Evaluation of Bank Erosion Inputs to the Blue Earth River with Airborne Laser Scanner

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Introduction

Nutrients, pesticides and sediment from agricultural activities are the leading surface water pollutants in the U.S. Many of the same issues that link agricultural activities to declines in water quality are common in the eight corn belt states that account for 80% of U.S. agricultural production (Fausey et al. 1995). At the root of the water quality issue are agricultural practices that allow sediment and nutrient transport to surface water bodies. Soil cultivation and drainage are practices necessitated by the climate and soils of the Midwest that make farming possible. Cultivation exposes soil to forces that can dislodge and transport it, and surface and tile drains provide a conduit for transport of sediment and soluble nutrients to surface waters. The interactions between cultivation of 55.7 million hectares and drainage on 20.6 million hectares have already affected the hydrologic regimes of many rivers with unintended consequences on channel erosion.

One such river in the upper mid-west is the Minnesota River, a tributary of the Mississippi River. The Minnesota River flows through a relatively flat agricultural landscape, but is fed by tributaries that are incised with steep and unstable stream banks. According to one estimate, the Minnesota River carries from 0.2 to over 2 million tons per year of suspended sediment at Mankato, MN. It is presently not known what proportion of this load is from surface runoff versus stream bank collapse. Gupta and Singh (1996) estimated the bank erosion contributions at 48-55% of the total sediment load in the Minnesota River at Mankato for the 1990-1992 water years. Another report estimated that 25% of the sediment in the Minnesota River was from non-agricultural sources (http://www.soils.agri.umn.edu/research/mn-river/doc/watqual.html#nine). About 55% of the suspended sediment load in the Minnesota River at Mankato is from the Blue Earth River. Bauer (1998) estimated that 36 to 84% of the sediment in the Blue Earth River was from bank erosion. However, these estimates were based on historical aerial photographs and ground measurements of elevation on one bank. Based on elevation measurements on seven banks, Sekely (2001) estimated that bank erosion contribution to the total suspended sediment in the Blue Earth River ranged from 31 to 44%. Manual elevation measurements of banks as reported by Bauer (1998) and Sekely (2001) are labor intensive and time consuming. Furthermore, the procedures to extrapolate a few bank measurements to full length of the river are full of assumptions that are not realistic. Procedures are needed that can fully characterize the bank erosion along the complete length of the river.

The Minnesota Pollution Control Agency (MPCA) has stated that a 40% reduction in sediment load at the edge of the Minnesota River Watershed is required to meet federal water quality standards in the lower Minnesota River. To achieve this goal MPCA recommends a 40% reduction in sediment transport to the river to meet this requirement. Thus far, the implicated sources of these pollutants are agricultural practices on lands in the Minnesota river basin that promote delivery of sediments and nutrients to the river (Randall et al. 1996). Land management activities such as tillage and cropping practice directly affect soil movement, hence agricultural practices that promote keeping soil in place are the focus of current best management practices (BMP) (Randall et al. 1996; Gupta and Singh, 1996). The MPCA assumption that 40% reduction in upland delivery of sediment to the river will reduce the sediment transport to the edge of the watershed by 40% implies most of the sediment in the river has its source in the uplands. This argument has not been verified. In fact, three non-point source pollution models used to estimate the effect of different management practices on Minnesota River water quality have revealed important gaps in our understanding of processes that are acting to control sediment delivery to the river (Gupta and Singh, 1996).

In order to implement effective management practices to address pollution sources there must be a clear understanding of which mechanisms are the largest contributors. For instance, if monitoring showed that large quantities of sediment were being contributed from stream bank collapse some effort could be re-directed to focus more attention on hydrologic processes both in-stream and via drainage networks that influence channel morphology.

This research is assessing the potential of a laser scanning altimeter to provide comprehensive stream reach mass wasting estimates. Operationally, this technology would be used by resource managers at federal, state and local levels to determine allocation of resources to projects with the greatest potential for pollution abatement. Additionally, isolating stream bank inputs and upland contributions by difference with total sediment load will help determine effectiveness of upland BMP soil erosion control efforts. Estimates of stream bank erosion are of special interest to NRCS, MPCA, MDA, BWSR, Metropolitan Council, and Joint Powers Boards which all have roles in improving water quality of the Minnesota River.

The goal of this research is to determine how accurately mass failure rates on the Blue Earth River can be measured with airborne scanning laser altimetry. Airborne laser altimetry measurement for stream bank mass failure rates have not been attempted anywhere, yet it has great potential for government agency and commercial application in erosion and water quality management. Collecting airborne laser altimetry data is an expensive investment, but the initial cost can be justified when considering the cumulative resources already spent addressing sediment pollution, even without a good understanding of pollutant source and mechanisms of delivery.

The objective of this research was to use a helicopter mounted scanning laser to construct a high resolution digital elevation model of the Blue Earth river valley along its length. For calculating mass wasting rates, the procedure will involve making two scans of the river valley at two different times. The first scan will serve as a baseline to which scans taken a year or more later will be compared. Changes in the 3-D topography measured by the laser scans will indicate the location and quantity of material that eroded into the river due to bank erosion.

Theory

General description of the scanning laser

The scanning laser is flown in a small aircraft at low altitude (300-400m) with a high precision inertial navigation system (INS). The distance between the aircraft and the land surface is determined as a function of the time it takes a laser pulse to be transmitted to the land surface reflect and return to the sensor. Thousands of pulses per second provide high spatial resolution coverage along a flight line even at air speeds greater than 100 m/s. The lateral positions of laser pulses are georeferenced using GPS and the INS, while the elevation of the measured surface above the ellipsoid is determined as the difference between aircraft elevation above the ellipsoid and distance between the aircraft and the ground (Krabill and Martin, 1987). Laser radiation is considered eye-safe at distances greater than 30 m (Krabill et al., 1984).

The base line elevation accuracy is determined by comparing elevations of a scanned stable surface such as an airport runway to elevations carefully surveyed by conventional or GPS survey methods. Accuracy of elevation measurements during the flights is calculated by a surface elevation differencing technique, which determines error in elevation measurements for the same geographic location scanned on intersecting flight lines collected on the same day. This is accomplished by taking the difference in elevation of each point in one file from elevations of points with in a fixed buffer in the other file. Both mean difference and root mean square error can then be calculated for the two data sets which serve as the standard for internal validity check (Krabill et al. 1995). This technique is only reasonable for flat homogenous surfaces. The range finding capability, or vertical error of scanning lasers are often as good as 10 cm (Abdalati and Krabill, 1999), but can range up to 20 cm (Krabill et al. 1995). Alignment of annual flight paths for repeat coverage is required for estimates of volume change due to stream bank slumping.

Data georeferencing

In addition to maintaining flight path alignment scanner data is georeferenced by flying over fixed land surface features such as highway bridges that serve as ground control points. These features, which are identifiable in the scanner data and have known geographic coordinates, serve as match points for co-registering data collected on different dates. A minimum of two fixed features are included in each flight path to ensure appropriate registration accuracy through out the full length of the flight. The equations for precise georeferencing of laser data using GPS and INS have been described by Vaughn et al. (1996).

Internal data registration is insured by flying stream reaches in the upstream direction, then downstream to obtain data overlap that can be used for internal validity check. Systematic elevation error for a single flight line can be as high as 7 cm, but this error can be significantly reduced by combining laser pulse footprints from independent flight lines over the stream reach collected on the same day. Systematic error in the sensor position recorded by the INS is an independent variable and can be reduced by combining multiple data from multiple passes. On the same day elevations of a single location will not change, thus allowing accuracy assessment of successive scans. Subtle differences in elevation on rough stream bank surfaces on the order of a few centimeters are expected due to random scatter and system noise.

As the aircraft moves along a predetermined flight line up to 7000 pulses per second are directed by a rotating mirror to the ground in a circular pattern centered on the flight line. Up to five echoes from each laser pulse are received by the sensor. Typically the first returned pulse is the top of vegetation canopy while the last is usually the ground. In situations where the last echo return is not the ground, filtering must be employed to remove these elevation data if interest is purely in the bare earth elevation (Ritchie 1994). Resulting data resolution depends on aircraft elevation and speed as well as laser pulse rate, scan width and scan rate. In a recent study of ice sheets in Greenland a flight altitude of 400m and laser pulse rate of 3000 sec^{-1} yielded approximately one elevation measurement per 6 m^2. Data were resampled and interpolated for statistical analysis to evenly spaced 1*1m grid cells (Abdalati and Krabill 1999). Working in deciduous forests can decrease the sample density due to interference from vegetation. However, sampling density can be optimized by collecting data with a slow flying helicopter in the fall or winter during leaf-off conditions.

Methods

Study area

This study was conducted on the Blue Earth River, a tributary of the Minnesota River. Bauer (1998) identified 136 eroding stream bank sites along 156.9 km the Blue Earth River between Mankato and Blue Earth, MN. The range in area of eroding stream banks was 102 to 18364 m^2. This stretch of the Blue Earth River has steep (up to 90^o) and unstable banks as high as 30m (Fig. 1). Bauer classified banks into minor, moderate and severely eroding. We focused on river reaches between the confluence of the Blue Earth and Wantonwan rivers and Amboy (~56km river length), which contain 10 minor sites, 30 moderate and 15 severely eroded sites greater than 3m high. Figure 2 shows an example of the bank sloughing along the Blue Earth River. There are 3 county road bridges that will be used as GCP's in this stretch of the river.

Field work

In February 2001, 35 miles of the river between Rapidan Dam and Vernon Center were mapped with a March III GPS to 5m accuracy (Fig. 3a) and stream banks on either side of the river were photographed and categorized qualitatively by size, erosion activity, and vegetation coverage. The start and end points of all large banks were recorded. This data set will be used to aid interpretation of the laser scan and to independently compute bank lengths.

Two stream banks were surveyed with a total station during February 2001 at better than 1cm accuracy (Fig. 3b). These surveys will be used as reference standards to determine absolute accuracy of the airborne scanning laser system. On April 28 and 29, 2001, 8 locations representing dominant vegetation cover types were surveyed for vegetation canopy density using a Geographic Resource Systems densitometer (Fig. 3c).

On April 24 and 25, we completed a 35 mile scan of the river corridor (between the confluence of the Watonwan and Blue Earth rivers and Amboy, MN) using a helicopter mounted laser range finding system (Figs. 4 & 5). Scan specifications were:

flight altitude - 375 m
flight speed - < 25 m/s
distance between footprints - 0.305 m
laser footprint diameter - 0.116 m
laser pulse rate - 7000 Hz
number returned echoes – 5
scan width - 273 m
scan angle - 20 degrees
mirror frequency 12.5 Hz
ground reference station - Trimble 4000 SSi dual frequency

Figure 1. A view of the bank sloughing along the Blue Earth River. Hanging fence showing the recent failure in the top portion of the bank. According to owner of this field, the banks have receded about 30 feet in his lifetime (60 years) giving bank erosion rate of 0.5 ft/year.

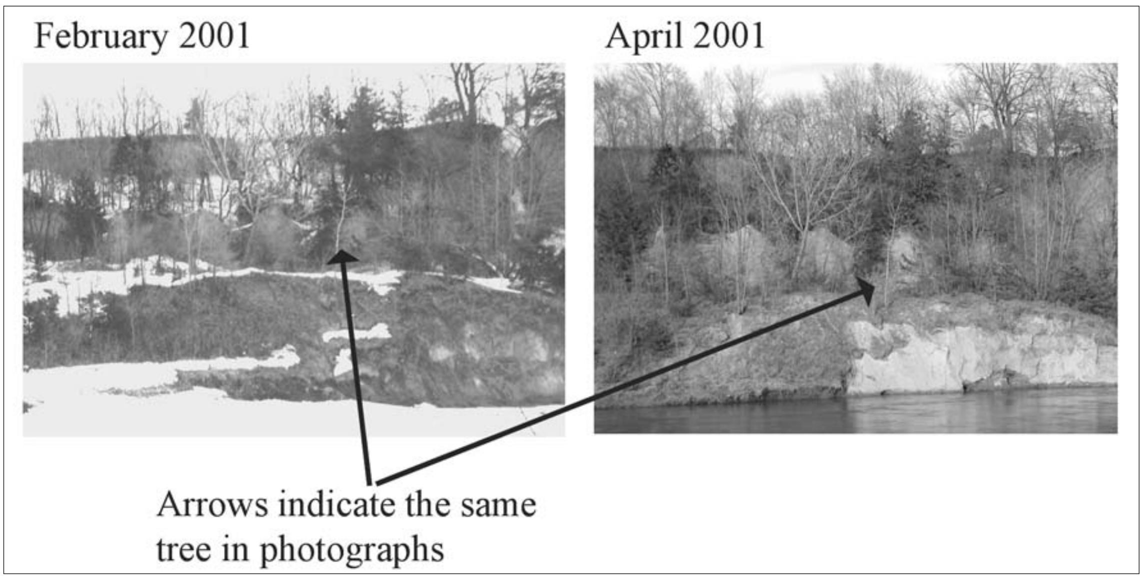

Figure 2. Two views of a bank along the Blue Earth River showing the occurrence of seasonal erosion. The light colored area in the lower right of April 2001 image is where some sloughing has occurred since February 2001.

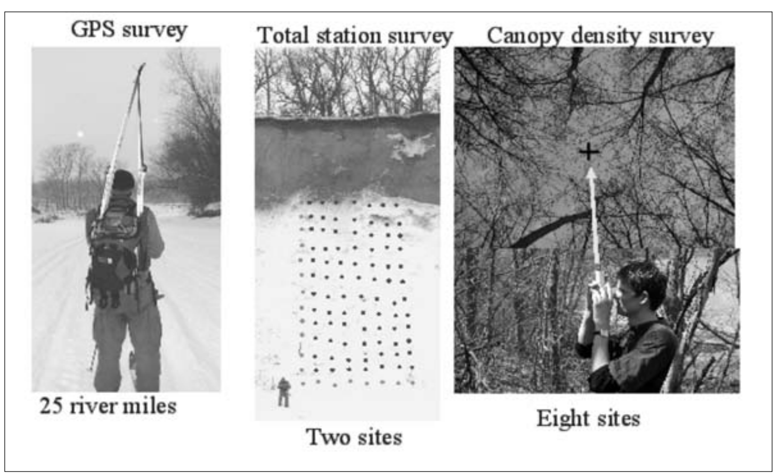

Figure 3. GPS, elevation, and canopy cover characterization of the Blue Earth River Banks. This information was used to interpret and verify the accuracy of the laser data.

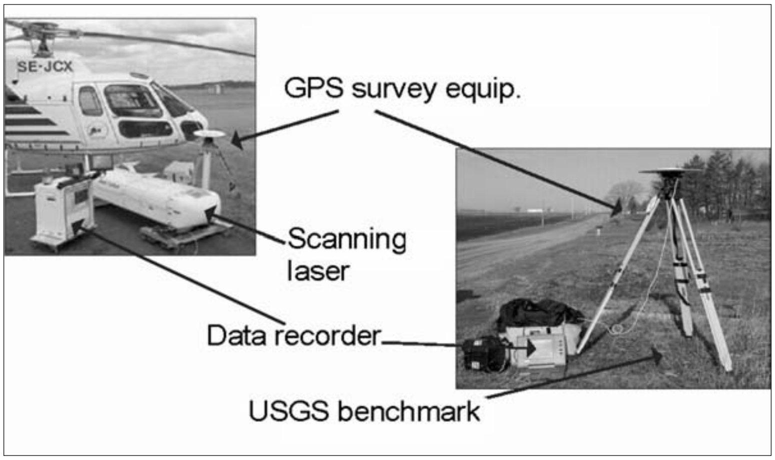

Figure 4. Components of the helicopter based laser system used to scan the Blue Earth River.

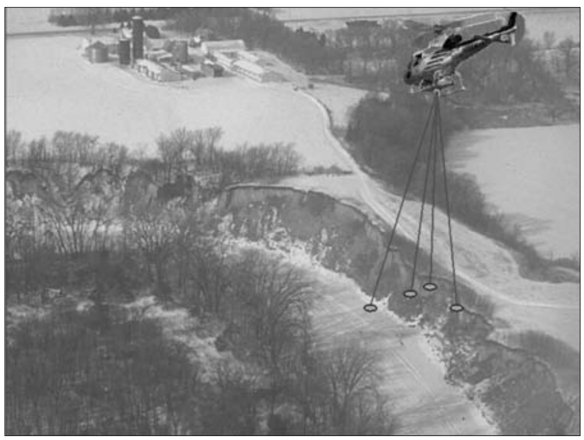

Figure 5. An aerial view of an eroding bank along the Blue Earth River.

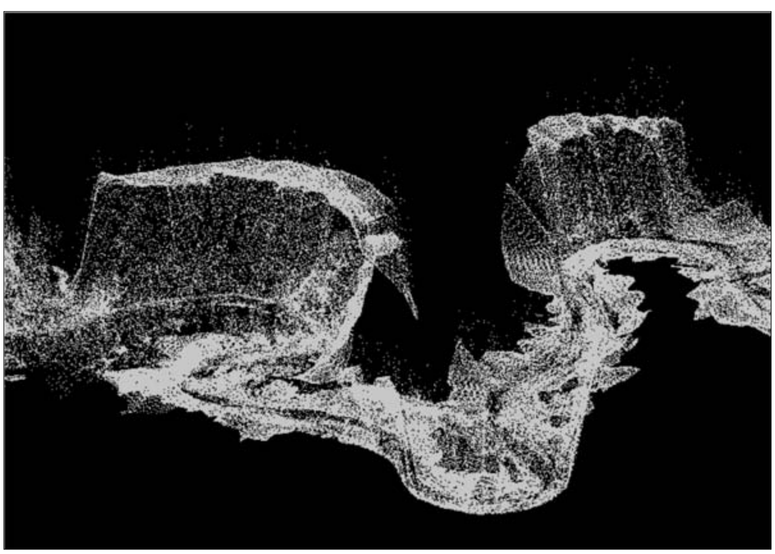

Figure 6. Scanned view of two banks along the Blue Earth River.

Results

The data has been filtered to remove presence of vegetation resulting in a bare earth model. The filtered data is currently being used to grid the river valley and then draw the contour. Figure 6 shows an example of the two scanned banks along the meandering Blue Earth River. Usually, there will not be any reflection of the laser pulses from the water body because of its tendency to adsorb infrared light. In Figure 6, there was some reflection of the laser pulses because of the presence of sediment in the river water. Plans are underway to compare the elevation measurements from the laser scan against the total station derived elevations. We are also in the process of undertaking a 3-D animation of the river valley using the facilities of the Minnesota Supercomputing Institute.

Depending upon the availability of funds, a second scan will be made in another year or so. The two 3-D images will be compared to calculate the volume change. The volume change will be converted to mass wasting rates using the bulk density values measured on bank sediments along the length of the Blue Earth River.

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