Digital Photogrammetric Change Analysis as Applied to Active Coastal Dunes in Michigan

Daniel G. Brown and Alan F. Arbogast

Abstract

A pilot study was conducted to investigate the applicability of digital photogrammetric methods to the study and management of dynamic dune systems. Two sets of panchromatic stereographic aerial photographs taken over Ludington State Park, Michigan, one pair each from 1965 (1:20,000-scale) and 1987 (1:15,000-scale), were obtained from historical archives. Stereo models were constructed for the stereo-pairs, using post-processed differential GPS ground control points, and digital elevation models (DEMs) were extracted from each at a resolution of 3 metres. The analysis involved computing differences between the two DEMs at each location, and computing a volume of sediment (sand) flux over the 22-year time period. Maps of elevation change were then constructed and interpreted to suggest patterns resulting from eolian processes. Processes of dune development, movement, and "blowout" were identifiable and measurable. The project illustrates how recent developments in photogrammetry have enhanced capabilities for monitoring geomorphologically sensitive landscapes such as dune fields.

Introduction

Landscapes consisting of unconsolidated sand (i.e., dune fields and sand sheets) easily mobilize when stabilizing vegetation is somehow reduced and strong winds prevail (Ash and Wasson, 1983; Heidinga, 1984). Large dune fields have been recognized throughout the central United States, in the semi-arid Great Plains (e.g., Ahlbrandt *et al.*, 1983; Muhs, 1985; Madole, 1995; Arbogast, 1996), the mesic upper Midwest (Grigal *et al.*, 1976; Keen and Shane, 1990), and along some shorelines of the Great Lakes (e.g., Olson, 1958; Farrand and Bell, 1982). Although most dune fields in humid climates are generally stable, periodic and sometimes extensive mobilization has been demonstrated in the past. Destabilization has been attributed to a number of variables. Dunes in the Great Plains, for example, were activated primarily during intervals of drought (Ahlbrandt *et al.*, 1983; Muhs, 1985; Madole, 1995; Arbogast, 1996). In contrast, dunes along the Great Lakes episodically mobilized as a result of lake-level fluctuations (Olson, 1958; Thompson, 1988).

Of specific interest to researchers in dune systems is the response of these sensitive environments to future environmental change (e.g., Muhs and Maat, 1993). This is especially true because dune fields are often heavily utilized, with dunes in the Great Plains typically cultivated and/or grazed (Muhs, 1985; Swinehart, 1990; Muhs and Maat, 1993; Arbogast, 1996), and coastal dunes being a basis for development and recreation (Santer, 1993). In general, previous work (e.g., Grigal *et al.*, 1976; Madole, 1995; Arbogast, 1996) has focused on the timing and magnitude of prehistoric change. Thus far, no systematic method for monitoring current and future change has been proposed.

Department of Geography, Michigan State University, East Lansing, MI 48824-1115 (brownda@pilot.msu.edu).

Theoretically, continual monitoring of dunes by remote sensing can be used to measure landscape response to environmental change, including the amount of sediment moved, direction of movement, and timing and magnitude of events. Monitoring of dune evolution in the past has been limited by the spatial resolution of the topographic representations, their accuracy, and the temporal frequency of re-measurement. Recent innovations permit the construction of relatively high quality, high resolution, and high frequency representations of a surface. These innovations include airborne and satellite radar, laser altimetry, and advances in softcopy photogrammetry. Altimeters, like the topographic mapping laser altimeter (TMLA), are designed for highly accurate topographic measurements worldwide. Although this instrument should have reasonable accuracy and temporal frequency, the spatial resolution is limited to 200 m, of insufficient detail for work on many eolian systems (Harding *et al.*, 1994). Furthermore, radar and laser altimetry cannot be used to gain a historical perspective on movement in earlier decades of this century.

Softcopy photogrammetry holds promise for topographic change detection as it becomes increasingly available on low-cost computer systems. The process of stereocorrelation, or extracting elevations from a stereopair by interpreting the horizontal offset, has widened the availability of photogrammetric methods by reducing the cost. Prior to the widespread availability of this method, photogrammetric methods of elevation data collection required expensive analytical stereoplotters (Welch, 1992). The process of stereocorrelation can be used to extract elevations from stereo satellite images (Giles and Franklin, 1996; Rao *et al.*, 1996), radar images (Welch and Papacharalampos, 1992), and aerial photographs (Welch 1989) on standard PCs and workstations. Vertical accuracies equivalent to 0.5 to 1.0 pixels have been reported (Welch, 1989). The applicability of the technique using aerial photographs allows for historical topographic change detection as far back as high quality aerial photographs are available.

This paper describes an application of stereocorrelation for automated digital elevation model (DEM) extraction to the study of active sand dunes along the eastern shore of Lake Michigan. The goal of the research was to assess and demonstrate the applicability of softcopy photogrammetry for topographic change detection in active eolian landscapes. Given that goal, we viewed the research as a pilot study, wherein the acceptable level of accuracy was lower than might otherwise be possible to reduce costs. We used archived paper prints of aerial photography to examine changes in the dunes over a 22-year period. The results of qualitative and quantita-

Photogrammetric Engineering & Remote Sensing,
Vol. 65, No. 4, April 1999, pp. 467–474.

0099-1112/99/6504–467$3.00/0

tive change analyses are interpreted to provide information on the processes of dune formation and change. We suggest opportunities for using topographic change detection for monitoring and managing these sensitive environments.

Study Area

Our study was conducted in Ludington State Park, along Michigan's eastern shore of Lake Michigan (Figure 1). In general, the park lies within a very active dune field in which a variety of linear and parabolic dunes are contained. Although precise age control is lacking, the dune field likely began to form at the end of the Nipissing transgression around 4000 years ago (Hansel and Mickelson, 1988). Given the results derived from other coastal dune systems in the Great Lakes region (Anderton and Loope, 1995; Larsen, pers. comm.; Arbogast, unpubl.), dunes at Ludington have probably been episodically active through time.

The nearest coastal weather station to Ludington that collects wind data is Muskegon (Eichenlaub *et al.*, 1990). Although Muskegon is about 80 km south of Ludington, the record there should generally be representative of conditions within the study area. Annual winds are multidirectional at Muskegon, with southwesterly and northwesterly winds the most persistant and strongest (Figure 1). As a result, net migration of sand at Ludington should be from west to east (or onshore).

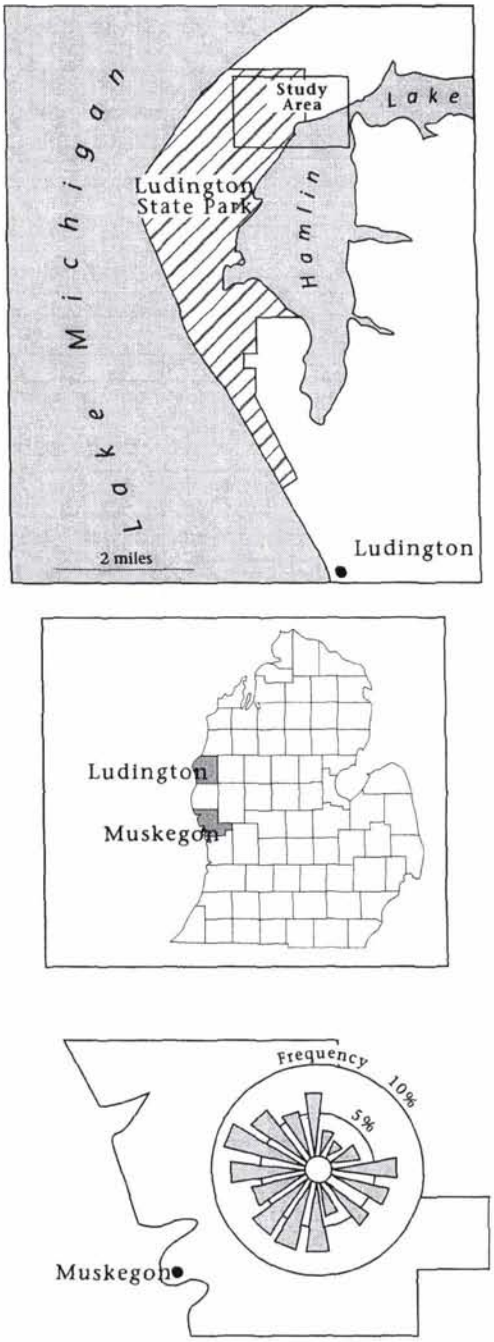


Figure 1. Location of the study area in Ludington State Park, northwestern lower Michigan, with a wind rose for Muskegon, Michigan, describing the frequency of winds from all directions.

Methods

Aerial Photographs

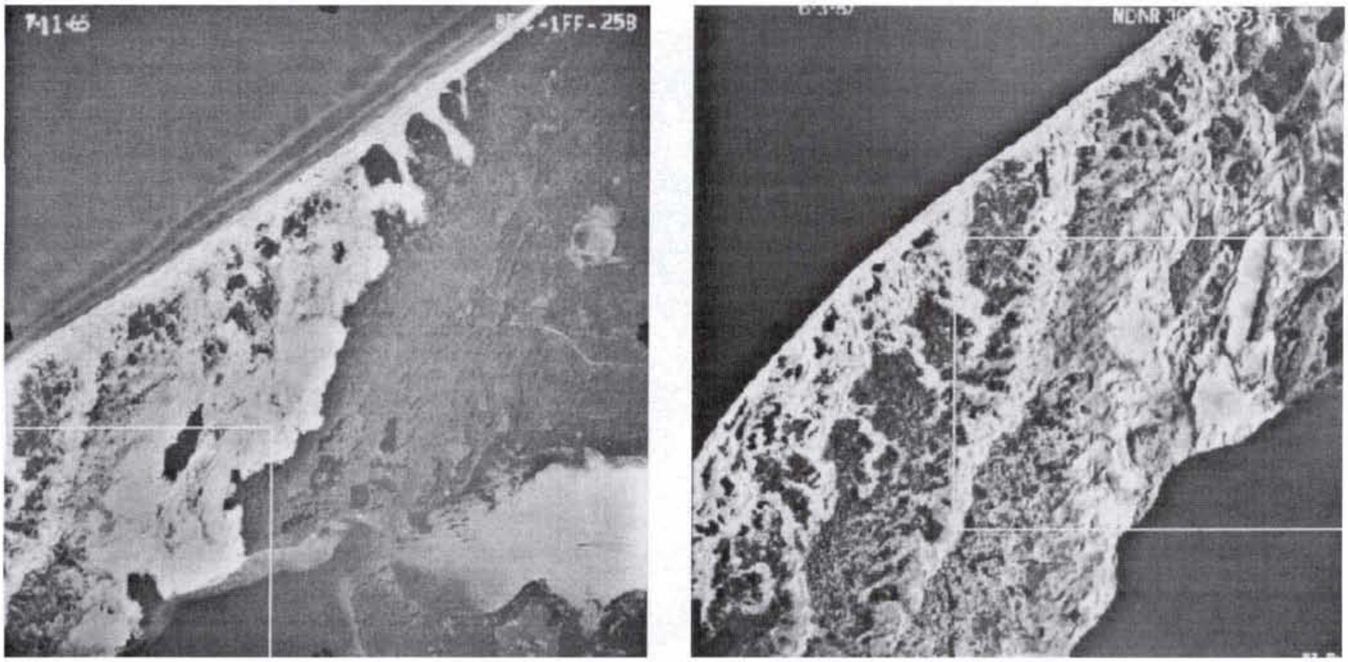
Paper prints of two stereo pairs of photographs were acquired for the study area. The first pair, representing black-and-white panchromatic conditions on 11 July 1965, was obtained from the aerial photo archives at the Center for Remote Sensing and GIS at Michigan State University. A second pair of photographs, a pair of black-and-white infrared photos taken on 03 June 1987, was acquired from the aerial photo archive at the State of Michigan Department of Natural Resources (DNR). The photos had nominal spatial scales of 1:20,525 and 1:15,917 in 1965 and 1987, respectively. The paper prints were scanned at 600 dpi using a Crosfield drum scanner and converted from tagged interchange format (TIFF) to the native PCI format for use in PACE and Orthoengine by PCI, Inc. (Richmond Hill, Ontario). The left photo of each pair is displayed in Figure 2, with the approximate area of overlap between all photos delineated in white.

Interior and Exterior Orientation

The first steps in processing the digital images involved interior and exterior orientation. Interior orientation required identification of fiducial marks on the image and the entry of the photo locations of those fiducial marks (in mm from the principal point). Locations of fiducial marks were given in the camera calibration reports issued by the photography company. Reports were obtained for the 1965 and 1987 photos from the U.S. Geological Survey and from Keystone Aerial Survey, Inc. (Philadelphia, Pennsylvania), respectively.

A CMT (Corvallis Microtechnology, Inc., Corvallis, Oregon) global positioning receiver and data logger were used to record the locations of 14 ground control points (GCPs) throughout the study area for the purpose of exterior orientation. GCPs consisted primarily of trees or distinct stands of trees that could be identified on both the 1965 and 1987 photos. Because trees are not at ground level, we recorded ground control points that were offset from the trees by a measured distance and direction and identified the locations of the points on each photo. One-hundred position fixes, taken every second, were recorded in the GPS data logger for each GCP location in universal transverse mercator (UTM) coordinates. The points were post-processed for differential correction using data collected at a Coast Guard base station in Sturgeon Bay, Wisconsin, approximately 122 km west of the study site. Based on informal evaluation of data collected at a benchmark, we estimate that the GCPs are correct to within 1 m in the horizontal direction and 3 m in the vertical direction.

The GCPs were used to solve for camera model parameters for each photo in each stereo pair using Orthoengine. GCPs were identified on each photo in each stereo pair to solve for



(a) (b)

Figure 2. Left photo in stereo pair for each date: (a) 1965; (b) 1987. Approximate location of overlap area is outlined in white. Lake Michigan is in the upper-left of each photo and Hamlin Lake is in the lower-right. North is at the top.

the parameters. Three of the GCPs, one each in different portions of the study area, were selected to serve as check points to test the accuracy of the camera model. Table 1 lists the root-mean-square (RMS) of the residuals (for GCPs) and error (for check points). We comment, in the discussion section, on potential reasons for the relatively high values attained. The number of control points exceeds 14 because values are averaged across both photos in each stereo pair. Not all points fell within the limits of all photos.

Following calculation of camera models for each photo, one photo in the pair was resampled into an epipolar projection of the other photo. This step ensures that the images are offset only in the horizontal direction, thereby simplifying calculations required to solve for elevation at every location (Cheng and Stohr, 1996).

DEM Extraction

DEMs were extracted from each stereo pair through a neighborhood matching procedure (Cheng and Stohr, 1996). Image neighborhood statistics were calculated for a defined window around a given pixel in the first image. Then, the second image was searched to find the window that best matched the description of the window in the first image. The difference in location between the center pixels in both neighborhoods was calculated and input the stereo model to calculate the elevation at that location.

The 1987 DEM was extracted with a spatial resolution of approximately 0.71 m (i.e., one DEM pixel per image pixel). The 1965 photos were originally processed with a spatial resolution of 0.83 m, but the prints were not of high enough quality to support such high resolution analysis. The image resolutions were degraded to 1.66 m and the DEM was extracted at that resolution.

Table 1. Statistics Describing Camera Model Registration Across Both Photos in Stereo Pairs

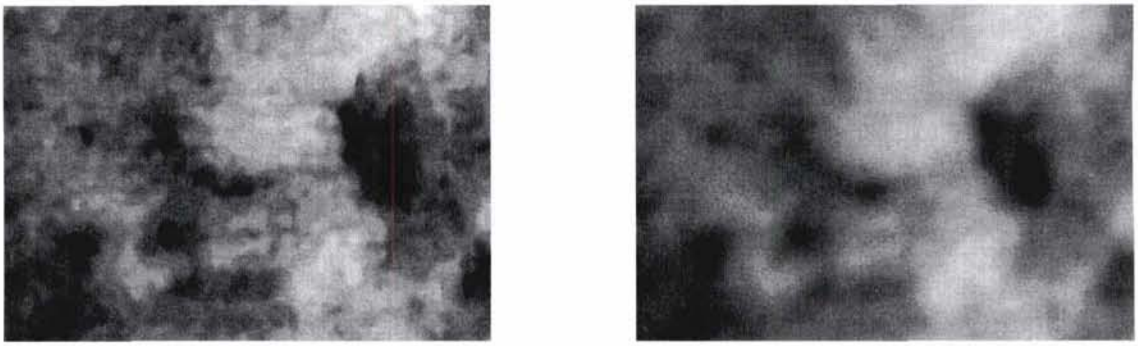
	1965		1987	
Camera Focal Length	209.5 mm		153.6 mm	
Nominal Scale	1 : 20,525		1 : 15,917	
	GCPs	Check Points	GCPs	Check Points
Number of Points	14	4	18	6
x RMSE	0.93 m	2.91 m	0.54 m	0.43 m
y RMSE	0.48 m	1.26 m	0.73 m	1.54 m

DEM Post-Processing

The resultant DEMs were edited to remove noise, interpolate values where a solution was not found (mostly in the lakes), and filter out spurious fine scale variability. Both DEMs were resampled to a resolution of 3 m because more detail was unnecessary for the analysis, and the horizontal and vertical precision of the GPS control points did not warrant more precision. The 1965 DEM exhibited a spatially autocorrelated pattern of apparent error (Figure 3a), similar to that described and displayed by Giles and Franklin (1996), with pits and hummocks in the landscape that are not apparent in the photos, on maps, or in the field. We smoothed both of the 3-metre DEMs, for consistency, with a 9 by 9 averaging filter to remove those apparent errors (Figure 3b). The analysis by Giles and Franklin (1996) showed that the accuracy of elevation values at control points did not suffer substantially with filtering, but that the representation of the shape of the landscape, measured by slope angle, incidence angle, and curvature, improved markedly.

Analysis

The accuracy of the DEMs was assessed by comparing the post-processed GPS elevations at the GCPs with the elevation value recorded in the DEM at the same location. Errors were calculated as the difference between GPS and DEM elevations



(a) (b)

Figure 3. A portion of the DEM generated from the 1965 aerial photos. (a) The raw DEM prior to filtering in which a pattern of spatially autocorrelated error is apparent. (b) the DEM smoothed with 9 by 9 averaging filter. Lighter shades indicate higher elevations.

and summarized using mean error (ME), root-mean-squared error (RMSE), and mean absolute error (MAE). The RMSE and MAE are indications of the similarity between elevation values and the ME indicates the presence of any bias in the DEM.

The analysis of elevation change took two forms: qualitative assessment of maps and perspective views and quantitative "cut and fill" analysis. The interactive visualization of the two elevation maps and perspective views derived from them permitted interpretation of wind patterns and identification of "blowouts" (i.e., circular depressions in the surface).

Two-dimensional maps of elevation were created by generating contours from the DEMs. The post-processed DEMs were used to orthorectify one photograph in each of the stereo pairs. The orthorectified photos were draped onto the DEMs for the creation of perspective views. The FLY! software (PCI, Inc., Richmond Hill, Ontario) was used to create the oblique perspective views.

Cut and fill analysis, using Arc/Info software (ESRI, Inc., Redlands, California), was conducted to quantify changes in sand volume and map areas of sand aggradation and degradation within the study area. The analysis was performed using both quantitative estimates of sand volume change and qualitative maps of areas of aggradation and degradation. We recognize the difficulties in estimating sand volume changes by differencing elevation values, where the elevation estimates are inaccurate. When two numbers are differenced, the error in the estimate of the difference is larger than the error in either of the two original numbers (Burrough, 1986). For this reason, the simplified results are presented to show areas of positive or negative elevation change. Such results, by virtue of reduced information content, have higher accuracy.

Because any change in the height of vegetation will influence the calculated changes in volumes of sand between two time periods, we focused our cut and fill analysis on locations where vegetation change was minimized (i.e., in unvegetated areas). Vegetated areas were broadly outlined by on-screen digitizing on the orthorectified aerial photographs. All locations that were vegetated at either time period were masked out and excluded from the detailed analysis.

Table 2. Error Analysis of Filtered DEMs Versus GPS Ground Control Points. Abbreviations Are Defined in the Text

GCP#	GPS (1996)	1965 DEM	1965 error	1987 DEM	1987 error
		(m)			
3	189	183	−6	194	+5
4	177	178	+1	185	+1
5	191	177	−14	182	−9
7	188	179	−9	178	−1
8	188	182	−6	191	+9
9	197	179	−18		
10	217	215	−2		
11	191	193	+2	196	+3
		ME =	−6.50		1.33
		RMSE =	9.23		5.74
		MAE =	7.25		4.67

Results and Discussion

DEM Accuracy

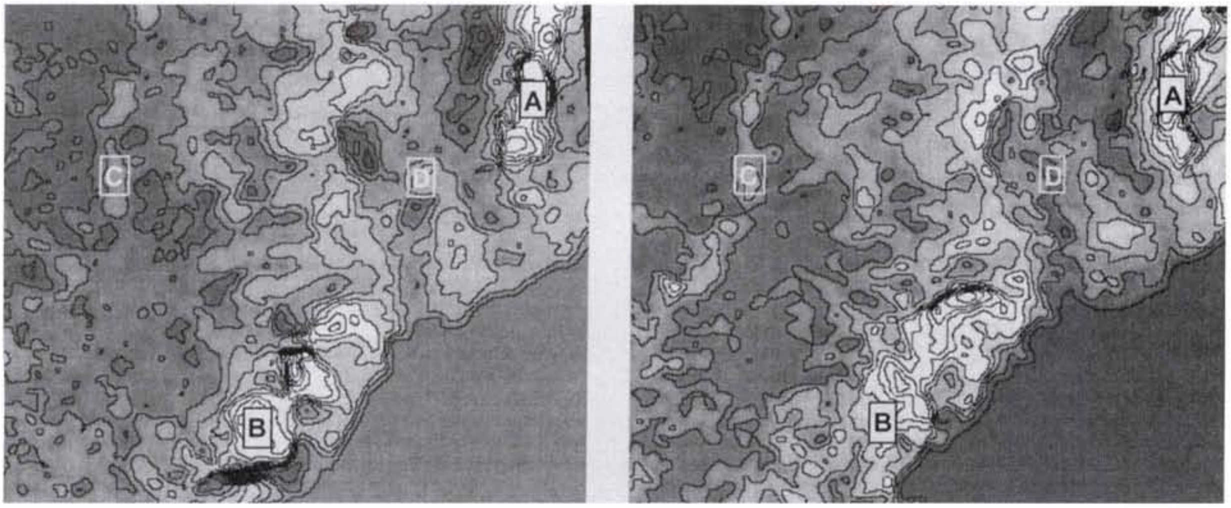
Table 2 lists the results of an analysis of the DEM accuracy. In general, the results are not as good as have been reported in previous literature (Welch, 1989). As might be expected, the 1965 DEM had higher error levels than the 1987 DEM, as measured by the MAE and RMSE. Also, the 1965 DEM had a relatively high negative mean error (ME). This suggested the possibility of bias in the 1965 elevation surface. The reasons for the lower accuracy in 1965 include smaller scale; a longer time period over for the paper to become distorted; the poorer tonal quality, with some scratches and other marks, processed at a coarser resolution (1.66 m versus 0.71 m for the 1987 photos); and a longer time span between field data collection and the 1965 photos than the 1987 photos (the surface is more likely to have changed in the intervening time).

A number of changes to the methods can be suggested to improve accuracy for future applications. First, diapositive prints of the photos should be acquired. Paper prints are prone to distortions that can become substantial over long time periods. Second, a higher quality scanner might be used to reduce any distortions resulting from the digitization process. Finally, higher accuracy GCPs can be acquired with improving GPS technology to reduce errors in the control network.

Regardless of the shortcomings of this pilot study, the DEMs were reasonably accurate and were within the range of accuracy needed for the analysis of dune evolution. What follows is a description of the results of the qualitative and quantitative topographic change analysis and the subsequent eolian process interpretations.

Visualization of Changes

Visualizing the patterns of change in the surface permits interpretation of eolian processes. We will focus on three specific process elements: wind direction, and blowout and



(a) (b)

Figure 4. DEMs generated from (a) 1965 and (b) 1987 aerial photographs with 5-metre contours. Lighter shades indicate higher elevations.

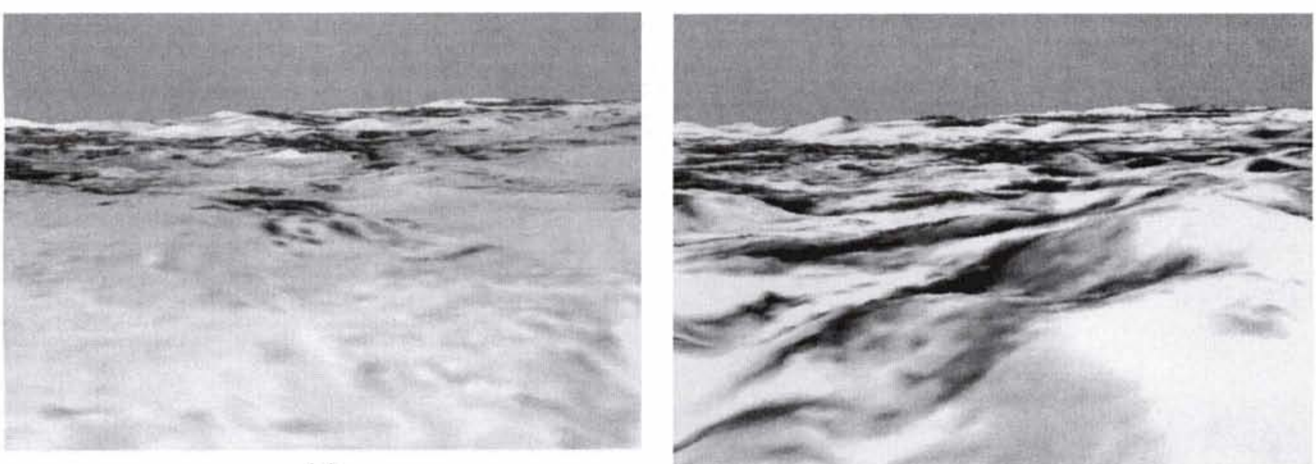
dune development. Wind directions are observable from the shifting of dune locations along the direction of wind flow. Blowouts are deflationary features observable as decreases in elevation. Dune growth typically occurs downwind of blowouts where the deflated sand accumulates.

To observe the influence of wind direction, we examined two-dimensional displays of the 1965 and 1987 DEMs (Figure 4) and used on-screen displays to "flicker" between the two DEMs. The type of movement observable can be illustrated by examining location A on both DEMs (Figure 4). Within the study area, location A has the highest elevations. A fairly dense forest anchors the core of this very high dune. Comparison of the two DEMs suggested that, although the central portion of this dune did not exhibit much change between 1965 and 1987, the flanks of the dune (north and south of the core) tended to migrate eastward.

A second illustration of dune migration is seen at location B (Figure 4). We have constructed an oblique perspective view of this area, looking at location B from the southeast (i.e., the view is to the northwest). Figure 5 shows an apparent accumulation of sand in the east and north of this view (i.e., right side) by 1987, at the apparent expense of sands in the west and south (i.e., left side) in 1965. This is verified by the general eastward drift of sand observed at location B (Figure 4).

Both visualizations described above are consistent with prevailing wind directions in the region (i.e., generally from the west; Figure 1), and allow for monitoring of their effects on the dune field. Although these are general findings, a more detailed examination of directional changes in dune locations, especially through the use of animation and on-screen flickering, allow for stronger inferences about local winds than can be illustrated in the context of printed text.

A good example of dune formation can be found along a dune ridge running south-southwest through location C (Fig-



(a) (b)

Figure 5. Perspective views of Location B, using DEMs with orthophotos draped, to illustrate changes in the dune surfaces: (a) 1965; (b) 1987. The view is to the north-northwest from near the shore of Hamlin Lake. Differences in the shading of the two photos, due to different spectral information, obscure some of the elevation differences.

ure 4). In 1965 the ridge is apparent, but lacks the relief and steepness observed in 1987. Given the lack of well defined blowouts adjacent to the ridge, the dune development was apparently the result of a continual reworking of the dune and the addition of eolian sand from the shoreline and other dunes to the west. Again, the DEMs allow for identification of such areas of active dune formation.

Blowouts are observable wherever dune elevations are substantially depressed between the two time periods. One such blowout is observable at location D in Figure 4, where a distinct depression developed between 1965 and 1987. The sand that was in the blowout was displaced to neighboring locations. Such an effect is observable in the south-looking perspective view of location D shown in Figure 6. The blowout is located in the lower-left foreground of the image, which shows a decrease in elevation from 1965 to 1987. Accordingly, dunes flanking this blowout show increased development from 1965 to 1987 (Figures 4 and 6).

Cut and Fill Analysis

The cut-and-fill analysis produced two types of results (Figure 7): (1) a map of differences between the DEM elevations at each time; and (2) a coverage that outlines the locations that have aggraded, degraded, or maintained their elevation. The darker shades in Figure 7 indicate that more elevation was added between 1965 and 1987, whereas lighter shades tended to lose elevation in that time period.

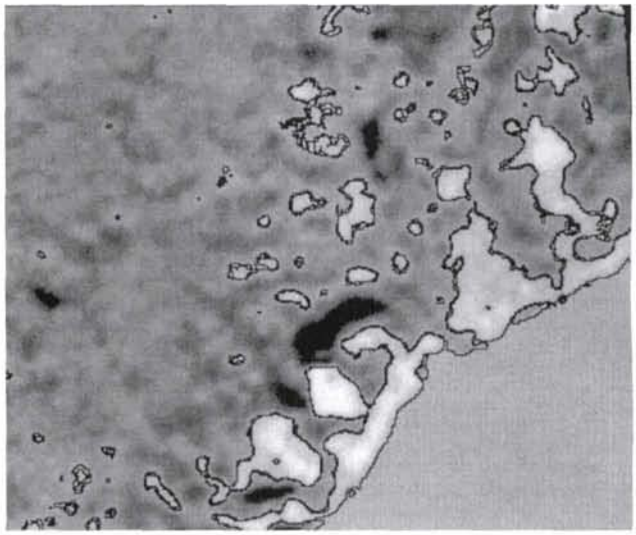
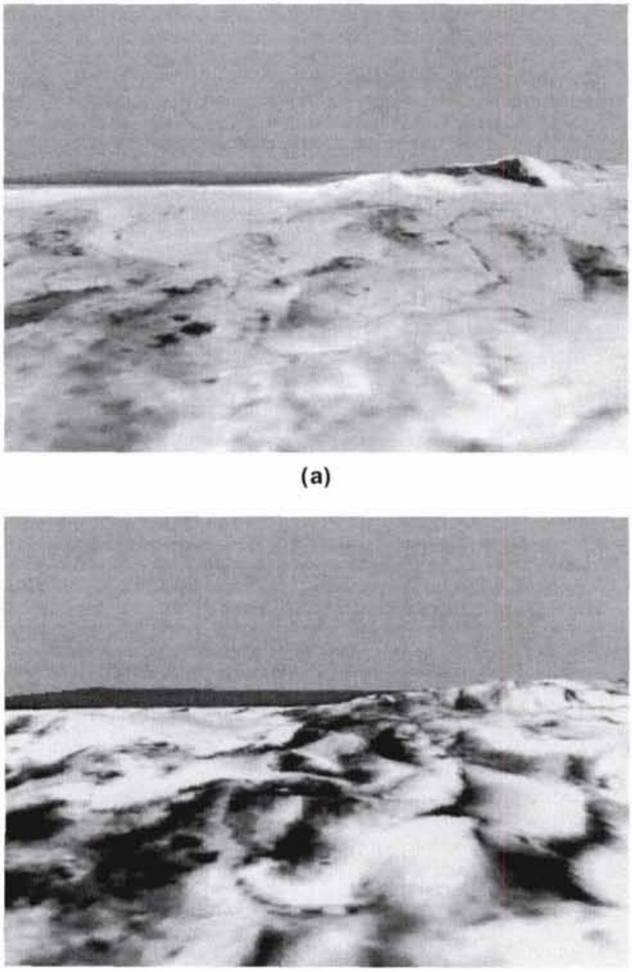


Figure 7. Map of differences between 1965 and 1987 elevation. Boundaries differentiate between areas of positive, negative, and zero elevation change. Darker shades indicate greater increase in elevation from 1965 to 1987.



(a)

(b)

Figure 6. Perspective views of Location D, using DEMs with orthophotos draped, to illustrate changes in the dune surfaces: (a) 1965; (b) 1987. The view is to the south, with Hamlin Lake visible in the background.

Data like those presented in Figure 7 can be used to quantify the approximate amount of volumetric change over time and, more importantly, show the spatial variations in this change. This information can be used to study the influence of various land-use and management decisions on dune processes. Table 3 lists the calculated changes in sand volumes in degraded and aggraded areas for the entire study area, a portion of the area that was never vegetated in the interval examined (Figure 8), and the blowout at location D (Figure 4). Also listed are the areas degraded, aggraded, and not graded for each area.

Data from the entire area indicate that the amount of aggrading area (i.e., adding sand) is greater than the amount of degrading area (i.e., losing sand), with a net addition of 1.3×10^7 m^3 volume of sand. This is likely an overestimate, however, because of the increase in tree height that occurred over the study interval. Nevertheless, the data from the unvegetated

Table 3. Results of Cut–Fill Analysis for the Entire Study Area, only the Unvegetated Area, and the Blowout Identified and Labeled as Location D in Figure 4

	Study Area		Unvegetated		Location D
Degraded Volume (m^3)	1,577,592		974,835		28,035
Aggraded Volume	14,570,316		5,306,895		0
Net Volume	+12,992,724		+4,332,060		−28,035
		%		%	
Degraded Area (m^2)	292,689	11.5	191,880	15.4	6,650
Aggraded Area	1,777,914	70.1	625,815	50.3	0
Area with no Change	466,317	18.4	425,619	34.2	0
Total Area	2,536,920		1,243,314		6,650

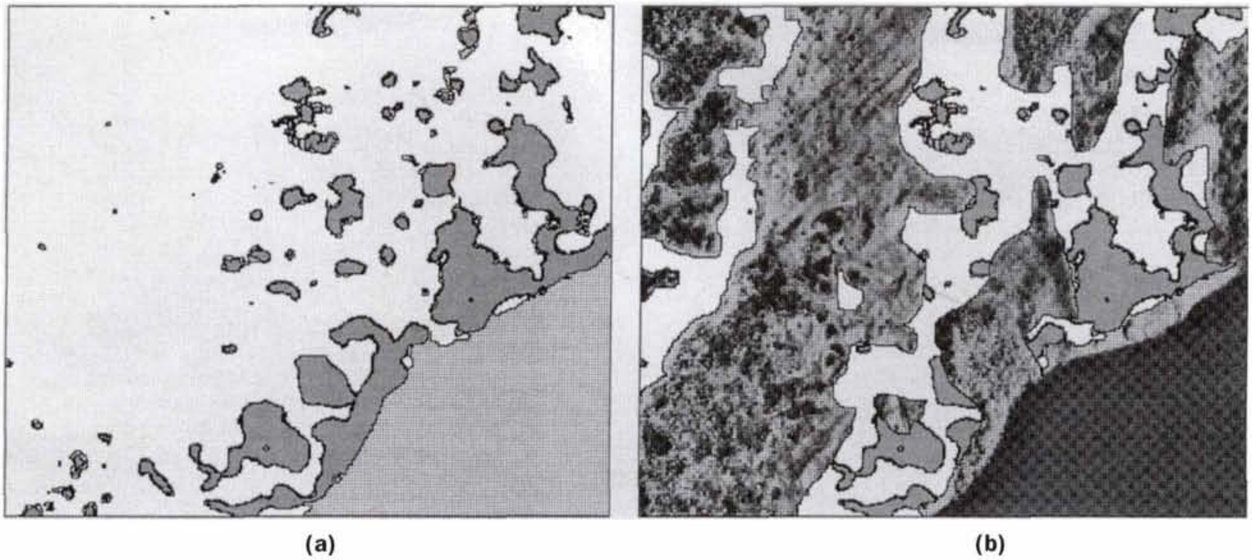


Figure 8. Results of cut-fill analysis. (a) All areas that increased (white), decreased (gray), or had no change (stippled) in elevation between 1965 and 1987. (b) same as (a) except that vegetated areas in 1965 or 1987 are masked out (stippled).

area support the interpretation that the overall volume of sand in the study area increased between 1965 and 1987. The sand volumes calculated in this pilot investigation should be interpreted rather loosely because of the possible bias in the 1965 DEM (Table 2), but, given the high supply of sand provided by Lake Michigan and the prevailing westerly winds, the addition of sand to the system is logical from a geomorphic standpoint.

Although sand volume likely increased over the entire area during the study interval, a reduction in sand volume occurred in specific areas. In particular, there was a net loss of approximately 28,035 m^3 from the blowout (6,650 m^2) at location D (Figure 4). As a result, these findings support the conclusions of the qualitative assessment, presented above, that the blowout deepened and enlarged between 1965 and 1987.

Conclusions

Landscapes consisting of unconsolidated sand (i.e., dune fields and sand sheets) may destabilize when vegetation is reduced and prevailing winds are strong (Ash and Wasson, 1983; Heidinga, 1984). Large dune fields, scattered throughout the central United States, are heavily utilized. In general, previous work (e.g., Grigal *et al.*, 1976; Madole, 1995; Anderton and Loope, 1995; Arbogast, 1996) has focused on the timing and magnitude of prehistoric change, and has verified the inherent sensitivity of dunes. As a result, research is beginning to focus on ways to monitor the response of dune fields should environmental change occur (e.g., Muhs and Maat, 1993). Thus far, no systematic method for monitoring contemporary events has been proposed.

Monitoring of dunes by digital photogrammetry can theoretically measure landscape response to environmental change, including the amount of sediment moved, direction of movement, and timing and magnitude of events. In this paper, a pilot study for monitoring dune evolution was conducted in an active coastal dune environment at Ludington State Park, Michigan, using digital photogrammetric change analysis. Results from a 22-year interval empirically show that the drift direction of sand and resultant landscape change could be observed. In addition, cut-and-fill analyses roughly quantified volumetric changes in sand distribution and were used to map areas of positive, negative, and negligible elevation change.

This study also illustrates the variables that influence the accuracy of digital change analysis in eolian environments. One of the most difficult problems encountered was establishing a reasonable network of control points that consisted of features that were (a) relatively stable across the period of study, (b) observable on the photographs, and (c) accessible. The reliance on trees for ground control probably limited the accuracy of the stereo models. We expect that, with higher quality photographic reproductions and in environments with better ground-level and stable ground control, like roads or other built structures, we can achieve higher accuracy.

Acknowledgments

We gratefully acknowledge financial support from the College of Social Science at Michigan State University (AFA), the State of Michigan Department of Environmental Quality (AFA), and a grant of equipment and software from the National Science Foundation (DGB; Award #9551118). We thank Randy Schaetzl for his careful reading of an earlier version of the manuscript.

References

Ahlbrandt, T.S., J.B. Swinehart, and D.G. Maroney, 1983. The dynamic dune fields of the Great Plains and Rocky Mountain basins, U.S.A., *Eolian Sediments and Processes* (M.E. Brookfield and T.S. Ahlbrandt, editors), Elsevier, New York, pp. 379–406.

Anderton, J.B., and W.L. Loope, 1995. Buried soils in a perched dunefield as indicators of Late Holocene lake-level change in the Lake Superior basin, *Quarternary Research*, 44:190–199.

Arbogast, A.F., 1996. Stratigraphic evidence for late–Holocene eolian sand mobilization and soil formation on the Great Bend Sand Prairie in Kansas, *Journal of Arid Environments*, 34:403–414.

Ash, J.E., and R.J. Wasson, 1983. Vegetation and sand mobility in the Australian desert dunefields, *Dunes: Continental and Coastal* (J. Jennings and H. Hagedorn, editors), *Zeitschrift für Geomorphologie, Supplementbände*, 45:7–25.

Burrough, P.A., 1986. *Principles of Geographical Information Systems for Land Resources Assessment*, Oxford University Press, Oxford.

Cheng, P., and C. Stohr, 1996. Automated digital elevation model extraction of a landfill site using stereo aerial photos, unpublished paper presented at ACSM/ASPRS Annual Convention, Baltimore, Maryland, 22–25 April 1996.

Cheng, P., and T. Toutin, 1995. High accuracy data fusion of airphoto and satellite images, *Proceedings, ACSM/ASPRS Annual Convention*, Charlotte, North Carolina, 2:453.

Eichenlaub, V.L., J.R. Harman, F.V. Nurnberger, and H.J. Stolle, 1990. *The Climatic Atlas of Michigan*, University of Notre Dame Press, Notre Dame, Indiana.

Farrand, W.R., and D.L. Bell, 1982. *Quaternary Geology (map) of Southern Michigan with Surface Water Drainage Divides*, 1:500,000 scale, Dept. of Geological Sciences, University of Michigan, Ann Arbor.

Giles, P.T., and S.E. Franklin, 1996. Comparison of derivative topographic surfaces of a DEM generated from stereoscopic SPOT images with field measurements, *Photogrammetric Engineering & Remote Sensing*, 62(10):1165–1171.

Grigal, D.F., R.C. Severson, and G.E. Goltz, 1976. Evidence of eolian activity in north-central Minnesota 8,000 to 5,000 yr ago, *Geological Society of America Bulletin*, 87:1251–1254.

Hansel, A.K., and D.M. Mickelson, 1988. A reevaluation of the timing and causes of high lake phases in the Lake Michigan basin, *Quaternary Research*, 29:113–128.

Harding, D.J., J.L. Bufton, and J.J. Frawley, 1994. Satellite laser altimetry of terrestrial topography: Vertical accuracy as a function of surface slope, *IEEE Transactions on Geoscience and Remote Sensing*, 32(2):329–339.

Heidinga, H.A., 1984. Indications of severe drought during the 10th century A.D. from an inland dune area in the central Netherlands, *Geological Changes in the Western Netherlands During the Period 1000-1300 A.D.* (H.J.A. Berendsen and W.H. Zagwijn, editors), *Geologie in Mijnbouw*, 63:1241–248.

Keen, K.L., and L.C.K. Shane, 1990. A continuous record of Holocene eolian activity and vegetation change at Lake Ann, east-central Minnesota, *Geological Society of America Bulletin*, 102: 1646–1657.

Madole, R.F., 1995. Spatial and temporal patterns of late Quaternary eolian deposition, eastern Colorado, U.S.A., *Quaternary Science Reviews*, 14:155–177.

Muhs, D.R., 1985. Age and paleoclimatic significance of Holocene sand dunes in northeastern Colorado, *Association of American Geographers Annals*, 75:566–682.

Muhs, D.R., and P.B. Maat, 1993. The potential response of eolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A., *Journal of Arid Environments*, 25: 351–361.

Olson, J.S., 1958. Lake Michigan dune development, 3: Lake-level, beach, and dune oscillations, *Journal of Geology*, 66:473–483.

Rao, T.C.M., K.V. Rao, A.R. Kumar, D.P. Rao, and B.L. Deekshatula, 1996. Digital terrain model (DTM) from Indian Remote Sensing (IRS) satellite data from the overlap area of two adjacent paths using digital photogrammetric techniques, *Photogrammetric Engineering & Remote Sensing*, 62(6):727–731.

Santer, R.A., 1993. *Geography of Michigan and the Great Lakes Basin*, Kendall/Hunt Publishing, Dubuque, Iowa, 421 p.

Stohr, C., R. Darmody, S. Aref, and P. Cheng, 1996. Digital orthophotos and DEMs combat closed landfills, *Earth Observing Magazine*, 5(9):51.

Thompson, T.A., 1988. Sedimentology and stratigraphy as tools in interpreting the evolution of wetland areas in the Indian Dunes National Lakeshore, *Interdisciplinary Approaches to Freshwater Wetlands Research* (D.A. Wilcox, editor), National Park Service Monograph, pp. 25–36.

Welch, R., 1989. Desktop mapping with personal computers, *Photogrammetric Engineering & Remote Sensing*, 55(11):1651–1662.

———, 1992. Photogrammetry in transition—analytical to digital, *Geodetical Info Magazine*, July:39–41.

Welch, R., and D. Papacharalampos, 1992. Three-dimensional terrain visualization on personal computers: An application with stereo SIR-B images, *Photogrammetric Engineering & Remote Sensing*, 58(1):71–75.

(Received 25 March 1997; accepted 20 May 1998)