CHAPTER 288

ACCURACY OF SAND VOLUMES AS A FUNCTION OF SURVEY DENSITY

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ABSTRACT

Hydrographic surveys are the primary tool for calculating beach nourishment project volumes. With costs for beach-quality sand as high as $30 US per cubic meter, miscalculating project design volumes can result in significant cost differentials. Because conventional bathymetry and topography of beach projects are collected along shore-normal profile lines spaced anywhere from 30 m to 300 m, calculation of project volumes relies heavily on the assumption that there is little along-shore variability from one profile to another. In most cases, however, the beach and nearshore are highly irregular and this assumption is violated. With the development of high-resolution bathymeters, such as the SHOALS airborne lidar system, it is now feasible to collect accurate, high-density beach surveys. These types of data sets create a highly accurate, quantitative measurement of beach and nearshore conditions. This paper describes the SHOALS system and lidar technology and presents a comparison of volumes calculated using high-density lidar data and conventional nearshore profile surveys. Volumes are calculated to compare differences for beaches on the Atlantic Ocean, the Gulf of Mexico, and the Great Lakes.

1.0 INTRODUCTION

Cost for a cubic meter of sand placed on a beach ranges from $5 US to $30 US, depending on many geographic and engineering factors. Beach nourishment projects range in size from several thousands of cubic meters, such as the 1993 project at St. Joseph, Michigan of 39,000 m^3, to millions of cubic meters, such as the project at Miami Beach, Florida of 12 million m^3. Underestimated project design volumes can result in cost overruns or a reduced amount of sand being placed on the beach, while overestimated project design volumes can result in excessive budgeting and planning. Hydrographic surveys are the primary tool for calculating project

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volumes. Conventional survey techniques use shore-normal wading depth surveys matched with offshore acoustic surveys, spaced at intervals along the beach ranging from 30 m to 300 m.

Calculation of project volumes relies on the assumption that there is little topographic or bathymetric variability from one profile line to the next, or that if there is variability, it averages out over the project limits. However, beach and nearshore topography are highly three-dimensional as a result of sub-aerial sand dunes, nearshore bars, hard-bottom outcrops, seawalls, and groins. At profile spacings typically on the order of 300 m, these assumptions are often violated. With the development of lidar (LIght Detection And Ranging) hydrographic systems, such as the US Army Corps of Engineer's (USACE) Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system, it is now economically feasible to collect accurate, high-resolution beach and nearshore surveys.

The following discusses the SHOALS system and its technology and discusses the benefits of high-resolution bathymetry and topography. Four beach projects surveyed with SHOALS are presented and analyzed to determine sand volume computation sensitivity to survey density.

2.0 SHOALS SYSTEM

In 1994, the USACE introduced a new airborne hydrographic survey system capable of remotely collecting high-resolution, accurate bathymetry. The SHOALS system is an airborne-lidar system operating from a Bell 212 helicopter (Figure 2.1). The system uses state-of-the-art lidar technology to measure water depths (Guenther, 1996). A laser-transmitter/receiver is housed inside a pod mounted underneath the aircraft. As the laser pulses at 200 Hz, it is scanned in an arc producing a swath width equal to approximately one-half the aircraft altitude. This yields a uniform sounding spacing, nominally 4-m by 4-m. The laser pulse travels from the airborne platform to the water surface where part of the energy reflects back to the receiver (Figure 2.2). The remaining energy penetrates the water column and reflects off the sea bottom. The time differential between these two returns indicates the water depth (Lillycrop et al., 1996).

Figure 2.1 The SHOALS system

Table 2.1 gives SHOALS current performance specifications. SHOALS has a vertical accuracy of ±15 cm and a horizontal accuracy of ±3 m and meets the USACE Class I, dredge payment, performance specifications (Riley, 1995). Operating at a nominal speed and altitude of 30 m/s and 200 m, SHOALS surveys 8 km^2 per hour. In optically clear water, SHOALS records to depths of 40 m. Since early 1995, SHOALS also records accurate topographic

Table 2.1 SHOALS performance

maximum depth	40 m
minimum depth	< 1 m
vertical accuracy	±15 cm
horizontal accuracy	±3 m
sounding density	4 m
operating speed	30 m/s
swath width	110 m

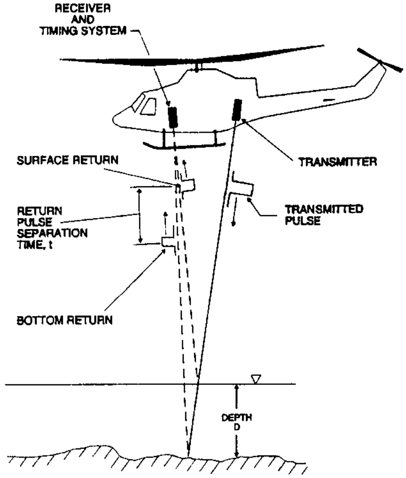

Figure 2.2 SHOALS operating principle

elevations of adjacent beaches allowing full mapping of both the beach and nearshore. To date, SHOALS surveyed over 80 USACE projects totaling 2,000 km^2.

3.0 SITE DESCRIPTIONS

Because SHOALS collects very dense bathymetry, typically 120,000 soundings per square kilometer, it is an ideal tool for monitoring the beach and nearshore in dynamic, irregular areas. For a particular stretch of beach, SHOALS data provides detailed bathymetry and adjacent beach topography allowing accurate identification of high-erosion areas and complex nearshore features. The four data sets presented herein include Longboat Key on the Gulf of Mexico, Island Beach State Park on the Atlantic, and St. Joseph and Presque Isle on the Great Lakes. Each of these sites is characterized by irregular cross-shore and/or along-shore variation in topography.

3.1 Longboat Key

Longboat Key, Florida is on the east shore of the Gulf of Mexico and is situated between Longboat Pass, to the north, and New Pass, to the south. Over 2 million cubic meters of beach-quality sand were placed on the southern-most 8.5 km of the key in 1993 to protect the shoreline from further erosion. SHOALS surveyed the area 5 times since March 1994 to monitor the nourishment project (Irish and Truitt, 1995). The high-resolution SHOALS bathymetry collected in November 1995 reveal a complex sand-bar system in the nearshore (Figure 3.1). The dual-bar system merges together and separates as it parallels the shoreline. At the southern end of the key, the seaward bar diverges into the ebb shoal of New Pass. Conventional profile data are regularly collected along profiles spaced 300 m apart and outline the dual-bar system; however,

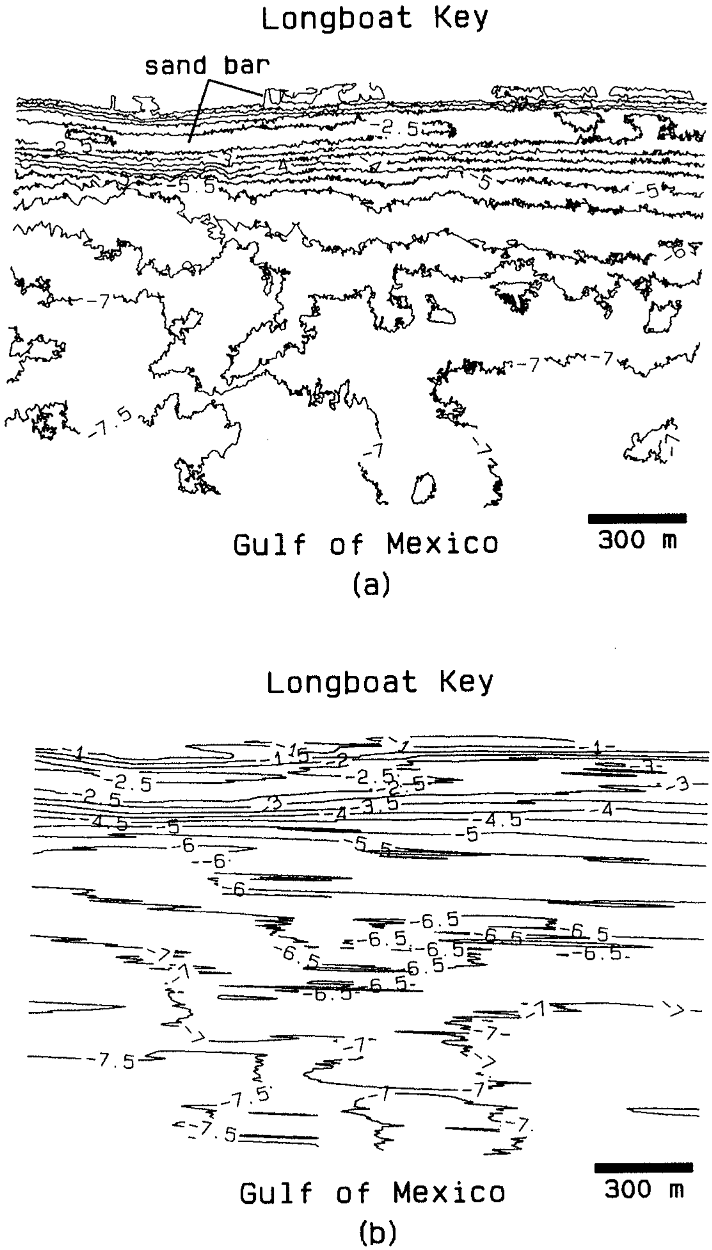

Figure 3.1 Longboat Key, Florida, November 1995: a) representative section of SHOALS bathymetry, b) simulated profile bathymetry at 300-m spacing. All depths are in meters referenced to NGVD.

these data sets do not reflect local complexities in the nearshore. The southern-most 3.4 km were analyzed in this investigation.

3.2 Island Beach State Park

A 2.5-km stretch of Island Beach State Park, New Jersey, just north of Barnegat inlet was surveyed with SHOALS in 1994. The park is directly exposed to the Atlantic Ocean and is characterized by shore-perpendicular sand ridges stretching from the dry beach through the nearshore. Because the area is a state park, no man-made alterations are permitted. However, Barnegat inlet, which is jettied on both its north and south sides, does impact Island Beach. SHOALS surveyed the southern-most 2.5 km of Island Beach in June 1994 (Figure 3.2). The survey details the beach's three-dimensionality quantifying the sand formations and the shoaled areas formed by inlet processes.

3.3 St. Joseph

St. Joseph, on the southeastern shore of Lake Michigan, was authorized as a Federal beach nourishment project in 1976. In 1903, two jetties were constructed to stabilize the St. Joseph River entrance. These jetties interrupt the natural southerly longshore transport of 84,000 m^3 per year, and as a consequence, the downdrift beach experienced erosion and the lake bed suffered downcutting (Parson and Smith, 1995). Since 1976, the USACE annually places dredged material from the maintenance dredging of St. Joseph Harbor south of the entrance to form a feeder beach to replenish 6 km of shoreline. Additionally, coarser material from an upland source is periodically placed. Typically, bathymetric and topographic data are collected along survey lines spaced 152 m apart through the fill area and 800 m apart south of the fill area. In August 1995, SHOALS surveyed the project collecting nearly 400,000 soundings (Figure 3.3). The SHOALS data quantify areas of severe lake-bed downcutting and identified a previously undiscovered headland feature with a 2-m relief. The entire 6-km project was analyzed in this investigation.

3.4 Presque Isle

Presque Isle Peninsula is on the south shore of Lake Erie at Erie, Pennsylvania. The peninsula historically tends to migrate easterly causing erosion of the lake-side beach. Occasionally the area breaches causing dangerous navigation conditions in Erie Harbor, situated between the peninsula and the mainland. The USACE has taken several measures to prevent erosion including beach nourishment and the construction of groins (Grace, 1989). In 1992, the USACE installed 55 breakwaters offshore of Presque Isle. Each breakwater is 47.5-m long and is separated by a 106.7-m gap. Additionally, 285,000 m^3 of beach fill material were placed initially and renourishment occurs annually (Mohr, 1994). Ongoing project monitoring of the performance of the breakwater system includes bathymetry and topography collected annually along profiles spaced 300 m to 600 m apart. In August 1995, SHOALS surveyed this breakwater system detailing the salient and tombolo formations shoreward of the structures and the fairly uniform bottom seaward of the structures (Figure 3.4). The entire 9.9-km long project was used in this investigation.

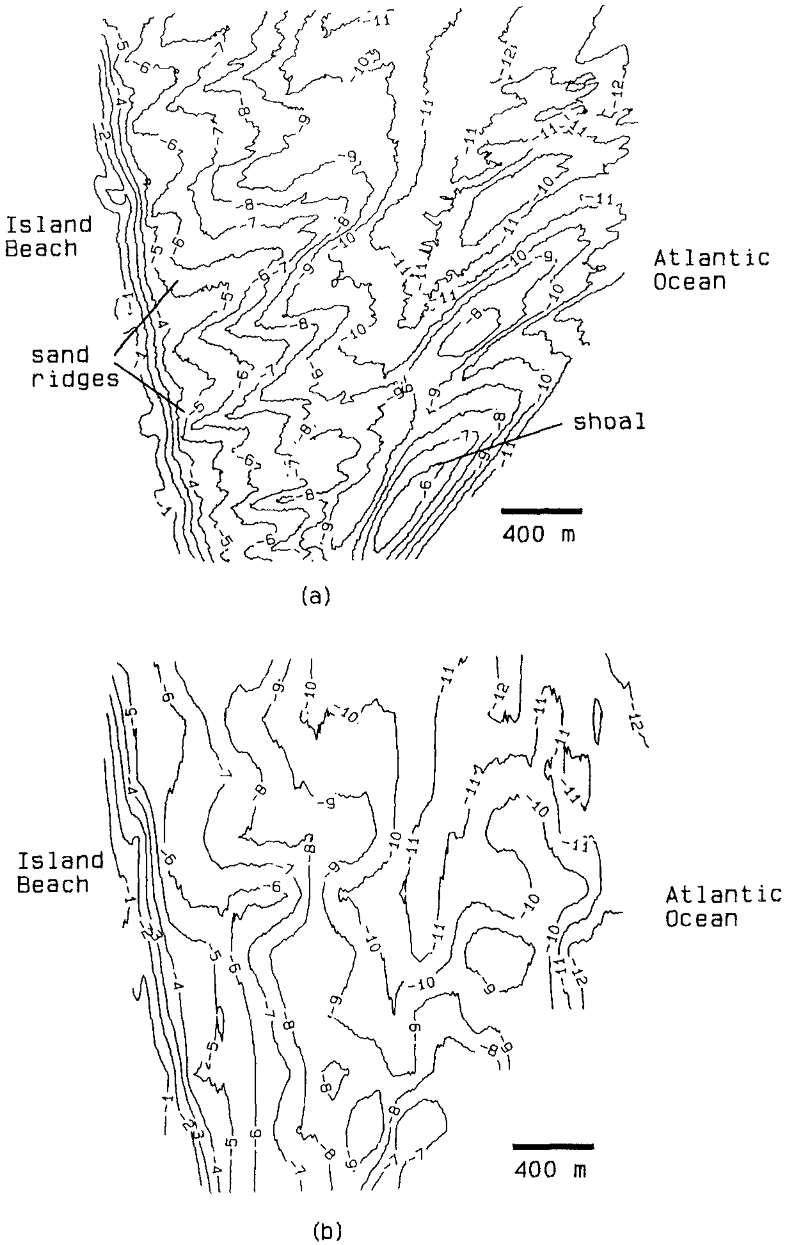

Figure 3.2 Island Beach State Park, New Jersey, June 1994: a) SHOALS bathymetry, b) simulated profile bathymetry at 300-m spacing. All depths are in meters referenced to NGVD.

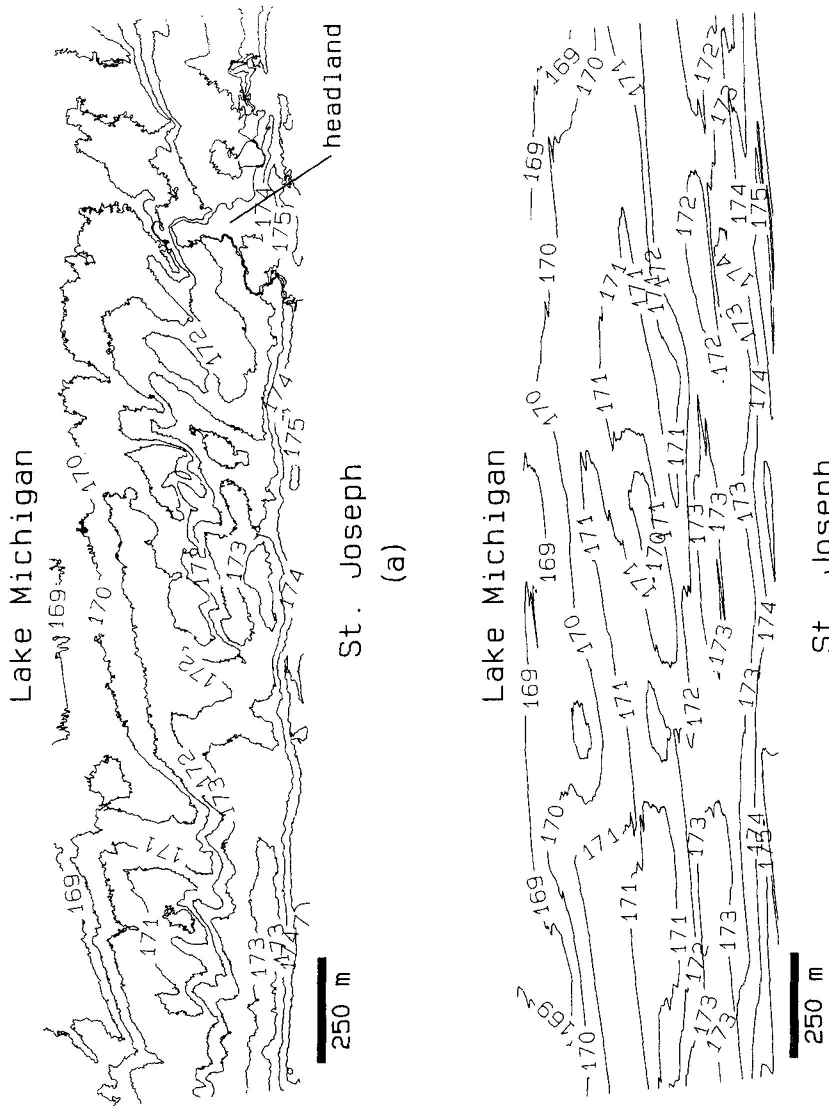

Figure 3.3 St. Joseph, Michigan, August, 1995: a) representative section of SHOALS bathymetry, b) simulated profile bathymetry at 300-m spacing. All depths are in meters referenced to IGLD.

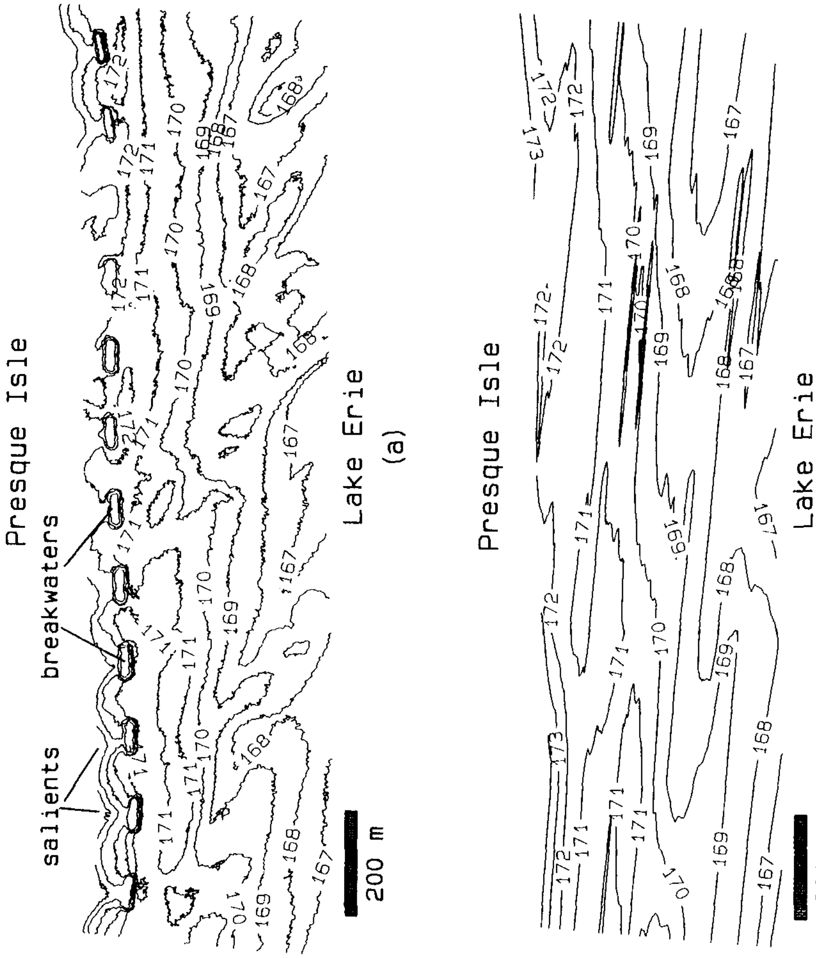

Figure 3.4 Presque Isle, Pennsylvania, August, 1995: a) representative section of SHOALS bathymetry, b) simulated profile bathymetry at 300-m spacing. All depths are in meters referenced to IGLD.

4.0 COMPARISON PROCEDURE

To evaluate the importance of data density on beach nourishment volume calculations, profile data along spacings varying from 5 m to 300 m were simulated from the SHOALS bathymetry using a commercially available CAD and engineering package, TERRAMODEL™. First, profile alignments spaced every 5 m were created along the project length. A digital terrain model (DTM) of the SHOALS data was created to represent it mathematically. The SHOALS depths, as represented by the DTM, were then projected onto the profile lines at 4-m intervals. The resulting bathymetric contours for the simulated profiles at 300-m spacing are in Figures 3.1b, 3.2b, 3.3b, and 3.4b illustrating the loss of detail with such a wide spacing.

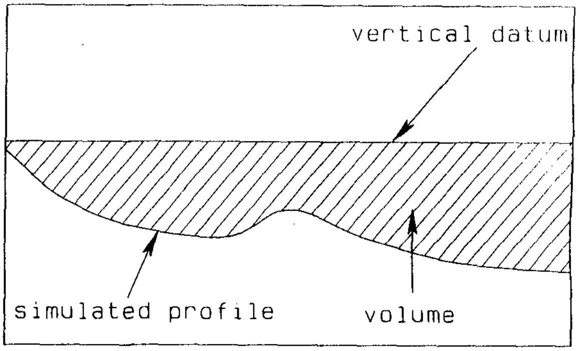

Figure 4.1 Cross-sectional area

To simplify calculations, volumes were computed between the horizontal plane representing a mean water vertical datum and the bottom topography as represented by the simulated profiles (Figure 4.1). Volumes were computed using the well-known area-end method for each profile spacing. When employing the area-end method, the cross-sectional area between the bathymetry and mean water at each profile location was first calculated. (Only the area below the mean water vertical datum was computed.) The calculated area at one profile location (A_1) is then averaged with that of the next consecutive profile (A_2). The product of this averaged area and the length between the two consecutive profiles (L) gives the volume (V) between the profiles:

$$V = \frac{A_1 + A_2}{2} \cdot L$$

The total volume for the entire project is then equal to the summation of the volumes. The computed results are presented in Table 4.1 as volume difference between the highest resolution set, 5-m spacing, and the stated spacing, in cubic meters per meter length of beach. Positive differences indicate that the stated spacing resulted in a volume larger than the 5-m spacing volume while negative differences indicate a smaller volume.

5.0 DISCUSSION

The results, in general, show that as the spacing between survey profiles increases, so too does the error in computed volumes. Figure 5.1 gives a plot of

Table 4.1 Computed volume differences

Profile spacing	Volume difference (m^3/m) Longboat Key	Island Beach	St. Joseph	Presque Isle
5	0.0	0.0	0.0	0.0
10	-0.4	0.1	0.0	1.2
25	0.0	-0.1	-0.4	1.9
30	-1.8	0.1	0.2	0.8
50	0.2	-0.3	-1.7	3.3
60	-3.1	0.2	2.3	0.9
100	-1.6	-1.9	-3.3	6.1
150	-0.7	-0.3	-6.5	-10.4
200	2.2	5.3	-18.5	0.8
250	-6.6	-15.9	8.4	4.2
300	12.3	-19.8	-5.3	-9.8

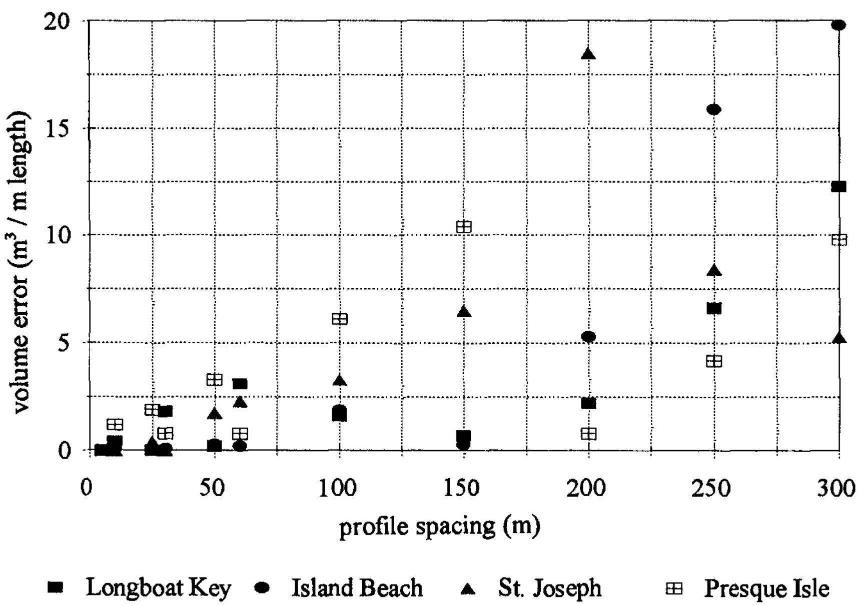

Figure 5.1 Measured volume error

absolute deviation from the 5-m volume (volume error) versus profile spacing for all four sites. In general, the volume error becomes more random and larger in magnitude as profile spacing increases. This is consistent with the findings of Saville and Caldwell (1952). In their investigation, the use of average profiles at spacings varying from 120 m to 2,800 m to represent lengths of a fairly uniform beach were analyzed for accuracy in evaluating engineering volumes. The spacing error, defined as the accuracy measurement of a particular profile in representing a section of beach, was evaluated by comparing the selected profile with the average profile for that section. The spacing error was then translated into a volume error, defined as the total volume difference over the project length. Their conclusions state that the volume error increases nearly linearly as profile spacing increases. Saville and Caldwell's results do not indicate a randomness in volume error; however, the results from this investigation do. This is most probably attributed to the irregularities in the bathymetry evaluated herein.

Of the four sites, the bathymetry at Longboat Key shows the least along-shore variation. This is reflected in the results where the volume error at Longboat Key is within 5 m^3/m for profile spacings as great as 200 m. However the area is still highly three-dimensional, and the volume error when using 200-m, 250-m, and 300-m spacings continually increases and is as much as 12.3 m^3/m. The calculations for Island Beach indicated similar findings. Here, the volume error is small for profile spacings less than 200 m, and as the spacing increases beyond 200 m, the measured volume error increases. In contrast to Longboat Key, the bathymetry at Island Beach is highly variable along-shore with shore-normal sand ridges occurring every 400 m to 500 m. This investigation indicates that bathymetric variations associated with these large features do not impact volume computations until the profile spacing exceeds 200 m.

The analysis at St. Joseph shows that profile spacings larger than 100 m result in significant volume error. Differing from Longboat Key and Island Beach, as the profile spacing is increased at St. Joseph, the volume error does not continually increase. The measured volume error at St. Joseph when a 250-m spacing is used is significantly lower than that measured when a 200-m spacing is used. However, all spacings greater than 100 m result in volume errors larger than 5 m^3/m.

Of the four projects, Presque Isle is most affected by survey spacing changes between 5 m and 50 m, and volume computations deviate significantly with spacings greater than 50 m. Of the spacings evaluated at Presque Isle, the volumes computed using 150-m spacing yielded the largest error, 10.4 m^3/m. When the spacing is increased to 200 m, the volume error dramatically decreases. Because of the uniform repetition of salient formations every 155 m corresponding to the breakwater field, it is probable this decrease in volume error is a result of these features. By chance, the profile locations at the 200-m spacing were such that the volume error between consecutive profiles averaged out over the project length.

The economic impact of profile spacing is evident in Figure 5.2 where the cost error, or absolute cost difference per cubic meter per unit length of beach, for the Presque Isle project is displayed. The lower and upper cost error boundaries were calculated using a cost per cubic meter of beach-quality sand equal to \$5 US and \$30 US, respectively. Even at profile spacings as small as 50-m, the cost error is as great as \$100 US/m. As the profile spacing increase to 100 m or greater, the cost error

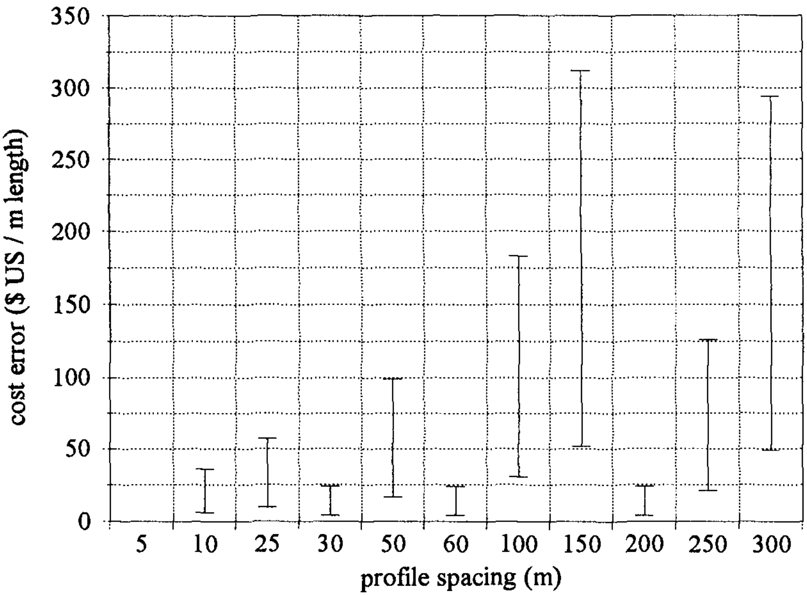

Figure 5.2 Cost error at Presque Isle, Pennsylvania

becomes as great as $325 US/m, translating to a total project cost difference well over $3 million US. With renourishment at $22 US to $26 US per cubic meter occurring annually at Presque Isle, higher density surveys are certainly warranted. Typical monitoring at profile spacings of 300 m or greater may result in cost differentials around $2.5 million US over the project length.

Similar cost impacts may be observed at the other three projects. At Longboat Key, a 300-m profile spacing results in cost differentials between $ 200,000 US and $1.2 million US over the 8.5-km project length. At Island Beach and St. Joseph, profile spacings greater than 150 m may result in cost errors in excess of $75 US/m. At all four projects, the economic benefits of higher density bathymetry are obvious.

Hydrographic surveys serve as the base for engineering planning and design of beach nourishment projects. Usually, a fixed budget for a particular project is developed from volume calculations between the design profile and the collected bathymetry. If design volumes were computed using sparse data, a fixed budget may result in too little, or too much, sand placement at the site. Ultimately, project performance is affected: an under-designed project will not adequately protect against further shoreline erosion.

6.0 CONCLUSIONS

This investigation clearly indicates the economic and planning benefits of high-resolution bathymetry for beach nourishment along irregular beaches. Low density data may result in gross miscalculation of fill volumes ultimately impacting project performance and financial management. The conclusions of this analysis are based on engineering volumes computed with respect to the below-water portion of the profile and only reflect underwater bathymetric irregularities. However, initial design, maintenance, and monitoring of beach nourishment projects also encompasses the above-water portion of the profile. There are commonly occurring irregularities on the above-water portion as well including sand dunes and features associated with man-made structures. Based on the findings herein, inclusion of the above-water portion of the profile should result in even greater inaccuracies in engineering volumes when wide profile spacings are used.

Data density for a particular hydrographic survey mission should be governed by the degree of along-shore variability and the intended engineering application of the data set rather than the capability of the survey instrument. For example, high-density data may not be required when monitoring long-term regional coastal evolution; however, high-density data are required when preparing plans and specifications for a beach nourishment project in an area with irregular bathymetry. High-density bathymetry are also valuable when evaluating the performance of erosion-control structures such as groins or detached breakwaters.

The findings herein prompted several new investigations including the expansion of this study to include the above-water portion of the project. Furthermore, studies are ongoing to optimize profile locations to best represent a project while minimizing data collection requirements. Finally, similar investigations are evaluating the impacts of data density on other engineering computations, such as dredging volumes.

With complete coverage, accurate bathymetry now available at costs nearly two-thirds that of conventional methods, engineers can more accurately and cost-effectively plan, design and monitor beach nourishment projects. Furthermore, future research will provide new guidance for determining necessary survey densities for accurate engineering computations.

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