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Airborne laser scanning for riverbank erosion assessment

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Abstract

Understanding the proportion of sediment and phosphorus having its source from agricultural fields versus river banks is a difficult yet important question for determining cost effective erosion control practices. This research was designed to characterize the contributions of sediment and phosphorus due to bank erosion along the main stem of the Blue Earth River. Detailed topographic data was collected twice on an annual basis in April 2001 and April 2002 over a 56 km length of the Blue Earth River with a helicopter mounted Topeye laser system. The database includes X, Y, Z coordinates of laser returns from the river valley spaced at 60 to 100 cm intervals. Interpolated one meter grid cell resolution bare earth digital elevation models were made by stripping vegetation laser returns. The two models were differenced to determine volume change over time which was then converted to mass wasting by multiplying volume change and bulk density. Mass wasting rates were converted to sediment load based on percentage of transportable material in the bank strata. The percentage of sediment in the river sourced from bank materials was determined as the proportion of mass wasting to sediment load measured at a downstream gauging station. The percentage of sediment from bank erosion varied from 23 to 56 depending on the range of textural material that was considered transportable once in the river. Based on analysis of riverbank samples, total P contributions were estimated at 201 Mt/yr due to bank erosion and slumping.

Keywords: sediment pollution, laser altimetry, LIDAR, bank erosion

Introduction

The National Water Quality Inventory report (USEPA, 2000) indicates 12% of assessed rivers and streams in the U.S. are impacted negatively by sedimentation. Negative impacts of siltation include suffocation of fish eggs, decreased light penetration for photosynthesis, decreased aesthetic value for recreational uses, and added cost of water treatment. Agriculture is implicated as the major source for sediment pollution in many rivers. However, because of its diffuse nature reductions in sediment are difficult to achieve except through the implementation of best management practices (BMPs). Conservation tillage and grassed waterways as well as buffer strips at field edges can reduce sediment transport to surface waters (Randall et al., 1996; Gupta and Singh, 1996). However, sediment sources in agricultural landscapes include both bare fields as well as riverbanks in dynamic fluvial systems. Therefore, determining the proportion of sediment having its source from either of these locations is a difficult yet important question for cost effective implementation of BMPs.

The Blue Earth River watershed in south central Minnesota is a good example of a landscape where non-point source sediment pollution is prevalent, but difficult to apportion between upland and bank erosion. The Blue Earth River is a major tributary of the Minnesota River and contributes roughly 55% of the sediment load carried by the Minnesota River at Mankato, MN (Payne, 1994). The river flows through a deeply incised landscape with river banks as tall as 30 m. Comparatively, the landscape in the Blue Earth River Basin is relatively flat; 54% of the land area has 0-2% slope, and 82% of the land has 0-6% slope. The flat landscape is however, connected to the river through surface inlets that carry runoff and sediment into tile lines which in turn empty into ditches and thus the river.

The Minnesota Pollution Control Agency (MPCA, 1985) stated that a 40% reduction in sediment load is required to meet federal water quality standards and beneficial use criteria. The agency assumes that a major proportion of these pollutants are from upland areas of the watershed. Therefore, the strategy for controlling these pollutants has focused on agricultural practices that promote delivery of sediments and nutrients to the river (Randall et al., 1996). However, this strategy may not be effective since it is not clear what proportion of the sediment and nutrient pollution in the Minnesota River is from upland erosion or stream bank collapse.

Airborne laser altimetry, or Light Detection and Ranging (LIDAR), has been used in numerous topographic and land use change detection studies (Krabill et al., 1999; Murakami et al., 1999; Huising and Pereira 1998; Irish and Lillycrop, 1999 and Sallenger et al., 1999). Laser altimetry has also been used for gully erosion estimates (Jackson et al., 1988; Ritchie et al., 1994), earthquake fault mapping (Harding and Berghoff, 2000; Hudnut et al., 2002) and to map riverbank elevations for flood management (Pereira and Wicherson, 1999).

As the aircraft moves along a predetermined flight line many thousands of laser 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 to compute elevations based on laser travel times. Typically, the first returned pulse is the elevation of 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 et al., 1994). The typically high density of data from combinations of multiple passes allows averaging without loss of systematic variation in the landscape surface (Ritchie et al., 1994). Resulting data resolution depends on aircraft elevation and speed as well as laser pulse rate, scan width, scan rate, and vegetation cover. Data collection in the fall or winter during leaf-off conditions optimizes sampling density and accuracy of bare earth models.

The objectives of the study were: 1) to quantify mass wasting and phosphorus inputs along a 56 km length of the Blue Earth River, and 2) to estimate proportion of total annual suspended sediment load due to bank and bluff collapse.

Methods

Research focused on the Blue Earth River reach between Amboy, MN and the confluence of the Blue Earth and Wantonwan rivers (~56 km, Figure 1) that contained 10 minor, 30 moderate and 15 severely eroded sites according to Bauer (1998). Severely eroded sites were classified as exposed river banks greater than 3m high. In this stretch of river, there were 5 county highway bridges that were used as ground reference control.

1. Scan specifications

Laser scans were conducted annually on April 23-24, 2001 and April 26-28, 2002 with a Saab Topeye helicopter mounted laser range finding system. Laser pulse rate was 7 kHz with foot prints spaced 0.30 m and foot print diameter of 0.16 m. Scan width was 273 m.

2. Fieldwork

Twelve soil samples were collected from 6 exposed riverbanks representing typical strata and textures in bank materials. The taller stream banks were primarily composed of glacial till and glacial lake sediments (Bauer, 1998), while shorter banks were composed of river alluvium. On replicates of each sample, bulk densities were determined using the clod method (Blake and Hartge, 1986), and the textural analysis was done using the hydrometer method (Gee and Bauder 1986). Averages of bulk density and textural analysis were used in conjunction with laser determined volume change to derive mass wasting rates, and then mass suspended solids. All samples were analyzed for extractable phosphorus (Kuo, 1986) using 0.01 M $CaCl_2$, and total P via perchloric acid digestion (USEPA, 1981).

Elevation accuracy of both annual scans was determined by comparing scan elevations for bridges crossing the river to bridge elevations determined by rea-time kinematic global positioning system (RTK-GPS) survey. A total of 137 bridge reference points were collected on 5 highway bridges that crossed the scanned portion of the Blue Earth River. Accuracies of scan elevations on the bridge surfaces were determined as the difference between a bridge reference point and the nearest scan point that fell on the surface.

The planimetric accuracy was determined by matching bridge edges in the 2001 scan to edges in the 2002 scan. Edges were determined by linear regression of scan line points that fell closest to, but still on, the bridge surface. The average distance between points on the best fit lines describing the bridge edges served as an estimate of planimetric shift.

3. Scan characteristics

Raw scanning laser data were differentially corrected and stripped of vegetation returns using a proprietary smoothing filter. Any last-return point greater than 1.5 m above ground surface was considered a return from vegetation and was removed by the algorithm. Because data points were not uniformly distributed along the flight path due to mirror rotation and aircraft trajectory, they were gridded to a uniform $1 m^2$ spacing before being used in volume change calculations. The resulting data product was an ordered set of 24 million and 30 million X,Y,Z coordinates for the 2001 and 2002 scans respectively.

4. Mass wasting estimates

All data points below the 2001 high water mark were eliminated from both data sets manually by digitizing and clipping. Vertex matching produced two dry surface files (2001 data and 2002 data) with identical X,Y coordinates that differed only in the Z (elevation) dimension. The differences in Z values were determined for every vertex and summed. The sum was then multiplied by the spatial extent of the scans to derive an estimate of volume change that occurred due to erosion or deposition between the two scans.

Mass wasting estimates were made by multiplying the volume change determined from the laser scans with the average bulk density. Similarly, phosphorus load was derived by multiplying the concentration of extractable and total phosphorus in sediment samples by the mass wasting estimates.

Results

1. Properties of bank materials

The bulk density of bank materials ranged from 1.46 to 2.13 Mg/m^3 with an average of 1.83 Mg/m^3. The clay content of bank materials ranged from 6.1 to 29.3% with an average of 20.1%. Silt content ranged from 0.74% to 41.6% with an average of 27.3%, while sand content ranged from 32.8% to 92.4% with an average of 55.7%. The extractable P concentration for bank materials ranged from 0 to 0.25 mg/kg with an average of 0.08 mg/kg, while the total P concentration ranged from 249 to 452 mg/kg with an average of 392 mg/kg. For comparison purposes, a surface soil (0-2 cm) collected from the summit of an eroding bank had an extractable P concentration of 3.1 mg/kg and total P concentration of 622 mg/kg.

2. Accuracy

The vertical accuracy of the real RTK-GPS reference points was determined to be between 1.22 cm and 1.83 cm in 2001 and 2002, respectively. The strong correlation coefficient ($r^2 = 0.9998$) between elevations of the bridge reference points and LIDAR scan points (Figure 2) indicated a very close fit over an elevation range of 10's of meters across approximately 16km of horizontal survey distance.

A close inspection of vertical error indicated the average error for the 2001 scan (2.5cm) was less than that for the 2002 scan (8.8cm), but distribution of error terms was somewhat normally distributed in each. Both scans were biased in that they under estimated true elevation relative to bridge reference point elevations.

3. Mass wasting and P inputs

A volume change of –281,454m^3 was computed as the difference in elevations between the 2001 and 2002 LIDAR scans without applying a vertical or horizontal bias correction. This was equivalent to 512,247 t of sediment, 201 t total P, and 40 kg extractable P input to the river assuming a bulk density of 1.83 Mg/m^3, average of 392 mg/kg total P, and an average extractable P concentration of 0.08 mg/kg, in the bank materials. More precisely these values represented net input of sediment and extractable and total P from above the 2001 water line.

The mass of sediment transported past the gauging station near the mouth of the Blue Earth River for the period between the two scans was 407,252 t (Heather Offerman, Metropolitan Council Environmental Services, personal comm.). This amount represents the sediment carried by the Blue Earth and the Watonwan Rivers. However, not all of the eroded bank and bluff materials that made it to the river were transported past the gauging station within the year. For this reason a range of bank contributions to the suspended sediment load (23 to 56%) was provided assuming different proportions of the clay plus silt fractions were transportable (Figure 3).

Discussion

1. Scanner accuracy

The vertical bias in the scans is most likely due to GPS positioning errors resulting from a less than optimal satellite configuration or tropospheric factors that degrade GPS signals (James Hawkins, Aerotec LLC; Adrain Borsa, Scrips Institute of Oceanography, personal comm.). In spite of the seemingly large error in 2002 relative to 2001, both scan errors are less than the specified noise level of the Topeye system (15cm). The mean elevation error in this study was similar to mean elevation errors reported in the literature (Krabill et al., 1995; Abdalati and Krabill, 1999; Huising and Gomes Pereira, 1998; Favey et al., 1999).

Planimetric accuracy was more difficult to determine than vertical accuracy. An attempt was made to quantify planimetric accuracy by surveying bridge edges, but because scan line points typically didn't fall on bridge edges it was impossible to determine accurately where bridge edges fell in the scan image. Nevertheless, the difference between bridge edges determined from the scaned data and edges surveyed on the ground with RTK-GPS averaged 0.83 m.

2. Mass wasting accuracy

No vertical or planimetric correction was applied in the calculation of mass wasting because error budgets were determined only for flat homogenous bridge surfaces that were not representative of steep, rough and variably vegetated riverbanks. Furthermore, the detected errors were predominantly within the noise level of the measurement system, and were somewhat normally distributed. Additional research is needed to determine the cause of vertical and planimetric error before application of correction factors.

While bias changes significantly due to time dependent variables associated with resolving GPS positions, it is less likely that variance, or system noise, will change significantly in future scans. One-way to minimize the impact of variance on mass wasting estimates is to have a longer time period between scans. If erosion continues at a high rate the real topographic change will then be large relative to system noise, which will improve the capability to detect and measure change.

3. Vegetation effects on mass wasting estimate

Since laser scans were conducted before the leaves emerged on trees (April 2001 and 2002), the influence of forest canopy on the bare earth digital elevation model was negligible. This was also apparent because the last returned pulse of most laser 'shots' made it to the ground, as evidenced by the small proportion of 'shots' that were obviously reflections from canopy elements (to large change in vertical dimension over short horizontal distance) relative to the much larger number of points that represented reflections from the ground. The influence of low growing vegetation was difficult to determine. However, most of the actively eroding banks were devoid of vegetation that would cause interference, and banks with dense brush and grass cover were likely more stable and hence less likely to be contributing to erosion.

4. Effect of gauge accuracy on mass wasting estimate

The accuracy of sediment transport measured by the Metropolitan Council Environmental Services is unclear. The water intake is located near shore in fast current about 0.46m above the river bottom. Error in the sediment transport estimates is due to inaccuracies in measuring flow past the gauge and concentration of sediment carried by that flow. Flow accuracy is dependent on accuracy of rating curves that change over time, and the accuracy and timing of stage measurements. This particular site has had a stable stage / discharge relationship largely due to bedrock control of channel morphology.

Without information on grain size distribution of transported sediment it was difficult to precisely estimate what proportion of the sediment input to the river was transported as suspended load due to variations in particle size distributions of slumped materials and stream power available for transport. Material not transported as suspended load was transported as bed load or settled out in low velocity areas of the stream. For this reason a range of possible sediment transport values was presented (23 to 56%) based on the assumption that all the clay and some or all of the silt was transported (Figure 3). These estimates assume all material that made its way into the river became dispersed and all clay was transportable. The veracity of this assumption improves over longer time scales as slumped clay blocks disintegrate.

5. Interpretation of mass wasting results

In this study, the highest mass wasting estimate ranged up to 56% of the transported load measured by a downstream gauging station. This does not imply that 56% of the load in that year had its source in bank materials, because other sources were not measured. The other sources included sediment contribution from eroding banks upstream or downstream of the section scanned in 2001 and 2002, bed load, and overland erosion, specifically from the surface inlets commonly used to drain fields in the watershed. The contribution of bank materials downstream from the scan limit was assumed minimal as those banks were relatively stable and often composed of bedrock. Contribution from upstream banks was more likely, but will be relatively small as the most actively eroding sections were contained within the scanned reach. Of 18 severely eroding sites along 157 km of the Blue Earth River, Bauer (1998) identified only two that were above or below the section scanned in this study. It is important to note that the river gauging station was located downstream from Rapidan Dam, providing a settling reservoir for coarser particles. If significant settling of fine particles occurred in the reservoir, then the estimate of bank contribution would be proportionately less.

Conclusions

This study demonstrated the potential of scanning laser altimetry for partitioning non-point source sediment pollution. Using two scans made one year apart on the Blue Earth River in southern Minnesota estimated bank erosion inputs could represent up to 56% of the transported sediment measured at a river gauging station. For the same period up to 201 t of total P was added to the river via bank erosion. Bank erosion inputs are not directly related to transported sediment measured downstream unless the ratio of bedload to suspended load is consistent over long periods. Erosion or deposition below the waterlines could not be quantified because the laser wavelengths used were strongly absorbed by water. Similarly, bank loads above and below the scanned reach were not accounted in this estimate.

Interpretation of mass wasting estimates derived from scanner data must be made in light of several factors that affect accuracy. There are inherent errors in both laser altimetry measurements and river gauging station measurements that could significantly influence sediment partitioning results.

Bias in scan elevations and planimetric accuracy may be corrected if systematic error can be separated from system noise. However, for the two annual scans used in this study the vertical error was within specifications. While there were sources for error in partitioning sediment using this method, it should be recognized that there are no conventional means of surveying at this level of accuracy for such extensive areas.

This study illustrated how scanning laser altimetry could be used in conjunction with river gauging station data to estimate the contribution of eroding bank materials to total suspended load. Operationally, resource managers at federal, state and local levels would use this technology to determine allocation of resources to projects with the greatest potential for pollution abatement. In addition, isolating stream bank inputs and upland contributions by difference with total sediment load can help determine effectiveness of upland soil erosion control efforts.

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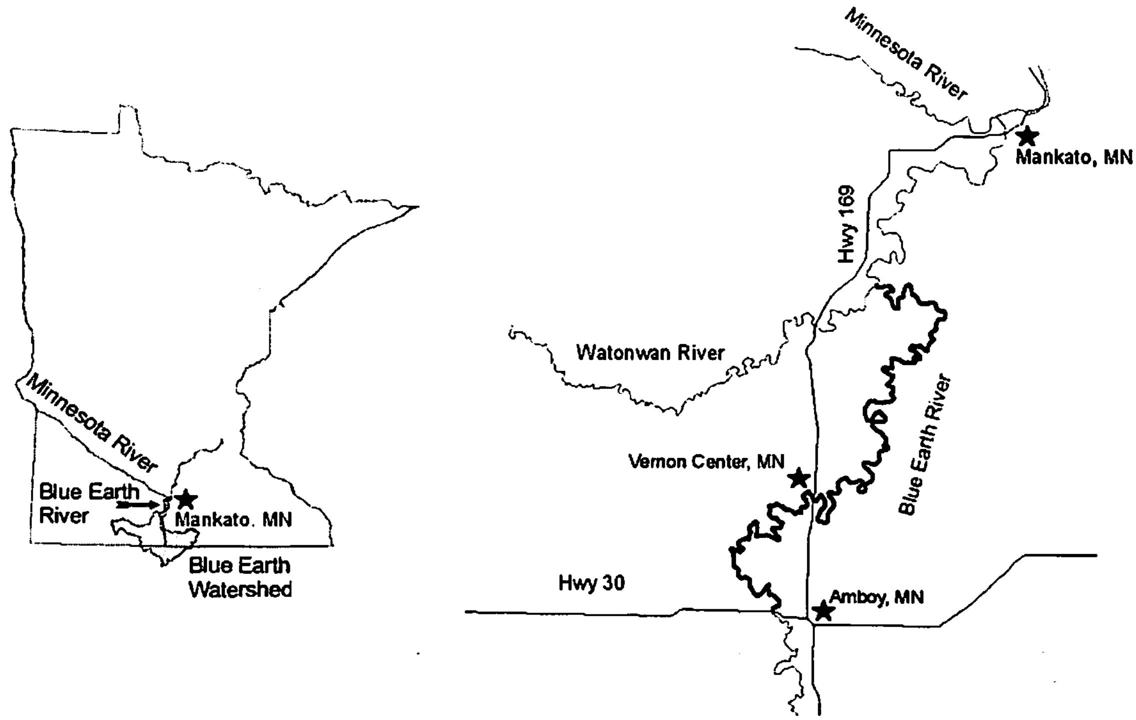

Figure 1. The study area location was a 56 km section of the Blue Earth River (thick line in the figure on right) scanned with a laser altimeter in 2001 and 2002. This reach of river is between the confluence of the Blue Earth and Watonwan Rivers and the Highway 30 Bridge near Amboy, MN

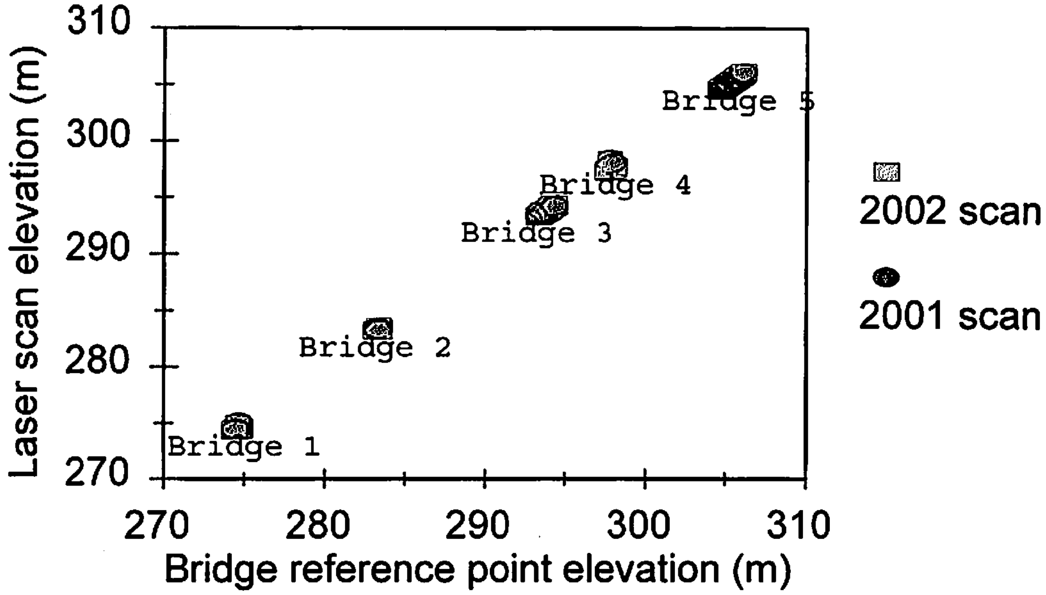

Figure 2. Correspondence of bridge surface elevations obtained via RTK-GPS survey on the ground versus elevations for the same surfaces determined by 2001 and 2002 LIDAR.

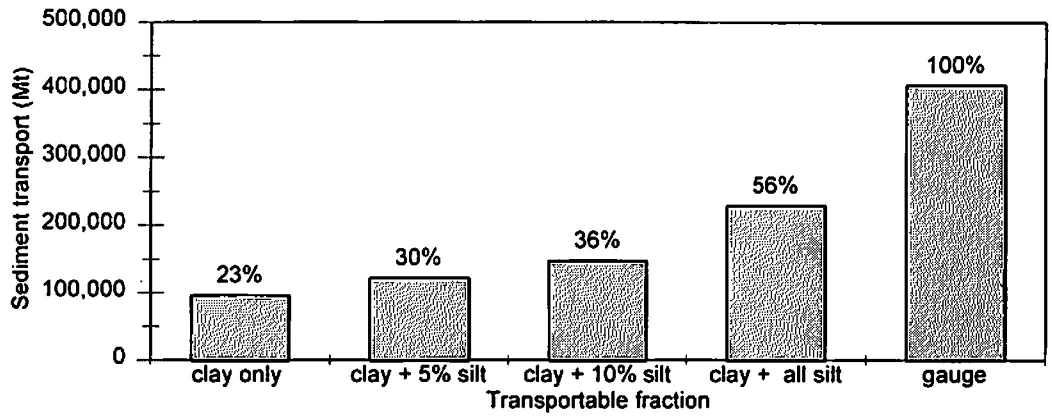

Figure 3. Range in fraction of transported sediment that had its source in riverbank materials based on particle size of sediments added to the flow. Numbers above bars represent percentage of total load due to bank erosion for the given size fraction