SPATIO−TEMPORAL ANALYSIS OF BEACH MORPHOLOGY USING LIDAR, RTK−GPS AND OPEN SOURCE GRASS GIS

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Abstract: Modern mapping technologies used for coastal studies such as LIDAR and RTK−GPS produce massive amounts of data characterized by oversampling and noise. The physical phenomena and landscape changes examined are often subtle and besides statistical accuracy, adequate representation of surface geometry is crucial for correct interpretation of measured data. We have explored the suitability of the Open source GRASS GIS and its spline based spatial interpolation for assessment of rapid changes in topography of nourished beach on Bald Head Island, NC based on the LIDAR 1997−2000 and RTK−GPS 2001−2002 data. Surface gradient and curvatures, needed for topographic analysis were computed simultaneously with interpolation. Raster map algebra was used for data management (masking, extraction of subsets) as well as for spatio−temporal analysis, such as computation of first and second order differences between surfaces and volumes of lost sand. Visualization of multiple 3d surfaces with moving cutting planes provided powerful tools for visual identification of features and beach morphology changes.

INTRODUCTION

Coastal topography is a result of complex interactions between anthropogenic activities and natural processes. Quantification of short−term spatial change in this dynamic environment is crucial for sustainable coastal management. Traditional monitoring methods have relied on survey transects and aerial photography, approaches that are rather time consuming and require substantial manual processing. Modern mapping technologies such as laser altimetry (LIDAR), Real Time Kinematic GPS (RTK−GPS), digital photogrammetry, and interferometric sonar greatly enhance the capabilities to gather 3D georeferenced data at unprecedented spatial and temporal resolutions. The efficiency of these highly automated technologies enables repeated surveys in relatively short time intervals, creating time series of data that provide critical information for areas with highly dynamic topography typical for coastal regions. For example, LIDAR has been used for regular mapping of coastal change since 1996 (NOAA−USGS 2002; LDART 2002). RTK GPS is being increasingly applied to cost effective, rapid beach monitoring (Morton et al. 1999; Freeman et al. 2003; Bernstein et al. 2003).

Significant challenges remain for using the full potential of this new type of data for important applications, such as disaster prevention and management, and sustainable development. The problems are usually related to the fact that the data sets are several orders of magnitudes larger than what the current GIS tools were designed for, and they have different spatial distributions and properties than data acquired by traditional methods. Recent developments of modular and extendable proprietary GIS tools as well as emergence of Open Source GIS (Neteler and Mitasova, 2002) have created an opportunity to extend the use of these systems to new types of data and applications. GIS is becoming an important tool for coastal monitoring, analysis and risk assessment, prediction of impacts using modeling and simulations, as well as planning and decision support (NOAA 2000; Wright and Bartlett 1999). Advanced 3D systems substantially increase efficiency in data processing and provide the tools to gain new insights into geospatial aspects of complex coastal systems.

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In this paper, we focus on methods for assessment of rapid changes in coastal topography and on the capabilities of Open source GRASS GIS to support processing and analysis of data from the topographic change monitoring programs.

METHODS

The methodology for monitoring and analysis of recent beach morphology evolution was developed for a South Beach nourishment site on the Bald Head Island which belongs to the system of North Carolina’s barrier islands. This site is located near the mouth of the Cape Fear river (Figure 1) and displays complex interactions between anthropogenic activities and natural processes. Analysis of historical maps and photographs (Cleary et al. 1989) has shown rotation of its shoreline around relatively stable pivot point area. The counter−clockwise rotation accompanied by growth of the west section of the South Beach (over 800m), observed during the period 1850 − 1962 was reversed in late 60ies when nearby Wilmington harbor channel was deepened to 12m and in some places reached the rock (Cleary et al. 1989). In spite of relatively restricted development, beach erosion, especially in areas close to the channel, has become an increasing problem requiring recent intervention.

To obtain new insights into the response of this beach to ongoing anthropogenic activities bathymetry and coastal elevation data from diverse sources were integrated and analyzed within GIS. Specifically, terrestrial LIDAR and RTK−GPS data have been combined with offshore single beam and interferometric sonar soundings to create an integrated model of bathymetry and beach topography (Figure 1) and its evolution in response to recent US Army Corps of Engineers beach renourishment, canal dredging, and storage of dredged materials in underwater mounds (see more information about the projects and monitoring programs at FRF 2002). The developed methodology involves data acquisition, preprocessing (including georeferencing, projection and rectification typically performed within a surveying system), data import into GRASS GIS and transformation to a common raster data model, and finally, spatial and spatio−temporal analysis and visualization.

Topographic surveys

Pre−nourishment beach evolution was analyzed using LIDAR data acquired during the Airborne LIDAR Assessment of Coastal Erosion (ALACE) project. The project was a partnership between the NOAA Coastal Services Center, NASA Observational Sciences Branch, and the U.S. Geological Survey Center for Coastal Geology. The partnership collected LIDAR data along the U.S. beaches from September 1996 to October 2000 using the NASA Airborne Topographic Mapper (ATM) sensor. Technical details about the surveys can be found on the project’s web site (NOAA−USGS 2002). The data for the study area were available for the years 1997, 98, 99 and 2000. They were downloaded using LIDAR Data Retrieval Tool (LDART 2002) as point clouds x,y,z in State Plane coordinate system in meters. While it was possible to download data already gridded we have chosen the x,y,z format, because it provided us with more flexibility for creating and analyzing DEMs at various resolutions once the data were downloaded. Beginning in 2001, the Center began contracting with the private sector for high−resolution topographic data to meet coastal management needs and no LIDAR data of South Beach are currently available after year 2000. Therefore an alternative method had to be used to continue monitoring, especially after the 2001 year nourishment.

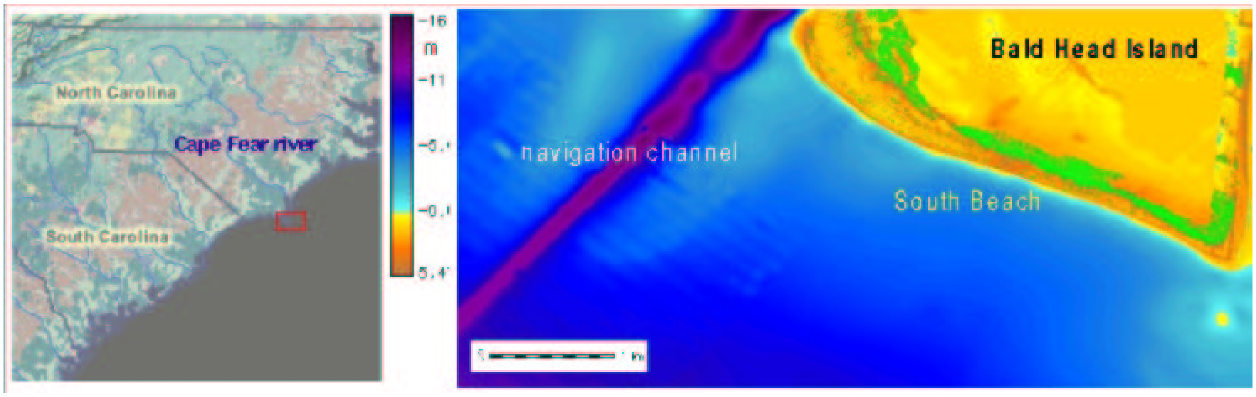

Figure 1. Location of Bald Head Island and bathy−topo DEM for August 2000.

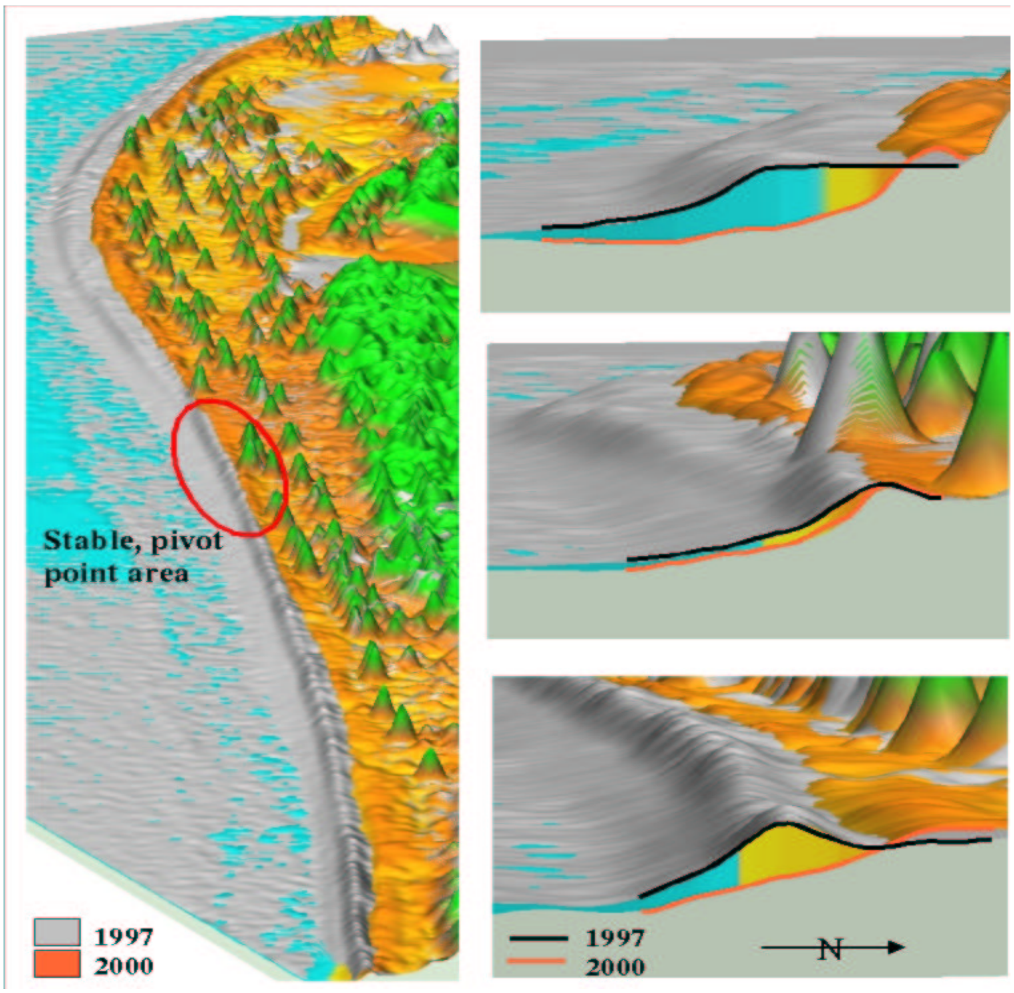

Figure 2. South Beach elevation surfaces 1997−2000: overlayed 1997 (grey) and 2000 (colored) LIDAR−based DEMs with highlighted stable pivot point area; change in typical west, central and east crossections. Blue color in profiles projects location of water in 2000.

To capture the dynamic response of the beach to nourishment RTK−GPS surveys were performed quarterly: December 2001, January, May, September and December 2002. Elevations were automatically sampled with 10cm vertical accuracy along the path of an all−terrain vehicle used in the surveys. The first two surveys focused on shoreline and included also several cross−shore profiles. The sampling pattern was later extended by additional shore−parallel profiles to improve the representation of beach surface (see Bernstein et al 2003 for more details about RTK−GPS survey designs for beaches). While data coverage along the survey path was dense (3−6m), the distance between paths was at least one magnitude larger (20−30 m for shore−parallel paths and 200−300 m for shore−perpendicular paths).

Open source GRASS GIS

The LIDAR and RTK−GPS data were imported into GRASS GIS (Geographic Resources Analysis Support System, Neteler and Mitasova 2002, http://grass.itc.it) to analyze the evolution of beach geometry, shoreline and to quantify the change in elevation volumes.

GRASS is a general purpose GIS developed in 1982 − 1995 by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) in Champaign, Illinois, to support land management at military installations (Goran 2002). Its recent revival can be attributed to the fact that the Open source and Free software, best known for its LINUX operating system, is being increasingly implemented in mainstream applications (FLOSS 2002, Markoff 2002) and the use of related geospatial tools is expanding as well. The current GRASS development model is embedded in the Free software movement style and uses well known tools for code management and dissemination (Mitasova and Neteler 2003). The main components of the development and software maintenance are built on top of a highly automated web−based infrastructure, sponsored by ITC−irst (Center for Scientific and Technological Research) in Trento, Italy, and numerous other worldwide sites where the code base is mirrored.

The massive data sets produced by LIDAR and RTK−GPS often pose problems for commonly used proprietary GIS, therefore the possibility to modify the code has made the use of Open source GIS worth exploring. GRASS GIS appeared to be a suitable choice as it provides the necessary tools for data processing, gridding, analysis and visualization.

Spatial Approximation and Surface Analysis

To produce temporal series of coastal elevation and bathymetry surfaces with minimum distortions in surface geometry an adequate gridding method is important. While TIN (Triangular Irregular Network) is often used to represent elevation models, its use becomes problematic when series of surfaces, each based on a different set of measured points, needs to be compared. The comparison is greatly simplified if all data are gridded at the same resolution and map algebra is used for computation of differences between surfaces and other measures. The selection of gridding method depends on the spatial distribution of input data, resolution of the output grid and the properties of modeled topography. For lower resolution models with grid cell size larger than the distance between the sampling points (in our case 10m and 5m grid based on LIDAR data) assigning points to grid is usually sufficient. Higher resolutions DEMs and RTK−GPS data require the use of spatial approximation.

Regularized Spline with Tension and Smoothing (RST, Mitasova and Mitas 1993; Mitas and Mitasova 1999) was used for creating grid DEMs from LIDAR point clouds and RTK−GPS path data, as well as for topographic analysis. The RST imitates a thin flexible sheet forced to pass close to the data points: the equilibrium shape of the sheet minimizes the bending energy which is closely related to the surface curvature. The tension parameter (Franke 1985; Mitas and Mitasova 1999) tunes the surface behavior from a stiff plate to an elastic membrane. The tension and smoothing parameters proved to be useful for minimizing artificial surface features such as waves along transects, or artificial peaks and pits, often found in the results of less general approximation techniques. The tension parameter can be generalized to a tensor which enables modeling of anisotropy (Mitasova and Mitas 1993) a feature which turned out to be especially important for modeling beach morphology based on RTK−GPS survey. Smoothing can be applied directly to the given points without previous gridding and it can be spatially variable, so differences in accuracy in measured points can be taken into account. Regular higher order derivatives make RST suitable for differential analysis and calculations of gradients and curvatures simultaneously with gridding (see the equations in Mitasova and Hofierka 1993; Mitasova et al. 1995). Therefore gridding, smoothing and computation of gradients (slope and aspect) and curvatures are performed simultaneously from the original data using the same approximation function. This approach ensures high accuracy and consistency of the results.

Processing of large data sets is supported by segmentation procedure using decomposition of the studied region into quadtrees based on the density of data points (Mitasova et al. 1995). For a given segment, the interpolation is carried out using the data points within this segment and from its neighborhood, selected automatically depending on their spatial distribution. This approach is different from the nearest neighbor search commonly used in geostatistical packages, which does not ensure surface continuity, especially for data patterns commonly generated by RTK−GPS. These methods use only a small number of data points (4−24) for computation of elevation value in each grid point, compared to over 100 data points and computation of entire segment of a grid using the same function for RST. As it has been pointed out by several authors (Wahba 1990; Cressie 1993) splines are formally equivalent to universal kriging with the choice of the covariance function determined by the smoothness seminorm. Therefore, many geostatistical concepts can be exploited within the RST framework.

The method, implemented in GRASS GIS as a module *s.surf.rst* was used to interpolate the grids, smooth the impact of noise and analyze the topographic features using different point densities and interpolation parameters (tension, smoothing).

Spatial analysis of temporal sequence of surfaces

The analysis of beach evolution focused on spatial pattern of changes in elevations, slope, shape and volumes. Because spatial extent of LIDAR data was different for each survey and included the vegetated and developed areas 2 masks were created that allowed us the extract only the points representing the beach during 1997−2000 period and the nourished beach mapped by RTK−GPS. To assess the spatial pattern and magnitude of changes first and second order differences in surface elevations were computed and they were used to estimate the lost and gained volumes of sand. Change in slope and shape was evaluated using 3D visualization with moving cutting planes along with quantitative analysis of relevant raster maps. Zero elevation contour was also extracted to illustrate the horizontal change.

RESULTS

In this paper we present the results for the 4.5km long South Beach section without the capes covering 36 ha for the pre−nourishment period and 40 ha after the nourishment. Both capes are highly dynamic and they have undergone dramatic changes in gained and lost volumes that can be one magnitude larger than the changes on the beach. Therefore we have performed our study separately for capes and the beach with the integrated study of the entire system including the bathymetry following in the future.

Pre−nourishment evolution analysis based on LIDAR data

The LIDAR data for 1997, 1998, 1999 and 2000 were imported into GRASS GIS and bined at 5m resolution for the entire Bald Head Island coast. South Beach was also interpolated to 2m resolution rasters with simultaneous computation of slopes and curvatures to obtain the pattern of geometrical features and to reveal subtle changes in beach geometry.

Comparison of series of surfaces based on the extracted 0m contour, 3D visualization with cutting plane, and computed surface differences reveals continuing erosion along most of the beach at spatially variable rates. The pattern of erosion has been very consistent throughout the study period, with the area around the shoreline inflection point (also called pivot point according to Cleary et al. 1989) being relatively stable while the areas west and east of it were eroding severely. The second order differences in surfaces permitted identification of the locations with accelerated erosion. As expected, the erosion acceleration was observed along the foot of the beach scarp while the flatter, lower beach areas have slowed rate of erosion. Volume changes were computed as an annual change and as a total between 1997−2000 (Table 1). The beach has lost 376,000m^3 between 1997−2000 while gaining 65,000m^3. Around 15% of the lost sand was moved over the beach dune increasing elevation in a thin strip beyond the original beach dune position up to 1.5m. By contrast, some of the areas in the east section experienced loss in elevation over 3 m, as the beach scarp in these areas was completely washed away (see Figure 2, east crossection). Interestingly enough, the shape of the beach profile has also changed its spatial pattern. The convex shape with berms in the west section and concave shape with scarp in the east section observed in 1997 gradually changed to concave with scarp in the west section and convex wide beach in the East in 2000 (Figure 2) with relatively smooth transition of shape around the pivot point area. Analysis of beach slope and shape for the fastest eroding area (Figure 3) shows the change in shape between 1998 and 2000 in greater detail. Approximation with higher smoothing was necessary to reduce the impact of noise from LIDAR on curvatures (Figure 3a) and to provide clear picture of change from berms to a scarp (Figure 3bc). Resolution and selection of RST parameters were important for analysis of beach shape change, however, their impact on the estimates of volume change was relatively low (Table 2) proving the advantages of the dense coverage by LIDAR data.

Table 1 Beach changes for 1997−2002 with pre− and post−nourishment study areas 36ha and 40ha respectively. Year 1999 is excluded because of missing data .

time period		loss [m^3]	gain [m^3]	loss rate [m^3/ha.year]	max. recession [m]
1 y	1997 − 1998	160000	42000	4400	20
2 y	1998 − 2000	254000	48000	3500	30
3 y	1997 − 2000	376000	65000	3500	40
5 mo	Dec.01 − May 02	220000	2000	13200	20
4 mo	May 02 − Sep 02	162000	80000	12100	15

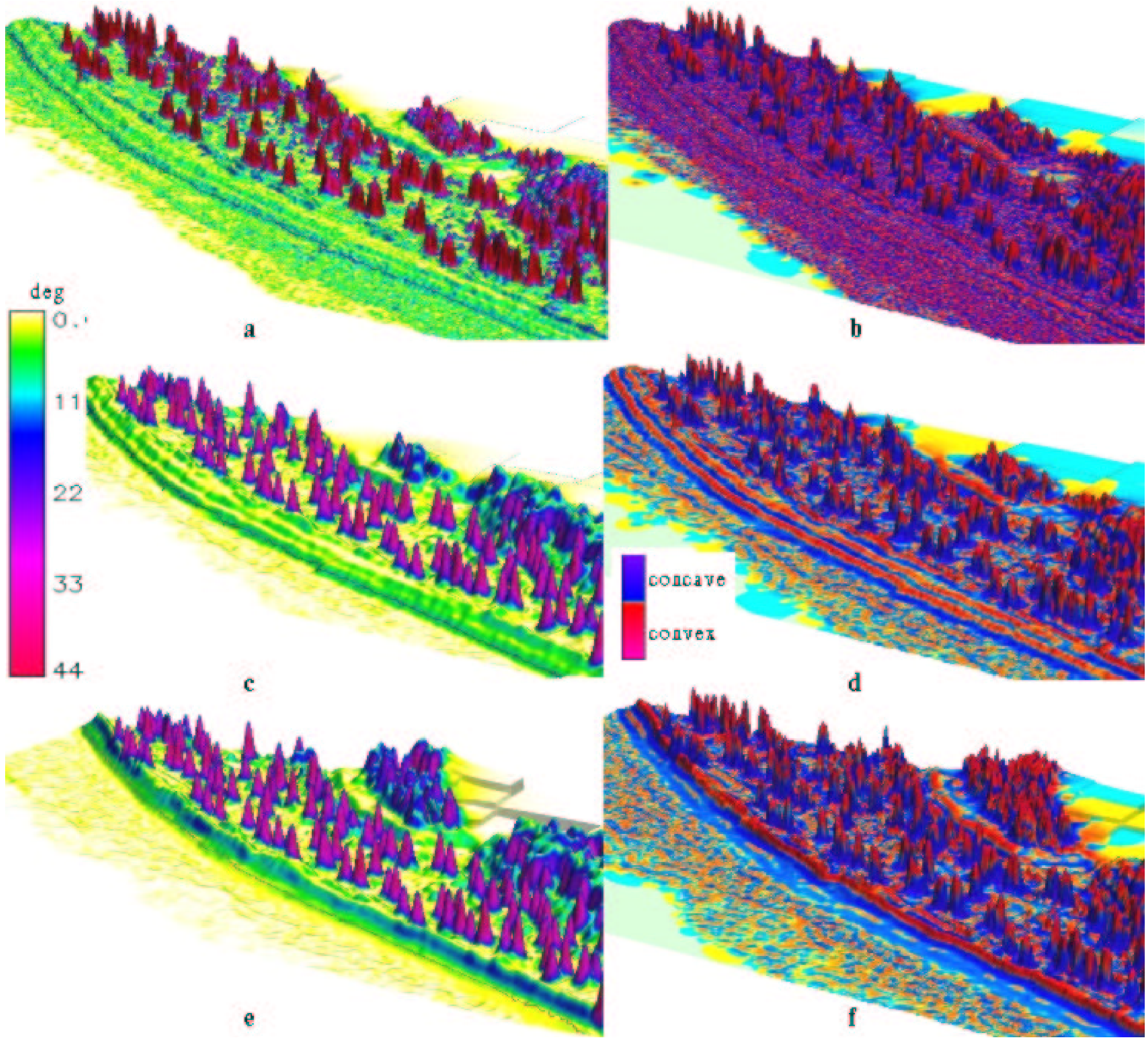

Figure 3. Slope and profile curvature for rapidly eroding beach section: a,b) 1997 at high level of detail; c,d) 1997 smoothed, highlighting the berms; e,f) 2000 concave shape and a scarp.

Table 2. Comparison of 1997−2000 LIDAR−based loss estimates with different gridding

gridding approach	lost sand volume [m^3]
10m resolution with first point found assigned to grid cell, rest ignored:	371,000
5m resolution with first point found assigned to grid cell, rest ignored:	376,000
2m resolution RST, low smoothing	384,000
2m resolution RST, high smoothing	375,000

Post−nourishment evolution

Post nourishment evolution was studied using RTK−GPS surveys performed in December 2001, May and September 2002. December 2002 were also acquired but they were not available for analysis at the time of the paper submission. Pattern of sampling combined paths parallel to shoreline with beach profiles and RST approximation with anisotropy was used to create beach surfaces at 5m resolution. The differences between the measured surfaces (masked to the extent of RTK−GPS mapping pattern) indicate severe erosion in the western section of the nourished beach, where all added sand was lost and the beach is back to its year 2000 level (Figure 4). The east section experienced lower rates of erosion and the comparison between the May and September surfaces (Figure 4) indicates that substantial volume of sand was moved to upper section of the beach rather than washed away, increasing the elevation on the upper beach up to 0.5m. The pivot point area again separates these two sections of the beach with different responses to nourishment.

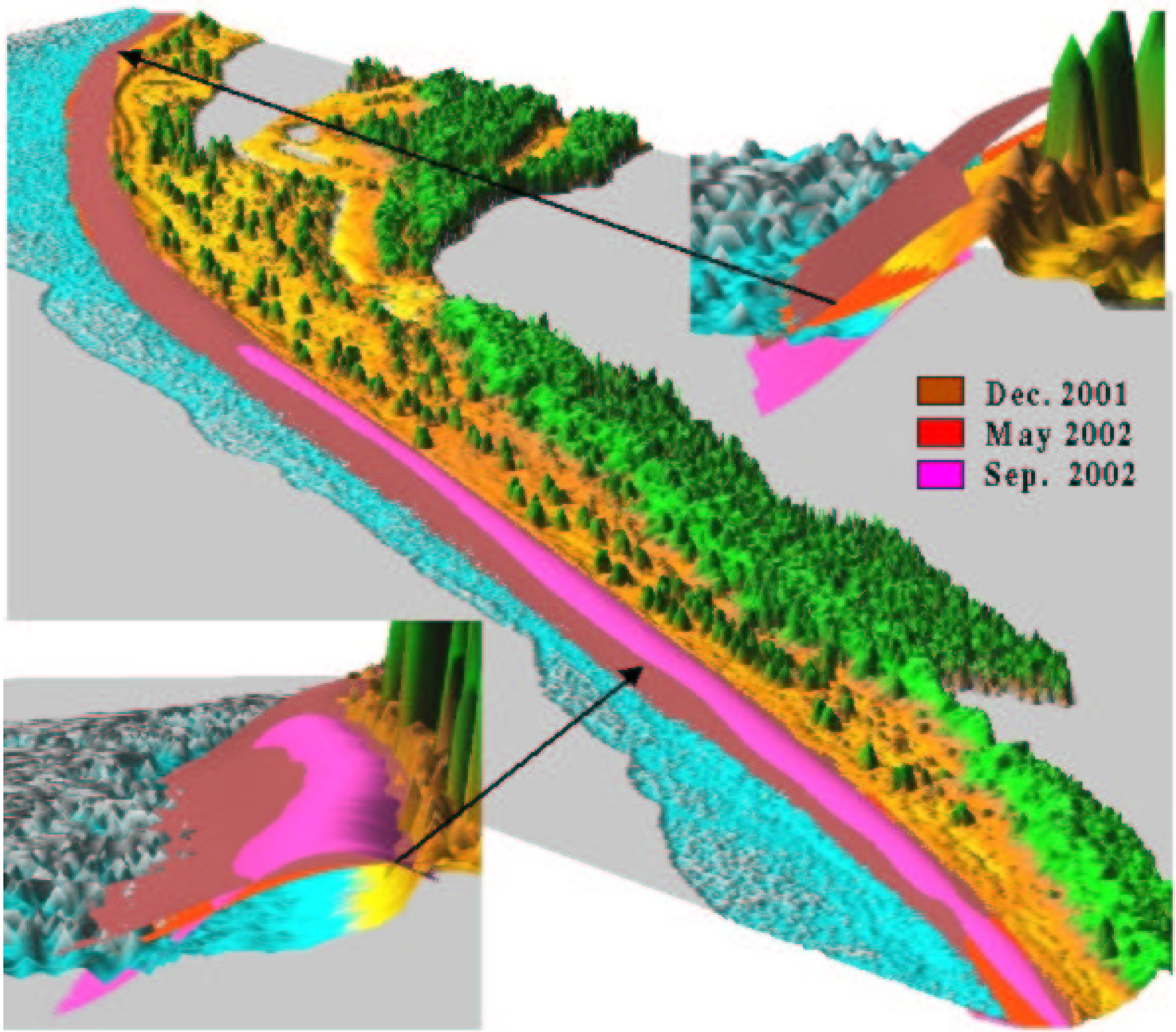

Figure 4. Overlayed surfaces and crossections representing South Beach in 2000 (LIDAR), Dec. 2001 (brown), May 2002 (red) and Sept. 2002(magenta).

The volume changes and erosion rates were several times higher than for the pre−nourishment time period (Table 1). Difference between December 2001 and May 2002 shows mostly loss of sand volume while May and September 2002 loss was accompanied with substantial volume gain (Figure 4, table 1). It is important to note that for the RTK−GPS surveys spatial approximation had substantial impact on volume estimates, Surfaces without anisotropy provided smaller volume change estimates than when anisotropy was used (for example May−Sep. 2002 volume change was 162000 and 120000 with and without anisotropy respectively) . This is mostly due to the fact that isotropic surfaces go to a similar trend in areas between the profiles, reducing thus the differences between the surfaces measured at different times. With sparser data coverage, typical for RTK−GPS, greater attention should be given to spatial interpolation and volume estimates.

Comparison with the modeling results (Becker et al. 2001) explains some of the features of the observed pattern. In particular, the pilot point area is characterized by very small velocity vectors, while the area near channel has much higher velocities. Unfortunately, the model results for erosion and accretion were too noisy to provide conclusive prediction of the observed distribution and rates of erosion and accretion. Improved models should be used to predict the possible future extent of erosion under the current conditions and to find more effective management solutions.

CONCLUSIONS

Results of this work demonstrate that the combination of modern mapping technologies and geospatial data analysis within GRASS GIS can provide new insights into the short term evolution of coastal landscape and supply important information for the management of studied areas as well as methodology and tools which can be applied to other coastal regions. The methodology both for the field measurements and data processing was enhanced to allow the study of changes in nourished beaches beyond the traditional 1−D shoreline, towards changes in surface geometry, volumes and spatial patterns of erosion and its acceleration. The presented approach allowed us to study the beach as a complex, continuous surface, analyze its geometry, and quantify its changes. The methodology produces temporal series of coastal elevation and bathymetry surfaces important for the development of routine, consistent, spatio−temporal monitoring of coastal areas undergoing significant changes due to anthropogenic activities (such as renourishment) or natural forces. Better understanding of dynamics in these areas will support sustainable coastal management and minimize the cost of protection and disaster management.

In our application, the spatio−temporal analysis has shown that the rotation of shoreline around relatively stable pivot point area is accompanied with reversal of convex/concave beach shape. The stable area also divides the beach into two sections with different response to nourishment, revealed by surface analysis. While shoreline analysis shows retreat of nourished beach, surface analysis shows that in the western section most nourished sand was lost offshore, in the east section most was pushed on the upper part of the beach.

Visualization by multiple surfaces was crucial in detecting important features, such as change in the beach shape, which are not directly detectable from the contour maps. The LIDAR data provide substantially more detail and more complete spatial coverage including the dunes and other areas which are hard to map on ground. The data, although massive, are easier to process within robust GIS designed to handle large data sets. On the other hand such data are not as readily available and easy to obtain as RTK−GPS. With proper survey design RTK−GPS can provide sufficient data coverage for description of surface change.

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