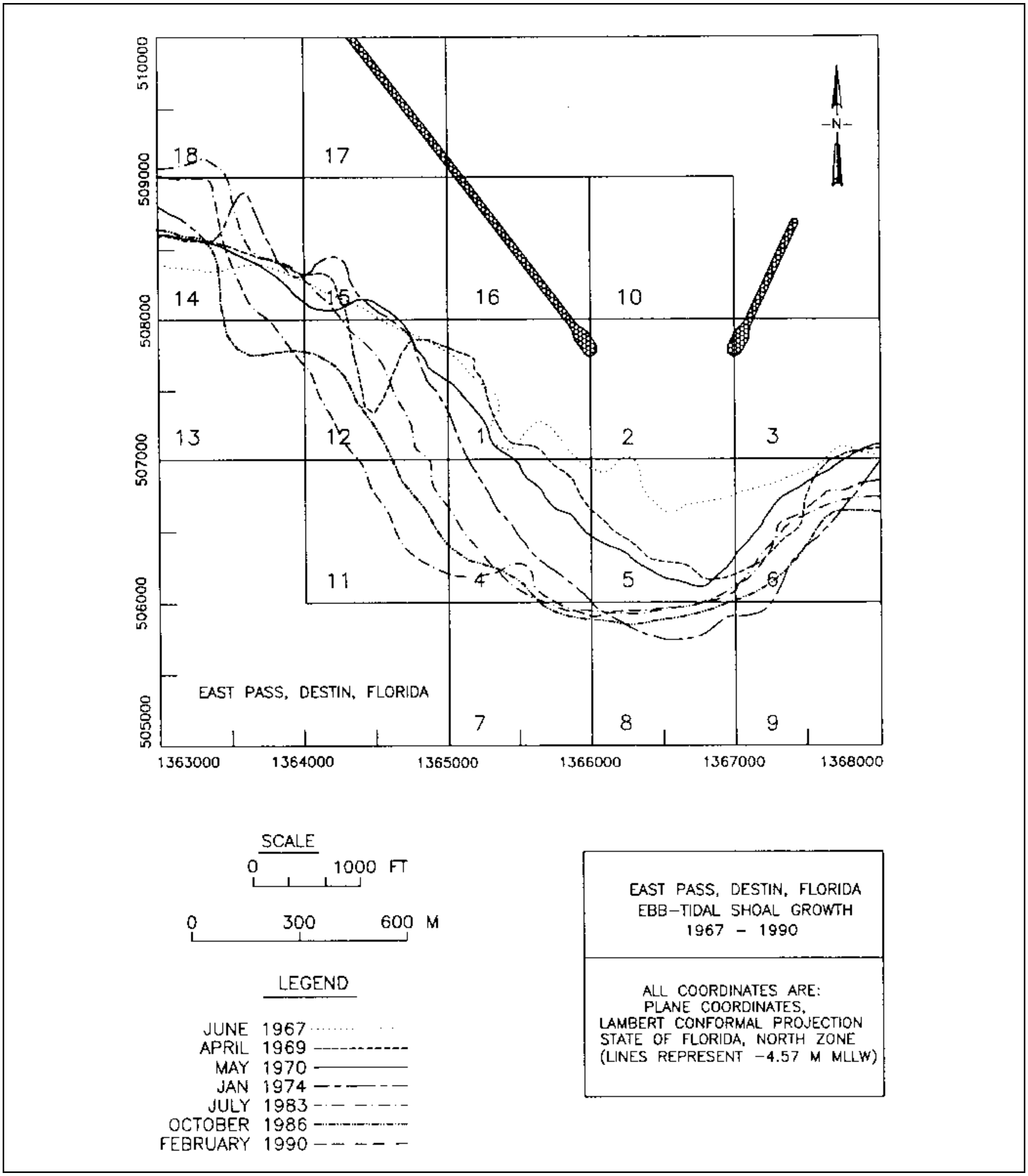


Figure 5-37. Overall growth of an ebb-tidal shoal over 24 years is shown by the advance of the 15-ft isobath. This isobath was chosen because it represented approximately the mid-depth of the bar front. The 1000-ft squares are polygons used for volumetric computations (Morang 1992a)

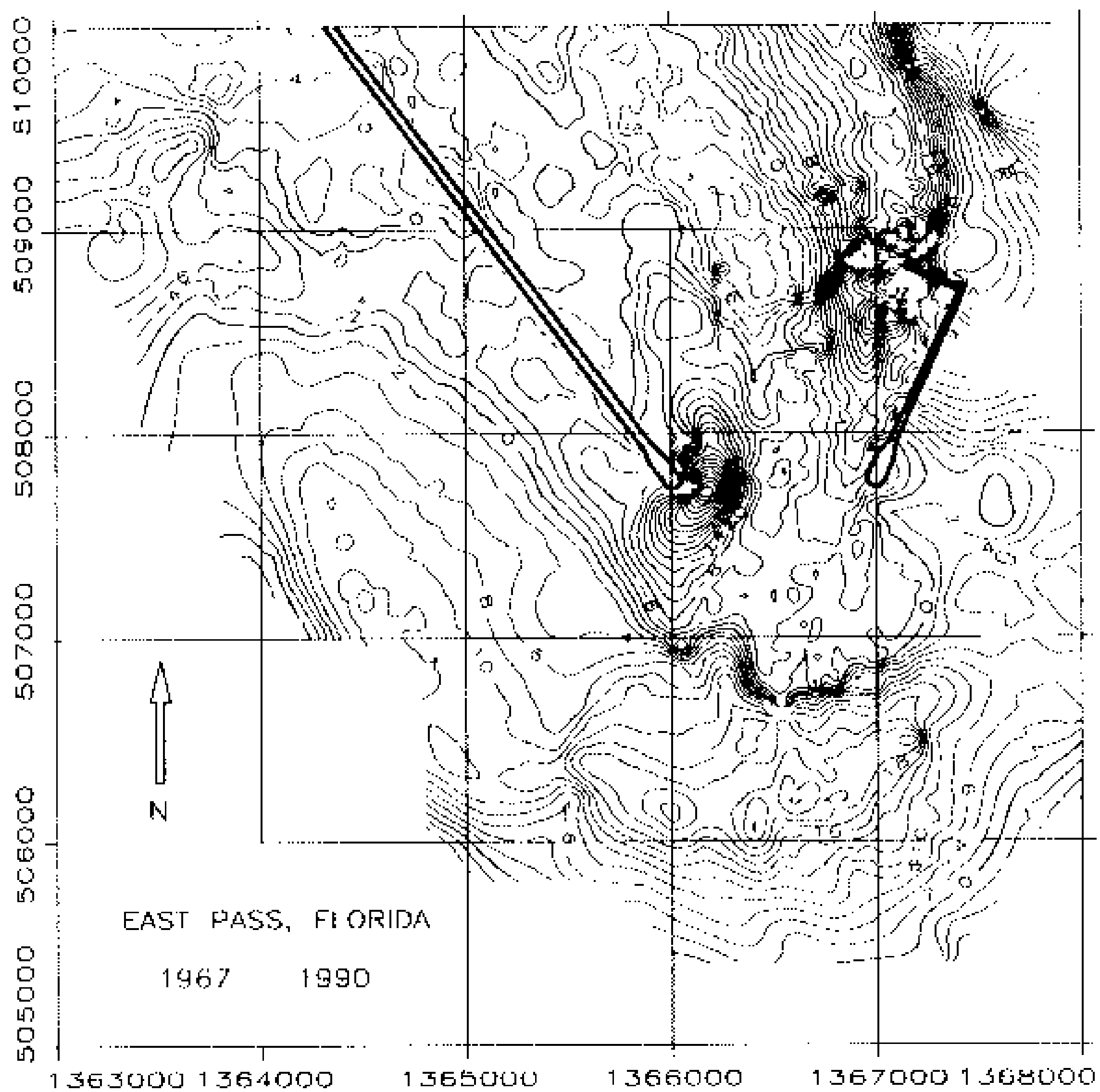


Figure 5-38. Isopach map showing overall changes in bottom configuration between 1967 and 1990 at East Pass, Florida. Red contours represent erosion, while green represent deposition (both colors at 2-ft interval). The black contour line represents the zero line (no erosion or deposition). The migration 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 1992a)

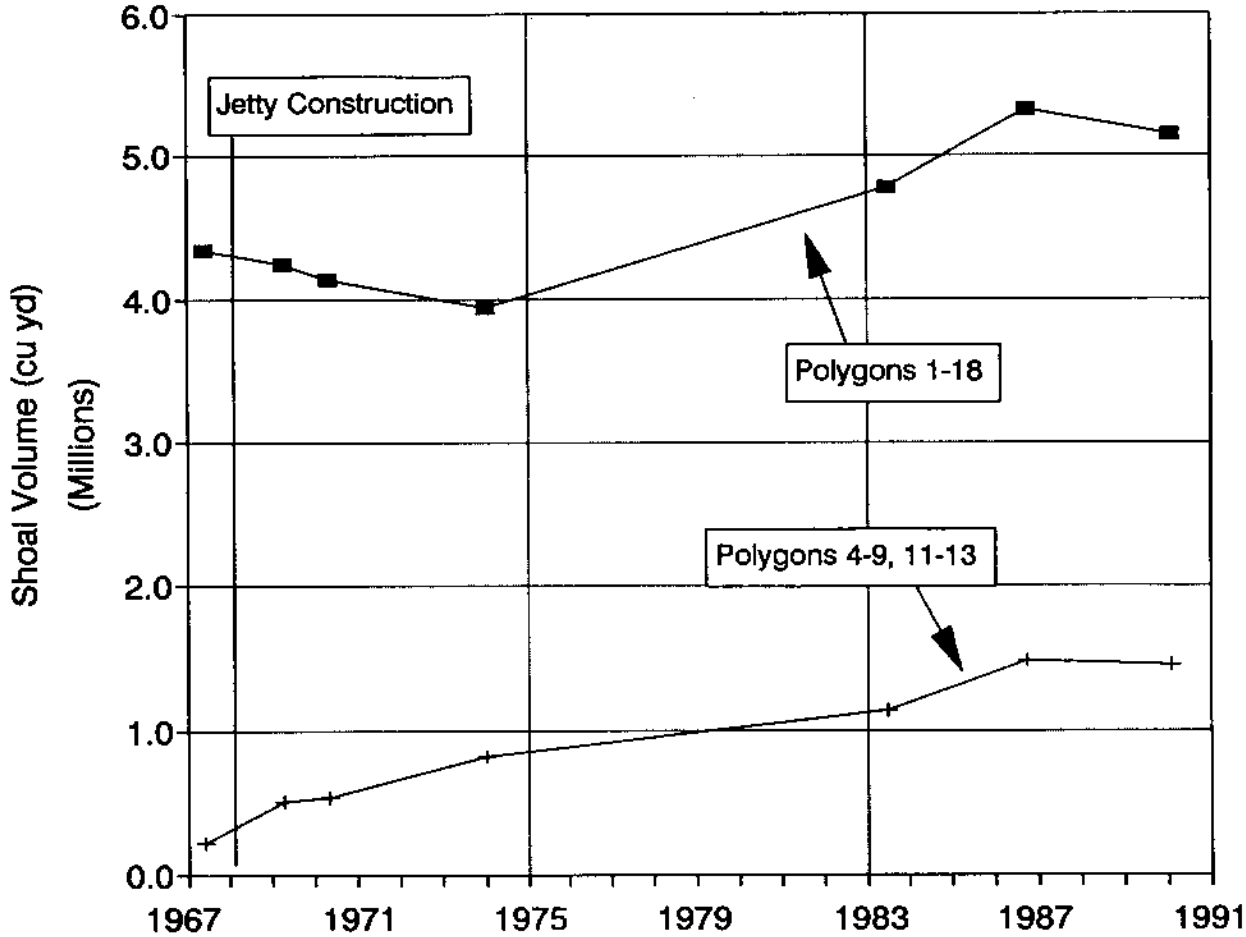


Figure 5-39. Growth of the ebb-tidal shoal at East Pass, FL. Areas used in the computations are shown in Figure 5-37. Growth rates are dramatically different depending upon which polygons are included in the volumetric computations

$$\frac{2 \times \Delta Z}{\Delta Z_{ave}}$$

For example, if $\Delta Z = 0.15$ m and $\Delta Z_{ave} = 1.0$ m, then MLE is:

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

Note that this is for a Class 1 survey; many offshore surveys are not conducted under such tight specifications. If $\Delta Z = 0.46$ 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 ± 91 percent.

(d) 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.

(e) 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.

h. Sediment grain size analyses.

(1) Introduction[1].

(a) The coastal zone is comprised of many dynamic morphologic features that frequently change their form and sediment distribution. Although a beach can display a large range of sizes and shapes, each beach is characterized by particular texture and composition representing the available sediment (Davis 1985). Textural trends alongshore and cross-shore are indicative of the depositional energy and the stability (or instability) of the foreshore and nearshore zones.

(b) Because of natural variability in grain size distributions, a sampling scheme should adequately sample the native beach in both the cross-shore and alongshore directions. Sediment sampling needs to coincide with survey profile lines so that the samples can be spatially located and related to morphology and hydrodynamic zones. Consideration of shoreline variability and engineering structures should be factored into choosing sampling locations. A suggested rule of thumb is that a sampling line be spaced every half mile, but engineering judgment is required to define adequate project coverage. On each line, it is recommended that samples be collected at all major changes in morphology along the profile, such as dune base, mid-berm, mean high water, mid-tide, mean low water, trough, bar crest, and then 3-m intervals to depth of closure (Figure 5-40) (Stauble and Hoel 1986).

(2) Grain size analysis statistics.

(a) Sediments should be sieved using U.S. Standard sieves at 1/4-phi (ϕ) unit intervals. *Phi* (ϕ) is defined as the negative logarithm of the grain dimension in millimeters to the base 2. The equation for the relationship of millimeters to phi scale is:

$$\phi = -\log_2(d_{mm}) \qquad (5\text{-}3)$$

where

d_{mm} = particle diameter in millimeters

[1] Text condensed from Gorman et al. (in preparation)

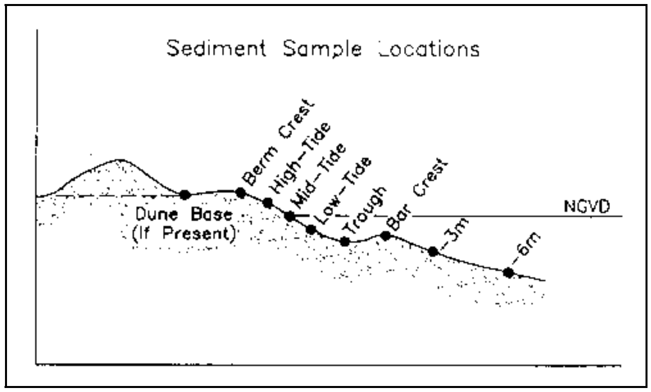


Figure 5-40. Recommended sampling locations at a typical profile line

(b) Grain-size analyses should include grain-size distribution tables, statistics and graphics of frequency, cumulative frequency and probability distribution (see "Calculation of Composite Grain Size Distribution" in the *Automated Coastal Engineering System* (ACES) of Leenknecht, Szuwalski, and Sherlock (1992) and ASTM Standard D 2487-92. Standard grain-size distribution statistics include:

- Median grain size or d_{50} - the particle size in the center of the population.
- Mean grain size or average grain size.
- Standard deviation or the spread of the distribution about the mean - defines the concept of sorting.
- Skewness or measure of symmetry of the distribution around the mean.
- Kurtosis or measure of the peakedness of the frequency distribution.

Each of these statistical parameters provides information on the grain-size distribution and its depositional environment. The mean is the most commonly used statistic to characterize the average grain size of the distribution. The median value can be read directly off a cumulative curve and is near-normal to the mean in a normal distribution but differs if the distribution is non-normal. The sorting gives the spread of the various grain sizes in the distribution. A *well-sorted distribution* contains a limited range of grain sizes and usually indicates that the depositional environment contains a narrow range of sediment sizes or a narrow band of depositional energy. A *poorly sorted distribution* contains a wide range of grain sizes indicating multiple sources of sediment or a wide range of energies of deposition. *Positive skewness* indicates an excess of fine grain sizes, whereas *negative skewness* indicates an excess of coarser grain sizes. The *kurtosis* measures the ratio between the sorting in the tails of the distribution relative to the central portion (sand size) of the distribution.

(c) These statistical parameters are commonly calculated by two different methods. The *graphic method* uses specific percentiles of a grain-size distribution (i.e., 5, 16, 25, 50, 75, 84, and 95) that are read from graphical data plots (Folk 1974) or can be calculated from sieve data. The values are used in simple equations to produce the approximate statistical parameters. Phi values are used to calculate these parameters, and only the mean and median should be converted to millimeter values. The *method of moments* uses the entire grain-size distribution values to mathematically produce the statistical parameters (Friedman and Sanders 1978). This procedure is more accurate, but was time-consuming to calculate before the use of computers; for this reason, older sediment statistical data are commonly based on the Folk graphic method. Additional consideration for the user of grain size statistics are listed below:

- The graphical and moment methods are *not* directly comparable. Because sediment statistics for many projects have historically been calculated by the graphic method, for uniformity it may be best to continue using the graphic method.

- The graphic and moment procedures have advantages and disadvantages. These are summarized in Table 5-15.

- Note that calculated statistical parameters are only an indication of the characteristics of the sediment in the field. The user must not assume that the whole population has exactly these characteristics.

- Accurate sediment grain-size statistics are dependent on adequate sample size. Recommendations for field sampling have been listed in Table 5-9.

The following sections list equations and provide verbal description of sediment grain-size parameters for both the graphic method and the method of moments. The equations are identical to those used in the USACE ACES software (Leenknecht, Szuwalski, and Sherlock 1992).

(d) Mean grain size. Table 5-16 lists formulas and descriptive criteria for classifying the mean grain size of a sample.

(e) Standard deviation (sorting). The standard deviation or measure of sorting uses the equations and verbal descriptors listed in Table 5-17.

(f) Skewness. The skewness or measure of symmetry shows excess fine or coarse material in the grain-size distribution. Table 5-18 lists equations used for the graphic method and method of moments, with the range of verbal descriptors.

(g) Kurtosis. Kurtosis or measure of the peakedness of the grain-size distribution relates sorting of the tails compared to sorting of the central portion of the distribution. The equations listed in Table 5-19 are used for the graphic method, which centers around graphic kurtosis K_G = 1.00, and the method of moments, which centers around the moment kurtosis k = 3.00. The range of

Table 5-15
Comparison of graphic and moment procedures for calculating grain-size statistics

Method	Advantages	Disadvantages
Graphic	Can be calculated from almost all distribution data	Does not use all data from all sieves
	Resistant to sampling and laboratory errors (i.e., a single faulty sieve does not invalidate the calculated statistics)	
	Can use open-ended samples (more than 5 percent of sample weight on either tail)	
Moment	Uses formula that has a greater number of parameters	Parameters have to be established in laboratory
	Uses data from all sieves	Parameters should be important to the application; otherwise may be more than needed or useful
		Open-ended distributions (more than 5 percent of sample in either tail) must be excluded, therefore losing the geologic information that these samples might reveal

Table 5-16
Mean Grain Size

Graphic Mean, M:

$$M = \frac{\phi 16 + \phi 50 + \phi 84}{3} \tag{5-6}$$

Where: ϕn = grain size of nth weight percentile in phi units

Moment Mean, *x*:

$$\overline{x} = \frac{\Sigma\, f\, m_\phi}{100} \tag{5-7}$$

Where: f = frequency weight percent
m_ϕ = midpoint of size class

Descriptive Criteria:

Grain size (mm)	Grain size (Phi)	Wentworth Classification
1.00 - 2.00	0.0 - -1.0	Very Coarse Sand
0.50 - 1.00	1.0 - 0.0	Coarse Sand
0.25 - 0.50	2.0 - 1.0	Medium Sand
0.125 - 0.25	3.0 - 2.0	Fine Sand
0.0625 - 0.125	4.0 - 3.0	Very Fine Sand

Table 5-17
Sample Standard Deviation (Sorting)

Graphic Sorting, σ:

$$\sigma = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \tag{5-8}$$

Moment Sorting, σ:

$$\sigma = \left[\frac{\Sigma\, f\, (m_\phi - \overline{x})^2}{100} \right]^{\frac{1}{2}} \tag{5-9}$$

Descriptive Criteria:

Sorting Range (Phi)	Description of Sorting
<0.35	Very well sorted
0.35 - 0.50	Well sorted
0.50 - 0.71	Moderately well sorted
0.71 - 1.00	Moderately sorted
1.00 - 2.00	Poorly sorted
2.00 - 4.00	Very poorly sorted
> 4.00	Extremely poorly sorted

Table 5-18
Sample Skewness

Graphic Skewness, *Sk*:

$$Sk = \frac{\phi16 + \phi84 - 2(\phi50)}{2(\phi84 - \phi16)} + \frac{\phi5 + \phi95 - 2(\phi50)}{2(\phi95 - \phi5)} \quad (5\text{-}10)$$

Moment Skewness, *Sk*:

$$Sk = \frac{\Sigma\, f\,(m_\phi - \overline{x})^3}{100\ \sigma^3} \quad (5\text{-}11)$$

Descriptive Criteria:

Skewness Range	Description of Skewness
+1.0 to +0.3	Very fine-skewed
+0.3 to +0.1	Fine-skewed
+0.1 to −0.1	Near-symmetrical
−0.1 to −0.3	Coarse-skewed
−0.3 to −1.0	Very coarse-skewed

Table 5-19
Sample Kurtosis

Graphic Kurtosis, K_G:

$$K_G = \frac{\phi95 - \phi5}{2.44\ (\phi75 - \phi25)} \quad (5\text{-}12)$$

Descriptive Criteria for Graphic Method:

Graphic Kurtosis Range	Description of Kurtosis
< 0.67	Very platykurtic (flat)
0.65 to 0.90	Platykurtic
0.90 to 1.11	Mesokurtic (normal distribution)
1.11 to 1.50	Leptokurtic
1.50 to 3.00	Very leptokurtic
> 3.00	Extremely leptokurtic (peaked)

Moment Kurtosis, *k*:

$$k = \frac{\Sigma\, f\,(m_\phi - \overline{x})^4}{100\ \sigma^4} \quad (5\text{-}13)$$

Descriptive Criteria for Moment Method:

Moment Kurtosis Range	Description of Kurtosis
< 3.00	Platykurtic (flat)
Around 3.00	Mesokurtic (normal distribution)
> 3.00	Leptokurtic

verbal descriptors of peakedness is based on the platykurtic (flat) curve versus the leptokurtic (peaked) curve, with a mesokurtic curve as normal.

(3) Composite sediments[1]. Combining samples from across the beach can reduce the high variability in spatial grain size distributions on beaches (Hobson 1977). Composite samples are created by either physically combining several samples before sieving or by mathematically combining the individual sample weights to create a new composite sample on which statistical values can be calculated and sediment distribution curves generated. Samples collected along profile sub-environments can be combined into composite groups of similar depositional energy levels and processes as seen in Figure 5-41. Intertidal and subaerial beach samples have been found to be the most usable composites to characterize the beach and nearshore environment area. After comparing several composite groups, Stauble and Hoel (1986) found that a composite containing the mean high water, mid-tide, and mean low water gave the best representation of the foreshore beach. They found that nearshore sample composite sediment distributions changed little over time. This suggests that active sorting and sediment transport occur on the active beach face and bar area and that nearshore sands remain uniform over time.

(4) Seasonal variability. There can be a wide variability in grain size distribution on a native beach between winter high wave periods and summer fair weather periods. This variability can be a problem in choosing a representative native beach. The winter grain size distribution usually is coarser and more poorly sorted than the summer distribution (due to the higher frequency of storms in the winter). The concept of the seasonal beach cycle is based on the frequency of storm-induced erosion and fair weather accretion. Extreme events, such as hurricanes that occur in the summer or early fall, as well as mild winters with few extratropical storms, may cause perturbations on the seasonal cycle. A sampling strategy to characterize the seasonal variability should take into account the recent local storm climate.

[1] Text adapted from Stauble (1994).

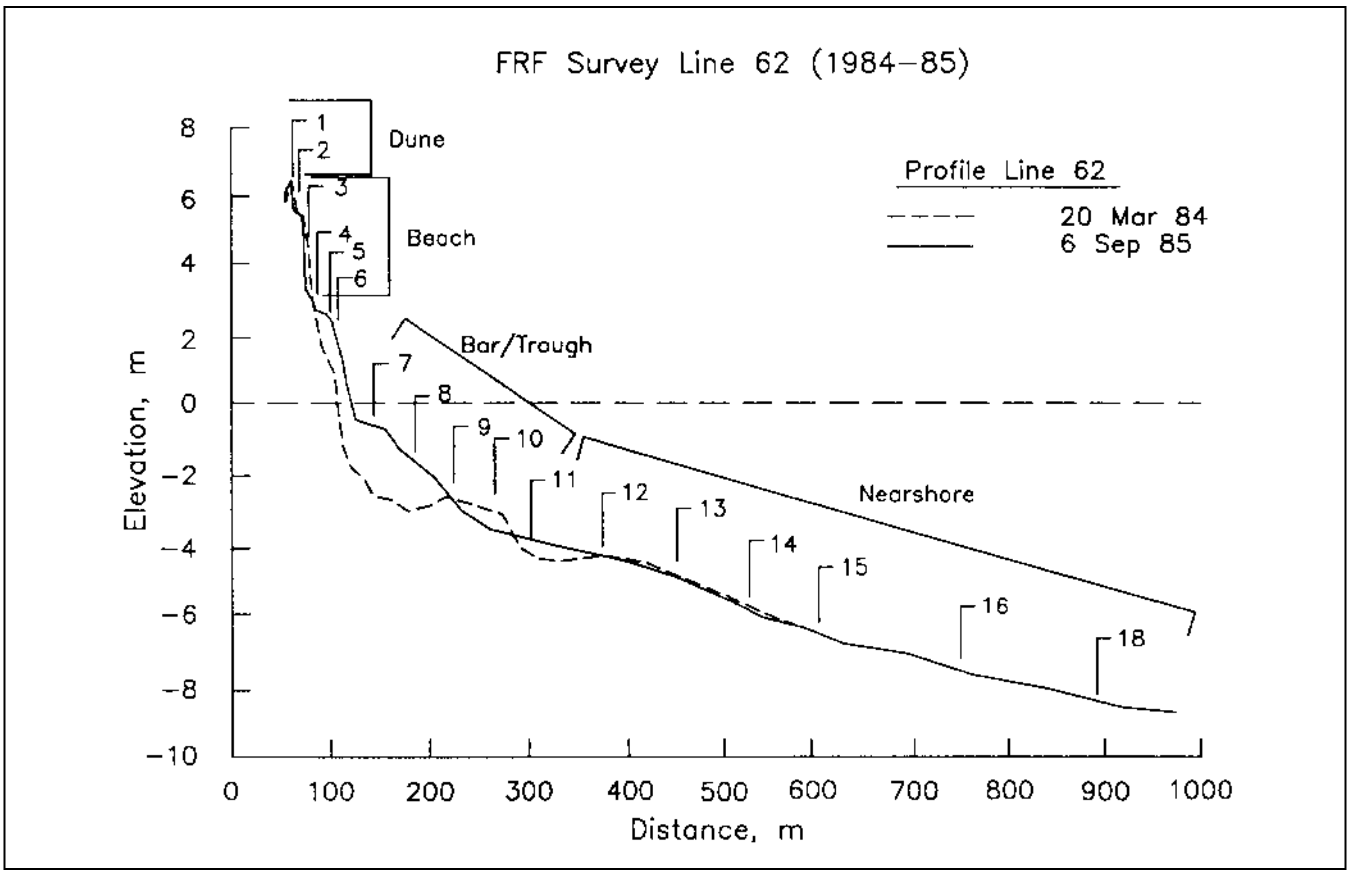


Figure 5-41. Combination of samples into composite groups of similar depositional energy levels and processes (example from CERC Field Research Facility, Duck, NC)

(5) Sediment data interpretation.

(a) Grain size distributions of beach sediment vary with both time and space. Because of the daily wave and tidal influence on sediment deposition on the beach foreshore, swash processes create an ever-changing foreshore sediment distribution. The use of composites helps to simplify the analysis and interpretation of these changes. The bar/trough area also experiences a wide variety of energy conditions and thus displays a variety of grain size distributions over time. Dune and nearshore grain size distributions have less variability due to the lower energy conditions that affect these areas. The dune is primarily influenced by wind transport, which limits change to the finer grain sizes except under extreme wave conditions, when the waves actually impact on the dune. The nearshore zone is dependant on regional and local coastal processes.

(b) An example of composite grain size distribution curves for the beach at the Field Research Facility, Duck, NC, is shown in Figure 5-42. Using the entire distribution from coarse to fine sizes shows the changes in size classes for various depositional regimes. The beach group composite is illustrated because it displayed the greatest variability in distribution during the study. The bimodal nature of the distribution can be seen, with increases in the coarse mode fraction after storms or when samples on the foreshore contained granule-size lag deposits. The coarsest material was present early in the study period during the winter storm period. Later, the distribution shifted to the finer mode except during July, 1985, when a coarse fraction was present. Swash processes of uprush and backwash are the principal transport mechanism in this area.

(c) Spatial variation along a beach is more complex. Analysis of grain size data from six profiles at Ocean City, MD, shows the influence of beach fill placement and storm processes. Figure 5-43 shows the change in mean grain size of the foreshore composites (high tide, mid-tide and low tide samples) for the six profiles located along the central section of the beach fill project. Between the pre- and post-fill sampling, the means became finer and the volume of the profile increased on five of the six locations as the fill was placed. Storm processes caused the foreshore means to become coarser, but a return to finer foreshore mean was found with storm recovery. From these studies, a general trend to coarser (and more poorly sorted) sediment grain size distribution occurred after high wave conditions. High wave power values and, to a lesser extent, wave steepness values correlated with times when the means became coarse. The shift to finer means occurred as the wave parameters decreased.

i. Coastal data display and analysis using Geographic Information Systems.

(1) Definitions.

(a) Geographic Information Systems - known as GIS - are information-oriented computerized methods designed to capture, store, correct, manage, analyze, and display spatial and non-spatial geographic data (Davis and Schultz 1990). Using computer-based technology, GIS methodology has revolutionized many of the traditional, manual methods of cartographic analysis and display. GIS is an outgrowth of many existing technologies: cartography, spatial analysis, remote sensing, computer mapping, and digital database management.

(b) GIS is based on the manipulation of spatial data. The term *spatial data* refers to “any data or information that can be located or tied to a location, regardless of the original form (tabular, map, image, or some other form). Essentially, spatial data possess attributes or characteristics that are linked to location.” (Davis and Schultz 1990).

(2) Components.

(a) Many of the data manipulation operations required to analyze bathymetric data, aerial photographs, and historic maps can be accomplished with GIS. Five major components of GIS include:

- Geographic database.
- Software.
- Hardware.
- User interface.
- Support for equipment and structure (people, organization, training).

(b) The major functions of GIS include:

- Collection.
- Storage.
- Retrieval.

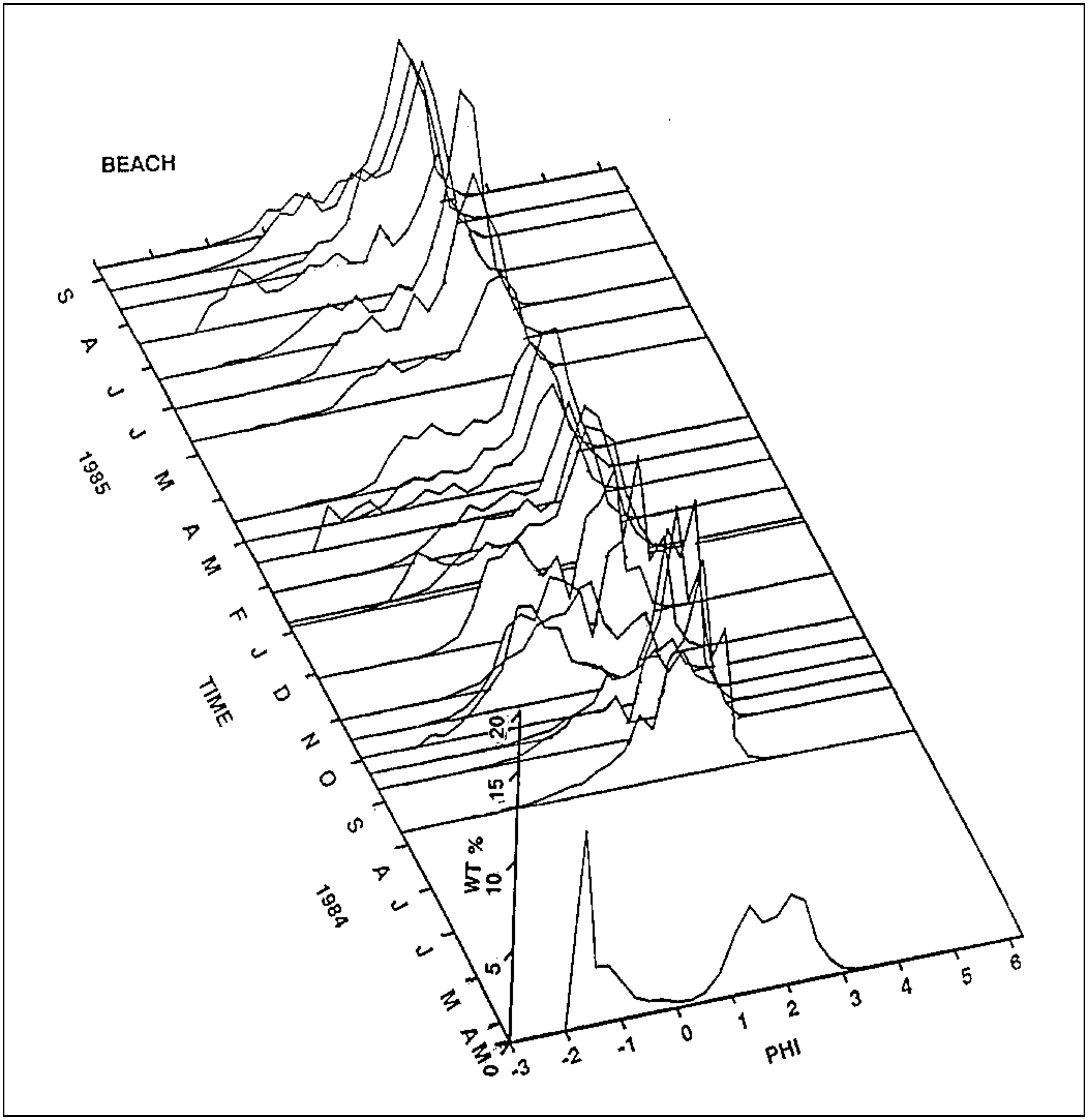


Figure 5-42. Plots of beach composite grain size distribution curves over time from the CERC Field Research Facility at Duck, NC

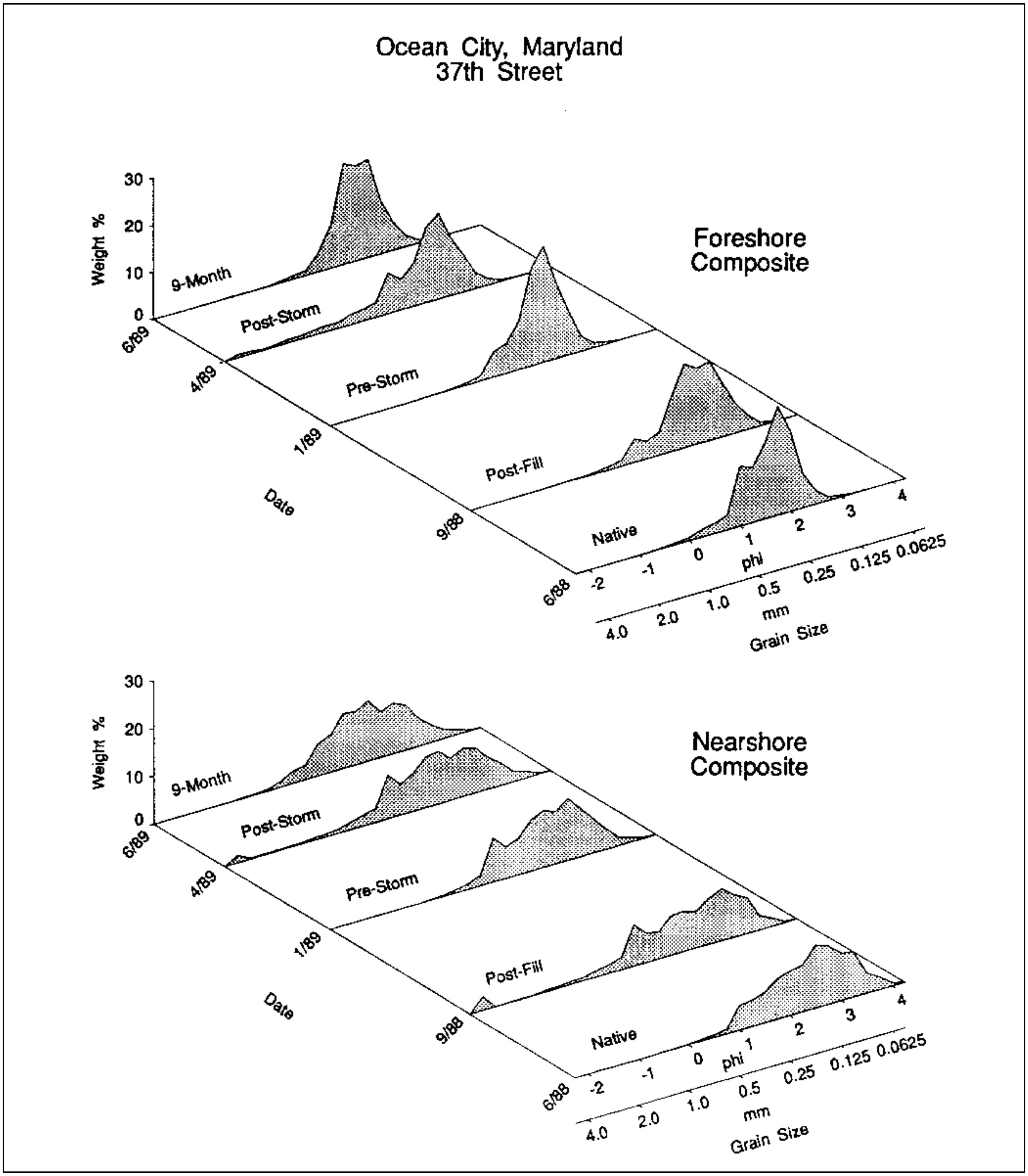


Figure 5-43. Change in mean grain size of the foreshore composites (high tide, mid-tide, and low tide samples) for six profiles located along the central section of the beach fill, Ocean City, MD

- Transformation.
- Analysis.
- Modelling.
- Display or output.

(c) The key operations that accompany the above functions are:

- Data capture and entry.
- Database management.
- Data manipulation, correction, and analysis.
- Reporting and map production.

(d) Although initially GIS was considered a subset of remote sensing and cartography, it has grown in recent years into a discipline with its own theories, approaches, techniques, and interests. The topic is too complex to cover in detail in this manual, and the reader is urged to refer to the pertinent literature. A readable primer (containing an extensive bibliography and glossary) is presented by Davis and Schultz (1990). More detailed coverage of GIS concepts and discussion of ARC/INFO® software is covered in Environmental Systems Research Institute (1992).

(3) Management and use of GIS. Rapidly declining hardware costs have made GIS affordable to an increasingly wider range of agencies. In addition, many scientists and planners are realizing that GIS may be the only effective way to interpret, display, and make more understandable vast quantities of geologic and terrain data. GIS, however, is not a panacea for all of an agency's data analysis problems. Use of a GIS in an organization requires a major commitment in training, funding, and managerial skill because the technology is relatively new and unfamiliar. Most agencies must accept new procedures in archiving and organizing data, performing quality control, updating and supporting software and hardware, and assigning key personnel to training and long-term practical projects. The latter point is critical - users cannot simply sit down at a terminal, experiment with the software for a few hours, and have any likelihood of producing effective or trustworthy data products. The decision to purchase and develop a GIS should not be taken lightly!

(4) Coastal data suitable for GIS. Some uninitiated users have the impression that GIS is a magic box that can display all kinds of geologic and marine data. In theory, this may be true. In reality, cost of hardware and data management is always a limiting factor. The more data that a particular database contains, the more costly the management, maintenance, and quality control of that information. Table 5-20 summarizes some of the types of coastal data that can be included in a GIS.

(5) Data quality.

(a) It is critical that only the highest quality data, whether original discrete points or interpreted results (e.g., shorelines extrapolated from aerial photographs) be archived in a GIS. The erroneous impression has spread that GIS automatically means high quality and high accuracy. GIS has the insidious effect that the output usually looks clean and sophisticated, and large numbers of charts and summary statistics can be quickly generated.

(b) Unfortunately, recipients of computer-drawn maps are often far removed from the assumptions and corrections used to enter and analyze the original data. Table 5-21 lists a series of steps involved in creating a modern GIS map from historic field data. Data manipulation and interpretation occur at least five times between the field operation and the completed map. Users of GIS maps must be appraised of the steps and assumptions involved in analyzing their particular data. As with any form of computerized analysis, garbage for input means garbage as output.

a. Coastal data interpretation with numerical models.

(1) Introduction.

(a) The use of numerical models in assessing changes in coastal geomorphology is rapidly increasing in sophistication. Models are designed to numerically simulate hydrodynamic processes or simulate sediment response on beaches, offshore, and in inlets. Specific types include models of wave refraction and longshore transport, beach profile response, coastal flooding, and shoreline change and storm-induced beach erosion (Birkemeier et al. 1987; Komar 1983; Kraus 1990). The judicious use of prototype data and models can greatly assist the understanding of coastal processes and landforms at a study site. Because models should be tested and calibrated, field data collection or mathematical simulation of

Table 5-20
Coastal data suitable for GIS

1. Index of all available geographic coastal data

2. Bathymetric
   - Original soundings - valuable for numerous purposes.
   - Gridded surface data - needed for volumetric computations (original data usually also retained).

3. Shoreline position - derived from:
   - Historic maps.
   - Recent field surveys.
   - Aerial photographs - photos require interpretation by an experienced analyst.

4. High-resolution seismic
   - Images of original records? No - too much data to store; not useable by most people without geophysical training.
   - Interpreted seismic results:
     1. Depth to reflectors.
     2. Sediment type.
     3. Channels, faults, gas, features.

5. Side-scan sonar
   - Images of original records? No - too much data to store; not useable by most people without geophysical training.
   - Interpreted sonogram results:
     1. Geohazards - debris, pipelines, shipwrecks.
     2. Surficial sediment - rock, sand, cohesive.
     3. Bedform orientation.

6. Surficial sediment (grab samples)
   - Mean grain size and other statistics (grain size distribution curve if possible).
   - Color - need standard nomenclature.
   - Organic content.
   - Carbonate content.
   - Engineering properties.

7. Core data
   - Photographic image of core? No - too much data to store.
   - Image of core log? Possible.
   - Grain size distribution and statistics at various depths.
   - Depths to interfaces (boundaries).
   - Organic content and other properties at various depths.
   - Engineering properties at various depths.

8. Oceanographic properties of the water column (temporal in nature)
   - Salinity, other seawater chemistry.
   - Currents at spot locations (temporal - vary greatly with time).
   - Suspended sediment concentration.

9. Biological
   - Bottom type if coral or reef.
   - Species diversity.
   - Individual species counts.
   - Pollutant concentrations.

10. Cultural (man-made) features
    - Shore protection.
    - Oil platforms, pipelines.
    - Underwater cables.
    - Piers, jetties, structures.
    - Real estate, roads, parking lots.

Table 5-21
Interpretation and data manipulation required to convert historic data to GIS product

1. Original structure or feature interpreted and measured by survey team in the field.
   - Field party skilful and methodical?
   - Best survey procedures used?
   - Equipment calibrated and maintained?

2. Information recorded onto paper charts or log books.

3. Additional interpretation occurs if data smoothed or contoured.

4. Historic maps and field logs interpreted by analyst many years later.
   - Changes in nomenclature?
   - Unusual datums?
   - Logs or notes incomplete? in same language?
   - Logs and maps legible?
   - Determination of date (old maps often display several dates).

5. Data translated into digital form for modern use.
   - Technician careful?
   - Appropriate corrections made for old datums or navigation coordinates?
   - Paper charts torn, stretched, or faded?
   - Adjoining maps same year? If not, use separate layers?
   - Digitizing or scanning equipment working properly?

6. Digital data incorporated into GIS database.

7. GIS maps (layers) interpreted by end user.
   - Data from different years correctly overlain?
   - Valid to compare data sets of greatly differing quality?

waves, tides, and winds at a project site is usually required.

(b) The advantage of tools like numerical models is that they can simulate phenomena only rarely observed, can generate complex and long-duration changes, and can incorporate judgements and measurements from many sources. The use of numerical models is a highly specialized skill, requiring training, an understanding of the underlying mathematics, and empirical ("real world") experience of coastal processes. This section summarizes types of models and introduces some of their strengths and limitations.

(2) Types of models[1].

(a) Coastal experience/empirical models. This represents the process by which an understanding or intuitive feeling of coastal processes and geomorphology is adapted and extrapolated from a researcher's experience to a specific project. Prediction through coastal experience without the support of objective quantitative tools has many limitations, including severe subjectivity and a lack of criteria to use for optimizing projects. Complete reliance on coastal experience places full responsibility for project decisions on the judgment of the researcher without recourse to testing the "model" with alternate tools. An empirical model is always necessary before chosing a numerical model.

(b) Beach change numerical models. Figure 5-44 summarizes the time ranges and spatial coverage of numerical models used by CERC. Summaries of the capabilities of the models follow:

- Analytical models of shoreline change. These are closed-form mathematical solutions of simplified differential equations for shoreline change derived under assumptions of steady wave conditions, idealized initial shoreline and structure positions, and simple boundary conditions. Because of the many simplifications needed to obtain closed-form solutions, these models are too crude to use for design.

[1] Material in this section has been summarized from Kraus (1989).

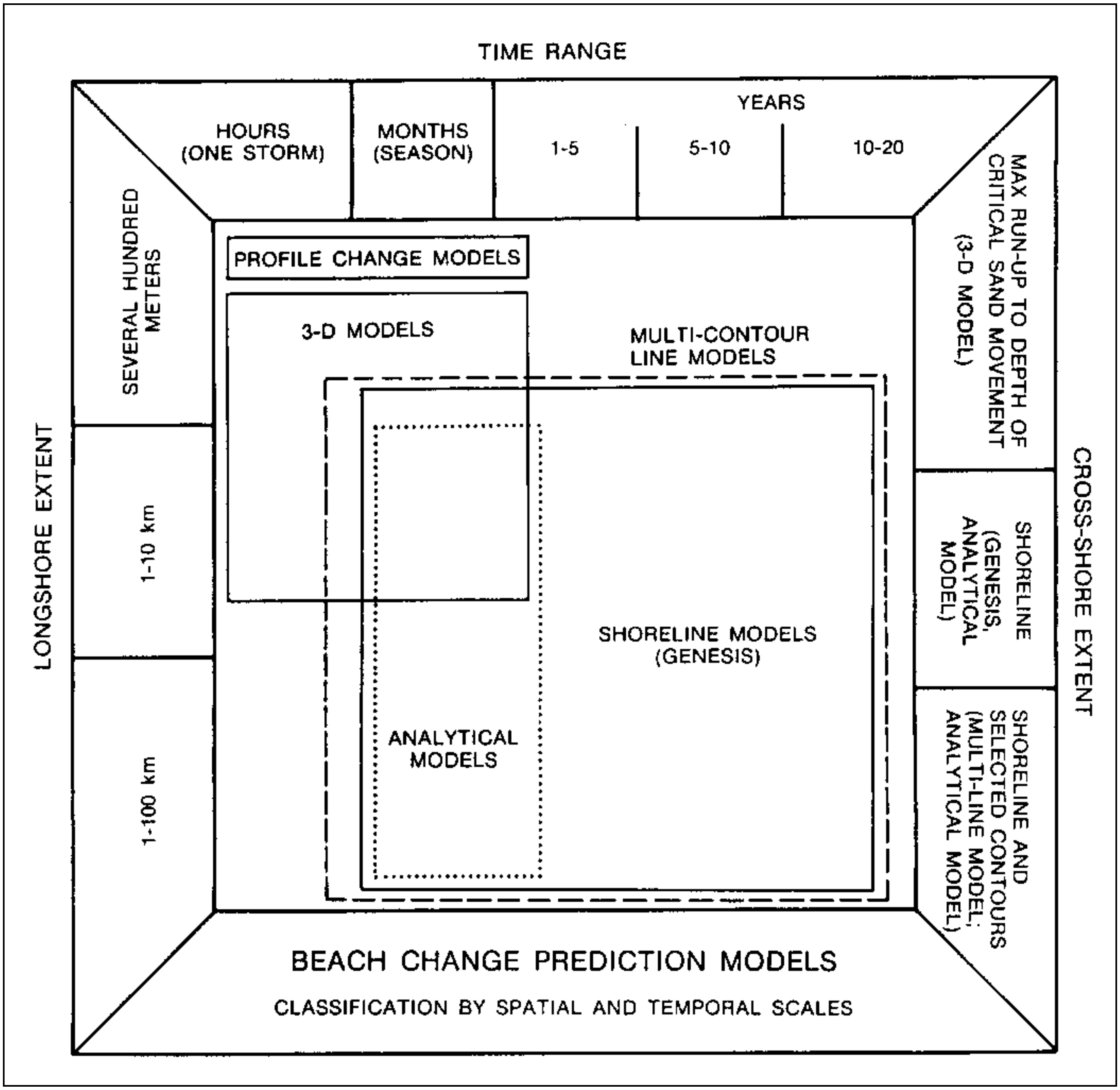


Figure 5-44. Classification of beach change models (Kraus 1989) error analysis of gridded bathymetry

- Profile change/beach erosion models. These are used to calculate sand loss on the upper profile caused by storm surge and waves. The models are one-dimensional, assuming that longshore currents are constant. Extra work needs to be done to extend their use to simulate major morphological features such as bars and berms.

- Shoreline change models. These models generalize spatial and temporal changes of shorelines analytically in response to a wide range of beach, wave, coastal structure, initial and boundary conditions. These conditions can vary with time. Because the profile shape is assumed to remain constant, onshore and offshore movement of any contour can be used to represent beach change.

These models are sometimes referred to as "one-contour line" or "one-line" models. The representative contour line is usually taken to be the shoreline (which is conveniently measured or available from a variety of sources). The GENESIS model has been extensively used at CERC (Hanson and Kraus 1989).

- Multi-contour line/schematic three-dimensional (3-D) models. These models describe the response of the bottom to waves and currents, whose intensity and geologic influence can vary both cross-shore and alongshore. The fundamental assumption of constant shoreline profile, necessary for the shoreline change models, is relaxed. The 3-D beach change models have not yet reached wide application. They have been limited by their complexity and their large requirements for computer resources and user expertise. In addition, they are still limited by our ability to predict sediment transport processes and wave climates.

(3) Calibration and verification.

(a) Model calibration is the use of a model to reproduce changes in shoreline position measured over a certain time interval. Verification is application of a model to reproduce beach changes over a time interval different than the one used for the model's calibration. Successful verification means that the model's predictions are independent of the calibration interval. However, if empirical coefficients or boundary conditions change (for example, by the construction of an entrance channel which interrupts sand transport) the verification is no longer valid. Therefore, a modeler must be aware of any changes in physical conditions at the study site that could affect the validity of his model.

(b) Unfortunately, in practice, data sets are usually insufficient to perform rigorous calibration and verification of a model. Typically, wave gauge data are missing, and historical shoreline change maps are usually spotty or unsuitable. In situations where data are lacking, coastal experience must be relied upon to provide reasonable input parameters. This underscores that considerable subjectivity is part of the modeling procedure, even if the model itself is mathematically rigorous.

(4) Sensitivity testing.

(a) This refers to the process of examining changes in the output of a model resulting from intentional changes in the input. If large changes are caused by minor changes in the input, the overall results will depend greatly upon the quality of the verification. Unfortunately, for many practical applications, there is some degree of doubt in the verification (Hanson and Kraus 1989) (Figure 5-44). If a model is oversensative to small changes in input values, the range of predictions will be too broad and will in essence provide no information.

(b) In summary, numerical models are a valuable complement to prototype data collection and physical (scale) models of coastal processes. However, useful numerical models require empirical input during the calibration and may be based on incomplete data sets.

Therefore, the reader is urged to be cautious of the output of any model and to be aware of the results of the verification and sensitivity tests.

5-6. Summary

a. Before initiating detailed field, laboratory, or office study, a thorough literature review and investigation of secondary data sources must be conducted. Existing sources of data are numerous, including information on processes such as waves, water levels, and currents, information on geomorphology such as geologic, topographic, and shoreline change maps, as well as information that has been previously interpreted in the literature or has yet to be interpreted such as aerial photography. If such a search is not conducted, assessment of geologic history is likely to be less reliable, field studies may be poorly planned, and considerable expense may be wasted because of duplication of existing information.

b. A wide variety of techniques and technologies are available for data collection, analysis, and interpretation of the geologic and geomorphic history of coasts. One means of acquiring coastal data is through field data collection and observation. These data may be numerical or non-numerical, and may be analyzed further in the laboratory and office depending upon the type of data collected. Laboratory studies are used to analyze geological properties of data collected in the field, such as grain size or mineralogy, or to collect data through physical model experiments, such as in wave tanks. Office studies are part of most investigations, in that they involve the analysis and/or the interpretation of data collected in the field and laboratory, from primary and secondary sources. Typically, the best overall understanding of environmental processes and the geologic history of coasts is acquired through a combination of techniques and lines of inquiry.

A suggested flowchart for conducting studies of coastal geology is illustrated in Figure 5-45.

c. Many recent developments and techniques are used in the analysis of coastal data sets. The evaluation of geologic and geomorphic history is largely dependent upon the availability and quality of research equipment, techniques, and facilities. New techniques are constantly being introduced, and it is important that the coastal geologist and engineer stay abreast of new techniques and methods, such as remote sensing and geophysical methods, computer software and hardware developments, and new laboratory methods.

d. In addition to keeping up with recent developments, the coastal scientist or engineer has the serious responsibility of making accurate interpretations of the geologic and geomorphic history of coasts. It is vital that the important research problem and objectives be clearly defined, that important variables be incorporated in the study, and that the inherent limits and errors of the research techniques and technologies be recognized, including problems and assumptions involved in data collection and analysis. To some extent, the coastal scientist or engineer can make some adjustments for various sources of error. However, because of the geologic and geomorphic variability of coasts, extreme caution should be taken in extrapolating the final interpretations and conclusions regarding geologic history, particularly from data covering a short time period or a small area. For these reasons, assessment of the geologic and geomorphic history of coasts is an exceptionally challenging endeavor.

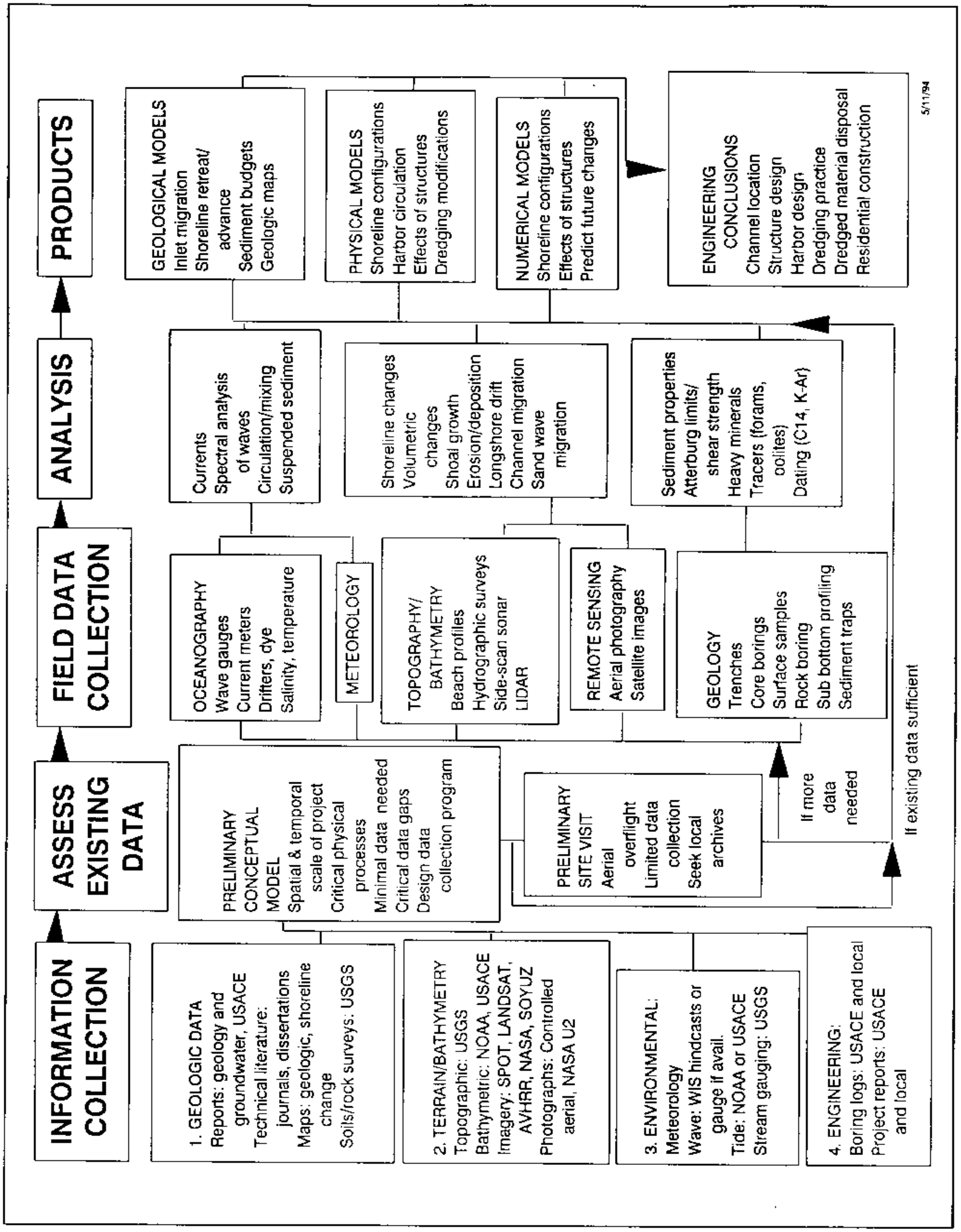


Figure 5-45. Flowchart for studies of coastal geology