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Rio Grande Lidar Bank Erosion Monitoring: Preliminary 2007-2008 Results and Survey Design Considerations

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Abstract: Bank stability is an important issue along the Albuquerque reach of the Middle Rio Grande. On one hand, stability and property protection is desirable along the urban corridor. However, stability may not be beneficial to the endemic species that inhabit the river and evolved in a much more dynamic system. To better understand the factors controlling banks stability and erosion along the Middle Rio Grande, we seek to apply high-resolution chronotopographic analysis using terrestrial lidar and erosion pin measurements coupled with in situ measurements of soil erosion parameters. The terrestrial lidar campaign along the densely vegetated Middle Rio Grande has required the development of new workflows and highlighted some of the limitations of terrestrial lidar in this environment. Nonetheless, the data collected during this study should provide useful information on seasonal to interannual changes at spatial resolutions that could not be achieved using other techniques.

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Preface

The research presented in this report was developed by the University of New Mexico (UNM) under the direction of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Technical Programs Office. Funding was provided by the Urban Flood Damage Reduction and Channel Restoration Development and Demonstration Program for Arid and Semi-Arid Regions (UFDP) and the Southwest Urban Flood Damage Program (SWDP) of the USACE General Investigation Research and Development Program. Authorization of the U.S. Army Corps of Engineers to conduct research and development is codified in 10 U.S.C. 2358.

Work was performed under the general supervision of Dr. Lisa C. Hubbard, UFDP and SWDP Program Manager, Dr. Jack E. Davis, Technical Director for Flood and Coastal Storm Damage Reduction, William R. Curtis, Program Manager of the Flood and coastal Storm Damage Reduction Research and Development Program, Dr. William D. Martin, Director, CHL, and Jose Sanchez, Deputy Director, CHL. This report was prepared by Dr. Tim F. Wawrzyniec, Jed D. Frechette, Dr. Julie Coonrod, and Dr. John Stormont, all of the University of New Mexico. Technical reviews was conducted by Darryl Eidson of the U.S. Army Engineer District, Albuquerque, and Dr. Hubbard.

COL Gary E. Johnston was Commander and Executive Director of ERDC and Dr. Jeffrey P. Holland was Director.

1 Introduction

Bank erosion is largely achieved by two end member processes, bank scour and mass wasting. Both processes may or may not operate in concert to transfer sediment from bank storage into the active fluvial system. Bank scour generally results from relative increases of flow velocity, while mass wasting is a catastrophic event that takes place after a high flow event or flood has saturated the bank. The transiently high pore fluid pressure results in slumping of material after the channel flow has returned to normal levels. Both types of bank erosion are influenced by natural and anthropogenic perturbations that can accelerate bank erosion beyond normal background levels where background erosion rates are largely a function of sediment cohesion, root density, and flow characteristics. Key changes in the channel system that can greatly accelerate bank erosion include incision of the bed or bedload sediment extraction, transient high pore-fluid pressures within the bank following a rapid drop in flow level, the introduction of features that redirect flow, removal of root mass and vegetation, and variation in surface wave dynamics (Queensland 2008).

Within the Rio Grande urban riparian corridor, the evolution of the banks and flood plains of the Rio Grande have undergone a wide range of anthropogenic modification since the late 1930s and the creation of the Middle Rio Grande Conservancy District (MRGCD; Scurlock 1998). Concerns over urban flooding and the restoration of agricultural lands after spring floods provided motivation to construct levees and insert jetty jacks to stabilize the banks and establish a single channel. Flood control efforts were further advanced by the construction of the Cochiti dam, which is located about 60 miles upstream of the urban corridor and allows district water managers to govern flow of the main channel. The only rapid changes in flow that now occur within the corridor result primarily from large precipitation events that take place in subsidiary drainages that enter the main channel downstream of the Cochiti structure.

Stabilization of the Rio Grande urban corridor has had important impacts on the riparian ecosystem, which is the subject of the efforts of many to mitigate stabilization effects on the habitat of endangered species including the Silvery Minnow and the Willow Fly Catcher. In accomplishing this objective, multiple agencies are working to restore native cottonwood stands, which are threatened due to a lack of over-bank flow and an abundance of invasive plant species originally introduced to encourage bank stability along the entire reach of the Rio Grande. Mechanical means are being used to remove invasive species and to encourage more frequent over-bank flows.

The purpose of this project is to conduct monitoring experiments that employ terrestrial lidar technology and traditional erosion pin measurements in an attempt to evaluate how mitigation activities affect bank stability along the Albuquerque reach of the Middle Rio Grande. Our specific objectives are to: (1) define a clear approach for conducting chronotopographic analysis along active fluvial channels; (2) establish a method for representing four-dimensional bank change; (3) establish a method for approximating bulk volumes of change; and (4) document error sources that affect the quality of these estimates. Terrestrial lidar is the primary tool for achieving these objectives, while erosion pin measurements provide valuable comparative data and a way to collect measurements under conditions where lidar cannot be used. In addition to collecting lidar and erosion pin data for chronotopographic analysis, we are also building a device that can be used to collect quantifiable measures of bank cohesion in the field. These two types of data will be used to investigate the relationship between soil cohesion and measured erosion.

2 Methods

Why terrestrial lidar for surveying change detection?

The use of airborne and terrestrial lidar scanning (TLS) technologies to create spatial models for a variety of purposes is rapidly becoming a mainstay requirement for a burgeoning field of geospatial analysis (Belliss et al. 2000; Hare et al. 2001; Gamba and Houshmand 2002; Charlton et al. 2003; Nagihara et al. 2004; Bellian et al. 2005; Wawrzyniec et al. 2007a and b). In more recent years, significant advancements in computing power, laser, and battery technology have resulted in the production of many high-resolution, terrestrial scanners that are eye-safe, lightweight, and can produce three-dimensional imagery with sub-centimeter precision and precision at distances of up to 2 km (Shirley 2003). Some additional gains have been made in distance capability, but most improvements since 2003 have resulted in faster, lighter scanners, and the coupling of scanning with high-resolution digital photography. The digital imagery is collected with a calibrated camera lens that allows the scanner system to assign Red Green Blue (RGB) color values to each point collected during scanning. It is these advancements that are providing a new range of observations that can be made quickly and in a geospatial reference frame.

One of the earliest applications of lidar technology to topographic change detection was the measurement of mass wasting rates to identify sites of erosion or instability. The measured rates of change at these sites was then used to estimate introduced bed and suspended loads as a means to evaluate fluvial contaminant transport (Thoma et al. 2001).

Terrestrial lidar provides the opportunity to conduct similar studies at a much finer scale. Depending on the specific mission parameters, instrument used, and target properties, the uncertainty associated with each airborne measurement is on the order of decimeters. For example, a mission flown at a height of 400 m has an uncertainty of approximately 25 cm (Baltsavias 1999). This level of performance is unable to accurately capture any changes less than about 0.5 m in scale (Bonham-Carter 1996). In this context, studies based on airborne lidar data are only able to capture major changes in bank modification. In addition, James et al. (2007) demonstrated that airborne data sets have difficulty accurately capturing the geometry of gullies at scales of centimeters to meters in depth. When compared to direct field morphometric characterization, digital elevation models generated from airborne lidar data sets recreate narrow channels with steep banks as having shallower depths with sloped banks and larger cross-sectional areas. This is due in part to the scale of the topographic change approaching the detection limit and resolution of the airborne data set. It also reflects a problem that results from the angle of incidence where the top of the bank generates a shadow that prevents direct measurement of the base of the bank, thus the entire geometry of the bank is not captured (James et al. 2007). In the context of change detection, apparent changes in bank geometry could occur solely as the result of changes in the location of the sensor platform. Such a shift would necessarily bias the data to show, possibly significant, change where none actually occurred.

In this investigation, ground-based lidar technology is evaluated as a tool to perform cost-effective high-resolution bank stability monitoring during on-going restoration and modification of the urban reach of the Rio Grande. In doing so, future investigations may use this data to estimate the total contribution of sediment that directly results from these efforts within the urban corridor.

Applications and limitations of terrestrial lidar

Ground based lidar technology has a range of applications that are ideal for capturing a variation of surface topography that is too fine to be observed accurately using airborne data sets. Nonetheless, there are limits to the accuracy and practicality of this approach.

Lidar technology, in general, is ideal for geospatial characterization for the purpose of change detection. No other method gives the sampling resolution without invasive modification of the site being monitored (e.g., total station surveying, erosion pins, etc., Wawrzyniec et al. 2007b). Based on the work presented here and previous studies, ground-based lidar is most applicable to locations where the desired lower limit of change detection is < 0.5 m, the channel has been recently modified, is free of vegetation, and where the bank geometry has a steep (> 45 deg) slope. Given these criteria, bedrock channels, braided streams, arroyos, and active steep banks are the ideal locations for capturing seasonal or even daily erosional contributions to the active fluvial channel.

To provide eye safety and limit noise from other emitters (e.g., the sun), terrestrial lidar systems use near infrared wavelengths that are strongly absorbed by water. This design limitation has a strong impact on their use for monitoring fluvial systems. Because nothing below the water's surface can be imaged, all data collection must occur during low flows or when water has been diverted from the target area.

Additional limitations are introduced by the ground-based view angle. Airborne data can often image the ground surface below a forest canopy. This is achieved by collection of many overlapping beam shots and full acquisition of the reflective waveform of the laser return. Post-acquisition processing allows the instrument operator to select those parts of the waveform believed to represent the deepest reflection below the canopy for each shot collected. Such results can be further filtered to derive a reasonable "bare-Earth" model. Ground-based instruments must be easily portable. To achieve this portability, the operating software only saves two major peaks of the laser return waveform detected by the electronics. The rest of the signal is discarded creating a highly compressed data file easily stored within on-board flash memory or to a slave portable computer. A related issue is the non-nadir perspective. Laser shots passing through a forest canopy vertically will hit the ground within 10-30 m, depending on the height of the canopy. Collecting data from a ground-base view requires the laser shot to pass through vegetative cover horizontally. Depending on topographic roughness, the beam may have to pass through 10s or 100s of meters of vegetation before potentially striking a ground surface. Thus, the probability of actually detecting the ground surface is greatly reduced.

We have identified a number of other issues specific to working within the riparian corridor of the Middle Rio Grande. First, the flow regime is highly regulated and the river no longer experiences the large floods and hydrograph variability that characterized the pre-Cochiti Rio Grande. As a result, many banks have become stabilized by dense vegetation and are relatively immobile (Meyer and Hepler 2007). Second, sampling bank geometry at sub-centimeter resolutions generates an enormous amount of data that tests the limits of existing computational hardware to process. Both of these limitations can be overcome by focusing on key parts of the stream where change is most likely to take place (e.g., construction sites, locations where vegetation have been removed, etc.). In selecting such reaches, a secondary limitation regarding scale is encountered.

In collecting data within selected areas instead of the entire reach, the spatial variability of bank modification processes may not be adequately sampled. This is of course an issue for any observational study and lidar represents our best opportunity to improve over traditional methods like the use of erosion pins. Nonetheless, by reducing the scope of the observations, the limitation does exist.

A final limitation that any modern process study must address is the question of how representative the period of observation is relative to the longer historical record. In a climate as variable as the southwestern United States, it is almost certain that any study lasting only a few seasons will not be able to fully represent the climate and associate geomorphic variability that can be expected on decadal, centennial, or longer time scales. During our studies' time frame, we may only capture processes that occur on a regular basis and only through serendipity will we capture the rare catastrophic event that leads to major changes in bank geometry. This is a problem if, as in the case of many other systems, these larger episodic events play a strong role in shaping the fluvial system.

Terrestrial lidar survey design

Any ground-based survey for chronotopographic analysis consists of multiple elements that must be considered before data acquisition. In general, it is necessary to consider the scale of change the investigation is attempting to capture, need of georeferenced data sets, monumenting for registration of data sets, site environmental conditions, potential sources of error, and useful metadata to record during acquisition and processing of the data.

Sampling resolution will guide the amount of data collected and dictate the scale of topographic changes that can be detected using lidar techniques. If surface roughness elements have a surface roughness with a magnitude of 2-3 cm with a similar spatial frequency, it is necessary to collect data with a resolution of 1.0-1.5 cm. In doing so, you will tend to capture the general character of surface roughness, but the full variation of the surface cannot be realized. Decreasing the sampling step values to below this half-step rule will provide an improved representation of the surface. However, improved resolution increases the number of data points exponentially, which places more demands on the processing environment. For this study, we are hoping to capture 2-5 cm scale change and most of our surveys were completed at 2-15 mm resolution at the median range to the target.

Georeferencing is only necessary if the resulting data sets will be compared to other geospatial data sets or if absolute differences must be measured. If this is the case, the georeferencing methods used must be chosen carefully to provide the accuracy required for meaningful comparisons. Sub-centimeter georeferencing of the data can be achieved by using an Real Time Kinematic (RTK) Global Positioning System (GPS) device or theodolite to survey in scanned targets or collection sites used during data acquisition. In contrast, relative differences may be adequate for many geologic applications, allowing all work to be done in a local coordinate system, greatly simplifying data collection and processing.

For this study we are most interested in measuring relative changes between collection trips. Therefore, high-precision georeferencing was not necessary. Most of the data were collected using a tribrach to level the scanner to within 8 min of arc. The orientation of the scanner during data collection was also recorded with a Brunton Pocket Transit. In addition, the approximate coordinates of collection sites were determined by averaging GPS measurement from a Garmin GPSMAP 60. Taken together the data are georeferenced within 2-4 m accuracy and could be fully registered to 0.5-1.0 m precision, if desired, by merging with one the airborne lidar data sets of Bernalillo County.

Regardless of whether high-precision georeferencing is required, surveys designed for chronotopographic analysis do require fixed monuments in the target area. For many natural systems, where a scanning campaign only lasts a few years, trees, rock outcrops, concrete footings, bridges and other enduring structures are ideal. By including these features within the target area, scans collected at different times can be coregistered into a local coordinate system. The precision of registration is strongly dependant on the resolution of the scan and instrument accuracy. In the absence of these features, surveyed benchmarks can be used but they require the placement of a detectable target or survey rod placed over the benchmark during data acquisition.

For this study, several temporary benchmarks were used consisting of 6.1 m of 1.27 cm diam rebar driven vertically into stable floodplain surfaces. During scanning, custom designed targets were placed over the benchmarks prior to scanning. The target consisted of a cross constructed of 3.81 cm diam schedule 80 polyvinyl chloride (PVC) attached to a mini-range pole equipped with an 8-min accuracy bubble level. The targets were placed over the monument and served to define vertical and horizontal axes over the target. The elevation of the center of the target over the monument was measured. To improve reflectivity, the target was covered with white gaffers tape, which was reflective to 905 n.m. near-infrared light. Scans that capture these targets allow the operator to define a registration point that represents the surveyed monument, which can be used for registration of multiple scan events for comparative analysis.

From acquisition to final processing, error is introduced from a variety of sources. Instrument design (Lichti and Jamtsho 2006), environmental conditions (MacKinnon and Blais 2008), and survey design (Gordon and Lichti 2004; Lichti et al. 2005) play the largest roles in acquisition related errors. Additional errors are introduced during processing and in data reduction to final model products (e.g., Bater and Coops 2009).

The instrument used for this study was an Optech Ilris 36D or equivalent. Compared to other ground-based scanners, the Ilris 36D is back-pack portable, provides raw (non-acquisition processed) data, and has a cylindrical beam design that provides minimum dispersion values at ranges up to 500 m under common scanning conditions. Dispersion of the beam and its initial diameter define the size of the laser spot that strikes the target. The spot size affects both the range and angular precision of the instrument (Lichti and Jamtsho 2006) and should be minimized for the most precise measurements. At a range of 100 m the Ilris 36D has a spot diameter of 2.9 cm. Improved resolution can be obtained by correlated sampling and the manufacturer claims precision of 0.7-0.8 cm at 100 m for the Ilris 36D. For complex scenes the accuracy is probably lower, however, at ranges of less than 200 m, which are typical for this study, the uncertainty associated with individual measurements is likely less than 4 cm (Lichti and Jamtsho 2006). Additional errors may be introduced by failures, however, these gross errors are typically easy to identify and can be corrected during processing.

Environmental errors are introduced by variations in atmospheric conditions. Variations in air density manifest as wind or heat shimmer can greatly reduce the range and accuracy of any lidar scanner. Because the laser beam is absorbed by water, rain or snow will diminish the signal and may diminish the apparent intensity of the target. With weaker intensity, the resulting data are less accurate. The same issue applies for surfaces that are wet or covered by a film of water. Airborne particulates can also serve to diminish the reflected intensity of the target by causing greater dispersion of the beam in flight. Vegetation, pedestrians, and flying objects can also move into the beam during shot acquisition and also reduce the reflective intensity of the return from the primary target. The latter may also result in gross errors that must be removed during processing.

Multipath reflections from the water surface have been one source of environmental errors that have had a major impact on the time required for data processing during this project. Although most of the energy in the 1,500 nanometer band used by the Ilris 36D scanner is absorbed by water (Hale and Querry 1973), a small portion may be reflected, strike a target above the water surface, and return to the scanner generating a low intensity mirror image of the target below the water surface. These multipath reflections are common in scans collected during the course of this project. Due to the large negative impact these reflections have on data quality it was necessary to remove them prior to further processing. A filtering algorithm was developed for automatically identifying and removing these multipath reflections based on the characteristic changes in reflection intensity and surface geometry that occur at the water surface (Frechette et al. 2008). Use of the program developed to implement this algorithm has greatly increased our ability to efficiently process data from environments where multipath reflections from water surfaces are common.

The final important source of error is related to processing. The instrumentation used in this study collects data in a 40-deg vertical and 40-deg horizontal field of view. To capture an entire outcrop it is necessary to merge overlapping scans. The primary method for doing this is a shape-based least squares fitting algorithm. During this project this task is completed using PolyWorks Version.10. With clean exposures and little or no vegetation, the best-fit error will be comparable to the instrument error (+/-5-35 mm). Non-woody vegetation may compound this error up to +/-13 cm. If more than three scans must be merged to represent an entire exposure, these errors can be compounded during the merging process. To minimize this effect, the central or most prominent scan is kept fixed and the other scans are aligned to this reference frame only using clearly exposed, bare Earth bank exposures. Therefore, it is critical that the operator select regions of overlap with clean exposures or visible monuments during data acquisition.

A final issue to consider during survey design, acquisition, and processing is the organization and completion of metadata. During acquisition of lidar data for chronotopographic analysis, it is critical to record the date and time of the scan, selected target resolution, scanner location, precision of location, facing direction of the scanner if scanner is level, orientation of the scanner's x- and y-axes, if the scanner is not level, and scanner functions employed for the scan. Temperature, humidity, and barometric pressure should also be noted. During processing, it is useful to note which scan is fixed during the primary alignment process (scans from one station), and which station is fixed in the secondary alignment process (combining two or more stations). The error for each aligned pair should also be recorded, as it is preferable to align stations using scans with the minimum amount of error associated with the primary alignment.

Direct measurement of soil erosion parameters

A submerged jet erosion apparatus is being used to measure erosion parameters on soils near the banks of the Middle Rio Grande. The jet erosion device is on loan from the U.S. Department of Agriculture-Agricultural Research Service Hydraulic Engineering Research Unit in Stillwater, OK. This device has been used to measure streambank soil erosion parameters, primarily in the Eastern United States (e.g., Hanson and Hunt 2007; Hanson et al. 2002; Wynn and Mostaghimi 2006). An American Society for Testing and Materials (ASTM) standard has been developed for this apparatus (ASTM Method D5852-95). We have made some preliminary measurements, and are in the process of building a jet erosion apparatus using the borrowed system as a template.

A photograph of the jet erosion apparatus is shown in Figure 1. The principal component of the apparatus is a cylindrical, open-bottomed submergence tank that is driven into the ground. Water is introduced into the top of the tank by means of a nozzle that creates a jet of water. The water erodes or scours the soil in the bottom of the submergence tank. A point gage is used to measure the depth of scour as a function of time and head used to create the jet. A standpipe fed by a pump is used to supply water under the desired value of head. Scour depth versus time data is interpreted to provide estimates of critical shear stress (the initiation of erosion) and erodibility (erosion rate). The scour created by the jet device at the conclusion of a test is shown in Figure 2.

Figure 1. Photograph of submerged jet apparatus being used near San Juan Chama Drinking Water Project diversion dam. Submergence tank is in middle of photograph with standpipe used to generate constant head to right.

Figure 2. Observed scour at conclusion of test using submerged jet erosion apparatus.

3 Lidar Monitoring Results

During the 2007-2008 field season three new TLS survey sites were established and data collection continued at sites established during 2006 (Figures 3 and 4). New scans were collected at the original Arroyo Calabacillas site; however, due to data quality and instrumentation issues, the focus of the monitoring campaign has shifted to smaller sites where higher quality data can be collected. Work to correct these issues and collect additional data at the Arroyo Calabacillas is ongoing. Monitoring at the other preexisting site downstream of the San Juan Chama Drinking Water Project diversion dam in Albuquerque has been more productive and has proven to be an excellent test case for developing a workflow to estimate losses of sediment. In addition to these existing sites, two new sites were established along the reach between Interstate-40 (I-40) and Central Avenue. These sites are located in areas where historical bank erosion has been documented by air photograph analyses (Swanson 2007). Finally, an as-built survey of the newly constructed off-channel fish habit adjacent to the Rio Grande Nature Center was completed during February and March of this year.

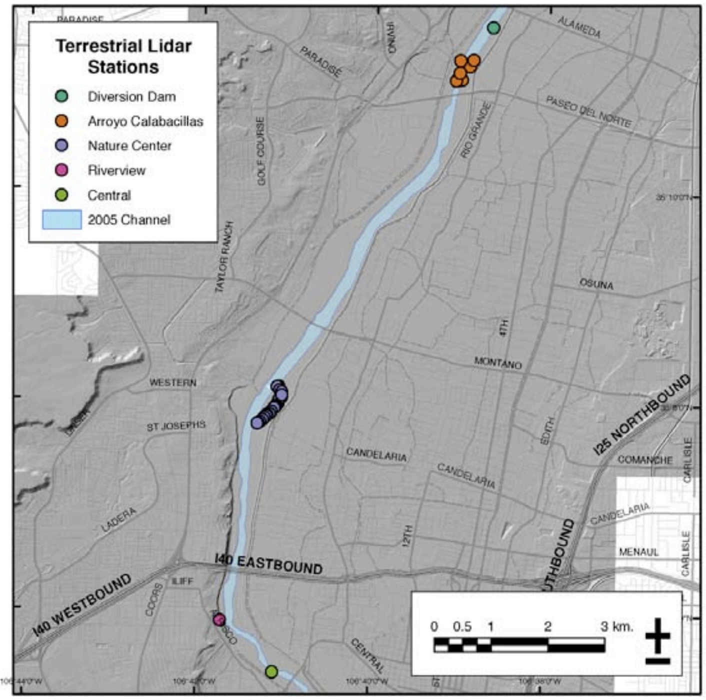

Figure 3. Scan stations for this study plotted on a bare-Earth, 1-m resolution DEM based on 2001 Bernalillo County airborne lidar dataset.

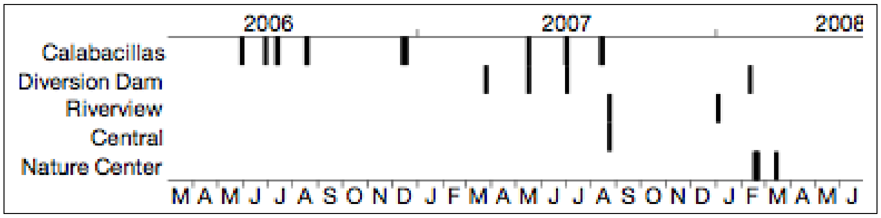

Figure 4. Vertical bars indicate dates when TLS scans were collected at sites (shown in Figure 3).

Arroyo Calabacillas

The Arroyo Calabacillas site is located just upstream of the Paseo del Norte bridge and encompasses both banks of the Rio Grande and the mouth of the arroyo (Figure 3). The site has been actively monitored using TLS since 31 May 2006 and using erosion pins since 21 July 2006.

On 31 July 2006, a thunderstorm produced flows out of the Arroyo Calabacillas that peaked at approximately 68 m^3s^{-1}. These flows deposited tens of thousands of cubic meters of, primarily sandy, sediment at the mouth of the arroyo, deposits that have continued to be modified by high flows up to the present time. The goal of the monitoring program at this site is to measure the magnitude of the initial event and document reworking and downstream transport of the resulting deposit to assess the impact of tributary sediment input on an already constricted reach of the Rio Grande.

The Arroyo Calabacillas site consists of six scan stations capturing over 800 m of channel around the mouth of the Arroyo Calabacillas. On average four or five separate scans from each station are required to capture the entire site. Vegetation at the site is dense and consists primarily of various herbs, forbs, and small trees that are poorly resolved by the TLS and therefore have a negative impact on the quality of shape-based alignment solutions. The error introduced during processing by the dense vegetation and lack of good targets coupled with the large number of scans that must be aligned has resulted in generally low quality models for this site.

Two separate paths are being pursued to improve models of the Calabacillas site and reduce errors to an acceptable level. The first approach involves constraining shape-based alignment solutions using a combination of natural and synthetic targets within the scan scene, and known mechanical constraints on the scanner setup. This approach has achieved mixed success. It has been possible to achieve good results with small numbers of scans, however, errors rapidly increase as additional scans are added.

Although extensive post-processing is the only remedy available for existing data, the profile data collection mode of the new TLS scanner acquired in the fall of 2007 may improve the situation significantly.

Profile mode increases the scanner's horizontal field of view from 40 to 360 deg and would reduce the number of scans required to capture the site from 26 to 6. This should greatly reduce the effect of alignment errors on model quality. Unfortunately, a series of mechanical failures has prevented any profile data from being collected at the Calabacillas site to date. Two other issues may also need to be addressed before profile mode can be used operationally. First, unlike in standard mode, the instrument does not periodically recalibrate itself during a profile scan, as a result measurement accuracy may drift throughout the scan. The manufacturer has stated that drift was negligible during test scans up to 180 deg. This would provide a large enough field of view at this site. However, it is unclear how variable performance is between instruments and how much it is likely to be affected by environmental conditions such as temperature. Reportedly, the manufacture is developing a calibration procedure for profile mode that may be available in a future firmware update. The other concern regarding profile mode arose during target testing. If not corrected for, precession of the scanner's vertical axis due to imbalance of the instrument has the potential to introduce large systematic errors at operational ranges. However, additional testing is still needed to evaluate the magnitude of this effect.

The primary objective for the coming year is to reconcile the existing data from the Calabacillas site with an additional set of profile scans and generate Digital Elevation Models (DEMs) and difference maps from all data sets. Lessons learned during the past 2 years of operation should enable minimized error in these models. Nonetheless, due to the difficult nature of the scanning environment and lack of constraints on some of the early data sets, model errors are likely to be relatively large compared to other TLS data sets and may be more similar to those associated with an airborne lidar survey. Therefore, another vital component of the work will be to accurately document and quantify these errors.

Diversion dam

Shortly after completion of the San Juan Chama Drinking Water Project's drinking water diversion dam, erosion of the west bank was observed downstream of the dam. The dam consists of a series of steel gates spanning the river than can be raised and lowered independently. Lowering the gates closest to the west bank focused flow along the bank leading to higher shear stresses and erosion downstream of the protective riprap. It was quickly realized that this presented an excellent opportunity to develop TLS methods for measuring bank erosion in a relatively controlled environment and a monitoring program was initiated in March 2007 (Figure 4).

In terms of developing methodology, the diversion dam site (Figure 3) offers many advantages over other sites along the river. Not least of which is that erosion is directly linked to operation of the diversion dam, largely removing our dependence on the vagaries of precipitation, irrigation, and dam releases far upstream. Furthermore, erosion is concentrated in a relatively small area allowing us to capture the entire site in a single scan, eliminating alignment errors at each time-step. Alignment errors between time-steps are also greatly reduced because much of the site was cleared of small trees and other vegetation during construction. The larger cottonwoods that remain, as well as the dam infrastructure, provide excellent tie points for alignments and make it easy to accurately assess the quality of alignments between scans collected at different times.

Alignments and vector analyses were performed using Innovmetric’s commercial software PolyWorks Version 10.1pr2. For alignment purposes the scan collected on 3 July 2007 was chosen as the reference scan because it was collected near the middle of the study period and discharge was lowest during that scan. Scans collected on 12 February 2008 and 17 May 2007 were aligned to the July scan and the scan collected on 26 March 2007 was aligned to the scan from May. Final alignment errors considering points within 5 cm were 0.0332 ± 2.0380, -0.0461 ± 1.7362, and -0.0315 ± 1.5650 cm respectively. After completing the alignments in IMAlign, a mesh with a sampling step of 2 cm was created from the March 2007 scan using IMMerge. This mesh was then edited to remove obvious vegetation and fill holes with linearly interpolated faces. Next the resulting mesh and the original point clouds were loaded into IMInspect for further processing and analysis. Planes were fitted to manually selected points along the waterline in each scan and all of the points resulting from multipath reflections below these planes were deleted. Then a plane was fitted to the points on the west dam abutment in the reference scan from July. The difference between each point cloud and the March 2007 mesh was then measured parallel to the normal vector of this plane (Figures 5 and 6). Although it has not been attempted with this data set, it should also be possible to use the method described by Wawrzyniec et al. (2007b) to directly measure the differences between point clouds. This would eliminate the necessity of creating a mesh, decreasing processing time, and eliminating another source of error.

Point cloud differences indicate that up to 1.2 m of retreat occurred locally between March 2007 and February 2008. These data also indicate maximum local progradation of 2.0 m during the same time period. While the “progradation” measurements appear to be accurate they are likely to represent vegetation growth rather than geomorphic change. Notice the vegetation growth in front of the signpost between the dam and the zone of maximum erosion (Figure 5). This highlights the need for close inspection of any results rather than simply stating statistical measures calculated from some portion of the data.

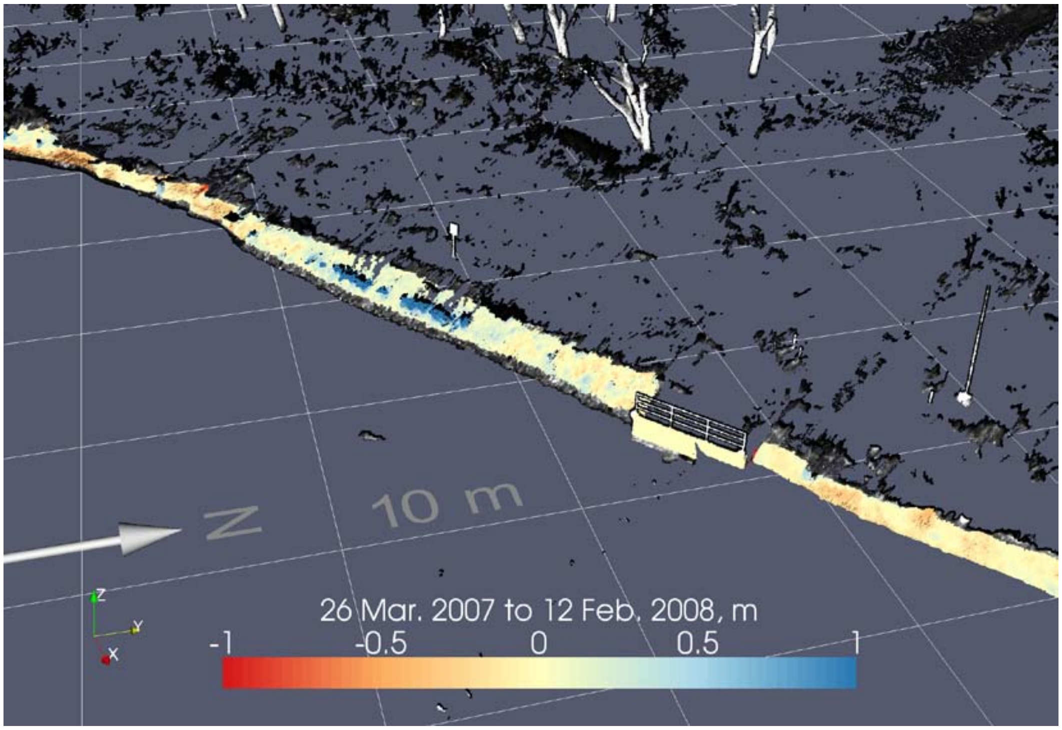

Figure 5. Points shown are from scan on 12 February 2008 and have been colored based on distance between that scan and scan collected 26 March 2007, measured parallel to dam abutment’s normal vector. The west abutment of diversion dam is structure in foreground with railing. The bank is eroding downstream of dam near upper left corner of image. Areas where no differences were calculated, due to lack of overlap, have a grayscale color map that corresponds to intensity of reflection recorded by the instrument.

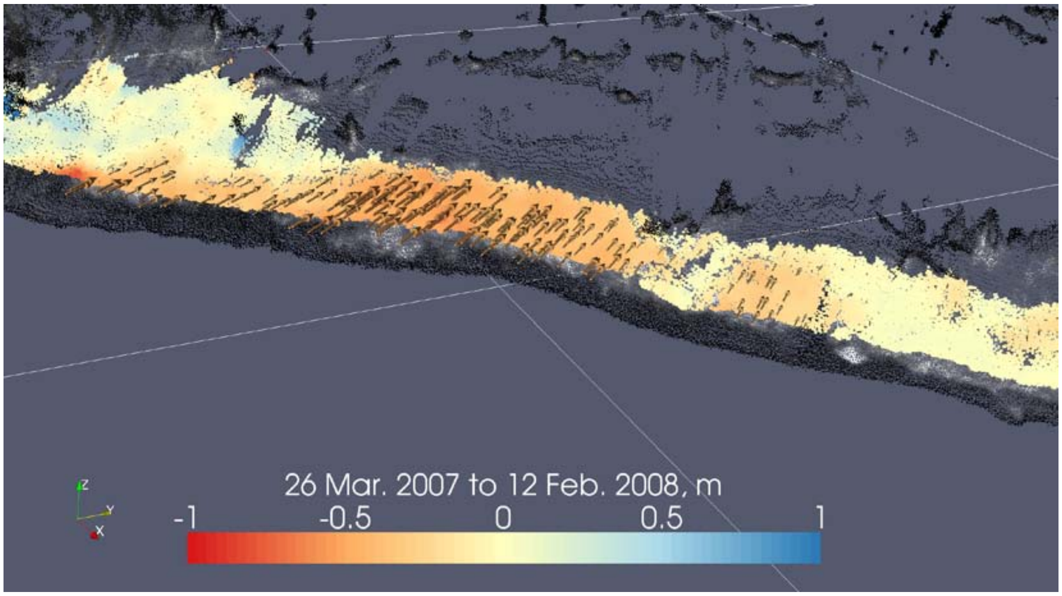

Figure 6. Close-up of bank segment where erosion has been greatest. Color scheme is same as in Figure 5 and vectors show measured erosion at select points.

To estimate the volume of sediment lost downstream of the dam, the TLS point clouds were imported into GRASS GIS and 2D raster distance maps oriented parallel to the dam's abutment were interpolated using a grid resolution of 2 cm. These maps were then subtracted to calculate differences relative to the March 2007 scans (Figure 7). Finally the differences were summed to obtain volumetric estimates of sediment loss. This analysis was limited to the area downstream of the riprap where erosion was greatest and vegetation growth was minor.

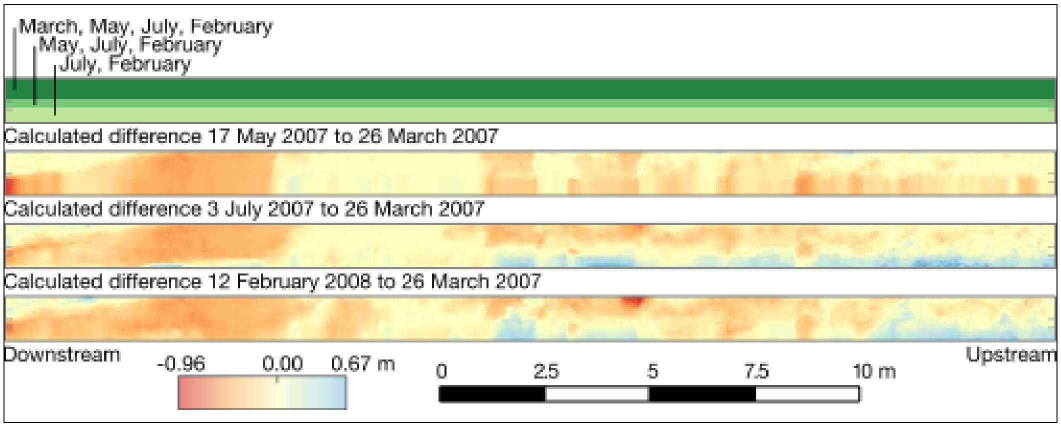

Figure 7. Calculated changes in bank location downstream of City of Albuquerque's drinking water diversion dam relative to first scan collected on 26 March 2007. Map plane is oriented parallel to dams abutment with the waterline at bottom of each panel and upstream end of bank, toward dam, on right. Top panel shows degree of overlap between scans. Dark green area is only area where no extrapolation was performed.

The interpolated grids were produced in two steps. First the raw points were aggregated into an initial raster map containing the mean distance to points within the cell. In addition to reducing the number of points used in later processing steps, this also normalized mean point densities that varied from 0.24 ± 0.38 pts/cm^2 in the May 2007 scan to 2.0 ± 0.95 pts/cm^2 in the July 2007 scan. Next an inverse distance squared (IDW) weighting function was used to calculate the final distance map using the initial raster map as input. These calculations were performed using the data region of the July 2007 scan, which imaged the largest amount of the bank. As a result the distance maps produced from the scans collected during higher discharges contain significant extrapolations in the lower portion of the map (Figure 7). Because an IDW function was used for the interpolation these extrapolated points are largely equivalent to projecting the bottom rows of the scan vertically.

It is arguable whether this much extrapolation is valid, therefore volumes were calculated both with and without the extrapolation. If the maximum data region is used then the change in volume between March 2007 and February 2008 is -3.5 m^3. However, if the minimum data region is used the change is -3.2 m^3. Both of these are minimum estimates, as the bottom of the channel was never imaged. The relatively small difference between the two estimates can probably be attributed to the apparent accretion near the base of the upstream bank (Figure 7). This apparent accretion is probably an artifact of the near vertical extrapolation performed by the IDW, when in reality the submerged bank sloped toward the channel.

Although the diversion dam site has been an extremely useful test case for developing methodology, the results summarized here are not directly relevant to other sites along the river due to the strong influence of dam operation. However, the site does present the opportunity to set up a relatively controlled experiment. With the cooperation of the dam's operators, it may be possible to monitor erosional processes during a single release. Collecting TLS data before and after the release would provide accurate erosion estimates. Coupling these estimates with flow parameter measurements during the release would enable interpretations about the erosional response to specific flow conditions that may be more broadly applicable. Such a medium scale experiment would provide a useful bridge between point data on erosion parameters collected using the submerged jet erosion apparatus previously described and aggregate spatial data collected using TLS and other remote sensing techniques.

Central Avenue to I-40 sites

Historical aerial photography has been used to identify locations and rates of bank erosion along the Albuquerque reach of the Rio Grande. However, because measured changes are often near the limits of detection, uncertainties in erosion rates are large, often 500 percent of calculated rates (Swanson 2007). With our current resources, it would be impractical to conduct regular TLS surveys of the entire Albuquerque reach. However, by surveying specific sites where erosion has been documented by air photograph analyses, we may be able to improve estimates of erosion rates over short timescales.

Monitoring of the Riverview and Central sites (Figure 3) was initiated during 2007. In addition to being sites of documented erosion (Swanson 2007) these sites were also subject to recent anthropogenic bank modifications aimed at increasing in-channel habitat. Therefore, in addition to measuring erosion, continued TLS monitoring of these sites can assess the effectiveness of the bank modifications. Baseline scans were collected at both sites and monuments were installed within the target area of the Riverview site. Both sites are relatively small and can be covered by a single scan station, therefore alignment errors should be small. The Central site is somewhat problematic compared to the Riverview site as it is covered by dense herbaceous vegetation and it is not clear if good data can be collected at this site. Fortunately, visibility at the Riverview site is good, and it should be possible to generate high quality models of this site.

Additional scans of the Riverview and Central sites will be collected during the coming year. DEMs and difference maps will also be constructed from this data. This should allow the assessment of what, if any, impact the prolonged moderate discharge during the spring of 2008 had on these sites.

Combining TLS monitoring with historical aerial photographic analyses seems like a natural extension of the current work. The strengths and weakness of both methods complement each other. On the one hand, photogrammetry can provide a historical perspective but may not be able to resolve small changes. In contrast, TLS monitoring is capable of detecting much smaller changes but lacks historical context. By combining these methods it may be possible to develop models that accurately represent spatial and temporal variations in bank stability and quantify contributions from various sediment sources.

Rio Grande Nature Center

In December of 2007, the U.S. Army Corps of Engineers broke ground on the construction of a high-flow channel that passes through the Rio Grande Nature Center (Figure 3). In February and March of 2008, more than 20 scan stations were collected to capture the topography of the channel in its “as-built” state. These data have been a relatively low priority and have not yet been fully processed. The objective was to capture the geometry of the channel following the spring run-off cycle, however, rehabilitation of the banks including the planting of willows and cottonwoods along the channel may preclude a useful chronotopographic analysis of this new high-flow channel.

4 Erosion Pin Monitoring Results

Two sites with a total of five erosion pin arrays have been the focus of direct erosion measurements throughout this study. One site is located between I-40 and Central Avenue and the other is immediately downstream of the Arroyo Calabacillas.

The Atrisco site between I-40 and Central Avenue was established in 2003 to study the effects of vegetation removal on bank stability (Figure 8). It consisted of three erosion pin arrays installed along the upstream side of a point bar with the farthest downstream array near the apex of the bar. A different treatment was applied to each array. The upstream array (1) was left unmodified as a control. At the middle array (2) Russian-olives (*Elaeagnus angustifolia* L.), including their roots, were mechanically removed. Finally at the downstream array (3) Russian-olives were cut, but their roots were left intact. This site was monitored until it was destroyed in 2007 by a State of New Mexico Interstate Stream Commission habitat restoration project.

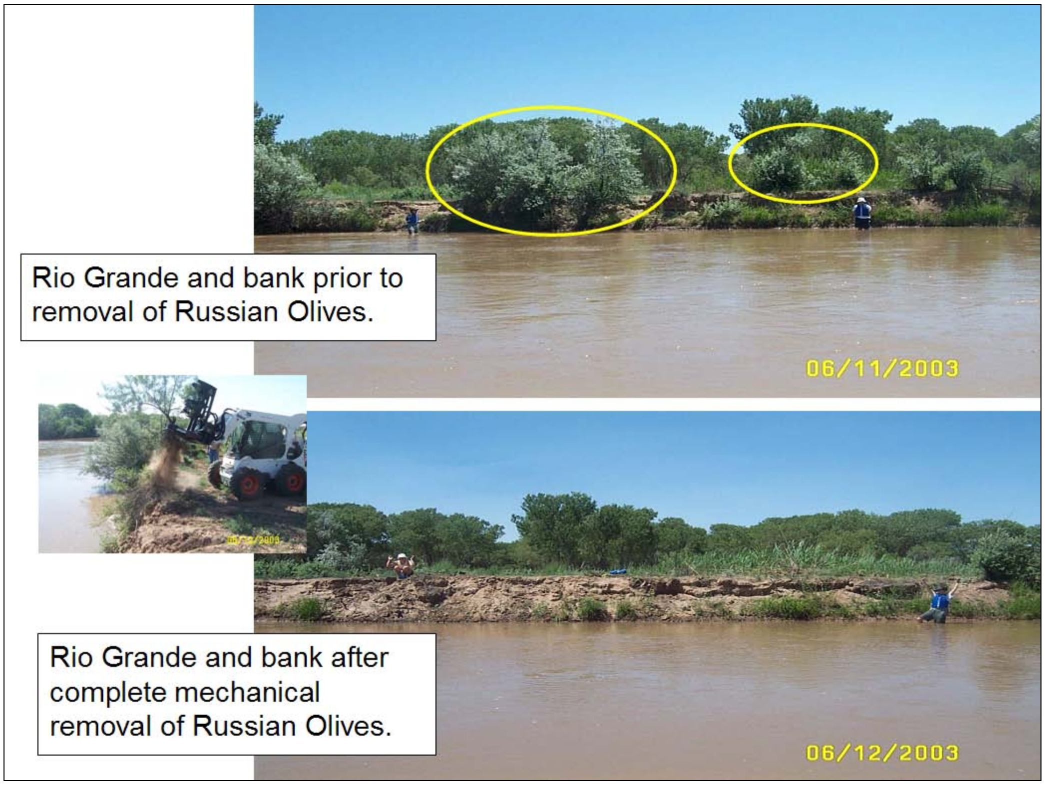

Figure 8. Photographs of Atrisco site between I-40 and Central Avenue before and after vegetation removal.

The erosion pin data collected at the Atrisco site is characterized by large amplitude high frequency variability (Figure 9). Changes in the length of exposed rebar of more than 20 cm between measurements are not uncommon. Although some of this variability may be due to measurement errors the majority likely reflects changes in bank geometry.

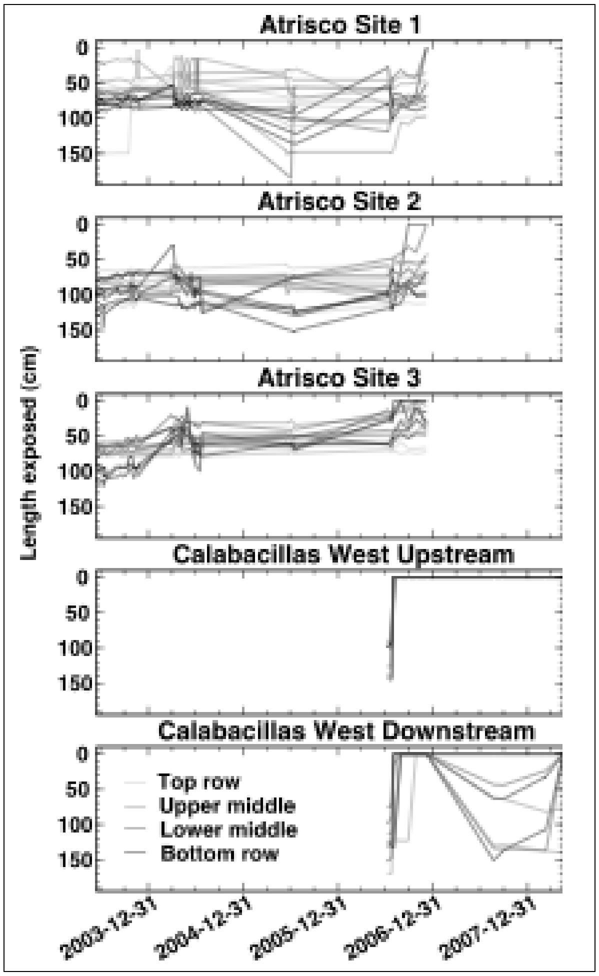

Figure 9. Erosion pin measurements collected at Atrisco site between I-40 and Central Avenue and Calabacillas site immediately downstream of Arroyo Calabacillas. Each erosion pin array contains multiple rows of pins, three at Calabacillas site and four at Atrisco.

Between July and December 2006, seven sets of measurements were made at the Atrisco site. During this period, the top row of pins at all three arrays never had been submerged and there were no visible changes in bank geometry that affected the upper pins. The average standard deviation for measurements taken from individual pins in the top row during this period was 2.3 cm. The maximum range was 11 cm and the minimum was 2 cm. This result suggests that although measurement errors can be considerable, they are unlikely to account for all of the high amplitude variability that is observed. Furthermore, high frequency variability is greatest in measurements from the lower rows, which are subject to inundation most frequently.

Although the Atrisco site was monitored for a relatively short period of time, a long-term trend is evident in the data from array 3. The data from this array indicate lateral accretion during the past 4 years. This array is located closest to the apex of the point bar and field observations suggest that gradation is being driven by accretion of thin layers of fine sediment (sediment which the Rio Grande carries naturally) during high flows, which allows the sediment to reach the upper erosion pins. This process may be enhanced by abundant herbaceous vegetation that increases roughness and anchors the sediment. The overall stability and local progradation observed at the Atrisco site is consistent with its geomorphic position and general narrowing observed along the Middle Rio Grande (Maker et al. 2006; Meyer and Hepler 2007).

The Calabacillas site is located on the Rio Grande's west bank immediately downstream of the Arroyo Calabacillas. The site was instrumented on 11 July 2006 and was almost immediately buried by deposits generated by a thunderstorm on 31 July 2006. The upstream array was completely buried by this event and has not been reexposed. In contrast, the downstream array was near the limit of fan deposition and was reexposed by erosion following the initial event (Figure 9). Erosion of the fan toe in the vicinity of the downstream array is primarily associated with low to moderate flows that occur throughout the year. When the Rio Grande's discharge increased during the spring of 2008, flows over the fan's surface remobilized sediment and reburied the lower pins in the downstream array.

Unlike the Atrisco site, where bank progradation is occurring parallel to the horizontal erosion pins, vertical aggradation and degradation of the channel bottom is occurring at the Calabacillas site. As a result the erosion pins are commonly completely buried or reexposed by a single flood, providing little quantitative information about the episodic sediment transport that is occurring. Although some reworking of the Calabacillas fan deposits did occur prior to spring 2008, the volume of sediment remobilized by prolonged moderate flows in 2008 appears to be much larger than in previous years. Neither the smaller spring runoff in 2007 nor the much larger peak discharges that occurred following summer storms were capable of mobilizing significant volumes of unconsolidated sandy sediment at the mouth of the Arroyo Calabacillas. This is consistent with the current model that in rivers similar to the Rio Grande major floods often determine channel characteristics (Knighton 1998).

The erosion pin measurements that have been collected can provide a useful supplement to the TLS surveys by providing data on subaqueous changes that would not be documented otherwise. Unfortunately, in a highly dynamic setting, such as the Arroyo Calabacillas fan, the coarse resolution of the erosion pin data often provides few tangible benefits over qualitative observations obtained by revisiting the site. If a complete picture of subaerial and subaqueous changes is required, it may be necessary to combine TLS surveys with sonar surveys or some other method that is capable of capturing subaqueous topography more faithfully.

5 Conclusions

Densely-vegetated riparian corridors such as the Middle Rio Grande present significant technical challenges to workers hoping to use terrestrial lidar technologies for chronotopographic analysis. The workflows developed during the course of this project have gone a long way toward making this application practical. Nonetheless, it is clear that terrestrial lidar alone is incapable of providing all of the data needed to understand bank stability and erosion along the Middle Rio Grande. By supplementing TLS with erosion pin networks and direct measurements of soil erosion parameters we hope to provide a clearer picture of the parameters driving bank stability and erosion along this river. Techniques such as underwater sonar surveys could further the understanding of bank dynamics where a smaller scale is of interest.

References

Baltsavias, E. P. 1999. Airborne laser scanning: Basic relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing* 54:199-214.

Bater, C. W., and N. C. Coops. 2009. Evaluating error associated with lidar-derived DEM interpolation. *Computers and Geosciences* 35:289-300.

Bellian, J., C. Kerans, and D. Jennette. 2005. Digital outcrop models; applications of terrestrial scanning lidar technology in stratigraphic modeling. *Journal of Sedimentary Research* 75(2):166-176.

Belliss, S., S. McNeill, J. Barringer, D. Pairman, and H. North. 2000. Digital terrain modeling for exploration and mining. *New Zealand Minerals and Mining Conference*. Wellington, New Zealand, 267-273.

Bonham-Carter, G. F. 1996. Geographic information systems for geoscientist: Modelling with GIS, Computer Methods. *Geosciences* 13. Tarrytown, New York: Elsevier Science, Inc., 416 p.

Charlton, M. E., A. G. G. Large, and I. C. Fuller. 2003, Application of airborne LiDar in river environments: The River CoQuet, Northumberland, UK. *Earth Surface Processes and Landforms* 28:299-306.

Frechette, J. D., G. S. Weissmann, and T. F. Wawrzyniec. 2008. TLSpy: An open-source addition to terrestrial lidar workflows. *EOS Transactions* 89. American Geophysical Union.

Gamba, P., and B. Houshmand. 2002. Joint analysis of SAR, LIDAR and aerial imagery for simultaneous extraction of land cover, DTM and 3D shape of buildings. *International Journal of Remote Sensing* 23(20):4,439-4,450.

Gordon, S. J., and D. D. Lichti. 2004. Terrestrial laser scanners with a narrow field of view: The effect on 3D resection solutions. *Survey Review* 37:448-468.

Hale, G. M., and M. R. Querry. 1973. Optical constants of water in the 200 nm to 200 µm wavelength region. *Applied Optics* 12:555–563.

Hanson, G. J., K. M. Robinson, and K. R. Cook. 2002. Scour below an overfall: Part II. Prediction. *Transactions of the American Society of Agricultural Engineers* 45:957-964.

Hanson, G. J., and S. Hunt. 2007. Lessons learned using laboratory jet test method to measure soil erodibility of compacted soils. *Applied Engineering in Agriculture* 23:305-312.

Hare, J. L., J. F. Ferguson, C. L. V. Aiken, and J. S. Oldow. 2001. Quantitative characterization and elevation estimation of Lake Lahontan shorline terraces from high-resolution digiatl elevation models. *Journal of Geophysical Research* B106(11):26,761-26,774.

James, L. A., D. G. Watson, and W. F. Hansen. 2007. Using LiDAR data to map gullies and headwater streams under forest canopy; South Carolina, USA. *Catena* 71(1):132-144.

Knighton, D. 1998. *Fluvial Forms and Process: A New Perspective*. New York, NY: John Wiley & Sons.

Lichti, D. D., S. J. Gordon, and T. Tipdecho. 2005. Error models and propagation in directly georeferenced terrestrial laser scanner networks. *Journal of Surveying Engineering* 131:135-142. ASCE.

Lichti, D. D., and S. Jamtsho. 2006. Angular resolution of terrestrial laser scanners. *Photogrammetric Record* 21:141-160.

MacKinnon, D., V. Aitken, and F. Blais. 2008. Review of measurement quality metrics for range imaging. *Journal of Electronic Imaging* 17(3):033003-1-14.

Maker, P., T. Massong, and T. Bauer. 2006, *Channel widths changes along the Middle Rio Grande, NM*. U.S. Bureau of Reclamation Unpublished Technical Report.

Meyer, G., and C. Hepler. 2007. *Vegetated island formation and change in the Middle Rio Grande near Albuquerque, New Mexico*. U.S. Bureau of Reclamation Unpublished Technical Report.

Nagihara, S., K. R. Mulligan, and W. Xiong. 2004. Use of Three-Dimensional Laser Scanner to Digitally Capture the Topography of Sand Dunes in High Spatial Resolution. *Earth Surface Processes and Landforms* 29:391-398.

Queensland, G. 2008. *Facts River Series: What causes bank erosion?* Fact Sheet Published on World Wide Web. Queensland Government, Australia: Natural Resources and Water Department, http://www.nrw.qld.gov.au/factsheets/pdf/river/r2.pdf.

Scurlock, D. 1998. *From the Rio to the Sierra: An environmental history of the Middle Rio Grande Basin*. U.S. Department of Agriculture Technical Report RMRS-GTR-5, 440 p.

Shirley, K. 2003. Barcelona posters see West Africa analogies; Spain outcrops hold deep secrets. *AAPG Explorer* 24(6):22-23.

Swanson, B. 2007. Personal communication with Benjamin Swanson. 14 June. Albuque, NM: Department of Earth and Planetary Sciences, University of New Mexico.

Thoma, D. P., S. C. Gupta, and M. E. Bauer. 2001. Quantifying river bank erosion with scanning laser altimetry. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 34:169-174.

Wawrzyniec, T. F., R. R. Jones, K. McCaffrey, J. Imber, N. Holliman, R. E. Holdsworth. 2007a. Introduction: Unlocking 3D earth systems--Harnessing new digital technologies to revolutionize multi-scale geological models. *Geosphere* 3:406-407.

Wawrzyniec , Y. G., L. D. McFadden, A. Ellwein, G. Meyer, L. Scuderi, J. McAuliffe, and P. Fawcett. 2007b. Chronotopographic analysis directly from point-cloud data: A method for detecting small, seasonal hillslope change, Black Mesa Escarpment, NE Arizona. *Geosphere* 3:550-567.

Wynn, T., and S. Mostaghimi. 2006. The effects of vegetation and soil type on stream bank erosion, Southwestern Virginia. *U.S.A. Journal of American Water Resources Association* 42:69-82.

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14. ABSTRACT

Bank stability is an important issue along the Albuquerque reach of the Middle Rio Grande. On one hand, stability and property protection is desirable along the urban corridor. However, stability may not be beneficial to the endemic species that inhabit the river and evolved in a much more dynamic system. To better understand the factors controlling banks stability and erosion along the Middle Rio Grande, we seek to apply high-resolution chronotopographic analysis using terrestrial lidar and erosion pin measurements coupled with in situ measurements of soil erosion parameters. The terrestrial lidar campaign along the densely vegetated Middle Rio Grande has required the development of new workflows and highlighted some of the limitations of terrestrial lidar in this environment. Nonetheless, the data collected during this study should provide useful information on seasonal to interannual changes at spatial resolutions that could not be achieved using other techniques.

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