Applications of 'Structure from Motion' Photogrammetry to River Channel Change Studies

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River Channel Change Studies

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APPLICATIONS OF ‘STRUCTURE FROM MOTION’ PHOTOGRAMMETRY TO RIVER CHANNEL CHANGE STUDIES

This study considers the feasibility and accuracy of using the Structure from Motion (SfM) technique to quantify changes in stream channel morphology. The SfM method utilizes common points across multiple photographs to create a three-dimensional representation of a study area. This model can then be georeferenced using ground control points. The camera locations and optics do not need to be known in this technique, making it simpler to implement in the field than traditional photogrammetry or ground-based lidar methods. Preliminary testing of this method was conducted in and around the Boston College campus during summer 2012 to determine the most appropriate tools and data collection plan for further fieldwork. I then applied the SfM method to a field site on the Souhegan River in southern New Hampshire, where I photographed two cross sections (one boulder-bedded, one sand-bedded) using a camera mounted on a 4.8 m pole. On the same day, I surveyed both cross sections using a total station with mm-scale accuracy. Inputting the photographs into the Agisoft PhotoScan software used for SfM reconstruction yielded several noteworthy results. First, when certain conditions are met, the model generated through SfM, built from a complex, high density (for example ~2,900 points per m²) point cloud, can then be used to deduce elevation data. Based on a point-by-point comparison, the SfM cross section averaged 3.6 cm (±3.4 cm standard deviation) higher than the total station survey. In other portions of the study site imaged for SfM reconstruction, a variety of difficulties prevented the development of a georeferenced three-dimensional model. These limitations, including shadowing, vegetation, camera vantage point, and location of ground control points, can be minimized in future studies to allow for better use of the SfM technique. As results of this study demonstrate, SfM reconstruction has the potential to generate accurate topographic data, which will be a powerful tool for future geomorphic studies, particularly for sites with relatively sparse vegetation and limited water.
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CHAPTER ONE: INTRODUCTION

1.1 Purpose and Scope

This thesis examines the feasibility of using the Structure from Motion (SfM) photogrammetric technique to measure rates of change in stream channels. SfM has the potential to provide both a low cost and time efficient method for collecting data on surface morphology. Structure from Motion is the detection of three-dimensional space from the interaction of multiple two-dimensional images. This process is performed by human eyes and can now also be accomplished using computer algorithms. The beauty of the SfM technique is in its simplicity; digital photographs alone can be used to construct a three dimensional surface or model. By identifying common points across multiple photographs, the point cloud generation software is able to relate hundreds, if not thousands, of points to each other spatially, without necessitating camera or photograph locations as are required in traditional photogrammetry. Thus SfM model generation can be performed with any set of overlapping photographs provided that the set contains sufficient image overlap and is of adequate quality. While it is possible to create similar models through terrestrial laser scanning (TLS), SfM results are achieved at a much lower cost and with a greater ease of use. SfM can both create a spatial model of a study area and extract meaningful ground distances and elevations once the data has been orthorectified. This means of gathering topographic data could prove particularly valuable in repeat surveys where the focus is on quantifying changes in morphology over time.

In this project, I compared SfM results with traditional total station survey data acquired concurrently in order to evaluate the accuracy of the SfM technique. First, preliminary SfM data collection tests were performed in order to develop the primary field plan. The major testing of
SfM was on data collected at a stream channel change site, one of the types of studies for which I hypothesized SfM to be a low-cost, accurate data analysis option. The requirements and success of SfM reconstruction were identified and compared to the total station survey parameters and results collected at the same site on the same day. The study findings contribute to the growing body of research on the utilization of SfM as a low cost, time efficient, and accurate data tool for future geomorphic research.

1.2 Previous Research on SfM

Applying SfM algorithms to geomorphic studies is an area of active methods development. SfM can create results comparable to other types of remote sensing. Elevation data, which is the objective of total station surveys, can be acquired through SfM. Similarly, the three dimensional point cloud data that SfM generates is comparable with that produced by terrestrial laser scanning, which has become a popular method of data collection over the past decade. The use of SfM in geomorphic studies has begun to be examined in earnest by several research teams, all of whom highlight the technique’s low cost and ease of use. Fonstad et al. (2013), James and Robson (2012), and Westoby et al. (2012) have all published papers on SfM in the last six months that have made attempts at assessing the accuracy of SfM model results.

Of the three recent studies, Fonstad et al. (2013) is most similar to this study because the scale and features of their study site are comparable to the river channel site modeled in this analysis. Their river field site for SfM testing was located in Pedernales Falls State Park in Texas, where a large exposed bedrock reach surrounds and controls river flow (Fonstad et al., 2013). They used a blimp for the collection of aerial photographic data, with heights above the
ground surface ranging from 10 m to 70 m. The 304 photographs they collected were processed to obtain a three-dimensional point cloud, using several free applications. Additionally, global positioning system (GPS) coordinates of specific points were determined after point cloud generation, enabling the authors to choose points that were certain to be identified in the reconstruction. Airborne lidar data had been obtained for this site in 2006 as part of a government effort to acquire accurate elevation data and was used as a comparison to the SfM results. An assessment was then made comparing SfM, GPS, and lidar data acquired for the site.

Fonstad et al. (2013) found that the mean elevation difference was smaller between SfM and GPS (0.07 m ±0.15) than between lidar and GPS (0.51 m ±0.18). This, however, they attributed to the relatively sparse point cloud acquired with airborne lidar, which creates the possibility of large errors, as opposed to the results from the SfM method. Fonstad et al. (2013) found a mean difference between SfM and lidar elevation values of 0.60 m (±1.08 m). Based on these comparisons it is apparent that the SfM reconstruction in this study was more accurate over this small scale than the airborne lidar scans based on the collected GPS data. This is to be expected as the scales of data collection between these two methods vary dramatically. Regardless, it provides an interesting comparison for their study and highlights the precision of the SfM technique, which can be completed at a much lower cost. The researchers also indicate that further testing is necessary to assess the possible distortions present in the highly computerized SfM technique. Overall they find great potential for use of SfM in small scale projects as a cost and time effective data collection tool.

Another research team, James and Robson (2012), explored different scales over which SfM reconstruction could be utilized. They used a combined method of SfM and multiview stereo (MVS), which filters potential noise in data to improve the generated point cloud and thus
the accuracy of their results. They collected and assessed photographs of a volcanic bomb with a
radius of ~0.05 m, a ~1 km wide volcanic crater, and finally a ~3 m high by 50 m long coastal
cliff (James and Robson, 2012). For each of these three scales, they used different techniques for
comparing the three dimensional model results. In the case of the volcanic bomb, 210 images
were used in a SfM reconstruction of the hand sample and compared to the results from a
laboratory-based Arius3D laser scanning system. This resulted in precise calculations with radial
differences between the techniques through two cross sections having means of 69 µm and 110
µm (James and Robson, 2012). For this sample, the point cloud generated through SfM was
significantly smaller than that of the scanner (40×10^6 points versus 100×10^6 points).

For the vastly different scale of a kilometer wide volcanic crater, James and Robson
(2012) compared SfM reconstruction to close-range photogrammetry, which they could run due
to the large number of ground control points (45 white sheets). In this example, the vertical
differences between the two digital elevation models (DEMs) generally agreed to a meter scale,
with some less complex areas resulting in smaller errors than the steeper volcanic faces.

The third assessment carried out by James and Robson (2012) focused on comparing SfM
survey results to those obtained with a Riegl Z210ii terrestrial laser scanner. The differences in
the results of this outcrop modeling had a root mean squared error (RMSE) value of 70 mm.
James and Robson did note, however, that in some areas error magnitude increased due to
oblique angles and vegetation near the top of the outcrop. This imaging and processing of the
erosive outcrop led to the application of SfM to a study of change over time, where six sets of
images were acquired over the course of a year and compared to evaluate changes in outcrop
geometry.
A third study by Westoby et al. (2012) also provides an assessment of the SfM technique compared with terrestrial laser scanning. For data processing they used the application bundle SFMToolkit3, which is available at no cost and bundles several other free applications. The primary field site was Constitution Hill, a ~80 m high cliff located in Wales. The researchers created a DEM of difference (DoD) that revealed that 86% of their SfM modeled area was within ±0.5 m of the TLS generated data (Westoby et al. 2012). Additionally the Westoby et al. (2012) study particularly notes the complications arising from dense vegetation cover.

1.3 Site Overview

The primary fieldwork for my study was conducted on the Souhegan River, a tributary of the Merrimack River in southern New Hampshire (Figure 1.1). The downstream-most reach of this river, from the Everett Turnpike Bridge to its confluence with the Merrimack River, has been the site of a multi-year dam removal and channel change study (Pearson et al., 2011; Conlon and Snyder, 2012). For that project, 12 cross-sections were identified and marked with pins in order to perform repeat surveys. The purpose of the research was to examine the effects of removal of the Merrimack Village Dam in 2008. Pearson et al. (2011) and Conlon and Snyder (2012) measured changes in channel morphology both upstream and downstream of the former dam site.

My research focused on two cross-sections, MVD03 and MVD04, both originally created for the Pearson et al. (2011) study (Figure 1.1). These two cross sections were chosen due to accessibility, proximity between the two (approximately 75 m), and diversity of channel morphology (Figure 1.2). Additionally each cross section featured sizeable subaerially exposed
portions of the active channel, which I hypothesized could be reconstructed using the SfM technique.

MVD03 is upstream from MVD04 and provides an example of a boulder-bedded river channel. This cross section has areas of fast flowing water as well as slower moving pools located between large boulders (0.75-1.5 m diameter; Figure 1.3). At the time of my fieldwork, four years after dam removal, essentially all impounded sand had been eroded from this cross section, leaving behind coarser sediments of the pre-dam river bed (Pearson et al., 2011). This cross section measures about 90 m across, stretching from a forested terrace on the left bank to an unforested terrace on the right bank.

MVD04, the next cross section downstream which measures about 110 m across, provided contrasting channel morphology. The channel in this location is sand-bedded, and features steeper, taller banks and exposed flat areas of sand at the water’s edge at low flow. In addition, MVD04 was known from the prior field research to crosscut a large non-vegetated sandbar, an area where positive SfM survey results were anticipated due to shallow slopes and exposed ground surface (Figure 1.4).
Figure 1.1: Aerial orthophotograph from May 2010 showing an overview of the Souhegan River study site adapted from Conlon and Snyder (2012). Cross sections imaged in this study are highlighted in yellow. The insert map in the upper left provides elevation data for the entire Souhegan River watershed.
Figure 1.2: A downstream view of the primary field site on the Souhegan River, as seen from the right bank of cross section MVD03, taken October 8, 2012.
Figure 1.3: A view across cross section MVD03 from the right bank highlighting the boulder based channel morphology, taken October 8, 2012.
Figure 1.4: A view upstream of the left segment of the Souhegan River that depicts the central sand bar through which cross section MVD04 runs (photograph taken October 8, 2012). The Everett Turnpike Bridge, the upstream extent of the dam removal study area, can be seen in the distance with the boulder dominated cross section MVD03 in between the bridge and the MVD04 sand bar.
CHAPTER 2: METHODS AND TEST CASES

The application of SfM to geomorphic studies is an emerging technique, necessitating development and testing. In this study, initial field tests were conducted by adjusting a variety of photographic and site parameters in order to determine how to most effectively model the ground surface. These findings were then utilized to facilitate the primary fieldwork, a test of the SfM technique for river channel modeling. The following describes the key decisions and findings of the initial testing that led to successful SfM modeling. Results of the two preliminary tests conducted during the summer of 2012 are documented below. Test Case 1 illustrates my attempt to model a large rock outcrop near the Boston College campus, while Test Case 2 shows the creation of a successful SfM model of a quadrangle area on the campus. Also discussed are the specific tools and approach to fieldwork selected for the main SfM feasibility testing on the Souhegan River. Lastly, the process of data input into the Agisoft PhotoScan software is described, highlighting the necessary steps for successful processing.

2.1 Preliminary Testing

Initial tests of the SfM technique were conducted in and around the Boston College campus during summer 2012. The purpose of the summer work was to gain familiarity with the reconstruction software by photographing a variety of subjects and processing the collected images to determine the characteristics of photographs that can be used to create successful SfM models.

After reviewing the various three-dimensional reconstruction software programs available on the commercial market, Agisoft PhotoScan Professional Edition, version 0.8.5 build 1423, was purchased in August 2012 (hereafter PhotoScan). PhotoScan was selected for this
project based on its reasonable cost, its reported ease of use, and its accuracy in spatial reconstruction with limited camera detail and location requirements. The PhotoScan software package bundles the three processes necessary to create a SfM model, which are frequently marketed as individual modules. Thus, using the selected software eliminates the need for multiple file transfers and repetitive data entry, which are steps required in lower cost software options. Due to the integrated design of PhotoScan, data processing is straightforward. Additionally, high quality models are able to be produced from a minimal number of photographs and limited spatial reference data.

Two cameras (a Nikon D90 digital single lens reflex, DSLR, and a Canon Powershot 3200 point-and-shoot) were used for the initial photography. The experiments included imaging both man-made and natural sites. A number of buildings, sidewalk segments and statues were photographed, as well as exposed bedrock, rainwater pools, and non-landscaped grass and shrubbery. Numerous photographs of each subject were shot from a wide variety of distances, heights, and angles using a diverse range of camera settings. The photographs of each site were uploaded into the PhotoScan software in a variety of combinations. Multiple processing tests were attempted in order to determine which types of photographs were most successfully processed by the software. Once useful image characteristics were determined, I would again photograph the site, refining the various camera settings and positioning. I then processed the new image data through SfM reconstruction. Using this iterative process, I photographed the same sites multiple times in attempting to improve the quality of the SfM models being produced. Over a number of weeks, the most advantageous photographic techniques for SfM reconstruction were determined through this process.
2.1.1 Test Case 1

For Test Case 1, I imaged a large bedrock outcrop near campus that was sparsely vegetated and had distinct small-scale (0.5-1.0 m) relief changes. Three different portions of the outcrop were photographed; the particular area displayed in Figure 2.1 represents a relatively flat top of the outcrop where some steep step-like features can be observed. The Canon Powershot was used to capture the imagery in this case. I took photographs from a handheld height of approximately 1.4 m at a 90 degree angle with the outcrop surface. The 124 photographs from this field collection were used in a successful SfM reconstruction (Figure 2.1). The cloud created in the PhotoScan software contained 20,816 points. From this point cloud the model shown in perspective in Figure 2.1 was constructed. This test was not georeferenced because ground control points were not collected for the particular study area.
Figure 2.1: A perspective view of the SfM reconstruction for Test Case 1 showing the three dimensional nature of the generated model. Blue rectangles represent interpreted camera locations and relative tilts established through SfM processing.

The mosaic aerial image (Figure 2.2) displays the capability of SfM to create a broad aerial view from a set of close-up photographs. Each individual photograph in the data set was only 1.4 m above the ground surface (Figure 2.3). This test was the first large (> 3 m) area successfully modeled. I hypothesized that the consistent camera angle and consistent height helped to match more common points between photographs and thus created a more accurate representation than in other photograph sets from the same outcrop. In prior attempts, photographs had been taken from widely varying angles, which appeared to cause difficulties in point cloud generation since distance from the ground surface is derived through model estimation and not input by the user.
Figure 2.2: Overview shot of Test Case 1 created in the PhotoScan software. This is a textured mosaic pieced together from the original photographs that then overlays the interpreted model geometry.
2.1.2 Test Case 2

The main success of initial field testing was the SfM model generation of a quadrangle on the Boston College campus (Test Case 2; Figure 2.4). This area was photographed using the Canon Powershot on a partially overcast morning in August 2012. Later that same day, a total station survey was run in order to collect reference points to be used in the orthorectification and georeferencing processes. Stationary ground control points (GCPs) that could be seen in the photographs, such as the edge of a drain or corner of a brick, were chosen as survey points. In the area reconstructed, five GCPs could be seen, which was sufficient to create an orthorectified model (Figure 2.4). I created this model through a process of generating small model areas and then meshing them together to create the larger model of the quadrangle area.
Figure 2.4: This image represents a top down view of the spatial model created in PhotoScan of Test Case 2, part of a quadrangle on the Boston College campus. It is a mosaic of the 82 photographs used to reconstruct this area. Small blue flags represent the locations of surveyed ground control points used to orthorectify and georeference the model. This is a view of the three dimensional model, shown for reference. The exported orthophotograph is displayed with scale and spatial orientation below (Figure 2.5).
Once the study area was georeferenced, I was able to export an orthophotograph and digital elevation model (DEM) directly from the PhotoScan software. Inputting these raster data sets into ArcGIS allowed for a qualitative comparison of the SfM-generated orthophotograph with available aerial imagery of the Boston College campus (Figure 2.5). This comparison confirmed that the study area was properly georeferenced. The creation of a DEM, which provides elevation data for every point in the model, was a central aspect of the success of this site test. A DEM is valuable in quantifying changes in the land surface, and creating a DEM is ultimately the goal of SfM reconstruction in this study. Furthermore, the creation of the DEM suggests that field methods used in Test Case 2 were adequate to generate meaningful data that could be extracted from SfM reconstruction (Figure 2.6).
Figure 2.5: The orthophotograph created through SfM modeling overlays a 1 m/pixel resolution base image of the Boston College campus (taken in 2011). The degree to which these images align is the result of georeferencing the SfM model in PhotoScan, not manual placement. This figure shows the accuracy of distances and orientation of the SfM model, which is in proper alignment with the base image.
Figure 2.6: DEM generated from the three dimensional model of the Boston College test site. This figure displays elevations derived from SfM modeling utilizing five GCPs (Figure 2.4) and accurately depicts the increase in height of the low walls and statue as opposed to the gradually sloping pathways.

The preliminary phase of the project identified a number of important observations and considerations to guide the fieldwork. The test results confirmed that sophisticated photographic equipment and expertise are not required for successful SfM processing. I learned that photograph resolution must be high and that vantage point can vary, but the larger the area encompassed by each photograph the better. It was also noted that shadows and vegetation seemed to disrupt the modeling process. Finally, it appeared that the quantity of the data directly impacted the performance of the software; where more photographs were collected the models
rendered were distinctly more robust. The testing concluded with the creation of the successfully georeferenced model of part of a BC quadrangle (Figures 2.4-2.6). This was a critical step, as it was not prudent to proceed with the fieldwork until the capability of the software to model, orthorectify and georeference a test site had been confirmed, utilizing the equipment and procedures I had selected.

2.2 Equipment

Based on the preliminary data testing, equipment for the primary fieldwork was selected and secured during the months of September and October, 2012. An available Canon EOS Rebel XT DSLR camera (hereafter referred to as the Rebel) was used for imaging. When working in the field, I set the aperture at F/6.64 and the ISO at 200. A fast shutter speed, 1/600, was required in order to capture images with minimal blur. The camera settings were adjusted to minimize shadows and provide the sharpest achievable resolution.

The tests on the BC campus established the necessity of time-lapse capabilities for data collection. Since the Rebel did not have an internal timer (or intervalometer), a Promaster multi-function timer remote was added to enable time-lapsed photographing. Once acquired, testing using the selected camera and intervalometer combination determined that an eight second interval was adequate to re-position the camera between shots without creating a lengthy delay in the work flow. If a new camera had been deemed necessary, a Ricoh CX3 or CX4, or a similarly compact model, would have been purchased. A small camera would have provided sufficient quality photographs with the advantage of lighter weight. In addition, a time-lapse feature is built into the Ricoh models.
A major decision in planning the Souhegan River fieldwork was to determine the method to be used for obtaining the necessary aerial photography. A weather balloon was initially considered to be the best option, providing a cost effective way to image a large area. Since preliminary testing results confirmed that modeling accuracy improved as the height from which the images were shot was increased, the balloon approach appeared advantageous. However, after further consideration, it became clear that the use of a weather balloon posed its own series of data collection difficulties. A substantial balloon would be required to support the camera and a method to stabilize the camera on the balloon would have been necessary. I was also concerned with our ability to precisely control the balloon's positioning. Additionally, the logistics of transporting either a helium tank or a pre-filled balloon from the parking area to our study site were problematic given the walking distance and the tree cover in portions of the pathway leading to the site.

The anticipated complications of the weather balloon approach led to the decision to test mounting the camera on a survey pole for the aerial shots. A hand-held survey pole, which telescopes to a height of 4.8 m, was equipped with a clamp and a tripod-like fitting allowing the camera to be attached at a fixed angle of between 0 and 90 degrees from the downward direction (Figure 2.7). This configuration was tested at a number of sites around the Boston College campus during the preliminary phase. The pole proved to be precisely maneuverable and allowed for stable photography, although the vantage point was not as high as desired. This low vantage point necessitated a greater number of photographs for the SfM modeling than would have been needed if the images had been obtained from a higher position. The test results also established the importance of insuring that the camera angle did not capture any of the pole in the photographs, as its inclusion in the photographs interfered with the modeling.
Once it was determined that the pole provided sufficient height for SfM modeling of small areas, this data collection technique was confirmed for the fieldwork (Figure 2.7). The pole approach made it feasible to use the Canon SLR because camera weight was not a direct limitation. At the field site, the survey pole was set at a height of 4.8 m and the camera was attached at an oblique angle of approximately 40 degrees. From this setup photographs with an average resolution of 0.7 mm/pixel were collected. The selected camera – pole combination proved to be adequate during the data collection process, providing a balance between the range needed for the aerial shots while keeping the desired photographic control.

A number of options were considered for the required GCPs. Although a wide range of targets are manufactured, it was determined that a more cost effective solution was to make our own. Ultimately, white rubber baseball bases were purchased and painted with water-resistant paint to create the GCPs used in the photographs. The bases were selected because they are able to be used in and around water and are heavy enough to remain stationary after being placed. The weight of the bases was important due to the boulder based nature of part of the study area. The bases were 0.25 cm thick, which was assumed to be thin enough to avoid creating artificial elevations in the modeling results.
2.3 Fieldwork

The field research was conducted on October 8, 2012, a clear day with minimal cloud cover and a temperature range of between 9 and 13 degrees Celsius. Since the date for the fieldwork was selected weeks in advance, it was fortunate that there were no weather conditions that interfered with the photography required for SfM processing.

As previously described, the field site was located on the Souhegan River in southern New Hampshire (Figure 1.1). The site was familiar to the research team; we had each
participated in total station surveys at the location during the summer of 2012. While 12 cross sections had been surveyed in the prior work studying the effects of dam removal (Pearson et al., 2011; Conlon and Snyder, 2012), I selected only two cross sections for inclusion in the SfM study. Despite being located in close proximity to each other along the river, the two cross sections, MVD03 and MVD04, lie in a transitional area in the field and thus present quite different morphologic features (Figures 1.2-1.4).

Each of the cross sections was prepared for imaging in the same way. Eight ground control points (GCPs) were laid out along the cross-section line, established previously between two rebar pins. While intervals of approximately 4 m between the GCPs were desired to establish georeferencing, in some instances the morphology dictated intervals of up to 10 m. While this spacing was not optimal, the site conditions and water flow limited the available placement options.

Once the SfM ground control points were established, the total station surveys and the SfM imaging proceeded simultaneously. Four team members participated in the field work, with two completing each process. While total station surveys require two participants, SfM imaging can be a solo task. Approximately the same time would have been required for the completion of each method; however, the total station necessitated a two-hour occupation in one place to collect accurate GPS data, which delayed the process. Methods of total station survey data collection followed those of Pearson et al. (2011) and Conlon and Snyder (2012), who surveyed the same cross sections over multiple years. Total station data were collected at intervals of approximately 2 m along the length of each cross section, with special note to survey all GCPs to be used for georeferencing the SfM models. GPS solutions for the total station surveys have average absolute accuracies of 0.059 m in the horizontal and 0.143 m in the vertical (See
Appendix). More significant to this study, the relative accuracy of the total station data is ~2 mm (Pearson et al. 2011).

Making certain not to make any changes in the location of the GCPs, photographs for SfM reconstruction were taken along each cross section. With the camera attached to the pole at a height of 4.8 m and the intervalometer set to eight seconds, the images were obtained by walking the pole and pausing about every meter to capture an image, thereby creating overlap in the photographs. The pole was set at each pause to minimize photograph blurriness. Approximately 650 images were collected during the 2.5 hours spent photographing the two cross sections.

Cross section MVD04 was comprised primarily of sand and had relatively slow water velocity (Figure 1.4), allowing for greater ease in data collection than MVD03. Because this location could be traversed safely, a field decision was made to walk the cross section twice, once in each direction. Because a large data set for point reconstruction was collected, it was hypothesized that high quality data would be obtained from the SfM model for cross section MVD04.

Cross section MVD03 was difficult to navigate due to fast flowing water in some segments and a number of boulders in the main channel (Figure 1.3). These conditions made it hard to maintain a consistent camera angle and tilt, which are desired for SfM processing. As a result of these site constraints, cross section MVD03 was walked only in one direction, from right pin to left pin.
2.4 Data Input

Once the primary data set was collected, the photographs for each cross section were entered into PhotoScan for synthesis into three dimensional models of the imaged areas. This requires three processing steps:

First, the software locates every point that is visible in multiple photographs. These points are then placed in spatial reference to each other, creating the three-dimensional point cloud (Figure 2.8).

Figure 2.8: A point cloud generated through the SfM data matching process using photographs from the Souhegan River field site. Each point represents a ground surface point that could be identified in two or more photographs.
Second, the program builds the geometry of the model by connecting points in the cloud to make a continuous 3D surface (Figure 2.9).

Figure 2.9: The model geometry created in the PhotoScan software from the determined array of points matched across photographs.
Third, texture is added to the model through a process that creates a mosaic of the original photographs. This is overlaid on the structural model generated from the point cloud (Figure 2.10).

Figure 2.10: A textured model created as the final step of the SfM process in PhotoScan. This image is comprised of photographic data pieced together to create a continuous image of the area modeled in which one GCP can be seen.
A continuous model across the entire channel could not be processed by the software for either of the cross sections imaged. After multiple unsuccessful iterations, the photographs from each cross section were divided into smaller processing units, identified as “chunks” in the software. Approximately 15 chunks were created from the 640 photographs obtained at the field site. Multiple variations of photograph combinations were processed, varying the number and content of the photographs, to maximize the quantity and quality of the segments able to be modeled. Processing smaller segments enhanced the computing speed and improved the cross section accuracy of what was able to be reconstructed by focusing on a smaller scale where more common points could be identified. However, some chunks were unable to be modeled even with these adjustments.

The successfully modeled areas were georeferenced where adequate photographs and GCP data were available. The northing, easting, and elevations of the ground control points were known through the total station survey data. Had the total station survey not been conducted, a hand-held differential GPS device would have provided sufficiently accurate location data for the ground control points, similar to Fonstad et al. (2013). Once geo-referenced, both orthophotographs and DEMs were generated directly from PhotoScan and exported for analysis and use in other software. The elevation data from the model was then compared to the cross section data generated through the total station survey of the same location, by overlaying the results of both processes in ArcGIS.
CHAPTER 3: RESULTS

Results from this study highlight the capabilities and constraints of using the SfM technique in geomorphic, specifically fluvial, fieldwork. Model results were considered successful for a portion of the study area but a continuous cross section from channel bank to channel bank could not be created due to limiting factors of the sites and data collected. However, the results do demonstrate the capabilities of SfM and its potential as a powerful data collection tool. Figure 3.1 gives an overview of the study site and displays the total station survey data that were collected at each cross section. These data points follow the cross section lines, connecting each pin and all of the ground control points used in SfM reconstruction. Both cross sections are characterized by bank scarps and wide channels. Although the aerial photograph in Figure 3.1 is from 2010, it is still possible to see the large boulders of MVD03 and the sandy-bottomed MVD04. Over the 110 m length of MVD04, 66 survey points were collected, while 40 survey points were collected over the 90 m length of MVD03.
Figure 3.1: Overview of the two cross sections, MVD03 and MVD04 (Figure 1.1), selected for SfM modeling. The base imagery is from May 2010 and blue dots represent total station survey data collected on October 8, 2012. The white boxes denote chunks where SfM modeling was at least partially successful, with numbering corresponding to the order in which these chunks are discussed in the following sections.
3.1 MVD04 Cross Section

Primarily sand-bedded, cross section MVD04 was chosen for SfM reconstruction testing due to its variety of slow moving deep channels, shallow pebble/cobble reaches, and exposed sand bars (Figures 1.4 and 3.1). This cross section was imaged by walking it in both directions, thus creating a data set with images from two different camera angles. A total of 486 photographs were taken between 1:25 p.m. and 2:35 p.m. Originally, the goal of data collection was to collect sufficient photographs to generate a continuous cross section model. However, due to various constraints, the cross section had to be separated into chunks for processing.

3.1.1 Central Sand Bar

The primary success of the study was the modeling of the central sand bar in cross section MVD04 (Figure 3.1, chunk 1). This sparsely vegetated, gently sloping sand bar met the conditions needed to create a successful model using the SfM technique (Figure 1.4). The model built in PhotoScan was orthorectified and georeferenced using the five GCPs placed in this portion of the study area. From this three-dimensional model with a point cloud density of ~2,900 points/m² (463,647 total points) an orthophotograph (Figure 3.2 (a)) and a DEM (Figure 3.2 (b)) were created.

The primary objective of my project was to compare elevation data estimated through SfM with data collected through total station surveys, which is possible through the creation of a DEM. With the continuous DEM generated through the SfM technique, I was able to create a cross-sectional profile for the central sand bar (Figure 3.2 (c)). This cross section is a collection of points that are related to each other spatially through the SfM process, which interpolates points between the known GCPs using multiple photographs. This sand bar was modeled using
68 images, angled from two different directions (Figure 3.3). A quantitative comparison between this cross section and one obtained through the total station survey method is carried out in the Discussion (Section 4.1).
Figure 3.2: (a) Exported orthophotograph of the central sand bar of MVDB4, chunk 1, comprised of a mosaic of the original photographs used to create the SFM model. Blue points represent the total station survey points collected on October 8, 2012, the same day as the photographs. This orthophotograph has a 1 mm/pixel resolution. (b) A DEM with 1.5 mm pixels of chunk 1 generated through SFM modeling, overlaid by a holdshade. Points are interpreted based on GCPs and multiple overlapping photographs of the ground surface. Blue dots represent total station survey data points. (c) A continuous, vertically exaggerated cross section generated from the DEM in (b) that runs through blue total station survey points. Differences in total station and SFM elevations can be seen in the small discrepancies between blue (total station) and green (SFM) points.
Figure 3.3: A screenshot of the MDV04 sand bar model in the PhotoScan software. Blue rectangles represent camera locations and tilts determined through SfM reconstruction, highlighting the overlapping nature of photographs taken from differing oblique angles. Blue flags represent pinned locations of GCPs where GPS data was collected in the field.

3.1.2 Other MVD04 Chunks

The steep, vegetated banks of MVD04 proved difficult for data collection and problematic for SfM reconstruction. Additionally, the deep and slow flowing channels also provided challenging constraints. Thus, other than the sand bar in this cross section (Figure 3.2), the flat near-channel banks were the only other portions of MVD04 where I had success in applying SfM methods (Figure 3.1, chunks 2 and 4).

The left bank of MVD04, similar to the rest of the cross section, was photographed from two different angles by walking the cross section in both directions (Figure 3.1, chunk 2). In assessing this data, I first processed the photographs taken by walking from the left bank to the
right bank, meaning the model was created from photographs consistently angled toward river right (Figure 3.4). Orthorectifying this model was not feasible since it included only one GCP to use in adjusting the model skew. In the field, it was assumed that more of the GCPs in the steeper area of the channel bank would be able to be utilized in the SfM modeling. This incorrect assumption is the reason there are an inadequate number of GCPs present in this modeled area. The consistent oblique angle of the photographs collected caused distortion in the model that SfM cannot adjust without multiple perspectives or sufficient GCP data to pin to the model surface.

Figure 3.4: Image of the SfM model for the left bank of cross section MVD04, which was created solely from photographs taken with a camera tilt toward river right. One GCP can be seen in this model, placed near the water’s edge.
The photographs collected from both directions of the left bank were then input into the PhotoScan software to be processed together (Figure 3.5). This combination of photographs created a model that appears more accurate in map view. As has been documented in prior studies, multiple camera angles allow for a more precise model of the study area. By providing more than one perspective, SfM algorithms can adjust for distortion in oblique-angle photographs of sloping ground surface. While this model was not able to be adjusted due to the limited GCP data input, it provides a more accurate representation as a result of the addition of data from a different vantage point. It is important to note, however, that all data should be of a similar type, i.e. oblique low altitude aerial photographs, because a large difference in camera angle, scale or vantage point is not conducive to the point matching process in SfM.

An additional note on this model is the visible presence of shadows in the mosaic of photographs overlying the geometry. While the effect on the flat, sandy surface was not large enough to obscure the model in this case, differences in lighting can prevent the SfM algorithm from identifying as many common points as possible across photographs, particularly if they are taken at different times with different lighting conditions. This lighting impact had the largest effect in modeling the steep bank scarps, as those areas had the most dramatic shadows.
Figure 3.5: The SfM model of chunk 2 created using overlapping photographs with different camera angles, with the same GCP seen in Figure 3.4.

Other portions of the MVD04 cross section, chunk 3 for example, are characterized by slow moving, deep flows (Figure 3.1). When input into PhotoScan, photographs collected of this area could not be modeled, either in a chunk by themselves or as part of a larger chunk. The excessive darkness of the photographs and lack of visual differentiation of objects on the channel bed between photographs was not conducive to SfM reconstruction (Figure 3.6).
Similar to the left bank, the near-channel chunk of the right bank (Figure 3.1, chunk 4) was able to be modeled through the SfM technique but could not be georeferenced because there was only one GCP placed in the modeled area (Figure 3.7). Photographs in this chunk were clear, likely due to minimal shadowing and flat ground, which facilitated a steady shot (Figure 3.8). Additionally, this near shore bank is sparsely vegetated which reduced noise in the imaging of the ground surface. While it was able to be modeled, this chunk could not be linked to the central sand bar due to the presence of the deep pool between the two segments (Figures 3.1 and 3.6). A final point to note in the model results of this chunk is the bit of shallow water that was resolved in this SfM model (top part of Figure 3.7). While not perfect, this area does suggest that
if sufficient textual differences can be detected and overlapped in photographs of shallow water, the water’s surface can be successfully modeled through SfM.

Figure 3.7: This image displays the model of chunk 4, the right bank of MVD04, which contains sufficient photographic data for modeling but only one GCP, thus preventing SfM from accurately georeferencing the chunk.
3.2 MVD03 Cross Section

Cross section MVD03 provided a different geomorphic setting for reconstruction: a channel bed of large boulders that posed difficulties for data collection and subsequent reconstruction (Figure 1.3). At MVD03, 154 photographs were taken from the survey pole between 10:00 a.m. and 11:00 a.m. When input into the SfM reconstruction software as a complete set, these photographs did not allow for the creation of a coherent model of the cross section. Thus the photographs were divided into smaller chunks with each chunk being independently input into PhotoScan (Figure 3.1). Moderate success was achieved in creating models of these smaller chunks of photographs.
The first model attempt depicts a portion of the left bank of MVD03 (Figure 3.1, chunk 5). Upon arriving at the field site, I found this area to be highly vegetated, a characteristic of most channel bank areas in the study reach. Attempts to model this area produced limited results, as can be seen by the sparse point cloud in Figure 3.9. Although 16 photographs from this general area were uploaded into the PhotoScan software, only four of the photographs could be identified as overlapping. Additionally, within these four overlapping photographs, the software was only able to establish a small number of common points to be used in the model generation (Figure 3.9).

Figure 3.9: The sparse point cloud generated for chunk 5 of MVD03 left bank. This represents the data points overlapping in four photographs, as those were the only photographs in which points were matched in this thickly vegetated bank area.
Next, despite the sparse point cloud, model geometry was constructed to further examine the software’s capabilities with few camera inputs. The generated model, shown in top view in Figure 3.10, was only able to reconstruct a small area of ground unaffected by vegetative cover. Vegetation appears to reduce the effectiveness of the SfM algorithm’s ability to resolve local topography. Because photographs are the only data input into the SfM model, it is not possible to extract any data completely obscured by vegetation. Figure 3.11 displays one of the photographs collected in this area which demonstrates the difficulty in deciphering ground data in areas where the vegetative cover is extremely thick, as in the right portion of the photograph.

Figure 3.10: The unusable model, chunk 5, generated from the point cloud in Figure 3.9. This shows the obstruction of vegetation and the imprecise nature of a SfM model with insufficient matched data points.
Figure 3.11: Sample photograph of chunk 5 reconstructed in Figure 3.10. The close vantage point and vegetation cover prevent an accurate model of ground surface from being created through SfM.

The second major area of analysis for the MVD03 cross section was the river channel itself, where the bed is comprised of a high percentage of boulders and has a shallow flow (Figures 1.3 and 3.1, chunk 6). Imaging this area was difficult due to the variation between riverbed and exposed boulders and the restricted vantage point resulting from a limited pole height. Consequently, SfM reconstruction in this site reach was not as coherent as expected. The goal to render a model across the river channel based on the exposed boulders and several ground control points could not be completed using the SfM reconstruction software. Data collected across this reach portrayed a complex mixture of boulders, water pools, and woody debris (Figure 3.12). As a result, only small portions of this area could be modeled due to the similarity of features and the small field of view of the imaged areas (Figure 3.13). Also, an
alignment of multiple chunks was not possible because too few ground control points were identified in the PhotoScan models.

Figure 3.12: Sample photograph of chunk 6 in the mid-channel reach of MVD03 that includes boulders, woody debris, water, and one placed GCP (taken on October 8, 2012).
Figure 3.13 (a) and (b): Examples of segments of chunk 6 of MVD03 modeled in PhotoScan that are not distinguishable enough to be accurately aligned into a coherent cross section, even with the GCP present in (a).
The final area of interest in cross section MVD03 is the near-channel portion of the right bank (Figure 3.1, chunk 7). The upper portion of the right bank, near the cross section pin, did not produce any usable data due to the dense vegetation (Figure 3.14). The near-channel portion of the right bank, however, was pieced together by modeling three separate chunks and then merging them through the automated process in PhotoScan. To achieve this result, I placed markers on the GCPs visible in the model and input the GCP spatial coordinates collected in the field through the total station survey. However, the resulting orthorectified model had issues of distortion when exported from the PhotoScan software (Figure 3.15). While the orthophotograph was georeferenced to the correct locations for the GCPs, the ends of the model were stretched, flattening out what should have been steep topography. When viewing the model in PhotoScan from directly above, this distortion problem was not apparent. When rotating to a perspective view or exporting an orthophotograph, the skew was clear (Figure 3.16). The cause of this distortion could not be directly determined primarily due to the automated nature of the software which has few changeable input or adjustment features. It is likely that inadequate data collection was the issue in this case. The characteristics of this reach, a steep bank scarp, patches of vegetation, and highly three dimensional boulders of various sizes, created abrupt elevation changes (Figure 3.15). Since the photographs were only taken at one angle, it was difficult for the software to interpret the steep changes in topography. Additionally the concentration of GCPs in the center of the model is likely to have contributed to the skew in the model.
Figure 3.14: Photograph of the MVD03 upper right bank that is so densely vegetated it could not be used for reconstruction because common points could not be determined (taken October 8, 2012).
Figure 3.15: A view down the bank scarp of chunk 7 on the left bank of MVD03, with a placed GCP at the base. This steep scarp creates problems for achieving a proper perspective of the ground surface topography (taken October 8, 2012).
Figure 3.16: (a) The SfM model of the right bank of cross section MVD03. The location of GCPs (blue flags) near the center of the model inhibited the orthorectifying of this model as distortion toward the edge of the image became an issue in orthophotograph and DEM generation. (b) An attempt to generate an orthophotograph from the model of chunk 7.
CHAPTER FOUR: DISCUSSION

The attempts to create SfM models of river cross sections at the Souhegan River field site had varying degrees of success. Where vegetation was minimal and photographs were collected from multiple angles, primarily the central sand bar of MVD04 (Figure 3.1, chunk 1), SfM model results could be quantified (Figure 3.2). In the areas with thick vegetation (Figure 3.14) or deep water (Figure 3.6), SfM processing was unable to identify sufficient common points for model reconstruction. Areas with steep bank scarps (Figure 3.15) also proved difficult for SfM to reconstruct, likely due to an insufficient amount of photographic data and GCPs spaced incorrectly or too far apart. Additionally, some areas, primarily the channel of MVD03 (Figure 3.13), could not be modeled in large chunks or pieced together as a result of a low camera vantage point and widely spaced ground control reference points.

4.1 SfM and Total Station Data Comparisons

For the successfully modeled central sand bar in cross section MVD04 (Figure 3.1, chunk 1), a quantitative comparison to total station survey data, collected on the same day, was carried out. A point-to-point assessment was made by looking at the extracted DEM values of the SfM model that correspond to the precise total station survey locations. Differences in the two methods were calculated with positive values corresponding to points where SfM model results were higher than the total station survey results (Table 1).
Table 1. The elevation values for total station survey and SfM modeling results are shown for each total station point of chunk 1. Point ID 132 is farthest towards the left pin while point ID 150 is farthest to the right pin (Figure 3.2). The elevation differences between the two methods are presented, with the average difference calculated to be 3.6 cm ±3.4 cm standard deviation. Substrate was interpreted by orthophotograph observation.

For these results, the average vertical difference between the two data collection techniques is +3.6 cm with a standard deviation of 3.4 cm, indicating that on average the SfM derived elevations are 3.6 cm higher than the corresponding total station survey points. The SfM elevation data set is generated through an interpretation of the model surface created with only photographic and minimal GPS coordinate data inputs.

There are several potential sources of error in the elevation data collected through these methods. The point comparisons with the largest differences, IDs 142-144, fall in the sandy area.
of the bar where there is little vegetation. In this area, there may have been a greater amount of sink by the reflector pole used for the total station survey than in other portions of the bar that are more consolidated or are comprised of larger size grains. The reflector pole used in this study did have a pointed end, which could easily sink 3-5 cm into sand when placed, causing the ground heights recorded by the total station to be below the actual elevation. The average difference between methods for points with a sand substrate is 0.052 m, as compared to an average difference of 0.024 m with a gravel substrate, suggesting the sink of the pole may have had a quantifiable effect on the results of the total station survey (Table 1). Another factor potentially contributing to the large errors could be the location of these points a distance away from GCPs. This requires more interpolation in PhotoScan to construct the model elevations.

In addition, interference from vegetation definitely affected certain portions of the DEM; the average difference between methods for points identified with vegetation is 0.040 m. While not as high as in the sand substrate points, the difference for vegetated points is above the 0.024 m average for gravel points (Table 1). Although not obvious from the point-to-point comparison, these effects can be clearly seen in the continuous cross section (Figure 3.2 (c)). The steep elevation changes displayed in the cross section match precisely with the vegetation shown in the orthophotograph (Figure 3.2 (a)).

It is possible that another source of error is the resolution of the DEM derived from the SfM model. The small (~0.5 cm) changes in height resolved in the DEM are likely noise in the model results as opposed to an accurate representation of ground heights. Although the texture of individual sediment grains can be seen in the three dimensional model and exported orthophotograph (Figure 3.2 (a)), the generated DEM cannot precisely pick out small scale changes between individual particles (Figure 4.1). In my study, this limitation is likely due to the
shadowing effects of the sides of gravel and the relatively sparse data collected as compared to the volume of photographs used to produce smaller scale differences in other comparable studies (e.g., James and Robson, 2012).

Figure 4.1: (a) A close-up view of the Figure 3.2 (a) orthophotograph. (b) A close-up view of the Figure 3.2 (b) DEM with hillshading. By observing these images next to each other, it is possible to observe that the slope changes indicated by the hillshaded DEM do not correspond to individual grains in the orthophotograph.

A point-to-point comparison provides a way to directly compare the SfM technique to a total station survey, yet does not highlight one of the primary advantages of SfM modeling. As Figure 3.2 demonstrates, the amount of data generated through SfM modeling far exceeds that which can be collected by human-power running a total station survey. The tan line in Figure 3.2 (c) represents a continuous cross section extracted from the 1.5 mm/pixel DEM of chunk 1, a
much larger data set than it is feasible to generate with total station surveying. Although individual grains could not be accurately tied to elevation data in this study (Figure 4.1), the enlarged data set nonetheless provides more detail to the topographic results. The potential downside to SfM modeling in some study sites, however, is the obstruction caused by vegetation. In Figure 3.2 (c) for example, the spike approximately 37 m from the left pin can be identified as vegetation since it corresponds with the vegetation in the orthophotograph (Figure 3.2 (a)). This shows a false peak in the SfM results while total station survey data avoids this error because only data of the ground surface is collected.

While this study focused on generating cross sectional elevation data, it is important to note that SfM generates much more than a two dimensional line of data points. In this regard SfM has similarities to terrestrial laser scanning (TLS) methods where a three dimensional model is created. In the successful reconstruction of the central sand bar of MVD04 (Figure 3.1, chunk 1), a model was generated that extended not only across the sand bar for a length of approximately 32 m, but also was built horizontally with a dense point cloud ranging between 2 m and 5 m based on the extent individual photograph overlap (Figure 3.2). This is an important advantage of the SfM technique. The elevation raster (Figure 3.2 (b)) I produced could be used in its own right for studying channel change, in addition to providing a mechanism for the extraction of cross sectional elevation data, which was the intent of this study.

4.2 Site Constraints

While my study confirmed that Structure from Motion (SfM) can be successfully used in geomorphic studies, it also identified a number of factors that should be modified in order to
make SfM more effective.

With regard to the specific conditions of the survey site, the water surface created the most significant obstacle. Research confirmed what is intuitively obvious. Because the PhotoScan software functions by matching identical data points, the inherent movement of water creates a condition which cannot be accommodated, unless photographs are taken from multiple vantage points at the exact same time. The SfM algorithms do not compensate for movement of the target surfaces over time, which is the case with the water surface in a river channel. Where the water is shallow (<0.25 m), pebbles/cobbles were identified in model reconstruction; however, they were interpreted as being the height of the water surface as opposed to the actual bed elevation (Figure 3.7). The presence of water caused the SfM algorithm to interpret all objects as simply having the water surface height. Additionally, where the water is deep and slow moving, the photographs of the water surface are so dark that the software cannot distinguish separate data points (Figure 3.6). The presence of water also inhibits connections between chunks, preventing model results from being combined into a continuous cross section (Figure 3.1). The non-continuous nature of the models generated in this study prevented georeferencing since there were insufficient GCPs in the individual chunks (Figures 3.5, 3.7, 3.13).

Vegetation also proved to be a limiting factor in the use of the SfM software (Figure 3.13). Although less significant than water, vegetative cover and its constant, subtle movement also interferes with data analysis because capturing photographs over time leads to slight variations in the photographed scene. Also, the complex vertical changes of branches and grasses would require a large number of photographs to accurately model the small, steep shifts (Figure 3.11). Even more significant, modeling of a vegetated terrain maps the top of the vegetation
cover instead of the underlying ground surface, thus obstructing geomorphic results (Figures 3.2 and 3.10).

The final site condition that negatively impacted the study results was inconsistent lighting, caused by either shadows or cloud cover (Figure 3.5). Both impact the clarity and color of the photographs and thus the resulting models. Although minimized by the time of day during which my images were shot, the segments in which shadows did exist rendered the software less effective.

4.3 Data Collection Constraints

A thoughtful field plan is essential when using SfM to ensure the necessary parameters are met for SfM reconstruction. Without a sufficient amount of photographic overlap (>40%) or enough photographs to accurately detail the site, the software is not able to correctly interpret spatial relationships between photographs. The same is true if the photographs are not of adequate quality; blurry photographs prevent point cloud estimation (Fonstad et. al., 2013). Furthermore, in order to accurately georeference and orthorectify modeling results there must be at least three GCPs per modeled area, a factor that can be controlled by camera height and GCP placement. A balance must be achieved between small-scale accuracy and a high enough vantage point to acquire photographs with >40% overlap, while also capturing the intended study area without excessive time or photographic data (James and Robson, 2012). Maintaining a consistent camera height and camera angle are also important for an accurate reconstruction of the study area.
Increased attention to the factors identified above would enhance the ability of the PhotoScan software to produce accurate reconstructions for use in channel change studies. To the extent feasible, it appears advantageous for future studies to focus on sites with small amounts of water and vegetation or to be conducted at times of the year when these conditions are minimized. While the camera specifications are not critical, a high vantage point, non-blurry photographs, consistent photograph angles and heights, and a large number of ground control points in the survey area would all enhance the PhotoScan modeling results.
CHAPTER 5: CONCLUSION

This study demonstrates that there is potential for the use of the Structure from Motion (SfM) method in channel change studies. As James and Robson (2012) and Westoby et al. (2012) demonstrated, SfM can be a tool comparable to ground based lidar (TLS) if the data input requirements for SfM reconstruction are adequately met. For Fonstad et al. (2013) the main challenge was obtaining clear photographs, whereas in my study a combination of ground control point location and low, oblique photographic vantage points impacted the success of the study. However, my study does show that with adequate photographic and GPS data SfM can approximate surface topography with reasonable accuracy as demonstrated in Figure 3.2. The volume of data SfM produced for this cross section far exceeded that collected in the total station survey of the same area (Figure 3.2 (c)). Furthermore, a point-to-point comparison confirmed that the model represented the topography of the sand bar within a reasonable range of error (Table 1, Figure 3.2 (c)).

Unlike the 45 GCPs James and Robson (2012) placed in their study area of a volcanic crater, GCPs in my study were positioned to provide only sufficient GPS data for a continuous model of the study area cross sections. Due to flowing channels, steep bank scarps, and areas of thick vegetation, an entire cross section could not be modeled continuously. As a result, the GCP data I collected was insufficient to georeference smaller chunks and therefore it was not possible to piece them together outside of the PhotoScan software (Figure 3.1). The limited positive results of my study were caused by a number of controllable factors. Both site and data collection constraints restricted the ability of the software to accurately create a useable model. In order to confirm the feasibility of using SfM in channel change studies with greater certainty, additional testing should seek to minimize these factors.
Based on my findings, future tests of SfM's use in channel change studies should focus on non-vegetated sites with minimal water and consistent lighting conditions. A higher vantage point, more ground control points and an increased number of well-focused photographs, as compared to this study, would likely produce more useable cross sections. Additionally it would be beneficial to continue the work of James and Robson (2012) and Westoby et al. (2012) in testing the accuracy of using the SfM technique as an alternative to ground-based lidar (TLS), which is more expensive and potentially less mobile in the field than SfM data collection.

Recent research has produced positive results in applying SfM methods to geomorphic studies. My study confirms that SfM can be a powerful tool for measuring rates of change in stream channels and producing large quantifiable data sets, given its low cost, ease of use, and potential to expedite data collection.
REFERENCES CITED


APPENDIX

MVD03 Setup:

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NGS OPUS SOLUTION REPORT

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

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ARP HEIGHT: 1.835

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ANT NAME: LEIAX1202A      NONE             # FIXED AMB:    27 /    32   :  84%
ARP HEIGHT: 1.835                                  OVERALL RMS: 0.015(m)


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Z:      4315930.314(m)   0.047(m)           4315930.293(m)   0.047(m)
LAT:   42 51 27.63095      0.041(m)        42 51 27.66602      0.041(m)
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W LON:   71 29 44.52605      0.022(m)        71 29 44.54039      0.022(m)
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ORTHO HGT:           35.489(m)   0.043(m) [NAVD88 (Computed using GEOID12A)]

US NATIONAL GRID DESIGNATOR: 19TBH9610548031(NAD 83)

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MVD04 Setup:

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NGS OPUS SOLUTION REPORT
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All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: ccarmistead@gmail.com                   DATE: November 07, 2012
RINEX FILE: 2___282q.12o                            TIME: 15:33:12 UTC

SOFTWARE: page5  1209.04 master2.pl 0821123      START: 2012/10/08  16:42:00
EPHEMERIS: igs17091.eph [precise]                  STOP: 2012/10/08  18:42:00
NAV FILE: brdc2820.12n                            OBS USED:  3546 /  3879   :  91%
ANT NAME: LEIAX1202A      NONE             # FIXED AMB:    28 /    34   :  82%
ARP HEIGHT: 1.79                             OVERALL RMS: 0.013(m)

X:      1486213.061(m)   0.044(m)           1486212.240(m)   0.044(m)
Y:     -4440582.026(m)   0.165(m)          -4440580.599(m)   0.165(m)
Z:      4315968.958(m)   0.043(m)           4315968.937(m)   0.043(m)
LAT:   42 51 29.35456      0.088(m)        42 51 29.38963      0.088(m)
E LON:  288 30 17.33956      0.049(m)       288 30 17.32522      0.049(m)
W LON:   71 29 42.66044      0.049(m)        71 29 42.67478      0.049(m)
EL HGT:            7.437(m)   0.143(m)                 6.240(m)   0.143(m)
ORTHO HGT:           34.982(m)   0.242(m) [NAVD88 (Computed using GEOID12A)]

UTM COORDINATES STATE PLANE COORDINATES
UTM (Zone 19)         SPC (2800 NH )
Northing (Y) [meters]     4748083.416            39799.014
Easting (X)  [meters]      296149.582           314014.563
Convergence  [degrees]    -1.69777099           0.11664061
Point Scale                1.00011125           0.99996908
Combined Factor            1.00011008           0.99996791

US NATIONAL GRID DESIGNATOR: 19TBH9614948083(NAD 83)

BASE STATIONS USED

<table>
<thead>
<tr>
<th>PID</th>
<th>DESIGNATION</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>DISTANCE(m)</th>
</tr>
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<tbody>
<tr>
<td>AF9520</td>
<td>WES2 WESTFORD CORS ARP</td>
<td>N423647.974</td>
<td>W0712935.968</td>
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<td>ZBW1 BOSTON WAAS 1 CORS ARP</td>
<td>N424408.558</td>
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NEAREST NGS PUBLISHED CONTROL POINT

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<th>DESIGNATION</th>
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<th>LONGITUDE</th>
<th>DISTANCE(m)</th>
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<tbody>
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<td>A 10</td>
<td>N425141.5</td>
<td>W0712915.2</td>
<td>727.0</td>
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</tbody>
</table>

This position and the above vector components were computed without any knowledge by the National Geodetic Survey regarding the equipment or field operating procedures used.