Testing the Application of Digital Photogrammetry to Monitor Topographic Changes of Sandbars in the Colorado River Ecosystem

Laura E. O'Brien[1], Andre Coleman[2], Brandy L. Blank[1], Paul E. Grams[1], and John C. Schmidt[1]

[1]Department of Geography and Earth Resources
Utah State University
Logan, UT 84322-5240

[2]GEO/Graphics Inc
1063 West 1400 North
Logan, UT 84321

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Grand Canyon Monitoring and Research Center
2255 N. Gemini Dr.
MS-5000
Flagstaff, AZ 86001

ABSTRACT

Ground-based topographic surveys can produce highly accurate measurements of sandbar erosion and deposition, but are time-consuming and costly, and therefore typically limited to small study areas. Mapping from aerial photographs can depict changes over long reaches, but is less accurate. The goal of this project was to evaluate the application of scanned, stereo aerial photography and digital photogrammetry to measure and monitor sand bar erosion and deposition in the Grand Canyon ecosystem. We used existing high-resolution scanned images of black-and-white aerial photographs taken in October 1984, March 1996, and September 1996 to develop topographic models using digital photogrammetry. These models were compared with ground-based topographic measurements made in March 1985, February 1996, and September 1996, respectively. Maps were produced for all products in order to view the spatial pattern of agreement and disagreement between the methods.

Tests of ground control points not used in image registration indicated average position errors of about 20 cm (3.4 pixels) and average elevation errors of about 6 cm (1.0 pixels). Human error involved in identifying the control points averaged 30 cm. Accuracy was less in most of the tests comparing ground-surveyed measurements of a sand bar to the photogrammetric models. The photogrammetric surfaces were generally within 25 – 30 cm of the surveyed surfaces over more than 84% of the bar area. In measuring erosion and deposition following the 1996 experimental flood, the photogrammetric method agreed with the topographic measurements over 62% of the area compared. The spatial distribution of agreement indicates that the photogrammetric method tended to overestimate erosion and underestimate deposition. These results indicate that the photogrammetry was not as accurate as the ground-based topographic surveys. Comparison between manual and automated means of topographic data collection within the digital photogrammetry software indicated that the automated method compared favorably with the manual method. The manual method produced more realistic topographic contours, but had systematic errors. The automatic method created topographic surfaces that more closely agreed with the surveyed surface and produced volume estimates that were within 10% of the surveyed volume.

The level of accuracy achieved in this study is adequate for measuring large-scale changes over long reaches, or for quantifying sand bar topography in historical aerial photographs for which no other means of measurement are possible. Higher level photogrammetric accuracy in the Grand Canyon ecosystem may be possible, but requires further research and development.

PURPOSE

One of the primary monitoring activities of the Grand Canyon Monitoring and Research Center (GCMRC) is the measurement of erosion and deposition of channel-side sand deposits along the Colorado River in the 470-km reach between Glen Canyon Dam and Lake Mead (herein referred to as the Colorado River ecosystem). Currently, sand erosion and deposition is evaluated by ground-based topographic survey (e.g. Hazel et al., 1999), detailed geomorphic mapping on aerial photographs (e.g. Schmidt et al., 1999), and field-based campsite inventory and area measurements (e.g. Kearsley et al., 1999). Each of these methods reflects compromise among measurement detail, number of measurement sites, and spatial extent of each site. Topographic surveys are detailed and accurate, but can only be made for a few sites; each measurement requires a river expedition with a crew of 7 to 10 scientists, technicians, and field support. Currently, such measurements are made at 35 sites at least once annually. Geomorphic mapping using aerial photograph base maps is less detailed and less accurate than ground-based surveys but provides a means to quantify sand erosion and deposition for entire 5- to 15-km reaches. The purpose of this report is to explore the application of digital softcopy photogrammetry as a sand-resource monitoring tool.

This study also examines the applicability of digital photogrammetry in the analysis of historical aerial photographs. Using digital photogrammetry, the potential exists to accurately determine the topography of sand bars from past photographs, thereby extending the detailed historical record of landscape change. In essence, this technology can provide a "time machine" for scientific investigations of the river corridor. Digital photogrammetry has the potential to dramatically increase the body of precise and accurate historical data that can be used to improve our understanding of sand bar change over time.

In softcopy photogrammetry, a trained technician uses computer software to create a digital terrain model (DTM) from scanned aerial photograph stereo pairs. This method has the potential to provide greater accuracy than the currently used reach-scale monitoring methods and greater spatial richness than the currently used sand-bar surveying methods while requiring only photo-acquisition overflights and minimal field work to establish ground control.

This exploration of digital photogrammetric techniques applicable to sand resource monitoring was recommended by the GCMRC Protocols Evaluation Program in May 1998. In accordance with that recommendation, the GCRMC implemented modification No. 002 of Cooperative Agreement No. 1425-98-FC-40-22640. This modification implemented the proposal by O'Brien (then McCarthy) and Schmidt, "Testing the Application of Digital Photogrammetry to Monitor Sandbar Evolution in the Colorado River Corridor of the Grand Canyon." A draft final report summarizing the findings of this project was submitted in fall 1999, and GCMRC's comments on the draft report were sent to the principal investigators on November 29, 1999. This final report partly responds to those comments.

As a supplement to the work outlined in the above proposal, we evaluated alternate methods of DTM creation using softcopy photogrammetry, and we explored the application of the technique to older photographs. In May 2000, we sent the GCMRC a draft report on this work, which was the undergraduate honors thesis by Brandy L. Blank, "Application of Digital Photogrammetry to Monitoring Sandbar Change in Marble Canyon, Arizona" (Blank, 2000). This expansion of our original research focus was also supported by the funds provided under Modification No. 002. GCMRC sent the thesis out for formal comment, and comments were received by us in July 2000. This final report represents an integration of the draft report of fall 1999, the Blank thesis of May 2000, and our responses to all reviewer comments.

BACKGROUND

Detailed topographic mapping with sub-meter accuracy is essential in many studies of fluvial geomorphic processes (Wall et al., 1991). In sediment-depleted systems downstream from large dams, accurate evaluation of topographic changes in channel-side sand resources can be an important component of ecosystem monitoring (Collier et al., 1996). Field-based methods of surveying and mapping are time-consuming, costly, and typically limited to specific sites (that have a maximum channel length of about 500 m). Currently, the need to understand changes in sand storage in longer reaches (5 to 15 km) has been met by geomorphic mapping from aerial photographs. This method, described in detail by Schmidt et al. (1999), relies upon classifying sand deposits into broad elevation categories based on interpretation of the aerial photographs when viewed in stereo. Shifts in elevation categories between photographs that bracket the evaluation period are used to estimate areas of erosion, deposition, or no significant change. Thus, this method can depict the spatial distribution of erosion and deposition for large areas, but can not be used to quantify the volume of sediment eroded or deposited. This method has been shown to agree with the detailed topographic methods over approximately 70% of the area where the methods overlap (Schmidt et al., 1999). The methods of Schmidt et al. (1999) permit limited analysis of submerged sand deposits. Turbidity in the Colorado River is highly variable, no photographic method has been successful at systematically and reliably measuring topographic change of submerged deposits.

Needs for detailed mapping of large areas conducted in a relatively short time and at minimal cost are increasingly being met through the use of digital photogrammetry. Recently, there has been increased use of digital orthoimagery and digital elevation models or triangulated irregular networks for the mapping of topographic features (Jensen, 1996). A digital elevation model (DEM) is a regularly spaced grid containing an elevation value for each grid cell. The resolution of the DEM is dependent upon the grid-cell size, which is dependent upon the data acquisition procedure. The DEM is the most common way to store and process digital elevation data, because it is efficient and standardized. It deviates from the true ground surface, however, because one elevation value is assigned to the entire grid cell. This problem can be minimized by decreasing cell size. A triangular irregular network (TIN) is an alternative procedure for digitally describing a topographic surface. The TIN algorithm may also be used to generate either a DEM or contour lines from irregularly-spaced point data. In a TIN, points of known elevation are connected by lines to form triangular facets. Each triangular facet is a plane with a known slope and aspect. Elevations can then be interpolated anywhere on the plane to form a DEM or to draw contour lines. The volume between topographic surfaces can be calculated using either DEMs or TIN models.

The creation of a DEM from digital stereo photography depends on image matching techniques that require, and result in, a high degree of geometric accuracy (Ackermann, 1996). These data, either incorporated into a GIS or used for the creation of maps, are particularly useful for the geoscience, geophysical, and geoexploration communities who need rapid generation and updating of DEMs and for mapping remote or inaccessible regions (Vincent, 1997). These techniques have been used to interpret satellite imagery, as well as aerial photography, for a variety of applications and at a variety of scales. Digital color-infrared orthophotos also have been used to monitor landfills by mapping changes in surface topography (Stohr et al., 1994). The city of Logan, Utah, acquired processed digital orthophoto maps at a ground pixel resolution of 8cm for use in storm and waste water management, and law enforcement (GEO/Graphics, 1999).

Digital photogrammetry can provide excellent resolution in the X, Y, and Z directions. For instance, a 1:4000 scale photo scanned at 1000 dots per inch, yields a spatial resolution of about 10 cm with an overall root-mean-square (RMS) error of 12 to 15 cm (Vincent, 1994). The company Documenta Architectural Photogrammetry mapped the movement of migrating sandunes in Egypt using black-and-white aerial photography at a scale of 1:4000 and were able to obtain spatial resolutions of 20 cm in the X, Y, and Z directions (P. Borges, Documenta Architectural Photogrammetry, personal communication, 1997). The creation of a DEM from SPOT panchromatic data for the Badia area of northeastern Jordan resulted in a RMS error of 6 m in the X and Y directions, and 8 m in the Z direction, which is less than the 10-m pixel size in these photos (Al-Rousan et al., 1997). Wall et al. (1991) compared manual with digital photogrammetric methods to improve geomorphic mapping using radar remote sensing. Using a camera mounted on a helicopter and flown 20 m above ground level, they obtained photographs with a spatial resolution of 5 cm with an average height error of 3-4 mm. It was found that the digital version performed comparably with the manual version, with the exception that the automated mapping procedure did not distinguish between the ground surface and vegetation. This problem can be compensated with a knowledge of vegetation characteristics. Ridley et al. (1997) used automated digital photogrammetry to create DEMs from 1980 and 1995 of 1:7500 aerial imagery scanned at 1.0 and 0.2 m resolutions to see if topographic change could be detected in a low-lying coastal area. Analysis showed that the imagery with the 1.0 m resolution was too coarse to detect topographic change but that the 0.2 m resolution imagery was sufficiently detailed to detect topographic change. Thus, these methods have been successfully used to measure subtle topographic change if the spatial resolution of the imagery is sufficiently detailed. These studies obtained horizontal and vertical accuracies in their final DEMs that ranged from less than half the image pixel size to no greater than double the image pixel size.

Differences in precision among these different techniques are related to a number of factors. Quality of ground control points (GCPs) is perhaps the most important. The triangulation and block adjustment are only as correct as the precision and accuracy to which ground control points can be located (Swanson, 1966). Some types of GCPs are easier to locate than others, and the studies mentioned above had a variety of target types. In some cases, the GCPs were specially designed targets; in others, GCPs were road intersections or golf balls. The degree to which the precise location of these GCPs is known also varies depending on whether coordinates were obtained from ground survey, global positioning systems (GPS), orthophotoquads, or other maps.

The scale of the imagery used also defines the obtainable precision. For 1:20,000 scale photographs, 1 m on the ground is approximately 0.045 mm on the photograph (Swanson, 1966). Thus, scale can strictly limit how precisely GCPs can be selected and how much detail can be obtained from the image. Because of this, large-scale imagery will produce more precise results.

STUDY AREA

The Colorado River ecosystem occurs in a narrow and deep canyon where channel width is typically constrained by bedrock, talus, or bouldery debris fans. Channel-side sand deposits are, however, common when exposed at low discharges. Some of these deposits are densely overgrown by native and non-native riparian trees and shrubs. There is a longstanding need to monitor the topography of the sand deposits because they are necessary for recreational camping, provide habitat for native fish, and are considered a valuable attribute of the natural canyon landscape (U.S. Department of the Interior, 1995).

The characteristics of the Colorado River ecosystem present many challenges to resource monitoring. The greatest challenge is accessibility. Most of the 470 km river corridor can only be accessed by costly and lengthy river expeditions. Maintenance of sensitive measurement equipment is difficult in the canyon environment and repairs are difficult to perform in the remote field locations. Moreover, because the river corridor is managed as a wilderness, frequent research and monitoring expeditions are considered a significant intrusion. While there are still challenges to obtaining aerial photography in the Colorado River ecosystem, many of the problems inherent in river expeditions are avoided. Ground-based surveys are only needed once, to establish control points. The existence of large, unmovable boulders whose location can be surveyed and that can be located on old photographs allows photogrammetric analysis of some historical aerial photographs.

We evaluated the use of photogrammetric techniques to reconstruct past topography at a site well known to Grand Canyon researchers. This site is Badger Creek Rapids (Fig. 1), first studied in detail by Schmidt and Graf (1990). We analyzed topographic changes for a 2-km reach extending from the backwater pool upstream from the rapids to the downstream end of the lateral separation eddies that occur downstream from the rapids (Fig. 2). Topographic changes of the separation bar on river left were analyzed in detail, because there is a long record of detailed field surveys for this area. We specifically compared photogrammetrically-derived topography with field surveys made in 1985, March 1996, and September 1996.

One advantage to working near Badger Creek Rapids was the accessibility to the site by boat and by foot. Ground surveys were made on two separate occasions and the ability to return to the site without having to mount a major river trip helped to minimize time and cost. The Badger

Creek Rapids area contains a variety of the topographic features typical of the Colorado River ecosystem. The area has relatively few saltcedar shrubs and other riparian vegetation, thereby minimizing problems that occur when vegetation obscures land surface topography.

METHODS

Data Sources

We analyzed black-and-white aerial photo stereo pairs taken on October 21, 1984, March 24, 1996, and September 1, 1996. The 1984 photographs were of an approximate scale of 1:3000 and the 1996 photographs were of an approximate scale of 1:4800. The topography generated from the 1984 photos was compared with a field survey of the bar made May 20, 1985 (Schmidt and Graf, 1990). The topography generated from the March 1996 photo was compared with a topographic survey made on February 16, 1996, and the topography generated from the September 1996 photo was compared with a survey made on September 14, 1996. Both of the 1996 surveys were conducted by Northern Arizona University (Hazel et al., 1999). Areas of erosion and deposition between March and September 1996 determined by comparison of the photogrammetrically-derived topography were also compared with areas of erosion and deposition determined by geomorphic mapping from the same aerial photographs (Sondossi and Schmidt, unpublished data).

Image Scanning and Collection of Control Points

Film diapositives of the images were scanned at a resolution of 12 microns such that the pixel size of the digital images was 5 cm for the 1996 photographs and 4 cm for the 1984 photographs. Within the ERDAS Imagine software, the digital images were registered to established GCPs and geometrically rectified. The field survey of coordinates of the GCPs was conducted twice. The first time field surveys were made, GCPs were not precisely located on the aerial photos. We learned that it is essential that the person responsible for the location of GCPs on the aerial photographs be present in the field so that each survey point is precisely located. In the image registration process, we also learned that the GCPs need to be distributed over as much of the photograph as possible. Wide distribution of these points is a more critical element than is the actual number of points.

Of the many GCPs surveyed, 20 could be identified to the precision of determining where on the digital photograph was the precise point where the survey rod had been placed in the field

(Fig. 3). Photographs taken in the field of the exact rod location were essential aids in locating these points in the office. For the aerotriangulation software protocol, only four GCP points are required, so 20 GCPs were sufficient for accurate photo registration. The GCPs were supplemented with numerous tie points for each stereo pair. The tie points are points identified by the user as common to each photograph that the software uses to more precisely tie the two photographs of the stereo pair together. The same 20 GCPs were used for both 1996 photo pairs. Only 12 of the 20 GCPs used for the 1996 photographs were identifiable on the 1984 photographs. Of these, 6 were used in the registration and 6 were used as controls to check the registration. An additional 15 tie points were used to register the 1984 images (Fig. 4).

Creation of Digital Stereo Images

The first step in image registration is performing an interior orientation of the images within the photogrammetry software (ERDAS Ortho*MAX* ™). This process requires that the technician locate the precise center of the fiducial marks on each photograph. This was not a problem on the 1996 photos but fiducial marks could not be located precisely in the 1984 photos because they were nearly blacked out. Thus, the RMS error for this step did not meet ERDAS recommendations for the 1984 photos. Values for the RMS error ranged between 5.5 and 7.8 for the three images; the recommended RMS error is 0.5. Because no other source of this high RMS error could be confirmed, we assumed it was due to the poor visibility of the fiducial marks and had to be accepted. The RMS errors for the 1996 photos were within the acceptable range.

The next step in the image correlation is the 'exterior orientation.' This step uses the GCPs and the tie points to perform an image-match correlation, which uses a triangulation algorithm that also incorporates a 'least-squares block bundle' adjustment. This process, termed the block adjustment, converts the independently-registered images into a digital stereo pair. A triangulation report is also produced that includes error estimates and identification of poor GCPs and tie points. If the error is not acceptable, GCPs and tie points may be adjusted or replaced and the correlation may be improved. The recommended acceptable range of the triangulation RMS error is from 0.5 to 2.0; 1.0 is perfect agreement (ERDAS, 1998). We obtained triangulation report RMS error values of 0.78 for the 1984 stereo pair, 0.74 for the March 1996 stereo pair, and 0.87 for the September 1996 stereo pair. Thus, despite the poor interior orientation of the 1984 photos, we achieved an acceptable block adjustment and produced a useable stereo pair. Following this step, the digital stereo pair can be viewed in 3-dimensions with stereo goggles.

Creation of Topographic Surfaces

The photogrammetry software interprets elevations from the digital stereo images. Elevations can be assigned either manually or by an automated process. In the automated process, the software "identifies" the ground surface elevation at every point on a specified grid. In the manual process, a technician, while viewing the image through the stereo goggles, uses a cursor that can be manipulated to appear to "float" above or "sink" below the surface. In this way, the surface can essentially be surveyed on the computer screen. We generated automatically created surfaces (ACSs) for all of the stereo pairs and a manually created surface (MCS) for the 1984 stereo pair. The 1984 MCS consisted of over 1300 individually 'surveyed' points. The ACS consisted of over 13,000 automatically selected points (Fig. 5).

Topography from the March and September 1996 photos was created only with the automated process. Elevations were collected for the entire study area on a 5-cm grid, which is the same as the pixel resolution of the images. This grid was spatially averaged at a 30-cm (or 6 pixel) resolution to create a TIN model of the surface topography.

Because the 1996 images and the 1984 images were analyzed by different technicians and at different times, slightly different procedures were used to analyze the topographic surfaces generated by the photogrammetry software. For the 1984 images, the coordinates and elevations of the points collected by the automated method and manual method were imported into the *Terramodel* software package, which was used to create a TIN for each surface. The TINs were then imported into ArcView version 3.2 for map preparation and comparison with the ground survey data. For both sets of 1996 images, the elevations collected by the automated method were used to generate a TIN in Ortho*MAX*™; these TIN models were exported to ArcInfo and analyzed as grids. Thus, although software use varied slightly, all analyses and comparisons were conducted using the grid (DEM) data format.

Once the MGCs, AGCs, and the contour map from the May 1985 survey had been imported to *Arcview*, a number of steps were taken to assist with analyzing the data. First, a TIN was created for each of the three contour files. These TINs were then converted into grids, that were then clipped to be the same area. The clipped area was the upper-most elevation portion of the bar, which was assumed to have experienced little or no change in the 7 months between October 1984 and May 1985, since no flows reached that elevation during that time. These two data sets were compared.

The geometric accuracy of the image registration and orthorectification was evaluated by comparing the surveyed coordinates of GCPs not used in the registration with coordinates for those points identified on the rectified images. The results of this test indicated that X-Y position is within 20 cm in the 1996 images and within 25 cm in the 1984 images. Elevation is within 6 cm in the 1996 images and within 19 cm in the 1984 images (Table 1).

Table 1. Test of geometric accuracy of 5 control points not used in the image registration and ortho-rectification process.

	Average error in indicated direction, in cm		
Year	X	Y	Z
1984	9	25	19
1996	11	20	6

RESULTS

Comparison Between Ground Surveyed Elevations and Elevations in Photogrammetric Surfaces

1996 Photos

We tested the accuracy of our topographic models in depicting the sand bar surface by comparing elevations for specific points as measured by topographic survey with those determined by our photogrammetric methods. This was done by obtaining spot elevations from our topographic models at the position coordinates of each point surveyed in the field. The March 24, 1996, surface was compared with points surveyed on February 16, 1996, and the September 1, 1996, surface was compared with points surveyed on September 14, 1996. More than 200 points were surveyed in the field on each occasion. Elevation agreement was evaluated at 10-, 30-, and 50-cm thresholds. The percentage of photogrammetric spot elevations that were within these thresholds was determined for each comparison (Table 2). Agreement for the February/March comparison was poor at all threshold levels, with only 9% agreement at the 10-cm threshold. Agreement for the September comparison was considerably better with 93% agreement at the 50-cm threshold but still only 34% agreement at the 10-cm threshold.

Maps of the distribution of surveyed points show that errors at the 10-cm threshold are distributed across all areas of the bar surface (Fig. 6). At the 30-cm threshold, errors were distributed across more of the bar surface, but tended to be greatest in areas where rocks are most abundant (Fig. 7). Although sand erosion and deposition during the elapsed time between the aerial photos and the ground surveys is a possible source of error, most of the large discrepancies occurred in the high elevation parts of the bar that were not inundated during these periods (Fig. 8).

Table 2. Comparison between surveyed sand-bar elevations and spot elevations from the photogrammetrically derived surface models.

Comparison	1996 Pre-Flood	1996 Post-Flood	1984 MCS	1984 ACS
Air photo date	24-Mar-1996	1-Sep-1996	21-Oct-1984	21-Oct-1984
Survey date	16-Feb-1996	14-Sep-1996	20-May-1985	20-May-1985
Threshold	Percent of spot elevations within indicated threshold of surveyed elevations.			
10 cm	9	34	na	na
30 cm*	42	81	79	80
50 cm	71	93	na	na

* Threshold is 25 cm for the 1984 comparisons.

1984 Photos

The accuracies of both the manually created surfaces (MCSs) and automatically created surfaces (ACSs) generated from the 1984 photos were tested against the May 1985 field data. In one test, coordinates for 86 survey points from the May 1985 field survey were "dropped" onto the 1984 MCS and a comparison was made of the elevation values. The same 86 points were then "dropped" onto the 1984 ACS to determine the accuracy of the elevations predicted by the computer (Fig. 9).

There was little difference between the average point accuracy of the manual and automatic methods; of the 86 points dropped onto each surface, 80% were within 25 cm of the surveyed elevations for the ACS, and 79% of the points were within 25 cm for the MCS (Table 2). On average, the points "dropped" onto the manual surface were within 17.5 cm of their surveyed elevations. The average error of survey points "dropped" onto the automatic surface was 17.4 cm, slightly less than the manual methods.

The type of error of the MCS and ACS methods differed substantially, however. Manual data collection methods resulted in a systematic underestimation of the elevations, because most of the errors were positive (Fig. 10). The histogram of the error associated with the surface created by automatic collection was more evenly distributed with equal amounts of positive and negative errors, indicating that the points were randomly located both above and below the actual surface. Histograms of the absolute value of the error associated with both types of surface may indicate automatic method was slightly more accurate (Fig. 11). However, a regression comparing the elevations measured from the photogrammetric surfaces with surveyed elevations shows that the methods were equally precise; the regression coefficient was 0.98 for each method (Fig. 12). Thus, although the ACS method was more accurate and did not contain systematic errors, the methods were equally precise.

To better understand why these two methods produced different types of errors, we examined the spatial distribution of the errors (Fig. 9). The greatest errors were concentrated in areas where there was a large change in elevation, such as the base of the talus slope, or around the large boulders located on the sandbar. Next, we viewed the 86 surveyed points in stereo in the Ortho*MAX*™ program. This revealed a slight lateral shift in some portions of the survey relative to the digital images. The shift was identified because some survey points were embedded into rocks, when they should have been located on the ground, adjacent to the rock. In the topographic surveys, the rod was always held on the sand surface and never on the top of adjacent rocks. There were also some discrepancies in the Z direction, with many points appearing slightly too high or low. Thus, while the actual survey data represents the surface of the sandbar in 1984 imagery fairly accurately, small differences in some points may be the cause of many minor discrepancies.

Comparison Between Photogrammetrically Derived Topography and Ground Surveyed Topography

1996 Photos

Comparison of topographic surfaces

This test compares the topographic surfaces generated from the photogrammetric analyses with those surfaces generated from the ground-surveyed data. The TIN model created from the ground-based surveys was generated from the same 200 irregularly-spaced points used in the point analysis. The TIN model was converted into a grid at the same 30-cm resolution for comparison with the corresponding surface model derived from the photogrammetry.

We then calculated areas of agreement and disagreement using the same 10-, 30-, and 50-cm thresholds used in the spot elevation analysis. The percentage of the bar area that is in agreement between the methods at each of these thresholds is very similar to the percentage of agreement in the analysis of spot elevations (Table 3). Maps showing the areas of agreement and disagreement at these thresholds for the March and September photogrammetry dates are shown in Figures 13, 14, and 15. As the spot elevation analysis showed, disagreement was greatest in the upstream and onshore part of the sandbar study area where boulders and some bushes exist. Although we removed many of the largest boulders and shrubs from our TIN, those that we did not remove must have influenced the final topographic surface.

Table 3. Comparison between surface models derived from ground-based survey and photogrammetry.

Comparison	1996 Pre-Flood	1996 Post-Flood	1984 MCS	1984 ACS
Air photo date	24-Mar-1996	1-Sep-1996	21-Oct-1984	21-Oct-1984
Survey date	16-Feb-1996	14-Sep-1996	20-May-1985	20-May-1985
Threshold	Percent of sand bar area where agreement was within the indicated threshold.			
10 cm	11	25	na	na
30 cm*	50	85	84	96
50 cm	75	96	na	na

* Threshold is 25 cm for the 1984 comparisons.

Sand bar area, volume, and change calculations

This test compares the modeled topographic surfaces of the bar, as computed from digital photogrammetry, with the surfaces computed from the ground surveys. The comparison uses the same ground surveys included in the spot elevation comparison. In one series of tests, we compared our results with surveys made by NAU in March and September 1996. For each comparison, we used the boundary area method defined by Hazel et al. (1999). In this method, the side and rear boundaries of the bar are fixed and the boundary along the edge of water is always the contour line of the 8,000 ft^3/s stage. Thus, this boundary shifts according to bar topography and the calculated area of the bar surface is actually the area within the rear and side boundaries that is above the 8,000 ft^3/s stage. Points outside of this boundary were not included in the comparison.

To ensure that our method of creating surface models and calculating bar volumes was consistent with that used by Hazel et al. (1999), we compared the volume that we calculated with their volume for the same data. We calculated a volume of 317 m^3 above the 8000 ft^3/s stage compared to 315 m^3 calculated by Hazel et al. (1999). Thus, surface model and volume calculation methods are not considered to be a significant source of error.

We then compared the areas and volumes for each date as determined by photogrammetry and field survey data (Table 4). There was a considerable difference between the area and volume estimates from these two data sets for the pre-1996 flood comparison, although the September comparison showed closer agreement. The photogrammetric method consistently over-estimated bar area and volume. Because this error was greatest in the pre-flood measurement, the 1996 flood-change calculation indicated much less deposition than was measured by the topographic survey.

Table 4. Comparison between sand-bar area and volume calculations.

Comparison	Surveyed Topography	Photogrammetric Topography	Difference between methods
		Area, in square meters	
Pre-1996 flood*	1422	1445	23
Post-1996 flood†	1472	1476	4
1996 Flood change	50	31	-19
		Volume, in cubic meters	
Pre-1996 flood*	1551	1957	406
Post-1996 flood†	1868	1991	123
1996 Flood change	317	34	-283

*February 16, 1996 topographic survey and March 24, 1996 aerial photos.

†September 14, 1996 topographic survey and September 1, 1996 aerial photos.

1984 Photos

Comparison of topographic surfaces

We compared topographic surfaces generated from the May 1985 field data with MCS and ACS data. The May 1985 survey data were transformed into the same coordinate system so that the three surfaces could be compared. A visual comparison was made by overlaying the MGC and the contours mapped in May 1985. A visual comparison was also made of the automatically generated contours (AGCs) and surveyed contours. We also created maps that detected differences between the created surfaces and the surveyed surface. These maps were made for both the MCS and the ACS. Volumes were also calculated and compared for the MCS, ACS, and surveyed surface.

The MGC method generates much more realistic topographic contours, based on a comparison of the contours generated by the three methods. The contours generated from the MCS are very similar in position and elevation to the field survey (Fig. 16). The AGC reflect an intricately dissected surface that does not exist (Fig. 17). Overall, the AGCs are generally located in the correct positions, but they are highly crenulated and do not reflect the smooth topography that exists in the photos. If the AGCs and MGCs are compared for the entire bar and not just the surveyed area, the AGCs differ radically, in some places, crossing as many as 3 of the MGCs (Fig. 18). When viewed in stereo, many of the AGCs in some portions of the bar poorly represent the surface. In some cases, the contours appear to be "floating" above the surface, while in others they appear to be embedded in the sand. Vegetation and abrupt changes in topography seem to be the main cause of errors such as these.

When the photogrammetric topographic surfaces are compared to the ground-surveyed topography, the manually-created surface shows systematic underestimation of the ground surface while the automated method has a non-biased error. However, the most inaccurate point on the MCS differs by 67 cm from the surveyed ground surface, while the most inaccurate ACS point was nearly 1 m different from the known elevation. The change detection map between the MCS and the actual surveyed surface shows that much of the surface was slightly underestimated (Fig. 19). The change detection map between the surveyed surface and the ACS shows that in some places the automatic method underestimated the elevation, while in others it overestimated it (Fig. 20).

Sand bar volume calculations

Both the MCS and the ACS underestimated the estimated volume of the sandbar in relation to the field survey. The volume of the bar in the clipped region above the 939 m contour was 772 m^3, estimated from the surveyed surface. The volume estimated at the same base level for the manual surface was 608 m^3, which was 21% less than the actual surface. The automatic surface volume estimate was only 8% less, 710 m^3. The automatic surface provides a more accurate estimation of volume than the manual surface because the positive and negative elevation errors canceled each other in the volume calculation, while in the manual method the errors were systematic.

Discrepancies in point data and the overall surfaces for both the manual and automatic surfaces can be attributed to a number of reasons. One possibility is the vertical and lateral shifts noted above. Another possibility stems from the varying densities of data. Approximately 1,300 points were used to create the manually-generated surface, while just over one-hundred points were used to create the field map. Thus, the manual contours may be capturing more detail, which causes the contours to change slightly. This could also be true for the automatic surface, which is again an order of magnitude richer in data density than the manual surface.

Change-Detection by Photogrammetry Compared to Change-Detection by Topographic Survey

We also performed an analysis of the accuracy of change detection to evaluate the effect of errors in the topographic models on calculations of areas of erosion, deposition, and no change. Using the topographic data of Hazel et al. (1999) and our photogrammetric data, we calculated separate pre- to post-1996 flood change detection maps for each method at three thresholds of change detection; a ±10 cm range of no significant change; a ±30 cm range of no significant change; and a ±50 cm range of no significant change. Change detection comparison was made only for the area inside both the February and September 8,000 ft^3/s boundaries, because this is the only region where both methods have sufficient data. The change-detection map for each method at the 10-cm change-detection threshold shows general agreement between the methods (Fig. 21). The photogrammetric method, however, greatly overestimated the area of significant erosion and underestimated the areas of significant deposition and no change. The photogrammetric change-detection map is much more patchy, a reflection of the dense grid of data collection points. The same trend occurs at the 30-cm change-detection threshold (Fig. 22). The photogrammetric method overestimates erosion and underestimates deposition, with no change being the greatest area of agreement. At the 50-cm change-detection threshold, nearly all of the agreement is in areas of no change (Fig. 23). This figure also illustrates that at a 50-cm limit of change detection, most topographic change caused by the 1996 flood is missed.

We then performed an error analysis on these change-detection maps, also at the corresponding 10 cm, 30 cm, and 50 cm agreement levels. Maps of agreement and disagreement at corresponding to these levels are shown in Figure 24. The largest areas of "severe" disagreement between the methods are where the topographic surveys indicate deposition and the photogrammetric method indicated erosion (Fig. 24a). The largest areas of "moderate" disagreement are where the topographic surveys indicated deposition or no change and the photogrammetric method indicated no change or erosion, respectively. The areas of agreement increase at the larger thresholds as the areas of no change expand (Fig. 24b and c). The methods agree over about 48% of the measurement area at the 10-cm change-detection threshold, 62% of the area at the 30-cm threshold, and 78% of the area at the 50-cm threshold (Table 5). This agreement is considerably better than the 11% and 25% agreement measured between the topographic survey and the photogrammetric surfaces for the pre- and post-flood surfaces themselves (Table 3). Thus, the ability of the photogrammetric method to detect significant change can exceed the accuracy of an individual surface.

Table 5. Matrices comparing agreement between areas of significant erosion, deposition, and no change as measured by topographic survey and photogrammetry. All values are percentage of total area compared.

		Topographic Survey		
		Deposition	No change	Erosion
		10-cm change-detection threshold		
Photogrammetry	Deposition	**38**	3	*0*
	No change	20	**9**	0
	Erosion	*16*	13	**1**
		30-cm change-detection threshold		
	Deposition	**10**	12	*0*
	No change	15	**52**	0
	Erosion	*1*	10	**0**
		50-cm change-detection threshold		
	Deposition	**3**	9	*0*
	No change	7	**75**	0
	Erosion	*0*	7	**0**

Bold typeface indicates areas where the two methods are in agreement and italics indicate areas where the two methods substantially disagree. The total area compared is the area where both measurements overlap and is 1354 m^2.

Change-Detection by Photogrammetry Compared to Change-Detection by Geomorphic Mapping on Aerial Photographs

Schmidt et al. (1999) developed an algorithm by which areas of significant erosion or deposition were determined by comparing GIS coverages. Sondossi and Schmidt (2000) used a similar method. Schmidt et al. (1999) and Sondossi and Schmidt (2000) compared the results of their algorithm with ground-based survey data (Hazel et al., 1999) and determined that their "areas of significant erosion" and "areas of significant deposition" represented topographic changes of ± 30 cm. Topographic changes less than 30 cm cannot be detected and are considered "no change". Sondossi and Schmidt (unpublished data) developed a map of areas of significant erosion and deposition for the period between March and September 1996 (Fig. 25). We compared his map to our map of erosion and deposition for the entire reach at the 30-cm change-detection threshold (Fig. 25). Boulders and shrubs were not edited out of this change-detection map for the reach, as they were for the map of the sand bar study area. We made this comparison for the areas of fine-grain alluvium only. A map showing the areas where the two methods were in agreement and in disagreement is shown in Figure 26.

A matrix showing agreement and disagreement was calculated between the photogrammetric and geomorphic mapping methods of change-detection (Table 6). The greatest area of agreement (44% of the area) was in the class of 'No-Change' between the two different dates. This is consistent with the topographic data for the sand bar study site, which shows large areas of no change at the 30-cm change-detection threshold. The greatest area of disagreement occurred where the photogrammetric method detected significant erosion and the geomorphic mapping method did not detect change (17% of the area). Substantial disagreement in the methods (i.e. where one method detected erosion and the other method detected deposition, or vice versa) occurred in 6% of the total area evaluated.

For the area of the reach where ground-based topographic measurements are available, the areas of areas of erosion, deposition, and no change determined by geomorphic mapping agreed with the topographic measurements for 75% of the area for which the methods overlapped (Sondossi and Schmidt, 2000). This is comparable to the 62% level of agreement at the 30 cm threshold between the photogrammetry and ground-based measurements discussed above. Because each method has substantial error when compared to the ground-based measurements, the level of agreement shown in this analysis is reasonable.

Table 6. Matrix comparing agreement between areas of significant erosion, deposition, and no change as measured by geomorphic mapping from aerial photographs and photogrammetry from the same aerial photographs. Values are in percent of total area compared.

		Area determined by photogrammetry, in percent		
		Deposition	No change	Erosion
Area determined by geomorphic mapping, in percent	Deposition	**2**	13	*4*
	No change	10	**44**	17
	Erosion	*2*	4	**3**

Bold typeface indicates areas where the two methods are in agreement and italics indicate areas where the two methods substantially disagree. The total area compared is 21,405 m^2 and includes only fine-grained deposits as mapped by Sondossi (2000).

Comparison Between the 1996 and 1984 Photogrammetry

The 1996 photogrammetry data are slightly more accurate than the 1984 photogrammetry, based on comparison of GCPs. The average error in the coordinates of 5 GCPs for the 1996 photogrammetry in the X, Y, and Z directions was 11 cm, 20 cm, and 6 cm, respectively. For the same 5 GCPs in the 1984 photogrammetry, the errors in X, Y, and Z were 9, 25, and 19 cm, respectively. The implication of these accuracies is that no point computed in Ortho*MAX*™ can be expected to be any closer to its true X, Y, Z position than these results indicate. However, the reader should keep in mind that the relief in the study area of 840 m^2 is approximately 3 m.

The precision of any identified point in the 1984 photo was within 20 cm of its true location. We compared the coordinates of 30 points selected in the 1984 and 1996 photogrammetry and found that they differed by between 10 and 20 cm. The average differences in the X, Y and Z directions were 11 cm, 18 cm, and 18 cm, respectively. This means that by selecting as close to the same point as possible for each year, a small positional error is introduced into the analysis. Part of this error is due to human error because each of the GCPs and the 30 points in both years were selected by hand. Human error is difficult to separate from actual differences between the block adjustments for the 1996 and 1984 imagery.

Human Error

Another test was conducted to assess the human error associated with correctly identifying the locations of the GCPs using the stereo-goggles. To do this, three different skilled technicians selected the same 10 GCPs in the 1984 imagery and their coordinates were compared to the actual surveyed locations of the GCPs.

In selecting GCPs, it was found that skilled technicians deviated from the true position of the GCPs by an average of 30 cm in the X, Y, and Z directories. The histogram of the error for all technicians in the X, Y, and Z directions show that the amount of error fluctuates greatly (Fig. 27). This is a significant finding, because the entire triangulation process depends on being able to accurately determine the location of the GCPs. Accurate placement of the GCPs depended on how well each technician was able to select the exact spot in which the survey rod was held from an oblique photograph taken using a 35 mm camera during the ground control survey. Although this error seems poor, it is primarily a reflection of techniques employed when the GCPs were originally established. The systematic bias of the MCS may also be a result of human error, however the cause of this bias is unknown since 4 different technicians independently evaluated that surface.

DISCUSSION

Manual and Automatic Surface Generation

Overall, both the manually and automatically generated surfaces were quite accurate in relation to the field survey. Although these methods did not reach the standards of traditional survey methods, they did reach a high level of accuracy. Thus, both methods have great potential to have a significant impact on the way that historical data in Grand Canyon are analyzed.

However, the accuracy and precision of the manual and automatic methods varied depending on what features were examined. The manual method produced much more realistic topographic contours, but introduced the opportunity to have systematic error. The automatic method excelled by creating topographic surfaces that agreed with the field survey over 96% of the surface. The automatic method also produced volume estimates within 10% of the surveyed volume. On a point-by-point analysis, both methods were actually very similar, with neither method noticeably better.

These findings are surprising, because many of the points that Ortho*MAX*™ automatically generates do not seem to truly capture the surface topography. When viewed in stereo, points often appear to be embedded or floating above the surface by up to 2 meters or more. In many instances, the software seemed to have become confused by vegetation, rocks, and other abrupt elevation changes. The contours also varied in quality; at some points they appeared to follow the surface closely, while at others they deviated substantially.

There are several possible ways to explain why the automatic surface was more accurate in respect to overall topography and volume calculations than the manual method. One possible explanation is that the higher density of points essentially disguises poor points and causes the overall surface to average out and be quite accurate. Another possible explanation for the high degree of accuracy obtained for the automatic surface is related to the area compared in this study. Because the area tested was gently sloping, contains few large rocks, and has little vegetation, the site represents essentially the most ideal condition under which the computer can automatically collect points. Finally, the better estimates for the volume of sand produced by the automatic method may be somewhat fictitious. The ACS may only appear to be a better estimator of volume because Ortho*MAX*™ created errors that both underestimated and overestimated the elevation of the sandbar. Thus, the "holes" and "hills" it created average out and are closer to the surveyed volume.

In the end, an integrated approach, which makes use of the benefits of both methods is probably the best strategy in applying softcopy photogrammetry to historical analysis of Grand Canyon sandbars. A skilled technician is an essential part of the digital photogrammetry process, because a technician is not likely to mistakenly place a point meant to represent the surface of the sandbar in the top of a tree or other similar errors. A technician can also better judge where points are needed to accurately map abrupt changes in a surface by either placing more points or creating breaklines. However, since the automatic method is much faster and cheaper, and on the whole more accurate, it makes sense to use Ortho*MAX*™ to quickly generate a surface. Technicians can then judiciously evaluate and edit the automatically generated topography to create the most representative surface possible. By using this integrated approach, there exists the potential to rapidly and accurately monitor on-going and historical changes in sandbar topography in Grand Canyon.

Accuracy of Digital Photogrammetry in the Grand Canyon Ecosystem

The level of accuracy that we obtained in this test photogrammetry study varied considerably between the different photo series analyzed and the type of test performed. The results of these tests are summarized in Table 7. The test of GCPs not used in image registration indicated average position errors of about 20 cm (3.4 pixels) and average elevation errors of about

6 cm (1.0 pixels) for the 1996 images, and somewhat less for the 1984 images (Table 7). This test measures the error between the coordinates of GCPs surveyed in the field and coordinates of the same points identified in the ortho-rectified images by a technician. We found that the human error involved in identifying the GCPs averaged 30 cm (Fig. 28). Unless this error can be reduced significantly, better positional accuracy is very unlikely.

Table 7. Summary of accuracy assements applied to the photogrammetric models of the sand bar.

Attribute	Manual Oct-84	Automatic Oct-84	Automatic Mar-96	Automatic Sep-96
Scale of photos	1:3000	1:3000	1:4800	1:4800
Scanned pixel size	4 cm	4 cm	5 cm	5 cm
RMS error (interior orientation)	5.5 - 7.8	5.5 - 7.8	--	--
RMS error (exterior orientation/block adjustment)	0.78	0.78	0.74	0.87
GCP check (X and Y directions)	25 cm	25 cm	20 cm	20 cm
GCP check (Z direction)	19 cm	19 cm	6 cm	6 cm
Spot elevations*	79	80	42	81
Topographic surface†	84	96	50	85
Volume calculations**	-21	-8	26	7
Change detection, percent agreement	na	na	62	

* Percent within 25 cm (1984) or 30 cm (1996) of surveyed coordinates.
† Percent of sand bar area where photogrammetric surface was within 25 cm (1984) or 30 cm (1996) of surveyed surface.
** Percent volume differs from surveyed volume above common datum, a positive value indicates overestimate of volume.

Accuracy was even less in most of the tests comparing ground-surveyed measurements of the separation bar to the photogrammetric models. With the exception of the March 1996 image, the photogrammetric surfaces were within 25 – 30 cm of the surveyed surfaces over more than 84% of the bar area (Table 7). In measuring erosion and deposition following the 1996 experimental flood, the photogrammetric method agreed with the topographic measurements over 62% of the area compared (Table 7). The spatial distribution of agreement indicates that the photogrammetric method tended to overestimate erosion and underestimate deposition. These results indicate that the photogrammetry was not as accurate as the ground-based topographic surveys.

The level of detail and accuracy demonstrated here could be used to monitor large-scale changes in sand bars over long reaches. Although we used 16 GCPs in the rectification of the 1996 photos, we achieved similar accuracy with only 6 GCPs in the 1984 photos. We estimate that 6 – 10 GCPs per km would be sufficient control to rectify and process images at approximately the accuracy achieved in this study. This photogrammetric method determined areas of erosion, deposition, and no change at a spatial accuracy comparable with that achieved by geomorphic mapping of Schmidt et al. (1999) and Sondossi and Schmidt (2000). The advantage of the photogrammetric method compared to geomorphic mapping is that it quantifies depth of erosion and deposition and can be used to make volume estimates. The photogrammetric method, however, cannot be applied to older (pre-1984) photographs that Schmidt et al. (1999) and Sondossi (2000) have used to compare the pre-dam distribution of deposits with present because resolution is poor, and detailed flight and camera information are not available. The feasibility of extending the methods used in this study over long reaches are discussed below.

This study also demonstrates the utility of photogrammetry in examining existing photographs. The 1984 and 1996 photos were analyzed in the same manor and any existing air photos for which detailed flight and calibration information are available could be analyzed similarly with likely comparable accuracy. This approach would probably be best suited to answer specific research questions at specific study sites.

Sources of Error

Location and Placement of GCPs

Precise location and placement of GCPs is essential. Errors in this step will affect accuracy at every stage of the photogrammetry process. We identified that the human error associated with identifying the precise location of a GCP on the digital image is significant (30 cm, or 5-6 pixels). This error can be compounded, depending on the type of GCPs that are used. For this study, many of the GCP's were taken on top of rocks, or on the edge of a rock, because these are the most stable points over time and the points most accurately identified on photos. Our positional accuracy was between 3 – 6 pixels in the X – Y direction. In many cases, this will cause the measured GCPs to be shifted off the rock and to 'float' above the surface of the rock. We had consistently better results from the GCPs that were taken on flat rocks near the bar surface. Although use of surface GCPs may provide better accuracy, it risks loss of the control points if they are buried by sand or debris-flow deposits.

Irregular Topographic Features and Vegetation Coverage

Large boulders or bushes that become incorporated in the photogrammetrically-generated surface and lead to inaccurate surfaces and poor volume estimates. This error can be reduced by manually removing these features from the TIN model. We found that removal of the largest of these features from the area of the sand-bar study site reduced the volume estimate by about 19%. The photogrammetric surfaces with vegetation and boulders removed was used in our analysis of the sand bar study site, but not in our analysis for the entire reach. In locations where vegetation cover completely obscures the ground surface over large areas, correction in these areas will be difficult. In these areas, photogrammetric methods would have to ignore areas of dense vegetation and map change only in areas where the ground surface is visible. Using color or color infrared imagery, areas of vegetation could be easily identified and mapped in an automated or semi-automated mode. Even if topography beneath vegetation could not be mapped, the area of vegetation cover could be tracked.

Image Quality

Some of the errors encountered in this analysis may result from the partial shadows in the 1996 imagery. This source of error could be reduced or eliminated by acquiring photos when shadows are smallest, which would be in the months of May, June, and July at the correct time of day.

Submerged Deposits

Measurements of changes to submerged sandbars offshore also are problematic using the digital photogrammetric method. In areas where the water surface was smooth and little reflection occurred, the Ortho*MAX™* software was able to generate fairly accurate subsurface estimates to any depth at which bottom features can be seen. If submerged deposits can be seen in the photos, these areas could be collected using the manual technique of collecting the TIN. However, for the most part, surface reflection existed and mapping of areas below the waterline was impossible. As a result, mapping of low- flows is limited unless the water level is below or at the low-flow level at the time of photo acquisition, another consideration when planning an overflight.

Estimates of Time and Cost

Photogrammetric analysis using the methods in this study has initial costs of hardware, software, and the training of skilled technicians. The Ortho*MAX™* software that we used costs between $25,000-$30,000 and needs a computer system costing approximately $13,000. Stereo goggles cost an additional $5000. There are also $3000-$5000 annual software maintenance fees.

Cost of the aerial photo acquisition must be considered if this method is to be compared with terrestrial survey techniques. The photos used in this study coast approximately $65,000 per photo series for complete coverage of the 470 km reach of the Colorado River Ecosystem. If annual aerial photography flights are to be made, the added cost to use these images for photogrammetry analysis is only the $20 per frame cost of high-resolution scanning.

There exists a fairly steep learning curve for the training of personnel on this software; however, we estimate the time per stereopair for all of the Ortho*MAX*™ work as well as analysis of the results (similar to that conducted in this project) is approximately 20 hours (Table 8). More than twice as much time is needed to generate manually created topographic surfaces. The costs of experienced technicians would also be reflected in the overall project costs. Although we used experienced technicians on this project, the nature of the geographical setting introduced many parameters not encountered before which resulted in a great deal of initial experimentation until it was felt all possibilities had been tested.

Table 8. Estimate of time needed for each step in processing a stereo pair (two photos). Does not include analysis, interpretation, or report writing.

Task	Time estimate (hours)	
	Auto (ACS)	Manual (MCS)
Project initialization and setup	1	1
Aerotriangulation	6	6
Stereopair generation	2	2
TIN surface generation (auto or manual)	2	40
TIN cleanup	5	5
Orthophoto generation	2	2
Orthophoto mosaics	2	2
TOTAL	20	58

Considerations and Recommendations

Application of Photogrammetry to Longer Reaches

The methods used in this pilot study could be applied to longer reaches to develop more quantitative histories of sand storage than are currently available. One of the advantages to this method is the ability to create historical models indicating patterns of change. This process allows for the continual updating of data through time, as well as the incorporation of historical photos in digital format using the previously surveyed GCPs. This ability to eliminate the need for continual ground surveying during each new monitoring period would certainly reduce the time, cost, and human-impact factors associated with survey trips in Grand Canyon. We estimate that 5 to 10 GCPs per km would be sufficient using 1:4800 scale photographs, as used in this study.

The use of historical photographs is limited, however, to those photos for which detailed information is available. In order for the aerotriangulation to be conducted on the stereo pairs, flight calibration information for each flight must be obtained. This information includes such details as focal length, lens distortion, calibrated principal point and fiducial mark coordinates. These calibration reports are usually obtained through the USGS but are often difficult to locate or do not exist for imagery acquired prior to 1970.

Based on our current time estimates a project of this scale could be expected to take about 3 months per 10 km reach per photo series (at 1:4800). Thus, in a 1-yr project, it should be possible to map and analyze one reach for four years of coverage.

Ground Surveys

As one of the critical aspects of this work is the ground-control, there would need to be one detailed ground survey done for every area to be mapped from the air photos, whether using rocks or panels for GCPs. (This could cover one-to- several stereo pairs depending on the scale of the air photos.) Additionally, there is a strong need for the surveyors and the photogrammetrist to both be present in the field during the collection of these points when rocks are used as the GCPs, so as to assure the correct positioning of these points by the photogrammetrist once back in the lab. Once the ground control is collected, these points can be used for past or future flights for aerial photo acquisition, but the initial survey is necessary. There are two conditions under which this technique would not perform well, however, and both are particular to sandbars in the Grand Canyon: areas of dense vegetation (where the top of the canopy would be recorded as the surface elevation), and areas of deep shadow where topographic details appear to be lost or blurred.

Use of Digital Photography

The use of digital imagery, or digital camera technology, should also be explored for its cost and accuracy components. Using digital camera technology for doing this type of mapping work could certainly be beneficial in the sense that it would cut out the need to acquire contact prints and diapositives, and eliminates the need to scan these materials. The problem with this method is that digital cameras currently cannot collect a sufficiently high resolution required for this process, especially since imagery needs to be collected in stereo (for this technology, this means more data storage at a faster rate). The collection of digital imagery has many potential benefits – faster processing time, the elimination of many of the preprocessing steps mentioned above – but currently the digital imaging technology is not well-enough developed to acquire good quality data in areas where there is both sunlight and shadow. Digital cameras balance the images literally on-the-fly to derive the 'ideal' image. In a situation where sunlight and shadow exist in the same frame, the sunlit areas will look fine, while the shadow areas are nearly black. Features in shadow would be virtually impossible to detect.

Approaches to Improved Accuracy

There are several strategies which may be used to improve the accuracy beyond that achieved in this study. Since precisely locating the GCPs was a substantial problem, other improvements may not boost accuracy if this cannot be addressed. Our analyses of the 1984 and 1996 photos were both essentially historical studies. The studies referenced in our literature review that achieved higher pixel-level accuracy were all studies utilizing air photos flown expressly for the photogrammetric study. Although the photos used in this study were of good quality, using rocks instead of GCPs may be a significant source of error. Ground panels have two significant advantages with respect to accuracy. First, the "X" pattern allows precise location of the cursor on the screen and will look the same from any angle. A point on a rock is less distinct and can appear different from the different angles in the photograph pairs. A second advantage is that the photo panel can be located on the flat ground surface, where small position errors will not result in equal or larger elevation errors. Although the use of panels may be impractical or even infeasible in the Grand Canyon ecosystem, it is possible that without panels, it may be difficult to significantly improve accuracy.

Another way to improve accuracy is to use larger scale photographs that when scanned at the same 12 micron resolution used in this study will have a smaller pixel size. Based on the accuracy we achieved with a 5-cm pixel size, an image resolution with 2-cm pixels would be needed to provide good accuracy at the ±10 cm level. Aerial photographs with a nominal scale of approximately 1:1600 would be required to achieve this resolution. This estimate assumes that all the errors stay at the same pixel level (i.e. GCPs can be identified to within 5 pixels, which would be 10 cm).

Alternatively, different methods of image correlation may be used to improve the accuracy of change-detection analyses without necessarily improving the accuracy of individual topographic surfaces compared to ground-based measurements. In this strategy, the accuracy of image-to-image correlation is improved, and the accuracy of the images to truth (ground control) is de-emphasized. Instead of independently registering each image to GCPs and using 10 to 20 additional tie points, images are correlated to one another using fewer GCPs and many more tie points. Using Ortho*MAX* ™, manually identifying dozens of tie points would be very time-consuming. We recommend exploring the use of software that uses automated routines to identify hundreds of tie points and filter them, using only the best matches in the correlation (Pat Chavez, US Geological Survey, Flagstaff, AZ, personal communication, 2000). Because the images are correlated using up to 100's of points, relative differences in elevation may be measured accurately, even if each individual surface does not correlate perfectly with ground-based measurements.

If the GCMRC wishes to push aerial photogrammetry to the limits of its accuracy, further evaluation studies are needed. This study included too many confounding factors to state with certainty that the highest possible accuracy was achieved or to identify with certainty the sources of greatest error. A more definitive study would include the following: (1) Use at least 2 study reaches, one in a relatively easy Grand Canyon reach and one in a more difficult section. The easy reach would be in an open section where vertical cliffs and shadows are not a problem and the difficult reach would be in a narrower canyon where cliffs and shadows are a problem and GCPs are more difficult to locate. (2) Acquire air photos specifically for the study and take them on the same day that ground surveys of the study reaches are made, eliminating change between measurements as a source of error. (3) Take photos at two different scales to enable determination of the minimum scale needed to achieve the desired 10-cm accuracy. We suggest photos at the standard 1:4800 scale and a set in the range of 1:1600 to 1:2000. (4) Use both flat panels and rocks for GCPs to enable a comparison between these methods of image registration. Be sure to use panels that are most appropriate for the scale of the photographs. Ideally, the GCPs and the ground-truth topographic survey would be made at the same time to reduce errors that may be caused by reprojections of the survey data.

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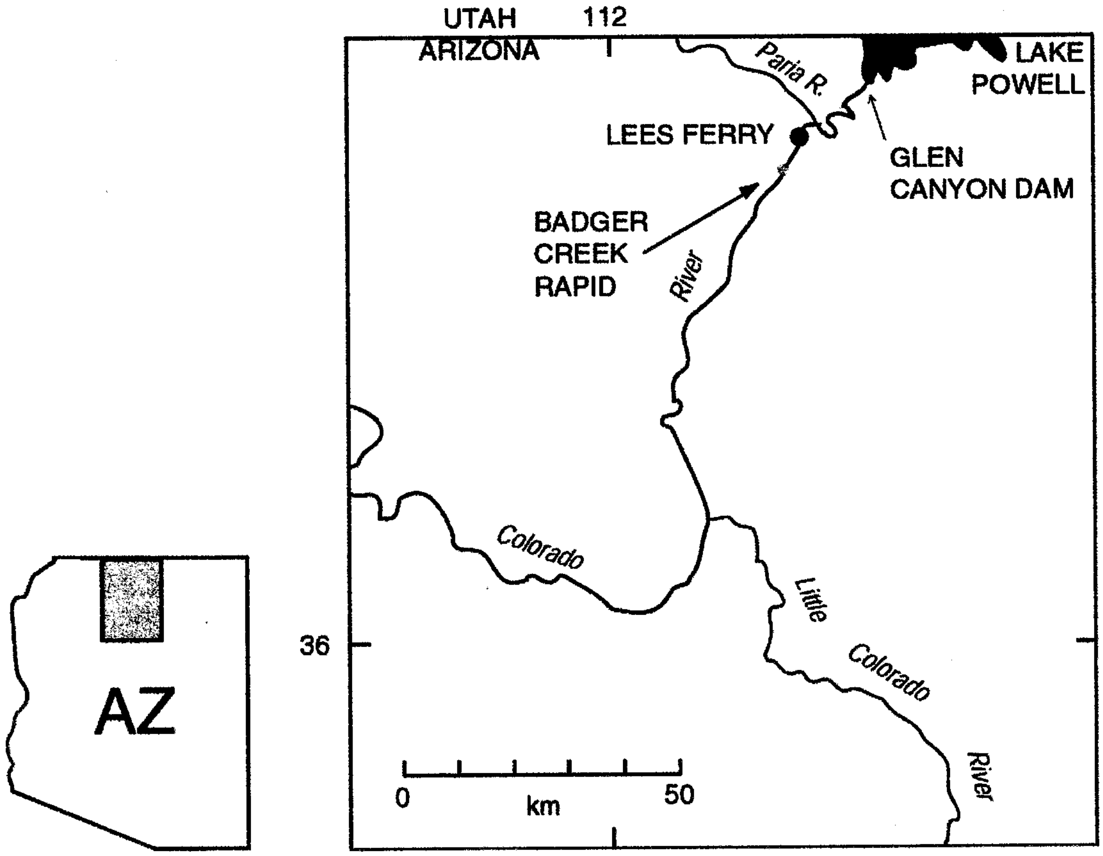


Figure 1. Location map of Badger Creek Rapids.

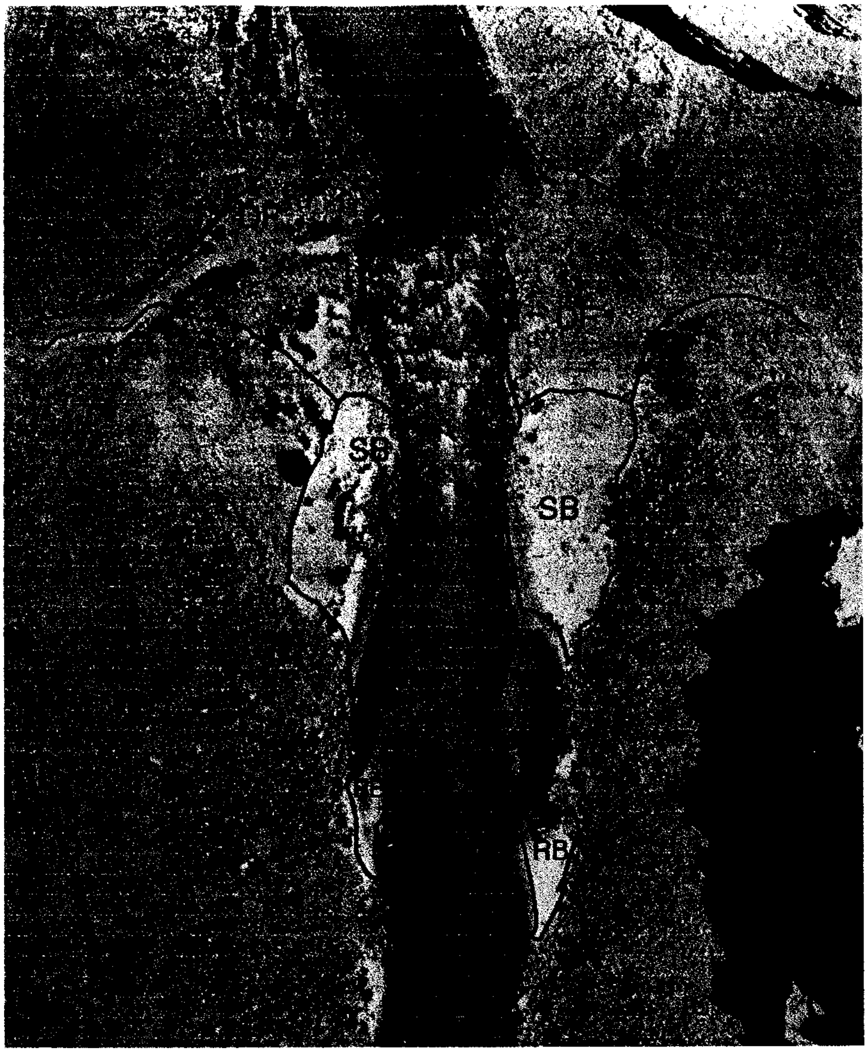


Figure 2. The fan-eddy complex at Badger Creek Rapids showing debris fans (DF), separation bars (SB) and reattachment bars (RB) as they existed June 16, 1973. The river is flowing from top to bottom in this photograph.

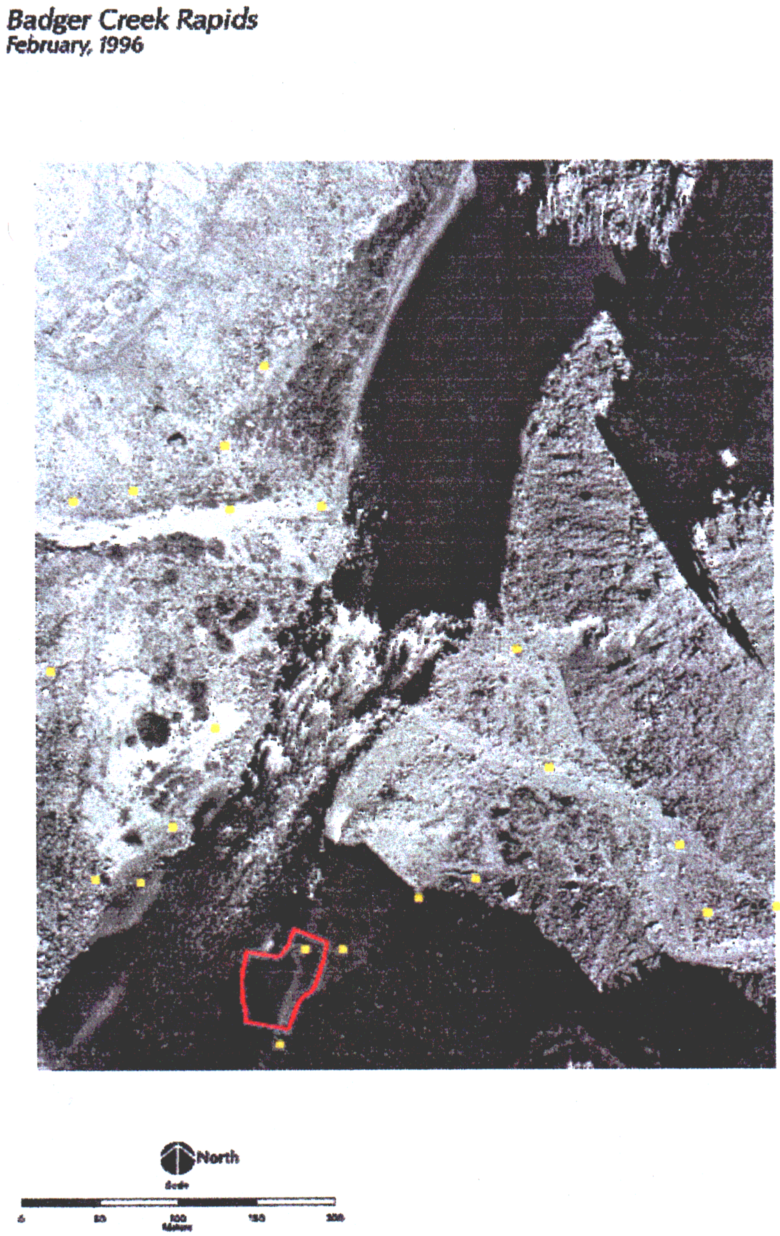


Figure 3. Orthorectified March 1996 photo showing the ground-control points used for the aerotriangulation of this and the September 1996 photo. The Northern Arizona University sand-bar monitoring site is outlined in red.

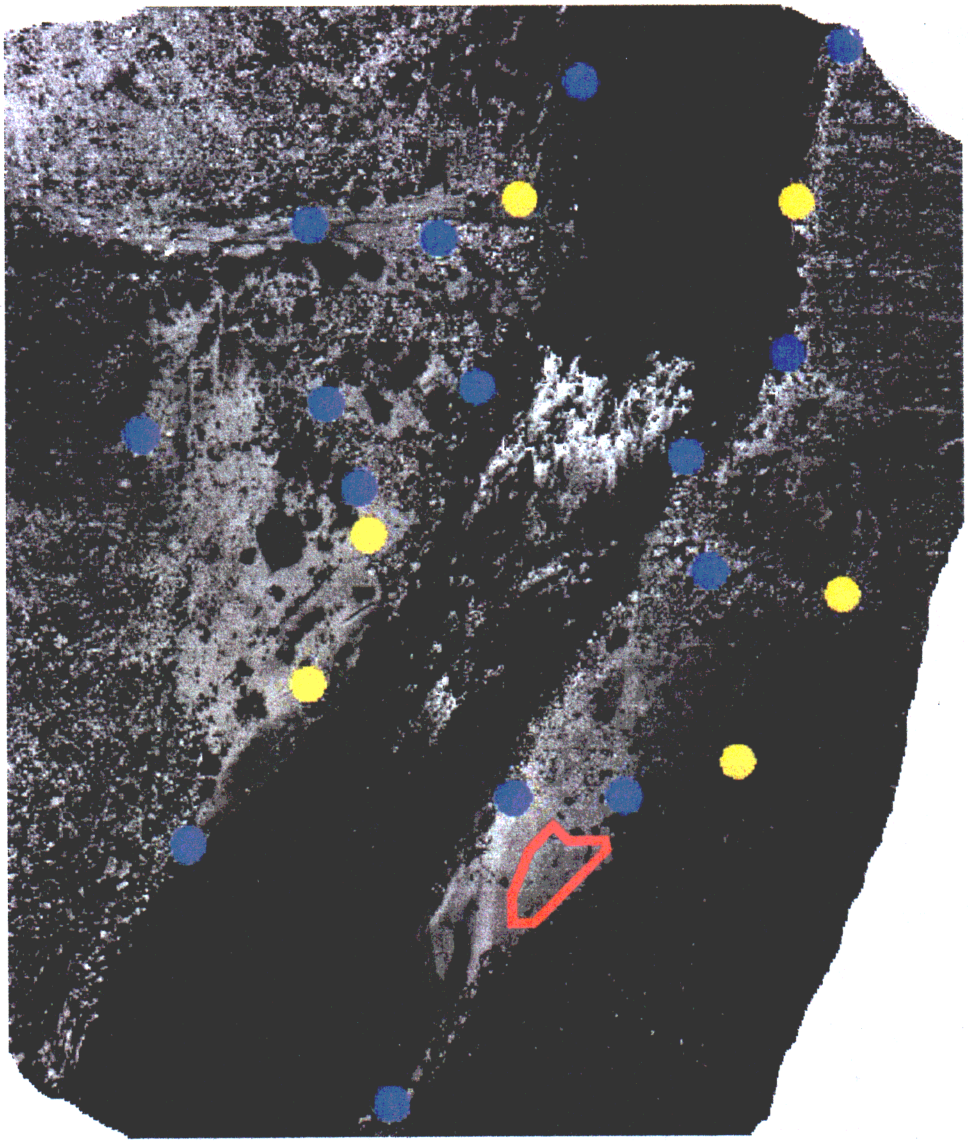
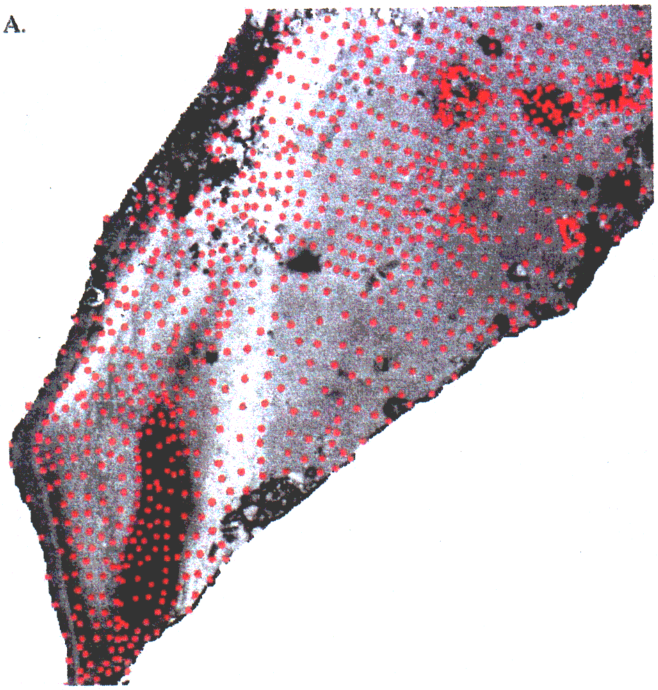


Figure 4. Image of the study area showing the distribution and location of ground control points (yellow) and tiepoints (blue) used in registering the 1984 photographs. The outlined area is the clipped region used in the change detection maps and volume calculations involving the 1984 photos and the 1985 topographic survey.

A.



B.

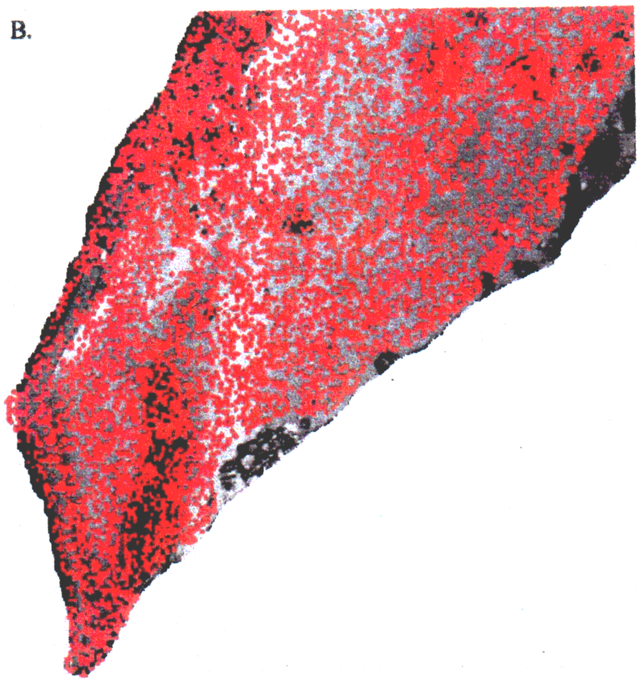


Figure 5. Image showing the manually (a) and automatically (b) collected points for the topography of the sand bar at Badger Creek Rapids from the 1984 photographs.

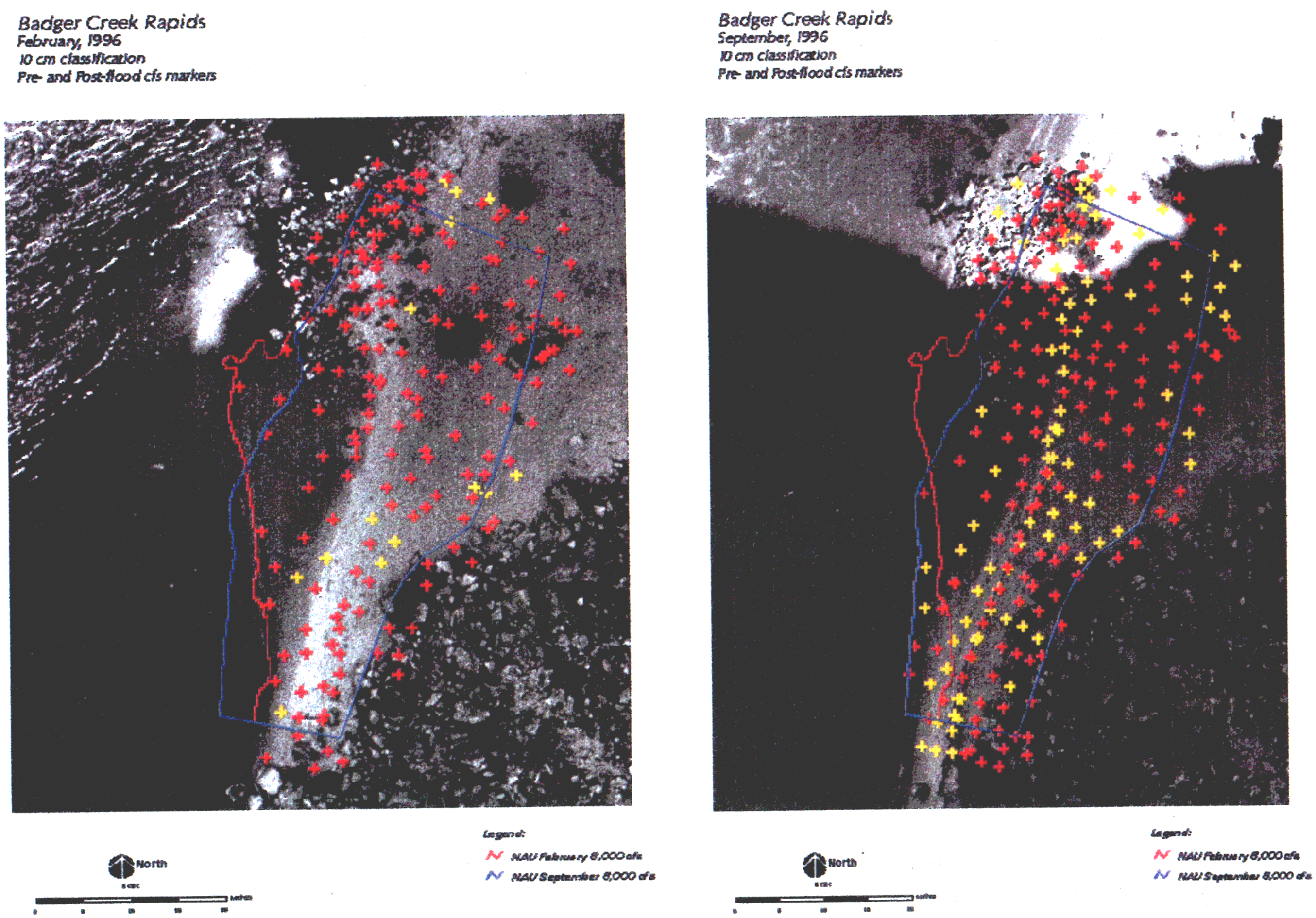


Figure 6. Comparison between elevations measured by topographic survey and photogrammetric methods. Yellow crosses show points where photogrammetric elevations were within 10 cm of surveyed elevations and the red crosses show points for which disagreement between elevations exceeded 10 cm.

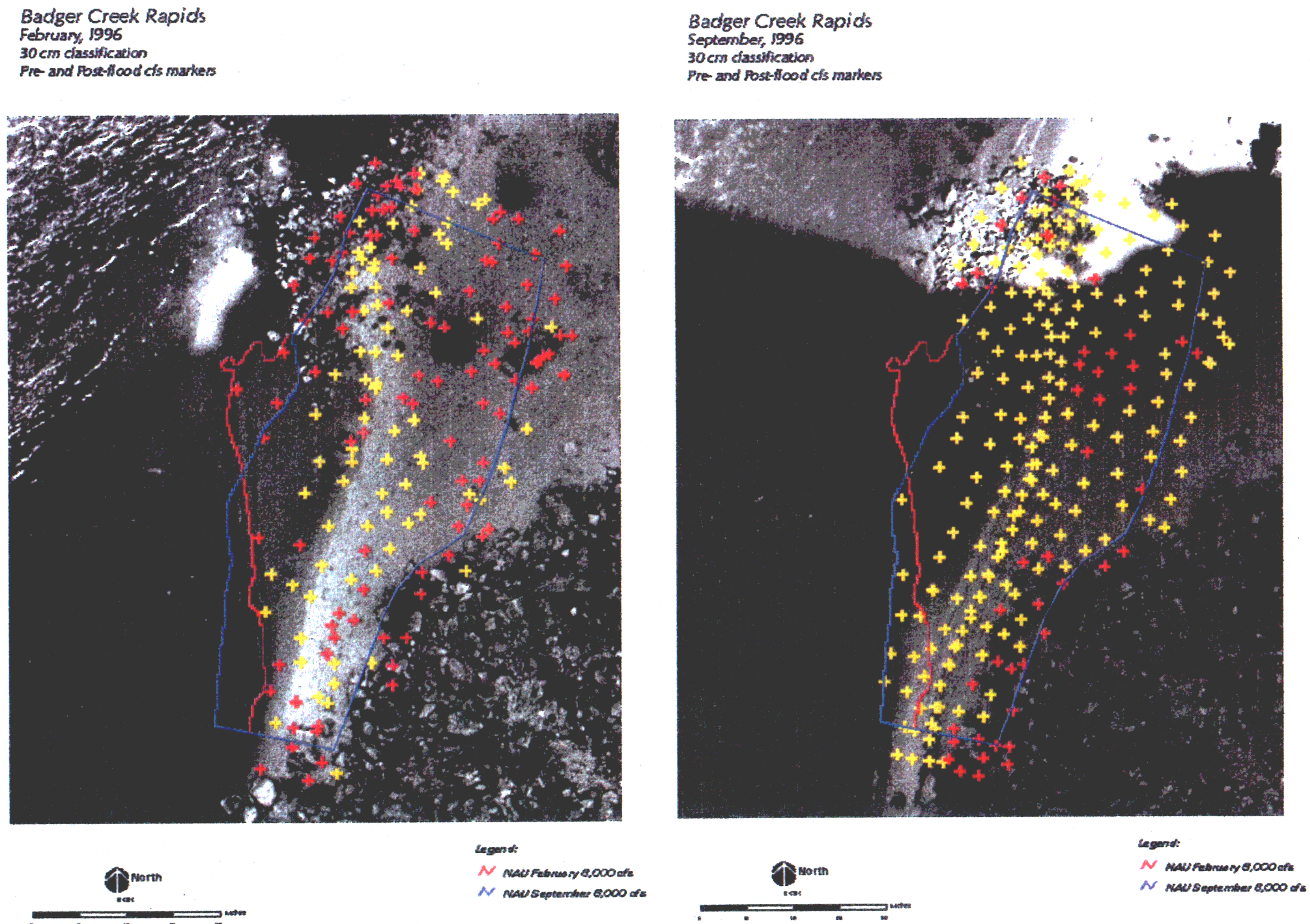


Figure 7. Comparison between elevations measured by topographic survey and photogrammetric methods. Yellow crosses show points where photogrammetric elevations were within 30 cm of surveyed elevations and the red crosses show points for which disagreement between elevations exceeded 30 cm.

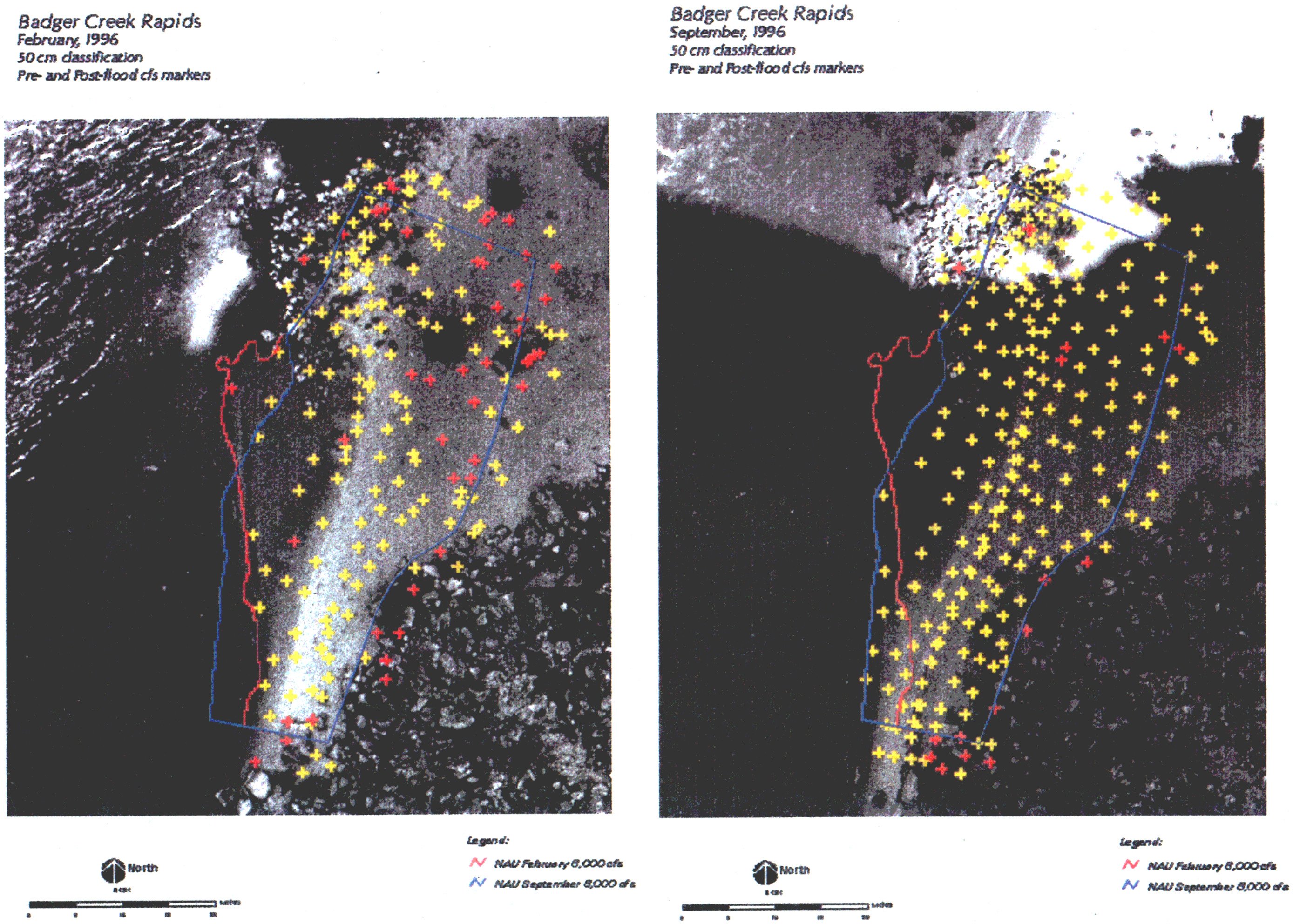


Figure 8. Comparison between elevations measured by topographic survey and photogrammetric methods. Yellow crosses show points where photogrammetric elevations were within 50 cm of surveyed elevations and the red crosses show points for which disagreement between elevations exceeded 50 cm.

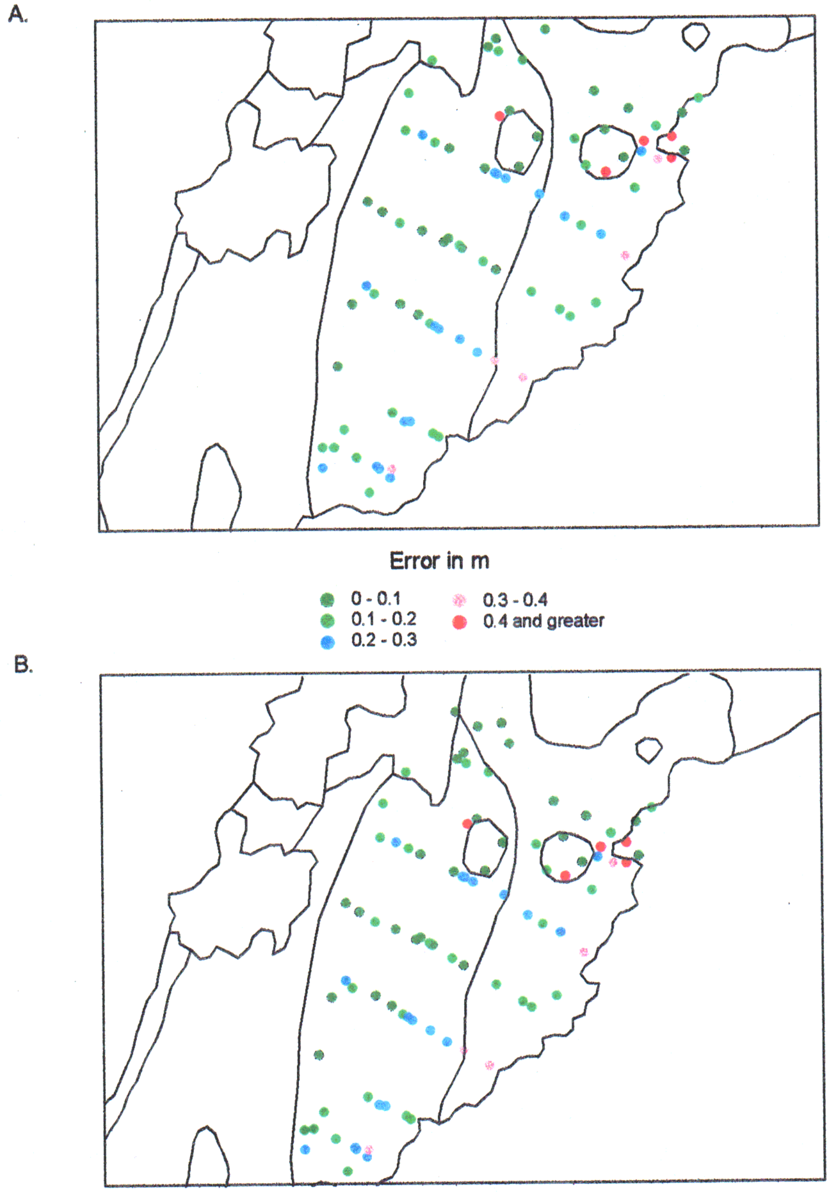


Figure 9. Maps of the 86 surveyed points and the amount of error for both the manual (A) and automatic surfaces (B).

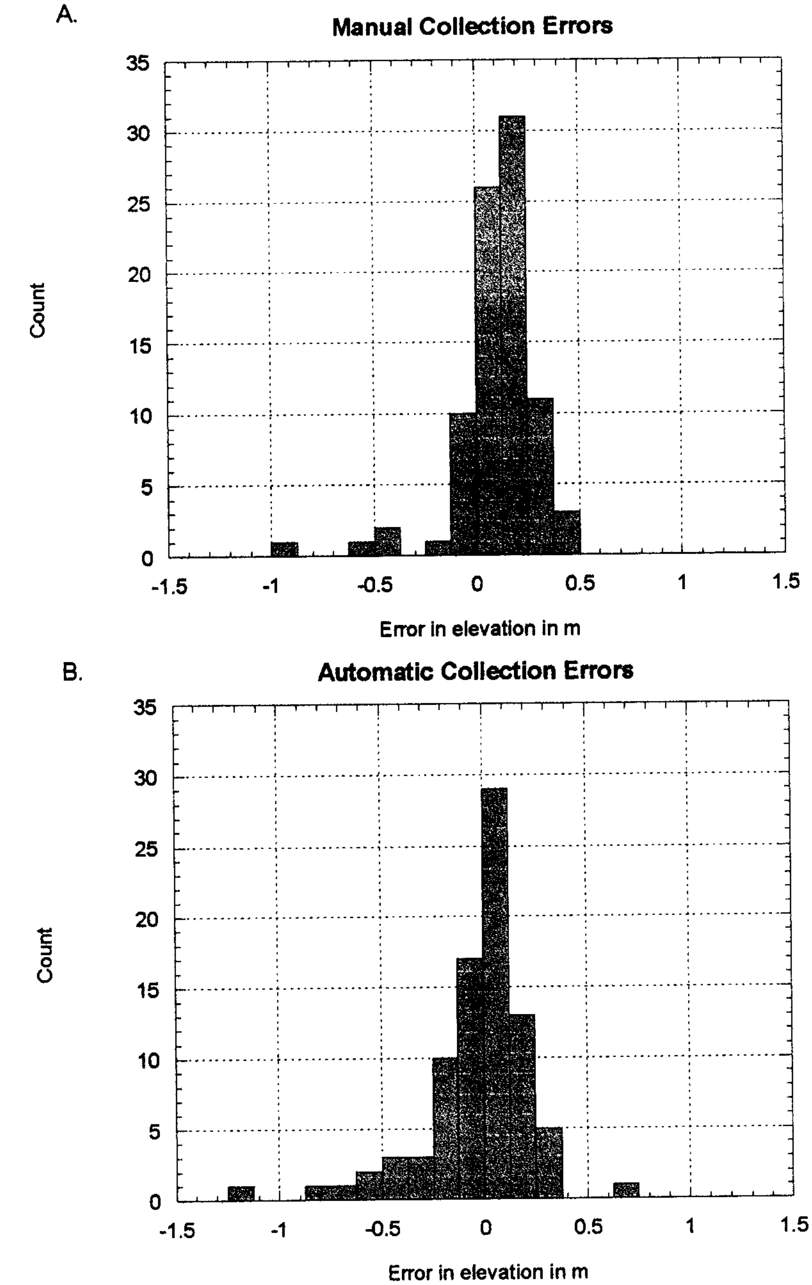
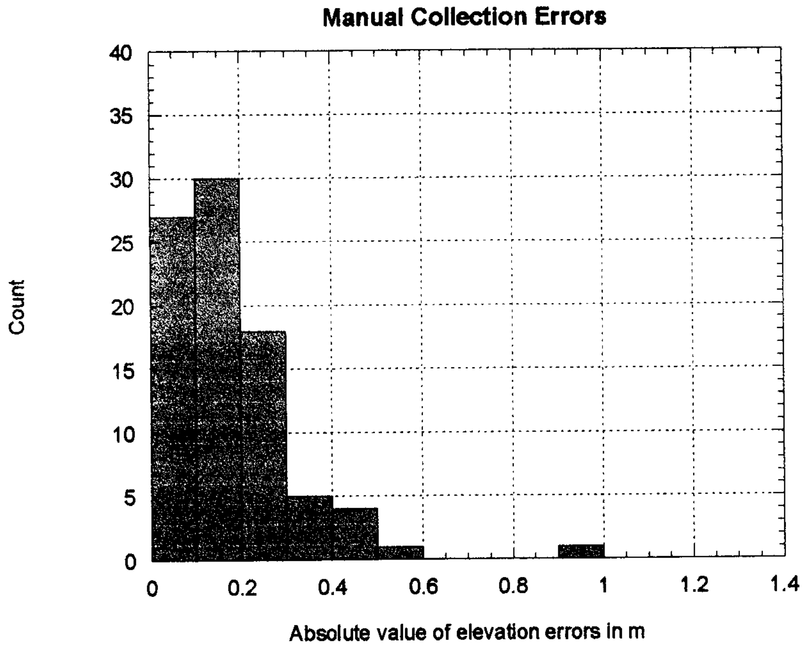


Figure 10. Histograms of the deviation of the elevation-values from their surveyed postion for the manually collected surface (a) and the automatically collected surface (b) for 86 points, using the 1984 images.

A.



B.

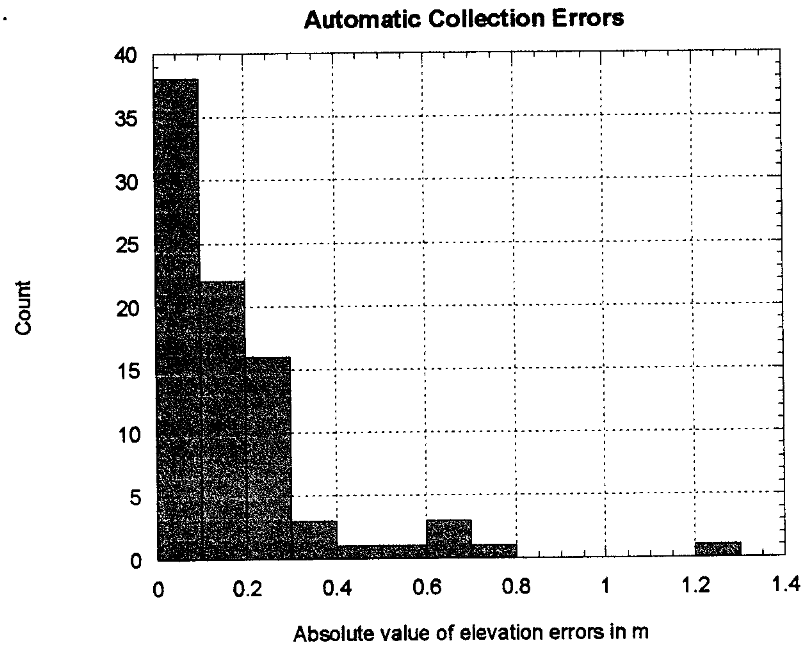


Figure 11. Histogram of the absolute value of the deviation of the elevation-values from their surveyed position for the manually collected surface (a) and the automatically collected surface (b) for 86 points on the 1984 images.

A.

B.

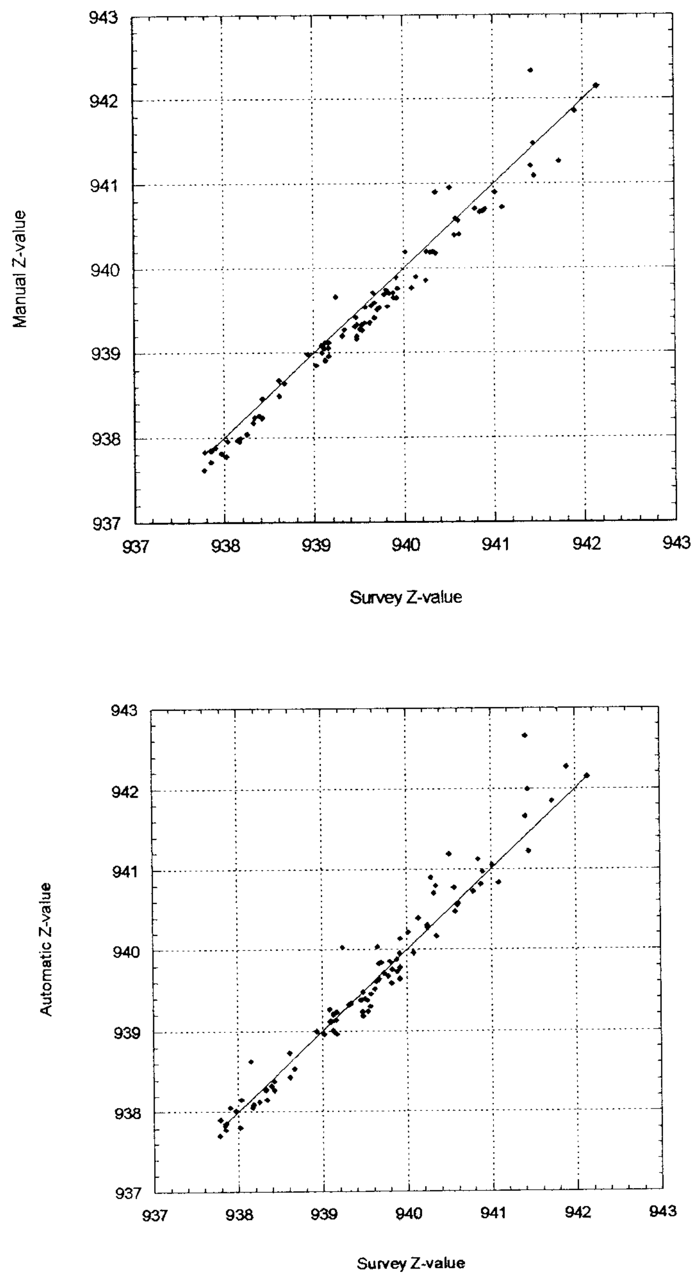
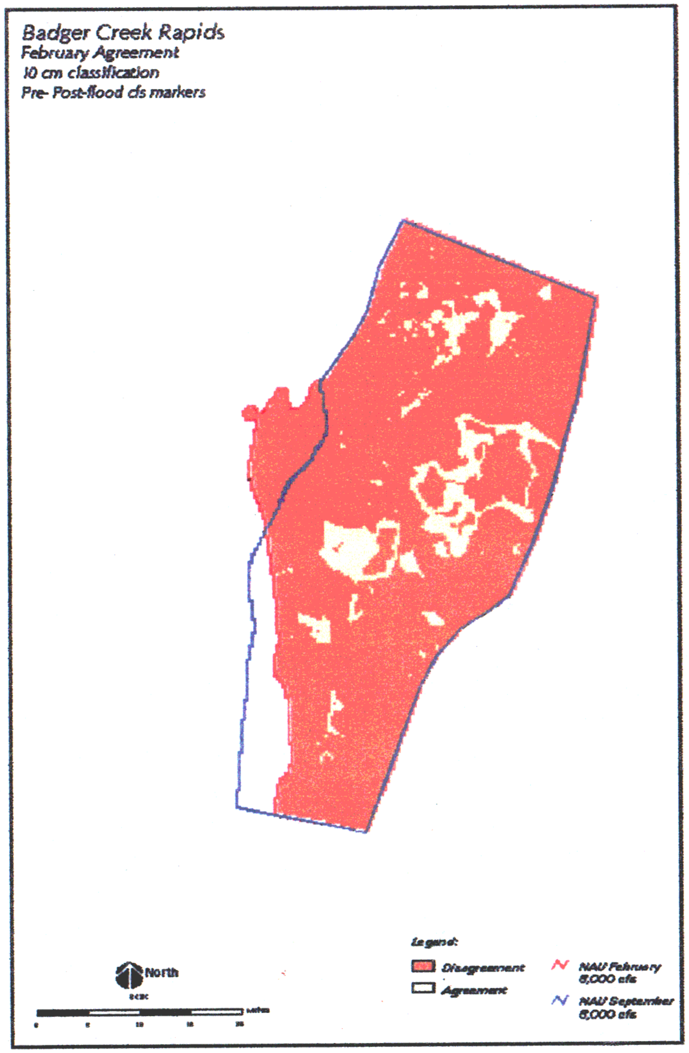


Figure 12. Regressions of the deviation of the Z-values from their surveyed position for the manually collected surface (a) and the automatically collected surface (b) for 86 points.



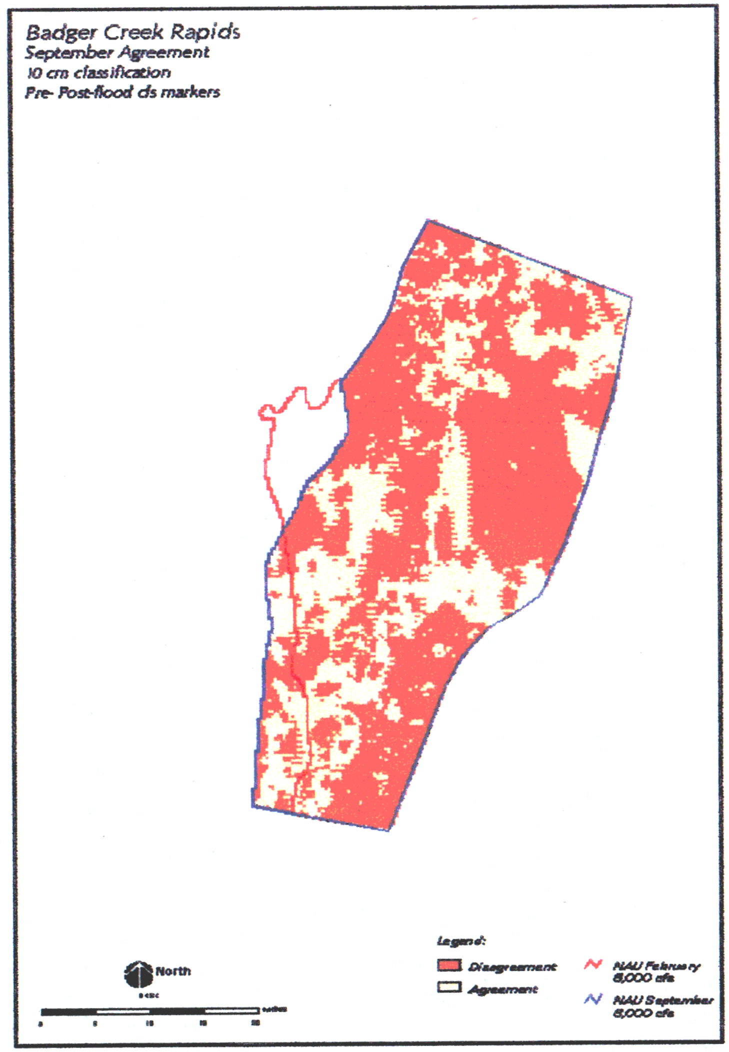
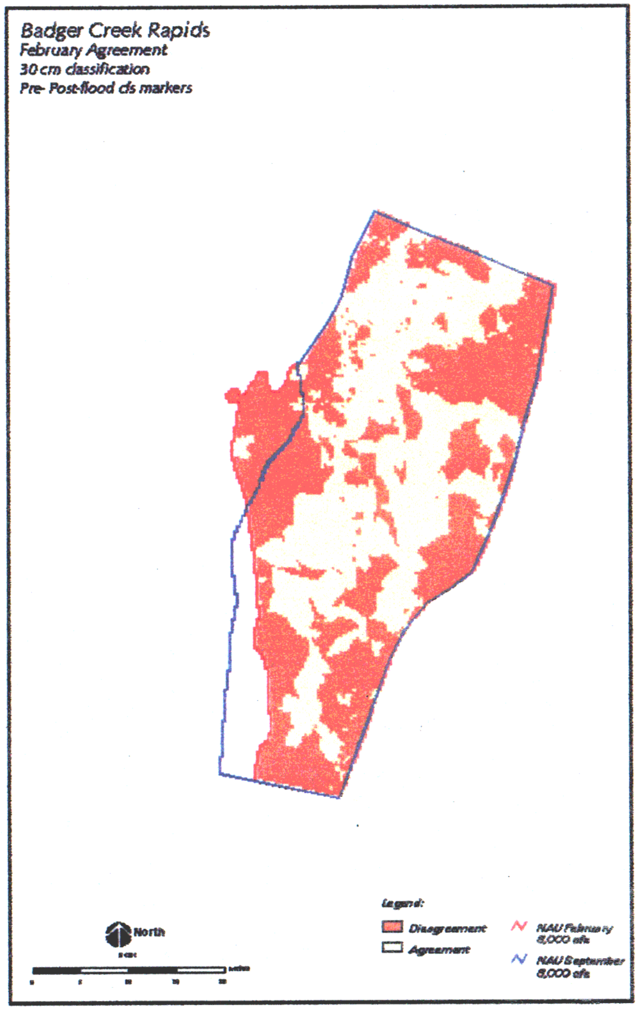


Figure 13. Maps showing areas where the photogrammetrically derived surface agrees with the surface created from ground-based topographic measurements within 10-cm.



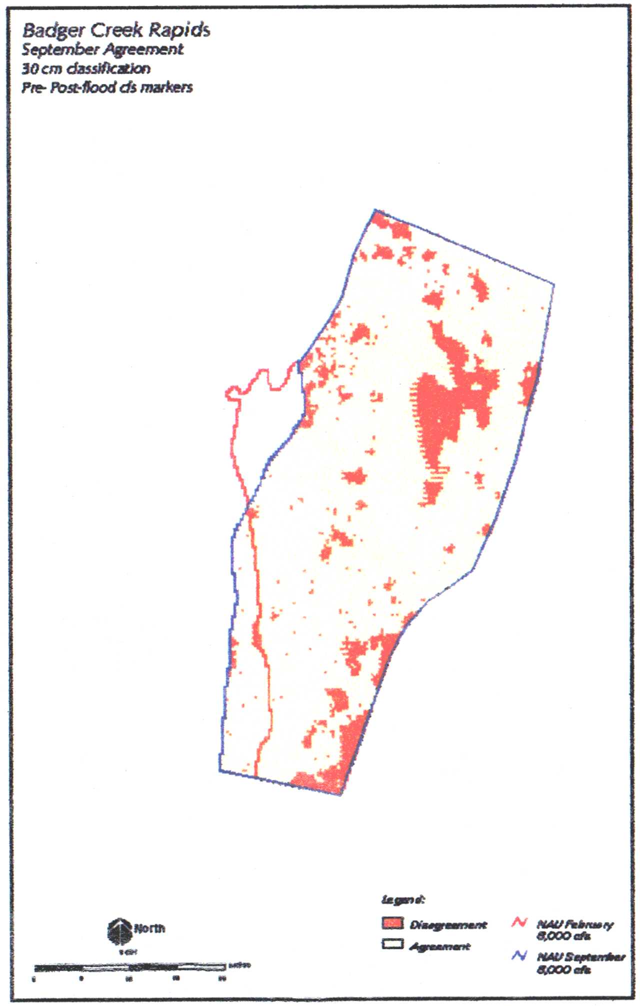


Figure 14. Maps showing areas where the photogrammetrically derived surface agrees with the surface created from ground-based topographic measurements within 30-cm.

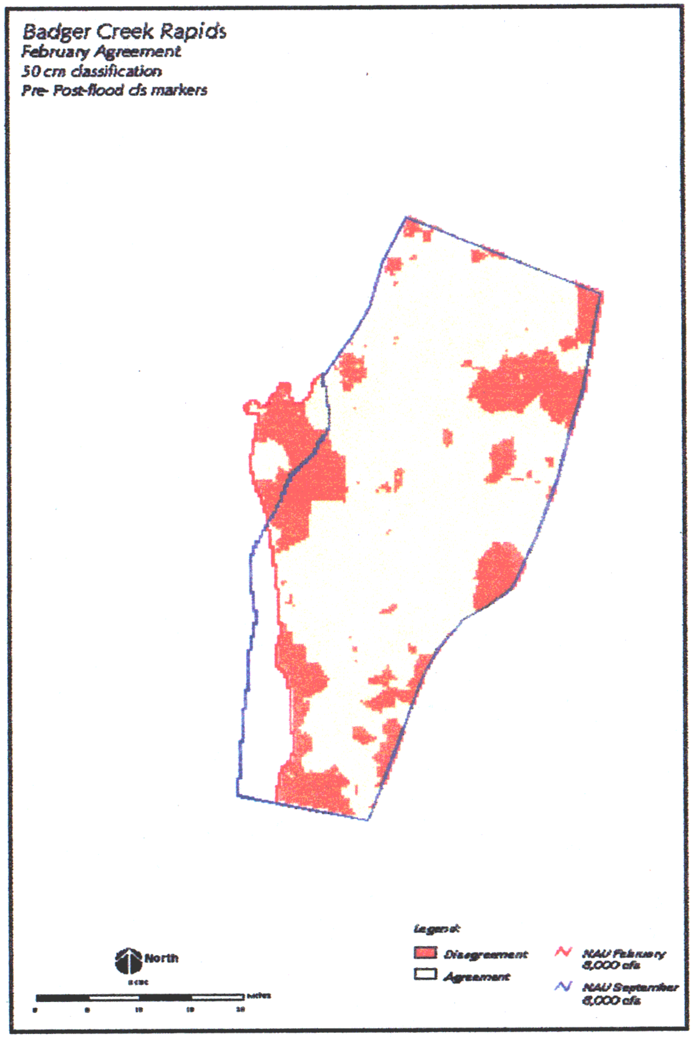


Figure 15. Maps showing areas where the photogrammetrically derived surface agrees with the surface created from ground-based topographic measurements within 50-cm.

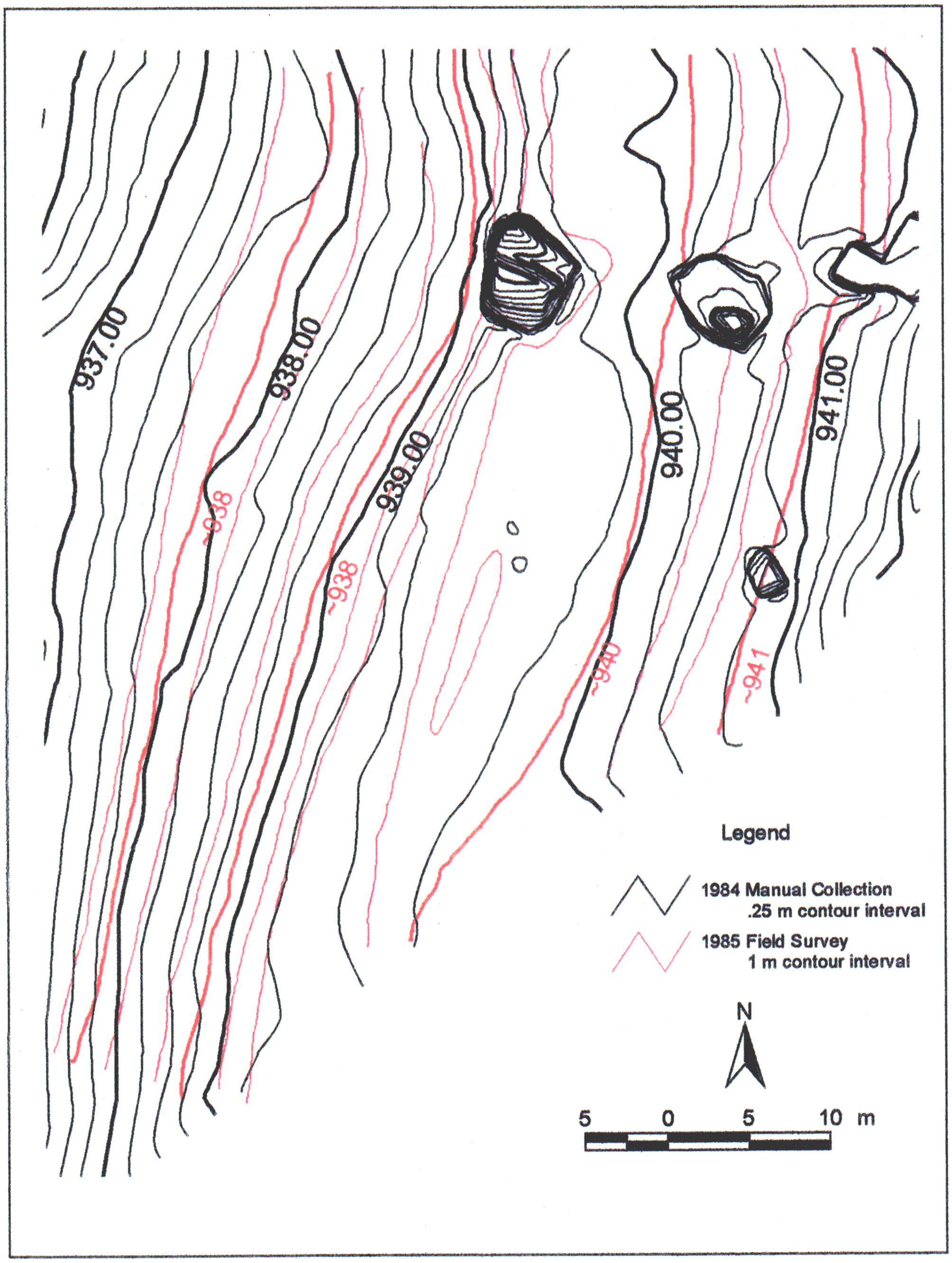


Figure 16. Map showing the manual and field survey contours.

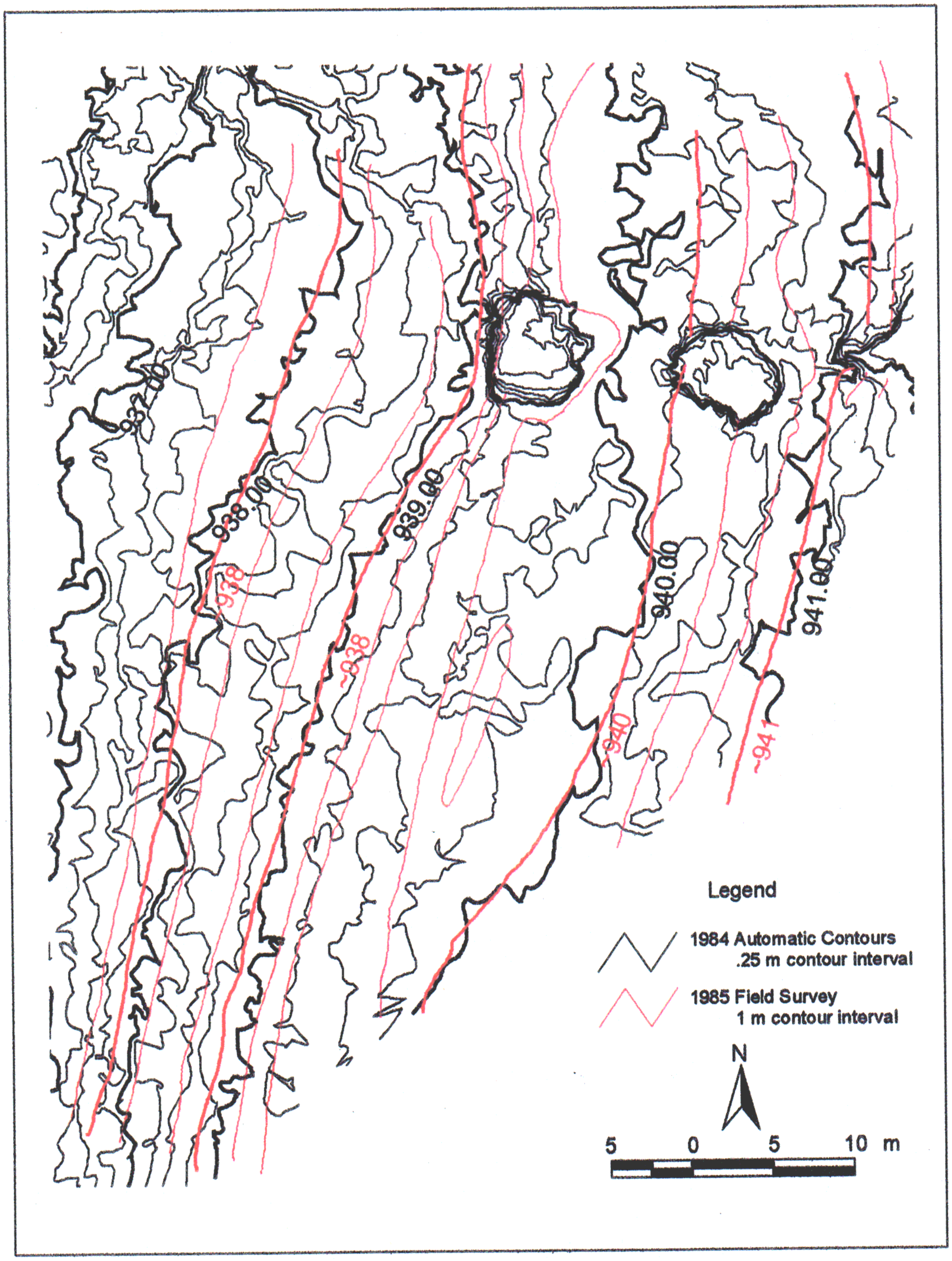


Figure 17. Map showing the automatic and field survey contours.

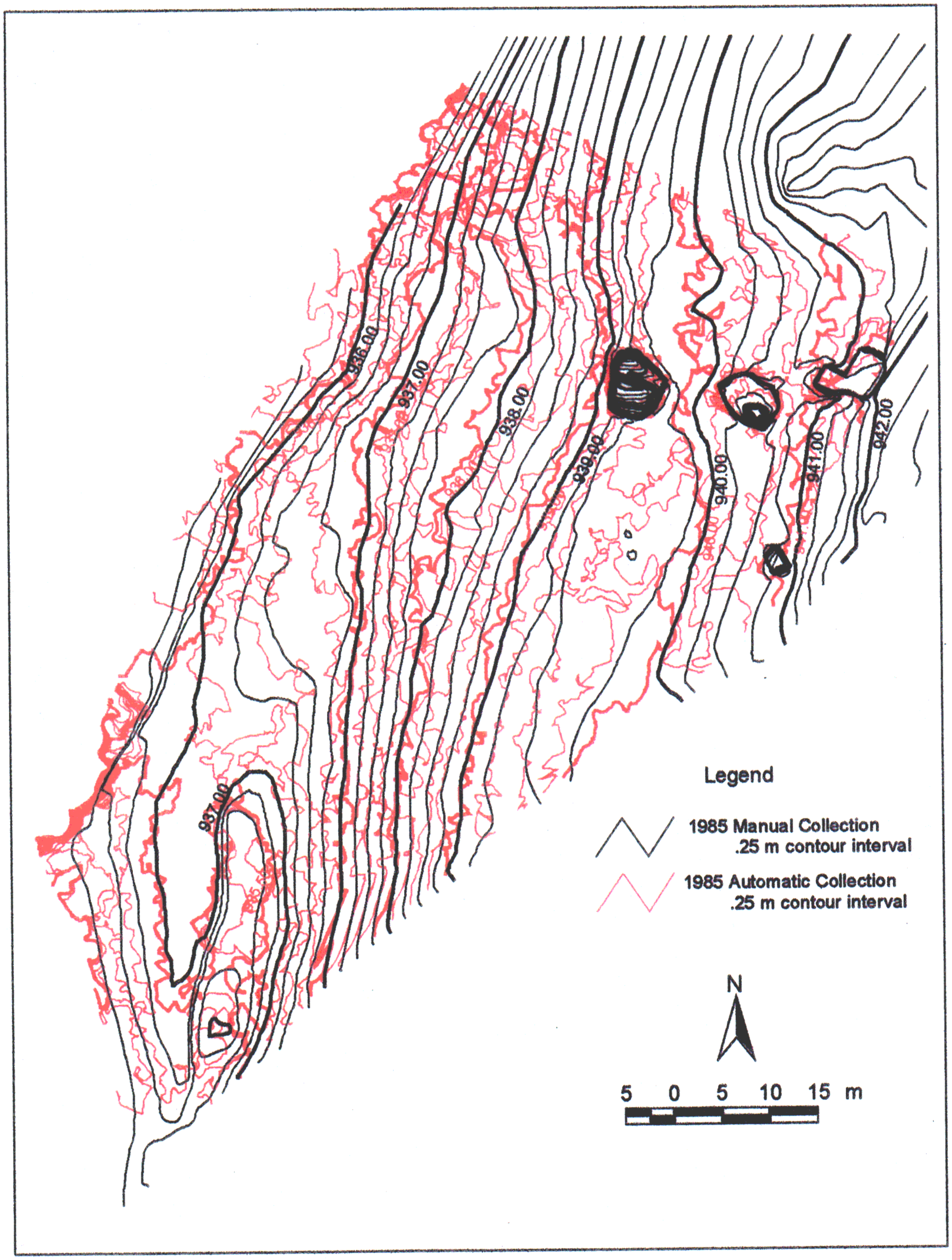


Figure 18. Map showing the manual and automatic contours for the entire sand bar.

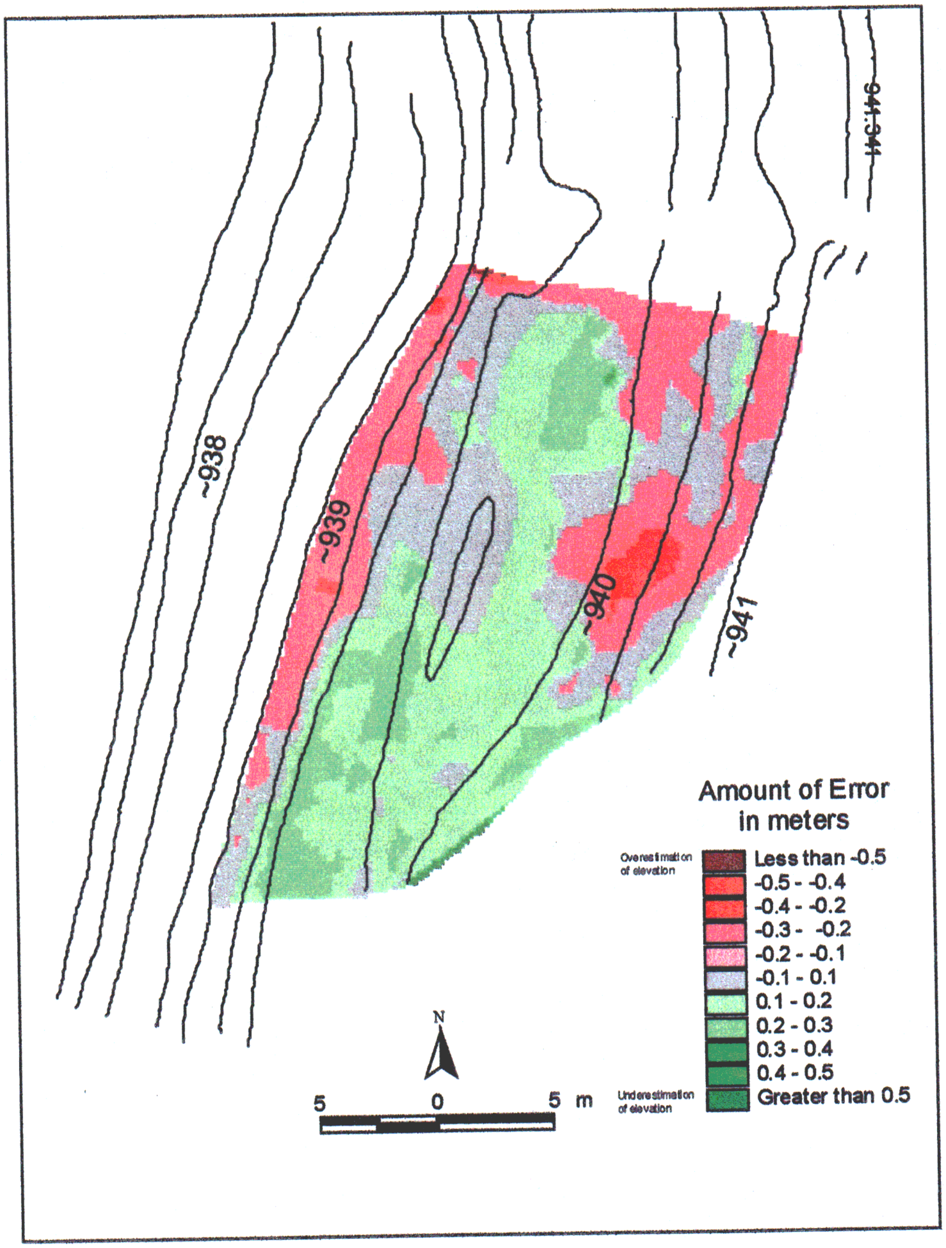


Figure 19. Map showing the error between the manually generated surface and the surveyed topography for Jackass Sand bar in October of 1984. The contours are from the survey field map.

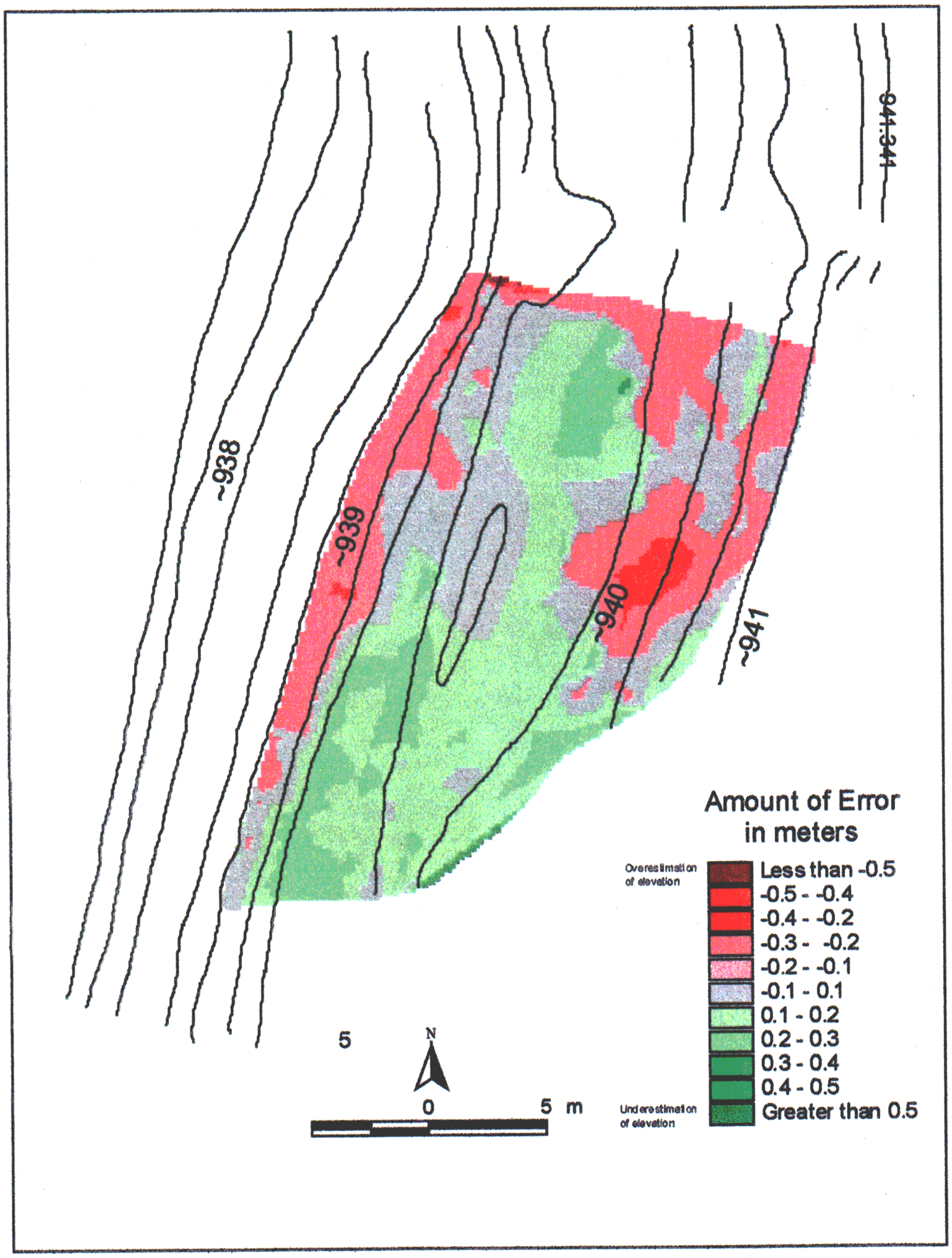


Figure 20. Map showing the error between the automatically generated surface and the surveyed topography for Jackass Sand bar in October of 1984. The contours are from the survey field map.

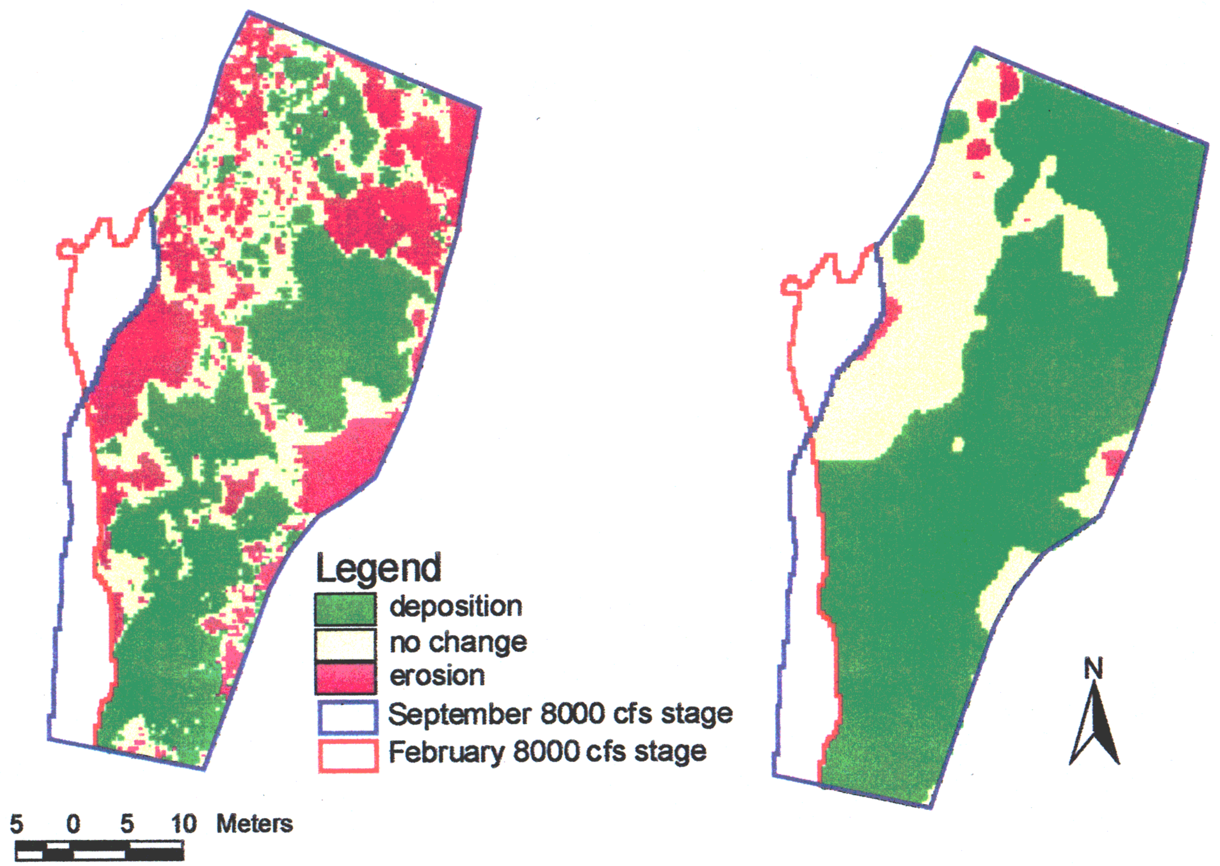


Figure 21. Areas of calculated erosion and deposition exceeding 10 cm and areas with less than 10 cm of erosion or deposition (no change). Change is calculated between March 24, 1996 and September 1, 1996 from the photogrammetric data (A) and between February 16, 1996 and September 14, 1996 from the topographic survey data (B).

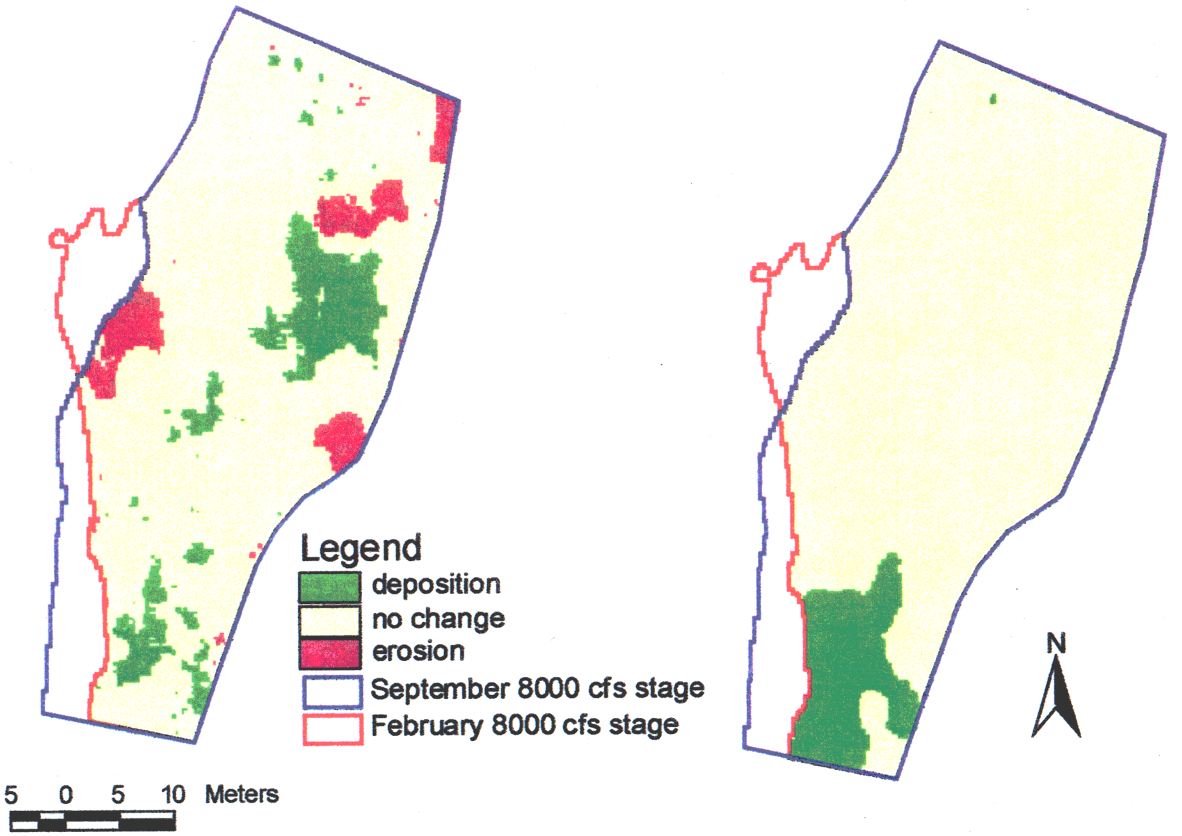


Figure 23. Areas of calculated erosion and deposition exceeding 50 cm and areas with less than 50 cm of erosion or deposition (no change). Change is calculated between March 24, 1996 and September 1, 1996 from the photogrammetric data (A) and between February 16, 1996 and September 14, 1996 from the topographic survey data (B).

Figure 22. Areas of calculated erosion and deposition exceeding 30 cm and areas with less than 30 cm of erosion or deposition (no change). Change is calculated between March 24, 1996 and September 1, 1996 from the photogrammetric data (A) and between February 16, 1996 and September 14, 1996 from the topographic survey data (B).

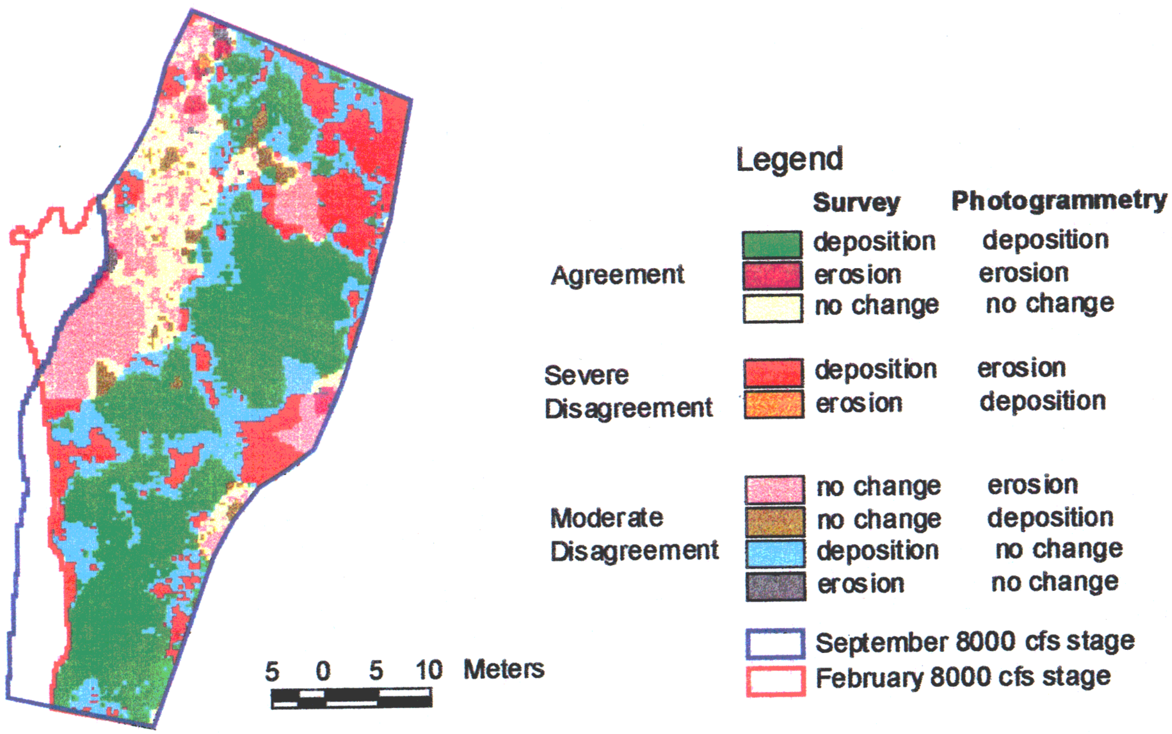


Figure 24. Agreement between change-detection maps at the 10-cm (a), 30-cm (b), and 50-cm (c) thresholds. Areas where both methods measured erosion, deposition, or no change are "agreement." Areas where the methods measured completely opposite response are "severe disagreement," and areas where one of the methods measured no change and the other method measured erosion or deposition are "moderate disagreement."

Figure 24b

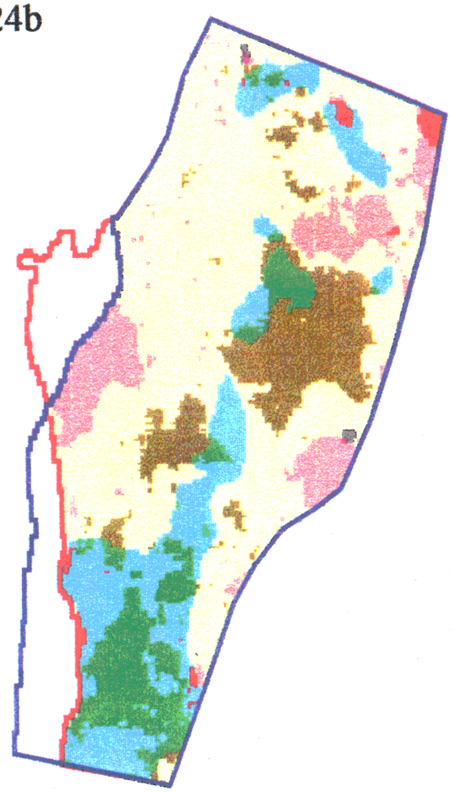
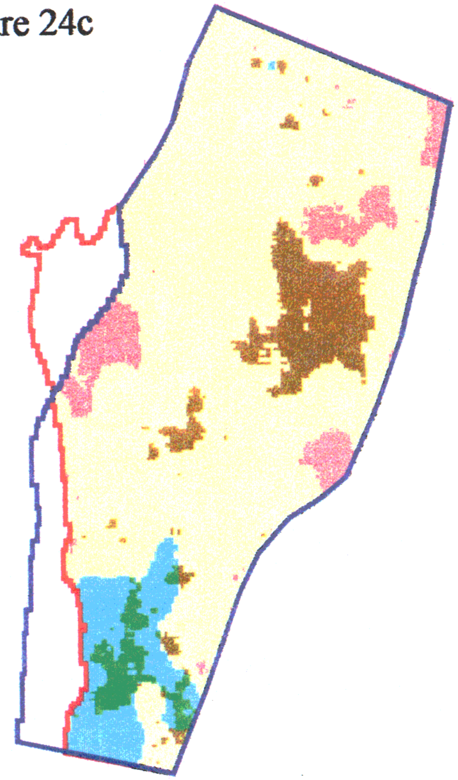


Figure 24c



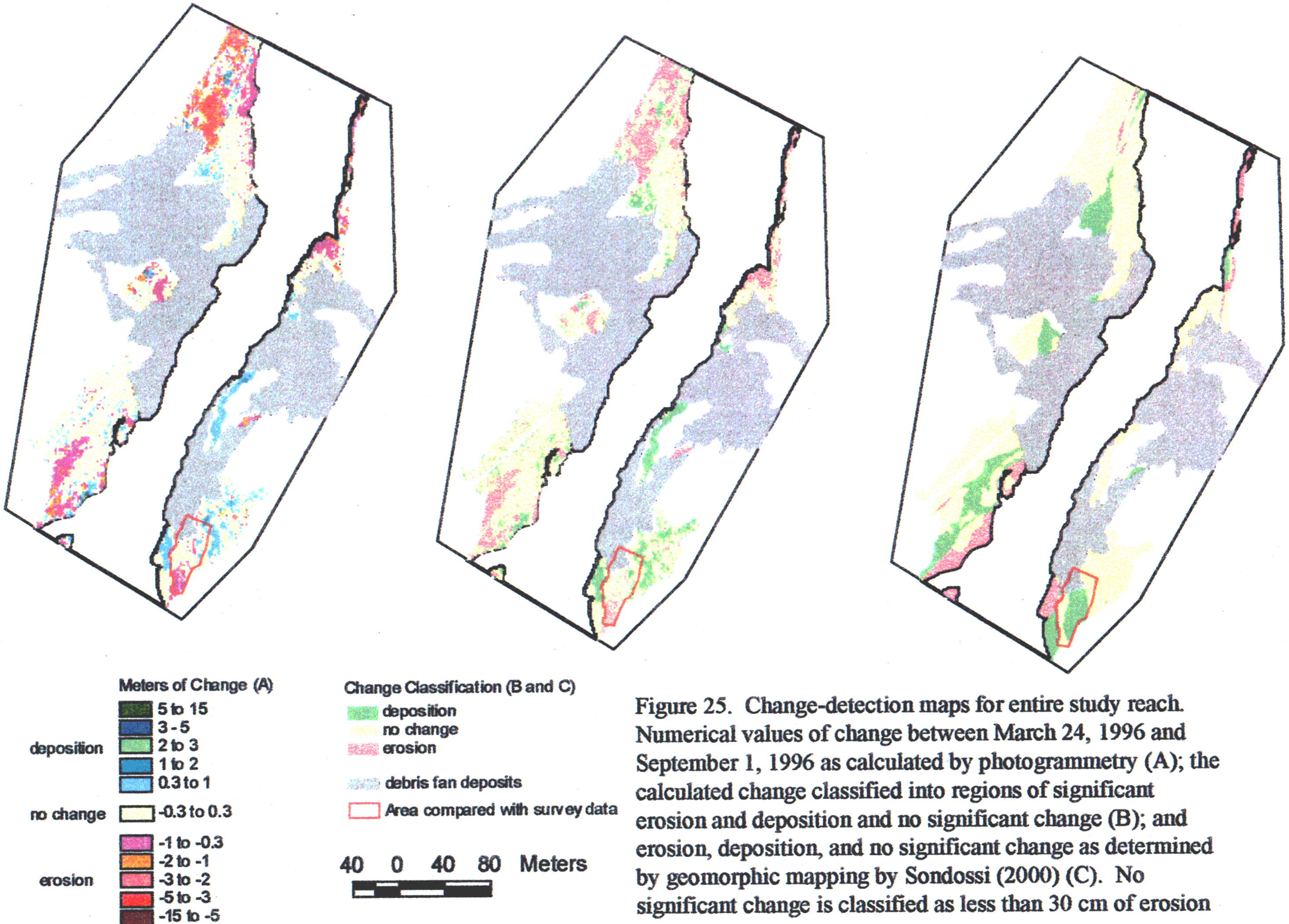


Figure 25. Change-detection maps for entire study reach. Numerical values of change between March 24, 1996 and September 1, 1996 as calculated by photogrammetry (A); the calculated change classified into regions of significant erosion and deposition and no significant change (B); and erosion, deposition, and no significant change as determined by geomorphic mapping by Sondossi (2000) (C). No significant change is classified as less than 30 cm of erosion or deposition.

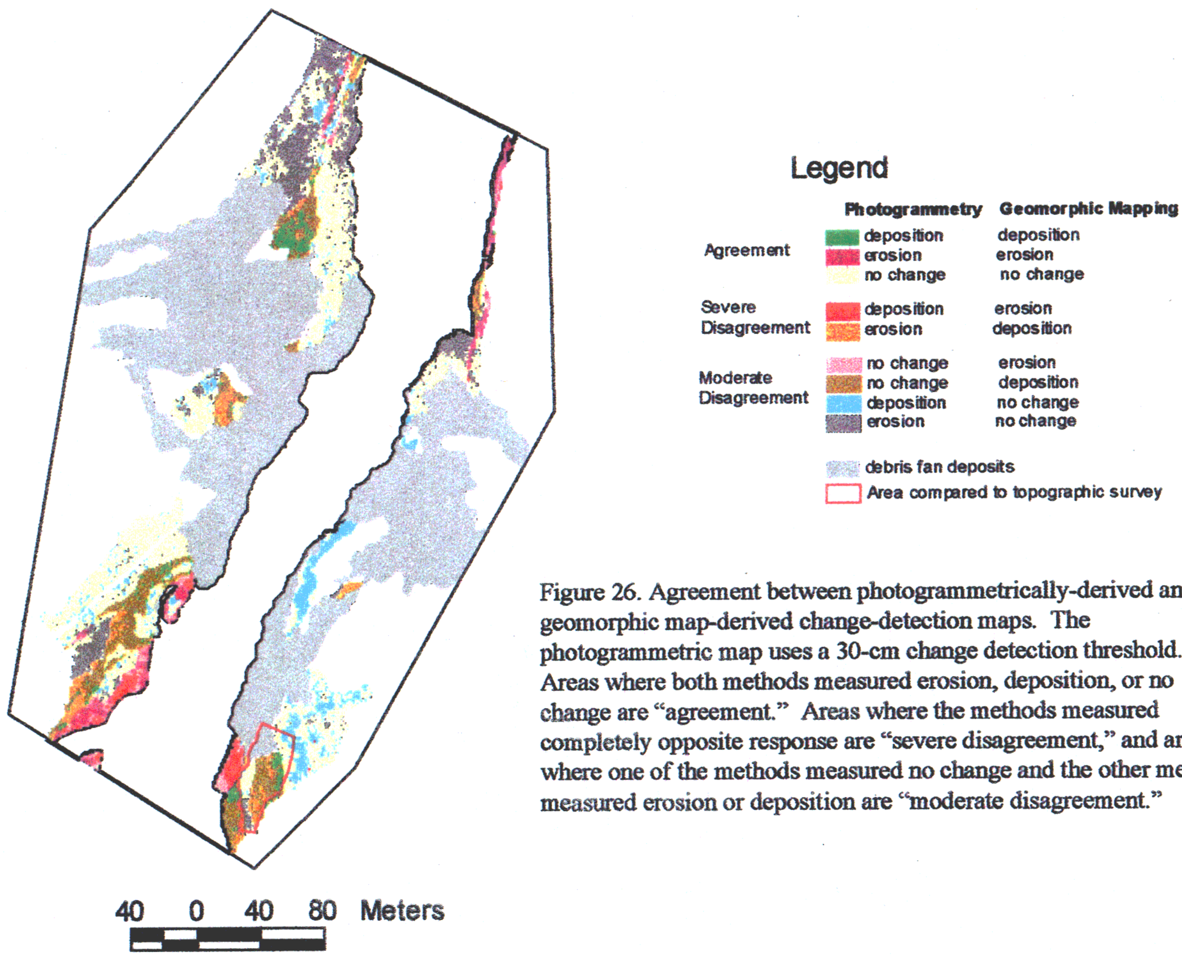


Figure 26. Agreement between photogrammetrically-derived and geomorphic map-derived change-detection maps. The photogrammetric map uses a 30-cm change detection threshold. Areas where both methods measured erosion, deposition, or no change are "agreement." Areas where the methods measured completely opposite response are "severe disagreement," and areas where one of the methods measured no change and the other method measured erosion or deposition are "moderate disagreement."

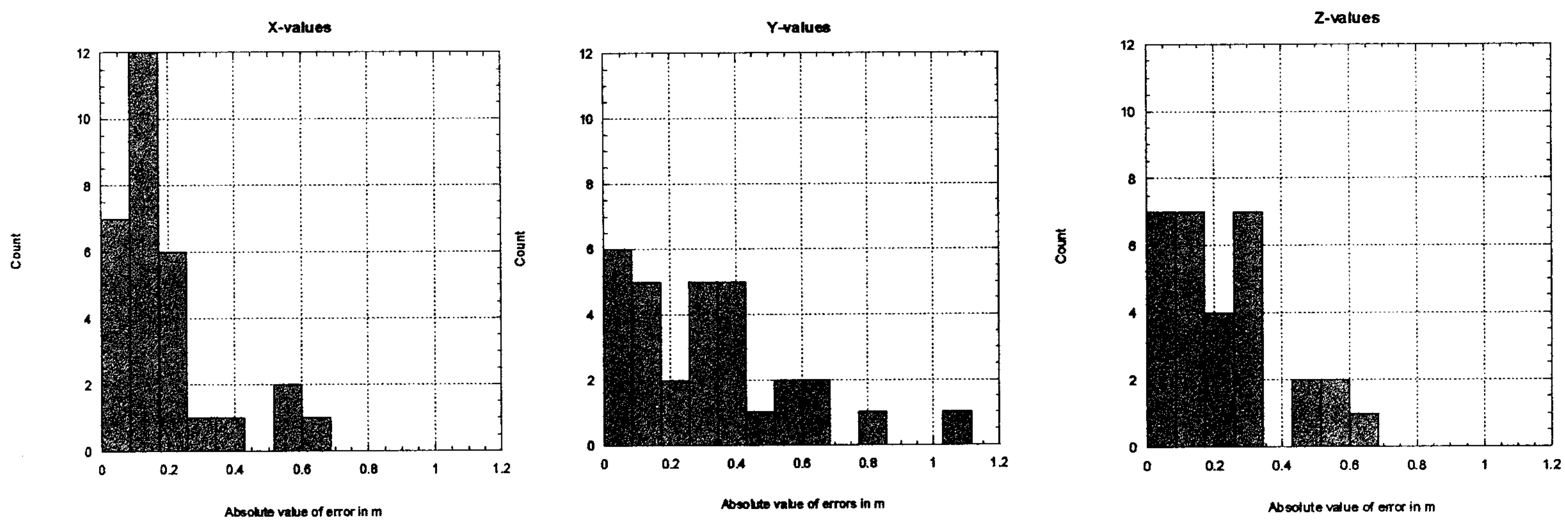


Figure 27. Histograms of the absolute value of error in placing GCPs for 3 technicians in the X, Y, and Z directions.