FACTORS AFFECTING STREAM BANK AND RIVER BANK STABILITY, WITH AN EMPHASIS ON VEGETATION INFLUENCES

An Annotated Bibliography
(annotations primarily author abstracts)

Compiled for the
Region III Forest Practices Riparian Management Committee

by
Robert A. Ott
Tanana Chiefs Conference, Inc. Forestry Program, Fairbanks, Alaska

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SUMMARY

In interior Alaska, concerns have been raised regarding the impact of forest management activities on fish habitat and water quality. The major concerns about the potential for timber harvest to affect fluvial systems seem to focus around riverbank erosion and large woody debris (LWD) recruitment. Vegetation has been shown to stabilize banks of rivers and streams in some systems, and LWD is known to be a critical component of anadromous and high value resident fish habitat, and to affect fluvial dynamics. It has been suggested that the harvest of riparian timber in interior Alaska can increase riverbank erosion rates with the result that productive spawning or rearing areas could be degraded through sedimentation processes or changes in channel morphology (e.g. simpler channels with fewer scour holes and fewer eddies and meanders). It has also been suggested that timber harvest near watercourses will decrease the supply of LWD that is recruited into a river through natural erosion processes. This literature review focuses on factors affecting stream bank and river bank stability, with an emphasis on vegetation influences. The role of LWD in fluvial systems is covered in another section of this report.

Although a formal definition of bank stability was not encountered in the literature, the context in which the term is used implies that a bank is stable if it does not change appreciably within a defined time frame. Bank stability is influenced by factors such as temperature regimes, composition of the bank material, hydraulic forces, presence or absence of permafrost, and vegetation (see Thorne (1982) for a description of bank erosion processes and mechanisms). Vegetation stabilizes banks primarily by increasing shear strength of the soil (Thorne and Lewin 1979, Gray and MacDonald 1989), reducing water velocity (Gray and MacDonald 1989), and armoring the bank (Thorne 1982). In arctic and subarctic regions where permafrost is present, vegetation also provides an insulating mat that helps protect frozen banks from erosion (Bray and Kellerhals 1979, Thorne 1982, Lawson 1983)—see the Permafrost and Silty Soils section of this report for additional discussion and references. The ability of vegetation to stabilize a bank is dependent upon factors such as plant vigor, density, and rooting depth (Heede 1980), interacting

with the other bank stability variables mentioned above. Predicting bank erosion rates can be difficult because of the interaction of the many variables that influence the process.

Bank erosion rates can vary according to the type of riparian vegetation that is present. Different vegetation life forms (e.g. herbaceous, woody shrub, tree) and species can have different root-shoot architectures and biomass—both above and below ground—which influence the ability of vegetation to stabilize banks of streams and rivers (e.g. Mallik and Rasid 1993). For example, differences in relative erosion rates have been noted between forested and non-forested banks, but the trend is not consistent. Studies where erosion rates of forested banks were less than those of non-forested banks include Mackin (1956) and Burckhardt and Todd (1998). Conversely, studies where erosion rates of forested banks were greater than those of non-forested banks include Murgatroyd and Ternan (1983), Davies-Coley (1997), and Trimble (1997).

The ability of vegetation to stabilize stream or river banks is partly dependent upon scale, with both the size of vegetation relative to the watercourse and absolute size of the vegetation being important. Vegetation stabilization tends to be most effective along relatively small water courses (Thorne 1982, Gatto 1984, Nanson and Hickin 1986, Davies-Colley 1997). On relatively large rivers, fluvial processes tend to dominate (Gatto 1984, Nanson and Hickin 1986). Large uprooted trees can serve to stabilize banks along large rivers, but on smaller streams those same trees may cause acceleration of water flow that results in local bank erosion (Thorne 1982). One must note, however, that local bank erosion may also result in the formation of scour pools and backwater areas that often are necessary for high quality fish habitat. Large trees may locally increase mass failure of banks because the surcharge weight can overcome any additional increase in soil shear strength due to root systems (Thorne 1982, Gatto 1984).

Vegetation (including LWD) influences channel development and geometry through its influence on bank erosion processes. Narrow stable channels often are associated with relatively high levels of riparian vegetation, while wider, unstable channels are associated with relatively less riparian vegetation (Rowntree and Dollar 1999). For example, braided channels (relatively wide and unstable) tend to be associated with sparely vegetated banks (Leopold et al. 1964, Heede 1980). Cause and effect of this relationship, however, has not been proven (Leopold et al. 1964). Vegetation also influences the degree of channel sinuosity (Murgatroyd and Ternan 1983, Ebisemiju 1994). Removal of LWD from a stream can result in local bank erosion and channel widening (Smith et al. 1993)—see the Large Woody Debris section of this report for further discussion and references pertaining to LWD influences on channel morphology.

This literature review was conducted in two phases. First, a search was conducted using the electronic databases at the University of Alaska Fairbanks. Once relevant papers and books were located, additional references were located using the literature citation sections of those materials.

REFERENCES

Abernethy, B., and I. D. Rutherfurd. 1998. Where along a river's length will vegetation most effectively stabilise stream banks? Geomorphology 23: 55-75.

Riparian vegetation has different impacts on stream processes depending upon its position in a catchment. Native riparian vegetation is increasingly becoming the favored stream management tool but managers need to locate revegetation schemes where they will most effectively achieve ecological, geomorphological, or other project goals. Using the Latrobe River in SE Australia as an example, this paper illustrates a structured decision-making approach for assessing the role of vegetation in stream bank erosion at different points throughout a catchment. Three bank-erosion process groups are identified: subaerial preparation, fluvial entrainment, and mass failure. Although these processes act on banks throughout the catchment there exists spatial zoning in the dominance of each process group over the others. Bank erosion in upper reaches is dominated by subaerial preparation, in mid-basin reaches by fluvial entrainment, and in the lower reaches by mass failure. The authors found that in upper reaches, windthrown trees are responsible for most bank sediment transfer to the flow. Where direct fluvial entrainment of bank material is the dominant erosion process, flow resistance due to vegetation becomes crucial. In reaches where bank slumping is the dominant erosion process, increased bank shear strength due to root reinforcement is the major role of vegetation in stabilizing banks. Other effects, such as tree surcharge, and altered bank hydrology appear to exert only minor influences on the slumping process. Considering the above variables the authors were able to define a critical zone in which revegetation will be most effective in reducing bank erosion. On the Latrobe River, this zone occurs in that portion of the river where it first leaves the mountain front and meanders across a broad floodplain. This reach occupies the second quarter of the river's length. This information, combined with other scale analyses (e.g. ecological, hydrological), will assist river managers to plan physically based riparian revegetation strategies.

Beeson, C. E., and P. F. Doyle. 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. Water Resources Bulletin 31: 983-990.

Following major floods in 1990 which resulted in widespread bank erosion in southern British Columbia, four streams typical of the region were evaluated for the effect which riparian vegetation played in reducing erosion. A total of 748 bends in the four stream reaches were assessed by comparing pre- and post-flood aerial photography. Bends without riparian vegetation were found to be nearly five times as likely as vegetated bends to have undergone detectable erosion during the flood events. Major bank erosion was 30 times more prevalent on non-vegetated bends as on vegetated bends. The likelihood of erosion on semi-vegetated bends was between that of the vegetated and non-vegetated categories of bends.

Bradbury, J., P. Cullen, G. Dixon, and M. Pemberton. 1995. Monitoring and management of streambank erosion and natural revegetation on the lower Gordon River, Tasmanian Wilderness World Heritage Area, Australia. Environmental Management 19: 259-272.

The wash from high-speed tourist cruise launches causes erosion of the formerly stable banks of the lower Gordon River within the Tasmanian Wilderness World Heritage Area. Speed and access restrictions on the operation of commercial cruise vessels have considerably slowed, but not halted erosion, which continues on the now destabilized banks. To assess the effectiveness of restrictions, bank erosion and natural revegetation are monitored at 48 sites using erosion pins, survey transects, and vegetation quadrats. The subjectively chosen sites are grouped on the basis of geomorphology and bank materials. The mean measured rate of erosion of estuarine banks slowed from 210 to 19 mm/year with the introduction of a 9 knot speed limit. In areas where cruise vessels continue to operate, alluvial banks were eroded at a mean rate of 11 mm/yr during the three-year period of the current management regime. Very similar alluvial banks no longer subject to commercial cruise boat traffic eroded at the slower mean rate of 3 mm/yr. Sandy levee banks have retreated an estimated maximum 10 m during the last 10-15 years. The mean rate of bank retreat slowed from 112 to 13 mm/yr with the exclusion of cruise vessels from the leveed section of the river. Revegetation of the eroded banks is proceeding slowly; however, since the major bank colonizers are very slow growing tree species, it is likely to be decades until revegetation can contribute substantially to bank stability.

Bray, D. I., and R. Kellerhals. 1979. Some Canadian examples of the response of rivers to man-made changes. Pages 351-372 *in* D. D. Rhodes and G. P. Williams, editors. Adjustments of the fluvial system. Kendall/Hunt Publishing Company, Dubuque, Iowa.

This paper documents a few Canadian cases of known man-caused changes in fluvial systems. One of the cases summarizes a study by Cooper and Hollingshead (1973)[1], in which construction of a logging road resulted in accelerated bank erosion along the Liard River, near Watson Lake, Yukon Territory. The road was constructed on a bank of the river comprised of permafrost and possessing a southern exposure. Air photo analysis indicated that the banks were stable for 20 years before the vegetation was removed during construction of the road. After road construction, bank erosion increased in the section where vegetation was removed, but the banks remained stable where vegetation was not removed. The probable processes resulting in increased bank erosion after road construction are:

1.) Before road construction, the active layer—which is probably less resistant to erosion than permafrost—was located above the maximum height attained by water during annual flood events.
2.) Removal of the vegetation mat from the top of the river bank resulted in an increased depth of the active layer so that it extended below the maximum height attained by water during annual flood events.

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[1] Cooper, R. H., and A. B. Hollingshead. 1973. River bank erosion in regions of permafrost. Pages 272-283 *in* Fluvial processes and sedimentation. Hydrology Symposium Proceedings No. 9, University of Alberta, Edmonton.

3.) During annual flood events, the active layer can now be eroded more rapidly than the surrounding frozen soil, resulting in accelerated erosion where the vegetation mat was removed.

Burckhardt, J. C., and B. L. Todd. 1998. Riparian forest effect on lateral stream channel migration in the glacial till plains. Journal of the American Water Resources Association 34: 179-184.

Dendrochronology analyses of point bar complexes were used to quantify the effects of riparian forests on local lateral migration of bends in seven streams in the glacial till plains of north central Missouri. Stream bends were paired with similar bank height, midchannel radius of curvature, soil composition, and watershed size. In each pair, one concave bank was forested and one was unforested. Stream bends with unforested concave banks had an average local migration rate three times greater than stream bends that had forested concave banks.

Davies-Colley, R. J. 1997. Stream channels are narrower in pasture than in forest. New Zealand Journal of Marine and Freshwater Research 31: 599-608.

In the Hakarimata Range, west of Hamilton, New Zealand, second-order streams appear to be wider in native than in pasture catchments, whereas streams in pine plantations (18 years old) appear to be suffering active stream-bank erosion. A working hypothesis to explain these observations was that pasture vegetation replacing original forest encroaches on the stream channel, causing it to become narrower. To test the hypothesis, channel widths were measured up stream and down stream of "transitions" from native forest to pasture in 20 streams of different size in marginal ranges of the Waikato Basin. Small streams (catchment area <1 km^2, width in forest <2 m) were found to be half the width in pasture reaches as in forest. The degree of channel narrowing decreased as stream size increased and was minimal in large streams (catchment area >30 km^2, width in forest >10 m). This narrowing of stream channels implies that native forest clearance in New Zealand has reduced stream channel habitat. A concern regarding riparian planting for stream restoration is that sediment stored in pasture stream banks could be mobilized if grasses are extinguished by shading, resulting in turbid streamwater and sedimentation of fines in the channel.

Dwyer, J. P., D. Wallace, and D. R. Larsen. 1997. Value of woody river corridors in levee protection along the Missouri River in 1993. Journal of the American Water Resources Association 33: 481-489.

Following the Midwest flood of 1993, a study was initiated along a 39-mile segment of the Missouri River to determine if there was an association between woody corridors and levee stability. A systematic sample of levee failures revealed that primary levees which did not fail had a significantly wider woody corridor than failed levees. Analysis of the total inventory of failed levees revealed that as the width of the woody corridor decreased, the length of the levee failure increased. Number of levee failures and their severity of damage could be reduced if woody corridors were at least 300 feet wide.

Ebisemiju, F. S. 1994. The sinuosity of alluvial river channels in the seasonally wet tropical environment: case study of river Elemi, southwestern Nigeria. Catena 21: 13-25.

Investigations carried out in the Elemi river basin, southwestern Nigeria suggest that small intermittent streams in the seasonally wet humid tropics have a tendency to develop very sinuous channels characterized by compound and highly convoluted loops. Analysis of arc symmetry and the repetition of symmetry indicate that the 153 bends along the 39.3 km long river are not true meanders as objectively defined by Brice in 1964. The dominant factor controlling the degree of sinuosity is channel bank resistance to lateral erosion as influenced primarily by the nature of riparian vegetation and secondarily by the percentage silt/clay in channel bank sediment. The influence of bank vegetation is particularly pronounced in view of the preponderance of low flow discharges, high proportion of suspended sediment and gentle bed slope. The high density of riparian trees account for the relatively short length of the straight reaches and the high frequency of bends, compound and convoluted loops. The implications for river management of the inherent instability of small channels in seasonally wet humid tropical environments, and of the considerable channel bank erosion which occurs at the numerous bends are briefly highlighted.

Gatto, L. W. 1984. Tanana River monitoring and research program: relationships among bank erosion, vegetation, soils, sediments, and permafrost on the Tanana River near Fairbanks, Alaska. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Special Report 84-21.

The objective of the analysis was to determine if available data are useful in identifying characteristics that contribute to erodibility of the banks along two reaches of the Tanana River. Existing data on bank vegetation, soils, sediments and permafrost were used. The data were visually compared to the locations and estimated amounts of historical recession to evaluate if any relationships were obvious. The results of the analysis showed no useful relationships. Vegetation was similar in eroded and uneroded areas and its distribution did not show any obvious relationship to the locations of bank recession. Surface sediments and soils in the eroded areas had little, if any, effect on bank erodibility because the river erodes the bank over its entire depth, which is well below this surface zone. The subsurface sediment from eroded and uneroded wells and along transects with high and low measured recession was similar. Permafrost occurrences are about equal in eroded and uneroded sites, although it appears that recession can be higher where permafrost is common compared to where it is absent.

Additional comments

The author notes that results from other studies indicate that vegetation increases bank resistance to erosion. He also notes, however, that vegetation is unimportant in limiting erosion along large watercourses, because the rivers erode the bank to a depth that is well below the rooting zone of the vegetation. Once a river has eroded a bank to the point where riparian trees are unsupported, the unsupported trees will fall into the river, carrying with them, large amounts of bank sediment. Through this mechanism, vegetation can actually contribute to bank erosion. It has also been suggested, however, that collapsed trees may protect banks from further erosion if they lie against the subaqueous (below water) portion of the bank while remaining attached to the subaerial (above water) portion of the bank. It can be argued that attached, collapsed trees located at or below the water surface protect banks from erosion, because they serve to divert currents from the bank and to reduce near-bank current velocities. It is the author's opinion, however, that hydraulic forces of the river and not vegetation, soils, or surface sediments, are the important factors influencing bank erosion along the Tanana River.

Gatto, L. W. 1995. Soil freeze-thaw effects on bank erodibility and stability. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Special Report 95-24.

When air temperature is below ground temperature, a thermal gradient is established in the soil that causes the soil to lose heat to the atmosphere. When the soil has lost sufficient heat for soil water to freeze, the newly formed ice changes soil structure by disaggregating, separating, and reorienting soil particles. The suction set up within the freezing soil draws water to the freezing zone through the film of unfrozen water surrounding soil particles, supplying additional water for freezing, so the volume of ice increases. When appropriate thermal and water supply conditions are in place, disseminated ice lenses can form in the soil. As the ice lenses grow, the soil surface is heaved in the direction of heat flow from the soil. Soil particles can be displaced down a bank face when surface ice in heaved soil melts. The amount of ice in a frozen soil by the end of winter can be higher than its water content when unfrozen. Thus, upon thawing, the previously frozen soil temporarily has an excess of soil water and a disrupted soil structure, which significantly reduces internal friction and cohesion and reduces the soil's shear strength. In this weakened state, thawed bank soils are usually more easily eroded by raindrop impacts, overland flows, river and lake ice forces, currents and waves, and are highly susceptible to mass failures. In some instances newly thawed soils are weaker than at any other time of the year. Some studies show that processes related to bank soil freezing and thawing cause more bank recession annually than other processes in areas where seasonal frost forms. However, with time, the strength of the thawed soil returns as excess water drains from the soil, and soil particle packing and interlocking increase. Thus, frost-induced reductions in soil strength and soil particle displacements must be included in bank migration and bank erosion models to be applied in regions with seasonal soil frost.

Gray, D. H., and A. MacDonald. 1989. The role of vegetation in river bank erosion. Pages 218-223 *in* M. A. Ports, editor. Hydraulic engineering. Proceedings of the 1989 national conference on hydraulic engineering.

Vegetation modifies the interface region between flowing water and the stream bank. Hydraulic and mechanical properties near this interface will be modified in ways that affect the resistance of the bank to both surficial erosion and mass wasting respectively. With regard to mass stability, plant roots reinforce a soil and increase its shear strength. Vegetation also interacts with flowing water to influence bank erosion through disturbance of the flow field. Two distinct conceptual interpretations of this disturbance are proposed. The first views bank vegetation as a "carpet" of roughness elements akin to individual, albeit larger, grains of sediment. The second views vegetation in the form of single, isolated tree trunks which behave much as bridge pilings.

Harmel, R. D. 1997. Analysis of bank erosion on the Illinois River in northeast Oklahoma. Ph.D. thesis. Oklahoma State University. (Cited in Dissertation Abstracts International Part B: Science and Engineering, 1998, vol. 59(2))

The objectives of this research were: (1) to measure short-term bank erosion for selected sites, (2) to measure long- term erosion with aerial photographs, (3) to evaluate the impact of riparian vegetation on short- and long-term erosion, (4) to compare the short-term results of this study to similar work by D. L. Rosgen, and (5) to estimate the contribution of bank erosion to sedimentation of Lake Tenkiller. In July 1996, a bank characterization trip was made to gather data on eroding and stable banks. Characterized banks were grouped according to physical and vegetative conditions and hydrologic influence. At least one bank from each group was selected for detailed field study. Erosion was measured using bank pins and cross-sectional surveys from September 1996 through July 1997. Bank erosion was also measured from 1958, 1979, and 1991 aerial photographs. Erosion averaged 4.5 ft and ranged from -0.03 to 26.5 ft after four, 2.0 to 2.5 yr return period flow events from August 1996 to September 1997. An additional 0.40 ft average was measured for 14 sites after two at or near bankfull events in the spring and summer of 1997. The average annual flow for the study period exceeded the long-term average by 20%. In the aerial photograph analyses, lateral erosion averaged 3.6 ft/yr in the period 1979 to 1991 and averaged 1.7 ft/yr from 1958 to 1979. During the periods 1979 to 1991 and 1958 to 1979, the Illinois River eroded a total of 195 ac and 64 ac of land surface area, respectively. The long-term analyses showed that forest vegetation is important in reducing and preventing bank erosion. Major short- and long-term erosion did occur on banks with each vegetation type, so natural forest vegetation does not always prevent erosion but can lessen the likelihood of its occurrence. In general, the Rosgen Level III bank erosion potential evaluation was easy to understand and apply in the field; however, as it currently stands, it performed relatively poorly in predicting short-term bank erosion. Individually, the bank erosion potential and Pfankuch Channel Stability ratings did perform relatively well in relating ratings to short-term bank erosion, but the near bank stress estimates did not. The contribution of bank erosion to sedimentation of Lake Tenkiller was not successfully estimated.

Harwood, K., and A. G. Brown. 1993. Fluvial processes in a forested anastomosing river: flood partitioning and changing flow patterns. Earth Surface Processes and Landforms 18: 741-748.

In an effort to further understanding of multiple channel systems, this paper presents data on the flood response of channels in one of the last wooded, semi-natural anastomosed systems in Europe. The Gearagh, Ireland, is characterized by hundreds of small islands separated by interconnected channels of low slope. These include channels that cross islands at right angles to the main flow and blind anabranching channels. Islands are relatively stable and wooded, with evidence of division by channel erosion and growth by in-channel sedimentation. Four active zone cross-profiles were surveyed, each containing between seven and 13 channels. Velocities were measured in several channels before and during two separate floods. From these observations channels have been categorized into three types: fast (shallow and trapezoidal); slow (deep and more irregular); and flood channels. During the floods, interchannel flows were caused by variations in water surface elevations due to backing-up behind debris dams, and it is suggested that this is the origin of the anomalous cross-island channels and one cause of island division. Another potential cause if island division, blind anabranching channels, is the result of concentrated bank scour between root masses. Biotic components such as debris dams, tree root masses and tree-throw pits play a key role in the partitioning of flow, and cause variations in channel velocities and the overbank velocity distribution. The implications of these observations for channel pattern maintenance are briefly discussed.

Heede, B. H. 1980. Stream dynamics: an overview for land managers. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-72.

This document provides a basic introduction to stream dynamics. Topics of discussion include: basic fluvial processes (subcritical and supercritical flow, laminar and turbulent flow, sediment transport), dynamic equilibrium, processes affecting channel pattern and shape, and processes affecting longitudinal profile.

Additional comments

Longitudinal profile, a measure of stream slope or gradient, is one of the major sources of channel pattern changes. Steeper streams have higher velocities and ,therefore, attack banks more strongly and carry higher sediment loads. For this reason, braided streams with their steeper profiles are more erosive than lower gradient meandering streams. Bank erosion, however, can only occur where erodible material is present. Braiding, for example, usually does not take place where banks are densely vegetated, but may occur where vegetation cover is sparse.

Bank stability is influenced by factors such temperature, chemistry of clay, and vegetation. The ability of vegetation to stabilize banks is dependent upon plant vigor, density, and rooting depth.

Hey, R. D., J. C. Bathurst, and C. R. Thorne. 1982. Gravel-bed rivers: fluvial processes, engineering and management. John Wiley & Sons Ltd., New York.

This book is a record of the proceedings of the International Workshop on ‘Engineering Problems in the Management of Gravel-bed Rivers’ held at Gregynog, Newtown, UK between 23 and 27 June 1980. Contributed papers deal with topics related to flow hydraulics, flow resistance, sediment transport, bank erosion, bar sedimentation, meander processes, hydraulics of mountain streams, dynamic modeling, regime equations, flow routing and river regulation, river stabilization and training, river regulation and channel stability, channel responses to changes in land use, and ecological implications of river regulation and training.

Huang, H. Q., and G. C. Nanson. 1997. Vegetation and channel variation; a case study of four small streams in southeastern Australia. Geomorphology 18: 237-249.

Channel vegetation of four small streams in southeastern Australia varies greatly in detail but it can be broadly categorized and even indexed for quantitative analysis. Such variations cause the hydraulic geometry of the study streams to differ significantly from each other and from patterns observed in most other geographical regions. Importantly, this study demonstrates that the impact of vegetation on channel form and velocity can be quantified in much the same way that other broadly based hydraulic geometry relations have been developed. Dense bank vegetation results in narrower channels whereas vegetation growing on the bed greatly increases flow resistance, causing channel widening, reduced flow velocity but no significant change in depth. The results obtained in this study, combined with those from other regions, permit an interpretation of the sensitivity of channel width to different forms of channel vegetation, information of use for river management.

Kondolf, G. M., and R. R. Curry. 1984. The role of riparian vegetation in channel bank stability: Carmel River, California. Pages 124-133 *in* R. E. Warner, and K. M. Hendrix, editors. California riparian systems: ecology, conservation, and management.

A narrow channel with well-vegetated banks developed on the lower 15 km. of the Carmel River by 1939, and by 1960 this condition had extended to the entire lower 24 km. of river channel. Noticeable die-off of riparian trees near water supply wells began in the 1960s and intensified during the 1976-1977 drought. Substantial bank erosion occurred during the winters of 1978 and 1980 along reaches which had suffered loss of bank-stabilizing riparian trees.

Kondolf, G. M., and R. R. Curry. 1986. Channel erosion along the Carmel River, Monterey County, California. Earth Surface Processes and Landforms 11: 307-319.

Historic maps, photographs, and channel cross-sections show that the channel of the Carmel River underwent massive bank erosion, channel migration, and aggradation in a major flood in 1911, then narrowed and incised by 1939. The channel was stable until 1978 and 1980, when bank erosion affected some reaches but not others. The narrowing and incision were in response to a lack of major floods after 1914 and construction in 1921 of a dam that cut off sediment supply from the most actively eroding half of the basin. Localized erosion in 1978 and 1980 occurred during low magnitude events along reaches whose bank strength had been reduced by devegetation. These events illustrate that the stability of a fluvial system can be disrupted either by application of a large erosive force in a high magnitude event (the 1911 flood) or in a low magnitude event, by reducing the resistance to erosion (bank devegetation). The Carmel River is a potentially unstable system. Its discharge and slope characteristics place it near the threshold between meandering and braided. On the Lower Carmel, the presence of bank vegetation can make the difference between a narrow, stable meandering channel and a wide shifting channel with braided reaches.

Lawson, D. E. 1983. Erosion of perennially frozen streambanks. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, CRREL Report 83-29.

A literature review indicated that the effects of permafrost on streambank erodibility and stability are not yet understood because systematic and quantitative measurements are seriously lacking. Consequently, general controversy exists as to whether perennially frozen ground inhibits lateral erosion and bankline recession, or whether it increases bank recession rates. Perennially frozen streambanks erode because of modification of the bank's thermal regime by exposure to air and water, and because of various erosional processes. Factors that determine rates and locations of erosion include physical, thermal and structural properties of bank sediments, stream hydraulics and climate. Thermal and physical modification of streambanks may also induce accelerated erosion within permafrost terrain removed from the immediate river environment. Bankline or bluffline recession rates are highly variable, ranging from less than 1 m/year to over 30 m/year and, exceptionally, to over 60 m/year. Long-term observations of the physical and thermal erosion processes and systematic ground surveys and measurements of bankline-bluffline recession rates are needed.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Company, San Francisco.

This book deals primarily with landform development under processes associated with running water. The general subjects covered in the book include climate and denudational processes, weathering, the drainage basin as a geomorphic unit, water and sediment in channels, channel form and process, hillslope characteristics and processes, geochronology, drainage pattern evolution, channel changes with time, and evolution of hillslopes.

Mackin, J. H. 1956. Cause of braiding by a graded river. Bulletin of the Geological Society of America 67: 1717-1718.

South of Haley, Idaho, the Wood River meanders in a forest for many miles, braids in a 3-mile segment where the valley floor is prairie, and returns to a meandering habitat where the river re-enters a forest. The river is stable or slowly degrading in all three segments. The essential cause of the drastic difference in channel characteristics in adjoining segments is a difference in bank resistance due to presence or absence of bank vegetation.

Sinuosity of rivers is determined by width/depth of their channels. Ribbon-candy meanders develop only because, in a channel of low width/depth, factors which inhibit growth of bends are outweighed by a self-accelerating interplay in a set of factors which causes continued outgrowth. With high width/depth, a balance is struck between opposed sets of factors when bends attain a low curvature. Sinuosity is inversely proportional to width/depth.

Incidence of channel islands is also controlled by width/depth. Channel-island index (length of channel islands/length of channel) varies systematically from zero for channels with low width/depth to more than 2 for channels with high width/depth.

Width/depth is itself determined by (1) erosional force applied to the banks, and (2) bank resistance; it varies directly with (1) and inversely with (2). Erosional force is proportional to transporting force and is determined by discharge and load. Bank resistance is determined by the nature of the bank-forming material plus a vegetation factor.

Madej, M. A., W. E. Weaver, and D. K. Hagans. 1994. Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA. Environmental Management 18: 235-250.

Channel changes from 1919 to 1989 were documented in two study reaches of the Merced River in Yosemite National Park through a review of historical photographs and documents and a comparison of survey data. Bank erosion was prevalent and channel width increased an average of 27% in the upstream reach, where human use was concentrated. Here, trampling of the banks and riparian vegetation was common, and banks eroded on straight stretches as frequently as on meander bends. Six bridges in the upper reach constrict the channel by an average of 38% of the original width, causing severe erosion. In the downstream control reach, where human use was minimal, channel widths both decreased and increased, with a mean increase of only 4% since 1919. Bank erosion in the control reach occurred primarily on meander bends. The control reach also had denser stands of riparian vegetation and a higher frequency of large woody debris in channels. There is only one bridge in the lower reach, located at the downstream end. Since 1919, bank erosion in the impacted upstream reach contributed a significant amount of sediment (74,800 tons, equivalent to 2.0 $t/km^2/yr$) to the river. An analysis of 75 years of precipitation and hydrologic records showed no trends responsible for bank erosion in the upper reach. Sediment input to the upper reach has not changed significantly during the study period. Floodplain soils are sandy, with low cohesion and are easily detached by lateral erosion. The degree of channel widening was positively correlated with the percentage of bare ground on the streambanks and low bank stability ratings. Low bank stability ratings were, in turn, strongly associated with high human use areas. Channel widening and bank erosion in the upper reach were due primarily to destruction of riparian vegetation by human trampling and the effect of bridge constrictions on high flow, and secondarily to poorly installed channel revetments. Several specific recommendations for river restoration were provided to park management.

Mallik, A. U., and H. Rasid. 1993. Root-shoot characteristics of riparian plants in a flood control channel: implications for bank stabilization. Ecological Engineering 2: 149-158.

Root-shoot dimensions and dry biomass of samples of ten dominant species from the bank profiles of the Neebing-McIntyre Floodway, Thunder Bay, Ontario, Canada were significantly different from one micro-habitat to another. These differences were used as the basis of interpreting allocation of energy in different components of plants that helped them colonize specific micro-habitats along the bank profiles of the floodway. Thus, *Deschampsia flexuosa*, the dominant plant on the bank slope, allocates about 90% of its biomass in its shallow but dense root systems (compared to its shoots), which provides protection to the bank slope from surface runoff. *Alnus rugosa* and *Salix bebbiana*, dominant on erosional scarps, allocate about equal amounts of biomass in their above-ground and below-ground components, but have long tap roots, which help them colonize the steep scarp face. Plants on the bench and under-water shelf, such as *Juncus nodosus* and *Saggitaria latifolia*, allocate disproportionately large amounts of biomass to their above-ground components, which are exposed to the dynamics forces of waves and currents. Overall, the study indicates that root-shoot architecture and biomass can be used as biotechnical criteria in selecting riparian plants for bank stabilization of flood control channels.

Morisawa, M. 1968. Streams: their dynamics and morphology. McGraw-Hill Book Company, New York.

This book provides a good introduction to fluvial geomorphology. Topics include: hydrology, hydraulics of streams, sediment load transport, erosion, deposition, slope and channel morphology, the graded profile of the steady state, dynamic equilibrium, channel patterns, and basic concepts at the scale of the drainage basin (e.g. drainage patterns; drainage density and stream frequency)

Morisawa, M. 1985. Rivers: form and process. Longman Group Limited, New York.

This book discusses the morphology of rivers and their watersheds, and the mechanics by which rivers degrade landscapes, and transport and deposit sediments. Topics include: stream denudation, hydraulics of streamflow , entrainment and transport, mechanics and landforms of fluvial erosion, river morphology, river deposition and fluvial landforms, quantitative basin analysis, structural and lithological controls, and the impact of man on rivers.

Murgatroyd, A. L., and J. L. Ternan. 1983. The impact of afforestation on stream bank erosion and channel form. Earth Surface Processes and Landforms 8: 357-369.

Modification of the land use of a small catchment through coniferous afforestation is shown to have influenced stream bank erosion and channel form. Field mapping and erosion pin measurements over a 19-month period provides evidence of more active bank erosion along forested channel reaches than along non-forested. Extrapolation of downstream increases in bankfull width, bankfull depth, and channel capacity with increasing basin area for the non-forested catchment has demonstrated that afforestation of the lower part of the catchment has had a marked effect on channel form. Channel widths within the forest are up to three times greater than that predicted from the regression. These changes in bankfull width have led to stream bed aggradation and the development of wide shallow channels within the forest, and channel capacities within the forest are over two times that predicted from the basin area. The relationship between channel sinuosity and valley gradient for non-forested reaches of the river also indicated decreased sinuosity resulting from afforestation. These changes in channel form result from active bank erosion within the forest with coarse material being deposited within the channel as point-bars and mid-channel bars. Active bank erosion is largely attributed to the suppression by the forest of a thick grass turf and its associated dense network of fine roots, and secondly to the river attempting to bypass log jams and debris dams in the stream channel.

Nanson, G. C., and E. J. Hickin. 1986. A statistical analysis of bank erosion and channel migration in western Canada. Bulletin of the Geological Society of America 97: 497-504.

Mean lateral-migration rates of 18 meandering river channels in western Canada are explained statistically in terms of hydraulic and sedimentological variables. The volume of sediment eroded from the outer bank of a meander bend is shown to be largely a function of river size and grain size of sediment at the base of the outer bank. These variables explain almost 70% of the volumetric migration rate for these relatively large, sand- and gravel-bed streams. It would appear that bank erosion and channel migration are essentially problems of sediment entrainment which is dependent on total stream power and sediment size. Vegetation on the outer bank is seen to have little significant effect in controlling channel migration. Further refinements of the type of data used here should permit the development of an accurate predictive model of regional channel migration. To this effect, it is most important to develop a precise relationship between bank resistance and the size of sediment at the base of the outer bank.

Nanson, G. C., A. V. Krusenstierna, E. A. Bryant, and M. R. Renilson. 1994. Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania. Regulated Rivers: Research & Management 9: 1-14.

Erosion of natural river banks by boat-generated waves is an increasingly serious problem on the navigable reaches of many rivers, particularly on the middle and estuarine reaches. An experiment designed to link bank erosion rates with easily measured wave characteristics, conducted on the scenic lower Gordon River in Tasmania, provides information useful for river management. Within a boat-generated wave train a number of characteristics were measured and most showed a high correlation with measured rates of bank retreat. Maximum wave height within the train is the simplest measure and is associated with a major threshold in erosive energy on unconsolidated sandy alluvium at wave heights of 30 to 35 cm. At maximum wave heights above 35 cm all but the most resistant bank sediments erode. Reducing maximum wave heights to < 30 cm by limiting boat speeds, and reducing the frequency of boat passages, caused a dramatic decline in bank erosion along the river.

National Technical Information Service. 1987. Soil erosion control: waterway embankments. January 1977-October 1986 (citations from the Selected Water Resources Abstracts database). National Technical Information Service, Springfield, Virginia. NTIS Order No.: PB88-850755/GAR.

This bibliography contains citations concerning the mechanisms of bank erosion and measures for erosion control. Land topography, river topography and currents, land use, weather factors, and waterway traffic are among the topics discussed. Retaining walls and vegetation renewal are considered as erosion control measures. Specific case studies are also included. (This updated bibliography contains 343 citations, none of which are new entries to the previous edition.) (Prepared in cooperation with Office of Water Research and Technology, Washington, DC (USA).)

National Technical Information Service. 1987. Soil erosion control: waterway embankments. November 1986 --October 1987 (citations from the Selected Water Resources Abstracts database). National Technical Information Service, Springfield, Virginia. NTIS Order No.: PB88-850763/GAR.

This bibliography contains citations concerning the mechanisms of bank erosion and measures for erosion control. Land topography, river topography and currents, land use, weather factors, and waterway traffic are among the topics discussed. Retaining walls and vegetation renewal are considered as erosion control measures. Specific case studies are also included. (This updated bibliography contains 56 citations, all of which are new entries to the previous edition.) (Prepared in cooperation with Office of Water Research and Technology, Washington, DC (USA).)

Rinaldi, M., and N. Casagli. 1999. Stability of streambanks formed in partially saturated soils and effects of negative pore water pressures: the Sieve River (Italy). Geomorphology 26: 253-277.

Streambanks of alluvial channels are usually composed of loose materials, which are unsaturated in ambient conditions. Unsaturated soils are subject to negative pre water pressures, which cause an apparent cohesion. The latter is the main factor in allowing the stability of near-vertical banks. Even during moderate in-bank flow events, the apparent cohesion can be strongly reduced as the material approaches full saturation; therefore, during the drawdown phase, as the confining pressure of the water in the channel disappears, a bank failure is likely to occur. Channel bed-level lowering along the Sieve River, Central Italy, has caused widespread bank instability. A geomorphological reconnaissance of forms and processes was followed by *in situ* tests to determine the shear strength of the banks. Interpretation of the tests and a streambank stability analysis were based on concepts of soil mechanics for unsaturated soils, in order to obtain relations between bank angle and height in limit equilibrium conditions. A stability chart was obtained with curves for different apparent cohesion values, and a stability analysis was performed taking into account the effects of flow events. In order to investigate the pore pressure effects, a series of piezo-tensiometers were installed in a streambank of the Sieve River. Data from a 1 year monitoring period show variations in pore water pressure and matric suction as a consequence of rainfall, evapotranspiration, and water stage variations. A planar failure with a tension crack occurred in the upper cohesive part of the bank during December 1996. The safety factor has been expressed as a function of the geometry of the bank and of the shear strength of the material. Safety factor variations through time are therefore shown as a function of seasonal variations in matric suction.

Rowntree, K. M., and E. S. J. Dollar. 1999. Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa. Earth Surface Processes and Landforms 24: 127-134.

Channel instability has occurred in the Bell River in the form of meander cutoffs, a number of which have occurred since 1952. Increased sediment loading from widespread gully erosion in the catchment has been proposed as the trigger for this instability. Willow species of the *Salix* family, in particular *S. caprea*, have been planted along the banks in an effort to prevent further channel shifting. This study reports the results of an investigation in to the effect of vegetation on channel form and stability over a 17 km stretch of channel. Results indicate that riparian vegetation has significant effects on channel form which have implications for channel stability. Riparian vegetation increases bank stability and reduces channel cross-sectional area, thereby inducing stability at flows less than bankfull. Evidence indicates that narrow stable stretches are associated with relatively high levels of riparian vegetation. Wider, unstable channels are associated with relatively less riparian vegetation. The effectiveness of riparian vegetation relative to bank sediments was investigated. A dense growth of willows was found to have an equivalent effect to banks with a silt-clay ratio of about 70 per cent. The channel narrowing induced by vegetation may contribute to channel shifting at high flows. The reduced channel capacity is thought to result in more frequent overbank flooding which may ultimately lead to avulsion. Thus where increased sediment loading is pushing the channel towards instability, vegetation may be effective in imparting local stability, but it is unable to prevent long-term channel shifts, and may rather help to push the system toward more frequent avulsions.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geological Society of America Bulletin 87: 857-860.

A series of experiments were performed on bank materials of anastomosed channels in flood-plain silt deposits in the Alexandra Valley in Banff Park, Alberta, to determine the effect of vegetation roots on bank erodibility and lateral migration of channels. Underground roots from the dense growth of meadow grass and scrub willow provide the reinforcement of bank sediment and a riprap-like protection of channel banks from river erosion. Results from the experiments suggest that in cool environments with aggrading river conditions where overbank deposition of silt, clay, and fine sand dominate the valley fill, vegetation roots are able to rapidly accumulate and decay very slowly, thus affording protection to banks from erosion in deeper parts of the channels.

Experiments were performed with a specially designed erosion box, used as a means to simulate natural erosion conditions and measure the influence of vegetation roots in reducing bank erosion. Results indicate that the bank sediment with 16 to 18 percent by volume of roots with a 5-cm root-mat for bank protection, typical of the area, had 20,000 times more resistance to erosion than comparable bank sediment without vegetation. Assuming five severe erosion days per year, potential lateral channel migration would amount to 4.2 cm per year. Such resistance, due to vegetation, accounts for the remarkable stability of channels during the last 2,500 yr in Alexandra Valley.

Smith, R. D., R. C. Sidle, P. E. Porter, and J. R. Noel. 1993. Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream. Journal of Hydrology 152: 153-178.

Experimental removal of woody debris from a small, gravel-bed stream in a forested basin resulted in dramatic redistribution of bed sediment and changes in bed topography. Removal of debris changed the primary flow path, thereby altering the size and location of bars and pools and causing local bank erosion and channel widening. Marked bed adjustments occurred almost immediately following experimental treatment in May 1987 and continued through to the end of the study period in 1991.Increased bed material mobility was attributable to destabilization of sediment storage sites by removal of debris buttresses, elimination of low-energy, backwater environments related to debris, and an inferred increase in boundary shear stress resulting from the removal of debris-related flow resistance. In contrast to these changes, which favored sediment mobilization, deposition was favored by the elimination of debris-related scouring turbulence and by increased flow resistance from a developing sequence of alternate bars. A more regularly spaced sequence of alternate bars replaced the pretreatment bar sequence, whose location, size, and shape had been strongly influenced by large woody debris as well as by bank projections and channel curvature. Following initial readjustment of the stream bed during the first posttreatment year, loss of scouring turbulence and increased flow resistance from alternate bars resulted in deposition of approximately 44 m^3 of sediment within the 96 m study reach. The loss of 5.2 m^3 to bank erosion left a net increase in sediment storage of 39 m^3. Mean spacing of thalweg cross-overs and pools did not change measurably following debris removal, although variability of spacing between thalweg cross-overs tended to decrease with time as the location of bars stabilized. No consistent pattern of change in mean residual depth of pools or in distribution of depths occurred within the first 4 years following debris removal.

Stott, T. 1997. A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, Central Scotland. Earth Surface Processes and Landforms 22: 383-399.

Stream bank erosion rates measured over a two-year period on a moorland and a forested stream in the Institute of Hydrology's Balquhidder Paired Catchments in central Scotland were compared. Bank erosion rates are generally higher on the mainstream of the moorland catchment and highest in winter on both streams. Bank erosion is correlated with the incidence of frost: minimum temperatures measured on stream banks of the forested stream were an average of 3.7^o C higher than on stream banks both outside the forest and on the moorland stream. This makes the incidence of frost on forested stream banks half as frequent. Volumes of material eroded from the mainstreams were combined with bulk density measurements and it is estimated that erosion of the mainstream banks is contributing 1.5 and 7.3 % of the sediment yield of the forested and moorland catchments, respectively. Analysis of the vertical distribution of erosion on the banks of both streams suggests an undercutting mechanism which is more pronounced in the moorland stream. The influence of trees on bank erosion and possible implications for the management of forest streams are discussed.

Tatinclaux, J. -C. 1998. Recent progress in river ice engineering research at CRREL. Journal of Cold Regions Engineering: 114-37.

The author reviews and summarizes the results of the research and development efforts in river ice engineering conducted at the U.S. Army Cold Regions Research and Engineering Laboratory over the last 10 years and their applications to the Civil Works mission of the U.S. Corps of Engineers. Topics discussed include winter operation of navigation projects on the major northern U.S. waterways; river ice processes; ice jam documentation, prediction, and mitigation; and bed and bank erosion due to ice. In addition, future challenges and areas of needed research in river ice engineering are discussed.

Thorne, C. R. 1982. Processes and mechanisms of river bank erosion. Pages 227-271 *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, editors. Gravel-bed rivers: fluvial processes, engineering and management. John Wiley & Sons Ltd., New York.

The importance of bank erosion to channel hydraulics and sedimentary processes makes it appropriate that a review and investigation of the way in which a river erodes its banks should be undertaken. To do this it is necessary to consider the processes responsible for the erosion of material from a bank and the mechanisms of failure resulting from the instability created by those processes. Processes of erosion fall into two main groups: fluvial entrainment, and subaerial/subaqueous weakening and weathering. Usually it is particular combinations of processes which are most effective in causing erosion. Mechanisms of failure depend on the size, geometry and structure of the bank and the engineering properties of bank material. Mechanical bank failures supply material to the toe. Its removal from there depends on fluvial entrainment.

The balance between rates of supply and removal may be described by the state of basal endpoint control. This has important implications for the profile, stability and retreat rate of river banks and schemes to protect banks from erosion.

Additional comments

This paper is part of a proceedings of a workshop. In a discussion with the audience after the paper presentation, several comments were made that were relevant to this literature review. It was pointed out by N.G. Bhowmik that wind- and boat-generated waves also cause bank erosion, and in some cases can cause more bank retreat than fluvial erosion. It was also noted that vegetation influences on bank erosion can be positive or negative; the issue is a matter of scale. Large uprooted trees along the banks of large rivers protect banks against erosion. The same trees along smaller rivers can cause local acceleration of the flow, thereby causing bank erosion. The author agreed with the assessment. In addition, the author noted that absolute size of vegetation is also important. Large trees reduce bank stability with respect to mass failure because the additional weight of trees on steep banks is always more significant than the increased shear strength afforded by root reinforcement. On the other hand, smaller forms of vegetation such as small trees, shrubs, and deep-rooted grasses increase soil shear strength without significantly increasing the weight of a bank.

A detailed discussion by M. Church and M.J. Miles regarding riverbank stability in permafrost regions also is included. Types of riverbanks peculiar to arctic and subarctic regions, and erosional processes related to permafrost and river ice are described. Church and Miles note that vegetation roots may act as riprap to stabilize banks; stabilization is most effective along relatively small channels.

Thorne, C. R., and J. Lewin. 1979. Bank processes, bed material movement and planform development in a meandering river. Pages 117-137 *in* D. D. Rhodes, and G. P. Williams, editors. Adjustments of the fluvial system. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Field observations of bank processes and bed material movement at a meander bend on the River Severn, U.K., are presented and discussed in the light of historical evidence for channel change in the past 150 years. Mechanisms of banks failure, in general dependent on bank structure and composition, are here dominated by fluvial undercutting and mechanical failure of cantilevers in the upper bank. Failed material accumulates at the bank foot from where it is removed by fluvial entrainment. Tracer experiments show that bank retreat rates are fluvially controlled though failure mechanisms are not. Measured retreat rates are around 0.5 m/yr comparing with up to 0.7 m/yr historically on the same reach.

Contrasting forms of planform development are apparent, including complex loop formation, neck and chute cut-offs, and the rapid abandonment of lengths of cut bank and deep channel. Upstream changes and large, but infrequent, discharge events have profound effects which are difficult to predict.

Channel change can be usefully regarded as a sediment transfer process involving bank failure, sediment entrainment, transport, and deposition. However, both field studies and documentary analysis are needed for a good understanding of the full range of contemporary channel change characteristics in space and time.

Additional comments

There was a large disparity in retreat rates between the lower portion of the bank where erosion was controlled by fluvial undercutting, and the upper portion of the bank where erosion was controlled by mechanical failure. This disparity of erosion rates resulted in the development of overhanging banks (cantilevers). The stability and dimension of these cantilevers was dependent upon the thickness of the upper bank material and its engineering properties. The mode of cantilever failure (shear, beam, or tensile failure) was also dependent upon the thickness of the upper bank material and its engineering properties. Developments of cracks in a cantilever was often the critical factor that brought about its failure. Roots and rhizomes of grasses enhanced the stability of the upper banks by reinforcing the soil, thereby inhibiting development of cracks.

Trimble, S. W. 1997. Stream channel erosion and change resulting from riparian forests. Geology 25: 467-469.

Forested stream banks, compared to grassed ones, can destabilize stream channels by promoting erosion. Four reaches of Coon Creek, Wisconsin, each with long-term grassed and forested subreaches were examined. Grassed reaches were narrower and had smaller channels (bankfull cross sections) than forested reaches, suggesting that grassed channel reaches stored about 2100 to 8800 m^3 more sediment per kilometer than forested reaches. Available evidence suggests that conversion of riparian forests to grass would allow storage of sediment along channels, possibly decreasing downstream sediment yields. These findings are important as many grassed riparian corridors are rapidly reverting to forest because of economic conditions and governmental policies.

Williams, J. R. 1952. Effect of wind-generated waves on migration of the Yukon River in the Yukon Flats, Alaska. Science 115: 519-520.

The author determined that summer wind-generated waves influence the migration of the Yukon River in east-central Alaska. Differences in soil development, vegetation, and alluvial features such as river islands and bars, between the north and south sides of the river suggest that the south bank has grown northward by deposition as the north bank has retreated by erosion. The strongest summer winds, which are from the southwest, produce choppy waves as they blow across the river. The waves attain their maximum height (up to three feet) and erosive power along the north bank of the river. In contrast, the south bank is protected from waves generated by the southwest summer winds. During winter, wind cannot form waves on the ice-covered river.

Wolman, M. G. 1959. Factors influencing erosion of a cohesive river bank. American Journal of Science 257: 204-216.

The sinuous channel of Watts Branch in Montgomery County, Maryland, traverses a grassy meadow nearly devoid of trees. The creek has a drainage area of four square miles and the river bank is composed primarily of cohesive silt. Resurveys of cross sections during the five years 1953-1957 have revealed as much as seven feet of lateral erosion. Over the past two years, additional measurements of the amount of erosion around rows of steel pins driven horizontally into the bank have been made at frequent intervals. These observations indicate several combinations of factors primarily responsible for the progressive recession.

Approximately 85 percent of the observed erosion occurred during the winter months of December, January, February, and March. A thickness of as much as 0.4 feet of sediment was eroded from the bank at specific points in a period of several hours during which a bankfull flow attacked banks which had previously been thoroughly wetted. Erosion was most severe at the water surface. Little or no erosion was observed during the summer despite the occurrence of the highest flood on record in July 1956.

Second in erosion effectiveness were cold periods during which wet banks, frost action, and low rises in stage combined to produce 0.6 foot of erosion in six weeks during the winter of 1955-56. Significant erosion also resulted from the combination of moist banks and low rises in stage. Lastly, crystallization of ice and subsequent thawing, without benefit of changes in stage, also produced some erosion as did flashy summer floods even on hard, dry banks. Inasmuach as such summer floods constitute the rare and “catastrophic” events on small drainage basins in this region, present observations suggest that the cumulative effect of more moderate climatic conditions on this process of erosion exceeds the effect of rarer events of much greater magnitude.

This preliminary analysis of several factors responsible for erosion of the cohesive river bank indicates that there is perhaps a crude correlation between precipitation and erosion during selected intervals of time. Precipitation exerts an affect both through increasing discharge in the channel and by increasing the moisture in the bank. Frost action acts similarly both to hold moisture in the soil and to comminute surface material, thus preparing it for erosion.