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Techniques for GIS modeling of coastal dunes

Brian D. Andrews, Paul A. Gares, and Jeffrey D. Colby

ABSTRACT

Coastal dunes present a unique problem to coastal scientists because of the dynamic nature of most coastal dune systems. Coastal dunes can change shape quickly and frequently due to storm-generated winds and waves. Prevailing winds can transport significant amounts of sand throughout the dune system. Topographic and volumetric changes in a 150×40 m site on the Outer Banks of North Carolina were assessed through a series of monthly field surveys conducted over a 1-year period from May 1997 to May 1998. This paper discusses the Geographic Information System (GIS) methodology used for data acquisition and analysis and presents one methodology developed to measure 3-D dune morphodynamics using a 2-D and 3-D GIS. It serves as a guide for other coastal researchers who may have limited surveying or GIS experience. Issues concerning sampling routine, data density and grid cell size are discussed. The methodology followed results in the production of a grid of interpolated elevation values that can be represented in a variety of ways, including as topographic maps, digital elevation models (DEM) or two-dimensional cross-sections of the dune system. The grid from the May 1998 survey is subtracted from the May 1997 grid to obtain elevation change information that in turn can be represented graphically. The results of the analysis show that volumetric change over the 1-year period was dominated by erosion along the seaward face of the dune. The monthly surveys show that this erosion was the result of two northeasters in January and February 1998. The loss of volume is partially compensated for by accumulation to the rear of the foredune ridge, primarily in locations where blowouts facilitate aeolian transport of sediment from the beach. The implication is that the dune system is eroding rapidly due to storm activity. It also suggests that there is a mechanism for offsetting some of the volumetric loss through aeolian transport into the dune system.

INTRODUCTION

Coastal dunes are difficult landforms to study because of the complex interaction between topography, vegetation and the aeolian processes that move the sand throughout the system. In addition, hydraulic processes may scarp, breach or wash over the dunes. Predicting changes in coastal dunes could be accomplished by developing process-based models, but little success has been obtained following this approach because of the complexity of the system. An alternative approach is to repeatedly measure the topography over time to develop a picture of the changes that have taken place. The monitoring of changes in coastal dunes has important ramifications for the management of coastal systems, but, as with most landforms, such monitoring involves balancing the desire for detail against the need for gathering information about large geographic areas. Collecting precise data is both labor-intensive and time-consuming, factors that preclude extending this type of measurement over large portions of the shoreline. However, when simpler data monitoring methods are applied to larger areas, enough detail may be lost that the natural spatial variability in the landform may be underrepresented. Clearly, the issue of scale is fundamental to developing a program that satisfactorily monitors changes in coastal landforms. In developing such a system, the coastal scientist must determine whether to focus on micro- (meters to tens of meters), meso- (tens of meters to hundreds of meters) or macro- (hundreds of meters to thousands of meters) scale techniques.

Today, technological developments allow for improved monitoring of coastal systems. New, high-resolution satellites provide coverage of large sections of coastline, although even the improved resolution does not provide sufficient detail to give precise measurements of changes in coastal dune topography. Aerial photographs still represent the best visual source of information about mesoscale changes. Horizontal dimensions of coastal landforms can be measured from the photos (Dolan and DeKimpe), but quantifying vertical dimensions is difficult. Light detection and ranging (LIDAR) systems deployed on low-level aircraft, have proven to give accurate horizontal and vertical measurements at both the meso- and microscale (Woolard and Colby, 2002). Although the resolution of these data is excellent, the enormous data sets that are generated have generally required workstation computing capability for processing and analysis. The recent development of more powerful PCs has made it easier to process and analyze these large data sets. Temporal coverage, however, is a limitation when relying on federal government-sponsored flights, and cost can limit commissioned data collection efforts. Ground surveys represent the best way to frequently obtain micro- to mesoscale topographic data. However, despite improvements in survey, the commitment of time and manpower to conducting surveys can limit the amount of detail obtained.

Once the data have been obtained from any of these sources, it is necessary to manipulate them in order to analyze spatial characteristics and to represent them graphically. The advent of Geographic Information System (GIS) technology has permitted such analysis. This approach has been refined in recent years through technological improvements in computer system hardware and in GIS software. This paper focuses on the use of GIS to manage data sets of coastal dune topography obtained by ground survey techniques. It presents a methodology developed to measure dune morphology and to analyze the data using two- and three-dimensional GIS capabilities. The description is designed to serve as a guide for other coastal researchers who may have limited surveying background and/or GIS experience. The purpose of the field investigation was to monitor monthly morphologic changes in a dune system on the Outer Banks of North Carolina in order to derive patterns of erosion and deposition within the system. Elevation change detection in coastal dunes has previously been researched (Gares; Gares and Arens), but the use of GIS for data management and analysis has not been fully addressed.

In this paper, we begin by reviewing some previous methodologies used in coastal dune research. The techniques used in coastal dune research vary in accuracy and scale of applicability, so it is crucial for coastal researchers to understand the benefits and limitations of techniques used to collect coastal data. The review also places new data-gathering techniques and analytical methodologies based on GIS into a historical framework. Next, we introduce the technology used in this investigation which involves a five-step sequence. We illustrate the procedure with field data collected at a site on the Outer Banks of North Carolina. The description of the procedure addresses issues that geomorphologists of all types should be aware of as they conduct similar research. Finally, we demonstrate how the technique can be used to evaluate spatial variations in topographic change of a coastal dune system.

BACKGROUND

Early research involving the measurement of coastal dunes focused on the macroscale and used dune-normal transects to monitor profile changes over time. Profiles, or cross-sections, were derived from point data representing the horizontal distance from a baseline along a line perpendicular to the dune crest and a corresponding elevation value. The transect approach has been used to characterize changes along the seaward face of the dune associated with storm events or with poststorm recovery (Smith; Morton; Byrnes and Arens), or it was used to provide a representation of changes in dune width or dune height over time (McCluskey; Inman and Arens). The transect approach fails to represent micro- to mesoscale variations in dune topography because it cannot account for any features that exist or changes that occur in the alongshore direction. In a sense, it is a static measure of a dune system in that it only shows the form of the feature. It does not allow the development of that form to be related to any surrounding topographic or vegetative features of the system, factors that research has shown are important parameters affecting aeolian sand transport (Sherman and Hotta, 1990). It also assumes that all changes are normal to the dune crest, whereas in fact, winds often blow oblique to the dune crest.

A more extensive surveying approach involves establishing a grid over the dune system and surveying the points on the grid. This method is time-consuming and sometimes cost-prohibitive because the grid needs to be established carefully using a tape to measure distance between points and a compass to establish that shore-normal and shore-parallel grid lines are perpendicular. However, placing markers at the grid points allows repeated measurement of elevation at that location, so that the establishment of the grid needs only be done for the initial survey. The use of a grid permits the determination of locational coordinates along with an associated elevation value. The visual representation of these data has been facilitated by the development of mapping software that permits the creation of a topographic map. Mapping packages require data to be entered in a x, y, z format, representing a shore-normal, a shore-parallel and an elevation dimension. Hence, there is a need for using a grid to provide the x and y values. The z-values are obtained using survey methods. Using the same grid, surveys conducted at different times allow the determination of elevation changes through time, and these changes can in turn be mapped using the x and y coordinates and the elevation change value as z. Early on, options for mapping were limited and the procedure was cumbersome. The SASGRAPH package was one option used successfully (Gares and Gares).

Today, technological improvements have resulted in survey instruments that can determine x, y and z for any point in a system. These total stations measure the distance between the instrument and a reflective target by recording the time it takes for a beam to travel to the target and back. It then computes the x, y and z values using the distance data and angular measurements. Thus, the survey area no longer needs to be manually gridded. This new system has a significant benefit. In the manually gridded system, elevation can only be recorded at the established grid points which means that there could be topographic features between the points that are not included in the survey. This introduces a certain amount of error into the survey. A survey obtained with a total station allows the inclusion of all topographic features in the system. Areas with few distinctive topographic features are represented with only a few survey points whereas areas of significant topography are sampled extensively to accurately represent the feature. The survey data points are then interpolated into a gridded, continuous surface from which a topographic map can be created. Elevation change over time can be computed by comparing gridded data sets in which the grid was developed based on a common set of fixed points included in each survey. This creates a consistent grid from one survey to the next and allows the surveys to be compared.

The critical step in creating topographic maps from survey data is interpolation. Data collected at point locations require interpolation to fill in the spaces where point data are not collected. Interpolation is the procedure of estimating the value of unsampled sites within an area covered by the point observations. The assumptions made about the spatial variation of elevation and location of data collection points are important because they can greatly effect the results. Burrough (1986, p. 165) advises that “it is unwise to throw one's data into the first available interpolation technique without carefully considering how the results will be affected by the assumptions inherent in the method.” This recommendation cannot be stressed enough. The selection of an appropriate interpolation model should be guided by the type of data, the degree of accuracy desired and the amount of computational effort required (Lam, 1983). Interpolation accuracy depends upon the extent of topographic variation in the original surface and the interpolation method itself (Kubik and Botman, 1976). The actual selection of an interpolation model for terrain analysis is a compromise between precision and shape reliability (Desmet, 1997).

The accuracy of the interpolation relies largely on the sampling routine used for data acquisition and the type of interpolation model used for converting the sampled point data into a continuous surface. Unknown values are interpolated by fitting a model of variation to the values of the known data points and then calculating the value at the unknown points. The primary issue in the interpolation procedure is the choice of an appropriate model to fit the data. Interpolation methods often used for topographic interpolation include inverse distance weighted, nearest neighbor, spline and kriging (Lam; Burrough and Burrough). Ultimately, the interpolation model, grid cell size and sampling density for digital elevation model (DEM) analysis require visual and statistical exploration before a final decision is made. For this research, kriging was chosen as the interpolation method because visual analysis suggested a better fit between measured data and interpolated data and because of its ability to incorporate geostatistics to assist in determining optimal grid cell size to represent the dunes.

Geostatistics, broadly defined, are underutilized in GIS in general and in coastal geomorphology in particular. Sophisticated geostatistical techniques applied towards the continuous representation of spatial data emerged in the early 1980s in the mining industry to enhance the location of ore reserves (Cressie, 1993). Among the geostatistical methods of interpolation derived from this work is kriging, perhaps the most widely used of these methods. Kriging offers advantages over other interpolation methods, such as the capability to estimate the quality of predicted elevation points in terms of an estimation of variance. Other interpolation methods would need to rely on a comparison with validation points to provide the same information. Also, kriging provides the capability to determine the distance past which sample points are no longer correlated, through interpretation of a semivariogram. This capability addresses the problem of determining the optimal weighting parameters or neighborhood search radius that is not directly available through other interpolation methods (Burrough and McDonnell, 1998).

Field measurement of elevation along discrete transect lines may require a short amount of time at the site, but it only measures one- and two-dimensional changes (change in elevation along x or y). It does not effectively represent the spatial variability of dune topography in the system statistically or cartographically because of the horizontal distance between transects. Digital elevation models (DEM) address these issues and they provide coastal geomorphologists with improved methods of display and analysis. A DEM is a digital representation of landform data represented as point elevation values (DeMers, 1997). Digital elevation models (here referred to as DEMs but also referred to as digital terrain models or DTMs) are models of the earth's surface, usually representing elevation. Landform analysis based on sampled point data can be modeled using either a digital elevation model (grid) or a triangulated irregular network (TIN) (Burrough and Burrough). DEMs are constructed from square grid cells of equal size that are interpolated or averaged to derive a continuous surface from point data. A TIN is based on irregularly sized triangles that form planes between data points and do not require interpolation (Kumler, 1994). One of the major differences between TINS and DEMs is that change detection between two DEMs will calculate not only net change but also where that change occurs on the grid, whereas TINs can only calculate gross change.

Grid cell size is user-defined. Like the investigation of interpolation model and sampling routine, it is essential to evaluate cell size before analysis and differencing operations. The optimal dimension of DEM grid size, or resolution, is a function of the morphologic feature under investigation, computing capacity and geostatistics (if kriging is used) (Burrough and Desmet). Although one would think the finest resolution possible would logically be the optimal size, this may not always be the case. For example, if the mapped feature is relatively homogeneous, such as a beach, a small grid cell size may introduce artifacts that are not there and make the beach appear uneven. Grid cell size can be too large as well. If the feature under study is a dune blowout with dimensions of 3×2 m, a grid cell size of 5 m would probably be too large and the dimensions of the blowout would be lost in the 5-m grid. A 1- or 2-m grid cell size may be more effective, depending on the density of the data collected around this blowout. The choice of a grid cell size may also depend on the purpose of the analysis. If visual representation of a landform is all that is required (e.g. Bauer and Foley), or if only gross landform change is desired (Van der Wal, 1996), then a larger grid cell size may suffice. Thus, Van der Wal, 1996. D. Van der Wal , The development of digital terrain model for the geomorphological engineering of the 'rolling' foredune of the Terschelling, the Netherlands. Journal of Coastal Conservation 2 (1996), pp. 55–62. View Record in Scopus | Cited By in Scopus (3)Van der Wal (1996) used elevation data from transects spaced 200 m apart to produce DTMs of a Dutch dune ridge in which cell dimensions were 50 m wide by 5 m deep. Although the coarse grid was sufficient to depict the topography of an artificial dune that was very linear and regular in form, a finer grid cell size may be needed for dunes with complex topography.

STUDY SITE

The research site is located at Coquina Beach, NC, approximately 2 km north of Oregon Inlet in the northern section of the Cape Hatteras National Seashore (Fig. 1). The site was chosen because of relative ease of access, minimal human activity and previous investigations at the same location (Beachley and Gares). The Outer Banks, like most ocean beaches on the East Coast of the United States, are on a leeward coast relative to the prevailing continental air masses, but tropical and extratropical cyclonic storms affect the area in the fall and winter. The beaches along this shoreline are relatively narrow, varying between 20 and 60 m in width depending upon the location and the season, and they are eroding at a rate of 1.5–3.0 m/year (Inman and Dolan, 1989). Beaches consist of fairly fine-grained sand with an average size from 250 to 500 μm (Inman and Dolan, 1989) which produce fairly gentle slopes of approximately 2°.

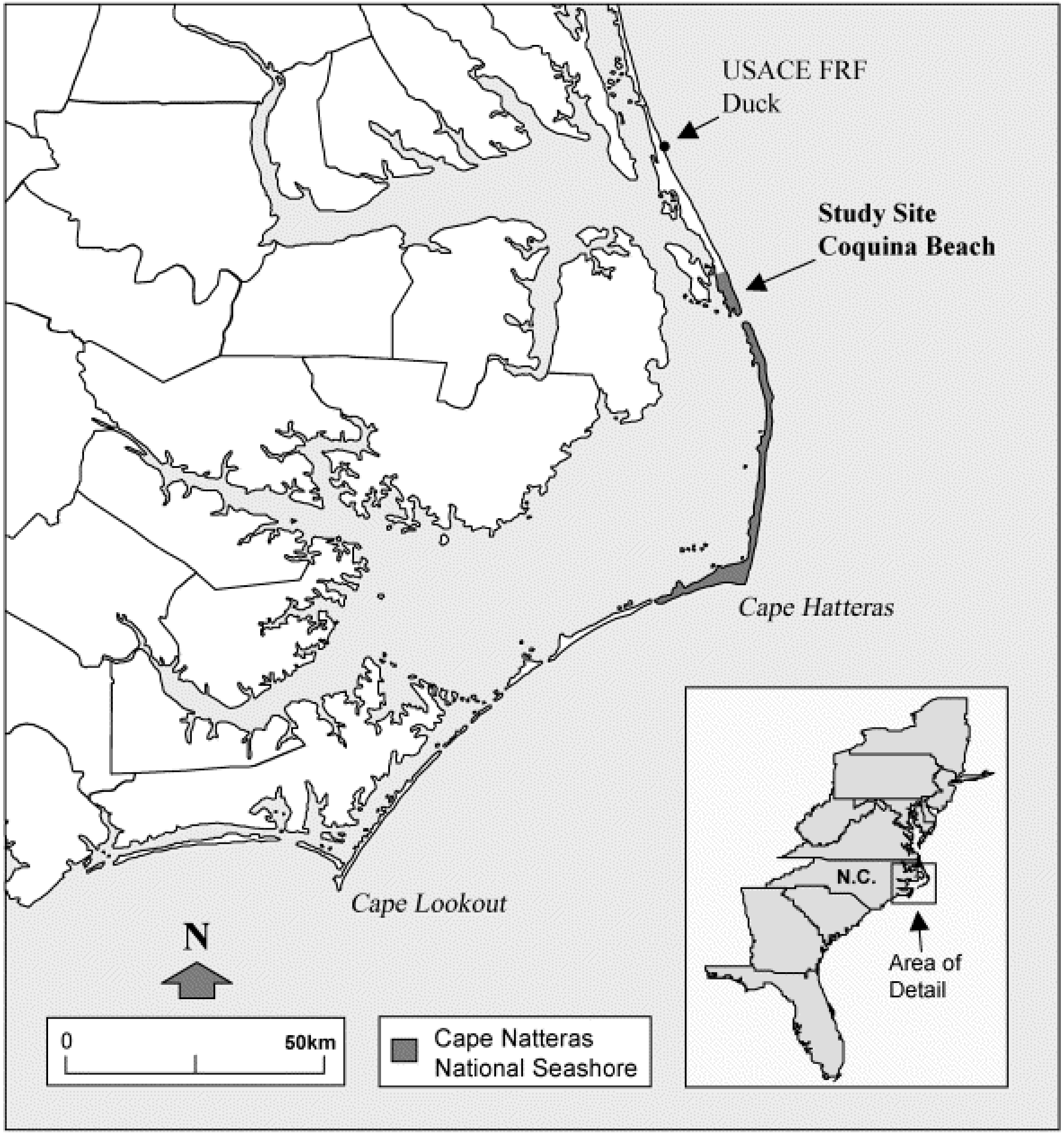

Fig. 1. The Outer Banks of North Carolina showing the location of the field site at Coquina Beach and of the US Army Corps of Engineers Field Research Facility at Duck.

The dunes in the Cape Hatteras National Seashore were constructed by the Civilian Conservation Corps in the 1930s–1950s (Dolan, 1972). The new, artificial, multiple-ridge dune system changed the morphologic character of the barrier islands from overwash-dominated systems to swash and aeolian dominated systems. There has been some controversy over the effect that this new dune system has had on the erosive nature of the contemporary beach. One argument is that the new dune has prevented overwash from occurring and has stabilized the landward end of the beach profile even while a lack of sediment in the system has caused the land–water interface to erode, narrowing the beach and increasing dune erosion (Leatherman, 1979). It is also obvious that winds blow with high enough speed along this shoreline to move sediment and to cause some landward migration of the dune system.

The study site consists of a 150×40 m (6000 m^2) section of dune. The dune is mainly a single foredune, 6–8 m high and 15–20 m wide, with a crest azimuth of approximately 10° magnetic (Fig. 2). The foredune is broken by three blowouts at various stages of development that are oriented NE–SW, apparently in response to the effects of strong northeasters that occur in the winter months when vegetation density is diminished. Blowouts 1 and 2 breach the dune crest in the middle of the study area, providing unhindered communication between the beach and the back dune. Blowout 3, located at the northern end of the study site, developed during the course of the field program. Dune vegetation in the area of the study site consists of four major species: American Beach Grass (*Ammophilia brevigulata*), Sea Oats (*Uniola paniculata*), Water Pennywort (*Hydrocotyle*) and Spike Grass (*Uniola laxa*).

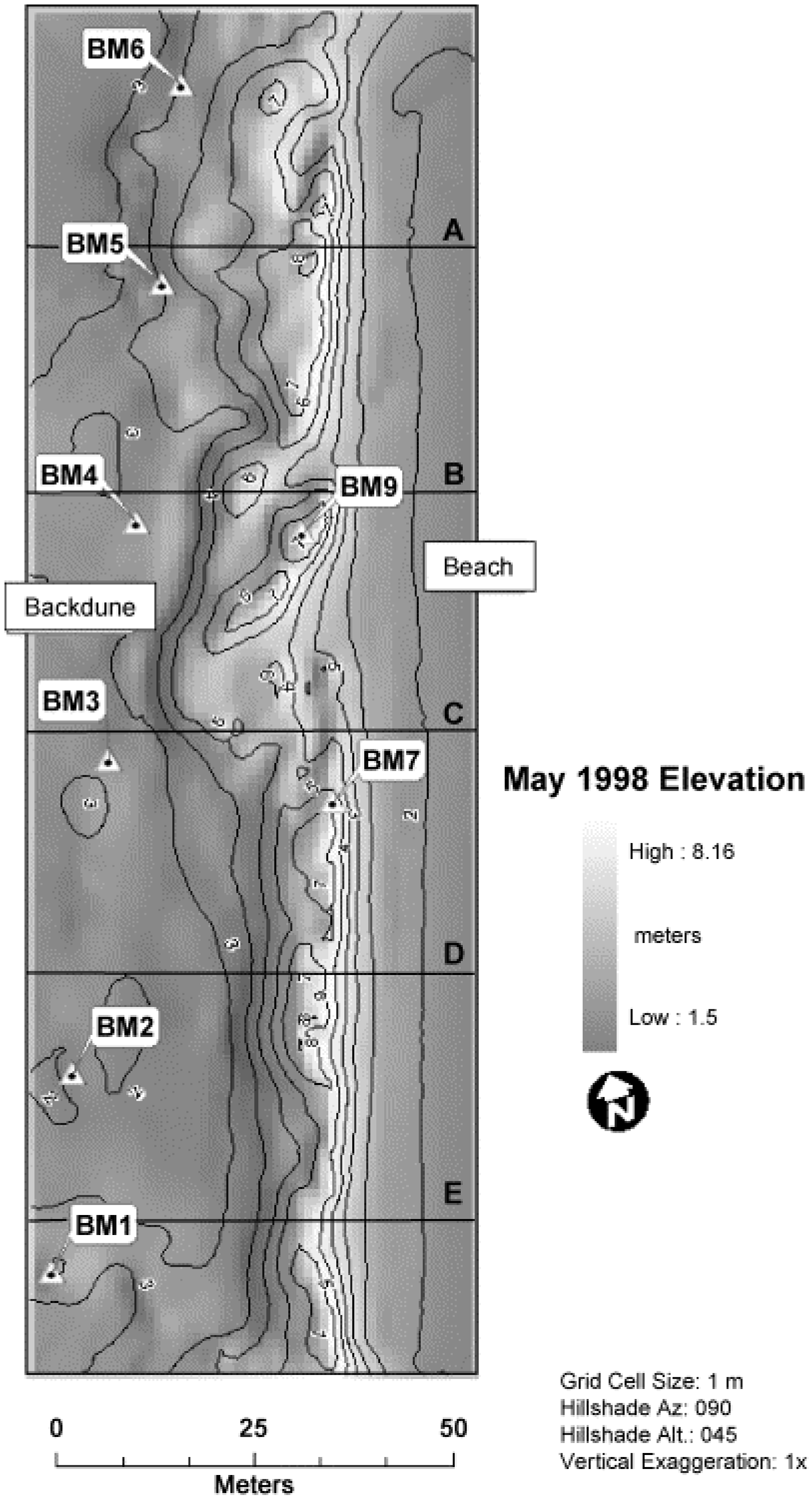

Fig. 2. Topographic map of the field site at Coquina Beach showing the foredune ridge and the blowouts, as well as the locations of the benchmarks and the survey transects shown in Fig. 6.

METHODOLOGY

This study uses dense elevation measurements, geostatistics and DEM analysis in a GIS to measure and calculate mesoscale (10 s, 100 m) sediment redistribution in a coastal dune system. The methodology used in this research consists of five general components (Fig. 3). The first step covers the procedures and considerations for primary data acquisition in the field. In Step II, the raw data are manipulated and preprocessed prior to preliminary map production which constitutes Step III. Step IV involves preparing the data for GIS input, and Step V consists of determining the procedures for final analysis.

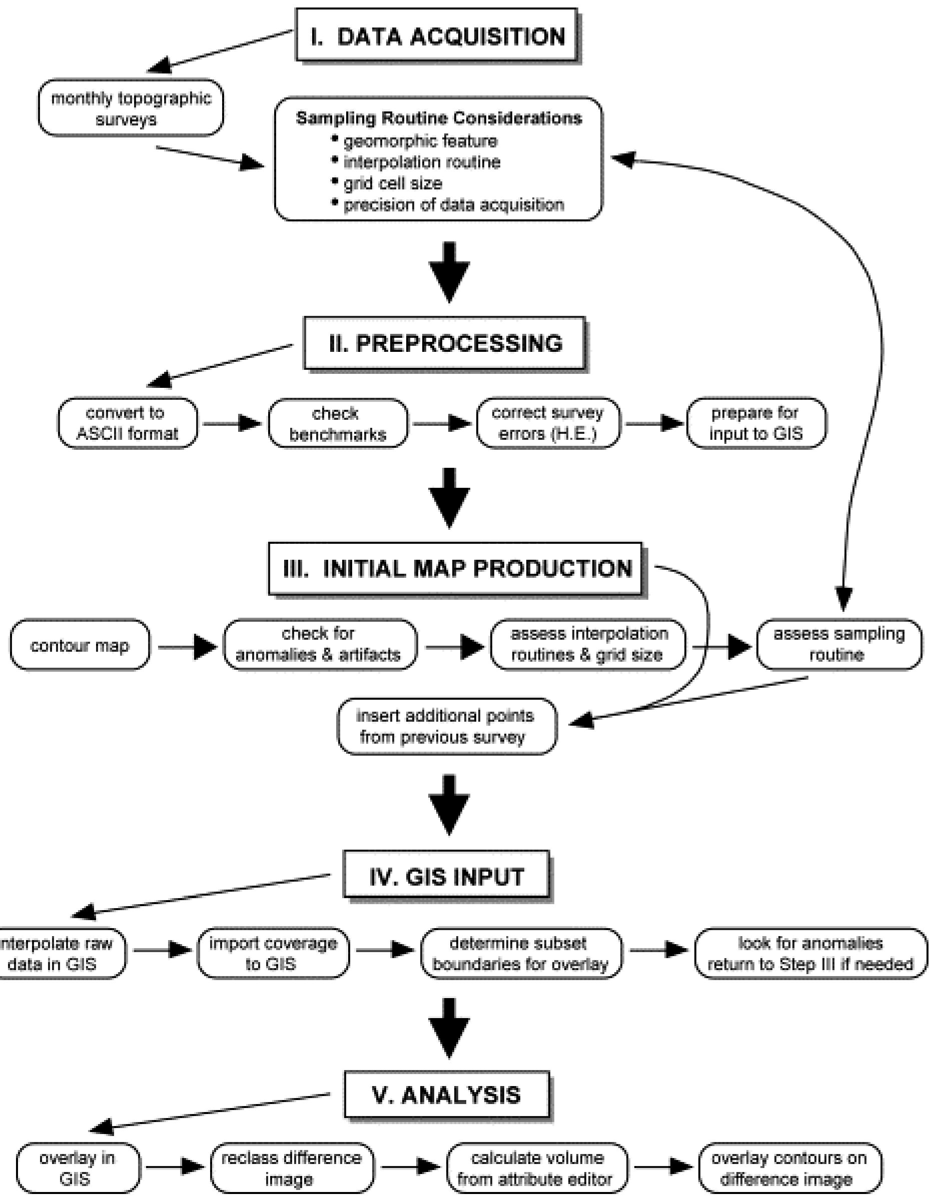

Fig. 3. Methodology followed in this study.

Data acquisition

The data acquisition phase of this research occurred from May 1997 to May 1998. Monthly topographic surveys were conducted by a two- to three-person crew using a Topcon CTS-3 total station and prism rods. Surveying involved one person operating the instrument and the others methodically moving about the survey area with the prisms. Considerable time was initially devoted to investigating effective point densities and sampling routines. After initial exploratory topographic surveys were conducted, the final sampling routine was determined by considering the following factors.

(1) *The spatial and temporal scale of the research question*. The size of the study area and frequency of visits to the site for surveying are important considerations. The size of the area determines the ability of the crew to complete the survey in the time available. The frequency of surveying may depend upon the availability of the crew members to conduct the surveys.

(2) *The general morphologic features*. The dimensions of the features will determine the number of sample points and the sampling pattern needed to accurately represent the landform in the GIS. An important consideration here is the form of the feature. Abrupt, steep slopes require more sample points than gentle, gradual slopes. The shape of the landforms dictates the number of sample points needed which affects the time required for each survey, which may affect the size of the survey area and the frequency at which surveys are conducted.

(3) *The cell resolution for overlay process*. There is a very important relationship between the sampling density and the cell resolution to be used in the interpolation routine. This is discussed in greater detail below.

(4) *Interpolation routine employed for point data*. The distribution of survey points can affect the interpolation routine selected. For example, a random distribution of points would allow the user to choose from a wide range of alternatives whereas points taken along transects would preclude using certain interpolation routines, or would require additional data manipulation before initiating the routine.

Within these guidelines, a flexible random stratified sampling routine was developed and altered as needed to permit surveying of new landforms, such as storm scarps and shadow dunes. An area used in a previous study (Beachley, 1997) was expanded to include locations in which new blowouts seemed to be developing to the north and south of the old site. The final size of the survey area was determined as the area of the survey team could cover in a full day of work. This determination involved recognizing that the topography in the northern part of the site was quite complex requiring many sampling points, whereas to the south, the topography was simpler consisting of a linear foredune ridge with a flat area to the rear which required fewer points. Most surveys obtained 800–1000 survey points.

Six benchmarks were established along a baseline in the back dune, with three more along the dune crest (Fig. 2). The benchmarks were measured in each survey to assure that the surveys could be compared to the each other. Benchmarks were periodically rereferenced during surveys to check for instrument and other random errors. Initially, the instrument was positioned on BM 7 for the entire survey because it was thought that using a consistent instrument position was necessary to allow surveys to be compared, and because it was thought that repositioning the instrument would introduce errors in the data set. A storm in January 1998 eroded the dune sufficiently to prevent the further use of BM 7, necessitating setting up the instrument in a different location. Great care was taken to precisely locate the repositioned instrument with respect to the benchmarks so that all the surveys could be confidently related to each other. It became apparent that moving the instrument resulted in more precise surveys because repositioning during a survey reduced the horizontal distance between instrument and prism, limiting the possibility of obstruction in the line of site between rod and instrument.

Survey routines and procedures were standardized for data continuity and error reduction. Surveys were started with the instrument set up on BM 7. The first rod readings were made on benchmarks 1–6 in the backdune. The obtained *x*, *y* and *z* data were compared to the values from previous surveys. Once it was established that the benchmark coordinates matched those of previous surveys, the survey crew would methodically work the site in loose transects parallel to the dune crest. The rod persons selected sampling points by examining the topography and taking elevation readings at topographic high and low points, along with selected locations in between so as to characterize the features in as much detail as possible. In places of large topographic variation (generally in the dune area), points were sampled every 1–2 m to represent the features accurately, whereas in places with little topographic variation, such as the beach, samples were collected every 10–20 m. *x*, *y*, and *z* values of each point were collected in meters to the nearest millimeter with an HP 43gx data logger connected to the total station. Each point was given a nominal descriptor (beach, dune crest, blowout, etc.) enabling the identification of important morphologic features and benchmarks.

The sampling routine was an interactive process that was occasionally refined as we learned more about the dynamics of the study site and about the interpolation model adopted for this project. Thus, the southwest corner of the site in the back dune showed no visible signs of sediment redistribution in the early surveys and, therefore, it was only fully surveyed in August 1997 and April 1998. The points from these areas of no change were appended into each monthly data set to develop a complete survey. Likewise, it was discovered that vertical surfaces are difficult to accurately depict with interpolated point data because most routines tend to smooth out the cliff or scarp. In coastal dunes, storm scarps and other near vertical surfaces require a greater sampling density along the top and bottom of the scarp to ensure that they are accurately represented on the topographic map. The sampling procedure was also evaluated by visual analysis of the contours on the resulting map and by statistical analysis of residual plots. It was determined that point data collected in a random stratified manner throughout the dune area provided better results than those taken in more discrete transects perpendicular to the dune crest.

Data preprocessing

This step manipulates the raw survey data into a usable ASCII format and corrects errors, such as improper data entries. Survey data from the data logger were downloaded to a computer in an ASCII text format. The ASCII formatted data were then imported into spreadsheet software where benchmark coordinates and elevations could be checked and analyzed for inconsistencies. Errors noted in the field, such as incorrect height of eye for the rod and nominal descriptors are corrected in this phase. Occasionally, a single month's survey was conducted in two or three consecutive surveys within a week of each other because of short winter days, bad weather, or equipment failure. This phase combined these consecutive surveys into one data set.

Preliminary map production

At this stage, point data are ready for preliminary interpolation into a gridded continuous surface. A basic mapping software program, such as SURFER® (Golden Software, Golden, CO) or ArcView (ESRI, Redlands, CA), is ideal for quick visual display of contours and 2.5-D relief prior to final interpolation. This cartographic representation of preliminary point data provides the first opportunity to analyze the spatial distribution of a continuous surface in order to assess the sampling routine, interpolation models, and grid cell size. Simple visual analysis of a preliminary DEM is an important step because elevation spikes and other artifacts can be identified in a three-dimensional representation better than a two-dimensional contour map. The relationship between a contour and the data points can be compared by overlaying the locations of the original data points on the map (Fig. 4). Analysis of the spatial and empirical relationship is important to understand because it can guide the survey team in deciding point densities for future surveys. Visual analysis of both the contour map and the DEM can identify artifacts (Krajewiski and Gibbs, 1991), spikes or other irregularities that require editing of the original data set. Areas of irregular or ‘bull's-eye’ contours usually result from insufficient data point density, or other surveying errors, such as incorrect height of the prism rod.

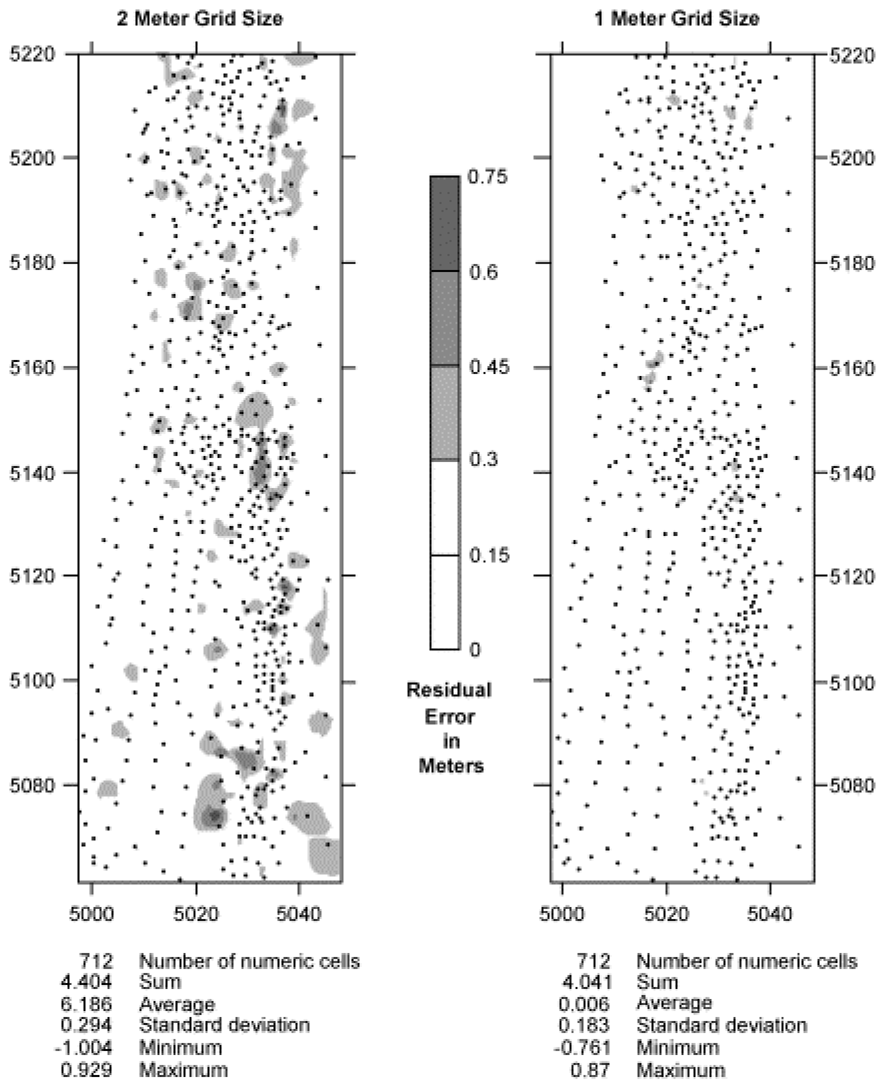

Fig. 4. Contour map of residuals of interpolated topographic data.

Once the distribution of sample points has been evaluated, it is necessary to select one of the several available interpolation models. Visual analysis of maps derived from different interpolation models is often sufficient to eliminate some interpolation methods for the particular variable being mapped (in this case elevation). Analysis of residual plots and their descriptive statistics can provide a further basis for deciding on an interpolation model. A residual is the difference between a grid cell value and the actual data point that falls within that grid cell. Contour maps of residuals, produced in SURFER, for example, can be examined to assess errors between the actual data points and the interpolated surface. Exploratory maps from early surveys were made using inverse distance weighted, nearest neighbor and minimum curvature and kriging interpolations. Fig. 4 is an example of this type of map made from the kriging interpolation data. From simple visual observations and residual analysis of these exploratory maps, inverse distance weighted, nearest neighbor and minimum curvature interpolation models were eliminated for use with these data because they did not accurately represent the continuous elevation of the dune. The data obtained through the kriging model show that the error as depicted by the distribution of residuals was very small, with only some locations showing any sizable departures from the actual elevations (Fig. 4).

Choice of grid cell size to be used in the interpolation is also analyzed by evaluating the distribution of residuals. Having determined that kriging provides the most accurate representation of the study area, different grid cell sizes were experimented with to determine the most accurate cell dimension to use in the detailed analysis. A 1-m grid cell size was determined to be the optimum size for the data point density obtained from the field surveys because the 1-m data had substantially lower residual error than the 2-m grid cell data (Fig. 4).

GIS input

In phase IV, the original raw point data were interpolated a final time using GIS Arc/Info and the parameters defined in the previous phase. The resulting grid was imported into a floating point raster format in ERDAS IMAGINE (ver. 8.2 for UNIX). IMAGINE was used for the overlay process because it is raster-based software and it was readily available. (ArcView with Spatial Analyst and 3-D Analyst could also work well at this stage.) As in Phase II, the DEM was inspected for artifacts and irregularities in the surface that deviated from the visual field observations.

Analysis

Overlay and difference operations are some of the defining features of any GIS. The requirements for the overlay operation are that both input grids need to have the same cell resolution, the same spatial and coordinate referencing system, and usually the same spatial extent. Each monthly survey had different seaward extents because of varying tide levels at the time of the survey. The data sets, therefore, needed to be modified so that they all had the same seaward spatial extent. Likewise, the surveys extended varying distances along the inland margins of the study area, and it was necessary to make these boundaries consistent for each survey. When two DEMs have the same grid cell size (established during interpolation), the same referencing system (established in the survey process), and the same spatial extent (established during data processing), the value of one cell in grid “A” can be subtracted from the value in the corresponding cell in grid “B.” The resulting value for cell “C” is the difference between the *z* values or elevations in cells “A” and “B.” The elevation change values can, then, be mapped using the same mapping software as that used to make the topographic maps. The resulting difference image requires colors to be assigned to a range of cell values in order to enhance visual analysis (Fig. 5). The spatial relationship between topography and sediment redistribution can be analyzed by plotting elevation contour lines on the DEM. This enables the spatial variation of elevation change to be visually correlated to the topographic conditions of the dune system.

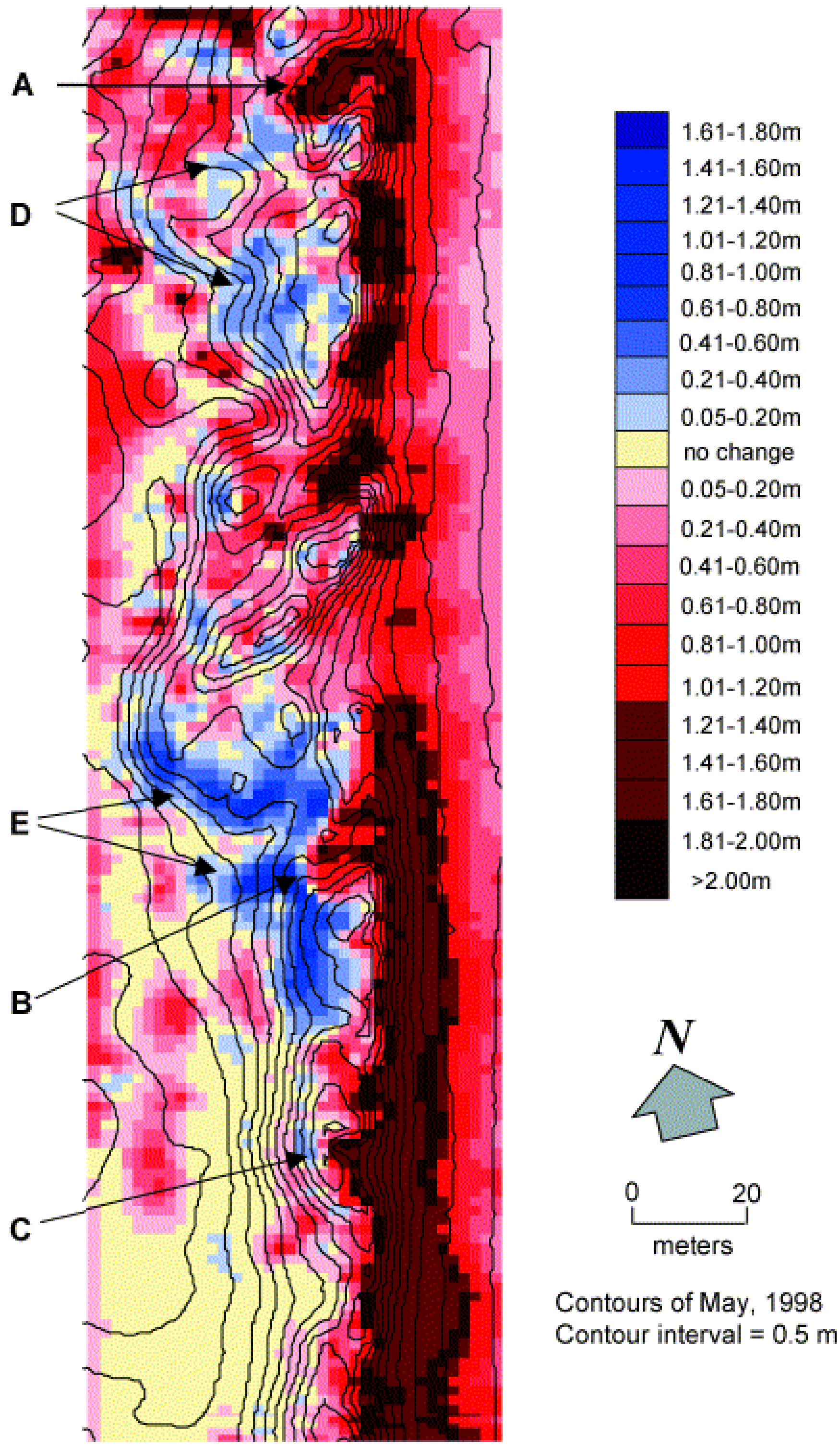

Fig. 5. Elevation change map produced by subtracting the interpolated 1998 topographic data from comparable 1997 data.

Volumetric calculations are generated from the sum of the cell values for elevation change. Many GIS software programs now have standard volume calculation tools that can be used to compute volumes. An alternative is to export the cell values in an ASCII format into a spreadsheet for calculation of total positive pixels (deposition) and negative pixels (erosion). In this study, values of $|z| \leq 0.05$ m were considered to be so small that these were defined as areas of no change. This classification allows the accommodation of potential errors associated with the positioning of the survey rod. The pixel or cell values from the areas of no change are then subtracted from the gross volume to derive the total net volume of erosion and deposition.

Once this phase is completed, further analysis of visible change and calculated change can occur. The magnitude and direction of wind events associated with pressure systems can be related to the redistribution of sediment. If vegetation surveys are conducted, the spatial distribution of vegetation characteristics can be mapped in the GIS and can be related to the pattern of elevation changes. It is also possible to examine two-dimensional profiles across the study area. Coordinate/elevation data can be extracted from the DEM along user-defined transects and these data can be graphed (Fig. 6). When they are oriented normal to the dune crest, two-dimensional profiles are useful for measuring storm erosion and poststorm recovery on the seaward face of the dune. Profiles could also be used for representing changes along the dune crest, or through a blowout, or along the landward slope of the dune. The actual cell data can also be used for various types of analyses, including the determination of some basic descriptive statistics (Fig. 7).

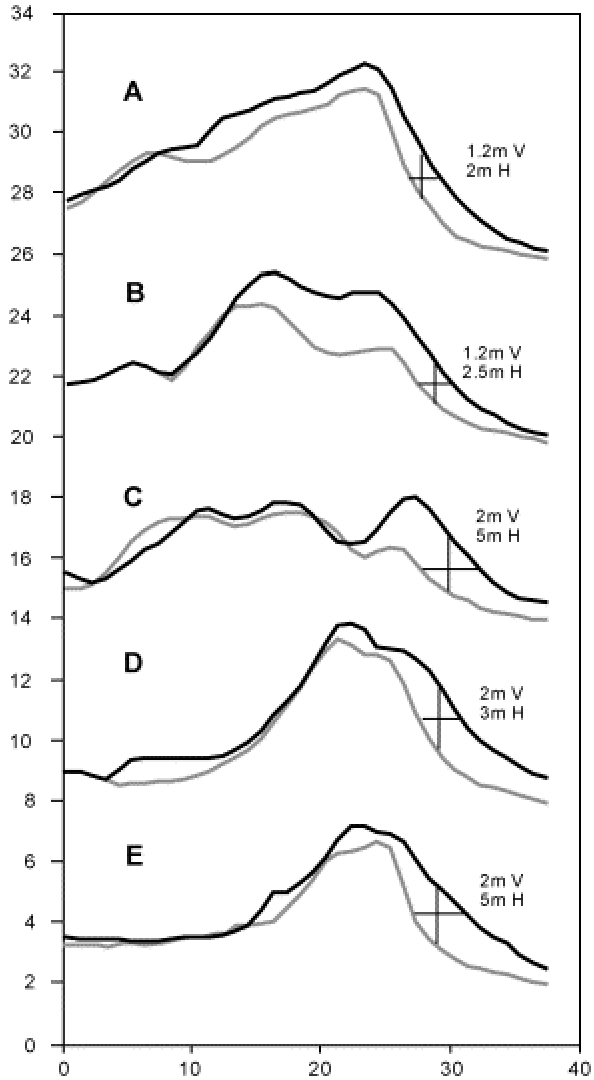

Fig. 6. Representative shore-normal profiles of the Coquina Beach dune data extracted from the interpolated topographic data.

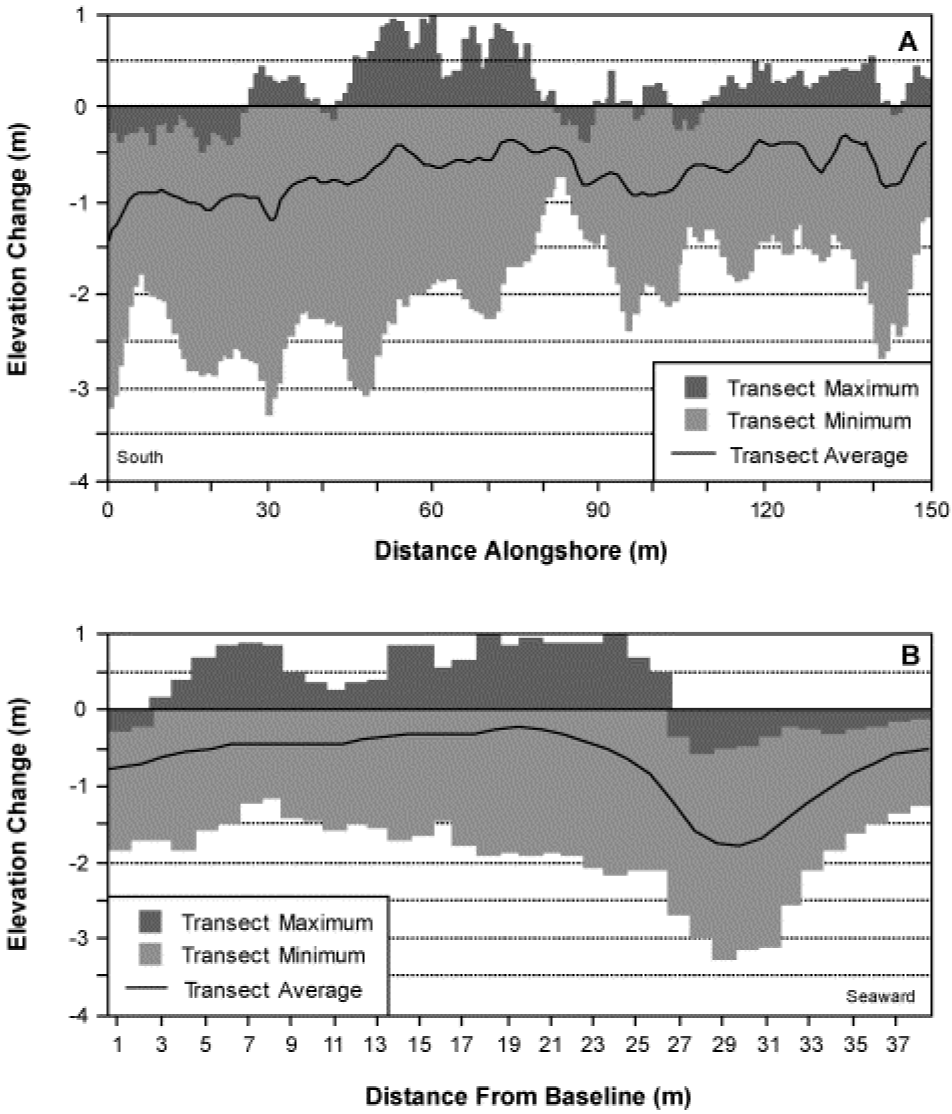

Fig. 7. Average, maximum and minimum elevation change along individual transects in the alongshore direction (A) and shore normal direction (B).

RESULTS

The topographic surveys of the Coquina Beach dune system reveal a complex system that includes two topographically distinct areas. The southern half of the site is characterized by a single, linear dune ridge that is 14–18 m wide (Fig. 2 and Fig. 4). The ridge has several indentations along the seaward face that appear to be of aeolian origin, one of which, located at the southern end of the ridge, is fairly large both in width and depth. These indentations could eventually be places where blowouts develop at some future time. The dune in the northern half of the site has a more complex topography. In general, the dune is 25–28 m wide, but there is a less continuous dune crest as the dune has been breached in several places, and the breaches have developed into blowouts. One such breach, at the northern end of the site, developed during the study period, and consequently it had not developed yet into a large blowout when the study ended.

The pattern of change at this site shows that areas of significant erosion occurred along the seaward face of the dune (Fig. 5). This erosion was the result of high water conditions associated with two large northeasters that affected this coastline on January 27–29 and February 3–8, 1998. Data from the US Army Corps of Engineers Field Research Facility at Duck, NC (Fig. 1), show that wind speeds associated with the storms ranged from 8 to 13 m/s, and these produced 4–5-m waves (www.frf.usace.army.mil). The erosion was exacerbated by the fact that the storms took place over several high tides, so that storm waves reached the base of the dune, causing extensive scarping all along the dune face. As a result, the vertical erosion was fairly uniform from the dune toe to the dune crest, generally ranging from 1 to 3 m (Fig. 5 and Fig. 6). This erosion produced horizontal retreat of the dune face as well, amounting to 2–5 m. In addition to wave erosion, there is evidence that the winds associated with these storms produced some significant erosion in specific places (locations A, B, C, Fig. 5). In May 1997, location A was a deep saucer-shaped blowout separated from the beach by a narrow dune ridge (Fig. 8). Erosion by the storm waves narrowed the dune sufficiently to create an opening through the ridge into the blowout. The elevation change data show that there was considerable erosion along the landward (western) face of the blowout wall. This location suggests that wind erosion occurred here during the 1998 storms, as the northeast storm winds were funneled through the opening in the dune ridge created by the wave erosion along the dune face. Other areas of wind erosion occurred along the dune crest in the southern part of the study area (locations B and C). It is assumed that the lowering of the ridge line in these locations was the result of wind rather than wave action because the depressions developed higher on the profile than could be reached by waves. The resulting topographic depressions that were present in May 1998 suggest that new blowouts may be forming.

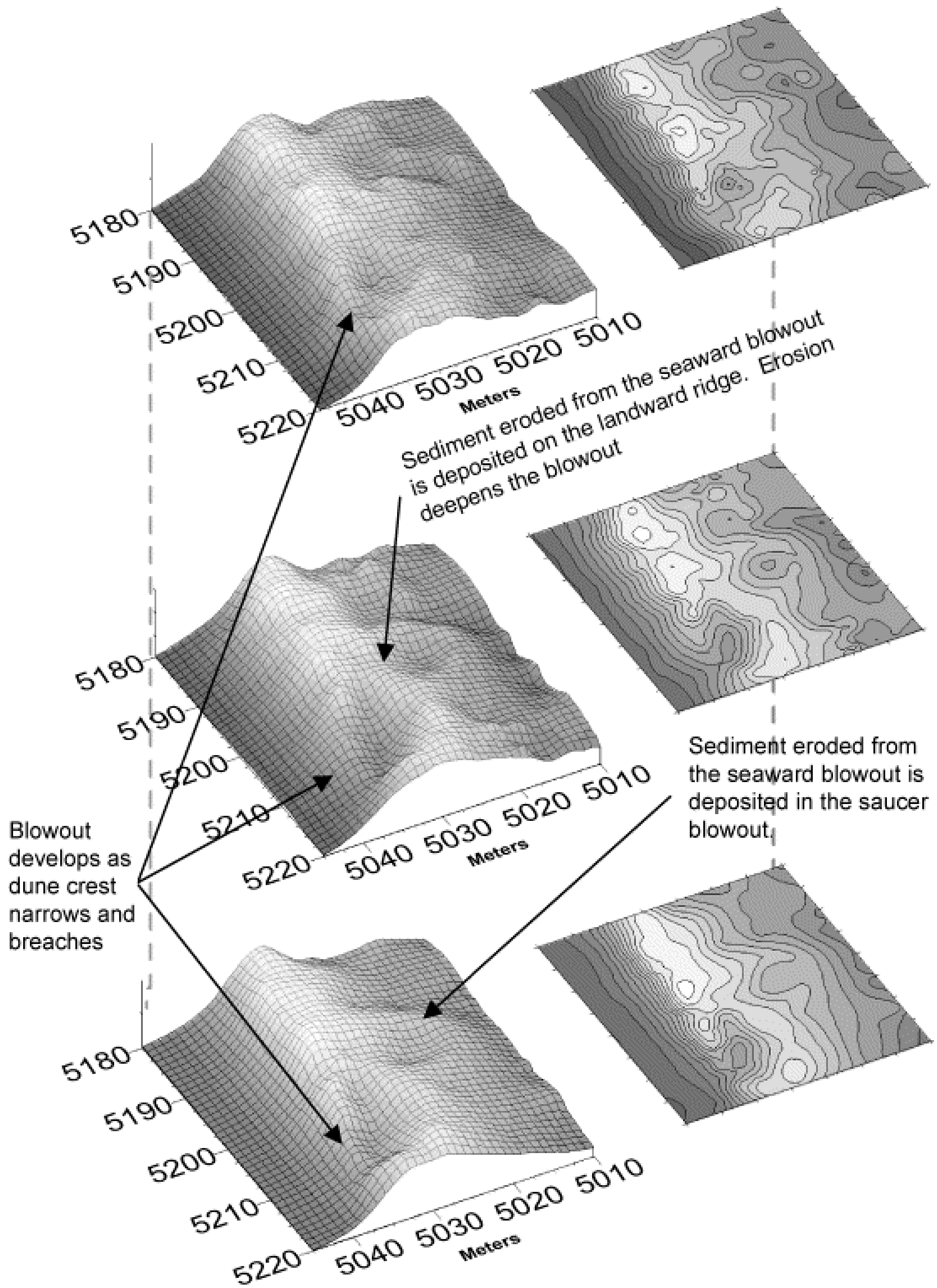

Fig. 8. The development of the blowouts at the northern end of the study area (Fig. 5).

DISCUSSION

The use of digital elevation models and geostatistics in coastal landform analysis has expanded throughout the decade of the 1990s, paralleling the development of Geographic Information Science technology. Early on, Dikau (1993) argued that the new techniques showed promise in the representation of landforms. Van der Wal (1996) showed that DEMs are useful in coastal landform analysis at the meso- and macroscales. This work demonstrates that GIS can also be used advantageously in coastal systems at the microscale, supporting similar work by Gares and Gares and by Arens (1997). One of the key issues is to determine the scale and grid cell size that will permit accurate cartographic representation of micro- to mesoscale coastal landforms. The success of such a project depends on following a stepwise sequence that begins with data collection in the field. While it is difficult and time-consuming to represent every shadow dune and small topographic variation, it is possible to portray them reasonably with dense sampling in the immediate vicinity of the feature. Assuming that the sample point distribution is dense enough, the next issue involves the interpolation routine adopted. The availability of geostatistics in the kriging routine makes it an attractive option because it is possible to evaluate the optimal grid cell size, and to analyze the accuracy of the predicted elevations through an analysis of residuals. This type of analysis demonstrated that a 1-m grid cell size was optimal for the spatial and temporal scale of this research, and it showed that the elevation values predicted by the interpolation routine accurately represented actual surveyed values. The determination of cell resolution is an important component of this type of analysis, and other researchers will need to establish the resolution appropriate to their specific situations.

This research also demonstrates the value of GIS in monitoring and analyzing landform development through time. The use of GIS facilitates the management and interpolation of the large spatial data files. The existence of the data in this format allows the surveys to be compared and the data to be manipulated in a variety of ways both visually and quantitatively. In this research, the interpolated grid of elevation data from one survey was subtracted from a comparable grid set from a previous survey to provide elevation change data. These elevation change data were then represented cartographically to provide a visual representation of the pattern of change at the study site (Fig. 5). The data themselves could be extracted and manipulated in any number of ways to accomplish a more quantitative spatial analysis of the changes (Fig. 6 and Fig. 7) or to focus on changes within a specific portion of the study area (Fig. 8). Although it is not the purpose of this paper to provide an exhaustive quantitative analysis of these changes, the examples provided show how this can be done.

The use of GIS leads to potential new observations about the way in which landforms change through time. One emerging method for observing temporal changes involves animating the display where each stage of development represents one-time “slice” or slide in a sequence of visual depictions of the study area. Putting each slide into an animation program (a simple version of this could be done in Powerpoint) would show the landform changes. This approach would necessitate having a sequence of surveys, so that each one would become a slide in the animation. Once past changes have been represented, it becomes desirable to predict future changes. GIS has been used to model other physical systems (Hutchinson and Raper). Three-dimensional modeling of dune systems has not been undertaken with much effect, although some two-dimensional modeling work has been done (Sherman and Lyons, 1994). GIS would enable parameters to be assigned to each grid cell that represent factors that cause a change to the landforms. The parameters would produce different outcomes for each cell because they would be dependent on the conditions within the cell or in adjacent cells. Thus, the combined individual cell changes would produce an overall modification of the landform in response to the dynamics of the system. Such modeling will be difficult to undertake because of the complexity of the morphodynamics of dune systems.

This research represents an expansion of early attempts (Gares and Gares) at moving away from measuring and quantifying dune morphodynamics with elevation profiles (McCluskey and DeKimpe) and it illustrates the benefits of investigating dunes as three-dimensional landforms. The analytical abilities of this methodology are illustrated by focusing on the initial and final surveys which show the distribution of the total amount of change that occurred at this site between May 1997 and May 1998 (Fig. 5).

The comparison of data obtained from the Coquina Beach site 1 year apart provides some insight into the behavior of this particular dune system. First, this dune area was predominantly erosional, with total volumetric loss far exceeding gain. It is evident that coastal storms are the driving mechanisms of dune change along this shoreline, as many before have observed (e.g. Dolan and Leatherman). The northeasters of January and February 1998 would be category three out of five or “significant” in the Dolan and Davis (1992) classification based up the duration of the storms and the wave height data recorded at the US Army Corps of Engineers Facility at Duck. The 2–5 m of erosion that the storms produced along the seaward dune face represents a loss of 10–30% of the width of the single dune ridge in the southern portion of the study area (Fig. 5). This would suggest that this entire dune system is indeed vulnerable to eventual destruction, as some have predicted (DeKimpe et al., 1991). However, in the northern half of the study site, the dune is some 10 m wider so the proportion of loss is on the order of 7–20% of the dune width. Thus, there is considerable variation in dune erosion within a relatively small section of shoreline.

Despite the general observation about linear retreat of the dune, there are spatial variations in the dimension of elevation change. The cartographic representation of the changes shows areas of deposition within the overall erosion that are related to the existence of blowouts through the foredune. The Coquina blowouts behave very much like blowouts in other areas, such as New Jersey (Gares and Gares) or Australia (Carter et al., 1990). The openings between the beach and backdune serve as transport corridors facilitating the movement of sediment to areas landward of the foredune. This is evident from the deposition that occurred at the landward ends of the blowouts located both within and outside the study area (Fig. 5). This deposition on the landward side of the dune ridge produces a wider dune in the northern section.

The blowout margins are also some of the most erosional locations within the dune system as the exposed lateral walls are susceptible to scour by high speed winds, just as they are in blowouts in other dune systems (Carter; Gares and Gares). The erosional surfaces also appear to be sources of sediment that are ultimately deposited downwind, such as on the blowout margin rims or on the backslope of the foredune adjacent to the opening of blowout 2 at Coquina.

One way of examining spatial variation in elevation change is by looking at transects through the dune system, either perpendicular or parallel to the beach. There are sections of dune where greater erosion predominates, separated by zones of lesser erosion (Fig. 7). The lower erosion areas are places where deposition to the rear of the dune offsets the erosion that predominates along the seaward face of the foredune. These areas are located in the northern part of the study area where sediment was carried through the blowout located just to the north of the study area boundary, and in the middle of the area where the main blowout was located (Fig. 7, transects 65–80). The range of elevation change along each transect reflects the combination of erosion along the dune face and deposition to the rear. The range of change is higher in the southern section. The main blowout area is where both the average transect elevation change and the transect range of change were lowest. This was due to the deposition of sediment along the landward margins of the blowout that offset the storm erosion at the opening of the blowout. This suggests that sediment budget is an important factor to consider, as indeed, Psuty (1991) has argued.

CONCLUSIONS

Current GIS and mapping software packages present a multitude of analysis and manipulation options. The choice of software is often determined either by the availability of software or the researcher's familiarity with the software. Regardless of the GIS package used, the five phases used in this research should be given consideration in other studies. While many GIS software packages offer similar functions, some key analytical and visualization requirements are needed for application in coastal dune morphology. The geostatistical and interpolation features of software are a primary consideration. Most GIS software packages have overlay or grid differencing functions that make it easy to perform arithmetic operations between grids with minimal understanding of the process. It is advisable to choose a number of random grid values from the two input grids and manually subtract them and compare it to the calculated value by the GIS difference operation. The ability to contour and render DEMs three-dimensionally is another valuable feature that facilitates the visualization of morphologic features and that identifies the spatial relationship between elevation and other attributes. In addition, most GIS packages have profile functions that allow the use to draw a line anywhere on a grid and extract the grid values along that profile. This operation can replace measuring along established transects in the field.

This paper presents one methodology developed to measure three-dimensional dune morphodynamics using GIS. It is designed to serve as a guide for other coastal researchers who may have limited surveying background or GIS experience. The recent development of GIS software enables coastal researchers to visualize coastal features in a much more intuitive way than simple two-dimensional profiles. The shift from two-dimensional concepts (transects) to the three-dimensional representation of volumetric change can enhance our understanding of complex coastal features.

Preliminary reconnaissance surveys should be conducted before attempting to survey coastal dunes to get familiar with survey instrumentation, procedures and the limitations of survey gear and personnel. If traditional land surveying techniques are employed, benchmarks with horizontal and vertical control need to be located for georeferencing the survey. Parameters, such as the time needed for a complete survey, frequency of consecutive surveys, general morphologic features and the intended resolution of the data, combined help dictate the actual spatial extent of the survey area. Once the reconnaissance survey(s) are conducted and the spatial extents of the survey area are determined, the spatial resolution of the data and underlying data model should be investigated.

Although the complexity of beaches and dune complicates the ability to understand these systems, volumetric calculations based on dense surveys and fine resolution DEMs can synthesize multiscale morphologic and atmospheric processes. Aeolian sediment redistribution is not a two-dimensional deterministic process quantified by systematic measurements along predetermined transects. Rather, this investigation illustrates the stochastic three-dimensional spatial variability of aeolian sediment transport at the mesoscale and establishes groundwork and methodology for further research into volumetric modeling of coastal dune morphodynamics.

The overall analysis of data from Coquina demonstrates that this erosional system cannot be considered as two-dimensional system dominated by linear retreat along the seaward face of the dune. This seems to be the case in the southern section of the study area where the erosion on the seaward side of the dune has narrowed the dune considerably with little addition on the landward side. However, in the north, breaches through the dune have lead to sediment accumulation inland that has widened the dune. Thus, it seems unlikely that the dune will be progressively and completely destroyed by linear retreat, unless a major storm occurs. It seems likely that, as the dune narrows, blowouts through the ridge will develop, leading to sediment transport through the landward side of the dune and the eventual widening of the dune. These dynamics would not be identifiable using two-dimensional transects, and this emphasizes the value of the three-dimensional monitoring approach employed here.

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