In cooperation with the U.S. Environmental Protection Agency

Analysis of Vegetation Controls on Bank Erosion Rates, Clark Fork of the Columbia River, Deer Lodge Valley, Montana

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Abstract

The Clark Fork of the Columbia River through Deer Lodge Valley, Montana, is a meandering stream that has experienced high cutbank erosion rates over the past several decades due to extreme thinning of woody riparian vegetation. Bank erosion rate data available for the period 1989 to 1997 were examined along with large-scale aerial photographs in order to assess the relation between vegetation along cutbanks in meander bends and cutbank erosion rates. These data clearly show a downward trend in erosion rate with increasing density of woody riparian vegetation. Where vegetation density is high and erosion rates are low, however, the amount of bank retreat cannot be determined from the aerial photographs. Consequently, a lower limit on erosion rate as a function of density of woody riparian vegetation cannot be calculated from the available data.

INTRODUCTION

The Clark Fork of the Columbia River through the Deer Lodge Valley, Montana (fig. 1), is vulnerable to high rates of bank erosion as a result of extreme thinning of woody riparian vegetation (Smith and others, 1998). In this valley, the Clark Fork is a highly sinuous river with well-developed cutbanks. A large flood in 1908 left silty deposits of mine tailings (called "slickens") along the flood plain, primarily within the meander belt of the river (fig. 2; Nimick and Moore, 1991). The recurrence interval for this flood was approximately 300 years, based on calculations of flood magnitude and an extrapolation of the flood-frequency curve for the Clark Fork at Deer Lodge, provided by Smith and others (1998). Where slickens or grassy fields extend all the way to the river's edge, the banks are particularly susceptible to erosion.

The presence of dense, woody vegetation on streambanks can decrease erosion substantially both by reducing the shear stress along the bases of the banks and by increasing the cohesion of the soil that forms the banks. Over the past several decades, rapid bank retreat (as much as 6 feet per year) has been occurring along the Clark Fork through the Deer Lodge Valley (R2 Resource Consultants, Inc., unpub. data, 1998).

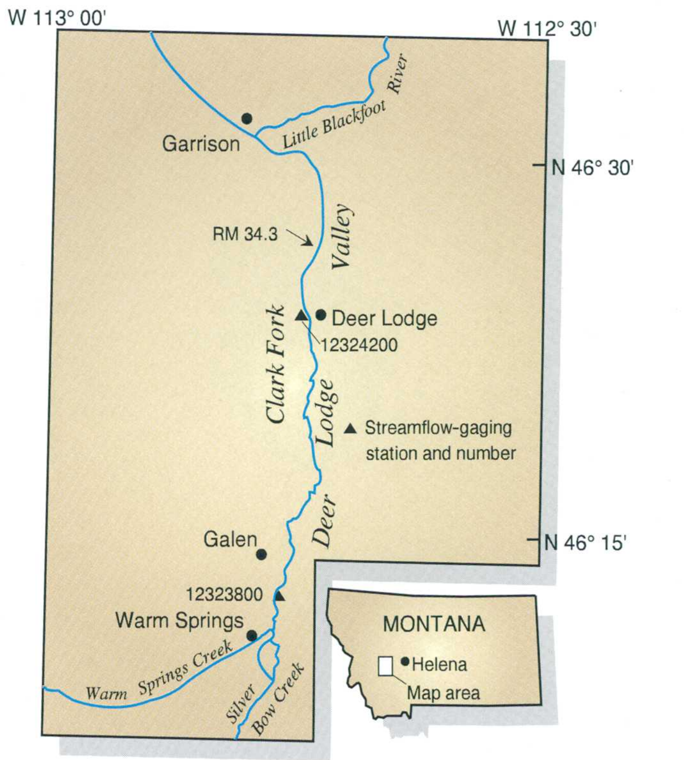


Figure 1. *Location of the study area. The Clark Fork of the Columbia River begins at the confluence of Warm Springs and Silver Bow Creeks, near Warm Springs, Montana (River Mile 0.0). The reach of interest in this study is from River Mile 0.0 to 34.3, through the Deer Lodge Valley.*

In this study, the effects of density and type of vegetation on cutbank erosion rates have been quantified. To do so, cutbank erosion rate data for the period 1989 to 1997 were examined for 276 bends between River Mile (RM) 0.0, near Warm Springs, and RM 34.3, downstream from Deer Lodge (fig. 3). These bends cover a total of 36 percent of the river centerline length through that reach. Density and types of vegetation along the outside bank of each of 211 of those bends were classified in a semiquantitative manner, and average erosion rates were computed for all bends in each of seven vegetation classes. Only one bankfull flow event (about 1,900 cubic feet per second [ft^3/s] at Deer Lodge) occurred during the 9-year study period, in June 1997. Flow was at or near bankfull at Deer Lodge for about 8 days during this event. All other peak discharges were less than 64 percent of the June 1997 peak discharge. However, a 2-day ice-breakup flow in February 1996, with a peak discharge of about 1,020 ft^3/s at Deer Lodge, caused significant bank erosion locally.

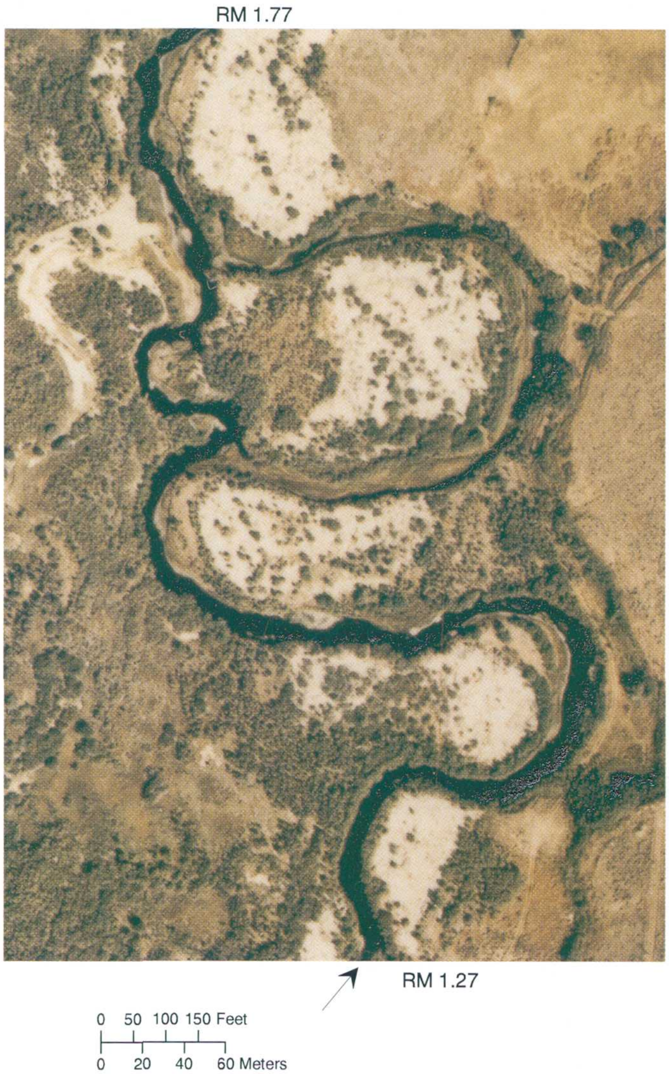


Figure 2. Example of slickens along a half-mile-long reach near Warm Springs in September 1988. (RM denotes river mile.) The arrow indicates flow direction. Vegetation is sparse on the silty overbank deposits contaminated with mine tailings (light-colored areas), which occur in many areas within the river meander belt. The slickens in this area were amended during the study period, and by 1997, the interior flood-plain tab surfaces were generally grass covered. However, vegetation along the riverbanks, which is the focus of this study, was not affected by the amendment work.

Available Data

Large-scale aerial photographs were taken in September 1988 at a very low flow (35 ft^3/s) and again in July 1997, when flow was about one-half bankfull (841 ft^3/s). Because the 1988 photographs were taken near the beginning of water year 1989 (October 1, 1988), the study period is considered to be 1989 to 1997, about 9 years. The 1988 photographs were taken at a scale of about 1:7,000 and the 1997 photographs at a scale of about 1:11,800. The photographs were scanned at high resolution, with a resulting pixel size of about 1 ft^2, then rectified to geographic coordinates. Bank erosion rates were determined by R2 Resource Consultants, Inc., (unpub. data, 1998) from the rectified images for short (average of about 21 ft long) bank segments along 43 river miles of the Clark Fork from Warm Springs to just upstream from the mouth of the Little Blackfoot River, near Garrison (figs. 1 and 3).

A geographic-information-system coverage containing the river centerline for the study period (fig. 3) was provided, together with the erosion rate data specified for either the left or right bank along the entire reach (R2 Resource Consultants, Inc., unpub. data, 1998). Owing to the intended use of the data for an equilibrium mass balance model, erosion was assumed to have occurred on only one side of the stream at any given location within the relatively short study period (9 years). Daily mean discharge data from the streamflow-gaging stations Clark Fork near Galen (station number 12323800) and at Deer Lodge (station number 12324200) are also available for the study period (fig. 4).

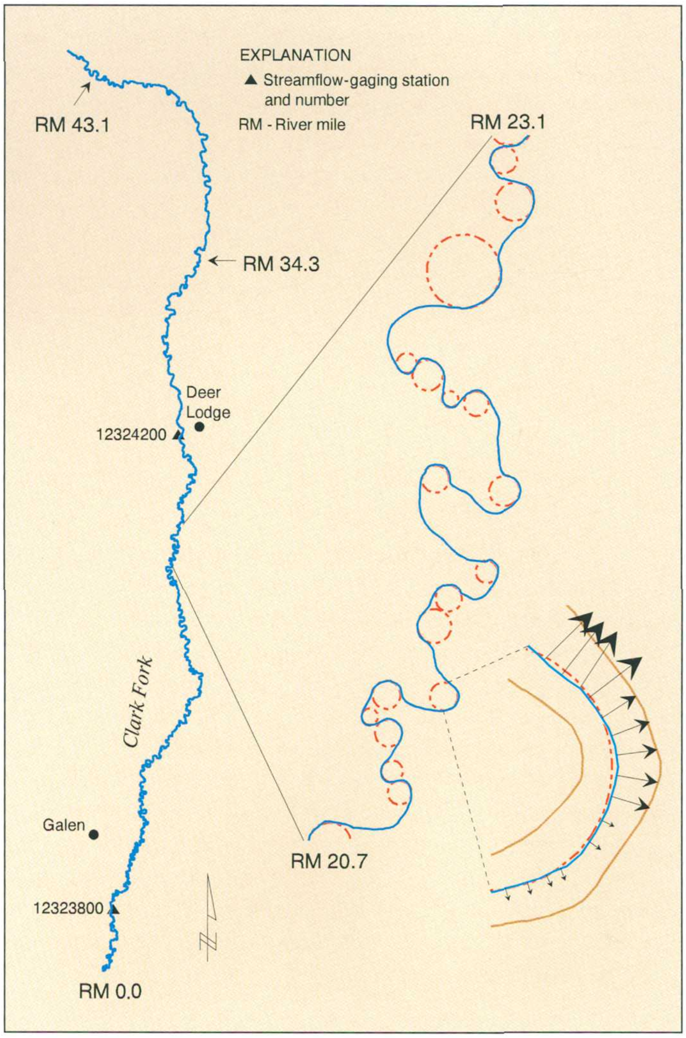


Figure 3. The river centerline through Deer Lodge Valley (blue lines), identified from large-scale aerial photographs (R2 Resource Consultants, Inc., unpub. data, 1998). In this study, radius of curvature was estimated, and average erosion rates were calculated for 276 bends (dashed circles) between RM 0.0 and 34.3. The edges of the channel (brown lines) are shown for one bend, and arrows generally indicate magnitude and direction of cutbank erosion along individual segments of the centerline arc (R2 Resource Consultants, Inc., unpub. data, 1998) through this bend.

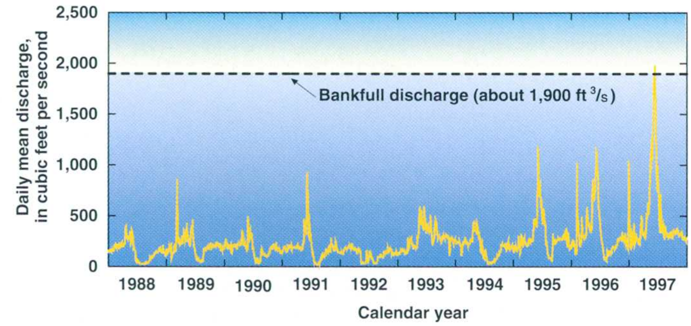


Figure 4. *Streamflow hydrograph for 1988 to 1997 at the gaging station Clark Fork at Deer Lodge (station number 12324200).*

Calculation of Average Erosion Rates through Bends

At the outset of the investigation, it was noted that more than one-half of the bank erosion occurred at the cutbanks on the outside of meander bends, so efforts were focused on these easy-to-characterize sites. Using the river centerline coverage, 276 bends were identified by drawing circular arcs generally fitting the curvature of the bends (fig. 3). The bend radius of curvature was expected to have a strong influence on erosion rate. Therefore, radius of curvature was estimated from the circular arcs, and bend length was computed from the distance along the centerline where it follows the circular arc. An average erosion rate for each bend was computed by multiplying the erosion rate associated with each centerline arc segment (R2 Resource Consultants, Inc., unpub. data, 1998) by the arc length (fig. 3), summing the result for all arcs through the bend, then dividing by the total bend length.

Average 1989–97 erosion rates for the 276 bends plotted as a function of distance downstream (fig. 5) show that the lowest rates occur primarily in the first 8 river miles. Erosion rates become more variable and much higher on average farther downstream. Exceptions to this general pattern occur locally, such as at the bend at RM 1.67, which had the highest measured erosion rate (4.25 feet per year). This bend is located in the middle of a recent change in the channel visible in figure 2. The much shorter path of the new channel results in a much steeper river slope, increasing the boundary shear stress at the base of the bank. Because of these anomalous conditions, this bend was excluded from the calculation of average erosion rate as a function of vegetation class.

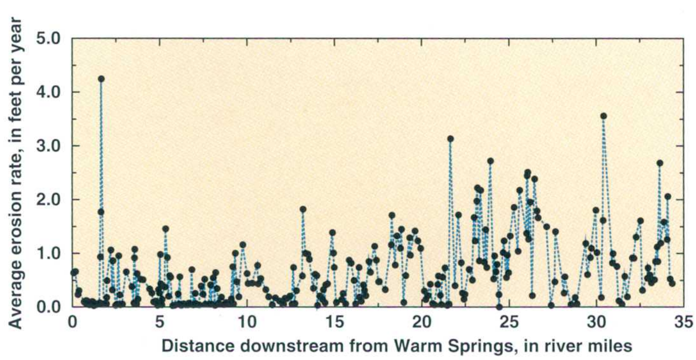


Figure 5. *Average bank erosion rate for each of 276 bends from September 1988 to July 1997 as a function of distance downstream from Warm Springs. The average erosion rate for all 276 bends was 0.62 foot per year, with a standard deviation of 0.66 foot per year, and an upward trend in the downstream direction.*

The cumulative eroded planimetric area as a function of distance downstream (fig. 6) shows the effect of the consistently high erosion rates, particularly between RM 23.0 and RM 27.7. From RM 0.0 to 34.3, the cumulative river centerline length through the bends is only 12.5 miles, or 36 percent of the total length. The eroded area through these bends makes up 52 percent of the total eroded area up to RM 34.3.

Local river slope and bank sedimentology and stratigraphy are important factors contributing to erosion rate, and neither of these parameters is known for the individual bends. It is assumed, however, that effects of differences in local slope and bank sedimentology will tend to average out in the large number of bends examined. Between RM 34.3 and RM 43.0, the river is confined to a narrow region between railroad and highway berms, resulting in shorter meander wavelengths and steeper average centerline slopes than for the river upstream. Therefore, bends in this reach were not included in the analysis. In addition, several streambank stabilization projects were conducted at four locations in the study reach between 1989 and 1997. Nine bends were affected by these projects. Because of bank and channel alterations made at these locations, these nine bends were also excluded from the analysis.

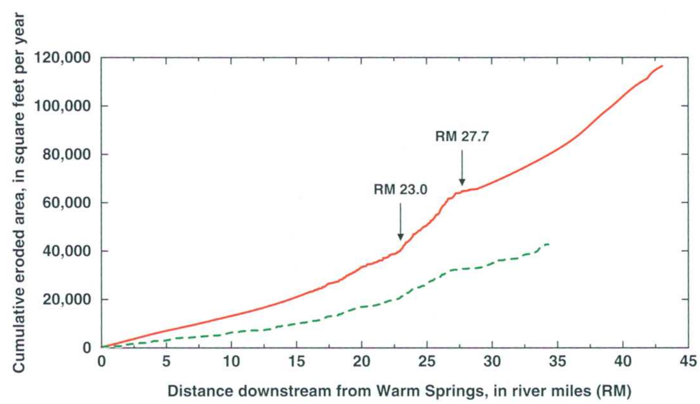


Figure 6. *Cumulative eroded area as a function of distance downstream. For each short arc segment along the river centerline, the arc length was multiplied by the average bank erosion rate for 1989 to 1997 to obtain eroded planimetric area along that arc for all centerline arcs (solid line) and for all arcs in bends (dashed line).*

Classification of Density and Type of Vegetation

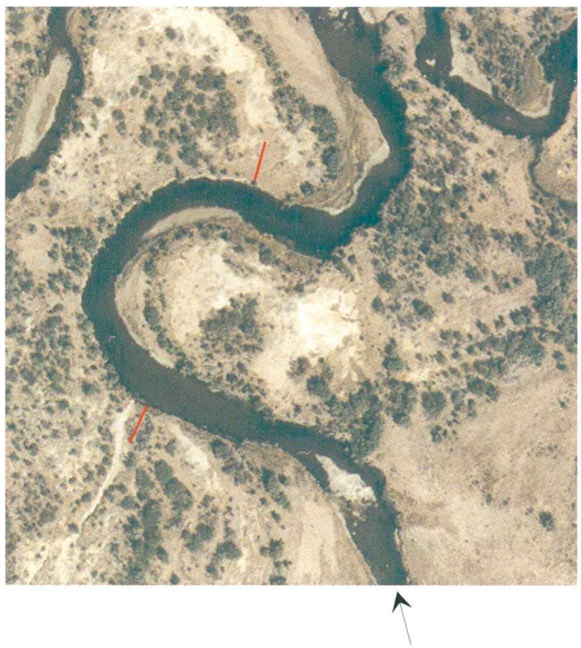
Vegetation density and type along the cutbanks on the outside of the bends were identified for 211 of the 276 bends for which the 1988 aerial photographic coverage was sufficient. The 1988 photographs were used in order to assess cutbank vegetation at the beginning of the study period, which was the condition generally acted upon during the study period. Shrubs common along the banks of the Clark Fork include water birch (*Betula occidentalus*) and a variety of shrub willows (*Salix* spp.).

A semiquantitative classification scheme was applied to evaluate differences in erosion rates as a function of the vegetation density and type immediately adjacent to the eroding cutbanks in the meander bends. The seven classes were based on types of vegetation present and, where there were shrubs, the relative distance between adjacent shrub canopies, as shown in figure 7. In vegetation classes 5 and 6, the shrubs were close enough that their canopies were in contact. Shrub canopies

Vegetation class 0–bare slickens

Vegetation class 1–all grass

Vegetation class 2–grass and a few shrubs

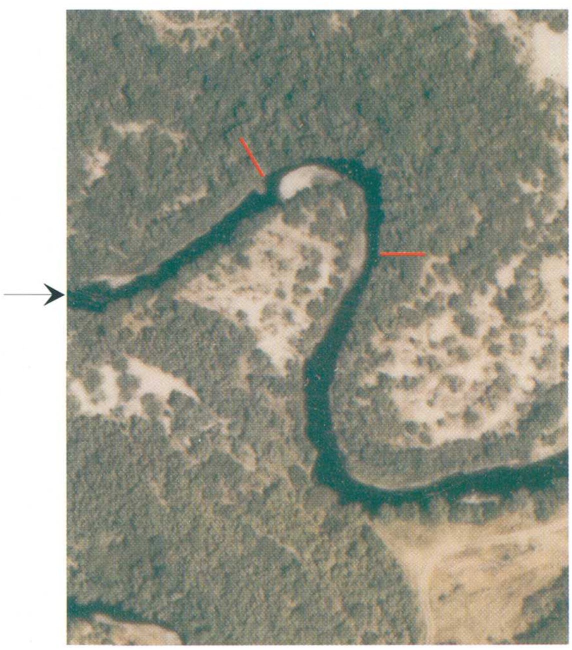


Vegetation class 3–grass and moderately spaced shrubs lining most of the outside of the bend

Figure 7. *Examples of the seven classes of vegetation density and type. The arrows indicate flow direction. The area of the bank between the two red lines in each image is the portion of the bank examined to classify vegetation. The bend shown with bare slickens along the outside bank (class 0) is located at River Mile 23.0, where the average erosion rate from 1989 to 1997 was 1.67 feet per year. The edge of the cutbank in vegetation class 6 was completely hidden by shrub canopy, and the amount of bank retreat (if any) could not be determined from the aerial photographs.*

Vegetation class 4–shrubs within one channel width apart all around the bend

Vegetation class 5–moderate to dense woody vegetation



Vegetation class 6–dense woody vegetation

Figure 7. *Examples of the seven classes of vegetation density and type. The arrows indicate flow direction. The area of the bank between the two red lines in each image is the portion of the bank examined to classify vegetation. The bend shown with bare slickens along the outside bank (class 0) is located at River Mile 23.0, where the average erosion rate from 1989 to 1997 was 1.67 feet per year. The edge of the cutbank in vegetation class 6 was completely hidden by shrub canopy, and the amount of bank retreat (if any) could not be determined from the aerial photographs—Continued.*

covered the entire cutbank in class 6, but there were short (less than 25 percent of the cutbank length) gaps in canopy cover in class 5.

Using this classification scheme, there was some subjectivity in assigning bends to particular vegetation classes. However, the high resolution of the aerial photographs and the consistent application of the classification criteria provided a systematic means of evaluating the bank-protecting effects of an increasing density of riparian shrubs.

RESULTS OF ANALYSIS

After determining vegetation density and type for a large number of bends (211) and assigning each to a vegetation class, the average erosion rate for each class was computed. An early hypothesis was that radius of curvature exerts a strong enough control on erosion rate to have a measurable effect. However, no direct correlation between radius of curvature and erosion rate was found, even for bends with similar vegetation density and type along the outside bank (fig. 8), probably because of the strong influence that local bank sedimentology has on erosion of moderately to sparsely vegetated cutbanks. Field observations indicated that the most rapidly eroding bends typically had a thick (about 1 ft) layer of well-sorted pebbles at or near the base of the cutbank.

A high degree of variability in erosion rate was found in each vegetation class, and the standard deviation of erosion rate was about the same as the mean. For bends in vegetation classes 2, 3, and 4, the location of woody vegetation in relation to the points of greatest radius of bend curvature and the sites of pebble layers in the banks probably produce variability in erosion rate within a given vegetation class. Regardless of the within-class variations, the average erosion rate decreases monotonically with increasing density of woody vegetation, as represented by vegetation class (fig. 9).

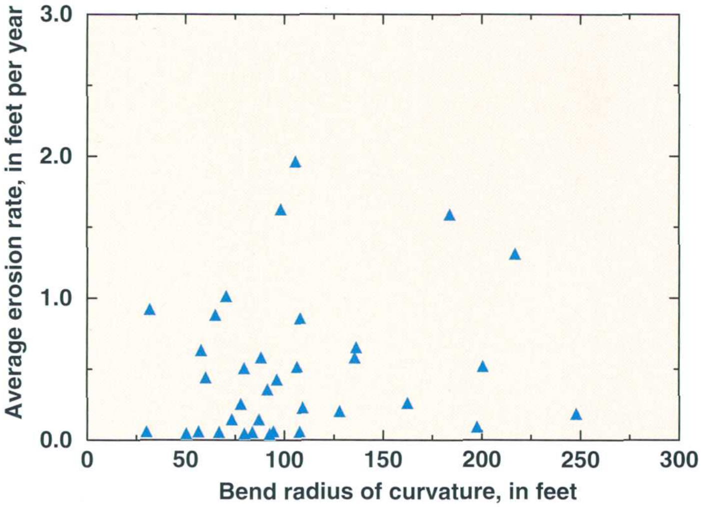


Figure 8. Average bank erosion rate as a function of bend radius of curvature for the 35 bends in vegetation class 4.

The class-average erosion rates calculated from the 1989 to 1997 erosion rate data decrease from 1.27 feet per year for the bends with bare slickens (class 0) to 0.27 foot per year for the bends with dense woody vegetation (class 6). The lowest cutbank erosion rates were expected in the densely vegetated bends, and the erosion rate data provided by R2 Resource Consultants, Inc., (unpub. data, 1998) do support that conclusion. However, at bends with moderate to dense woody vegetation (classes 5 and 6), visibility of the cutbanks in the aerial photographs was limited to the point that the extent of bank erosion could not be determined. For the class 6 bends, essentially all of the cutbanks were obscured by shrub canopies. The class 5 bends typically had 90 percent of the cutbank hidden by shrub canopies. In order to make accurate measurements of erosion on cutbanks, most of the bank must be visible in both aerial photographs (fig. 10). Therefore, the amount of bank retreat at the 35 bends in these two vegetation classes could not be measured from the aerial photographs, and a lower limit on cutbank erosion rate could not be determined. The hypothesis that the lowest possible erosion rate is zero cannot be disproved with the available data.

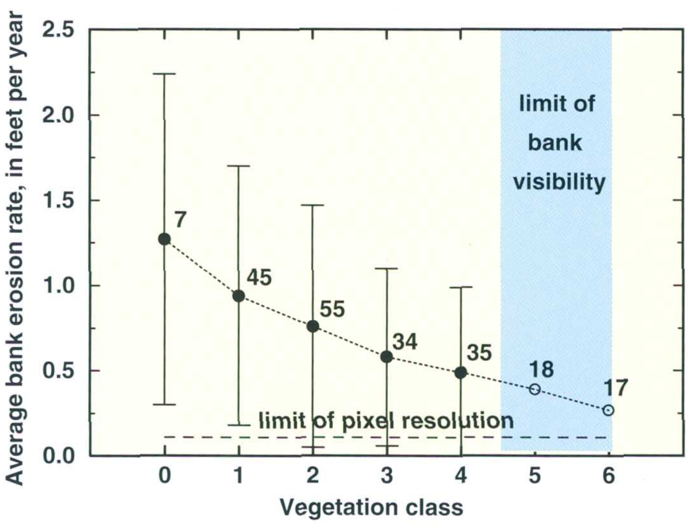


Figure 9. Average bank erosion rate as a function of vegetation class. The limit of pixel resolution (0.11 foot per year) is shown. The numbers above the points indicate the number of bends identified in each class. Error bars show the standard deviations for classes 0 - 4. Because of the limited bank visibility for the class 5 and 6 bends, erosion rates determined for these bends from the erosion rate data (R2 Resource Consultants, Inc., unpub. data, 1998) are not meaningful, even though they do follow the trend.

The vegetation classes were defined to represent an approximately linear increase in density of woody vegetation. Therefore, cutbank erosion rate as a function of density and type of vegetation in bends where most of the cutbank was visible (classes 0 through 4) can be transformed to an approximately linear decrease in erosion rate with increasing woody vegetation (fig. 11). The correlation coefficient for a linear regression on the class 0 through 4 data is –0.977. Extrapolating this linear decrease to vegetation classes 5 and 6 results in predicted average erosion rates of 0.23 ft/yr for vegetation class 5 and 0.04 ft/yr for vegetation class 6. Both of these values are consistent with the original data when considered in light of an error analysis, which is discussed in the next section.

Figure 10. A 0.6-mile (0.9-kilometer) reach in July 1997 where dense woody vegetation and shrub canopies obscured both banks through much of the reach.

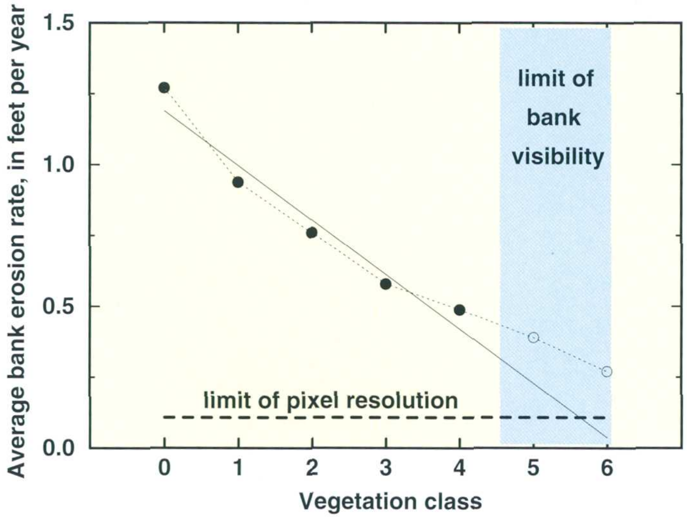


Figure 11. A linear regression (solid line) through the points for vegetation classes 0 through 4 and extrapolated to vegetation classes 5 and 6. If the extrapolation from quantifiable areas of bank erosion actually maintains a linear decrease, then it is predicted that the average erosion rate for cutbanks with dense woody vegetation is on the order of 0.04 foot per year.

Over one-half (107) of the 211 bends were identified as being in vegetation classes 0 to 2, having little to no woody vegetation. The average erosion rate for these bends between 1989 and 1997 was 0.87 ft/yr (fig. 9), resulting in an average total bank retreat of 7.83 feet in the 9-year period. Bends with moderately spaced woody vegetation along the cutbank (classes 3 and 4) make up 33 percent of the 211 bends. At these bends, the average erosion rate was reduced by about 40 percent, to 0.53 ft/yr and resulted in an average total bank retreat of 4.77 feet in the 9-year period.

Data are available on daily sediment loads at Deer Lodge for the erosion rate study period (Lambing, 1998). Significant local erosion of cutbanks occurred during a 2-day ice breakup flow in February 1996 (J.H. Lambing, U.S. Geological Survey, written commun., 2001), and the total sediment load measured at Deer Lodge for this event was about 3,640 tons. At low flows, the measured sediment flux comes primarily from rearrangement of the streambed, not from bank erosion. Assuming a threshold discharge for the initiation of bank erosion of one-fourth of the bankfull discharge (when flow would be sufficiently deep, on average, in the Clark Fork to begin eroding the cutbanks), 87 percent of the measured bank erosion can be attributed to four high-flow events during the study period. These four events were: (1) from June 3 to 30, 1995, when the daily mean discharge at Deer Lodge varied from 543 to 1,180 ft^3/s; (2) February 8 and 9, 1996, during the ice-breakup flow, when discharge was about 1,000 ft^3/s; (3) from May 14 to June 28, 1996, including 5 days when flow was over 1,000 ft^3/s; and (4) from April 28 to July 4, 1997, including about 22 days when flow was above one-half bankfull (about 950 ft^3/s) and 8 days of about bankfull flow (1,900 ft^3/s). The sediment fluxes from these four flow events indicate that over 10 percent of the sediment flux resulting from bank erosion came from the 2-day ice-breakup flow in 1996. This type of event occurs infrequently and causes high bank erosion and sediment transport rates.

Limitations on the Use of Large-Scale Aerial Photographs to Determine Bank Erosion Rates

Accuracy of erosion distances of retreating banks measured from two sets of aerial photographs is limited by properties of the scanned and rectified images. Locations of points or narrow linear features can only be identified to within one-half the pixel size, at best. Therefore, accuracy of bank retreat measured from two photographs is at best within one pixel width, which in this case is about 1 ft. Accuracy of the calculated 9-year average erosion rate for each arc is then at best 0.11 ft/yr and can be expected to be somewhat less accurate due to errors in geographic registration of the images. The accuracy of the registration of one set of images to the same geographic base as another is also limited by the pixel resolution, distortion in the photographs, and ability to recognize common features in both sets of images. Based on the experience of the authors and other USGS colleagues, a root-mean-squared error on the order of 3.3 ft is typical for this type of registration process when working with high-resolution images where terrain is relatively flat. This error appears to be consistent with results of other researchers, as well (Doucette and others, 1999). This error would limit the accuracy of measured erosion rates to approximately 3.3 feet per decade (about 0.33 ft/yr).

CONCLUSIONS

Two sets of large-scale aerial photographs scanned at a high resolution (to produce a pixel size on the order of 1 ft by 1 ft) and rectified to geographic coordinates can be used to determine erosion rates over long reaches by determining changes in bank position. The ability to quantify bank retreat, however, is limited where the banks are hidden by vegetation canopies. Most of the bank must be visible in both sets of aerial photographs in order to measure small amounts of bank retreat. In addition, the accuracy of the calculated erosion rate at a location is dependent on both the image pixel size and the accuracy of the geographic registrations of the two images. These factors limit the ability to measure accurately the amount of bank retreat where erosion rates are low. In the data set used for this investigation (R2 Resource Consultants, Inc., unpub. data, 1998), the likely degree of accuracy in measured erosion rate is no better than 3.3 feet per decade. Therefore, for the Clark Fork through Deer Lodge Valley, the hypothesis that erosion rates for the most densely vegetated bends are zero cannot be disproved with the available data.

The results of this analysis of vegetation controls on bank erosion rates clearly indicate a monotonically downward trend in erosion rate with increasing density of woody vegetation along cutbanks in meander bends. The trend suggests that dense, woody vegetation along the cutbank could reduce the average erosion rate in bends with no woody vegetation by a factor of 6 or more (from 1.27 ft/yr to less than 0.23 ft/yr). Even moderately spaced shrubs along the cutbank, where their canopies are not in contact (vegetation class 3), reduced the average erosion rate by about one-half, from 1.27 ft/yr at the bends with bare slickens to 0.58 ft/yr.

REFERENCES

Doucette, P., Agouris, P., Musavi, M., and Stefanidis, A., 1999, Automated extraction of linear features from aerial imagery using Kohonen Learning and GIS data, *in* Agouris, P., and Stefanidis, A., eds., Integrated spatial databases—Digital images and GIS: New York, Springer, p. 20–33.

Lambing, J.H., 1998, Estimated 1996–97 and long-term average annual loads for suspended sediment and selected trace metals in streamflow of the upper Clark Fork Basin from Warm Springs to Missoula, Montana: U.S. Geological Survey Water-Resources Investigations Report 98–4137, 35 p.

Nimick, D.A., and Moore, J.N., 1991, Prediction of water-soluble metal concentrations in fluvially deposited tailings: Applied Geochemistry, v. 6, p. 635–646.

Smith, J. Dungan, Lambing, J.H., Nimick, D.A., Parrett, C., Ramey, M., and Schafer, W., 1998, Geomorphology, flood-plain tailings, and metal transport in the upper Clark Fork valley, Montana: U.S. Geological Survey Water-Resources Investigations Report 98–4170, 56 p.

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