



ELSEVIER

Geomorphology 48 (2002) 269–287

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LIDAR: Cape Hatteras, North Carolina

Jason W. Woolard^{a,*}, Jeffrey D. Colby^b

^a*National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), National Geodetic Survey (NGS), Remote Sensing Division, Silver Spring, MD 20910, USA*

^b*Department of Geography, East Carolina University, Greenville, NC 27858, USA*

Received 15 January 2001; received in revised form 15 May 2001; accepted 24 January 2002

Abstract

The technological advancement in topographic mapping known as airborne Light Detection and Ranging (LIDAR) allows researchers to gather highly accurate and densely sampled coastal elevation data at a rapid rate. The problem is to determine the optimal resolutions at which to represent coastal dunes for volumetric change analysis. This study uses digital elevation models (DEM) generated from LIDAR data and spatial statistics to better understand dune characterization at a series of spatial resolutions.

The LIDAR data were collected jointly by the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS). DEMs of two study sites (100 × 200 m) located in Cape Hatteras National Seashore, North Carolina were generated using a raster-based geographic information system (GIS). Changes in the dune volume were calculated for a 1-year period of time (Fall 1996–1997) at grid cell resolutions ranging from 1 × 1 to 20 × 20 m. Directional statistics algorithms were used to calculate local variance and characterize topographic complexity. Data processing was described in detail in order to provide an introduction to working with LIDAR data in a GIS.

Results from these study sites indicated that a 1–2 m resolution provided the most reliable representation of coastal dunes on Cape Hatteras and most accurate volumetric change measurements. Results may vary at other sites and at different spatial extents, but the methods developed here can be applied to other locations to determine the optimum resolutions at which to represent and characterize topography using common GIS and database software.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: LIDAR; GIS; Coastal dune; Coastal geomorphology; Volumetric change; Scale; Spatial statistics

1. Introduction

Beach and dune areas are dynamic physical features with changes occurring at many spatial and temporal scales due to both gradual and catastrophic

* Corresponding author. Tel.: +1-301-713-2663x163; fax: +1-301-713-4572.

E-mail address: jason.woolard@noaa.gov (J.W. Woolard).

events. Increasing population and considerable investment make it necessary to gather accurate and timely data pertaining to beach and dune field topography. Until recently, morphological coastal studies have been based on a combination of ground surveys of widely spaced transects and maps or aerial photographs. The ground surveys can provide information about the vertical or horizontal changes at single locations. The maps and aerial photos can provide useful information on long-term and short-term advance or retreat of the coast, longshore movement of sediments, and human impacts caused by construction or dredging. However, several (potentially time-consuming) steps are needed to quantify the rate of change occurring. These steps include the assemblage of data sources, entering data, digitizing coordinates and features, analyzing potential errors, and computing change statistics. Even when these steps are followed carefully, only two-dimensional planimetric data are commonly obtained.

Remotely sensed satellite data provide another source of information for studying coastal areas. Cracknell (1999) states that the coastal zone represents the last important frontier for the application of remote sensing techniques. Much of the existing satellite data (e.g., Landsat Thematic Mapper) has a coarser resolution than film-based aerial photography. Although it is extremely valuable for studying phenomena over large spatial extents (e.g., White and El Asmar, 1999), satellite imagery is limited in its ability to provide detailed information about coastal features where the size of the feature is smaller than or barely exceeds the resolution of the data. Technology in remote sensing continues to evolve providing new and efficient ways to map coastal areas. Airborne Light Detection and Ranging (LIDAR) mapping is one such method that has introduced the use of aircraft-mounted laser scanners to gather high-resolution elevation data along the coastline in a timely, cost-efficient manner (Flood and Gutelius, 1997).

The purpose of this paper is to introduce airborne LIDAR as a valuable coastal data source for geomorphic studies. This study examined volumetric changes in sand dunes at two study sites along the Cape Hatteras National Seashore of North Carolina. Raster geographic information system (GIS) methods were used to conduct the volumetric change analyses based on airborne LIDAR data sets collected in the

Fall of 1996 and 1997. Specific objectives of the study were to calculate erosion and deposition, examine how these measurements varied at different spatial resolutions, and identify areas where significant change occurred. In addition, spatial statistics were implemented to characterize the topographic complexity of the dunes to better understand how the representation of these features changed with resolution.

This research is significant for two main reasons. First, previous studies of coastal dunes have been undertaken using the traditional data collection methodologies, which often provided coarse representations of the study areas, entailed interpretation (e.g., aerial photographs), or required extensive field collection of data (Andrews et al., 2002). In this study, LIDAR was employed to acquire accurate topographic data to model the dune systems in an efficient manner. The second contribution of the study involves examination of spatial and temporal scale. Sherman (1995) noted the difficulty of transferring information and concepts across spatial and temporal scales in studying coastal dune systems. Also, investigating issues of scale in representing physical processes has become an important research agenda within the field of geographic information science (e.g., Quattrochi and Goodchild, 1997).

2. Background

In recent decades, there have been several technological advancements in the mapping sciences. Once such advancement is the use of LIDAR. LIDAR is an active remote sensing system, much like radar, which uses pulses of light rather than microwave energy to illuminate the terrain (Lillesand and Kiefer, 1994). These systems are operated in a profiling mode at varying altitudes and are lightweight enough to mount onboard a fixed wing aircraft or helicopter.

Research into using lasers for topographic mapping has been underway for a number of years both within the U.S. federal government (e.g., Krabill et al., 1995, 2000; Vaughn et al., 1996; NOAA CSC, 1997; Hapke et al., 1998) and within academia (e.g., Samberg, 1996; Carter and Shrestha, 1997; Huising and Vaessen, 1997; Kraus and Pfeifer, 1998; Shrestha and Carter, 1998). The private sector has also experienced an increase in airborne LIDAR work (e.g., Romano,

1997; Flood and Gutelius, 1997; Flood et al., 1997; DeLoach, 1999). At least 5 companies have manufactured airborne LIDAR systems and 35 private vendors have offered LIDAR mapping services (Baltsavias, 1999).

One advantage to using airborne LIDAR data is that a spatially dense data set is generated over short periods of time, which can be used to provide comprehensive and accurate spatial representation of coastal dunes. Laser repetition rates have risen to 33 kHz or 33,000 measurements per second for some commercial systems, resulting in an extremely dense elevation data set. However, the number of points obtained on the ground can be variable depending on scan orientation and flying height.

National Aeronautics and Space Administration (NASA) has developed an airborne laser altimeter, the Airborne Topographic Mapper (ATM), which was originally designed for mapping ice sheets in Greenland (Krabill et al., 1995). Further applications for the ATM, such as beach mapping, have been investigated since its introduction. The ATM II is one of the systems used by National Oceanic and Atmospheric Administration (NOAA) to collect data pertaining to the coastline. The ATM II is a single return system and collects 3000–5000 spot elevations per second as the aircraft travels over the beach at approximately 60 m/s (135 miles/h). Using the ATM and Global Positioning System (GPS) satellite receivers, researchers have been able to survey the beach elevations to a vertical accuracy of 15 cm [root mean square error (RMSE)] and a horizontal accuracy of 0.8 m (RMSE) on the ground from an altitude of 700 m (Meredith et al., 1999). The ATM and other airborne laser swath mappers use a pulsed scanning laser ranging system, airborne GPS techniques, and an inertial measurement unit (IMU).

Due largely to collaboration between NASA, NOAA, and U.S. Geological Survey (USGS), airborne LIDAR technology is receiving much attention from the coastal science and management communities. The Airborne LIDAR Assessment of Coastal Erosion (ALACE) research project was initiated by these agencies to develop a set of protocols for using LIDAR to map coastal areas. A goal of the ALACE project was to provide the LIDAR data to coastal resource managers in a format that was useable and to

provide them with tools for analysis (NOAA CSC, 1997).

One ALACE experiment occurred on the northern portion of Assateague Island where LIDAR mapping was conducted using the ATM I sensor in November 1995 and the ATM II sensor in October 1996 (Krabill et al., 2000). The ATM LIDAR data sets were compared to each other and also to ground profile survey data collected by the National Park Service to achieve relative and absolute accuracies. The results showed that it was possible to represent detailed beach morphology and an agreement of 10–20 cm (RMSE) in the vertical component when compared to standard ground surveyed points (Krabill et al., 2000).

Another coastal LIDAR project was conducted by the University of Florida, Florida Department of Transportation, and the Florida Department of Environmental Protection in the Florida panhandle region during October 1995, shortly following Hurricane Opal (Bolivar et al., 1995). The objective of this project was to aid in the assessment of storm damage. A commercial airborne laser terrain mapping system was used to map 250 km of coastline. The data were collected in just over 2 h using the laser system, which provided continuous point coverage of the desired grid. After postprocessing of the data, the total number of individually georeferenced elevation points was approximately 27 million. A previous ground survey of this same area took a team of surveyors 6 months to complete, measuring profiles of the beach and dunes at 300 m intervals. Each ground survey profile had a few hundred data points beginning at the water and continuing to the edge of the dune region.

Although LIDAR has been embraced by the coastal community for applications such as floodplain and shoreline mapping, poststorm damage assessment and the generation of digital elevation models (DEMs) for coastal engineering projects, very few geomorphic studies of coastal dunes using LIDAR exist. Studies have focused mainly on the validation of the technology through accuracy assessments (Krabill et al., 2000) or deal specifically with erosion trends as a result of major storms (NOAA CSC, 1997). Issues of scale, optimal spatial resolution, and the use of spatial statistics to characterize topographic complexity have not been addressed. This research explores these issues.

3. Methodology

The methodology implemented in this research was organized into a series of logical steps (ESRI, 1997). Step 1 involved the procedures for data acquisition. In Step 2, the data were initially processed and manipulated. The data were then input into a GIS and analysis was undertaken in Step 3. Lastly, in Step 4, procedures were developed for presenting the results.

3.1. Study areas

Two 100 × 200 m study sites were chosen for this investigation. Both sites were located north of Oregon Inlet on the Outer Banks of North Carolina, within the Cape Hatteras National Seashore (Fig. 1). Site A is located approximately 1 km north of Site B. The dunes in Site A lack a prominent ridge and are characterized by a single large blowout in the northern

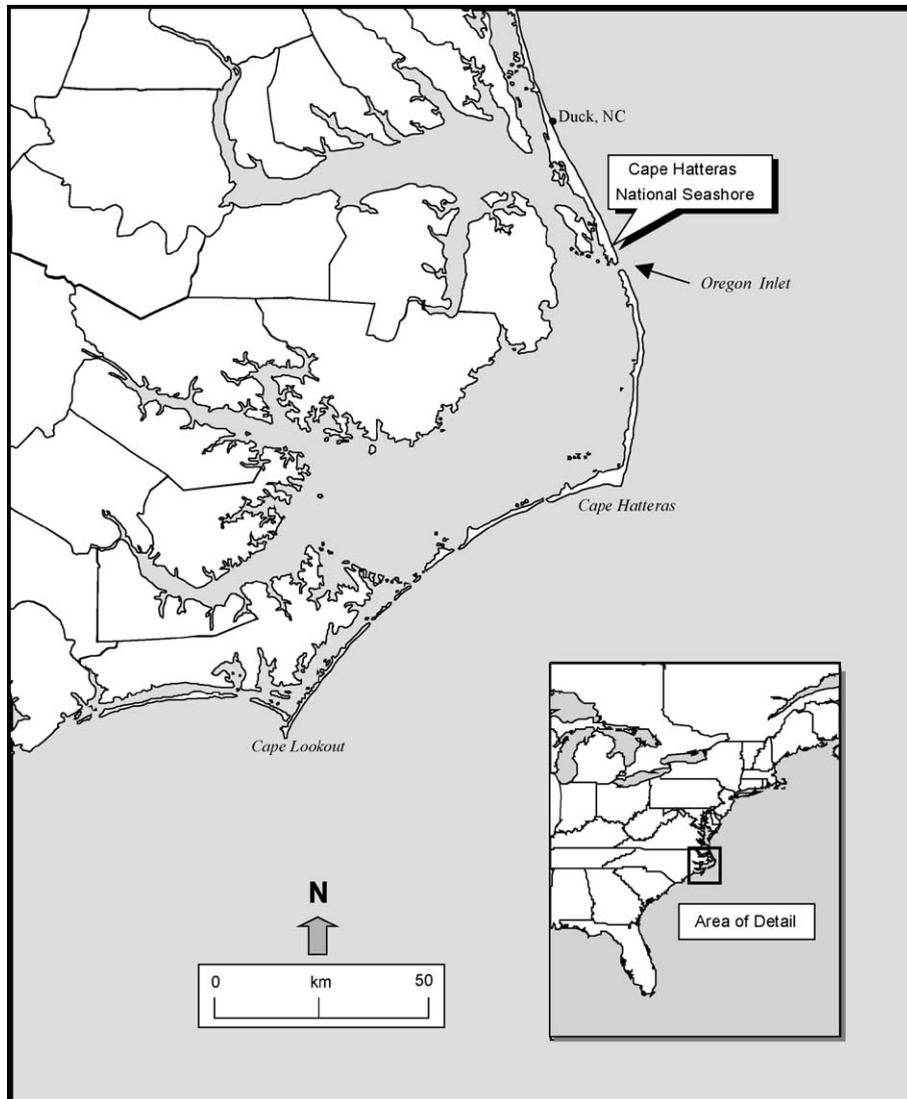


Fig. 1. Map of study area.

section. The elevation of the dune system of Site A ranged from approximately 4 to 11 m. The topography of Site B was quite different from Site A and was selected primarily due to this fact. Site B was characterized by a single foredune with elevations ranging from approximately 3 to 9 m. The dunes of the Cape Hatteras National Seashore are artificial, constructed by the Civilian Conservation Corps in the 1930–1950s. These dunes transformed the morphologic character of the barrier islands from overwash-dominated systems to swash and aeolian-dominated systems (Andrews et al., 2002).

A key issue in this type of research concerns vegetation and development on the dunes. Laser pulses may not be returned from the ground surface in vegetated and developed areas. Instead, heights may be returned from the leaf of a bush, small tree, or the top of a human-made structure. Cape Hatteras National Seashore was selected for this research because development is sparse and tightly controlled. Thus, although vegetation may have introduced a few spurious points in the data, the issue of structures was not of concern. The classification of LIDAR returns and extraction of features is an area of interest to many researchers (e.g., Maas and Vosselman, 1999; Haala and Brenner, 1999).

3.2. Step 1: data acquisition

During September and October, in 1996 and 1997, NOAA CSC in conjunction with NASA, flew several successful LIDAR data collection missions over the Atlantic coast of the United States. The analysis of the Cape Hatteras National Seashore was performed using ATM data collected during these missions and made available to East Carolina University. Much of the data from these flights and other missions have since become publicly available (NOAA CSC, 1997).

The technical specifications of the ATM included a Spectra Physics laser transmitter, which provided a 7 ns long, 250 microjules pulse at frequency-doubled wavelength of 523 nm in the blue-green spectral region (Meredith et al., 1998). The laser transmitter functioned at pulse rates from 2 to 10 kHz emitting beams directed downward at the Earth's surface through an opening or window in the bottom of the aircraft's fuselage. The laser recorded the time difference between the emission of the laser beam and the

reception of the reflected laser signal in the aircraft. The laser pulse was reflected using a small folding mirror mounted on the back of a secondary mirror of a rotating scan mirror assembly mounted directly in front of the telescope (Meredith et al., 1998). The scan mirror was rotated at 20 Hz and at a specific off-nadir angle of 15° to obtain the necessary swath width (Meredith et al., 1998). The optimal operational pulse rate for ATM beach surveying was 5000 Hz (Hz). The most effective flight elevation of 700 m provided a scan swath of close to 350 m, approximately 50% of the aircraft's altitude (Fig. 2). The missions flown over the Atlantic Coast used differential GPS with receivers located on both the aircraft and at a known ground station.

3.3. Step 2: data processing

One of the first issues addressed in data processing was the selection of a data model to represent the terrain in a digital environment. With raster data models, geographic space is segmented and features are represented within a continuous array of grid cells. Vector models represent the logical dual of their raster counterparts (Peuquet, 1990). With vector models, points, lines, and polygons represent specific features. The representation of elevation is possible with vector models through the use of triangulated irregular networks (TIN) where topographic data points can be connected to form a surface. For this study, the raster data model was the most appropriate model for

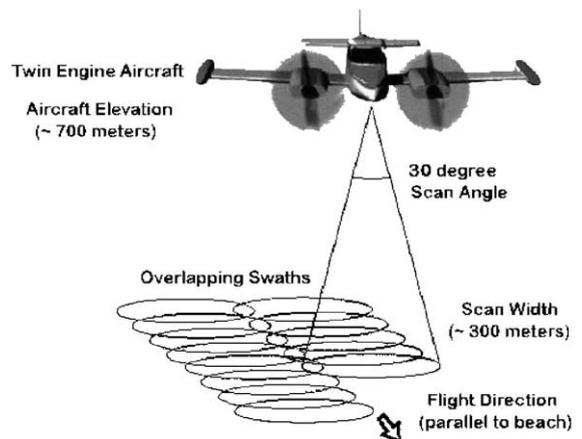


Fig. 2. ATM Scan Swath (Source: NOAA CSC).

volumetric analysis because its grid-shaped characteristics enabled image differencing and precise measurement and location of elevation change.

Once the data were obtained in a raw ASCII format, they were indexed for processing in a GIS. Creating an index for the data simply referred to assigning a numeric value to each comma-delimited row of x , y , and z points. This basic procedure could have been conducted in any spreadsheet program when dealing with small data sets. However, when faced with the challenge of working with data as dense as LIDAR, such a simple task would have become laborious. Due to file size limitations in the Microsoft Excel spreadsheet program, alternatives were explored to complete this procedure. The most convenient option available was to create a Microsoft Access database for the LIDAR data. Microsoft Access allowed for the manipulation of much larger data sets than common spreadsheet programs. Once the indexed database had been created, it was exported as an ASCII file for input into a GIS.

3.4. Step 3: input and analysis

Following the data processing stage, the ASCII text file of point data was ready for interpolation into a continuous surface. Various GIS software packages and computer platforms were explored at this stage. The Surfer surface mapping software (Golden Software, Golden, CO) provided the capability to interpolate the point data using a number of different algorithms and to display contours and 2-1/2 dimensional DEMs. However, due to the high density of the ATM LIDAR data points and large file sizes, the Surfer software consistently crashed while running on a Pentium I processor and the Windows 95 operating system.

ArcView GIS software developed by the Environmental Systems Research Institute (ESRI, Redlands, CA) installed on a PC with the Spatial Analyst extension provided several useful tools that were convenient when working with data in a raster environment. However, PC hardware limitations were again a limiting factor. ArcView 3.0 was found to be useful for performing analysis and displaying results on a PC, using smaller data sets that will be discussed later in this paper. The Arc/Info (ESRI) GIS software package running on the Unix platform was

determined to be the most efficient software for initial processing of the LIDAR data.

An assessment was undertaken at this stage to determine which interpolation routine would provide the best gridded representation of the data. The GRID module in Arc/Info offered several choices for interpolating the data. Kriging and inverse distance weighted (IDW) methods were examined.

Kriging is based on the regionalized variable theory that assumes the spatial variation of phenomena can be represented by three components: a structural component, a random but spatially correlated component, and random noise (Burrough and McDonnell, 1998; Cressie, 1993). Kriging is a statistically powerful interpolation method. However, if large variations exist between sample points within a neighborhood, kriging may not perform significantly better than any other interpolation routine (Clarke, 1995; DeMers, 1997).

The interpolation routine chosen was IDW. This technique is based upon the assumption that the value at an unsampled point can be approximated by a distance weighted average of sampled points occurring within a neighborhood (Burrough and McDonnell, 1998; Mitas and Mitasova, 1999). Based on the high density of the data points used for interpolation and a visual comparison of initial DEMs, IDW was selected for application in this research. It should be noted that this assessment did not represent a rigorous test determining the optimum interpolation routine, and the authors recommend that further research be carried out in evaluating interpolation methods for LIDAR data (e.g., Desmet, 1997).

After the interpolation routine was selected, the raw 1996 and 1997 airborne LIDAR data were interpolated (or reinterpolated) to 1×1 , 2×2 , 5×5 , 10×10 , 15×15 , and 20×20 m spatial resolutions. With a specific range of resolutions created for both the 1996 and the 1997 data, the floating-point grid coverages were transferred as binary files to ArcView 3.0 with the Spatial Analyst extension for the PC for analysis. The processing continued with the extraction of the two (100×200 m) research sites from the 1996 DEM at each resolution.

ArcView was determined to be useful for a portion of the analysis of this research for several reasons. First, the software was available and provided the capability to easily execute some of the necessary

tasks. Also, algorithms used to compute directional statistics for representing surface complexity were developed in the Avenue programming language for implementation in ArcView (Hodgson and Gaile, 1999). Lastly, the Spatial Tools ArcView extension developed by the USGS Alaska Biological Science Center provided a collection of graphical user interface (GUI) grid tools required for this research. Running simultaneously with the Spatial Analyst extension, Spatial Tools provided the capabilities for clipping grid subsets and altering DEM resolution through mean (or average) aggregation.

A key consideration in the development of these methods was to attempt to use software and hardware components that were widely accessible in state or local government offices, educational settings, or other coastal research facilities. A second consideration was to develop methods of processing the LIDAR data that were practical to implement.¹

The next step was the aggregation of the 1996 LIDAR data to coarser resolutions. Comparing three simple aggregation methods (mean, central pixel resampling, and median), Bian and Butler (1999) found that the mean method of aggregation produced the most statistically and spatially predictable behavior. Moreover, underlying spatial patterns may be detectable at scales within the range of spatial autocorrelation using this method (Bian and Butler, 1999). For these reasons, the mean aggregation method was chosen. Starting with 1×1 m resolution, the 1996 data were aggregated to 2×2 , 5×5 , 10×10 , 15×15 , and 20×20 m resolutions.

One significant issue concerning the 1997 data had to be addressed that was not a concern with the 1996 data. Beginning with the Fall data collections in 1997, the ATM II was implemented. The density of points collected in 1997 was significantly greater than the number that was collected for the same spatial extent in 1996. For example, for Site A (100×200 m), the number of points collected in 1996 was 5778, and in 1997 for the same area, 23,743 points were collected. Coastal LIDAR surveys indicated improved results with higher point sampling density (Huising and

Gomez-Pereira, 1998), but variability in sampling densities did not provide a consistent basis for comparative analysis. Also, the hardware available could not support the processing of the dense data set collected in 1997. A method was devised to reduce the number of data points collected for the 1997 data to more closely match the number collected for 1996. This was done using a short C program running on the Unix platform that extracted every other line (or x,y,z point) from the raw ASCII text file. This method was repeated several times until the file sizes were comparable for 1996 and 1997. Once the sample size of the data was reduced, interpolations were completed and the same procedures for clipping the grids and aggregating to coarser resolutions were replicated for the 1997 data set.

The volumetric change analyses were performed using the reinterpolated data sets. Differencing of the mean aggregated data sets for volumetric change analyses would have resulted in obtaining equal values through the range of resolutions. Directional statistics were compared for both the reinterpolated and the mean aggregated data sets. Reinterpolation simply involved interpolating the raw data points for each cell size to be studied. This method recreated the terrain for each resolution or cell size. The mean aggregation method on the other hand involved the scaling up of data from some known resolution based on the average of surrounding pixels.

One of the key features of the GIS was the ability to perform overlay and difference operations with relative ease. The volumetric analyses were undertaken using ERDAS Imagine, a raster-based image processing software package. With Imagine's Spatial Modeler function, a model was created to difference two DEMs having the same spatial extent, grid cell resolution, and referencing system. Each grid cell in layer "B" was subtracted from the corresponding grid cell in layer "A" resulting in grid cell values for layer "C". Grid cell values for layer "C" represented the differences in the z value or elevation. The resulting elevation change or difference image was reclassified to represent areas of erosion (negative change) and deposition (positive change). The total volumes were calculated by adding the values. To perform the calculation, the attribute file for the differenced image was exported to a spreadsheet software program. The attribute file listed the differenced elevation values for

¹ At the time this research was undertaken, it was not possible to fully process large LIDAR data sets using PC hardware. Today, PC technology has advanced and can provide the capability to handle these data sets.

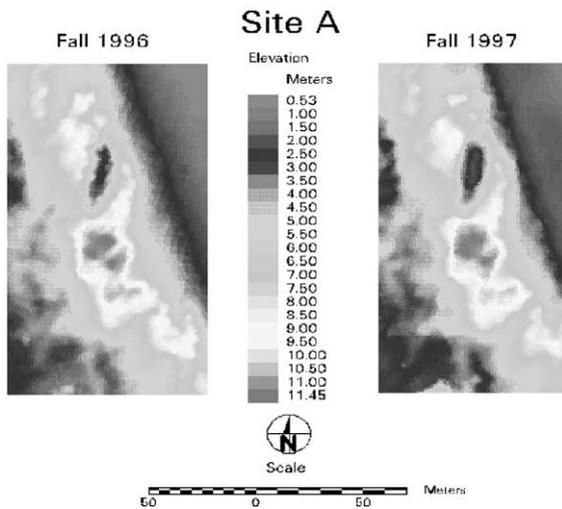


Fig. 3. Site A (100 × 200 m).

each grid cell. These values were sorted to list the negative and positive values. From this list, the negative values were summed to calculate total erosion and the positive values were added to determine total deposition or net volumetric change for the image. Cells assigned a zero value were classed as cells of no change between Fall 1996 and 1997.

For the purpose of this experiment, only the areas from the beach to the back dune were analyzed. Because the ATM II system does not have bathymetric mapping capability, the surface elevation of the water was measured. To avoid entering erroneous data values into the volumetric calculations, an area of interest was digitized to exclude the water and focus only on the dry beach and dune systems. This same area of interest was delineated on both of the images being differenced.

After completing the volumetric change analyses, directional statistics were compared over the range of resolutions for both the 1996 and the 1997 data sets. These statistics took into account the bidirectional angle, which was a combination of the slope and aspect angles. The bidirectional angle was different from the unidirectional angle in that it was represented in 2-1/2 dimensional hemispherical space (Hodgson, 1995). These algorithms provided an estimate of mean surface slope and aspect based on the vector from a 3×3 neighborhood window and were freely available for downloading (Hodgson and Gaile, 1999). The ratio

of the length of the projected vector on the x - y plane and the z component were computed to achieve the mean surface slope. The mean aspect was derived algorithmically from the signs of the ratio of the summed x and y components. The combination of the slope and aspect formed the bidirectional angle (Hodgson and Gaile, 1999). From these calculations, a mean standard deviation (of the bidirectional angle) was derived for an entire DEM as a 3×3 window was passed over the image. The standard deviation was derived from the nine vectors of each window and then a mean was calculated for the entire image. These measurements provided significantly more information about the variability of the terrain surface orientation than a single elevation or z value obtained from a DEM. When comparing two DEMs over spatial scales, the mean standard deviation of the bidirectional angle provided an indicator of surface orientation and complexity. The resulting statistic was similar to the local variance for image analysis proposed by Woodcock and Strahler (1987). However, whereas the Woodcock and Strahler statistic was calculated from a two-dimensional surface, the bidirectional angle is a vector derived from a 2-1/2 dimensional surface. Understanding the topographic complexity of a DEM assisted in identifying the spatial resolution or range of resolutions at which features were best represented and at which volumetric analyses should be undertaken.

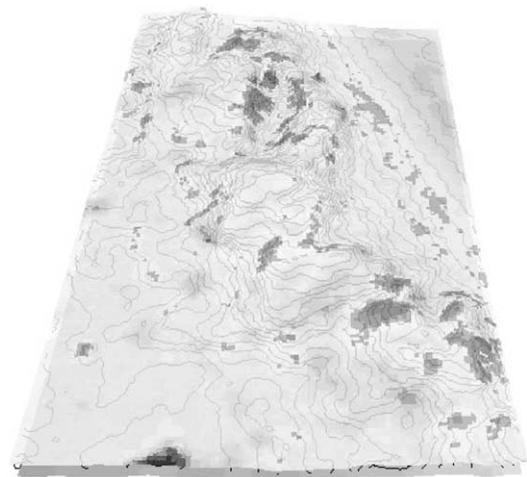


Fig. 4. Site A, erosion and deposition, volumetric change between 1996 and 1997 (net change = 7576 m³).

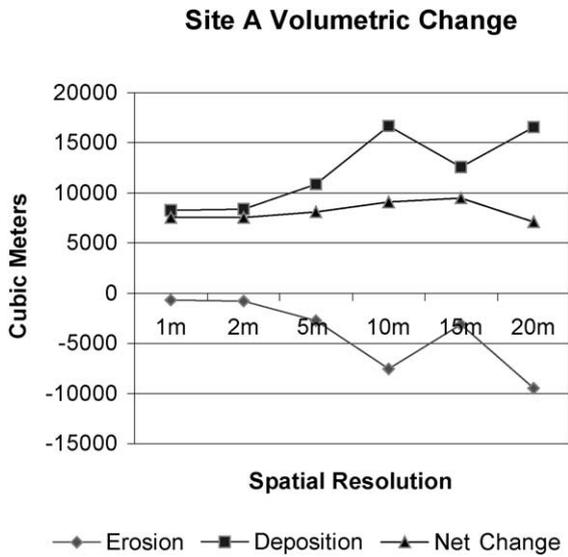


Fig. 5. Site A, volumetric change vs. resolution.

3.5. Step 4: presenting the results

The final step in this GIS-based methodology involved the presentation of results. Several different software packages were chosen to present the findings of this project. The map composer in ERDAS Imagine was useful for creating a side-by-side comparison of the 1996 and 1997 DEMs for Sites A and B. The display of volumetric changes of the sites was best represented using ESRI’s ArcView with the 3D Analyst extension. With 3D Analyst, the differenced images were classified to show areas of erosion (negative change) and deposition (positive change) while also providing a 2-1/2 dimensional view of the area. In addition, the surface profile tool in ERDAS

Imagine provided the capability to illustrate changes in feature representation through the selected resolutions.

4. Results

4.1. Site A

Site A was a highly depositional environment during the 1996–1997 study period (Figs. 3 and 4). At 1 m resolution, the total negative change or erosion for the site was 681 m³ and the total positive change was 8257 m³, equaling a positive net change of 7576 m³. Significant areas of erosion were found along the dune crest. The greatest amount of erosion occurred in the areas surrounding a blowout located in the northern portion of the site. The depositional areas were found throughout the site and areas of significant deposition were found in the backdune areas.

When reinterpolating the raw point data, the volumes of erosion and deposition varied (Fig. 5). At 2 m resolution, the total erosion for the site was 799 m³ while the deposition was 8380 m³, equaling a positive net change of 7580 m³ (Table 1). The difference in volume calculations between 1 and 2 m resolution DEMs for Site A were minimal (4 m³). At the 5 m resolution, however, more significant changes took place. With total erosion amounting to 2715 m³ and deposition, equaling 10,850 m³, the total positive net change equaled 8134 m³. This was a notable increase of 554 m³ of positive change over the 2 m grid cell size. When aggregating further to 10 and 15 m resolutions, the increase continued suggesting deposition was the dominant trend. Also, at 10 m, a distinct

Table 1
Sites A and B volumetric change (m³)

	1 m	2 m	5 m	10 m	15 m	20 m
<i>Site A</i>						
Erosion	- 681.57	- 799.48	- 2715.58	- 7529.00	- 3136.50	- 9452.00
Deposition	8257.58	8380.16	10,850.25	16,655.00	12,615.30	16,568.00
Net change	7576.01	7580.68	8134.67	9126.00	9478.80	7116.00
<i>Site B</i>						
Erosion	- 231.35	- 258.72	- 2860.00	- 7544.00	- 1908.00	- 5064.00
Deposition	8773.66	9180.04	13,088.75	20,327.00	14,370.75	18,576.00
Net change	8542.31	8921.32	10,228.75	12,783.00	12,462.75	13,512.00

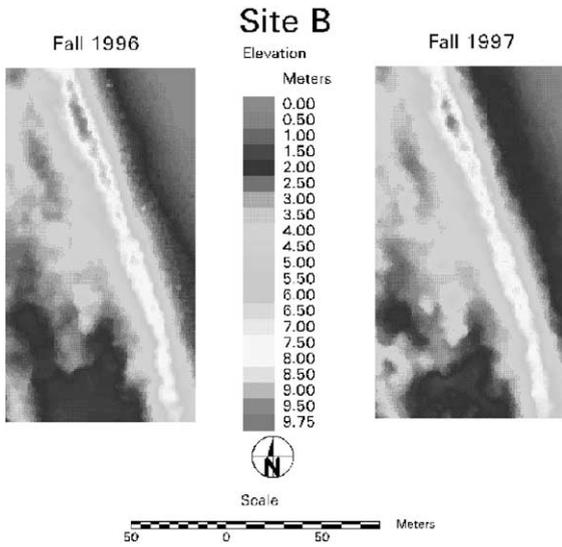


Fig. 6. Site B (100 × 200 m).

increase in both deposition and erosion appeared in the data. At 20 m, deposition was still evident, although a decrease in the total positive net change occurred (7116 m³), which was less than the amount calculated at 1 m.

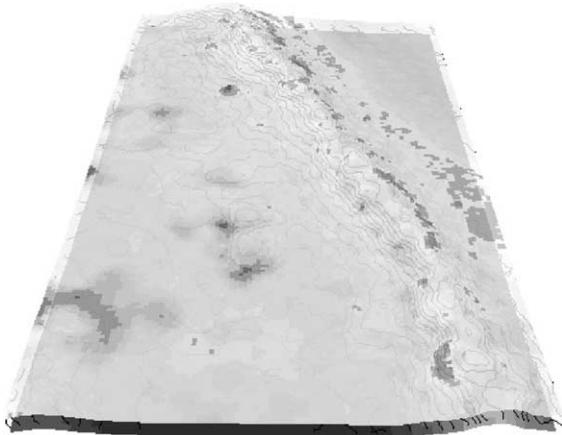


Fig. 7. Site B, erosion and deposition, volumetric change between 1996 and 1997 (net change = 8543 m³).

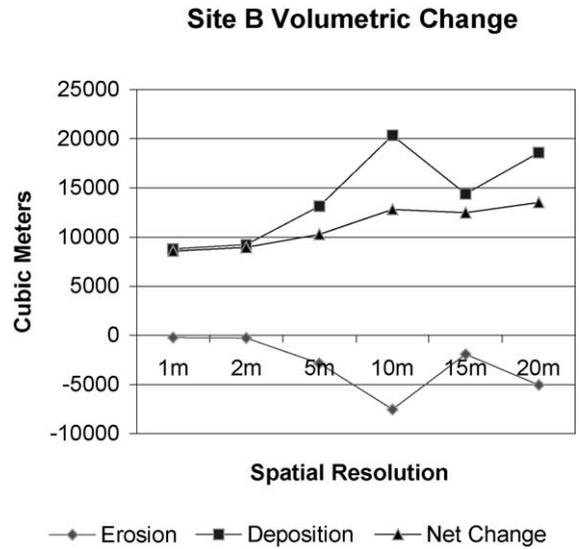


Fig. 8. Site B, volumetric change vs. resolution.

4.2. Site B

For Site B during the study period, analysis indicated that deposition was the dominant trend at this research site as well (Figs. 6 and 7). At 1 m resolution, the total erosion was 231 m³ while the total deposition was 8773 m³, equaling a positive net change of 8542 m³. The erosion at this site occurred mostly along the dune crest. The high deposition areas were located in the backdune.

Site A Mean Standard Deviation (re-interpolated)

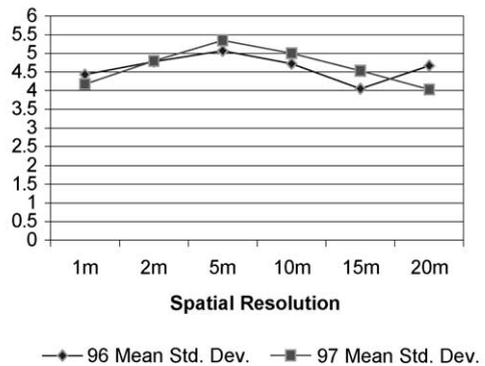


Fig. 9. Site A, mean standard deviation of bidirectional statistics vs. resolution reinterpolated data.

Table 2

Site A mean standard deviation of the bidirectional angle

	1 m	2 m	5 m	10 m	15 m	20 m
<i>Reinterpolated data</i>						
1996	4.43	4.78	5.07	4.72	4.05	4.67
1997	4.17	4.8	5.35	5.00	4.53	4.03
<i>Mean aggregation data</i>						
1996	4.43	4.48	4.62	4.11	3.79	3.33
1997	4.17	4.55	4.9	4.48	4.00	3.43

As in the case of Site A, representing the data from Site B at coarser resolutions resulted in increasingly larger volumetric changes (Fig. 8). At a 2 m grid cell size, there was 258 m³ of erosion and 9180 m³ of deposition, equaling a positive net change of 8921 m³ (Table 1). This resulted in a difference of 379 m³ of positive change between 1 and 2 m resolution DEMs. When the data were aggregated to 5 m, the total erosion was 2680 m³ and deposition was 13088 m³, equaling a positive net change of 10,228 m³. This increase in volume generally continued as the resolution became coarser. The same rise in the data at 10 m found in Site A appeared in Site B. At 20 m resolution, a total positive net change of 13512 m³ occurred.

Site A Mean Standard Deviation (mean aggregation)

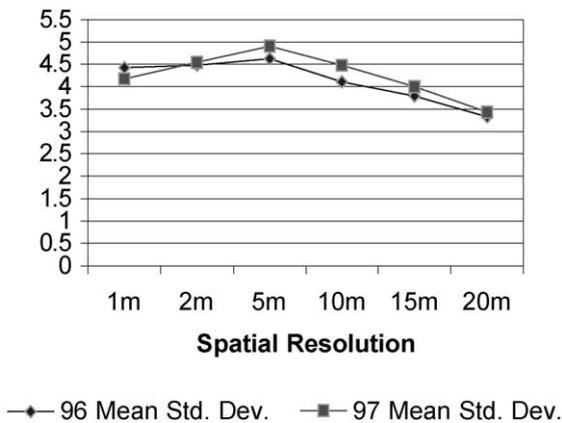


Fig. 10. Site A, mean standard deviation of bidirectional statistics vs. resolution mean aggregation.

Site B Mean Standard Deviation (re-interpolated)

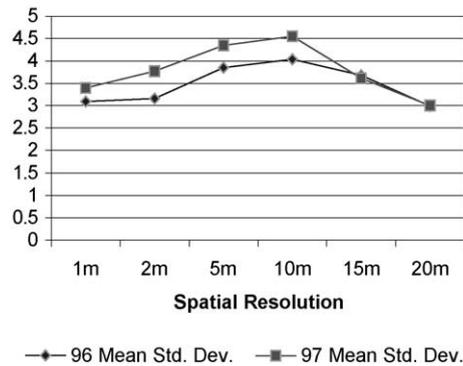


Fig. 11. Site B, mean standard deviation of bidirectional statistics vs. resolution reinterpolated data.

4.3. Bidirectional statistics

The bidirectional statistics for the study sites provided information about the topographic variability of the terrain at different resolutions. Results obtained from DEMs generated for Site A using the reinterpolation method suggested the mean standard deviations were highest at the 5 m resolution in both the 1996 and 1997 DEMs (Fig. 9 and Table 2). These results suggested that the variance in elevation values or complexity of the terrain was greatest when using a 5 m grid cell size for analysis.

DEMs aggregated from 1 m using the mean aggregation method for Site A indicated a similar trend. However, except at 1 m resolution, lower overall values were obtained (Fig. 10 and Table 2). For example, at 10 m for the 1996 DEM, the mean standard deviation calculated using the reinterpolated data was 5 (Fig. 9), whereas the mean standard deviation calculated using the mean aggregation data was 4.48. (Fig. 10).

Table 3

Site B mean standard deviation of the bidirectional angle

	1 m	2 m	5 m	10 m	15 m	20 m
<i>Reinterpolated data</i>						
1996	3.09	3.16	3.85	4.04	3.68	2.99
1997	3.4	3.77	4.35	4.55	3.61	3.00
<i>Mean aggregation data</i>						
1996	3.09	2.98	3.65	3.74	3.08	2.64
1997	3.4	3.58	4.14	4.17	3.22	2.65

Site B Mean Standard Deviation (mean aggregation)

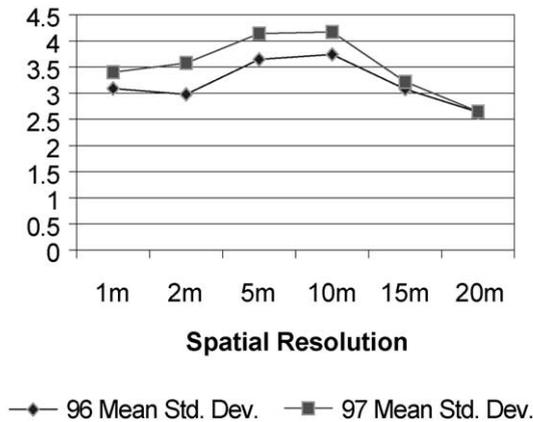


Fig. 12. Site B, mean standard deviation of bidirectional statistics vs. resolution mean aggregation.

The bidirectional statistics for Site B suggested some different trends in the DEM data. Based on the estimated slope and aspect angles, the variability of the terrain using the reinterpolation method was greatest at 10 m for both the 1996 and the 1997 data (Fig. 11 and Table 3). These results varied somewhat from those generated at Site A where 5 m resolution data produced the highest variance. In addition, at Site B, the mean standard deviations calculated for the 1996 DEMs were noticeably lower than those calculated for the 1997 DEMs (Figs. 11 and 12). This separation between yearly values was not as distinct for Site A (Figs. 9 and 10).

Application of the mean aggregation method for Site B suggested that for the 1996 and 1997 data the terrain variability was greatest at 10 m although the variability was nearly as high at 5 m resolution, after which a sharp decline occurred (Fig. 12). As found with Site A (except at 1 m resolution), the mean standard deviations generated using the mean aggregation method were generally lower than those generated using the reinterpolated method (Fig. 11).

5. Discussion

The scaling up of spatial data has become a common practice in a large number of scientific

disciplines. Cao and Lam (1997) note that two questions of scale frequently arise in geographic studies: (1) At what spatial scale and resolution should a study be conducted and (2) can results obtained from a study at one scale be extrapolated to other scales? These questions can be applied to coastal geomorphic studies. For example, what resolution or range of resolutions should be used to represent coastal dunes and their physical processes? In this research, volumetric changes in coastal dunes are calculated at a range of spatial resolutions with the objective of understanding how volume measurements changed as the cell size increased. If the volume measurements do not vary significantly as the spatial resolution increases, a justification can be made for using coarser resolution data in future studies. Practical advantages achieved here would include reduced computational demands such as data processing capability and disk storage space.

Brown and Arbogast (1999) have described potential errors in volumetric studies such as the current one. The error in differenced volumetric measurements will be larger than the errors in the original DEMs. Further research into sources of error in DEMs generated using LIDAR data is justified (Huisin and Gomez-Pereira, 1998). In contrast, the focus of this study is on the relationship between volumetric measurements obtained at different resolutions rather than the evaluation of specific values. The reported accuracy of the LIDAR data used in this study (15 cm) is sufficient for this purpose.

The results from the analysis of the data for the two study sites suggest that considerable deposition occurred between the Fall of 1996 and the Fall of 1997. However, because this is an open system, there are various processes at work and it is difficult to determine the exact source of all the sediment entering the sites.

Analysis of the DEMs created using the LIDAR data indicates that the amount of deposition recorded at both sites varies according to resolution. The measurements for the 1 and 2 m resolution data are very similar. At spatial resolutions greater than 2 m, the net volumetric change increases. These increases are due, in part, to how the dunes are characterized at the different resolutions. At finer resolutions (i.e., 1 and 2 m), the grid cell is smaller than the coastal dune feature it represents. Therefore, the details of the

feature are well represented. For example, a grid cell located on the dune crest may be 8 m in height while its neighbors may slope downwards toward the base of the dune at a height of 1 or 2 m. At coarser resolutions, the grid cell approximated then becomes larger than the dunes. When approximating the size of the dunes, a grid cell may occur at the top of a dune,

and fewer neighboring cells would represent the slope to the base of the dune. At resolutions larger than the dunes, the dune peaks and depressions would be more coarsely represented. This generally results in loss of detail in topographic change data. Application of directional statistics can assist in further understanding feature representation at different scales.

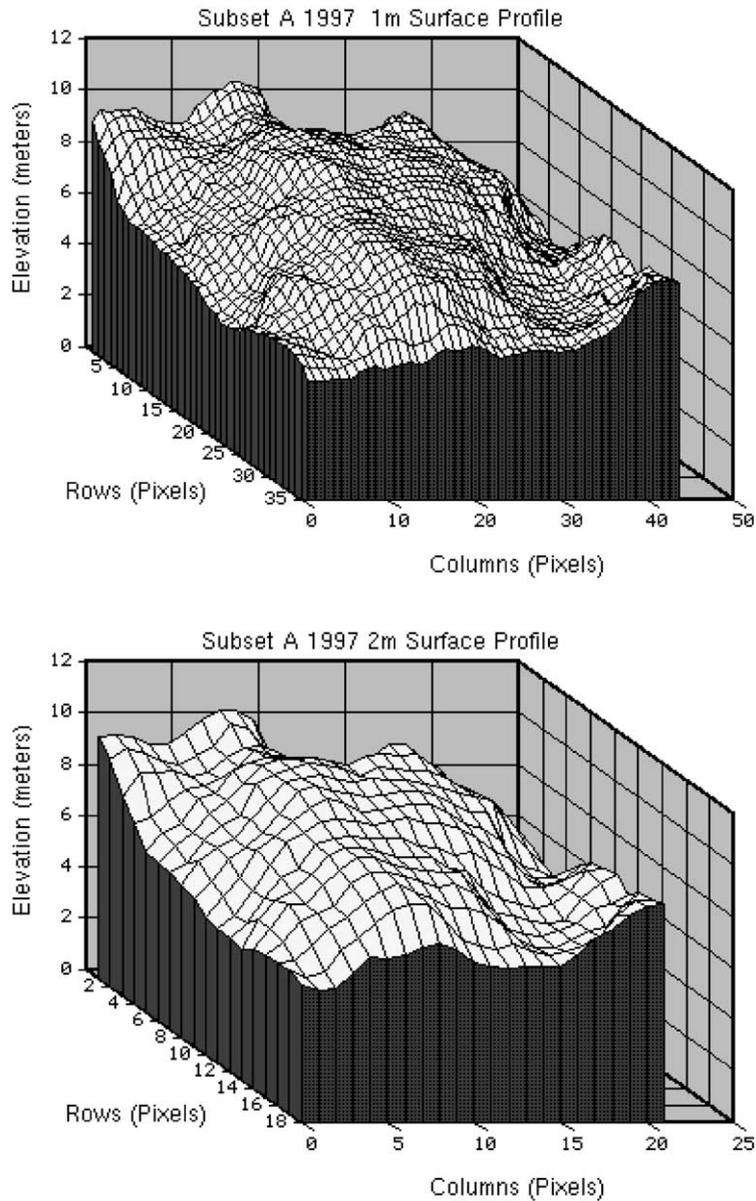


Fig. 13. Subset A 1997, 1 and 2 m surface profiles.

The use of directional statistics to achieve measures of central tendency in surface orientation in a DEM is a new approach in GIS applications. Commercial GIS and image processing systems have yet to include the bidirectional operators necessary to efficiently construct topographic surface orientation related models (Hodgson and Gaile, 1999). This is

unfortunate as these methods may provide an enhanced understanding of the variability of terrain as represented by a DEM.

In this research, a mean standard deviation of the bidirectional angle was computed for each of the LIDAR-based DEMs. One of the general assumptions that could be made is that a 1 m resolution would

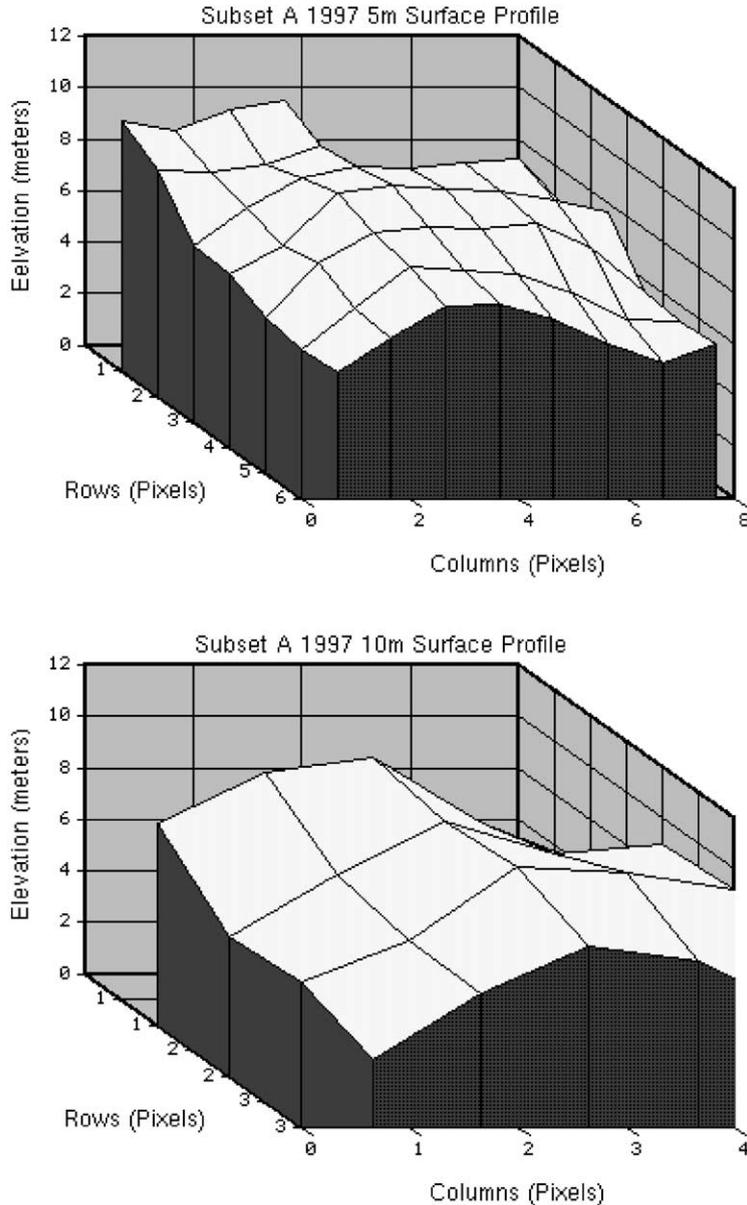


Fig. 14. Subset A 1997, 5 and 10 m surface profiles.

provide the greatest variance in topographic structure. This is not found to be true for either research site. For these sites, using either the reinterpolation or the mean aggregation method, the mean standard deviation increases as the spatial resolution increases from 1 to 5 m for Site A and from 1 to 10 m for Site B. Afterwards, a decrease in the mean standard deviation begins to occur.

This trend can be explained by the spatial resolution of the data and the size of the features being represented in the scene. If a grid cell is much smaller than the features in a scene, local variance will be low because the measurements will be highly correlated with their neighbors. If the grid cell approximates the size of the features, the measurements will be different and local variance increases. As the size of the grid cell increases and many features are found within one single cell, the local variance will decrease (Woodcock and Strahler, 1987, Cao and Lam, 1997). This concept is indicated in this study.

Surface profiles are useful for illustrating the relationship between the features under study and the resolution at which they are represented. The profiles in Fig. 13 indicate that the dunes in Site A are well represented at 1–2 m resolution. At 5 m, the

resolution begins to approximate the size of the main features of the dunes while the overall shape of the dunes is still representative (Fig. 14). The dunes at Site A are wider than at Site B and lack a prominent ridge (Fig. 3). This could account for the highest local variance measurements being obtained at the 5 m resolution. At 10 m, the dune shape is less clearly defined, significant details of the character of the dunes are lost (Fig. 14), and local variance drops. At 15 m, the original shape of the dunes is difficult to recognize (Fig. 15). These observations correspond to the values obtained for the mean standard deviations calculated for this series of resolutions (Figs. 9 and 10) and to the principles of local variance measurements proposed by Woodcock and Strahler (1987).

At Site B, a similar correspondence exists between local variance and relationship between grid cell resolution and representation of coastal dunes. However, the highest local variance occurs at 10 m resolution (Figs. 11 and 12). Inspection of Fig. 16, selected as representative of this site, indicates similar results to those obtained for Site A. However, at the 10 m resolution, the main features are perhaps better approximated and the overall shape of the dunes is still represented (Fig. 17).

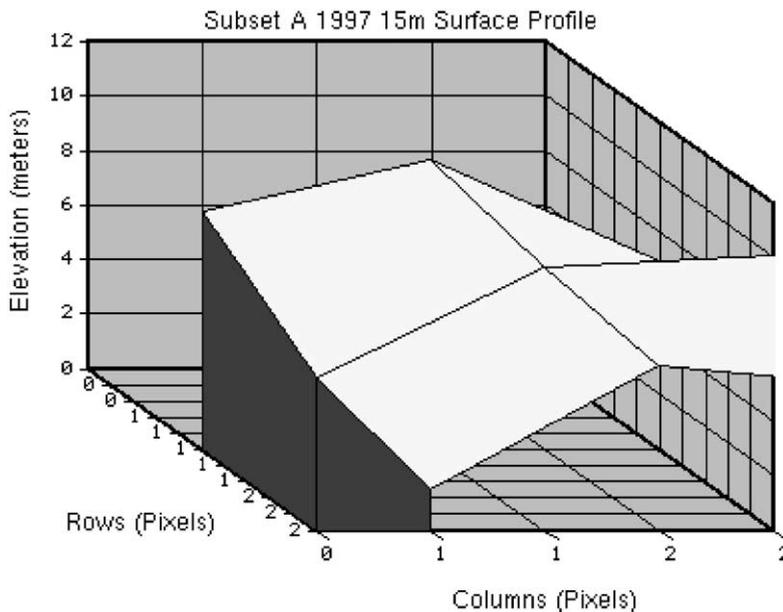


Fig. 15. Subset A 1997, 15 m surface profile.

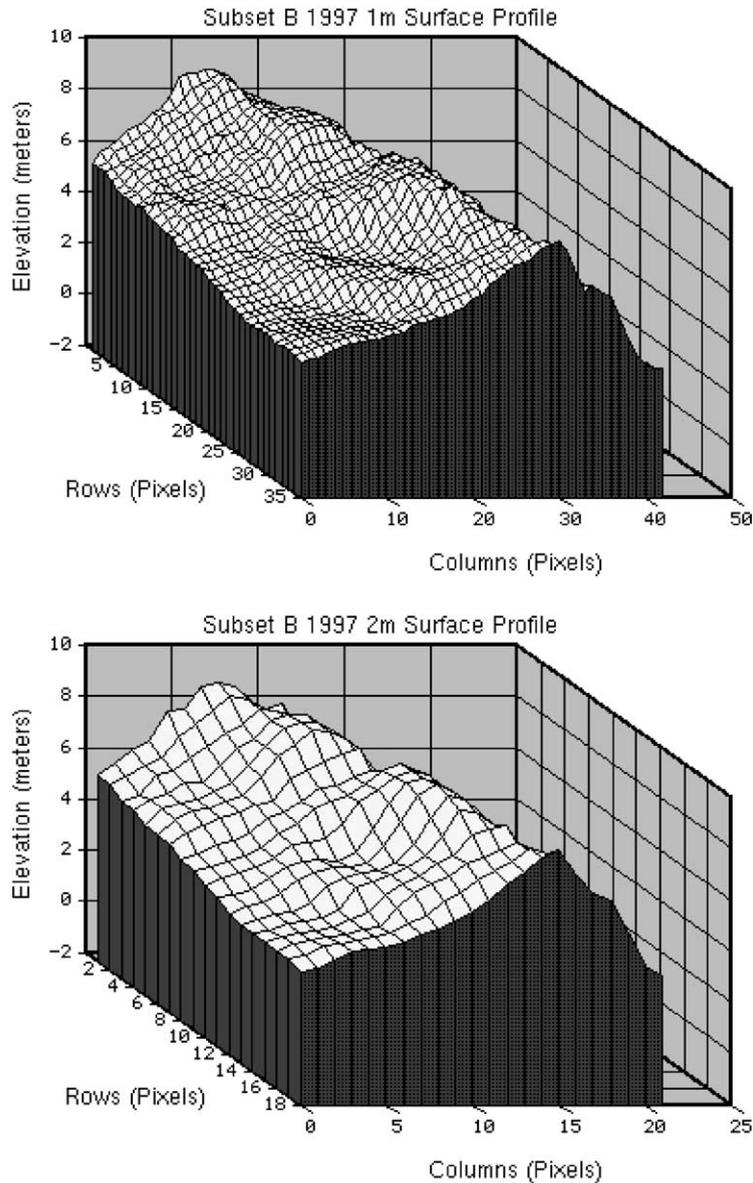


Fig. 16. Subset B 1997, 1 and 2 m surface profiles.

Calculation of the bidirectional statistics provides some additional information regarding the methods selected for representing the data at coarser resolutions. Use of the mean aggregation method results in generally lower bidirectional statistics. These lower values seem to indicate that coarsening the resolution of the data using the mean aggregation method results in smoother terrain than reinterpolating the data to

coarser resolutions, although the trends in variance across resolutions are similar (Figs. 10 and 12). Also, the bidirectional statistics calculated for the 1996 DEMs for Site B are lower at the 2–10 m resolutions than those calculated for the 1997 DEMs. This discrepancy does not occur in the data for Site A. The difference between yearly values for Site B seems to be a function of the larger amount of sediment being

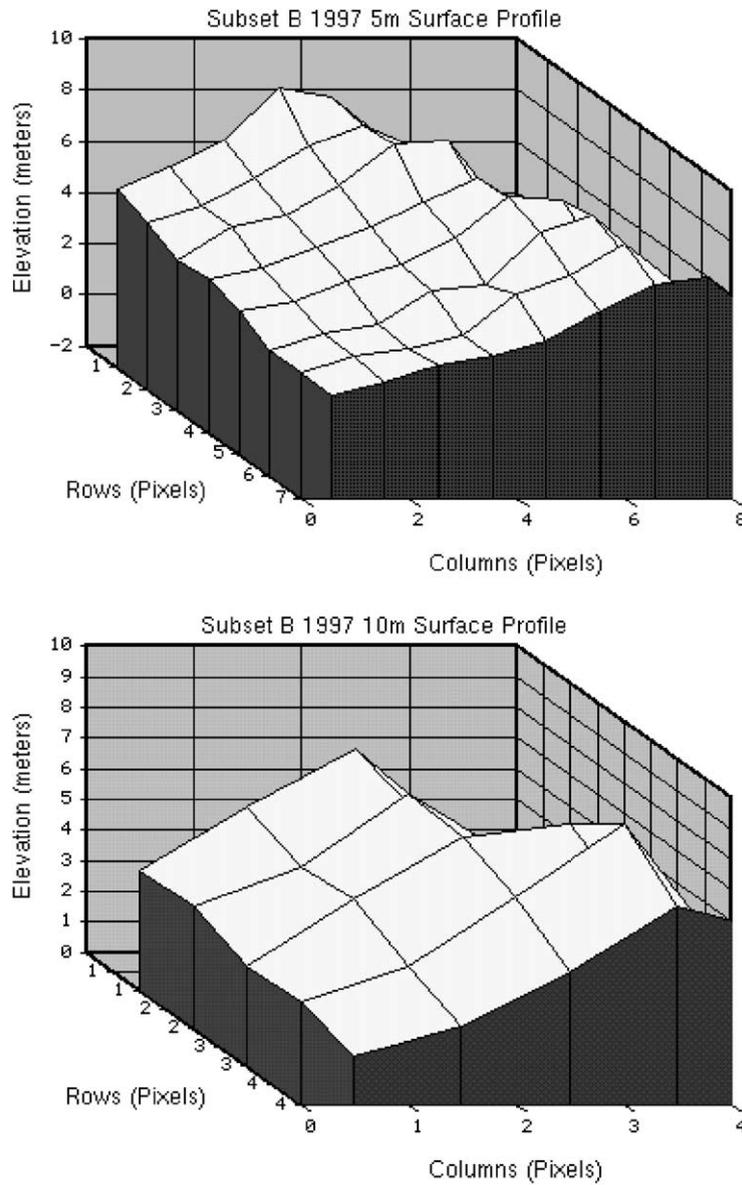


Fig. 17. Subset B 1997, 5 and 10 m surface profiles.

deposited at Site B than at Site A and the resolution at which the dunes were being represented (Table 1).

6. Conclusions

From a geomorphic standpoint, studying coastal dunes at the temporal scale used in this study does not

provide a large amount of information regarding the evolution of the dune system. This temporal scale merely provided a “snapshot” of what occurred over a 1-year period. To fully understand the changing morphology of a dune system, monthly or quarterly elevation surveys spanning all four seasons (conducted from the air or on the ground) should be undertaken (e.g., Andrews et al., 2002). This approach

would provide more frequent data that could be correlated with local storm events and weather patterns such as wind direction and speed. The focus of this research was on the development of methods to characterize and better understand coastal dune systems using airborne LIDAR data, which have been collected annually.

When studying a particular dune system, consideration should be given to the amount of detail required. Characterization of the dunes themselves will require more detail than beach areas because of the greater topographic variability. Some geomorphic studies of dunes may require a finer representation of features than others. According to this research, the most reliable measurements of volumetric change were obtained at 1 or 2 m resolutions. Results obtained at 5 m resolution may provide a reasonable approximation for some studies. Measurements obtained at 10 m resolution and greater for these study sites should be considered less reliable.

Characterization of the structural complexity of the dune systems undertaken using spatial statistics indicated that detailed representation of the dunes was achieved using 1–2 m resolution. The grid cell resolution began to approximate the features of the dunes at 5 m for Site A and at 5–10 m for Site B. The local variance method determines the level of maximum variability. However, for this study, it was determined that the optimum resolution for volumetric change analysis occurred below the threshold of maximum variability. This information may prove useful in other studies. For example, after determining the resolution at which maximum variability occurs, selection of a resolution occurring just below that level may provide satisfactory feature characterization.

To better understand the relationship between topographic characterization, spatial resolution, and volumetric change of coastal dunes, it would be necessary to test several other sites, including areas of varying spatial extents. In addition, the results from this study were influenced by the selection of interpolation and aggregation methods. Other methods of interpolation and aggregation could be tested as well as additional metrics for spatial characterization such as fractals.

LIDAR technology provides the capability to undertake investigations along coastal dune areas. This new method of topographic data collection

advances the potential for geomorphic dune studies by providing high sampling point densities and accurate data in an efficient manner. This new wave of mapping technology offers increased spatial coverage and convenience compared to previous data sources. LIDAR missions can be flown at almost any time and in most weather conditions. These options were not previously available using other data collection methods such as traditional surveying or satellite remote sensing. Areas for which it once took weeks to collect and process topographic data can now be studied in a matter of hours using LIDAR technology. This research serves as one of the first attempts to develop methods for quantitatively characterizing coastal dunes and assessing differences in volumetric measurements through a series of grid cell resolutions using LIDAR data. The methods developed in this study can be used to assess the optimum resolutions at which to represent coastal dunes in other areas for various research or management objectives using common GIS and database software.

Acknowledgements

The authors would like to thank John Brock with the USGS Center for Coastal Geology, Mark Jansen with the NOAA's Coastal Services Center (Charleston, SC), Michael Hodgson with the Department of Geography at the University of South Carolina, and Paul Gares and Yong Wang with the Department of Geography at East Carolina University for their support in this research effort.

References

- Andrews, B., Gares, P.A., Colby, J.D., 2002. Techniques for GIS modeling of coastal dunes. *Geomorphology*, [this issue](#).
- Baltsavias, E.P., 1999. A comparison between photogrammetry and laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 83–94.
- Bian, L., Butler, R., 1999. Comparing effects of aggregation methods on statistical and spatial properties of simulated spatial data. *Photogrammetric Engineering and Remote Sensing* 65, 73–84.
- Bolivar, L., Carter, W., Shrestha, R., 1995. Airborne laser swath mapping aids in assessing storm damage. *Florida Engineering*, 26–27.
- Brown, D.G., Arbogast, A.F., 1999. Digital photogrammetric change analysis as applied to active coastal dunes in Michigan. *Photogrammetric Engineering and Remote Sensing* 65, 467–474.

- Burrough, P.A., McDonnell, R.A., 1998. *Principles of Geographical Information Systems*. Oxford Univ. Press, Oxford, 333 pp.
- Cao, C., Lam, N.S., 1997. Understanding the scale and resolution effects in remote sensing and GIS. In: Quattrochi, D.A., Goodchild, M.F. (Eds.), *Scale in Remote Sensing and GIS*. CRC Press, Boca Raton, FL, pp. 57–72.
- Carter, W.E., Shrestha, R.L., 1997. Airborne laser swath mapping: instant snapshots of our changing beaches. *Proceedings of the Fourth International Conference on Remote Sensing for Marine and Coastal Environments*, Orlando, FL.
- Clarke, K.C., 1995. *Analytical and Computer Cartography*. Prentice-Hall, Englewood Cliffs, NJ, 334 pp.
- Cracknell, A.P., 1999. Remote sensing techniques in estuaries and coastal zones—an update. *International Journal of Remote Sensing* 19, 485–496.
- Cressie, N., 1993. *Statistics for Spatial Data*. Wiley, New York, 900 pp.
- DeLoach, S.R., 1999. Photogrammetry—NOT! *Professional Surveyor*, May 8–14.
- DeMers, M.N., 1997. *Fundamentals of Geographic Information Systems*. Wiley, New York, 498 pp.
- Desmet, P.J., 1997. Effects of interpolation errors on the analysis of DEMs. *Earth Surface Processes and Landforms* 22, 563–580.
- Flood, M., Gutelius, B., 1997. Commercial implications of topographic terrain mapping using scanning airborne laser radar. *Photogrammetric Engineering and Remote Sensing* 63, 327–366.
- Flood, M., Gutelius, B., Orr, M., 1997. Airborne terrain mapping. *EOM*, 40–42 February.
- Haala, N., Brenner, C., 1999. Extraction of buildings and trees in urban environments. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 130–137.
- Hapke, C., Gibbs, A., Richmond, B., Hampton, M., Jaffe, B., Dingler, J., Sallenger, A., Benumof, B., Brown, K., Griggs, G., Moore, L., Scholar, D., Storlazzi, C., Krabill, W.B., Swift, R.N., Brock, J., 1998. A collaborative program to investigate the impacts of the 1997–98 El Niño winter along the California coast. *Shore and Beach*, 24–32 July.
- Hodgson, M.E., 1995. What cell size does the computed slope/aspect angle represent? *Photogrammetric Engineering and Remote Sensing* 61, 513–517.
- Hodgson, M.E., Gaile, G.L., 1999. A cartographic modeling approach for surface orientation-related applications. *Photogrammetric Engineering and Remote Sensing* 65, 85–95. http://www.cla.sc.edu/geog/faculty/hodgsonm/directional_web_page.html.
- Huising, E.J., Gomez-Pereira, L.M., 1998. Errors and accuracy estimates of laser data acquired by various laser scanning systems for topographic applications. *ISPRS Journal of Photogrammetry and Remote Sensing* 53, 245–261.
- Huising, E.J., Vaessen, E.J., 1997. Evaluating laser scanning and other techniques to obtain elevation data on the coastal zone. *Proceedings of the Fourth International Conference on Remote Sensing for Marine and Coastal Environments*, Orlando, FL.
- Krabill, W.B., Thomas, R.H., Frederick, E.B., 1995. Accuracy of airborne laser altimetry over the Greenland ice sheet. *International Journal of Remote Sensing* 16, 1211–1222.
- Krabill, W.B., Wright, C.W., Swift, R.N., Frederick, E.B., Manizade, S.S., Yungel, J.K., Martin, C.F., Sonntag, J.G., Duffy, M., Hulslander, W., Brock, J.C., 2000. Airborne laser mapping of Assateague National Seashore beach. *Photogrammetric Engineering and Remote Sensing* 66, 65–71.
- Kraus, K., Pfeifer, N., 1998. Determination of terrain models in wooded areas with airborne laser scanning data. *ISPRS Journal of Photogrammetry and Remote Sensing* 53, 193–203.
- Lillesand, T.M., Kiefer, R.W., 1994. *Remote Sensing and Image Interpretation*. Wiley, New York, 750 pp.
- Maas, H.G., Vosselman, G., 1999. Two algorithms for extracting building models from raw laser altimetry data. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 153–163.
- Meredith, A.W., Krabill, W.B., List, J., Reiss, T., Frederick, E.B., Martin, C.F., Brock, J.C., Swift, R.N., Holman, R.A., Morgan, K.L., Manizade, S.S., Sonntag, J.G., Sallenger, A.H., Hearne, M.G., Hansen, M., Wright, C.W., Yungel, J.K., 1998. An assessment of NASA's Airborne Topographic Mapper instrument for beach topographic mapping at Duck, North Carolina. *National Oceanic and Atmospheric Administration Coastal Services Center Technical Report, CSC/9-98/001*.
- Meredith, A.W., Eslinger, D., Aurin, D., 1999. An evaluation of hurricane-induced erosion along the North Carolina coast using airborne LIDAR surveys. *National Oceanic and Atmospheric Administration Coastal Services Center Technical Report, NOAA/CSC/99031-PUB/001*.
- Mitas, L., Mitasova, H., 1999. Spatial interpolation. In: Longley, P.A., Goodchild, M.F., Maguire, D.J., Rhind, D.R. (Eds.), *Geographical Information Systems*. Wiley, New York, 1101 pp.
- NOAA Coastal Services Center (CSC), 1997. Airborne LIDAR assessment of coastal erosion (ALACE) project. *National Oceanic and Atmospheric Administration Coastal Services Center Report*, Charleston, SC. <http://www.csc.noaa.gov/crs/tcm/index.html>.
- Peuquet, D.J., 1990. A conceptual framework and comparison of spatial data models. In: Peuquet, D.J., Marble, D.F. (Eds.), *Introductory Readings in Geographic Information Systems*. Taylor and Francis, New York, pp. 250–285.
- Quattrochi, D.A., Goodchild, M.F., 1997. *Scale in Remote Sensing and GIS*. CRC Press, Boca Raton, FL, 406 pp.
- Romano, M., 1997. Airborne laser terrain mapping for cut and fill solutions. *EOM*, 38–39 June.
- Samberg, A., 1996. Airborne laser mapping systems. *Maankaytto* 3, 5–9.
- Sherman, D.J., 1995. Problems of scale in the modeling and interpretation of coastal dunes. *Marine Geology* 124, 339–349.
- Shrestha, R.L., Carter, B., 1998. Instant evaluation of beach storm damage: using airborne laser terrain mapping. *EOM*, 42–44 March.
- Vaughn, C.R., Bufton, J.L., Rabine, D., 1996. Progress in georeferencing airborne laser altimeter measurements. *Proceedings 2nd International Airborne Remote Sensing Conference and Exhibition*, San Francisco, CA.
- White, K., El Asmar, H.M., 1999. Monitoring changing position of coastlines using Thematic Mapper imagery. *Geomorphology* 29, 93–105.
- Woodcock, C.E., Strahler, A.H., 1987. The factor of scale in remote sensing. *Remote Sensing of Environment* 21, 311–332.