89-11-281

Special Report 88-3

February 1988

US Army Corps of Engineers

Cold Regions Research & Engineering Laboratory

Techniques for measuring reservoir bank erosion

Lawrence W. Gatto

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

ERRATA

Special Report 88-3

Last paragraph on page 14, lines 4 and 5, should read:

"... horizontally (parallel to bankline) and **1-m** spacings vertically (perpendicular to the bankline). Lawler (1986) used a grid pattern that had **1-m**... ."

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755-1290

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Special Report 88-3	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Cold Regions Research and Engineering Laboratory 6b. OFFICE SYMBOL (If applicable) CECRL	7a. NAME OF MONITORING ORGANIZATION Office of the Chief of Engineers
6c. ADDRESS (City, State, and ZIP Code) 72 Lyme Road Hanover, New Hampshire 03755-1290	7b. ADDRESS (City, State, and ZIP Code) Washington, D.C. 20314
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER CWIS 31568
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Techniques for Measuring Reservoir Bank Erosion

12. PERSONAL AUTHOR(S)

Gatto, Lawrence W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ______ TO ______	February 1988	34

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Erosion, Recession
			Lakes, Reservoirs
			Rates, Rivers

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report summarizes the processes that cause and conditions that contribute to bank erosion along reservoirs, lakes, rivers and coasts. It suggests measurements, techniques and measurement frequencies for four different levels of bank erosion study. Details on specific procedures for a particular technique must be obtained from references cited. There are neither standard measurements to make nor standard methods to use during erosion studies, but this report can be useful to investigators selecting an approach for future work.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Lawrence W. Gatto	22b. TELEPHONE (Include Area Code) (603) 646-4100 22c. OFFICE SYMBOL CECRL-RE

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

PREFACE

This report was prepared by Lawrence W. Gatto, Geologist, of the Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by Corps of Engineers Civil Works Project 31568, Erosion Potential of Inland Shorelines and Embankments in Regions Subject to Freezing and Thawing.

Technical reviewers were James Wuebben, CRREL, and Ron Pearson, Bureau of Reclamation (Denver). Karen Henry, CRREL, also reviewed an earlier manuscript. They provided many useful suggestions.

The author thanks Donna Harp for typing the manuscript, Eleanor Huke for preparing the figures and Edmund Wright for technical editing. His suggestions significantly improved the manuscript.

CONTENTS

	Page
Abstract	i
Preface	ii
Introduction	1
Bank erosion study data requirements	2
Erosion processes and contributing conditions to be measured	3
Ice action	6
Water processes	7
Nearshore bed and beach conditions	9
Bank conditions and processes	9
Bank changes to be measured	13
Changes in a bank face	13
Sediment removed from a bank	19
Bank crest recession	20
Conclusions	22
Literature cited	23

ILLUSTRATIONS

Figure

1.	Idealized cross section of a reservoir shore zone	6
2.	Spot checks of wave heights (a) and bottom changes (b)	8
3.	Erosion pins	15
4.	Bank profiles	16
5.	Profiling a bank using stadia rods	17
6.	Scale markers used as reference in hand-held stereo photographs	18
7.	Plastic sheet placed at a bank toe	19
8.	Sediment trap near bank toe	20

TABLES

Table

1.	Data requirements for four levels of bank erosion studies	4

TECHNIQUES FOR MEASURING RESERVOIR BANK EROSION

Lawrence W. Gatto

INTRODUCTION

A number of studies have addressed bank erosion along the shores of reservoirs, lakes, rivers and coasts. These studies have measured and documented selected environmental conditions, the changes in bank, beach and nearshore bed configurations resulting from erosion, and the characteristics of bank sediments at eroding sites. These field data are then used to calculate erosion and recession rates, and regression analyses are often done to correlate the field data and rates to aid in evaluating the causes of erosion. The results of these correlations have also been used to estimate future bank erosion and the rate and areal extent of recession.

Bank erosion occurs in all climates throughout the year. Consequently, year-round data collection is required to do a thorough study of erosion processes in any location. The techniques described here include those required for year-round study. Since similar processes erode banks along reservoirs, lakes, rivers and coasts, the techniques described here are useful in studies of all four.

There are no standard measurements to make, methods to be used or frequencies of data collection to be followed, nor am I proposing any. Investigators must use those methods and approaches that meet their own project needs. I have prepared this report so that future investigators can follow procedures that have worked for others, if they so choose. New approaches should be tried when the need arises.

Researchers who must be aware of the variety of data collection techniques previously used may find this report useful, although it was written primarily for Corps of Engineers personnel responsible for collecting field data on bank erosion. Information on bank erosion processes and contributing conditions would be useful to the Corps of Engineers and other agencies responsible for planning new reservoirs and related land acquisitions, for operating and maintaining reservoirs where bank erosion is a problem, for estimating the life of a reservoir and for understanding the factors affecting reservoir water quality. Sediment from bank erosion contributes to reservoir in-filling and can reduce water quality, and therefore evaluating and designing appropriate bank stabilization options are necessary. Improvements in the predictions of bank recession and reservoir in-filling may be especially important to the Corps if it is involved in future development of hydropower reservoirs or redesign of existing reservoirs for hydropower.

BANK EROSION STUDY DATA REQUIREMENTS

Collection of field data on reservoir bank erosion depends on several factors: (1) objectives of a project, (2) precision and accuracy requirements of a project, (3) equipment available for doing the work, (4) budget, manpower and time constraints, (5) bank characteristics and site conditions and (6) the suspected amount of erosion and recession occurring at the sites to be studied. In Table 1, I list some of the factors to be measured and some data sources and measurement techniques, and I suggest measurement frequencies to meet the objectives of projects at four different levels of detail. Undoubtedly some techniques and data sources have been used that are not mentioned in Table 1, but the most frequently used techniques or some variation thereof are given. If more than one technique is shown in Table 1 for making a measurement or documenting a condition or process, the reader can choose which is appropriate for his needs. The reader should consult the references for the specific procedures and precautions when using various survey and data collection techniques.

The distinctions between the four project levels are not rigid and overlap is typical. I have simply proposed them for purposes of discussion in this report. The amount of work in and the details of accomplishing studies at the four levels decrease from levels 1 to 4. A level 1 study is primarily research requiring year-round field measurements and observations of bed, beach and bank changes, and bank erosion and recession rates, to evaluate as many factors contributing to bank erosion as possible. A level 2 study requires the same year-round data but only to evaluate the most likely factors contributing to bank erosion. These factors would be selected on the basis of field observations of site conditions, previous experience and any existing site data. A level 3 study is limited to measuring bank erosion and recession rates, with associated observations that provide "best guesses" regarding the causes of the erosion. Year-round data would not be collected. A level 4 study consists of measuring bank recession rates only, and suggesting possible causes on the basis of previous experience, available data and whatever field observations were made.

Background information available in reports, soils maps, general reconnaissance maps, photographs, and geologic descriptions should be reviewed before field work for any level of study is begun. This review is useful in documenting past bank conditions and changes (Dolan et al. 1978, 1979, Eckert and Callender 1987, Hagerty et al. 1981, Leatherman 1983, Fulton undated) which may help in providing insights on the causes of past and present bank erosion.

After the background review, the approach normally taken is to document, photograph and measure initial bank conditions and the changes in the geometric configuration of a bank, environmental conditions, active processes, and disturbances that occurred to a bank during a certain interval of time. The photographs taken and field observations recorded during each site visit constitute a valuable permanent record of bank conditions as they change (Edil and Vallejo 1977, Hagerty et al. 1981), and can be used to make qualitative assessments of erosion processes and contributing conditions. The field data and observations are then used to evaluate which processes caused or contributed to the measured bank changes during that interval. This is done repeatedly as many times as is required to meet project objectives.

In some cases it may be impossible to identify which processes and conditions caused a measured bank change. However, the more frequently the field measurements and observations are repeated, the more likely will be the identification of what caused the changes, since fewer complicating factors will likely have been active during shorter intervals.

EROSION PROCESSES AND CONTRIBUTING CONDITIONS TO BE MEASURED

Many processes and conditions interact in very complex ways to cause and contribute to reservoir bank erosion (Pincus 1962, Seibel 1972, Simons et al. 1978 and 1979, Sterrett 1980, Lawson 1985, U.S. Army Corps of Engineers 1981). Each site has unique characteristics and the importance

Table 1. Data requirements for four

PROCESSES, CONTRIBUTING CONDITIONS, CHANGES TO BE MEASURED / DATA SOURCES*	A	B	C	D	E	F	G	H	I	J	K	L	M
Ice action													
Ice scour	1-4							1			1,2		
Ice push	1-4							1			1,2		
Ice rafting	1,2												
Water processes													
Waves	4	3	2		1	2,3							
Currents							1						
Water level fluctuations				1-3									
Nearshore bed													
Shape								1	2		1		
Slope									1,2				
Vegetation	1												
Beach													
Shape									1,2		1		
Slope									1,2		1		
Width									1,2		1		
Sediment texture	1,2												
Vegetation	1,2												
Bank													
Orientation	1-4												
Height	1-3												
Slope	1-3												
Bank sediment erodibility													
Mechanical strength													
Sediment size distribution	2,3												
Sediment water content													
Sediment structure	1-3												
Sediment grain shape	1,2												
Bulk density													
Sediment minerals													
Chemical weathering	1												
Vegetation	1-4												
Raindrop impact	1		1										
Overland flows	1-3										1		
Sheet flow													
Rill and gully erosion													
Groundwater level										1			
Groundwater piping	1-3										1		
Mass wasting	1-4												
Freezing and thawing			1								1,2	1,2	
Frost heaving			1								1,2		
Man- and animal-induced disturbances	1-4												
Bank face changes	1-4										1	1-3	1
Bank sediment removed	1,2										1	1,2	
Bank crest recession	1-4												

*DATA SOURCES KEY:

A. Field observations, photographs, video tapes
B. Wind and precipitation data from nearest NWS station
C. On-site, recording anemometer, precipitation gauge, ground thermistors
D. Water level recorder, staff gauge
E. Recording wave gauge
F. Wave estimating equations
G. Recording current meter
H. Sonar, sidescan sonar
I. Tape, weighted line, rod
J. Piezometers
K. Topographic surveys

levels of bank erosion studies.

N	O	P	Q	R	S	T	U	V	FREQUENCY OF MEASUREMENTS
									Just before freezeup and after breakup (1-3); weekly during ice season (1); just after breakup (4); after windy or very cold periods (1)
									Same as for ice scour
									During breakup
									Continuous (1); hourly (2,3); during high water (4)
									Continuous
									Continuous (1); hourly (2); daily average (3)
1									Initially, before and after storms, before freezeup, after breakup
									Initially, before and after storms
									Whenever on site
1									Same as for nearshore bed
1									Same as for nearshore bed
1									When water levels are very different
									Whenever on site
									Whenever on site
									Initially (once)
1-3									Initially (once)
1-3									Periodically during project
	1,2	1,2							Initially (once)
	1								Initially (once)
	1								Weekly, after storms
	1	1							Initially (once)
	1								Initially (once)
	1								Initially (once)
	1								Initially (once)
									Initially (once)
									Whenever on site
									Before and after storms; whenever on site
									Before and after storms (1); whenever on site (1-3)
									Continuous readings
									After storms and weekly (1); whenever on site (1-3)
									Weekly (1), after storms (1,2), monthly (3), whenever on site (1-4)
									Weekly during freeze-thaw season (1,2); continuous ground temperatures (1)
									Same as for freezing and thawing
									Whenever on site
1-3									Initially, after storms (1-3); weekly (1,2); whenever on site (1-4)
						1	2	1	After storms (1,2); weekly (1)
			1	3,4	1-4				Initially, after storms (1-4); monthly (1,2)

L. Erosion pins
M. Close-range photogrammetry
N. Bank profiles
O. Standard, soils engineering, lab analyses
P. Standard, soils engineering, in-situ field methods
Q. Bank crest maps
R. Aerial photographs, video tapes
S. Measurements from stakes
T. Sediment collection sheets or traps
U. Sediment accumulation shapes and volumes
V. Sediment tracer grains

of a process or condition varies at different sites and times. In fact, the same processes or conditions may cause erosion at one time and prevent erosion at another.

Ice Action

Ice on a reservoir can scour or push bed and beach sediments and can displace sediment frozen into it by rafting. This scouring, pushing and rafting can indirectly lead to erosion of an adjacent bank by reducing the protection from waves provided by a beach and bed and by reducing the stability of beach sediment adjacent to the toe of that bank. If the water level is high enough, these ice actions can also directly erode a bank (Fig. 1).

Changes to the bed and beach caused by ice can be assessed by surveying topography just before freeze-up and just after breakup. It is likely that the changes between these surveys would be caused primarily by ice action since waves and resultant currents are usually minor when an ice cover exists. Ice push along a beach could also be observed directly (Gilbert and Glew 1986), and resulting ice push features can be measured during the winter and just after breakup before such features are destroyed by wave action.

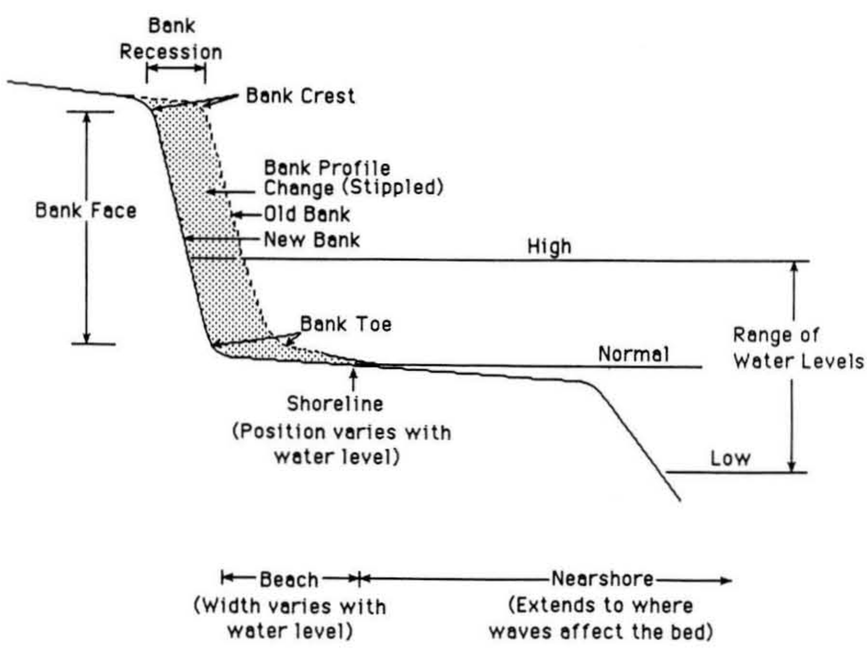


Figure 1. Idealized cross section of a reservoir shore zone (some terms may not conform to common usage).

The amount of sediment entrained in ice, or deposited on its surface, and later moved by ice rafting, can be observed in the field during the winter. One method of estimating rafted sediment is as follows:

1. Cut blocks of nearshore ice with a saw during breakup.
2. Measure block volumes.
3. Melt the ice blocks and weigh the amount of sediment remaining.
4. Repeat this process for several sites.

Of course, the ice that is sampled should be mobile ice, not ice that is melting in place. Frequently, ice along a lake or reservoir shoreline will melt in place and not transport sediment.

<u>Water Processes</u>

Water level determines where waves and resultant currents will be active. Waves cause bank erosion directly when the water level is high enough for wave action to remove bank face sediment (Fig. 1). If the water level is not high enough for direct wave action on a bank, waves can remove sediment that has been eroded from the bank face and accumulated at the toe of the bank. Since this accumulated sediment often acts as toe protection, its removal prevents the bank from establishing a stable slope and bank erosion and recession continue. Waves and currents also change a nearshore bed and beach by redistributing and transporting sediment, which can lead to bank instability and erosion.

To evaluate the erosive power of waves at a particular site, the wave heights, periods and directions can be measured using standard methods with commercially available wave gauges. Current velocities can be measured with commercial current meters. Wave estimating methods (CERC 1984) that do not require direct measurements can be used and spot checks can be made with a staff or surveyor's rod (Fig. 2a).

Water level fluctuations can alternately inundate and expose bank sediments. When a water level is lowered along a bank, positive pore water pressure in saturated bank sediment can induce variably sized sediment flows or slides. If the water level is lowered enough to expose nearshore bed sediments, similar flows and slides can occur there, which could lead to instability at a bank toe.

a. Measuring wave heights.

b. Determining bottom changes.

Figure 2. Spot checks of wave heights (a) and bottom changes (b).

Continuously operating water level recorders are available for level 1 studies. Hourly and daily average water level readings from a staff gauge would probably suffice for level 2 and 3 studies, respectively.

Nearshore Bed and Beach Conditions

The shape, slope, and vegetative cover of the nearshore bed, plus the shape, slope, width, sediment texture and cover of the beach, influence the bank's stability and the amount of wave energy that reaches a bank. The shape of the nearshore bed and the beach can be mapped with standard topographic surveying tools (i.e. compass and tape, plane table, transit, or electronic distance measuring device). Once the initial conditions at a site are determined, surveys repeated before and after major storms and before ice formation and after ice breakup would usually be sufficient to document any shape changes.

If the nearshore bed does not change much, less accurate spot checks can be made with a rod, tape or weighted line at selected locations (Fig. 2b). These checks must be made at the same locations each time, and the water surface elevation must be known each time they are made since the datum for these spot checks of bottom changes is the water level.

Surveys of conditions farther offshore can be done with sonar (Reid et al. 1986), continuous seismic reflection profiling and side-scan sonar (May 1982, Thorne 1981, Duck and McManus 1985, Pope 1985). The side-scan sonar also provides useful information on locations of scour holes and underwater sediment failures which may affect stability of adjacent banks.

Bank Conditions and Processes

The amount of erosion along a bank caused by waves, currents and ice actions is influenced by the power of these processes and the erodibility of bank sediment. The orientation of a bank to predominant and storm wind directions, the shoreline configuration, and the bank slope will affect the water levels and the power of wave, currents and ice actions at a site. The erosive power of waves and the amount of sediment transported by longshore currents is greatest when a shoreline is perpendicular to the wind directions. As bank slope increases, the more unstable and the more easily eroded is the in-situ sediment in its face.

Along a bank above where these processes are active, bank face erosion is also influenced by bank sediment erodibility and caused by such processes as raindrop impact, sheet flow, rill and gully erosion, groundwater piping, mass wasting, frost heaving, freezing-thawing and disturbances caused by man and animals. The erosion caused by all processes, whether above or below the waterline, varies spatially and temporally between banks and along the same bank.

Bank sediment erodibility. The amount of erosion that occurs along a bank is partially dependent on the resistance of in-situ bank sediment to being dislodged and moved, i.e. erodibility. Factors that directly influence erodibility include mechanical strength, sediment size distribution, sediment water content, sediment structure, grain shape, bulk density, mineral content, degree of chemical weathering, and presence of vegetation.

The mechanical strength indicates the amount of resistance that sediment deposits offer to tensile, compressive and shearing forces. In general, deposits with high mechanical strengths tend to be resistant to many erosive forces. Regarding sediment sizes, sands or gravels are usually less cohesive than silts and clays, so that banks of sands and gravels are usually more easily eroded. Where water content in a sediment deposit is high, the water tends to lubricate sediment grains, reduce the strength of the deposit, make intergranular movement more likely, and, consequently, make the deposit more erodible. Sediment structure reflects how individual grains have joined together, grain shape influences how tightly they are fitted together, and bulk density is partially affected by the packing of sediment grains. Tightly fitted and packed sediments tend to be more resistant. Sediment minerals influence the amount of cohesiveness of a deposit and the degree of chemical weathering. The more weathered a deposit, the more its original minerals and structure have been changed and the more erodible the deposit will likely be.

Bank vegetation can dampen wave action along a bank, and the root systems can increase the tensile strength of bank sediment (Thorne 1981). However, some studies suggest that once trees along a bank have been undermined and have started to lean over and are falling (sometimes very slowly), they can remove a large volume of bank sediment within their root zone when they finally collapse. This happens to lesser degrees when brush and grasses are falling and collapse.

A number of standard field techniques can be used to measure the mechanical strength of sediment (Thorne 1981, Eckert and Callender 1987, Hanna 1985). Sediment structure and weathering (Munsell colors) should also be observed in the field. Laboratory analyses of bank face samples and of sediment cores taken behind the bank crest must be done to determine sediment size distributions, bulk density, water and mineral contents and sediment grain shape. Eckert and Callender (1987) as well as the Geotechnical Testing Journal and reference books published by the American Society of Testing and Materials discuss field and lab techniques for sediment analysis.

Rain and Overland Flows. Close inspection of a bank face would show evidence of erosion by rain-drop impact and overland flow, i.e. sheet flow, rills and gullies. To evaluate the potential erosive power of rain drop impact, wind and precipitation data should be collected at the erosion site. The size of rills and gullies on a bank face can be measured and their density documented on photographs.

Ground water. Zones of stained or wet sediment along strata in a bank face would suggest that ground water may be contributing to bank erosion. In extreme cases, holes and cavities may form in the bank face due to water discharging from the bank and concurrently removing sediment from its face (Ullrich et al. 1986). This is ground-water piping and, since ground-water levels influence whether piping occurs, piezometers installed to monitor ground water in a bank are useful (Wolman 1959, Reid 1985). Piezometers would probably not be necessary if evidence for ground-water seepage is not present.

Mass Wasting. Direct observation at a site will tell if mass wasting (i.e. falls, topples, slides, spreads and flows) has occurred along a bank. Such mass wasting takes place when chunks of bank sediment fall away as a single mass, or when individual sediment grains are dislodged and slide down a bank face (Mathewson 1981). Tension cracks that have formed in the sediment landward of a bank crest are frequently visible and show where blocks of sediment are separating and will fall in the future.

Ground Freezing. Freezing, thawing and frost heaving disrupt soil structure (Gifford 1984) and can dislodge in-situ sediment in a bank face, or decrease the mechanical strength of bank sediment which can lead to increased thaw failure of a bank in the spring (Yen and Molnau 1982, Vallejo 1977, Reid 1984, 1985), can cause surface sediment along a bank face to be more easily eroded by other processes and can erode sediment directly by moving it downslope.

When interstitial ice holding in-situ sediment grains together in a frozen bank sublimates, the sediment can be released from the bank face and is free to move downslope (Reid 1985). Depending on the bank slope, sediment from this sublimation can accumulate on the bank face or at the bank toe.

The number of daily freeze-thaw cycles that occur in the ground can be determined by measuring ground temperatures (Osterkamp 1984, Atkins 1981, Brockett and Howe 1982) at the surface of the bank face. It is not acceptable to measure the number of air temperature freeze-thaw cycles; the air and ground temperature cycles will not be concurrent. The amount of ground that freezes (depth of frost) over the winter can be measured with frost tubes (Reid 1984) or thermistors (or thermocouples). The amount of frost heave that occurs over a winter is more difficult to measure accurately, however.

A simple method would be to attach a plate to the bottom of a pipe or rod. Bury the pipe (rod) before the ground freezes so that the plate is well below normal frost depth and the top of the pipe is above the ground surface. The difference between the top of the pipe and the surface is measured repeatedly during the winter. The change will be the heave caused by frost during the measurement intervals.

To attempt to determine the amount of bank face change caused by freeze-thaw and frost heave during a certain interval of time, one should measure the ground freeze-thaw cycles, frost heave and amount of loosened bank sediment at the following times:

1. Early spring when the bank is still frozen but just prior to the start of ground freezing and thawing for changes that occurred while the bank was frozen.

2. Late spring after freezing and thawing has stopped for changes that occurred while the bank was freezing and thawing.

3. Early fall prior to freezing and thawing for changes that occurred while the bank was unfrozen.

4. Late fall prior to the ground becoming frozen for changes that occurred while the bank was freezing and thawing.

Man- and Animal-Induced Disturbances. Disturbances to a bank caused by man and animals must also be evaluated. These include walking over a bank, irrigation landward of a bank, vehicles moving on a bank, construction activities and animals burrowing into or walking over a bank. The structure and, therefore, the strength of bank sediments are affected and sediment can be loosened or moved by such activities. However, for all practical purposes, it is impossible to separate the amount of this sediment from that loosened or moved by natural processes. But by observing and photographing the evidence for disturbances by man or animal, at least it can be shown that they contribute to the erosion observed at a site.

BANK CHANGES TO BE MEASURED

This section describes some of the methods for documenting and measuring changes in the shape and position of a bank that result from erosion, amounts of sediment removed from a bank and bank crest recession. Measurements should be made as frequently as possible to attempt to discern the processes that may have contributed to the measured changes (Knighton 1973). Precautions should be taken in the winter to get accurate data and to avoid discomfort and injury while in the field. Snow and ice increase the likelihood of personal injury and damage to surveying equipment.

Changes in a Bank Face

Comparative Photographs. Comparative analysis of hand-held photographs provides a rapid method of monitoring qualitative changes in a bank face (Hagerty et al. 1983), but the qualitative information should be supplemented with measurements. The repetitive photographs should be taken from the same station with the same orientation, camera, lens, film type and general lighting (Weigel and Hagerty 1983, McClay 1985).

Video Imagery. Video imagery is also useful for documenting qualitative changes in a bank. The spatial resolution of video imagery is insufficient for accurately measuring bank changes, however. If acquired from the air (Meisner 1986), video imagery can document long reaches of bank in a short time and at low cost, as long as qualitative information is acceptable to a project.

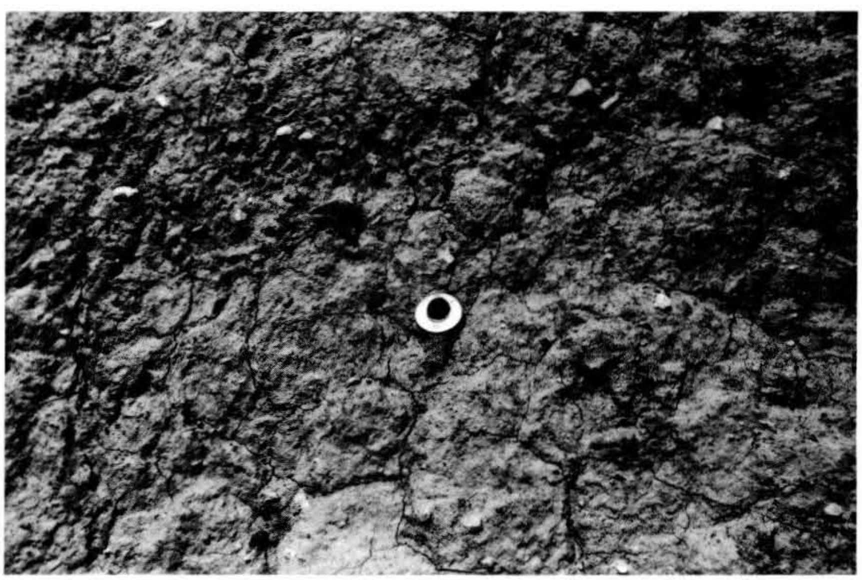
Close-Range Photogrammetry. Close-range photogrammetry has been used to measure stream channel changes (Welch and Jordan 1983), streambank erosion (Collins and Moon 1979) and small-scale landform changes (Lo and Wong 1973). Photographs are taken with a hand-held or tripod-mounted camera. Normal, analytical photogrammetric techniques are then used to measure changes directly from the photographs (Wolf 1984). This technique causes no disturbance to a bank face, provides a permanent photographic record of bank conditions and is useful when the bank is highly irregular and detail is important. Usually, standard 35-mm single-lens reflex cameras provide acceptable data (Welch and Jordan 1983) and accuracies of ± 3.0 mm along a bank face and ± 6.5 mm perpendicular to the face can be achieved. Detailed discussions of close-range photogrammetry are presented in an American Society of Photogrammetry Handbook (1985).

Erosion Pins. Erosion pins are usually metal (Hooke 1979, Thorne 1981, Twidale 1964, Wolman 1959), although plastic tubes have also been used in lower portions of a bank where passers-by could be injured if they fell on metal pins (Hagerty et al. 1983). Pins of various sizes have been used, from 10 to 80 cm in length and from 2 to 8 mm in diameter. The pins work best in sandy or finer sediment; they do not work well in gravelly sediment (Hooke 1979, 1980, Thorne 1981).

The pins are pushed perpendicularly into a bank (Edil and Vallejo 1977). Some investigators leave a portion of the pin exposed (Fig. 3a); others push them flush with the bank surface (Fig. 3b). Reid (1984) pushed the pins flush on the upper bank where sediment is usually removed, and he left part of each pin exposed when located on the lower bank where sediment can temporarily accumulate as it moves downslope. The distance between the top of a pin and the bank surface is measured, and repeated measurements give the amounts of change along the bank face. Frequent measurements are especially important in case pins have been removed by vandals or lost because of rapid erosion (Hudson 1982). Thorne (1981) recommends that pin measurements be made after every high water, rainfall or frost event and at intervals in between.

The arrangement and number of pins to be inserted into a bank is not standard. Some have been arranged along a line from the bank top to bottom (Reid 1984). Hagerty et al. (1983) used a grid pattern with 1.5-m spacings horizontally (parallel to bankline) and 1-mm spacings vertically (perpendicular to the bankline). Lawler (1986) used a grid pattern that had a 1-mm spacing horizontally between vertical rows of 4-8 pins. Hill (1973) used

a. Installed with a portion exposed.



b. Installed flush with the bank face (Reid 1984).

Figure 3. Erosion pins.

two horizontal lines of pins placed about 60 cm apart. Thorne (1981) recommended that at least two pins be placed vertically along a bank at a given location. The placement of pins should be determined by the complexity of the bank shape and the needs of the project.

Some investigators suggest that erosion pins could increase the tensile strength of bank sediment, which would decrease the rate of sediment collapse and bank retreat (Thorne 1981). Twidale (1964) reports that the pins probably affect sediment movement but that project accuracy requirements should determine if this is acceptable, while Hooke (1979) feels that pins do not substantially affect erosion processes.

Frost heave can move the pins out of the bank some unknown amount. I am not aware of any methods to eliminate this possible problem, but one could make frequent measurements, thereby minimizing the amount of measured change due to heave.

Ice could also disrupt or destroy the pins if water level fluctuations are large enough. Snow may cover the pins, and one may have to remove snow from around the pins to take winter readings. Special care should be taken to avoid disturbing the sediment surface around the pins when the snow is removed.

Bank Profiles. Changes in bank profiles show where sediment has been removed or deposited along a bank (Fig. 1 and 4). Profile data can be used

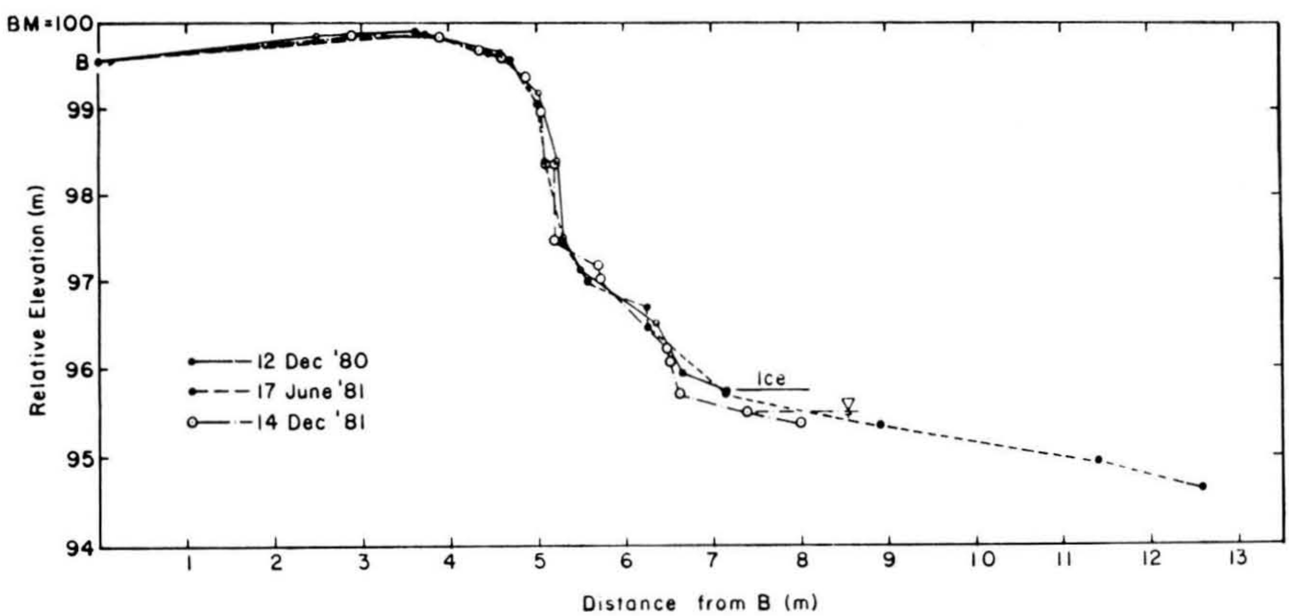


Figure 4. Bank profiles (elevations relative to a local temporary benchmark assigned a 100-m elevation; distances from a reference pin, B, in ground).

to calculate volumes of sediment moved and amounts of bank recession. If the profiles extend into the nearshore zone they provide data on bed conditions and changes along the profile line. The locations of profiles should be tied to a reference landward of the bank crest so that repetitive profiles can be made at the same location (Hemsley 1981). Snow cover can cause some problems when doing profiles. Snow should be carefully removed along profile lines so the true bank face surface can be measured.

The following five methods, or some variation thereof, have been used for measuring bank profiles:

1. Leveling. A surveyor's level, rod and tape are commonly used to measure bank profiles (Thorne 1981), although leveling can be done by using stadia readings instead of taping the distances between level and rod. Leveling procedures are described adequately by Tovey (1982) and Birkemeier (1981) and in any text on surveying.

2. Rod Measurements. Stadia rods can be used as horizontal and vertical references for measurements from the rods to a bank face (Fig. 5). One or two people are required to make the measurements and a precision of ± 5 cm is reported (Hudson 1982). A similar approach for banks between 0.1 and 3 m high uses a straight beam inclined down a bank face from a fixed reference point (Leeks 1981). Distances are measured perpendicularly from the beam to the bank. This method provides graphical profiles as shown in Figure 4 and data similar to those obtained with erosion pins.

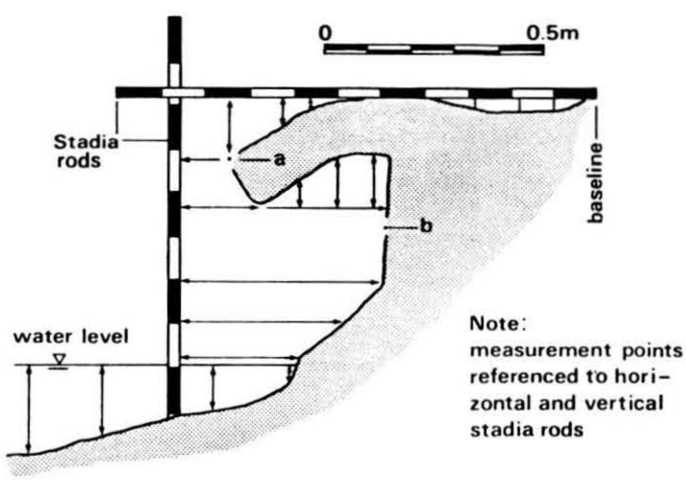


Figure 5. Profiling a bank using stadia rods (Hudson 1982).

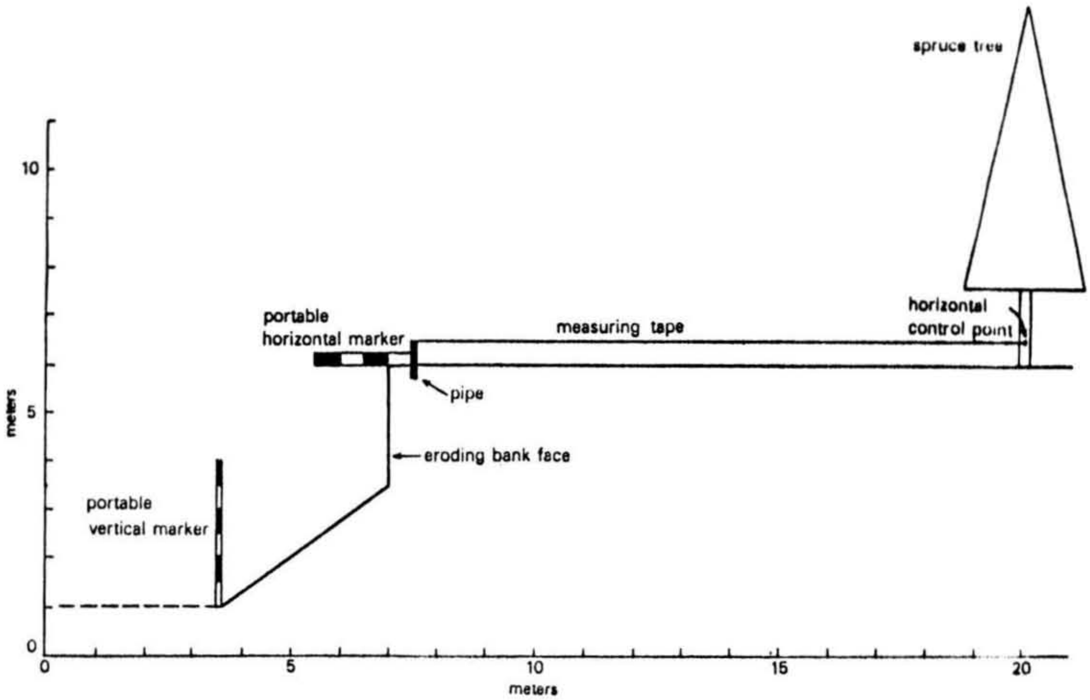


Figure 6. Scale markers used as reference in hand-held stereo photographs (Outhet 1974).

3. Stereo Photographs. Changes in bankline and bank shape can be measured on hand-held stereo photographs taken with scale markers placed along a bank face as a reference (Fig. 6). I think that this method would be considerably less accurate than leveling or rod measurements.

4. Slope Measurements. Approximate profiles can be determined by measuring the average slope angle between selected spots along a bank face from its toe to its crest (Reid 1984). Profile lines should be referenced to a stake landward of the bank crest. Usually, profiles drawn in this way do not show all the irregularities of a bank because only the average slope is measured.

5. Electronic Distance Measurement (EDM). EDM is especially useful where banks are high or composed of sediment that is easily disturbed (Leeks 1981). Distances are measured from fixed points to a prism reflector attached to a pole and placed flat against a bank face. A theodolite is used in conjunction with the EDM to measure angles to the reflectors. Repetitive surveys are made from fixed reference points (usually steel pins in the ground). Accuracy of this method depends on the size of the angles and distances. An accuracy of ± 5 mm over distances of up to 1000 m is reported (Leeks 1981).

Figure 7. Plastic sheet placed at a bank toe (Reid 1984).

Sediment Removed from a Bank

Several techniques have been used to measure the amount of bank sediment eroded from a bank face. Hill (1973) used sediment collection trays to catch the sediment. This method gives only estimates of the amounts of sediment eroded because some fine-grained sediment frequently gets washed out of the trays. Plastic sheets have been laid along a bank toe (Fig. 7) much like the trays and the amount of sediment deposited on the sheets is weighed to give an estimate of eroded sediment (Reid 1984). Reid (1984) also used garden edging set into a bank face (Fig. 8) to direct sediment moving down a bank through a funnel into a bucket. These traps do not always work well because the funnel can get plugged with sediment or the bucket fills and overflows.

Experience shows that some of the sediment removed from a bank does not come to rest on or in these devices, but they are convenient, simple ways to get an estimate of the minimum amount of sediment removed from the bank. In areas with snow and freezing rain, it would be nearly impossible to get reliable sediment catchment with these techniques.

Spray painting sections of in-situ bank sediment of gravel size or larger (Thorne 1981) also provides a method of tracing sediment as it is moved from one bank face location to another.

Figure 8. Sediment trap near bank toe (Reid 1984).

Bank Crest Recession

As sediment is removed from a bank face the bank crest does not necessarily recede concurrently. Bank crest recession is the result of the erosion that occurs along a bank face or mass wastage of a bank. Consequently, measurements of the recession alone are insufficient for analysis of bank erosion. The bank face measurements previously described must also be made. Recession measurements are required in determining the rate of land lost, which is of most concern to property owners bordering a water body whose bank is actively eroding. Snow can obscure the bank crest in winter and may have to be removed to get accurate measurements of its position.

Aerial Photographs. Considerable work has been done on the use of aerial photographs and photogrammetric techniques for monitoring the changes in position of shorelines and coastal features (Clow and Leatherman 1984, Shabica et al. 1984, Leatherman 1983; Dolan et al. 1978, 1979). Photographs have also been used for estimating historical bank recession along reservoirs (Gatto and Doe 1983, 1987) and for measuring the areal amounts of bank land lost (Guy 1981).

For measuring on-going bank recession, aerial photographs do not show the detail necessary and, if uncorrected, contain inherent distortions that can cause large measurement errors. The U.S. Geological Survey (Engineer Topographic Laboratories 1984) is testing a computer-assisted photo interpretation research (CAPIR) system for monitoring stream erosion and channel migration. Since aerial photographs provide a view of a larger portion of a bank than is visible during field work, it is worthwhile to use the photographs along with field data whenever possible.

Reference Stakes. Most frequently a series of reference stakes (metal or wood) are positioned landward of a bank crest. The distance between the stakes and crest is measured repetitively along the same line (i.e. a compass azimuth) to determine bank recession rates (Reid 1985, Reid et al. 1986, Hughes 1977, Wolman 1959, Twidale 1964, Hagerty et al. 1983, Guy 1981). Measurements can also be made from trees or other stable features. If stakes are used, they should be referenced to a temporary benchmark farther inland in case they are lost by bank recession or vandalism. By this referencing of the position of a stake, an estimate of the amount of recession could be made even if a stake is lost.

Frequency of measurement depends on how rapidly recession is occurring, although measurements must be made at least before and after high water (Guy 1981). If recession is rapid the reference stakes should be reset farther inland to avoid loss.

Bankline Maps. Plane table mapping, compass and tape measurements, a surveyor's transit and tape measurements, and an EDM can be used to make a map that shows bankline positions as they change (Thorne 1981, Tovey 1982). I have used the transit and tape method and am most familiar with it. The transit is positioned over a metal bar, which serves as a reference point. The bar is driven flush with the ground surface and found before each survey with a metal detector. This bar is referenced to a temporary benchmark (a nail in the base of a tree) farther inland. Both should be inland far enough to be safe from loss due to recession.

The line from the reference point to the benchmark is a zero azimuth. During a survey a rod is placed along the bank crest at locations of major change in shape. The angle from the zero azimuth to the rod location and the distance from the reference point to the rod are recorded. These data are then used to map the bank crest shape and, by repetitive surveys, the changes in crest positions.

Problems common to these methods are selecting locations along the crest for placing the rod, getting accurately taped distances if there is brush in the area, or sighting through the brush.

CONCLUSIONS

The amounts of erosion and resultant recession at a given bank vary temporally and spatially. Because of this site-specific variability and because several studies have shown that erosion and recession are usually episodic, field measurements and observations repeated over a number of years are required to get true values for bank erosion and recession rates and to evaluate the processes and conditions responsible for causing the bank erosion. This report has highlighted some of the methods that have been used to measure these rates and do the evaluations.

As mentioned earlier, project requirements and site characteristics will determine the methods appropriate for a particular site. Erosion pins and profiles are most frequently used to measure bank face changes and reference stakes are typically used to document changes in bank crest positions. Whichever methods are used, however, photographs should be taken to document conditions during every site visit.

Studies are underway to investigate the possibilities of automating some of the field data collection techniques and transmitting field data via satellite data collection systems.* As a result of new automated techniques, future work may require fewer field trips to collect the required data.

* Personal communication with H. McKim and T. Pangburn, CRREL, 1987.

LITERATURE CITED

American Society of Photogrammetry (1985) Close-range photogrammetry and surveying: State-of-the-art. Falls Church, Virginia, 941 pp.

Atkins, R.T. (1981) Using electronic measurement equipment in winter. USA Cold Regions Research and Engineering Laboratory, Cold Regions Technical Digest No. 81-1.

Birkemeier, W.A. (1981) Fast, accurate two-person beach surveys. Coastal Engineering Research Center, USA Engineer Waterways Experiment Station, Coastal Engineering Technical Aid No. 81-11.

Brockett, B. and K. Howe (1982) Location, installation and use of CRREL ground and air temperature instrumentation, Prudhoe Bay and Kuparuk oil fields, Alaska, 1982. USA Cold Regions Research and Engineering Laboratory, Technical Note (unpublished).

Coastal Engineering Research Center (1984) Wave and water level predictions. In Shore Protection Manual. USA Engineer Waterways Experiment Station, Chapter 3, p. 3-1 to 3-143.

Clow, J.B. and S.P. Leatherman (1984) Metric mapping: An automated technique of shoreline mapping. In Proceedings of the ASP-ACSM Convention, Washington, D.C., p. 309-318.

*Collins, S.H. and G.C. Moon (1979) Stereometric measurement of streambank erosion. Photogrammetric Engineering and Remote Sensing, 45(2):183-190.

Dolan, R., B. Hayden and J. Heywood (1978) A new photogrammetric method for determining shoreline erosion. Coastal Engineering, 2:21-39.

Dolan, R., B. Hayden, C. Rea and J. Heywood (1979) Shoreline erosion rates along the Middle Atlantic Coast of the United States. Geology, 7: 602-606.

*Duck, R.W., and J. McManus (1985) A sidescan sonar survey of a previously drawn-down reservoir: A control experiment. International Journal of Remote Sensing, 6(5):601-609.

*Eckert, J. and G. Callender (1987) Geotechnical engineering in the coastal zone. USA Engineer Waterways Experiment Station, Coastal Engineering Research Center, Instruction Report CERC-87-1.

*Edil, T.B. and L.E. Vallejo (1977) Shoreline erosion and landslides in the Great lakes. In Proceedings, 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Japan, 2:51-57.

* References that are especially useful.

Engineer Topographic Laboratories (1984) CAPIR supports stream erosion study. Tech-Tran, 9(4):6.

*Fulton, K. (undated) A manual for researching historical coastal erosion. Report No. T-CSGCP-003, University of California, Santa Cruz, California.

Gatto, L.W. and W.W. Doe (1983) Historical bank recession at selected sites along Corps of Engineers reservoirs. USA Cold Regions Research and Engineering Laboratory, Special Report 83-30.

Gatto, L.W. and W.W. Doe III (1987) Bank conditions and erosion along selected reservoirs. Environmental Geology and Water Sciences, 9(3): 143-154.

Gifford, G.P. (1984) Assessment of shear strength loss of a silty sand subjected to frost action. Ph.D. Dissertation (unpublished), Worcester Polytechnic Institute, Worcester, Mass.

Gilbert, R. and J.R. Glew (1986) A wind-driven ice-push event in eastern Lake Ontario. Journal of Great Lakes Research, 12(4):326-331.

Guy, P.R. (1981) River bank erosion in the mid-Zambezi Valley, downstream of Lake Kariba. Biological Conservation, 19:199-212.

*Hagerty, D.J., M. Sharifounnasab and M.F. Spoor (1983) River bank erosion - A case study. Bulletin of the Association of Engineering Geologists, 20(4):411-437.

*Hagerty, D.J., M.F. Spoor and C.R. Ullrich (1981) Bank failure and erosion on the Ohio River. Engineering Geology, 17:141-158.

Hanna, T.H. (1985) Field instrumentation in geotechnical engineering. Trans Tech Publications, Clausthal-Zellerfeld, Federal Republic of Germany.

Hemsley, J.M. (1981) Guidelines for establishing coastal survey base lines. Coastal Engineering Research Center, USA Engineer Waterways Experiment Station, Coastal Engineering Technical Aid No. 81-15.

*Hill, A.R. (1973) Erosion of river banks composed of glacial till near Belfast, Northern Ireland. Zeitschrift fur Geomorphologie N.F., 17(4):428-442.

*Hooke, J.M. (1979) An analysis of the processes of river bank erosion. Journal of Hydrology, 42:39-62.

Hooke, J.M. (1980) Magnitude and distribution of rates of river bank erosion. Earth Surface Processes, 5:143-157.

*Hudson, H.R. (1982) A field technique to directly measure river bank erosion. Canadian Journal of Earth Science, 19:381-383.

Hughes, D.J. (1977) Rates of erosion on meander arcs. In River Channel Changes, K.J. Gregory (Ed.). New York: John Wiley & Sons, Chapter 12, p. 193-205.

Knighton, A.D. (1973) Riverbank erosion in relation to streamflow conditions, River Bollin-Dean, Cheshire. East Midland Geographer, 40: 416-426.

Lawler, D.M. (1986) River bank erosion and the influence of frost: A statistical examination. Trans. Inst. Br. Geogr. N.S., 11:227-242.

Lawson, D.E. (1985) Erosion of northern reservoir shores, an analysis and application of pertinent literature. USA Cold Regions Research and Engineering Laboratory, CRREL Monograph 85-1.

Leatherman, S.P. (1983) Shoreline mapping: A comparison of techniques. Shore and Beach, 51:28-33.

Leeks, G.J. (1981) Development of field techniques for assessment of river erosion and deposition in mid-Wales, U.K. In Catchment Experiments in Fluvial Geomorphology (T.P. Burt and D.E. Walling (Ed.). Norwich, England: Geo Books, Chapter 18, p. 299-309.

Lo, C.P. and F.Y. Wong (1973) Micro-scale geomorphology features. Photogrammetric Engineering, 39(12):1289-1296.

Mathewson, C.C. (1981) Engineering Geology. Columbus, Ohio: C.E. Merrill Publ. Co.

May, J.R. (1982) The application of waterborne geophysical techniques in fluvial environments. USA Engineer Waterways Experiment Station, Geotechnical Laboratory Technical Report GL-79-7, Report 3.

McClay, P.L. (1985) The use of photography to record geologic data. Bulletin of the Association of Engineering Geologists, 22(2):143-151.

Meisner, D.E. (1986) Fundamentals of airborne video remote sensing. Remote Sensing of Environment, 19:63-79.

Osterkamp, T.E. (1984) Temperature measurements in permafrost. State of Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska, Report No. FHWA-AK-RD-85-11.

*Outhet, D.N. (1974) Bank erosion in the Southern Mackenzie River delta, Northwest Territories, Canada. M.S. Thesis (unpublished), Department of Geography, University of Alberta, Edmonton, Alberta, Canada.

Pincus, H.J. (1962) Recession of Great Lakes shorelines. In Proceedings, Symposium of the American Association for the Advancement of Science, 29-30 December 1959, Chicago, Illinois. AAAS Publ. 71, p. 123-137.

Pope, J. (1985) Side-scan sonar survey of Bailey's Dam, Red River, Alexandria, Louisiana. USA Engineer Waterways Experiment Station, Coastal Engineering Research Center Miscellaneous Paper CERC-85-9.

*Reid, J.R. (1984) Shoreline erosion processes, Orwell Lake, Minnesota. USA Cold Regions Research and Engineering Laboratory, CRREL Report 84-32.

*Reid, J.R. (1985) Bank-erosion processes in a cool-temperate environment, Orwell Lake, Minnesota. Geological Society of America Bulletin, 96:781-792.

Reid, J.R., B.S. Sandberg and M.D. Millsop (1986) Bank recession: Causes and rates: Past, present, future, Lake Sakakawea, North Dakota. Bulletin No. 86-01-EES-01, Department of Geology and Geological Engineering, University of North Dakota, Grand Forks, North Dakota, 743 pp.

Seibel, E. (1972) Shore erosion at selected sites along Lakes Michigan and Huron. Ph.D. Dissertation (unpublished), University of Michigan, Ann Arbor, Michigan.

*Shabica, S.V., R. Dolan, S. May and P. May (1984) Shoreline erosion rates along barrier islands of the North Central Gulf of Mexico. Environmental Geology, 5(3):115-126.

Simons, D.B., M.A. Alawady and R.M. Li (1978) Literature review and discussion of erosion processes. Contract report for USA Cold Regions Research and Engineering Laboratory (unpublished).

Simons, D.B., J.W. Andrew, R.M. Li and M.A. Alawady (1979) Report on Connecticut River streambank erosion study, Massachusetts, New Hampshire and Vermont. Contract report for Corps of Engineers, New England Division, Waltham, Massachusetts.

Sterrett, R.J. (1980) Factors and mechanics of bluff erosion on Wisconsin's Great Lakes shorelines. Ph.D. Dissertation (unpublished), University of Wisconsin, Madison, Wisconsin.

*Thorne, C.R. (1981) Field measurements of rates of bank erosion and bank material strength. In Erosion and Sediment Transport Measurement, Proceedings of the Florence Symposium, June 1981. IAHS-AISH Publication No. 133, p. 503-512.

Tovey, N.K. (1982) Surveying. In Environmental Science Methods (R. Haynes, Ed.). New York: Chapman and Hall Ltd., Chapter 9, p. 317-347.

*Twidale, C.R. (1964) Erosion of an alluvial bank at Birdwood, South Australia. Zeitschrift fur Geomorphologie, 8:189-211.

Ullrich, C.R., D.J. Hagerty and R.W. Holmberg (1986) Surficial failures of alluvial stream banks. Canadian Geotechnical Journal, 23:304-316.

U.S. Army Corps of Engineers (1981) Geotechnical research. Appendix C, Final Report to Congress on the Streambank Erosion Control Evaluation and Demonstration, Washington, D.C.

Vallejo, L.E. (1977) Mechanics of the stability and development of the Great Lakes coastal bluffs. Ph.D. Dissertation (unpublished), University of Wisconsin-Madison.

*Weigel, T.A. and D.J. Hagerty (1983) Riverbank change - Six Mile Island, Ohio River, USA. Engineering Geology, 19:119-132.

Welch, R. and T.R. Jordan (1983) Analytical non-metric close-range photogrammetry for monitoring stream channel erosion. Photogrammetric Engineering and Remote Sensing, 49(3):367-374.

Wolf, P.R. (1974) Elements of photogrammetry. New York: McGraw-Hill Book Company, 562 pp.

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

Yen, E.S., and M. Molnau (1982) Frozen soil effects on the erosion hazard. Research Technical Completion Report, Project A-070-IDA, Agricultural Engineering Department, University of Idaho, Moscow, Idaho, April.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1988--500-050--62077