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A quantitative analysis of shoreline erosion processes, Lake Sakakawea, North Dakota

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A QUANTITATIVE ANALYSIS OF SHORELINE EROSION PROCESSES, LAKE SAKAKAWEA, NORTH DAKOTA

By:

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This thesis submitted by Mark D. Millsop in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

John R. Reid
(Chairman)

5/3/85
Dean of the Graduate School

Permission

Title A Quantitative Analysis of Shoreline Erosion Processes,

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Department Geology

Degree Master of Science

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Date April 25, 1985

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patience and cooperation have helped to make this a successful, pleasurable learning experience.

ABSTRACT

Shoreline erosion is a problem at Lake Sakakawea and Lake Audubon, North Dakota. Land is lost, water quality is adversely affected, and reservoir storage capacity is decreased.

Instrumentation of the eastern shores of both lakes began in 1983 to quantify bank erosion by process (e.g., wave erosion, rainsplash and runoff, and frost-thaw failure). Other data gathered included: pool level fluctuations; wind velocity, direction, and duration; precipitation; soil moisture; frost penetration; freeze-thaw cycles; and geology (e.g., texture, clay mineralogy and structure).

The magnitude of shoreline erosion is highly variable, especially within Lake Sakakawea. For the interval of May 1983 through August 1984 the banks receded between 0.6 and 5.9m (0.5 to 4.6m/yr). Measurement of aerial photographs for 1966 to 1976 yielded similar average recession rates (0 to 4.3m/yr).

The predominant activating cause of bank recession at Lake Sakakawea is wave erosion; it is responsible for about 87 percent of total bank recession. The most important variables include: pool level; wind velocity, direction and duration; bank orientation, geology, geometry and vegetation cover; natural rip-rap; offshore bathymetry; and near-shore islands. Results indicate that banks that are shorter than 5m, which face the north or northeast, and are composed of well-jointed till or mudstone, have the highest recession rates, especially during high pool levels. At Lake Audubon, the most important activating factors are lake ice-shove and subsequent wave erosion. These factors caused most of the 0.8 to 1.4m (0.7 to 1.2m/yr) of bank recession.

Because of the nearly vertical banks, the effects of rain on the primary sediment and bedrock are minor. Most of the 2 to 52mm of bank slope erosion at each lake occurred in colluvium at the toe of the banks. This colluvium, primarily derived from sublimation and thaw failure, ranged from 0.13 to 3.30m^3 per metre of shoreline at Lake Sakakawea in spring 1984. Thaw failure accounted for about 13 percent of total bank recession and was greatest for those banks facing west and northwest, and which are composed of well-jointed till or mudstone. Measured colluvium volumes for Lake Audubon varied from 0.7 to 1.8m^3 per metre of shoreline.

Erosion at Lake Sakakawea begins in late winter as frost sublimates. The loosened aggregates accumulate as a thin apron at the foot of steep banks. Spring thaw results in slab failures, followed by earthflows and mudflows. As summer approaches, the lake rises until maximum pool level is reached sometime in mid-summer. Storm waves easily erode the loose colluvium along the base of the banks. If all the colluvium is eroded, the waves can remove the primary sediment or bedrock, effectively under-cutting the banks. At the top of such banks, extensional joints are initiated. The joints expand until bank failure releases the stresses. Bank failure continues until a relatively stable profile has formed. Late summer to early winter is an extended period of relative quiescence, after which time release of aggregates by sublimation again occurs.

Ultimate bank recession at Lake Sakakawea primarily depends upon the wave energy that reaches unprotected banks. Thus, as long as the pool level is not kept at or below about 562.0m msl., the beaches and banks will not stabilize and bank recession will continue.

INTRODUCTION

Statement of Problem

In 1953 the Missouri River was dammed near Riverdale, North Dakota, creating Lake Sakakawea (Figure 1). This multi-purpose reservoir was developed by the United States Army Corps of Engineers (Corps of Engineers) to help control floods, supply water for irrigation and municipalities, generate power, conserve fish and wildlife, and improve downstream water quality. The reservoir filled from 1953 to 1969, when the maximum normal pool level of 564.3m (1,850 ft) msl. was first achieved.

Since the normal pool level was first reached, erosional processes have claimed a substantial amount of the shoreline, and have caused many other environmental problems. Some include altered water quality, decreased reservoir storage capacity, modified nearshore/shoreline habitats, and diminished aesthetic quality. Recent attempts by the Corps of Engineers to predict the time required for a slope to reach a non-eroding equilibrium position have failed (Cordero, 1982). The assumption made was that material eroded from the upper section of the steep banks would ultimately accumulate at the base, mostly offshore, thereby diminishing the effectiveness of waves to erode the base of the banks. As a result, the upper banks would eventually become stabilized at a reduced angle and further recession of the top would cease. The problem, then, was to evaluate why this assumption was not valid.

Purpose

The purpose of this project was to examine the mechanics, causes, and magnitudes of erosion processes along the eastern shores of Lake Sakakawea and the adjacent Lake Audubon, located in Mercer and McLean Counties, North Dakota (Figure 1). The processes were to be evaluated through data collected from a series of measurement stations installed at these lakes (Figure 2).

Another objective was to lay the foundation for predicting the potential "ultimate" bank recession rates along Lake Sakakawea. Also, the observations and conclusions were to be compared with those from the Orwell Lake, Minnesota study recently completed by Reid (1984).

General

Garrison Dam and Lake Sakakawea are located on the Missouri River about 121km (75 mi) upstream from Bismarck, North Dakota. Garrison Dam is one of the largest rolled earthfill dams in the world and the resulting Lake Sakakawea is one of the largest man-made lakes in the world (United States Government Printing Office, 1977). At maximum pool level, the lake reaches 286km (178 mi) upstream to just beyond Williston, North Dakota, and has a surface area of about 946,000 hectares (383,000 acres) (United States Government Printing Office, 1977). Table 1 summarizes some physical characteristics of the reservoir. Characteristics of Lake Audubon, an impoundment separated from Lake Sakakawea by the Snake Creek embankment, are listed in table 2.

Climate

The climate of the area is semi-arid, with about 400mm annual precipitation. The weather is typically variable (Table 3). Summer is

Figure 1. Location of study area.

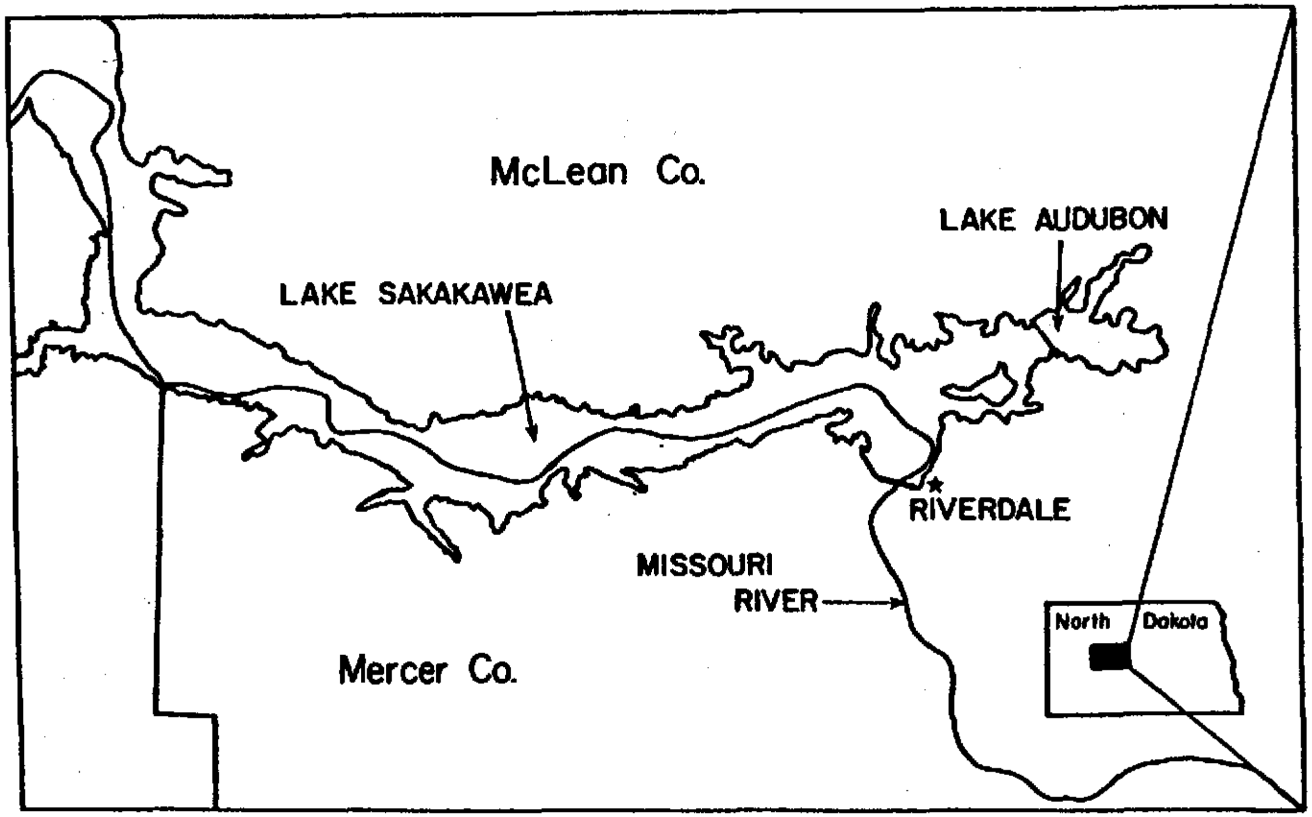
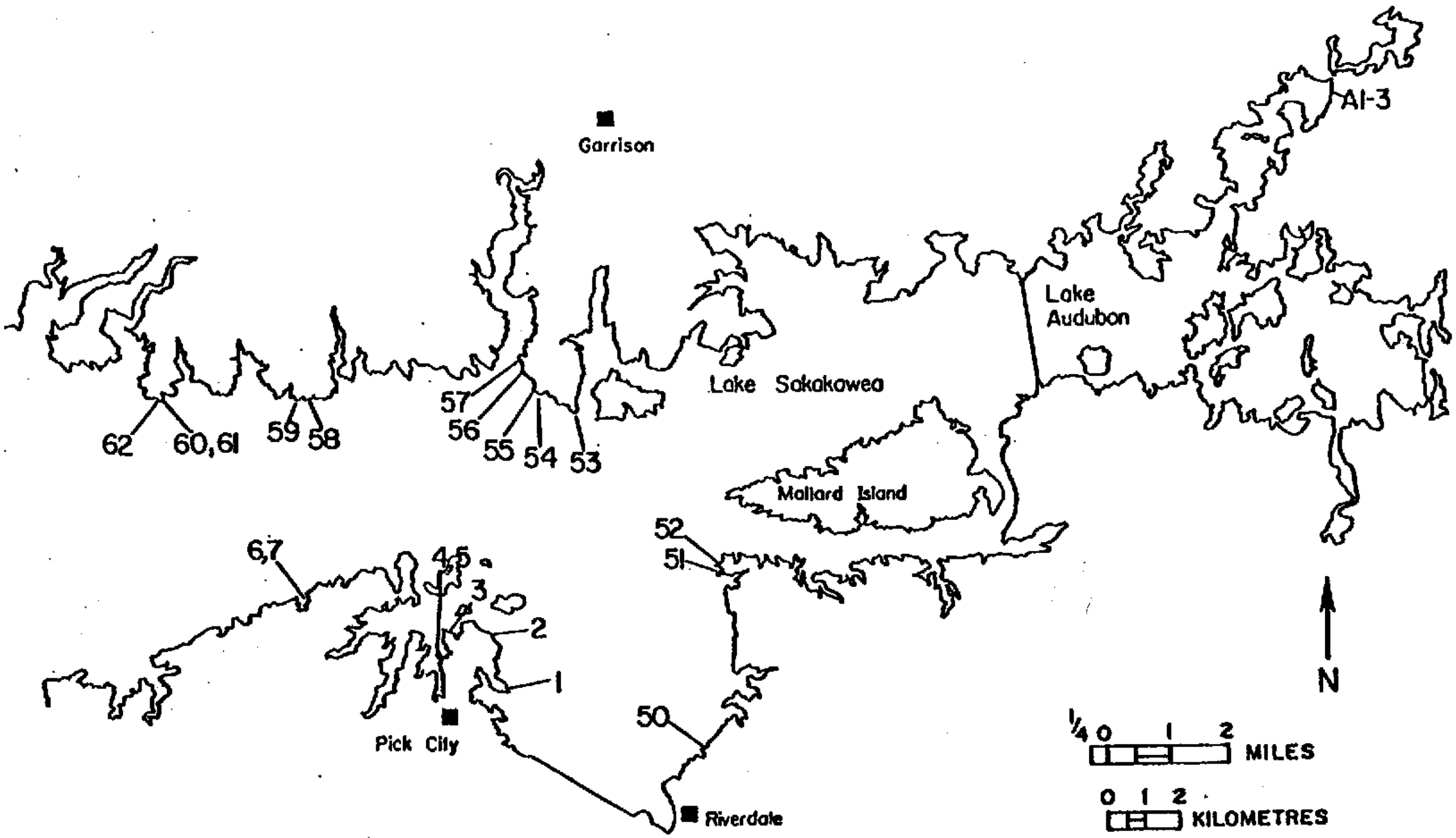

McLean Co.
LAKE AUDUBON
LAKE SAKAKAWEA
RIVERDALE
MISSOURI
RIVER
North
Dakota
Mercer Co.

Figure 2. Bank erosion stations along the eastern shores of Lakes Sakakawea and Audubon, North Dakota.



Garrison
Lake Sakakawea
Lake Audubon
Mallard Island
Pick City
Riverdale
AI-3
62
60,61
59
58
57
56
55
54
53
52
51
50
6,7
4,5
3
2
1
N
¼ 0 1 2 MILES
0 1 2 KILOMETRES

TABLE 1

Physical Characteristics of Lake Sakakawea, North Dakota, at Maximum Normal Pool Level, 564m (1850 ft.) msl. (from Gatto and Doe, 1983, and U.S. Army Corps of Engineers, 1983)

Drainage area above dam	469,624 sq km (181,322 sq mi)
Average width	4.82km (3 mi)
Length	286km (178 mi)
Shoreline length	2,155km (1,339 mi)
Surface area	131,414 hectares (507 sq mi)
Maximum depth	54.9m (180 ft)
Mean depth	21.3m (70 ft)
Volume	2.79×10^{10} m^3 (98.7×10^{10} ft^3)
Hydraulic residence time	1.13 years
Mean outflow	774.3 m^3/s (27,655 ft^3/s)

TABLE 2

Physical Characteristics of Lake Audubon, North Dakota, at Maximum Pool Level, 564m (1850 ft.) msl. (from U.S. Army Corps of Engineers, 1983)

Surface area	7076.2 hectares (27.3 sq mi)
Mean depth	5.9m (19.2 ft)

TABLE 3

Riverdale, North Dakota Weather Summary
* (January 1 through August 30, 1984, only)

	Precipitation		Temperature					
Year	Inches	mm	Average		Maximum		Minimum	
1980	14.04	356.6	40.4°F	(4.7°C)	102°F	(38.9°C)	-35°F	(-37.2°C)
1981	16.30	414.0	43.1°C	(6.2°C)	103°F	(39.4°C)	-22°F	(-30°C)
1982	19.36	491.7	38.0°F	(3.3°C)	95°F	(35°C)	-29°F	(-33.9°C)
1983	13.48	342.2	40.8°F	(4.9°C)	99°F	(37.2°C)	-32°F	(-35.5°C)
1984	13.23*	336.0*	-	-	99°F	(37.2°C)	-33°F	(-36.1°C)

warm and generally dry, even though it is the wettest season. Fall and spring are cool with variable precipitation. Finally, winters are usually cold and dry. The first frost normally occurs in early to mid-October and the last frost generally occurs in late April or early May.

Geologic Setting

The banks of the eastern end of Lake Sakakawea range from about 2 to 25m (6 to 82 ft) in height and typically are almost vertical. The banks consist of Tertiary and Quaternary sediments and sedimentary rocks. Figure 3 is a representative stratigraphic column for this area. The lowermost stratigraphic unit exposed in the study area is the Paleocene Sentinel Butte Formation (Ulmer and Sackreiter, 1973). It consists of lignite interbedded with sandstone, siltstone, mudstone, and occasional clinker ("scoria"). This formation is present in the lower parts of most banks and, in a few instances, it forms nearly the entire bank. Overlying the Sentinel Butte Formation are glacial sediments of the Pleistocene Coleharbor Group and eolian silt of the Holocene Oahe Formation (Ulmer and Sackreiter, 1973) in which a haploboroll soil has developed (United States Department of Agriculture, 1978). Meyer (1979) and Bluemle (1971) have published summaries of the Tertiary and Quaternary geologic history of the area.

The glacial sediments (till and sand) are over 10m (32.8 ft) thick in places, whereas the overlying eolian silt is typically less than 0.5m (1.6 ft) thick. Glacial sediments are the predominant bank lithology for 13 of the 20 stations at Lake Sakakawea (Table 4). Tertiary sediments dominate only one station and six stations have banks with a mixed lithology.

Figure 3. Stratigraphic column and dominant lithology of formations cropping out in the study area (from Ulmer and Sackreiter, 1973).

AGE	UNIT NAME		DOMINANT LITHOLOGY
Holocene	Oahe Formation	Riverdale Member Pick City Member Aggie Brown Member Mallard Island Member	Coarse silt
----?----------	Coteau Formation		Dirty (containing organic material), poorly sorted, gravelly, sandy, silty clay
	Snow School Formation		Bouldery, pebbly, sandy, silty clay
Pleistocene	Horseshoe Valley Formation		Bouldery, pebbly, sandy, silty clay
----?----------	Medicine Hill Formation		Bouldery, pebbly, sandy, silty clay, with silt inclusions
Pliocene?	Charging Eagle Formation		Silty sand and sandy silt
Paleocene	Sentinel Butte Formation		Sandstone and shale

TABLE 4

Bank Recession Pin Site Installation Data and Physical Characteristics

Bank Recession Pin Site	Number of Pins	Total Length (m)	Maximum Bank Height (m)	Orientation	Predominant Lithology
Lake Sakakawea					
1	14	115.9	3.7	NE	Till
2	8	47.0	7.0	NE	Mudstone (Ms)
3	6	61.0	3.8	N	Till
4	4	36.6	4.5	NW	Till
5	4	18.3	5.0	SW-NW	Till/sand
6	3	18.3	18.0	N	Till
7	4	27.5	14.5	N	Till
50	5	24.4	20.9	NW	Till/Ms
51	12	83.9	12.4	S-NW	Till
52	7	54.9	7.0	W-NW	Till
53	12	134.2	9.0	SE-SW	Till
54	5	24.4	6.2	SW	Till
55	9	60.0	10.5	SW-W	Till/Ms
56	8	36.6	11.8	W	Till/Ms
57	8	42.7	11.2	W	Till/Ms
58	7	36.6	9.1	S	Till/sand
59	4	22.9	8.2	SE-S	Till
60	1	-	7.9	E	Till/Ms
61	1	-	6.5	SE	Till/Ms
62	6	24.4	12.1	W	Till/Ms
Total	128	874.0			
Lake Audubon					
A1	8	42.7	1.7	W	Till
A2	4	18.3	1.5	W	Till
A3	4	18.3	1.0	NW	Till
Total	16	79.3			

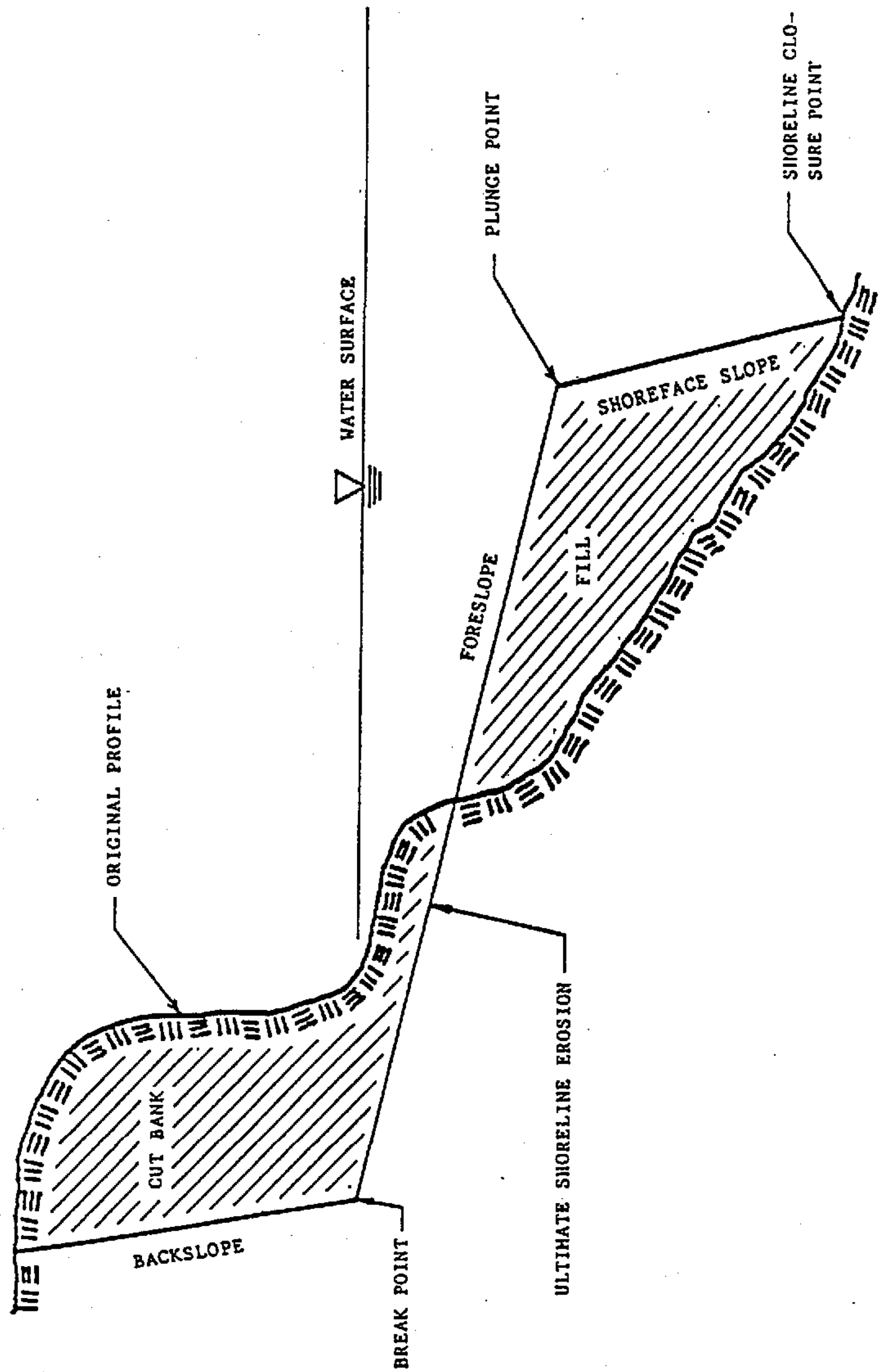
In contrast to Lake Sakakawea, the banks at Lake Audubon are only about 1 to 2m (3-7 ft) high. They, too, have a haploboroll soil developed in eolian silt which overlies Pleistocene glacial sediment (till).

Previous Work

In 1982, Cordero reported on the conventional technique used by the Corps of Engineers for evaluating bank erosion at Lake Sakakawea. This technique is based on conservation of volume, where the amount of sediment eroded from the bank is equal to the amount deposited at the toe (Figure 4). Furthermore, it assumes that this sediment would form a stable beach and the slopes would then stabilize above maximum wave influence. The problem with this is that the toe sediment continues to be removed by wave and current action. Thus, a stable beach is a rare occurrence at Lake Sakakawea. Cordero found that with the use of the conventional technique at each survey section, the erosion had already exceeded the projected ultimate limit in 80 percent of the cases. Therefore, it was concluded that both the conventional technique and the ultimate erosion estimates were in need of re-evaluation.

In the only other relevant study concerning erosion at Lake Sakakawea, Gatto and Doe (1983) reported on historical bank recession rates based on measurements from aerial photographs. They found that rates for 1958-1966 averaged 4.3m (14 ft) per year and rates for 1966-1976 averaged 5.8m (19 ft) per year. Because of the scale of the photographs, these rates were approximations, at best. Gatto and Doe concluded that inundation and wave erosion were the two most important causes of land loss at the reservoir from 1958-1976. They also tested the correlation between recession and other variables such as water

Figure 4. Conventional procedure used to predict ultimate shoreline recession by the U.S. Army Corps of Engineers (from Cordero, 1982).


WATER SURFACE
PLUNGE POINT
SHORELINE CLO-
SURE POINT
SHOREFACE SLOPE
FILL
FORESLOPE
ORIGINAL PROFILE
ULTIMATE SHORELINE EROSION
CUT BANK
BACKSLOPE
BREAK POINT

level, and bank and reservoir characteristics. However, the regression results did not prove useful in evaluating the erosion processes and bank conditions that contribute to shoreline erosion because significant correlations were generated only for variables that were obviously not important (e.g., duration of ice cover).

Finally, preliminary results of this study were the basis of a report submitted to the Corps of Engineers in late 1984 (Reid and Millsop, 1984).

PROCEDURES

Selection of Stations

The first priority was to identify and establish measurement stations that were both relatively accessible and exhibited active erosion. Some sites that exhibited little or no erosion were also chosen as control sites. The eastern end of Lake Sakakawea was chosen because it is closer to Grand Forks, North Dakota and because relevant pool and weather data are collected at Riverdale. The stations selected are shown in figure 2.

Three additional stations were established at the northeast end of Lake Audubon, whose level is regulated by the Snake Creek Pumping Station. This lake was included in the study primarily because it experiences only a small fluctuation in pool level compared to Lake Sakakawea.

Wave Erosion

Bank Recession Pins

As at Orwell Lake (Reid, 1984), bank top recession due to wave erosion at each of the stations was measured by inserting a series of pins, 152mm (6 in) long nails, about 3m back from the bank edge. Remeasurement of the pins revealed the amount of bank recession. Any extensional joints along the pin lines were also measured and recorded; the joint width was subtracted from the recorded recession measurement to arrive at a more accurate bank recession value. The locations of the bank recession pin sites are shown in figure 2. Sixty pins were inserted into north shore banks, seventy-two pins in south shore banks and sixteen at the Lake Audubon sites. The number of pins at each site, and other pertinent data, are given in table 4. The pins were measured each time the lakes were visited.

Profiles

Beach and bank profiles were measured at each erosion station by determining the average slope angle with a Brunton compass over given intervals (usually 0.8m) from the shoreline to the top of the bank. Each profile was tied in to a bank recession pin on the top of the bank. Table 5 lists the location and orientation of each profile site. The area of bank sediment eroded between profile dates was calculated using computer programs.

Offshore profiles were also measured beginning in June 1984. They were measured in conjunction with the onshore profiles as often as possible. It was hoped these would provide some evidence as to where the eroded sediment was going. If a stable platform were being built up, it would help to dissipate wave energy before it reached shore. These profiles were measured from a boat with a Raytheon sonar recorder (May, 1982). A stadia rod attached to the boat was read at about 15m (50 ft.) intervals from a transit onshore. The sonar operator marked the sonar readout sheet at each of these intervals. Thus, the depth and distance were known and could be plotted.

Pool Levels and Wind

Pool level data for Lake Sakakawea were obtained directly from the power plant at Garrison Dam for the period of January 1980 to August 1984. Pool level data for Lake Audubon were not collected because the

TABLE 5

Location and Orientation of Profile Sites,
Lake Sakakawea, North Dakota

Station and Location	Orientation (at right angle to slope)
1, BRP #11	N66E
2, BRP #1	N48E
3, BRP #3	N4E
4, BRP #2	N31W
5, BRP #3	N43W
6, Erosion Pins	N48W
7, BRP #2	N5W
50, BRP #4	N62W
50, Erosion Pins	N67W
51, Range Post	S50W
52, BRP #4	N68W
53, Erosion Pins	S66E
53, BRP #4	S22W
55, BRP #2A	S30W
56, BRP #7	S67W
57, BRP #2	S67W
58, BRP #3	S10E
59, BRP #1	S64E
60, BRP #1	N72E
61, BRP #1	S48E
62, BRP #6	S70W

pool level fluctuates very little. Wind data (four times daily) were obtained from the Riverdale weather station.

Overland Erosion

Erosion Pins

Similar to Orwell Lake (Reid, 1984), measurement of erosion by rainsplash and overland flow was attempted by observing the changes in exposure of erosion pins at the stations (Figure 2). Forty-seven of these were along the banks of Lake Sakakawea, and the remaining five in the significantly smaller banks of Lake Audubon. The erosion pins, actually spikes 304mm (12 in) long, were inserted normal to the bank surface, protruding about 100mm (4 in). The number of erosion pins installed at a particular site was a function of bank height, slope, orientation, lithology and accessibility. Measurement of the length of the pin protruding from the bank was always done on the same side of the pin because sometimes there were significant differences between the two sides. The amount of erosion and deposition were determined by comparing measurements from different dates. The pins were reset as needed.

Precipitation

Historic weather data for west-central North Dakota were made available by Dr. John Enz, Department of Soil Science, North Dakota State University. Daily work-day meteorological observation records from the Riverdale weather station were provided by the Riverdale office of the Corps of Engineers.

In order to establish a data base to compare north-shore precipitation with that at Riverdale and relate the effects of precipitation variations on slopewash erosion, one rain gauge was installed at Fort

Stevenson State Park. The park Rangers kindly recorded each precipitation event there.

Groundwater

Piezometers

Piezometers are commonly used to monitor groundwater fluctuations along reservoirs (Reid, 1984) and lakes (Mickelson and others, 1977). Although no piezometers were installed for this study, a large slump site is included in the area covered by a network of water level monitoring stations installed by the Corps of Engineers. In order to analyze the importance of groundwater at the site, the data for the relevant piezometers for the years 1982, 1983 and 1984 (partial) were obtained from the Riverdale office of the Corps of Engineers.

Frost-Thaw

Colluvium Volumes

After spring thaw was complete, the volume of colluvium due to thaw failure was calculated using two techniques. The most accurate method required excavation of a trench at representative colluvium sections. The colluvium was removed by shovel and placed in a bucket of known volume. When the contacts with the undisturbed bank and beach were reached, the volume of the trench was ascertained by counting the number of buckets removed and multiplying by the bucket's volume. Using these trenches as standards, the volume of colluvium for the entire section was estimated by pacing along shore. This estimated value was probably a minimum value because sediment that had fallen on the ice over the winter and early spring was lost when the ice melted. It must also be understood that some sediment included as thaw failure colluvium had actually fallen since cessation of thaw, due to other processes.

The second technique utilized bank recession pins, bank heights and station length measurements. The amount of bank recession measured from the time of first frost was multiplied by both the average bank height and the station length to yield a volume of eroded sediment for a particular site.

Finally, bank recession pins and bank profiles also were used to quantify erosion by frost-thaw processes.

Frost Tubes and Thermograph

In order to measure frost depth and duration, holes were drilled at five sites during the summer and fall of 1984 and 35mm PVC casing tube was installed. At a later date, a 15mm o.d. polyethylene tube filled with methylene blue-dyed water was inserted. To measure the frost depth, the tube was lifted up and the thickness of the frozen section measured, the base being equivalent to the depth of the zero degree isotherm. These tubes are similar to those used by Reid (1984), and Rickard and Brown (1972).

Tubes 1, 2 and 3 were installed on level ground far from exposed banks. A fourth tube was installed into a bank and the last tube was installed in colluvium at the base of a bank. These last two frost tubes became inaccessible over the winter and data could not be collected. For the others, the frost depth was measured regularly from the time of the first frost until the time of complete thaw.

A seven-day thermograph was installed at Fort Stevenson State Park in October, 1983; the chart was changed weekly by the Rangers there, especially Brad Pozarnski. It recorded temperatures throughout the winter, enabling freeze-thaw cycles to be counted and recorded.

Geology

The banks at each station were examined, described, sketched, photographed and measured regularly throughout the project. In the fall of 1983, the banks were scraped clean and samples were collected for subsequent laboratory analyses. Joint orientations were also measured at that time.

In June, 1984, additional sediment samples were collected for the purpose of determining their moisture content and dry density. There were two days of steady, light rainfall and one day of dry weather prior to the day the samples were collected. The surface of the bank was scraped clean and a metal cylinder of known volume was then pounded into the bank. When the cylinder was fully inserted and filled with sediment, it was removed. Next, more sediment was added if the cylinder was not completely full. Finally, the sediment in the cylinder was extruded into a sealable bag and weighed to the nearest gram at the close of the day. Where the sediment was too hard, blocks were collected. These were measured and their volumes calculated and recorded. They were also stored in sealable bags and weighed to the nearest gram.

Laboratory Analyses

Most of the laboratory time was involved in analyzing sediments. The main purpose was to describe and correlate stratigraphy, especially the glacial tills as many other researchers have done (Landon and Kempton, 1971). In addition, clay mineralogy was determined because some clays expand more than others and clay expansion may be an important factor in bank failure at the lakes.

Other laboratory analyses involved aerial photograph measurements and computer-generated statistical analyses. Procedures for these analyses are discussed in the sections entitled Historical Bank Recession and Regression Analysis.

Color and Texture

First, the Munsell Soil Color Chart (1973) was utilized, in natural light, to define the dominant color and mottles of the dry samples.

Next, the standard North Dakota Geological Survey hydrometer and sieve method (Perkins, 1977) was used to determine the gravel, sand, silt and clay percentages of the samples. The hydrometer was used to find the amount of clay in each sample before the sand and gravel were separated by wet-sieving. Then, the separated sand and gravel were oven-dried and sieved at half-phi intervals, from -1.5 phi to 4 phi. The gravel weight was subtracted from the total weight and the sand, silt and clay weight percentages were normalized to 100 percent. The samples were then classified according to the United States Department of Agriculture textural classification (Walter, Hallberg, and Fenton, 1978).

About 15 grams were saved from each sample for a subsequent Sedigraph analysis of the silts and clays. Each subsample was soaked in 50 milliliters of 4 percent Calgon solution (dispersant). After soaking for about 24 hours the solution was wet-sieved through a 4-phi screen. Most of the clays and silts passed rapidly into a jar, leaving mostly sand and gravel. At this point, some distilled water was used to wash the remaining silts and clays through the screen into a second jar. Next, after most of the silts and clays had settled, the majority of the water in the jar was decanted. The remaining water, with the silts and clays, was then rinsed into the first jar. This wet-sieving technique was recommended (Forsman, 1984, oral communication) to produce an adequately dense solution for Sedigraph analysis. Next, this solution was allowed to settle for a few hours and then inspected for signs of flocculation. If flocculation existed the solution was centrifuged and re-inspected. If there was no apparent flocculation the solution was ready to be analyzed in the Sedigraph. This machine analyzes the samples using x-rays and produces a cumulative curve for a desired range of phi-sizes, in this case the 4 phi to 12 phi-size range. Thus, when the hydrometer, sieve and Sedigraph results were combined, the total data range for a sample was from -1.5 phi to 12 phi with a data point for every half-phi interval.

Coarse Sand Lithology

The lithology of the very coarse sand grains (1-2mm) from the till samples was determined for possible use as a till differentiation/ correlation tool. These grains were saved from the sieving procedure.

The grains were grouped into seven lithologic categories: dolomite, limestone, crystalline (igneous and metamorphic), quartz and feldspar, shale, sandstone, and other (which included gypsum, chert and lignite). The grains were identified under a binocular microscope with 10 to 40 power magnification. Dolomite and limestone grains were differentiated by degree of reaction with dilute hydrochloric acid. In all, 3789 grains from 17 till samples were identified.

Matrix Carbonate

A Chittick apparatus was used to determine the percentages of calcite and dolomite in the matrix of each of the 17 glacial till samples. The apparatus and the procedure for using it are described by Boellstorff (1978), who modified a procedure developed by Dreimanis and others (1962). This procedure (and associated tables) was followed exactly. These data provided another tool for the possible correlation of till units.

Clay Mineralogy

Clay mineralogy of the till and mudstone samples was determined with a Phillips diffractometer, using copper radiation. In preparation, the samples were dispersed in distilled water for one to three days. (If calgon is used as a dispersant, it is impossible to differentiate sodium montmorillonite from calcium montmorillonite. The type of montmorillonite (smectite) is important because sodium montmorillonite expands more than other types.) Next, the solution was stirred briskly and, after a predetermined settling time, the less than two micron fraction was pipetted and placed upon a glass slide which was fastened to a carbon plug. The appropriate settling time was determined according to a formula defined by Folk (1980).

Oriented non-glycolated and glycolated samples were x-rayed with copper radiation from 2 degrees through 35 degrees at 2 degrees per minute at a rate of 250 counts per second. Short scans of oriented glycolated samples, x-rayed from 24 degrees to 27 degrees at 0.25 degrees per minute, were also run. Diffractograms of the oriented non-glycolated samples were used to determine whether sodium montmorillonite or calcium montmorillonite (or both) were present. At a later date, some samples were run at 0.25 degrees per minute from four to seven degrees as a check against the results from analysis of the non-glycolated samples. As a further check, a few samples prepared on glass slides were analyzed by a scanning electron microscope. The short scans, from 24 to 27 degrees, were useful in separating the kaolinite and chlorite peaks. The results from these scans were extrapolated to the diffractograms of the oriented glycolated samples using a conversion factor. This factor was found after running several standards of both clay types at the previously mentioned speeds. Then, a calibrated chart was superimposed on the diffractograms of the oriented glycolated samples to determine the overall clay mineralogy. Next, peak heights were measured and, finally, relative percentages of various clay minerals were determined by comparing their respective peak heights. Hallberg, Lucas and Goodman (1978) present a good outline of diffractogram analysis as well as sample preparation.

Moisture Content and Dry Density

The samples of known volume, collected in June 1984, were oven-dried at 40 degrees celsius for about six days and then weighed to the nearest gram. The difference between the initial weight and the oven-dried weight divided by the initial weight defined the moisture content (Fetter, 1980). The final dry weight of the sample was used to determine its dry density.

DISCUSSION OF OBSERVATIONS AND RESULTS

Reservoir Bank Erosion

General

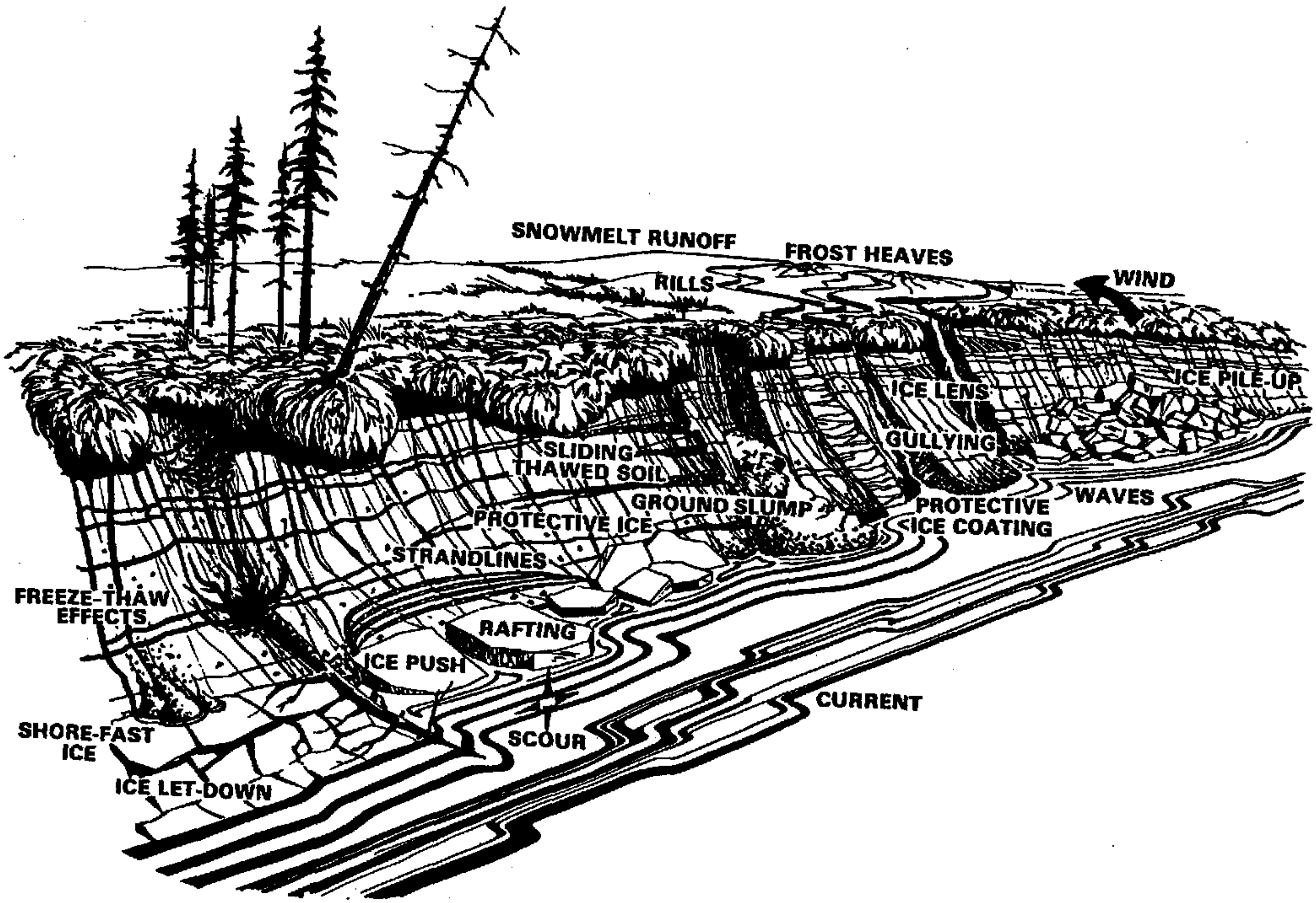
There are many erosion processes active in seasonally frozen environments such as at lakes Sakakawea, Audubon and Orwell. These include wave erosion, rainsplash and runoff, and frost-thaw (Figure 5).

Most bank erosion at Lake Sakakawea and other reservoirs takes place through bank failure rather than by surface erosion processes (e.g., corrasion, rainsplash and runoff) (Reid, 1984; Doe, 1980; Kachugin, 1980). The stability of a reservoir bank depends on the balance of driving and resisting forces associated with the most critical mechanism of failure (Doe, 1980). A stable bank is one in which the net resultant driving forces (shear stress, tensile stress) are equal to or less than the net resultant resisting forces (shear strength, tensile strength). In most cases, bank failure will occur if, along a plane, the shear stress exceeds the shear strength. However, in other instances (e.g., overhangs), failure results when the tensile stress overcomes the tensile strength.

The shear stress of the bank materials is determined primarily by gravitational forces resulting from the weight of the material, as well as any structure resting on it (Doe, 1980), the bank height and the slope angle (Mickelson and others, 1977). Shear strength is usually expressed in terms of the Mohr-Coulomb Failure Criterion:

$$S = c + \sigma \tan \emptyset,$$

Figure 5. Erosion processes active in seasonally frozen environments (from Gatto and Doe, 1983).


SNOWMELT RUNOFF
FROST HEAVES
RILLS
WIND
ICE PILE-UP
ICE LENS
GULLYING
SLIDING
THAWED SOIL
GROUND SLUMP
PROTECTIVE ICE COATING
WAVES
PROTECTIVE ICE
STRANDLINES
FREEZE-THAW EFFECTS
RAFTING
ICE PUSH
CURRENT
SHORE-FAST ICE
SCOUR
ICE LET-DOWN

where S is the shear strength, c is the cohesion of the material, σ is the normal stress, and $\emptyset$ is the angle of internal friction of the material. Higher c and $\emptyset$ values each lead to greater shear strength and less likelihood of bank failure (Freeze and Cherry, 1979, p.467). There is a wide range in c and $\emptyset$ values and thus, shear strength for different materials (Wu and Sangrey, 1978; Chandler, 1977). For example, for dry sands and fractured rocks, $c \rightarrow 0$ and the shear strength is controlled mostly by the angle of internal friction. However, for saturated clays under undrained conditions, $\emptyset \rightarrow 0$ and the shear strength is mostly predicated on cohesion (Freeze and Cherry, 1979, p.467).

These generalizations ignore the factor of pore water. When the materials are saturated, effective stress rather than total stress is the critical factor in failure (Holtz and Kovacs, 1981, p.215; Terzaghi, 1923). The effective stress (σ_e) must be calculated using the formula:

$$\sigma_e = \sigma - p,$$

where p is fluid pressure. Because the shear strength of rocks and soils is strongly influenced by drainage conditions, those conditions must be accounted for (Wu and Sangrey, 1978). Substituting in the Mohr-Coulomb equation:

$$S = c + (\sigma - p) \tan \emptyset,$$

where c and $\emptyset$ are determined for saturated conditions. Therefore, an increase in fluid pressure decreases the shear strength.

Another important stability relationship is that concerning tensile stress and strength (Thorne and Tovey, 1981). Tensile stress is "a normal stress that tends to cause separation across the plane on which it acts" (Bates and Jackson, 1980). Most often this is caused by gravity (e.g., overhanging sediments) or forces exerted on tension joints (e.g., ice growth) (Varnes, 1978). The ability of a material to resist this type of stress is its tensile strength.

For a more thorough discussion of soil mechanics and slope stability see McCarthy (1977), Perloff and Baron (1976), Spangler and Handy (1973), Sowers and Sowers (1970), Terzaghi and Peck (1967) or Terzaghi (1950).

Bank Movements

When stress exceeds strength and bank failure occurs, there is a wide variety of movements that may take place (Varnes, 1978; Coates, 1977). Varnes' (1978) classification (Table 6) is based on the kind of material being moved and the type of movement. In the following discussion, the types of bank movement are defined according to current usage. However, it should be understood that most bank movements are caused by many factors. As Sowers and Sowers (1970, p.506) explain,

> "In most cases a number of causes exists simultaneously and so attempting to decide which one finally produced failure is not only difficult but also incorrect. Often the final factor is nothing more than a trigger that sets in motion an earth mass that was already on the verge of failure. Calling the final factor the cause is like calling the match that lit the fuse that detonated the dynamite that destroyed the building the cause of the disaster."

Falls

Falls occur when a mass of overhanging earth material of any size is detached from a steep slope or bank and descends mostly through the air by freefall, bounding, or ricocheting (Varnes, 1978; Coates, 1977). Falls are most common in well-jointed materials that have been undercut by erosive agents and are the result of shear failure, tensile failure or beam failure (Thorne and Tovey, 1981). Resulting movements are very

TABLE 6

Types of Bank Movements (from Varnes, 1978)

Type of Movement			Type of Material		
				Engineering Soils	
			Bedrock	Predominantly Coarse	Predominantly Fine
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	Rotational	Few units	Rock Slump	Debris slump	Earth slump
Slides	Translational	Few units	Rock block slide	Debris block slide	Earth block slide
Slides	Translational	Many units	Rock slide	Debris slide	Earth slide
Lateral Spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow (deep creep)	Debris flow	Earth flow
				(soil creep)	
Complex	Combination of two or more principal types of movement				

rapid to extremely rapid (3×10^{-3} to >3 m/sec) and may be preceded by minor movements leading to failure of the mass (Varnes, 1978). Falls have been observed at Lake Sakakawea and Orwell Lake (Reid, 1984) as well as other reservoirs (Erskine, 1973), lakes (Mickelson and others, 1977; Hadley, 1976) and rivers (Thorne and Tovey, 1981; Hooke, 1979; Sharpe, 1938).

Topples

Toppling, caused by forward tilting of overturning moments, occurs when a mass rotates forward about some pivot point (below the center of gravity of the unit) under both the action of gravity, and forces exerted by fluids or ice in adjacent joints (Varnes, 1978; Coates, 1977). Toppling commonly occurs where tension joints have developed such that they occupy a significant proportion of the bank height (Thorne and Tovey, 1981). Because of this, tensile failure is the usual cause of topples. Movements are very rapid to extremely rapid (3×10^{-3} to >3 m/sec) and also may be preceded by minor movements leading to failure (Varnes, 1978).

This type of movement has only recently gained attention. The most detailed descriptions have been given by Thorne and Tovey (1981), de Freitas and Walters (1973), and Hoek (1972). Although no mention of topples was found in the literature concerned with reservoir bank failure, they surely exist and, in fact, are common at Lake Sakakawea.

Slides

Slides are initiated by shear failure along one of several planes (Coates, 1977). The character of the shear plane determines whether the slide is translational or rotational (Varnes, 1978). Translational, or planar slides move approximately parallel to the bank surface and are commonly associated with structure. A planar slide in which the moving mass is not greatly deformed or broken up may be called a block slide or glide (Varnes, 1975). These slides generally move at extremely slow to slow rates (<3 x 10^{-10} to 3 x 10^{-7} m/sec) (Varnes, 1978). Planar slides which have resulted in deformation or break up of the mass can be subdivided further into slab failure and avalanches (Ritter, 1979, p.152). Movement of these types of slides may range from very slow to extremely rapid rates (3 x 10^{-9} to >3 m/sec) (Varnes, 1978).

Rotational slides, or slumps, move along a shear plane that is concave upward. Upon failure, the mass is rotated and the block is tilted backward. Movements may be at extremely slow to moderate rates (<3 x 10^{-10} to 3 x 10^{-5} m/sec) and may be progressive (Varnes, 1978).

Both planar and rotational slides occur at Lake Sakakawea and Orwell Lake (Reid, 1984), and other reservoirs (Doe, 1980; Erskine, 1973), and lakes (Sterrett, 1980; Mickelson and others, 1977).

Lateral Spreads

Spreads are "lateral extension movements in a fractured mass" (Varnes, 1978, p.236). The most common, best understood and most important spreads owe their movement to liquefaction or plastic flow of basal material. Lateral spread, or lateral extension, is accommodated by shear or tensile fractures. The coherent upper units may rotate, translate, disintegrate or subside, or they may liquefy and flow. Lateral spread movements vary from extremely slow (e.g., gabbro) to very rapid (e.g., clay) rates (<3 x 10^{-10} to 3 m/sec) (Varnes, 1978).

No lateral spreads have been identified along Lake Sakakawea and there were no descriptions of lateral spreading along reservoirs or lakes found in the literature. However, Mitchell and Markell (1974), and Youd (1973) describe failures of this type in other areas and these failures also probably take place along reservoirs, especially in those banks composed of clay-till and fractured mudstone (e.g., Lake Sakakawea banks).

Flows

Flow movements in rocks are distributed among many fractures, causing folding or bulging and are generally extremely slow (Varnes, 1978). No examples of rock flows along reservoirs were found in the literature nor were any recognized at Lake Sakakawea but many other examples have been described (Radbruch-Hall, 1975; Tabor, 1971).

Debris flows and earthflows are the result of an increase in water content of the soil mass (Varnes, 1978). Commonly, the soil mass actually liquefies and flows like a viscous fluid (Ritter, 1979, p.153). Flows often occur at the foot of slumps (Doe, 1980; Mickelson and others, 1977). Flow rates depend largely on the amount of water in the material and the texture of the materials but they can range from very slow (creep) to extremely rapid (3×10^{-9} to >3 m/sec) (Varnes, 1978).

Reid (1984) observed debris flows, earthflows and mudflows at Orwell Lake. Such flows are also common at Lake Sakakawea and other reservoirs (Gatto and Doe, 1983; Doe, 1980; Erskine, 1973) and lakes (Mickelson and others, 1977).

Complex Movements

Most bank movements "involve a combination of one or more of the principal types of movement described above, either within various parts of the moving mass or at different stages in development of the movements" (Varnes, 1978, pp.20-21). A few of these are topple-slides, topple-falls (Varnes, 1978), debris slide-earthflows (Hutchinson and Bhandari, 1971) and slump-flows (Doe, 1980; Mickelson and others, 1977).

Lake Sakakawea and Lake Audubon

Bank Recession and Joint Propagation

Bank recession at both Lake Sakakawea and Lake Audubon is ultimately caused by mass movement, i.e. the sudden failure of slabs, clumps or blocks of the bank material. Most failure planes correspond to joints, whether in till or in the Paleocene bedrock.

Waves impacting at the base of steep slopes are the major activating cause of bank recession at Lake Sakakawea. The degree to which such erosion occurs, though, is highly diverse and there are numerous variables which affect it, especially wind direction, strength and duration, concurrent with high pool levels. One purpose of this study, then, was to identify the activating factors of bank erosion and their dependent variables. It has become clear that several major factors are involved in whether or not erosion occurs at a given site, and in the degree of that erosion. These are summarized in table 7.

Bank movements which directly or indirectly result from these activating factors are summarized in table 8. The most common movements are falls and planar slides caused by wave undercutting of the bank toe, whereas slumps are relatively rare and are primarily due to groundwater. Finally, flows are most common in the winter and spring due to frost-thaw processes.

Bank recession pin measurements have proven to be the most valuable technique in the documentation of erosion magnitudes. The cumulative average bank recession for a measurement interval was determined for each

TABLE 7

Activating Factors and Associated Dependent Variables at Lakes Sakakawea and Audubon

Activating Factor	Dependent Variables
Wave Erosion	bank orientation, geology and geometry; natural rip-rap and vegetative cover; offshore profile; offshore islands; pool levels; wind direction, strength and duration.
Overland Erosion (Rainsplash and Runoff)	pre-existing moisture condition; bank orientation, geology and geometry; vegetative cover; precipitation intensity, duration and direction.
Groundwater	bank geology and geometry; topography; precipitation and snowmelt amounts; pool level fluctuations.
Frost-Thaw	pre-existing moisture condition; bank orientation, geology and geometry; vegetative cover; frost rate, depth and duration; volume and concentration of ice; freeze-thaw cycles; rate of thaw; snowmelt amounts.
Lake Ice-Shove	bank orientation, geology and geometry; pool level; degree of ice cracking and refreezing; wind strength, duration and direction.
Vibrations (man-made, wave-induced or storm-induced)	location, intensity and duration.

TABLE 8

Activating Factors and Bank Movements, Lake Sakakawea, North Dakota

Activating Factor	Falls	Topples	Planar Slides	Slumps	Flows	Topple-falls	Topple-slides	Slide-falls	Slump-flows
	rde*	rde	rde	rde	rde	rde	rde	rde	rde
Wave Erosion	BBB**	BBB	BBB	BBB	-DD	BBB	BBB	BBB	-DD
Overland Flow	---	---	---	---	-DD	---	---	---	---
Groundwater	BBB	BBB	BBB	BBB	-DD	BBB	BBB	BBB	-BB
Frost-Thaw	DDD	DDD	DDD	DDD	-DD	DDD	DDD	DDD	-DD
Lake Ice-Shove	BBB	BBB	III	-II	-II	BBB	BBB	III	-II
Vibrations	DDD	DDD	DDD	DDD	-DD	DDD	DDD	DDD	-DD

Key:
* Type of material (Varnes, 1978):
r = rock
d = debris
e = earth

** D = usually factor directly causes the particular movement
I = usually factor indirectly causes the particular movement
B = factor can cause the particular movement either indirectly or directly

station by summing the bank recession values for all the pins and dividing that number by the number of pins measured. Graphs of the cumulative average bank recession for each station for the study period are provided in Appendix B. The total cumulative average bank recession, seasonal amounts, and yearly recession rates for each station are listed in table 9. For Lake Sakakawea, bank recession ranged from 0.63 to 5.87m (2.6 to 19.3 ft) and averaged 2.29m (7.5 ft) over the period of 15 to 17 months. In their historical approach, Gatto and Doe (1983) found the average bank recession to be about 5.79m (19 ft) for the years 1966 to 1976. This is significantly greater than the averages found from this study.

According to Morton (1978), two common, but invalid, assumptions regarding bank recession rates are: 1) calculated rates of recession are constant over a particular time period; and, 2) the trend of recession is also invariant over the same period. However, upon examination of cumulative average bank recession graphs (Appendix B), it appears there are uniform recession rates for certain periods. This is simply a function of the length of the measurement intervals. For example, if the pins could be measured every day, no doubt the amount of bank recession would vary. In fact, probably the only time rates would be uniform would be during periods of no erosion.

A question may arise as to whether the average cumulative bank recession values are typical of the majority of the remaining banks in the study area. From a new perspective in the summer of 1984 (from the water instead of just the land), it was concluded that the measured rates of recession are probably representative of rates for other active banks

TABLE 9

Cumulative Average Bank Recession at Each Station
Lakes Sakakawea and Audubon, May, 1983 through August, 1984
* (Warm Weather: 5/83 to 10/16/83 and 6/1/84 to 8/24/84;
Cold Weather: 10/16/83 to 6/1/84.)

Station	Number of Pins	Cumulative Average Bank Recession (m)	Warm Weather Recession (m)*	Cold Weather Recession (m)*	Bank Recession Rate (m/y)
Lake Sakakawea					
1	14	3.71	3.70 (99.9%)	0.01 (0.1%)	3.05
2	8	1.95	1.93 (99.2%)	0.02 (0.8%)	1.60
3	6	2.50	2.49 (99.7%)	0.01 (0.3%)	2.05
4	4	2.14	2.01 (94.1%)	0.13 (5.9%)	1.76
5	4	1.93	1.89 (98.0%)	0.04 (2.0%)	1.59
6	3	0.87	0.72 (82.5%)	0.15 (17.5%)	0.63
7	4	3.19	2.77 (86.7%)	0.42 (13.3%)	2.32
50	5	1.01	0.48 (47.6%)	0.53 (52.4%)	0.74
51	12	2.80	2.69 (95.9%)	0.12 (4.1%)	2.04
52	7	2.39	2.36 (98.8%)	0.03 (1.2%)	1.74
53	12	0.63	0.50 (79.0%)	0.13 (21.0%)	0.49
54	5	3.17	2.48 (78.4%)	0.68 (21.6%)	2.49
55	9	5.87	4.74 (80.7%)	1.13 (19.3%)	4.61
56	8	3.57	2.59 (72.6%)	0.98 (27.4%)	2.81
57	8	0.77	0.63 (81.5%)	0.14 (18.5%)	0.61
58	7	0.78	0.72 (92.1%)	0.06 (7.9%)	0.61
59	4	0.96	-	-	0.76
60	1	0.71	0.62 (87.3%)	0.09 (12.7%)	0.56
61	1	5.78	4.93 (85.3%)	0.85 (14.7%)	4.54
62	6	1.13	0.99 (87.3%)	0.14 (12.7%)	0.89
Average	-	2.29	2.06 (87.3%)	0.30 (12.7%)	1.79
Lake Audubon					
A1	8	1.44	0.20 (14.0%)	1.24 (86.0%)	1.22
A2	4	1.08	0.23 (21.4%)	0.85 (78.6%)	0.92
A3	4	0.81	0.29 (35.6%)	0.52 (64.4%)	0.69
Average	-	1.11	0.24 (21.7%)	0.87 (78.3%)	0.94

beyond the station sites. The study by Gatto and Doe (1983) and this study each emphasized sites of active erosion.

The cumulative average recession for Lake Audubon stations ranged from 0.81 to 1.44m (2.7 to 4.7 ft) and averaged 1.11m (3.6 ft). The banks of Lake Audubon are typically less than 1m high (3.3 ft). So even if these recession rates are representative, the volume of erosion is a couple of orders of magnitude less than at typical Lake Sakakawea stations.

Many of the bank failures are preceded by a period of vertical joint expansion, parallel to the bank. Most are opened because of undercutting of the bank by wave action, whereas others owe their origin to frost-thaw processes or desiccation. Table 10 provides joint width measurements for all the stations from June 1983 through August 1984. Generally, joints expand as bank failure progresses. Apparent periods of joint width reduction may be due to clay swelling, frost heave, or measurement error. Figures 6 and 7 summarize the joint data in terms of season and orientation. Most joints both initiated and failed during the warm weather months.

Area Eroded

Bank profiles were another method used to monitor bank changes due to erosion. From repeated profile measurements, the area between the initial and subsequent profile could be determined. Areas eroded ranged from 3.23 to 55.24m^2 (34.75 to 594.38 ft^2) (Table 11) for similar intervals. Profiles for selected sites and intervals are presented in Appendix C.

The area eroded depends directly on bank height and bank recession. For a given distance of recession, the higher the bank the more the

TABLE 10

Extensional Joint Development at Bank Recession Pin Sites,
Lake Sakakawea, North Dakota
(* = Joint Initiation; F = Joint Failure)

Station	#1			#2		#5		#6		#7		#50
Date/pin	#9	#12	#1	#2	#3	#4	#2	#3	#1	#3	#4	#5
06/21/83			*									
07/13/83			20 cm									
07/28/83			26 cm	6 cm*								
08/24/83			F	6 cm								
10/16/83	*	*										7 cm*
05/09/84	4 cm	2 cm		8 cm		5 cm*	1 cm*	2 cm*	2 cm*, 1 cm*	5 cm*		F
05/31/84	F	F		8 cm		15 cm	3 cm	4 cm	1 cm, 1 cm	6 cm		
07/13/84				11 cm	3 cm*	F	50 cm	2 cm	F, 2 cm	F	3 cm*	
07/23/84				F	F		F*		F		3 cm	
08/23/84					17 cm*		5 cm	3 cm				

Station				#51					#52		#55
Date/pin	#3	#6	#7	#9	#10	#11	#12	#3	#5	#6	#4
06/21/83		11 cm*	20 cm*	15 cm*							
07/13/83		13 cm	27 cm	17 cm	*						
07/28/83		F	24 cm	14 cm	11 cm						
08/24/83			25 cm	14 cm	F			5 cm*			
10/16/83			28 cm	11 cm				F			
05/09/84			27 cm	17 cm		1 cm*	6 cm*		1 cm*, 1 cm*		
05/31/84		*	23 cm	15 cm		?	7 cm		F, 5 cm	6 cm*	4 cm*
07/13/84	5 cm*	17 cm, 1 cm*	F	15 cm			5 cm			F	F
07/23/84	?	F, 2 cm		F			2 cm				
08/23/84	3 cm	F					4 cm*, 2 cm				

TABLE 10 (continued)

Station	#56				#57						#58	
Date/pin	#2	#4	#5	#7	#1	#2	#3	#4	#6	#8	#3	#5
06/24/83			*			*						*
07/13/83						15 cm		*		*		
08/23/83						14 cm	1 cm*	7 cm		10 cm		5 cm, 1 cm*
08/24/83			8 cm									
10/15/83						10 cm	5 cm	8 cm		8 cm	3 cm*	
10/16/83	5 cm*		F									
05/10/84	F					12 cm	9 cm	F		F	F	4 cm, 1 cm
05/31/84				1 cm*								
06/01/84					*, 5 cm*	14 cm	F, 1 cm*	7 cm*		3 cm*		5 cm, 1 cm
07/13/84		5 cm*		3 cm	F	15 cm	6 cm	9 cm		3 cm		7 cm, 1 cm
07/23/84		4 cm	7 cm*	F								
07/24/84						12 cm	4 cm	12 cm	10 cm*	2 cm		2 cm*, F
08/23/84		3 cm	13 cm									
08/24/84						12 cm	9 cm	14 cm	F	F		F

Station	#59		#62				
Date/pin	#3	#4	#1	#2	#3	#4	#5
06/24/83			12 cm*	25 cm*		14 cm*	
07/13/83			F	24 cm	12 cm*	F	
07/28/83				F.		*	
08/23/83			30 cm*		22 cm, 1 cm*	15 cm	
08/24/83	1 cm*	1 cm*					
10/15/83			F		F, 4 cm	F	
05/10/84	5 cm	7 cm	19 cm*		F	14 cm*	
05/31/84	F						
06/01/84			16 cm			22 cm	14 cm*
07/13/84			F			19 cm	7 cm
07/23/84		7 cm					
07/24/84						F	F
08/23/84		5 cm					
08/24/84			8 cm*			4 cm*	

Figure 6. Relationship of extension joint initiation to orientation and season.

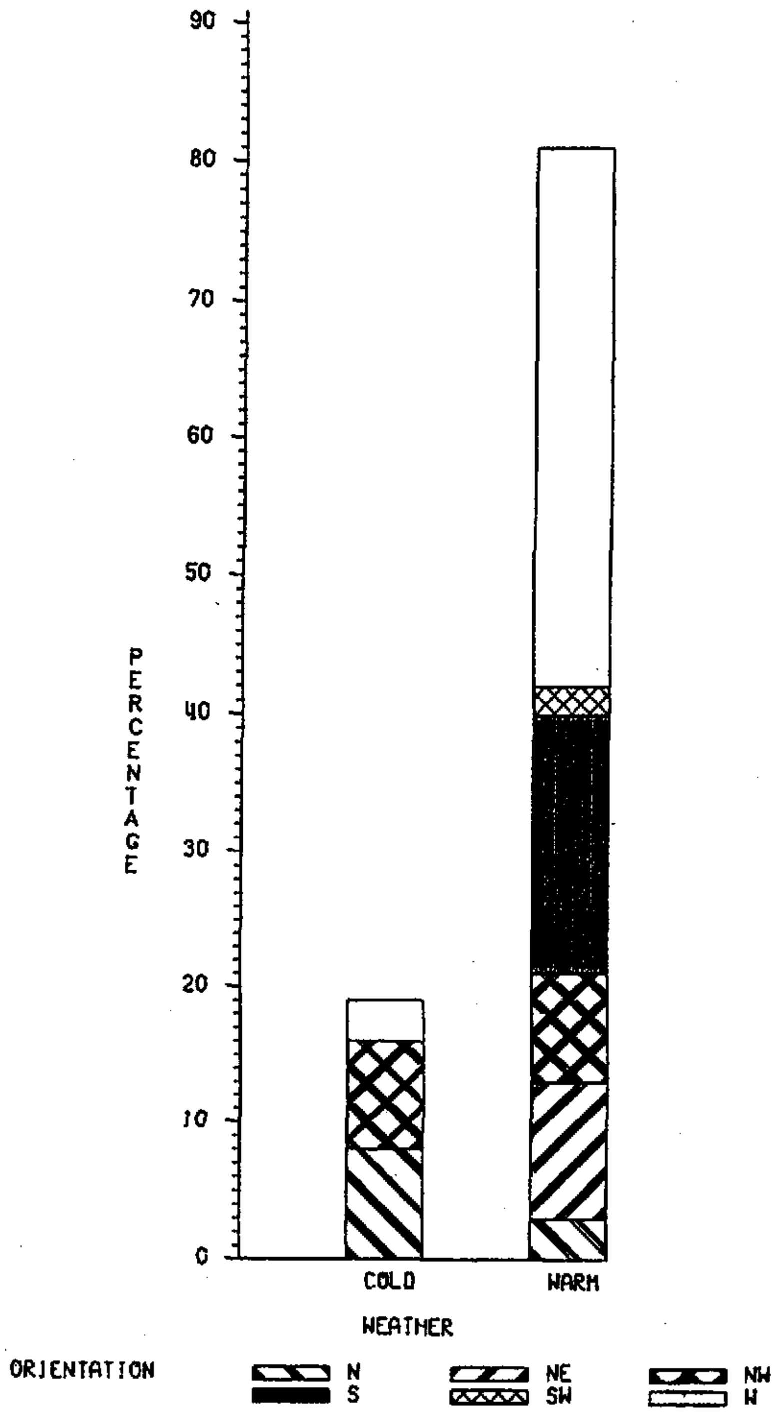

90
80
70
60
50
40
30
20
10
0
PERCENTAGE
COLD
WARM
WEATHER
ORIENTATION
N
NE
NW
S
SW
W

Figure 7. Relationship of extension joint plane failure to orientation and season.

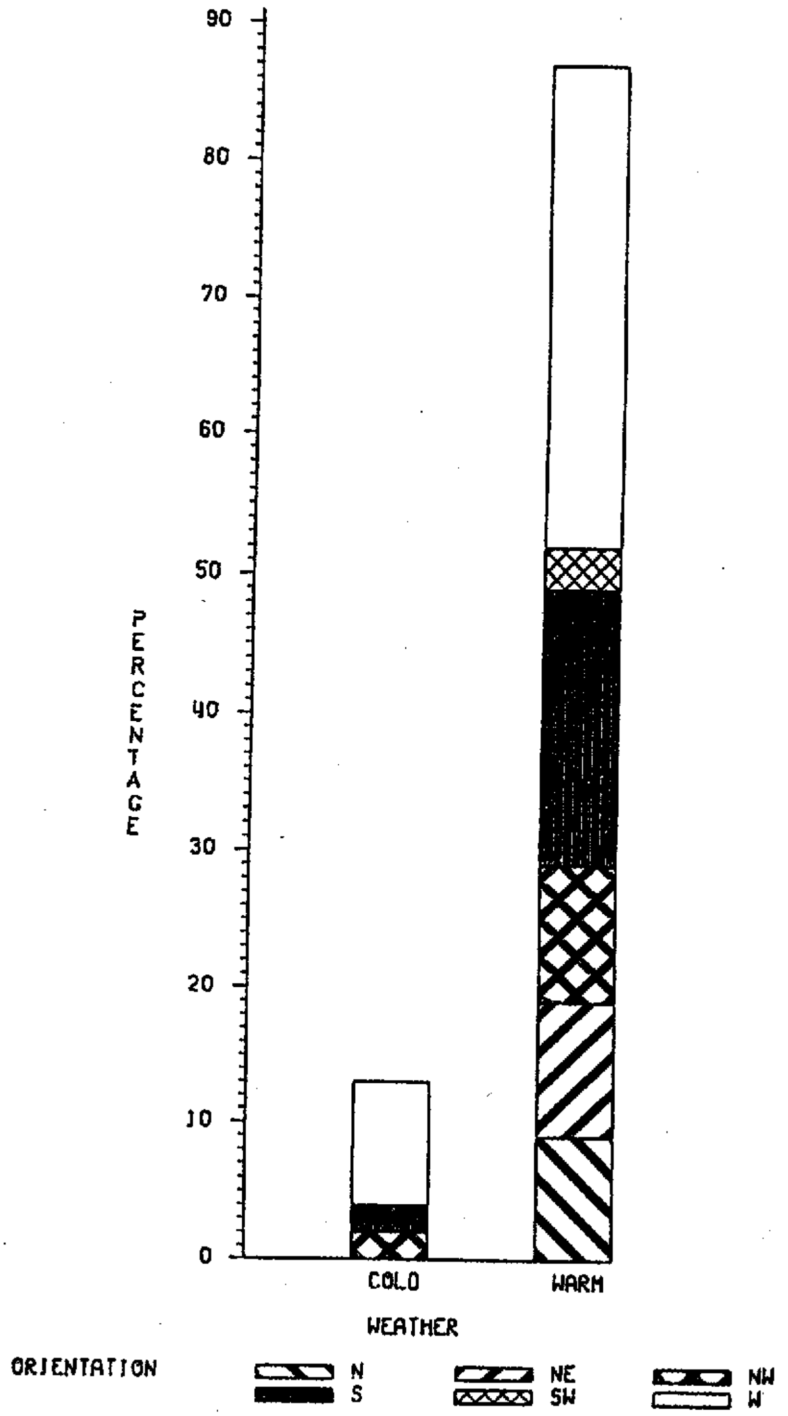

PERCENTAGE
90
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TABLE 11

Area Eroded at Lake Sakakawea Bank Profile Sites for Similar Intervals

Station	Measurement Interval	Area Eroded (m^2)
1	10/16/83 - 10/13/84	6.84
2	10/16/83 - 10/13/84	21.60
3	10/16/83 - 10/13/84	5.41
4	10/16/83 - 10/13/84	8.87
5	10/16/83 - 10/13/84	6.76
7	06/13/83 - 05/31/84	7.90
50	07/12/83 - 07/23/84	15.67
51	10/15/83 - 10/13/84	55.24
52	10/15/83 - 10/13/84	23.61
53	06/01/84 - 10/14/84	43.04
55	06/18/84 - 09/14/83	5.37
56	10/15/83 - 10/14/84	20.15
57	10/15/83 - 10/14/84	14.75
58	08/22/83 - 10/14/84	14.78
59	10/15/83 - 10/14/84	9.75
60	10/15/83 - 10/14/84	9.26
61	10/15/83 - 10/14/84	11.69
62	10/15/83 - 10/14/84	30.03
Average		17.26

resulting area that is eroded. For example, stations 1 and 56 have nearly the same average bank recession (Table 9), but the bank height and the area eroded at station 56 are about three times greater than those at station 1 (Figures 74 and 87, Appendix C). Also, for two banks of about the same height, the higher bank recession rate will result in a greater area eroded. Stations 1 and 3, each about the same height, display this relationship (Figures 74 and 75, Appendix C); station 1 has the greater bank recession (Table 9) and, therefore, the higher amount of area eroded.

Another factor that affects the magnitude of area eroded is the amount (volume) of colluvium existing at the bank toe when measurements commenced. For example, sites 56 and 62 have similar orientations, heights, bank materials and bank recession rates, (Tables 4 and 9) but over 1 1/2 times more area was eroded at station 62 (with less bank recession) (Table 11, and Figures 87 and 90, and Appendix C). The main reason for this was the presence of a large, loose colluvium slope at that station that was readily eroded in the summer of 1984.

Thus, bank height, bank recession rate and the initial colluvium volume are the most important factors affecting the area of erosion as defined by repetitive profiling. It should be understood, however, that factors such as pool level fluctuations, freeze-thaw cycles, bank orientation and bank geology are also important in affecting bank erosion at the sites.

Factors of Bank Erosion

Geology

Bank geology is one of the most important factors affecting reservoir bank stability (Doe, 1980; Edil and Vallejo, 1980). Not only does bank geology define the strength of the bank but also the type of movement that will result upon bank failure (Varnes, 1978), and the magnitudes of erosion processes (Reid, 1984, 1985).

The stratigraphic units exposed in the study area are shown in figure 3. Only two of the formations, the Charging Eagle and Coteau, are absent from the erosion stations on Lake Sakakawea. Figure 8 illustrates the stratigraphy at each of the bank profile sites. The stratigraphy at Lake Audubon is limited to the upper Snow School, and Oahe formations.

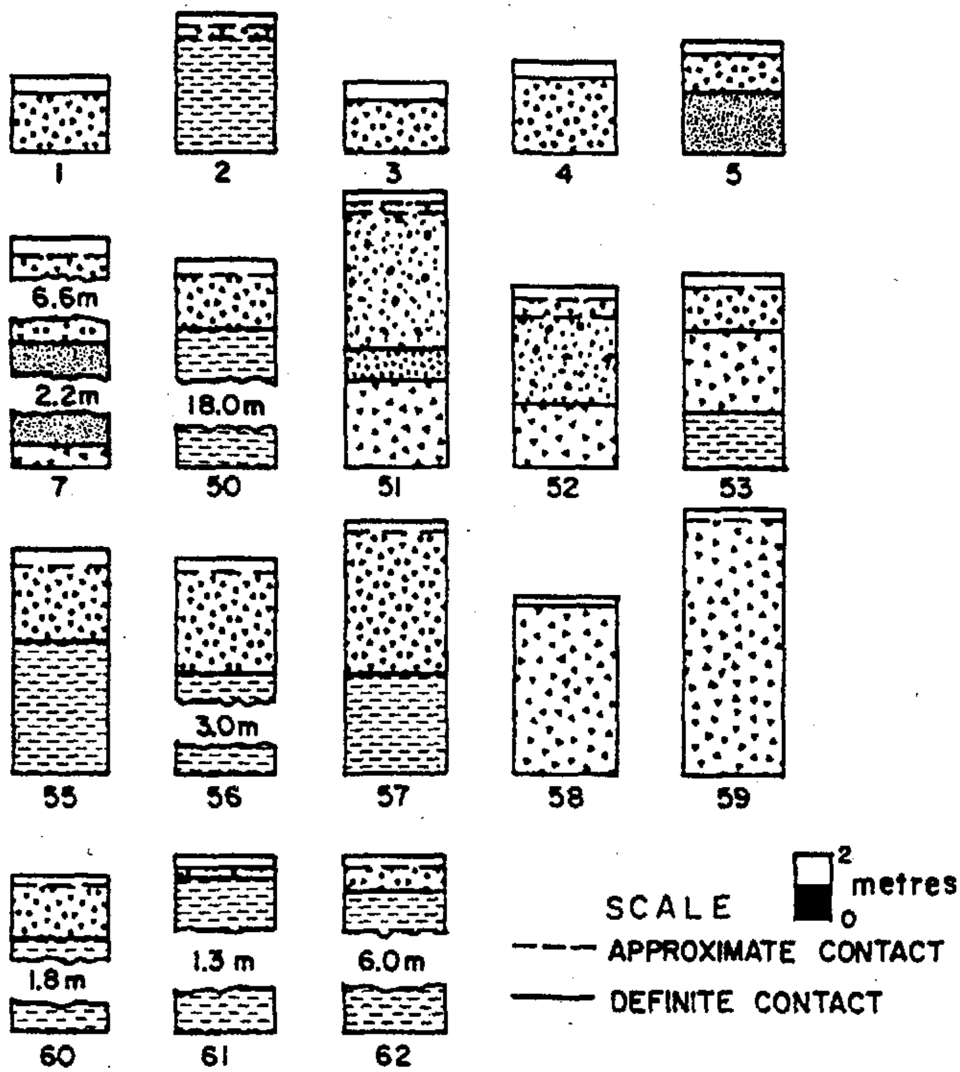
Sentinel Butte Formation

The Sentinel Butte Formation is the lowermost unit exposed in most parts of the study area. It generally comprises less than 50 percent of the exposed bank. The unit is areally extensive and where not visible it is probably present below water level. The thickness of the unit varies from about 75 to 200m (245 to 655 ft) (Jacob, 1976).

Crawford (1967, p.10) describes the Sentinel Butte Formation as "a repetitive sequence of dark gray and brown sandstone, siltstone, and lignite beds with many brown limonitic sandstone concretions". It is characterized also by the presence of clinker, leaf molds and petrified wood. Jacob (1976) provides a more detailed description of the sediments and their depositional environments.

Silty clay (poorly consolidated mudstone) is the most common lithology of the Sentinel Butte Formation in the study area. The color varies from pale olive (5Y 6/3) to gray (10 YR 5/1) but is most often light brownish-gray (2.5Y 6/2). Changes in color can give the formation a banded appearance. Moisture content and density of the silty clays varies greatly (Table 26, Appendix A).

Figure 8. Stratigraphy of profile sites at Lake Sakakawea. The station number is below each column. The bottom of the columns are at pool level (563.5m msl.) at the time of measurement. (See Figure 2 for locations.)



SYMBOL	FORMATION	AGE
	OAHE	HOLOCENE
	UPPER SNOW SCHOOL	PLEISTOCENE
	LOWER SNOW SCHOOL	PLEISTOCENE
	UPPER HORSESHOE VALLEY	PLEISTOCENE
	LOWER HORSESHOE VALLEY	PLEISTOCENE
	UPPER MEDICINE HILL	PLEISTOCENE
	SENTINEL BUTTE	PALEOCENE

Textural analyses of 12 samples of the mudstone yielded average sand-silt-clay percentages of 2.2 percent, 47.4 percent and 50.4 percent, respectively (See Table 27, Appendix A for individual sample results). The sediments comprising the mudstone are extremely poor to poorly sorted, positive skewed or nearly symmetrical, and most often mesokurtic (the textural parameters used are as defined by Folk, 1980). The average median diameter is 7.7 phi (fine silt). Average clay mineral ratios of nine mudstone samples is given in table 28 (Appendix A); smectite is the dominant clay type.

The bedding of the mudstone is essentially horizontal throughout the study area. Joints are developed both along bedding planes and nearly perpendicular to the bedding. Also, the unit is highly fractured in most places, typically forming blocks a few centimetres in diameter. There are also many normal faults developed in the unit. These are most easily seen by displaced lignite beds. The contact with overlying units is always sharp.

Along the shores of Lake Sakakawea, the Sentinel Butte Formation is especially susceptible to wave erosion because of its stratigraphic position, high smectite content, and characteristic jointing, fracturing and faulting.

Medicine Hill Formation

The Medicine Hill Formation (Ulmer and Sackreiter, 1973) is composed of two distinct members. The lower member is not exposed at any erosion stations. According to Ulmer and Sackreiter (1973), who reported exposures north of Riverdale, near Wolf Creek Bay, the unit consists of sand, pebbles and cobbles, and is locally cemented into conglomerate; most often the sediments are unconsolidated. Contacts with other units are sharp and undulating. This member is likely to be a very erodible unit where not cemented.

The upper member of the Medicine Hill Formation is a pebble loam (glacial till) and is exposed at a number of erosion stations, where it typically overlies the Sentinel Butte Formation and is overlain by the Snow School Formation. The contacts are sharp and undulating. The unit is extensive, and where not exposed it is probably present below lake level. It ranges from 1 to 15m (3.3 to 49.3 ft) in thickness along the bluffs of Lake Sakakawea (Ulmer and Sackreiter, 1973). The color of this member varies from light brownish-gray (2.5 Y 6/2) to light gray (10 YR 7/1) (Table 26, Appendix A). The average sand-silt-clay percentages for four samples are 24.7 percent, 45.4 percent and 29.9 percent, respectively (Table 12). These compare favorably to Ulmer and Sackreiter's (1973) average percentages, 23 percent, 47 percent and 30 percent. This upper member is extremely poorly sorted, nearly symmetrical (skewness), and mesokurtic with an average median diameter of 5.9 phi. For this unit, the average density is 2.98 gm/cc and the average moisture content is 7.5 percent (Table 13). Clay mineral ratios are given in table 14, and matrix dolomite and calcite percentages are provided in table 15. Finally, the results of the coarse sand identification are listed in table 16. See Appendix A for individual sample laboratory data.

This upper member contains large inclusions of bedded silt (stations 58 and 59). These presumably were ripped up from a nearby lake and incorporated into the till (Bluemle, 1971). Alternatively, the unit may have been deposited on ice and became deformed upon melting.

TABLE 12

Average Texture and Textural Parameters of
Glacial Till Units, Lake Sakakawea, North Dakota

Formation	Number of Samples	% Sand	% Silt	% Clay	Sorting	Skewness	Kurtosis	Median Diameter
Upper Snow School	10	26.4	41.3	32.3	3.415	-0.013	0.837	6.2 ∅
Upper Horseshoe Valley	2	32.5	35.0	32.5	3.495	0.153	0.627	5.7 ∅
Upper Medicine Hill	4	24.7	45.4	29.9	3.148	0.010	0.927	5.9 ∅

TABLE 13

Average Density and Moisture Content of Glacial Till Units, Lake Sakakawea, North Dakota

Formation	Number of Samples	Density (gm/cc)	Moisture Content (%)
Upper Snow School	10	2.94	10.2
Upper Horseshoe Valley	2	1.64	0.5
Upper Medicine Hill	4	2.98	7.5

TABLE 14

Average Clay Mineral Ratios for Glacial Till Units, Lake Sakakawea, North Dakota

Formation	Number of Samples	Kaolinite	Chlorite	Illite/ Muscovite	Smectite
Upper Snow School	10	.11	.07	.24	.58
Upper Horseshoe Valley	2	.16	.05	.21	.58
Upper Medicine Hill	4	.20	.07	.21	.52

TABLE 15

Average Matrix Dolomite and Calcite Percentages for Glacial Till Units, Lake Sakakawea, North Dakota

Formation	Number of Samples	% Dolomite	% Calcite	% Total Carbonate
Upper Snow School	10	11.5	7.5	19.0
Upper Horseshoe Valley	2	11.0	5.1	16.1
Upper Medicine Hill	4	10.3	4.2	14.5

TABLE 16

Average Coarse Sand Lithology of Glacial Till Units, Lake Sakakawea, North Dakota

Formation	Number of Samples	% Dolomite	% Limestone	% Crystalline	% Quartz & Feldspar	% Shale	% Sandstone	% Other
Upper Snow School	10	10.5	8.9	22.9	28.4	18.1	10.7	0.5
Upper Horseshoe Valley	2	11.2	9.2	27.4	24.3	18.3	8.3	1.3
Upper Medicine Hill	4	6.0	8.7	8.6	16.4	35.7	13.2	11.4

This member is usually exposed low in the banks and, consequently, is subject to direct wave contact. However, its unjointed, massive nature helps it withstand wave erosion relatively well. Its high smectite content also is a factor affecting its erodibility.

Horseshoe Valley Formation

The Horseshoe Valley Formation (Ulmer and Sackreiter, 1973) also has two members. The lower member is discontinuous and is exposed at only one site in the study area, station 51 (Figure 2). Ulmer and Sackreiter (1973) reported other exposures near Wolf Creek Bay. At station 51, the lower member consists of an iron-stained conglomerate overlain by a light yellowish-brown (2.5 Y 6/4) dirty sand (Table 26, Appendix A). The conglomerate averages about 0.3m (1.0 ft) thick and the sand about 0.8m (2.6 ft) thick. The sand is flat-bedded with some cross-bedding. The bedding planes generally dip north-northeast (Ulmer and Sackreiter, 1973). Lignite fragments are concentrated along some bedding planes. Textural analysis of the sandy loam yielded sand-silt-clay percentages of 68.4 percent, 14.1 percent, and 17.5 percent, respectively (Table 27, Appendix A). It is poorly sorted, positively skewed, and leptokurtic with a median diameter of 1.8 phi. Contacts with overlying and underlying units are sharp and undulating. The sand is very erodible when directly impacted by waves, whereas the conglomerate acts as natural rip-rap.

The upper member of the Horseshoe Valley Formation is a pebble loam (glacial till) and is exposed at only two stations. At station 51 it overlies the lower member of the Horseshoe Valley Formation, whereas at station 52 it overlies the upper member of the Medicine Hill Formation. At both stations the unit is overlain by the upper member of the Snow

School Formation (till) and/or the Oahe Formation (loess). All contacts are sharp and undulating. The unit is also exposed in other banks along the shore north of Riverdale near Wolf Creek Bay (Ulmer and Sackreiter, 1973). It ranges in thickness from about 2.5 to 5.0m (8 to 16.5 ft) at the stations but may be as thick as 6.0m (19.7 ft) (Ulmer and Sackreiter, 1973).

The color of this member varies from light brownish-gray (2.5 Y 6/2) to light yellowish-brown (2.5 Y 6/4) (Table 26, Appendix A). The average sand-silt-clay percentages for two samples are 32.5 percent, 35.0 percent and 32.5 percent, respectively (Table 12). These results compare favorably with Ulmer and Sackreiter's (1973) average percentages which were 29 percent, 36 percent, and 34 percent, respectively. The unit is extremely poorly sorted, positively skewed, and platykurtic with an average median diameter of 5.7 phi. The average density is 1.64 gm/cc and the average moisture content is 0.5 percent (Table 13). The average clay mineral ratios, matrix dolomite and calcite percentages, and coarse sand lithologies are given in tables 14, 15 and 16. See Appendix A for individual sample laboratory data.

Even though the upper member of the Horseshoe Valley Formation is never in direct contact with waves at any station, the unit displays strong columnar jointing which decreases its strength and, together with its high smectite content, contributes greatly to its erodibility.

Snow School Formation

The Snow School Formation (Ulmer and Sackreiter, 1973) consists of three members. The lowest member is exposed at stations 4, 5 and 7, and is also exposed at other scattered locales throughout the study area (Ulmer and Sackreiter, 1973). It is composed of a lower iron-stained conglomerate overlain by flat-bedded and occasionally cross-bedded dirty sand. Lignite fragments occur along some of the bedding planes which generally dip east-northeast (Ulmer and Sackreiter, 1973). The color of the sand varies from light brownish-gray (2.5 Y 6/2) to pale brown (10 YR 6/3) (Table 26, Appendix A) and may be iron-stained. Textural analyses of five samples yielded average sand-silt-clay percentages of 69.1 percent, 19.1 percent and 11.8 percent, respectively (Table 27, Appendix A). The sand has a median diameter of 2.7 phi, is poorly sorted, positively skewed, and leptokurtic. Where exposed, the unit averages about 1m (3.3 ft) thick and the contacts with overlying and underlying units are sharp and undulating. The sand is very susceptible to wave erosion, whereas the conglomerate forms natural rip-rap.

The middle member of the Snow School Formation is not exposed at any erosion station but is present at a few sites within the study area (Ulmer and Sackreiter, 1973). This unit averages about 1m (3.3 ft) thick and contains beds of sand, silt, and clay, but the most abundant sediment is a reddish-brown, sandy pebble-loam (till) (Ulmer and Sackreiter, 1973). Where exposed, this distinctive unit is a good marker bed.

The upper member of the Snow School Formation is a very compact, columnar jointed pebble loam (till), and is exposed throughout the study area. This unit and the Sentinel Butte Formation are the two most commonly exposed units along the eastern end of Lake Sakakawea. It may be exposed at the water line or high above lake level. It is typically overlain by the Oahe Formation (loess), and is usually underlain either by the lowest member of the Snow School Formation, the upper member of the Medicine Hill Formation, or the Sentinel Butte Formation. The contacts are sharp and undulating. The thickness varies from 0.2 to 6.0m

(0.7 to 19.8 ft) (Ulmer and Sackreiter, 1973). Also, the till may have pockets of sand and gravel near the contact with the Oahe Formation.

The color of this member varies from light brownish-gray (2.5 Y 6/2) to pale olive (5 Y 6/3) (Table 26, Appendix A). Calcium carbonate precipitate is common along joint planes. The average sand-silt-clay percentages for 10 samples are 26.4 percent, 41.3 percent, and 32.3 percent, respectively (Table 12). These results compare well with those calculated by Ulmer and Sackreiter (1973), which were 28 percent, 38 percent, and 33 percent. The member is extremely poorly sorted, negatively or positively skewed, and platykurtic with an average median diameter of 6.2 phi. The average density is 2.94 gm/cc and the moisture content averages 10.2 percent (Table 13). The average clay mineral ratios, average matrix dolomite and calcite percentages, and average coarse sand lithologies are given in tables 14, 15 and 16. See Appendix A for individual sample laboratory data.

This unit is very erodible because of its prominent jointing and high smectite content.

Oahe Formation

This is the uppermost stratigraphic unit throughout the study area. It is interpreted to be wind-blown sediment (loess). The formation has been differentiated into four members (Bickley, 1972), but distinguishing them was not relevant to this study.

Textural analyses yielded average sand-silt-clay percentages of 7.8 percent, 71.8 percent and 20.4 percent (Table 27, Appendix A). The average median diameter was 6.0 phi. The sediments are poorly sorted, positively skewed, and leptokurtic. The color of the loess ranges from light gray (5Y 7/2) to dark grayish-brown (10 YR 4/2) (Table 26, Appendix

A). The thickness of the unit varies from about 0.2 to 0.5m (0.7 to 1.6 ft) and averages 0.3m (1.0 ft).

The Oahe Formation is highly subject to swelling and shrinking upon alternate wetting and drying because of its high smectite content (Groenewold, 1972). It also tends to draw water up to the freezing zone, causing frost heaving (Groenewold, 1972). Nevertheless, the loess is heavily root-bound which contributes to making the formation probably the most stable unit in the area. The underlying tills often break away at the contact leaving the Oahe Formation as an overhang. Thus, the bank failures characteristic of this unit are debris or earth falls.

Criteria for Differentiating the Pleistocene Formations

The lower members of the Pleistocene Medicine Hill, Horseshoe Valley and Snow School Formations are very similar and difficult to distinguish unless the upper members are also present. Because these are present in the study area, the lower members were identifiable.

Only the Snow School Formation contains a middle member. Its massive structure, characteristic red color and high silt content combine to make it a very distinctive unit, a good marker bed (Ulmer and Sackreiter, 1973). This unit was not present at any of the stations, however.

The upper members of the three Pleistocene formations can be identified using several criteria. These include both observable and laboratory-derived criteria.

1. Stratigraphy: Exposure of two or more of the formations at one site presents the opportunity to work one's way stratigraphically downward or upward using other visible criteria,

such as jointing, color, etc. Good examples of this occur at stations 7, 51, 52, and 59 (Figure 2).

2. Jointing: Both the Upper Horseshoe Valley and Upper Snow School Formations display columnar jointing; the Upper Medicine Hill Formation does not. Good examples of this are at stations 7, 51, 52, and 59 (Figure 2). This is a major criterion for differentiating the Upper Medicine Hill Formation. Also, calcium carbonate precipitation is especially abundant along joint planes of the Upper Snow School Formation.

3. Color: Without support, this usually is an unreliable differentiation criterion. Generally, the Upper Medicine Hill Formation is the yellowest (or lightest) of the three units. Good examples of this are at stations 7 and 52. The Upper Snow School Formation, on the other hand, commonly has a dark layer near the contact with the Oahe Formation (paleosol?). Finally, the Upper Horseshoe Valley Formation often displays iron-stain mottling (stations 51 and 52).

4. Texture: Table 12 indicates that each upper member has a characteristic texture. The higher percentage of sand and lower percentage of silt is a major differentiation criterion for the Upper Horseshoe Valley Formation. The Folk statistics are not different enough to be a reliable criterion, though. Also, the Upper Medicine Hill Formation appears to have the highest percentage of cobbles and boulders, contains the largest lignite clasts, and contains sand lenses.

5. Density and Moisture Content: Table 13 lists the average density and moisture contents of the three upper members. It

can be seen that the Upper Horseshoe Valley Formation has a lower density and moisture content than the other two upper members. This is another major criterion for differentiating the Upper Horseshoe Valley Formation from the other two upper units, especially the Upper Snow School Formation.

6. Clay Mineralogy: Average clay mineral ratios for the upper members are presented in table 14. The Upper Medicine Hill Formation can be differentiated by its relatively low smectite ratio. The Upper Horseshoe Valley Formation usually has a higher kaolinite ratio than the Upper Snow School Formation but, again, this should not be used as a distinguishing criterion unless supported by other data.
7. Matrix Dolomite and Calcite: Table 15 lists the average matrix dolomite and calcite percentages for the three upper members. In each case, the percentage of dolomite is about twice that of the calcite. Starting with the Upper Snow School Formation and moving down-section, the carbonate percentage decreases. Thus, the Upper Snow School till generally has the highest amount of matrix carbonate. However, this may be an unreliable criterion because it is unknown what percentage of calcite is primary.
8. Coarse Sand Lithology: Table 16 provides coarse sand lithology percentages for the three members. The Upper Medicine Hill Formation is easily differentiated because of its relatively high shale and "other" (lignite) content, and relatively low carbonate, crystalline/quartz and feldspar content. The results for the other two members were too similar to be utilized confidently without further supportive data.

The Upper Medicine Hill Formation, therefore, is chiefly characterized by the absence of columnar jointing, a relatively light color, a low sand but high cobble content, relatively large lignite clasts, a relatively high shale coarse sand fraction, a high kaolinite ratio, and a low matrix carbonate content. The Upper Horseshoe Valley Formation is characterized by columnar jointing, iron-stain mottling, a low density and moisture content, and nearly equal sand-silt-clay percentages. Finally, the Upper Snow School Formation is distinguished by columnar jointing, a low sand content, a high smectite but low kaolinite ratio, and a high matrix carbonate content.

Weathering

A second factor affecting bank erosion is weathering. The strength of reservoir bank materials is reduced by physical and chemical weathering processes (Kachugin, 1980). The ultimate influence of weathering on shear strength is to reduce the cohesion to a small value and, to a lesser extent, reduce the angle of internal friction (Spears and Taylor, 1972). Weathering most affects those argillaceous rocks and sediments which have bonded structures (Kenny, 1975).

Major weathering processes which cause a reduction in shear strength in glacial tills include fissuring, frost action, carbonate removal by leaching, and hydrolysis which produces new swelling clays (Quigley, 1975). With subsequent weathering, these expandable clays are especially susceptible to progressive failure (Bjerrum, 1967).

Finally, although weathering does reduce bank strength, it should be remembered that other factors (e.g., changes in pore water pressure) produce much larger and faster reductions in strength. Thus, overall, weathering is a relatively minor process affecting bank erosion.

Waves

General

A third factor of bank erosion is wind- and sometimes boat-generated wave action (Carter and Guy, 1983; Quigley and Gelinas, 1976; Young, 1972). In fact, many recent studies have concluded that wind-induced wave erosion is the dominant process along reservoirs (Reid, 1984; Gatto and Doe, 1983; Kachugin, 1980), lakes (Sterrett, 1980; Hadley, 1976; Mickelson and others, 1976), and rivers (Gatto, 1982; Simons and others, 1979).

The effect of wave action on the bank takes place in both active and passive ways. Active wave erosion is accomplished by three major processes (Ritter, 1979, p.534): attrition, corrasion and hydraulic action. Attrition decreases the size of particles, which allows subsequent waves to carry them to the bank face, thus causing erosion by particle impact (corrasion). Hydraulic action is erosion caused by the water itself and includes wave shock pressure and pneumatic quarrying by air trapped in joints. A final way waves can activate bank failure is through vibrations.

Wave erosion is also a passive factor in many bank failures. The removal of material from the bank toe, and subsequent undercutting, is the underlying cause of most bank failures along Lake Sakakawea and other reservoirs (Reid, 1984; Doe, 1980) and lakes (Carter and Guy, 1983; Hadley, 1976). This reduces both underlying and lateral support (Varnes, 1978) and indirectly causes falls, topples and slides. Most of these failures are progressive and many initiate as tension joints along the bank top (Thorne and Tovey, 1981; Quigley and Gelinas, 1976). Furthermore, bank strength is reduced by saturation (Carter and Guy, 1983), and chemical action of the water (Kachugin, 1980).

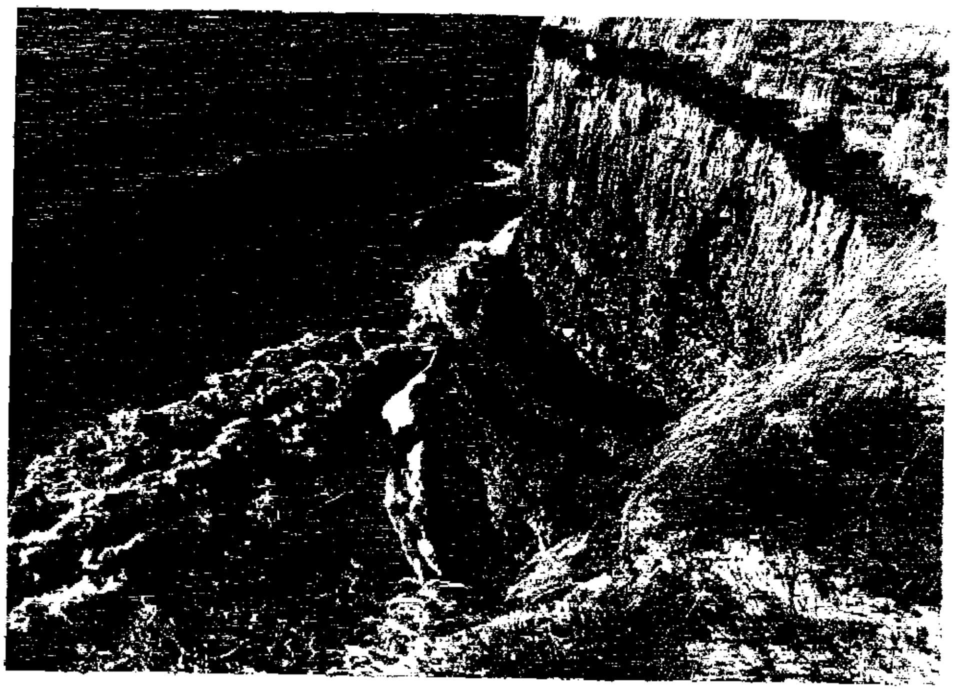
Many factors affect the magnitude of wave-induced erosion at a given site. Water level is the most important factor at Orwell Lake (Reid, 1984) and most other reservoirs (Doe, 1980) and lakes (Quigley and Gelinas, 1976; Mickelson and others, 1976). When lake levels are high enough that waves can directly attack the banks, many factors control erosion rates. These include wave climate (wind velocity and duration, fetch, and water depth) (Reid, 1984; Hadley, 1976), bank orientation (Carter and Guy, 1983), bank geology (Quigley and Gelinas, 1976), beach and offshore sediments (Sunamura, 1982), offshore bathymetry (Edil and Vallejo, 1980), and vegetation cover (Hoffman, 1978).

Although most studies support the importance of wave erosion along reservoir and lake shores, there are relatively few quantitative studies. Many workers advocate the use of repetitive profiling or similar surveying techniques (Reid, 1984; Buckler and Winters, 1983; Cordero, 1982; Goldsmith and Oertal, 1978; Young, 1972; U.S. Army Corps of Engineers, 1966, 1939). However, erosion pins (Hooke, 1979), the micro-erosion meter (Trudgill, High and Hanna, 1981; Robinson, 1977), and the contour gauge (Haigh, 1981) could be useful when daily measurement is possible, or especially before and after storms. In this study, a combination of methods was employed to measure wave erosion and the factors affecting wave erosion.

Lake Sakakawea and Lake Audubon

Wave erosion is the dominant erosional process at Lake Sakakawea as well as at Lake Orwell, Minnesota (Reid, 1984). Figure 9 shows wind-

Figure 9. Waves eroding a bank of Paleocene mudstone and lignite overlain by till and a thin veneer of loess. *Station 54, December 3, 1984.*



induced waves impacting the base of a bank along the west side of Fort Stevenson State Park. Relatively speaking, this process is minor at Lake Audubon both because the banks are low and because the pool level fluctuations are small. Figures 10-13 depict a typical bank at Lake Sakakawea affected by wave erosion. Even though the photos were taken at different stations, they are typical of the sequence that occurs. Wave action removes accumulated colluvium and erodes the primary bank materials, leaving a vertical or undercut bank. Consequently, slides, falls and topples occur as the bank again stabilizes.

As at Lake Orwell (Reid, 1984), the most important variables which affect the quantity of wave erosion are wind direction, duration and strength, concurrent with high pool levels. Other important variables are the offshore bathymetry, and bank orientation, geology and geometry.

Bank Recession and Joint Propagation

The amount of bank recession due to wave erosion is likely to be reflected in the amount of bank recession over the warm weather (high pool) months. Of course, there are other factors which cause minor bank recession over those months (e.g., groundwater, vibrations) but such erosion is most likely offset by delayed, wave-induced failures which occur after the warm months.

Bank recession due to wave erosion ranged from 0.48 to 4.93m (1.57 to 16.17 ft) and averaged 2.06m (6.77 ft) for the 20 stations at Lake Sakakawea between May 1983 and September 1984 (Table 9). The high variation in bank recession is due to many interrelated factors. For example, stations 55 and 61 both receded about 5m (16 ft) because of wave erosion. Their banks are composed of Sentinel Butte siltstone and mudstone at the wave impact zone, overlain by Snow School till and Cahe

Figure 10. Relatively stable slope, characterized by vegetated colluvium. Station 59, July 14, 1983.

Figure 11. During high pool levels, colluvium is removed by waves and subsequent undercutting of the primary sediment and/or bedrock occurs. Station 1, August 22, 1983.

Figure 12. Extension joints may be propagated due to wave undercutting and, subsequently, bank failure will result. Station 2, June 19, 1984.

Figure 13. After the pool level recedes, the undercut, wave-worn banks will once again reach a relatively stable profile. Station 3, October 20, 1984.

loess. But so are stations 2, 50, 53, 54, 56, 57, 60 and 62, whose recession ranged from 0.48 to 2.59m (1.57 to 8.49 ft). Also, stations 55 and 61 have different bank heights. The reason they have similar bank recession amounts is probably their respective orientations. Although their orientations are different, both stations are headlands (Figure 2) which are oriented so that longshore currents and prevailing waves carry the eroded sediment into deeper parts of the lake. Thus, a stable beach and offshore profile is not being built and, therefore, because of the deeper water nearer shore, breaking wave energy at the bank is probably higher than at other stations.

Wave erosion accounts for about 87 percent of the total bank recession at Lake Sakakawea (Table 9). Because of their low bank height, the banks around Lake Sakakawea State Park (stations 1-5, Figure 2) show the highest percentage of total bank recession due to wave erosion (Table 9). In contrast, station 50, with one of the highest banks, has the lowest percentage. The small percentage at station 50 is explained by the presence of a large colluvium slope at the bank toe throughout 1983 and most of 1984, although the higher pool levels of 1984 removed most of it (Figure 80, Appendix C).

The majority of the joints along bank recession pin lines both initiated and failed over the warm weather months as an indirect result of wave erosion at the base (Figures 6 and 7). As the toes of banks are eroded and the banks are oversteepened, their center of gravity is raised and extension joints may be initiated. With time the stresses are released and a slide, fall or topple results.

Area Eroded

Most of the area eroded at the profile sites was also due to wave erosion. For the 11 sites analyzed between mid-October 1983 and mid-October 1984, over 83 percent of the erosion occurred from about June 1 to October 14, 1984 (Table 17). The areas ranged from 4.42 to 44.94m^2 (47.58 to 483.73 ft^2) and averaged 14.32m^2 (154.14 ft^2).

Station 3 had the least area eroded by waves. This is primarily due to the its low bank height even though the bank recession rate there was above average (Table 9). The relatively high erosion at station 51 is not surprising. The profile site, a west-facing point (Figure 2), was especially susceptible to large northwesterly and westerly waves in 1984. The higher than usual pool level allowed waves to attack directly the highly erodible Lower Horseshoe Valley sand (Figure 14, and Figures 81, 82, 83 and 84, Appendix C). Undercutting took place and subsequent upper bank recession occurred through slides and falls along joint planes. These failures continued even after the pool was lowered. Many of the failed blocks of Upper Horseshoe Valley and Upper Snow School till came to rest on the platform built by the more resistant Upper Medicine Hill till and Lower Horseshoe Valley conglomerate. Their removal will be facilitated next year as wave erosion again oversteepens the platform. This site is an excellent example of the significance of pool level and lithology to wave erosion.

Pool Level

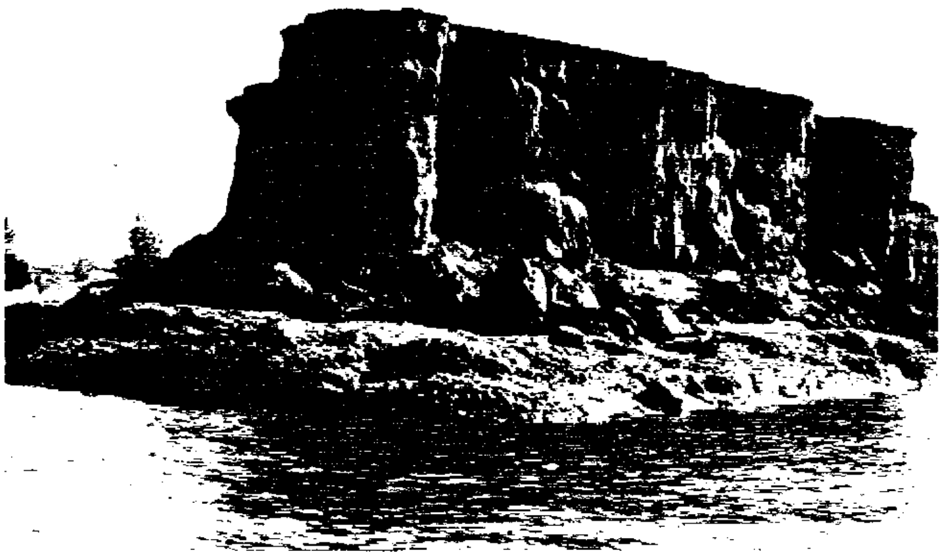
In order for waves to erode the banks, the pool level must be high enough for the waves to impact the bank. The high pool levels for lakes Sakakawea, Audubon, and Orwell typically occur in the late spring and summer. These, then, are the times of greatest wave erosion. The effect

TABLE 17

Area Eroded at Lake Sakakawea Bank Profile Sites During the Warm Weather Months

Station	Measurement Interval	Area Eroded (m^2) and % of Total Area Eroded for that Site
1	05/30/84 - 10/13/84	5.43 (79.4%)
2	05/30/84 - 10/13/84	10.51 (48.7%)
3	05/30/84 - 10/13/84	4.42 (81.8%)
4	05/30/84 - 10/13/84	7.42 (83.7%)
5	05/30/84 - 10/13/84	6.65 (98.4%)
7	----	----
50	----	----
51	05/31/84 - 10/13/84	44.94 (81.4%)
52	05/31/84 - 10/13/84	23.59 (99.9%)
53	----	----
55	----	----
56	----	----
57	----	----
58	----	----
59	06/01/84 - 10/14/84	6.18 (63.4%)
60	06/01/84 - 10/14/84	7.91 (85.4%)
61	06/01/84 - 10/14/84	11.57 (99.0%)
62	06/01/84 - 10/14/84	28.86 (96.1%)
Average		14.32 (83.4%)

Figure 14. When the very erodible sand units are undercut by waves, subsequent upper bank failures occur. At station 51 the Lower Horseshoe Valley sand (delineated by white lines) is overlain by the jointed Horseshoe Valley and Snow School tills and the Oahe loess, and is underlain by the massive Medicine Hill till.



of pool level fluctuations on bank recession values can be seen in figure 15 and on the bank recession graphs for Lake Sakakawea erosion stations (Appendix B). These show the characteristic sharp increases in bank recession during the high pool levels. The graphs for Lake Audubon (Appendix B) show an inverse relationship; ice-shove is the dominant factor in bank recession at Lake Audubon, at least for the east end of the lake in 1984.

The pool level of Lake Sakakawea typically fluctuates seasonally (Figure 16) because of three general streamflow conditions that exist. Normal winter water contribution is largely from baseflow because water courses are frozen. The pool is lowered over the winter to accomplish flood control and water-management obligations downstream, and to make room for the usual spring runoff. The pool level typically reaches its yearly low by mid-March to mid-May. In the spring, two rapid rises in pool level usually occur. The first is caused by snowmelt on the plains and the second by snowmelt in the mountains. The second is usually much greater (Figure 16). Either may be accelerated or modified by rainfall. Peak discharge is usually after the first spring rise, but maximum yearly pool level is commonly reached in July or early August (Pine and Johnson, 1958). From late summer onward, discharge subsides and the pool level drops.

The pool levels were unusually high during the spring and summer of 1984, partly because water was being held back to aid already flooded central Plains states downstream. As a result of the high water that year, bank erosion was intense. Pool level data for Lake Audubon were not collected because pool levels fluctuate little compared to Lake Sakakawea.

Figure 15. Relationship of Lake Sakakawea pool level fluctuations (msl.) and bank recession (station 1), 1983-1984.

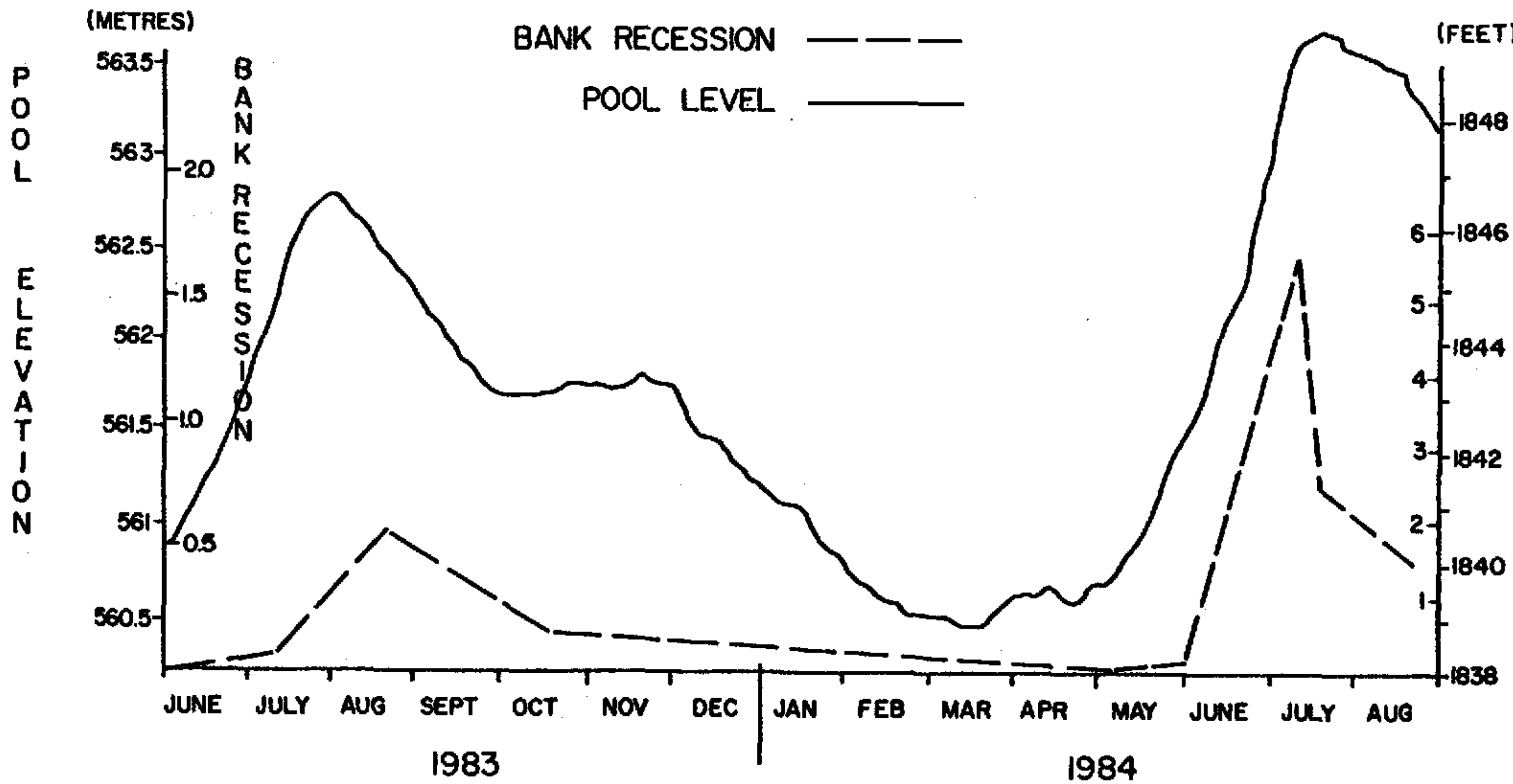
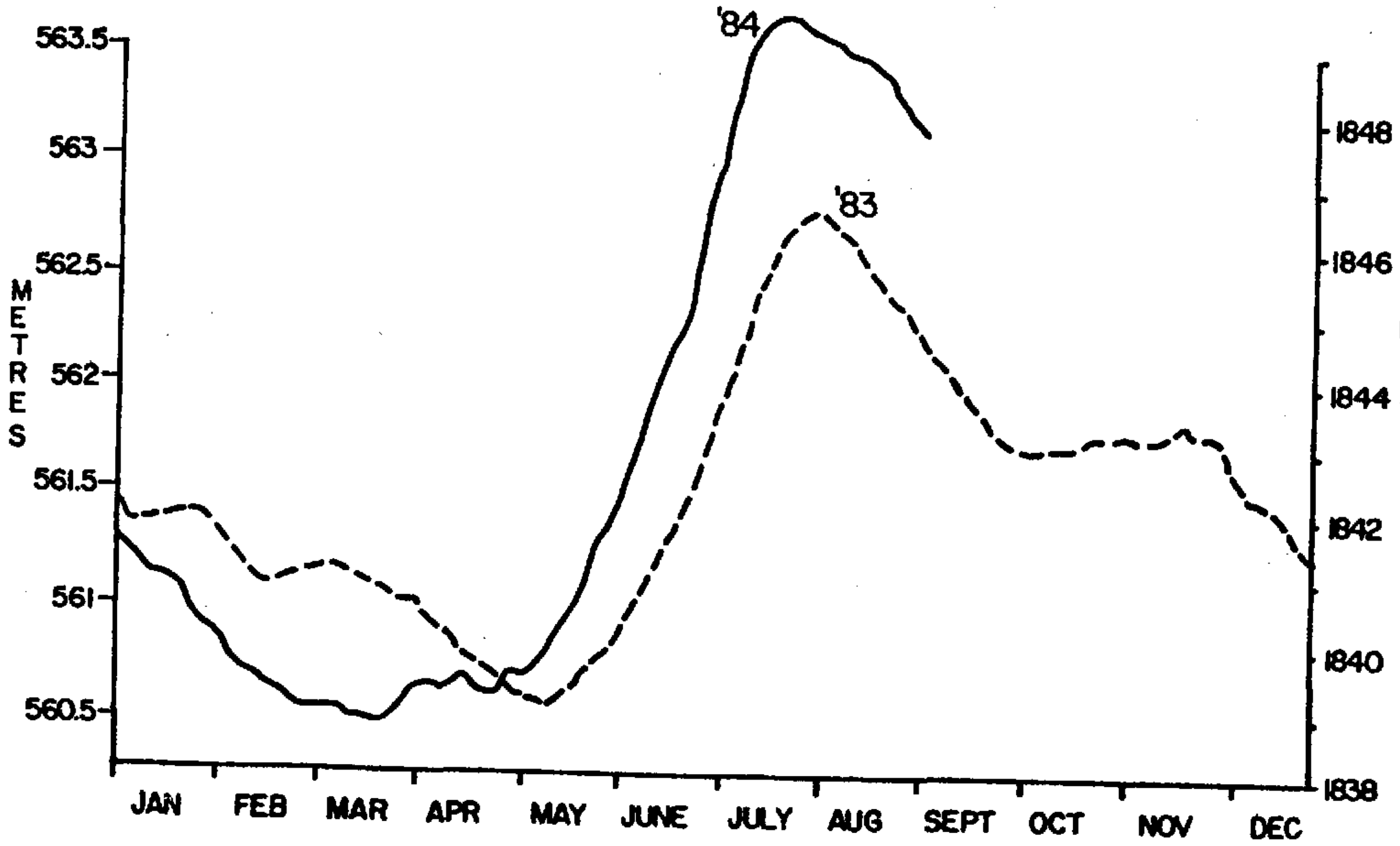

BANK RECESSION
POOL LEVEL
(METRES)
POOL ELEVATION
BANK RECESSION
(FEET)
563.5
563
562.5
562
561.5
561
560.5
2.0
1.5
1.0
0.5
6
5
4
3
2
1
1848
1846
1844
1842
1840
1838
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
1983
1984

Figure 16. Lake Sakakawea pool level fluctuations (msl.), 1983 and 1984 (partial).


'84
'83
563.5
563
562.5
562
561.5
561
560.5
METRES
1848
1846
1844
1842
1840
1838
FEET
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC

Wind

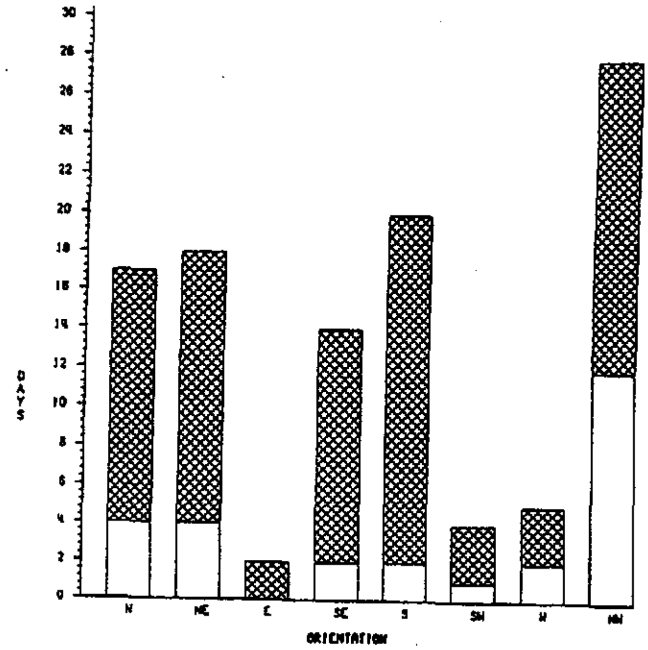
Directly related to pool levels in the assessment of wave erosion is wind direction, strength and duration. When strong winds accompany high pool levels, waves break at the base of the banks, initiating the process of undercutting (Carter and Guy, 1983).

A dominant control on the erosion rate is the amount of wave energy that strikes the bank (U.S. Army Corps of Engineers, 1966). Quigley and Gelinas (1976) reported an approximate linear relationship between the 150-year erosion rate and breaking wave energy at Lake Erie. Wave height is a measure of wave energy (Doe, 1980) and the highest waves are produced by the strongest winds along the longest, widest fetch. Figure 17 illustrates the frequency of daily high winds and those winds in excess of 40km/hr (25 mph) during the periods of high pool levels of Lake Sakakawea for 1983 and 1984 (through August).

For Lake Sakakawea and Lake Audubon, the greatest fetch is achieved by westerly winds (Table 32, Appendix D). The frequency of strong winds from that direction is low; winds in excess of 40km/hr blew from the west only two days in both 1983 and 1984 (Figure 17). By far, the most frequent direction of strong winds was from the northwest and north. Southerly and southeasterly winds are also common, and precede low pressure systems. Once a cold front passes, the winds quickly switch to the north and northwest, which accounts for the other major direction of strong winds.

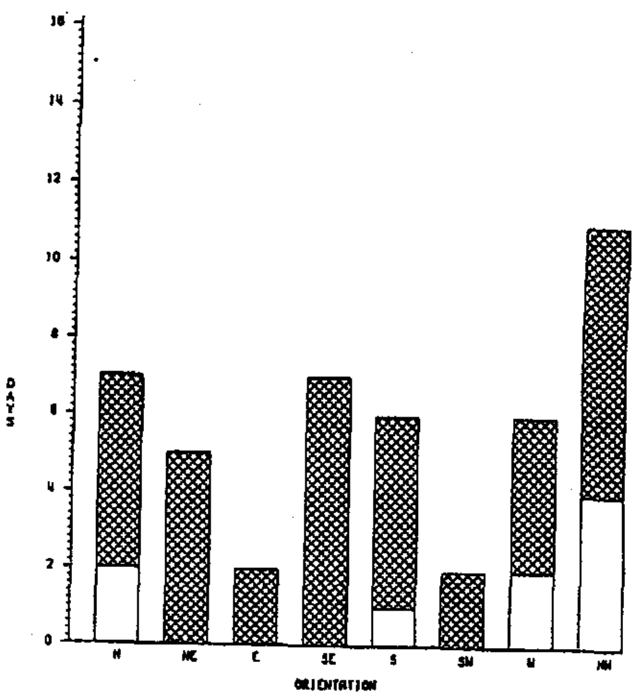
The duration of strong winds is also a factor in wave generation. At Lake Sakakawea and Lake Audubon, strong southerly winds rarely lasted more than 24 hours, whereas northwesterly and northerly winds often

Figure 17. Highest daily wind direction during high pool levels, 1983 and 1984 (partial).



JULY 1 THROUGH NOVEMBER 15 1983, EXCLUDING WEEKENDS

DIRECTION FREQUENCY OF HIGHEST DAILY WINDS
DAYS DURING WHICH WIND EXCEEDED 40 KPH (25 MPH)



JUNE 28 THROUGH AUGUST 30 1984, EXCLUDING WEEKENDS

DIRECTION FREQUENCY OF HIGHEST DAILY WINDS
DAYS DURING WHICH WIND EXCEEDED 40 KPH (25 MPH)

lasted for several days (U.S. Army Corps of Engineers, Riverdale, North Dakota, weather records).

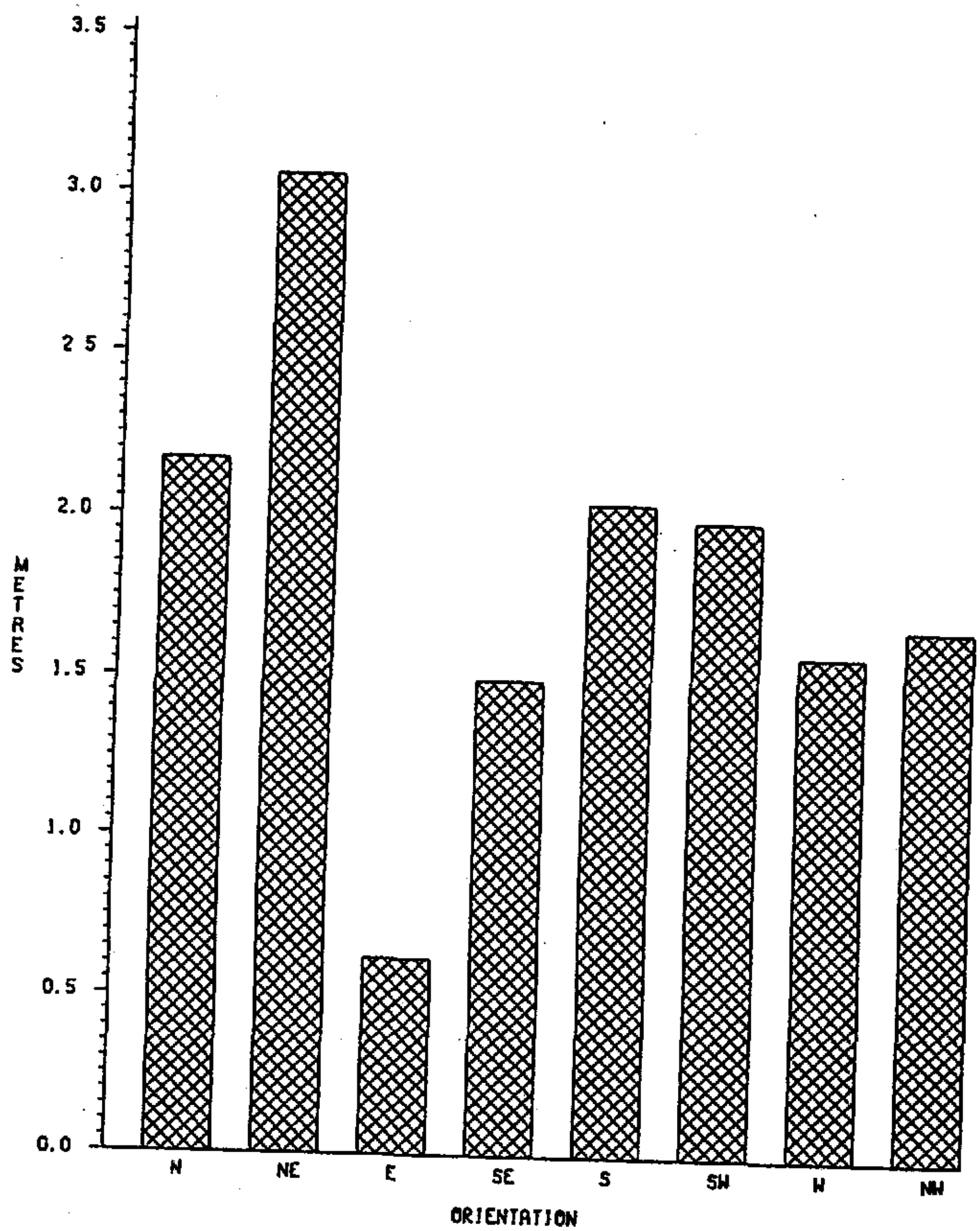
Bank Orientation

Bank orientation is important because banks exposed to wind-driven waves are the ones most susceptible to wave erosion. Buckler and Winters (1983) found that bluff retreat rates at Lake Michigan are highest for bluffs oriented facing the dominant high wind directions. This relationship is also true at Orwell Lake during high pool levels (Reid, 1984). Thus, for lakes Sakakawea and Audubon, it would be expected that banks facing northwest and north (Figure 17) would have high amounts of recession, whereas banks facing east and southwest should experience low recession.

Figure 18, and table 33 (Appendix E), show the relationship between cumulative average bank recession due to wave erosion according to bank orientation for Lake Sakakawea. Recession ranged from 3.06m (10.04 ft) for northeast-facing banks to 0.62m (2.03 ft) for east-facing banks. North-facing banks showed the second greatest recession but northwest-facing banks showed less recession than four other orientations, including southwest-facing banks. This indicates that wave refraction is important and that bank orientation, by itself, is not the primary factor affecting wave erosion.

Analysis of extensional joint data (Figures 6 and 7) was somewhat more revealing. Joint initiation and failure were most frequent in west- and south-facing banks (headlands on the north side of the lake) at Lake Sakakawea. This is primarily because banks facing those directions are subjected to waves generated from the west, the longest fetch direction. However, it should be noted, that west- and south-facing banks are also

Figure 18. Relationship of warm weather (high pool level) cumulative average bank recession to bank orientation.


3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
METRES
N
NE
E
SE
S
SW
W
NW
ORIENTATION

most prone to desiccation-induced jointing because of greater solar exposure.

Profile results also indicate west-facing banks to be highly susceptible to wave erosion. The three sites with the highest areas eroded (stations 51, 52 and 62; Table 17) face westerly (Table 5).

In conclusion, bank orientation is an important variable determining the efficacy of wave erosion at Lake Sakakawea.

Bank Geology

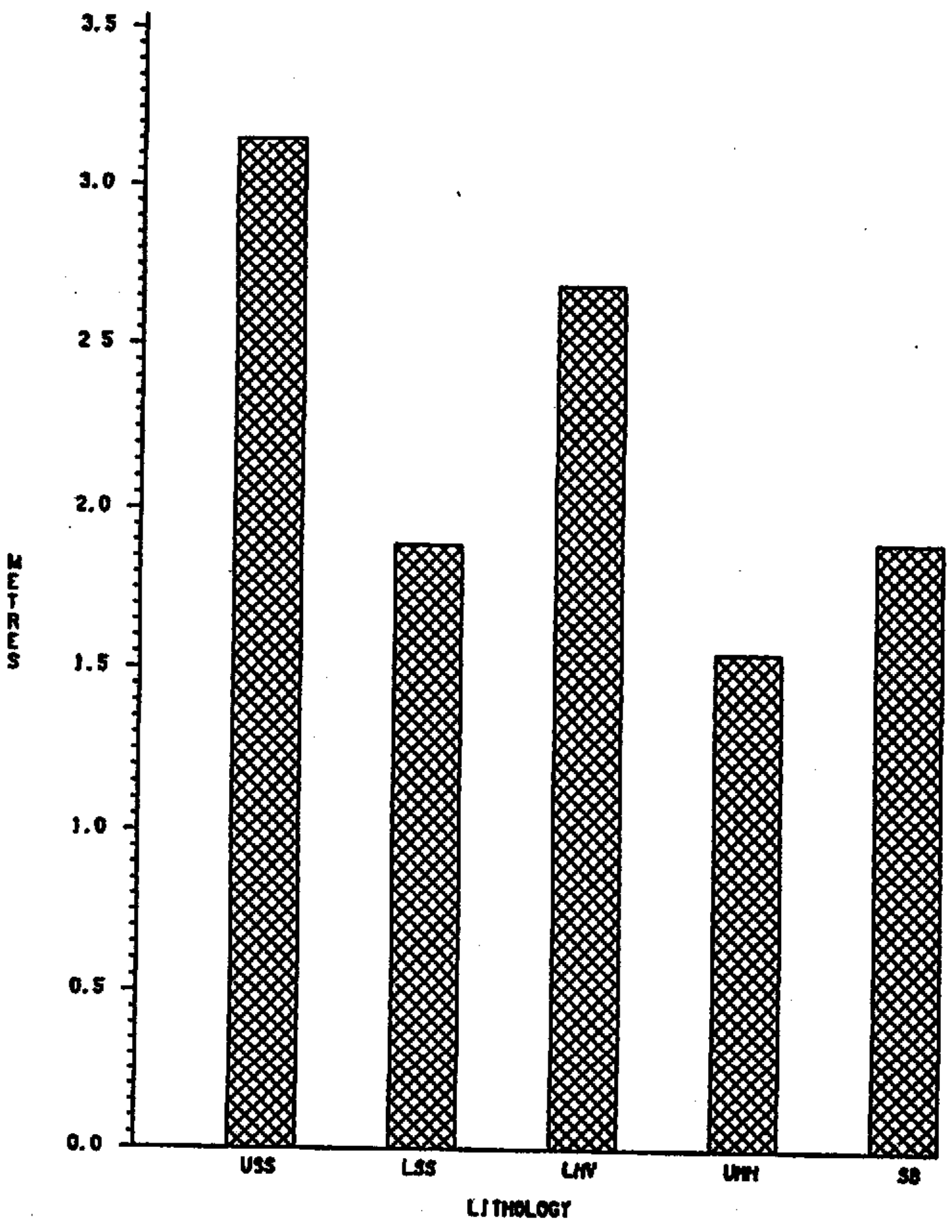
In any study of shoreline erosion the physical characteristics of the bank sediment must be analyzed to determine their importance and relationship to wave erosion (Reid, 1984; Buckler and Winters, 1983). As stated earlier, lithology at the wave impact zone during high pool level is of paramount importance in determining recession rates.

At Lake Sakakawea, one would expect the sand units to be more erodible than either the glacial tills, or the Paleocene siltstones or mudstones. Figure 19, and Table 34 (Appendix E), show cumulative average bank recession due to wave erosion compared to bank lithology at the wave impact zone. It can be seen that the Upper Snow School till is the most erodible, whereas the Upper Medicine Hill till is the least erodible. The Lower Horseshoe Valley sand is relatively erodible, but the Sentinel Butte siltstones and mudstones are as erodible as the Lower Snow School sand.

There are several reasons why these relationships differ from what is expected based on lithology alone. First, the low recession value for the Lower Snow School sand is due to the fact that the only station where it is exposed is located in a sheltered bay (station 5, Figure 2). Secondly, the Lower Horseshoe Valley sand crops out only at station 51,

Figure 19. Relationship of warm weather (high pool level) cumulative average bank recession to bank lithology at the wave impact zone.

USS = Upper Snow School Formation
LSS = Lower Snow School Formation
LHV = Lower Horseshoe Valley
UMH = Upper Medicine Hill
SB = Sentinel Butte Formation

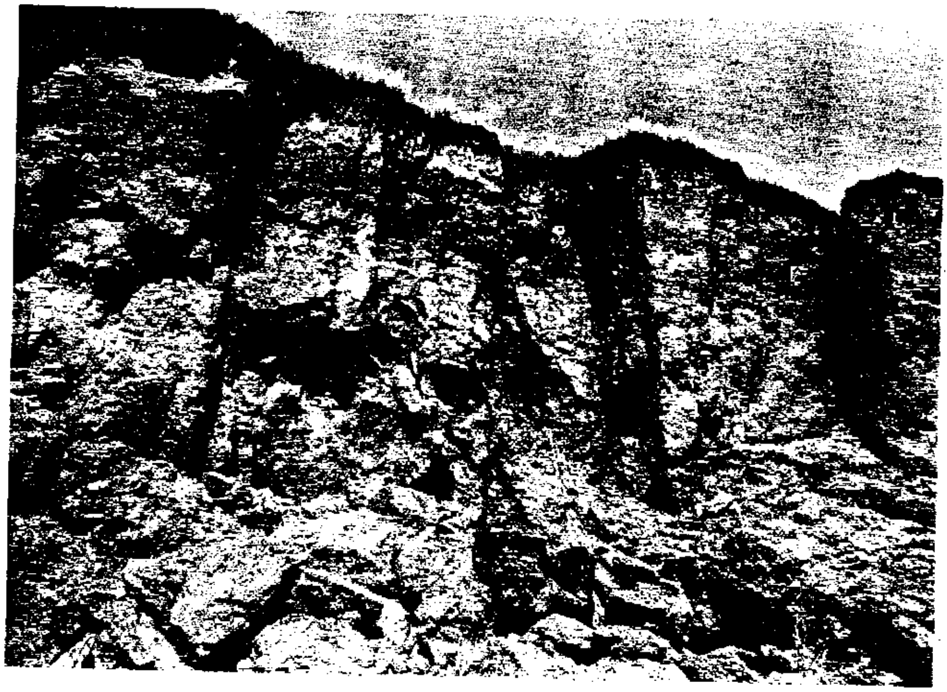

3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
METRES
USS
LSS
LMV
UMM
SB
LITHOLOGY

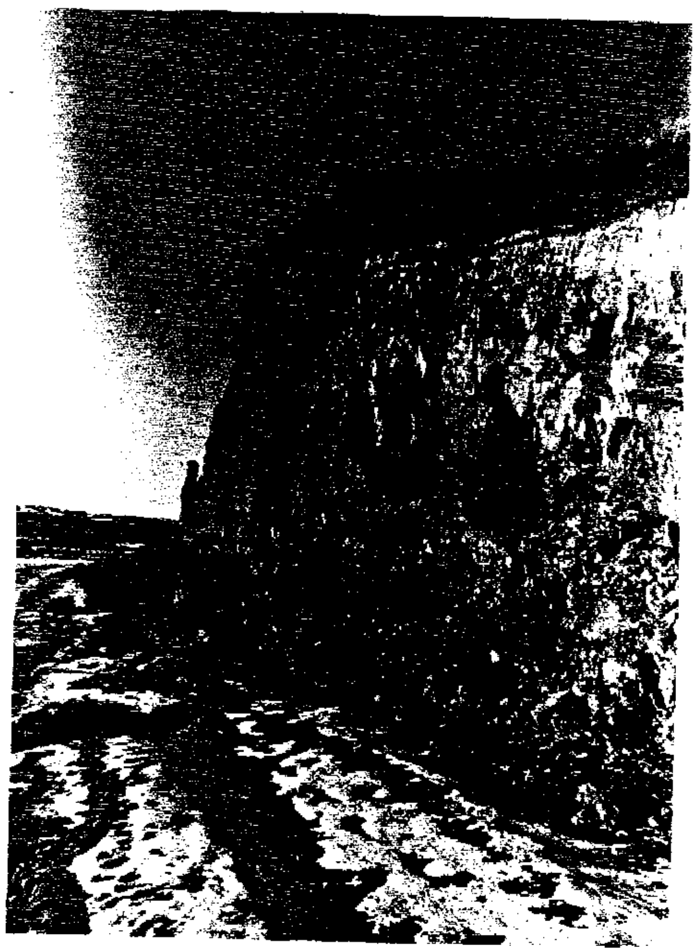
on the edge of west-facing headland (Figure 2). Because of its relatively high stratigraphic position (Figure 14), waves attack the sand only when pool level is near maximum, as in 1984. However, during that period, the banks at that station were eroded more than any others at Lake Sakakawea stations (Table 17). Thirdly, the degree of induration or consolidation of the bedrock or sediment is important. For example, the banks of stations 56 and 57 face west, are nearly the same height, and are composed of the same lithologies (Table 4). However, their cumulative average recession values vary greatly (Table 9). This is due mostly to the well-indurated, more massive lenses of siltstone which occur at, and slightly above, the wave impact zone at station 57. Finally, the erodibility of the glacial tills and Paleocene bedrock is controlled mainly by structure rather than texture.

Structure, i.e. jointing and faulting, is a very important variable affecting wave erosion at Lake Sakakawea. Figure 20 shows the distinctive columnar jointing in the Upper Horseshoe Valley and Upper Snow School Formations (tills). Most of these joints were probably formed because of crustal expansion due to deglaciation (Sterrett, 1980; Grisak and Cherry, 1975), although some joints are probably due to desiccation. Figure 21 illustrates the more complex horizontal and near-vertical joints in the Sentinel Butte Formation (mudstone); a blocky appearance results. Joints are not only important in weakening the bank materials but also they provide an avenue for exploitation by waves. Small caves or tunnels along vertical joints are common along the shoreline, especially during times of high pool levels. Another structure caused by wave erosion along joints, a narrow till ridge, was first observed in September 1984. Three of these extended outward from the bank at station

Figure 20. Vertical jointing characteristic of the Horseshoe Valley and Snow School tills. Note large blocks at base. Station 51, May 16, 1983.

Figure 21. Vertical and horizontal jointing typical of the mudstone and siltstone of the Sentinel Butte Formation. Note the fragments along the base of the bank. Station 53, December 3, 1983.





52 (Figure 2). It is hypothesized that these formed between caves which were expanding toward one another. The sediments above the caves then failed, leaving the till ridges projecting into the lake.

Faulting is another important bank structure. Although faults are rare at Lake Sakakawea, where they do exist, the Sentinel Butte Formation is highly fractured along the fault planes. Thus, not only are the bank materials weakened by faulting, but once again an avenue is provided for wave exploitation and subsequent undercutting. Most of the faults observed in the study area are normal faults and are restricted to the Sentinel Butte Formation. There are two graben structures along the west shore of Fort Stevenson State Park (station 54). Both have been preferentially eroded because of the resulting structural weakness.

Thus, it can be concluded that lithology, jointing, and faulting are important variables controlling the amount of bank erosion at Lake Sakakawea.

Clay mineralogy is another factor in bank failure because the amount and type of clay mineral determines the formation of water-stable aggregates (Bryan, 1974). The clay mineralogy of all the exposed formations in the study area is dominated by expandable smectite clays. Laboratory analyses did not reveal whether the smectites were predominantly calcic or sodic; they appear to be a mixture. The relationship of this to wave erosion at lakes Sakakawea and Audubon needs to be studied further. Nonetheless, when the smectites swell upon saturation by waves, the sediments should become more stable. However, when the pool level is lowered and the clays shrink, the sediments will become unstable again.

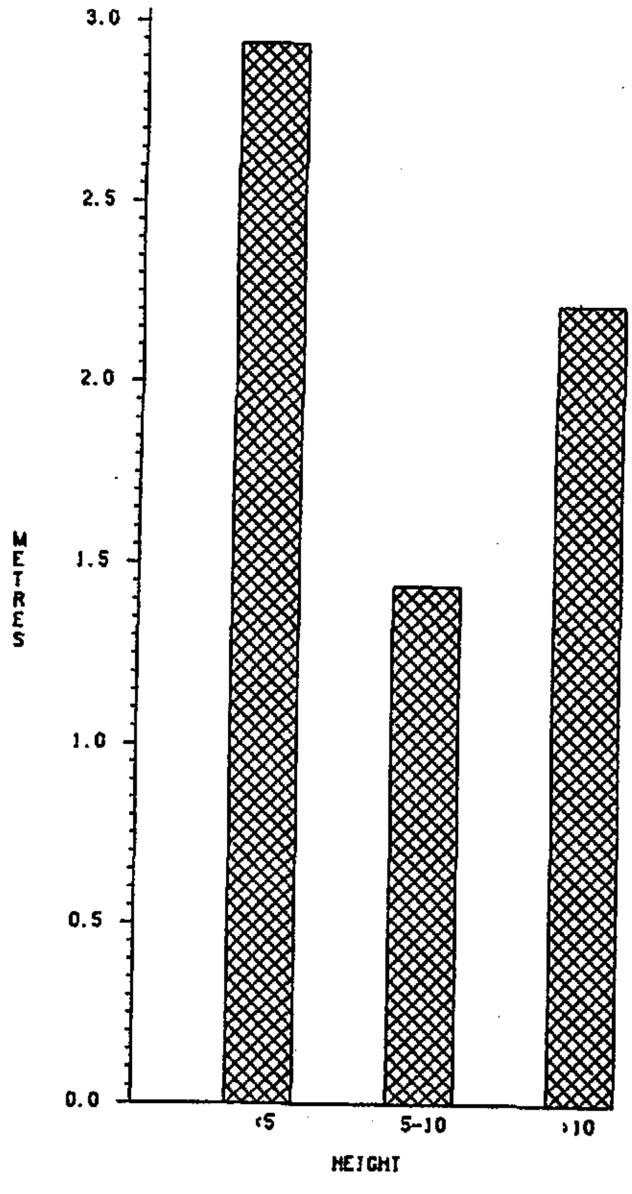
Bank Geometry

Bank slope angle and length, and bank height also affect recession rates. Steeper slopes are generally more unstable than more gentle slopes (Edil and Vallejo, 1980). At Lake Sakakawea and Lake Audubon the banks are typically vertical. This greatly increases the probability of both undercutting by wave action, and subsequent mass wasting. Stable slopes rarely occur except in sheltered areas or during years of relatively low pool levels.

High banks can reach an unstable condition faster than lower banks with similar slopes as their slope angle changes by an equal amount (Edil and Vallejo, 1980). Also, achievement of slope stability for high banks generally requires more time than for low banks (Buckler and Winters, 1983). However, long term bank recession rates at Lake Michigan appear not to be directly related to bank height; in fact, rates for high and low banks are similar (Buckler and Winters, 1983).

The banks in the study area are variable in height. Lake Audubon banks are generally less than 1m (3.3 ft) high, whereas Lake Sakakawea banks range from about 2 to 25m (6.5 to 82 ft) high. Figure 22, and table 36 (Appendix E), show the relationship between wave-induced cumulative average bank recession and bank height for Lake Sakakawea; banks less that 5m (16.4 ft) high were eroded the most, and banks 5 to 10m (16 to 33 ft) high were eroded the least. This is probably best explained by the comparison of volumes involved in these two extremes. Removal of a unit of sediment from a low bank will result in a rapid response at the top of that bank. Removal of the same unit from the base of a high bank will cause it to be replaced by sediment transferred from a larger area and the effect at the top of the bank generally will be smaller.

Figure 22. Relationship of warm weather (high pool level) cumulative average bank recession to bank height.


3.0
2.5
2.0
1.5
1.0
0.5
0.0
METRES
<5
5-10
>10
HEIGHT

However, following this reasoning, banks more than 10m high should experience the least amount of recession. But this is not the case.

It is concluded that although low banks will probably be more susceptible to higher bank recession, bank height is just one of many complexly interrelated factors controlling wave erosion.

Vegetative Cover

The amount and type of vegetation on a bank also affects wave erosion (Mickelson and others, 1977). Once a semi-stable slope is allowed to form and vegetation is able to take root (Figure 23), the vegetation can contribute to subsequent bank stability. Vegetation not only can protect the surface but also roots help hold the sediment together (Figure 24).

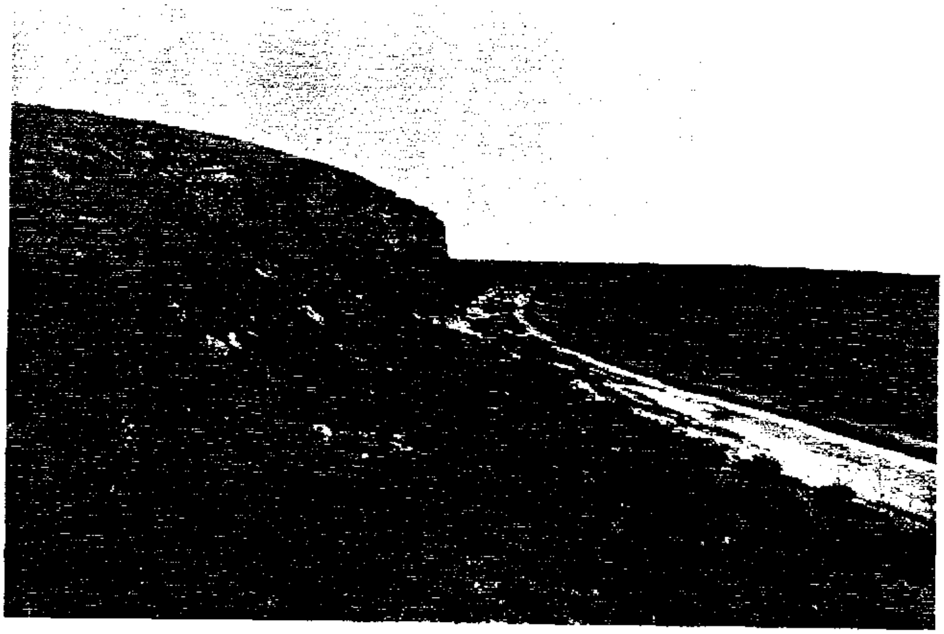
Natural Rip-Rap

Indirectly related to bank characteristics is the presence of objects at the bank base which tend to absorb the wave energy. An example is the presence of lag concentrations of boulders (eroded from till) at some sections of the shore. Such concentrations are typically restricted to short segments of the shore, such as at stations 51, 52 and 57 (Figure 2). In every case, though, the boulders are submerged during times of high pool level. Concretions, which also accumulate at bank bases, are especially common at station 50 and immediately south of there. These concretions are up to 1m in diameter. As the mudstones in which they are formed are eroded, the concretions come to rest at the base.

Natural rip-rap materials also include petrified logs. Logs are common near stations 2 and 61, and between stations 53 and 54. The logs

Figure 23. A stable slope (foreground), characterized by vegetation, and a slope in the process of becoming stable (background) as colluvium accumulates along the lower slope. Station 59, December 3, 1983.

Figure 24. Overhanging root-bound loess above more-erodible Snow School till. Station 1, July 14, 1983.



typically are compressed and resistant to erosion. Finally, there are the channel sands; these are linear ridges that formed as channel fillings in former deltas (Jacob, 1976). Because the sand was less porous than the silts into which the channels were cut, subsequent dewatering and compaction of the sediments left the channel fillings as ridges. Such channel fillings are especially common at station 50 and are also present between stations 3 and 4. In conclusion, these resistant features (boulders, concretions, petrified logs, and channel fillings) most effectively impede wave erosion before they become submerged by rising pool levels.

Offshore Profile

The form of the offshore profile is critical to the efficacy of wave erosion (Mickelson and others, 1977; U.S. Army Corps of Engineers, 1966). In fact, some workers have concluded that the integration of storm waves with the nearshore sand system is the most important variable associated with site to site variations in bank recession (Buckler and Winters, 1983; Davis, 1976; Davis and others, 1973). The measurement of offshore profiles at Lake Sakakawea was begun in June of 1984. Insufficient data were collected to merit quantitative interpretations of what is happening offshore, but some general observations can be made. Littoral currents and river currents appear to be important in carrying much of the eroded sediment (especially from headlands) to the deeper parts of the lake. Typically, the profile appears to be alternately eroded and built up at those sites, e.g., stations 53 and 61 (Figures 86 and 89, and Appendix C). At other sites (especially bays), a relatively stable profile appears to be maintained, e.g., stations 4 and 56 (Figures 79 and 88, and Appendix C).

Islands

Islands also serve to reduce wave erosion and there are many such islands in the two lakes, especially in Lake Audubon. In Lake Sakakawea, Mallard Island, positioned north of stations 51 and 52 (Figure 2), effectively reduces the fetch of northerly wind-driven waves at these stations. The several small islands north and northwest of station 3 (Figure 2) also reduce erosion of the main shore. Of course, these islands are being eroded themselves; once they are gone the full effect of wind-driven waves will be directed on the main shore. However, in the meantime, the the islands protect the main shore.

Overland Flow

General

A fourth factor of bank erosion is rainsplash and overland flow. Reid (1984, 1985) and Sterrett (1980) both concluded that erosion caused by rainfall was the least significant of the dominant erosion processes at Orwell Lake and Lake Michigan, respectively. Bank slope erosion by rainfall involves the detachment of soil particles by raindrop impact and/or runoff shear, and transportation by raindrop splash and/or runoff (Ritter, 1979, p.158-160; Carson and Kirkby, 1972, p.188-194). Erosion usually begins with the detachment of soil particles by raindrops (Carson and Kirkby, 1972, p.188) whose erosive potential depends on fall velocities, total mass at impact, drop size distribution, and thickness of any surface water film (Hudson, 1971). Next, when the rainfall intensity exceeds the infiltration capacity, runoff or overland flow occurs (Kirkby, 1978; Young, 1972, p.63) and interrill and rill erosion take place. Interrill, or sheetwash erosion, is the shearing of soil particles by the unconfined flow of water on a slope, primarily from raindrop impact and splash. Rill or gully erosion is the shearing of soil particles by concentrated runoff and is usually much more intensive than interrill erosion (Sterrett, 1980).

Rainfall may have other destructive effects on soil. It may destroy soil structure and break apart clay aggregates, making soil more susceptible to further erosion (Ritter, 1979, p.159). Furthermore, the dispersed clays may form a semi-impermeable crust which inhibits infiltration and promotes runoff (Bryan, 1976).

The magnitude of bank slope erosion by rainfall depends mainly on the erosive potential of rain (Ritter, 1979, p.159; Hudson, 1971), wind velocity and direction (Reid, 1984; Churchill, 1982), surface conditions (Reid, 1984; Bryan, 1976), slope length (Evans, 1980; Linsley, Kohler and Paulhus, 1975), and slope angle (Morgan, 1983; Bryan, 1974). Besides causing interrill and rill erosion, rainfall events may also cause various types of flows (Varnes, 1978; Quigley and Gelinas, 1976). Furthermore, other bank movements may be activated (e.g., slides, falls, topples, spreads) through vibrations set up by raindrops and associated thunderstorms.

Quantification of erosion by rainfall is commonly attempted. Although some workers have quantified rainsplash and runoff separately (Bryan, 1979), most workers measure the magnitude of erosion caused by the two processes together. Erosion pins are usually employed (Reid, 1984; Haigh and Wallace, 1982; Haigh, 1977; Tinker, 1970) but alternatives include the linear erosion/elevation gauge (Toy, 1983), the contour gauge (Haigh, 1981) and sediment traps (Reid, 1984; Young, 1972).

Many workers have also tried to estimate average annual slope erosion by using the Universal Soil Loss Equation (USLE) (Reid, 1984;

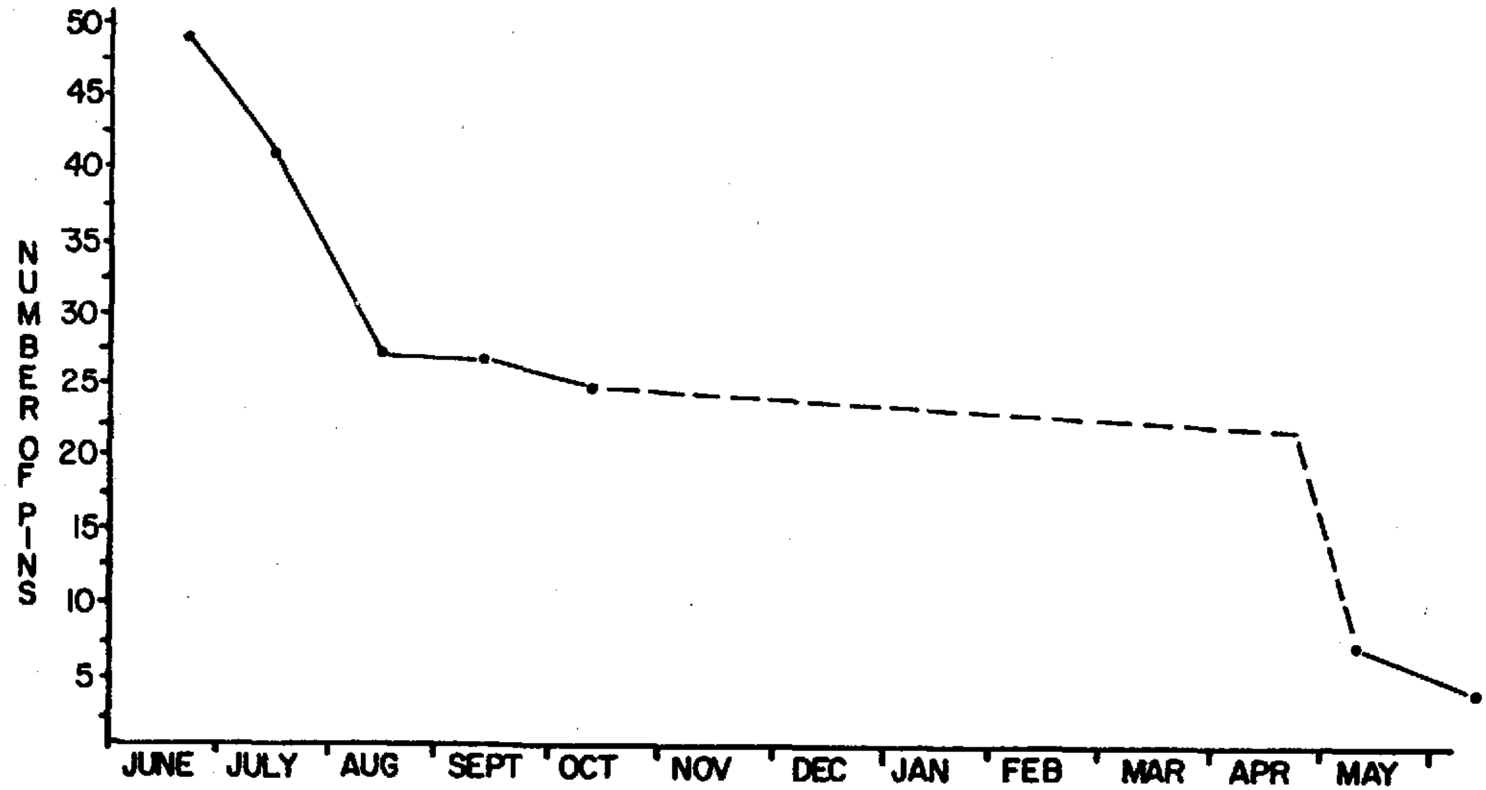
Sterrett, 1980; Wischmeier and Smith, 1978; Wischmeier, 1974). However, when the technique was used for the slopes at Orwell Lake, Reid found the results to be inconsistent with those derived from erosion pin measurements. He concluded that the bank slopes were too steep for reliable estimates even using the modified USLE. Because of the predominance of steep slopes at Lake Sakakawea and Lake Audubon this method of calculating overland erosion was not used.

Lake Sakakawea and Lake Audubon

In contrast to wave erosion, overland erosion by rainsplash and runoff is a minor process at both Lake Sakakawea and Lake Audubon. The steep banks, coupled with relatively dry summers, are the most important reasons for this.

The effectiveness of erosion pins inserted normal to bank surfaces was poor, whereas at Orwell Lake they provided most of the erosion data (Reid, 1984). The problem was that the massive failure of the Lake Sakakawea banks tended to either remove pins along with blocks of sediment or tended to bury them. In either case the data collection from these pins was minimal. Figure 25 illustrates the rate of loss of pins at Lake Sakakawea. In late spring 1983, 48 pins were being measured. Within two months there were only 27 left. Of these, 25 lasted through the winter. But by May 1984, there were only 7 pins. Of course, many of the pins were reset as soon as it was discovered they were missing. In the meantime, however, no data could be collected for those sites. On the basis of the collected data and other relevant observations, it was concluded that overland erosion is relatively unimportant and that bank erosion pins do not last long enough to define erosion rates anyway. Thus, no effort was made in 1984 to establish new bank erosion stations.

Figure 25. Rate of loss of bank erosion pins at Lake Sakakawea stations, 1983-1984.


NUMBER OF PINS
50
45
40
35
30
25
20
15
10
5
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY

It is just as well, because mass wasting of the banks was considerably greater that summer than the previous one.

Figures 26 and 27 are the plots of bank surface erosion at Lake Sakakawea. The depth of erosion at these stations ranged from only 8mm (station 58) to almost 48mm (station 50) (Figure 27) after the first summer of installation. The data show the typical lack of erosion over the winter, as was the case at Orwell Lake.

Besides causing interrill and rill erosion, runoff may also cause earthflows and debris flows. Although they are rare at Lake Sakakawea, they can create cirque-like depressions extending beyond the bank edge. The wetting of a desiccated clay-rich soil or sediment often activates such failures (Quigley and Gelinas, 1976).

Lake Audubon erosion was significantly lower, except for station A-1 (Figure 28). The greater erosion at that station was due to spalling of the bank face along joints, not to rain erosion.

Other variables, besides bank height and slope angle, which affect the quantity of overland erosion at the lakes are surface conditions, wind/bank orientation and rainfall erosivity.

Rainfall

The intensity and duration of rainfall are the most important factors affecting overland erosion (Ritter, 1979, p.158-161). Although no attempts were made to correlate rainfall statistically with bank slope erosion, the relationship is obvious. For example, most of the erosion at Station 50 (Figures 27 and 29) resulted from runoff accompanying a thunderstorm on June 19, 1983. Subsequent storms also effected erosion there.

Figure 26. Cumulative overland erosion, stations 1-7, Lake Sakakawea, 1983-1984.

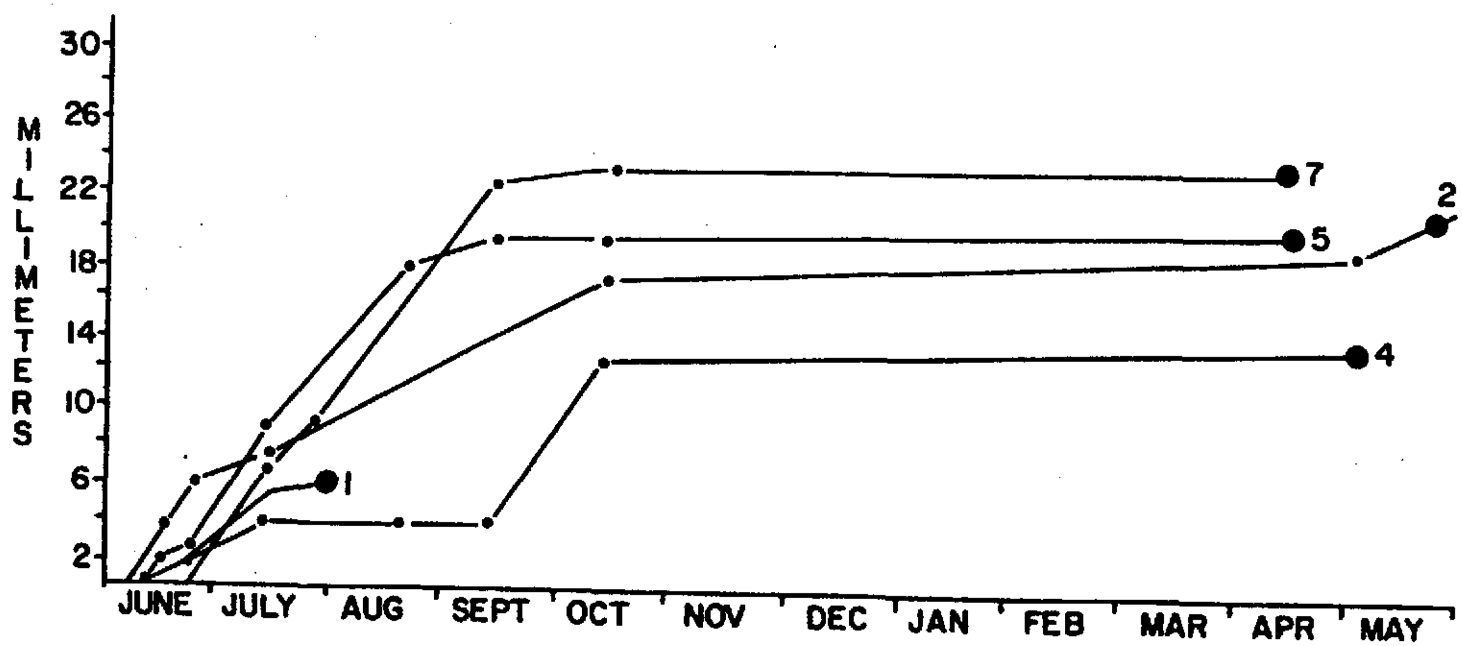

MILLIMETERS
30
26
22
18
14
10
6
2
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
1
2
4
5
7

Figure 27. Cumulative overland erosion, stations 50-59, Lake Sakakawea, 1983-1984.

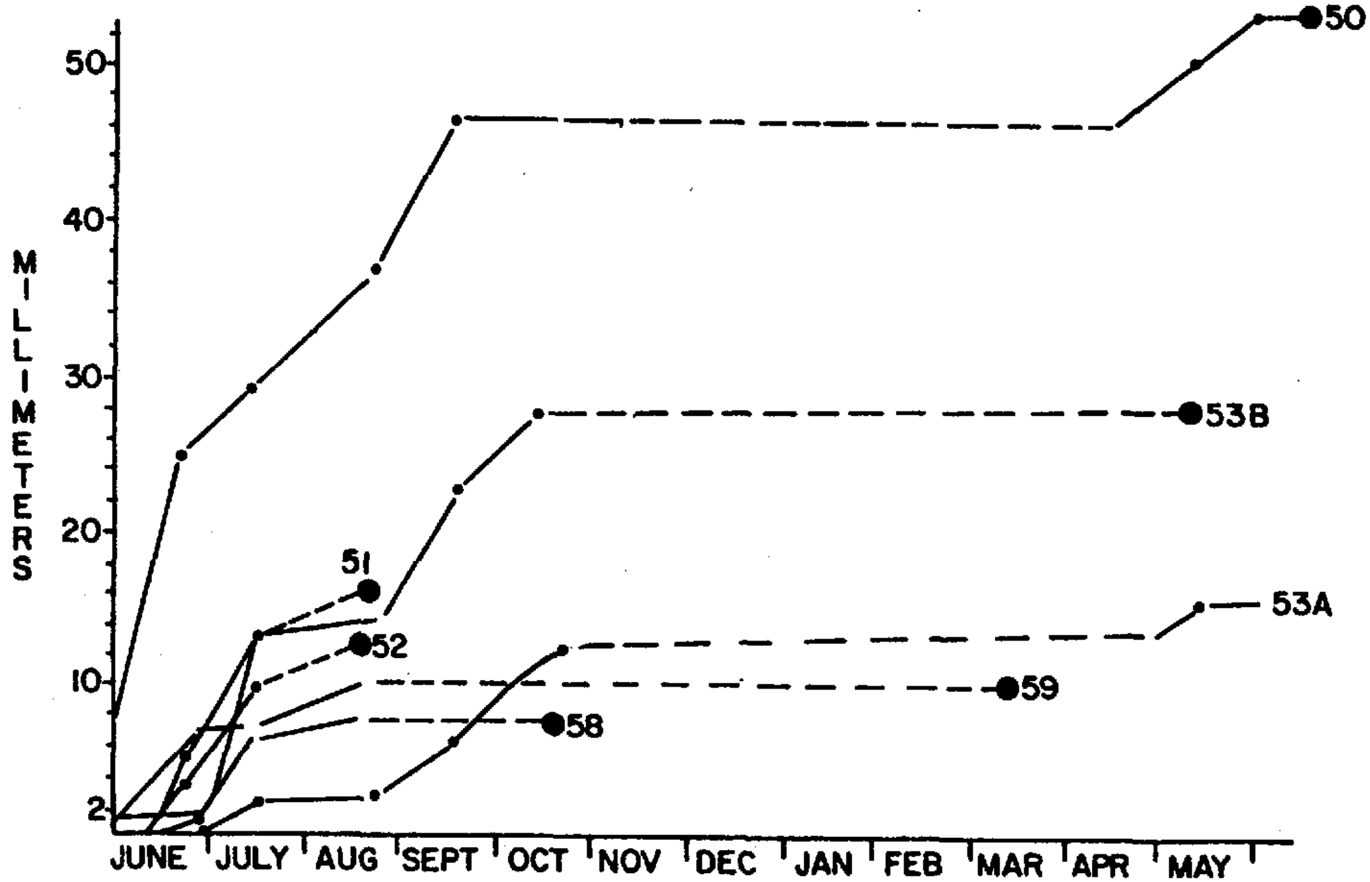

MILLIMETERS
50
40
30
20
10
2
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
50
53B
53A
51
52
59
58

Figure 28. Cumulative overland erosion, Lake Audubon, 1983-1984.

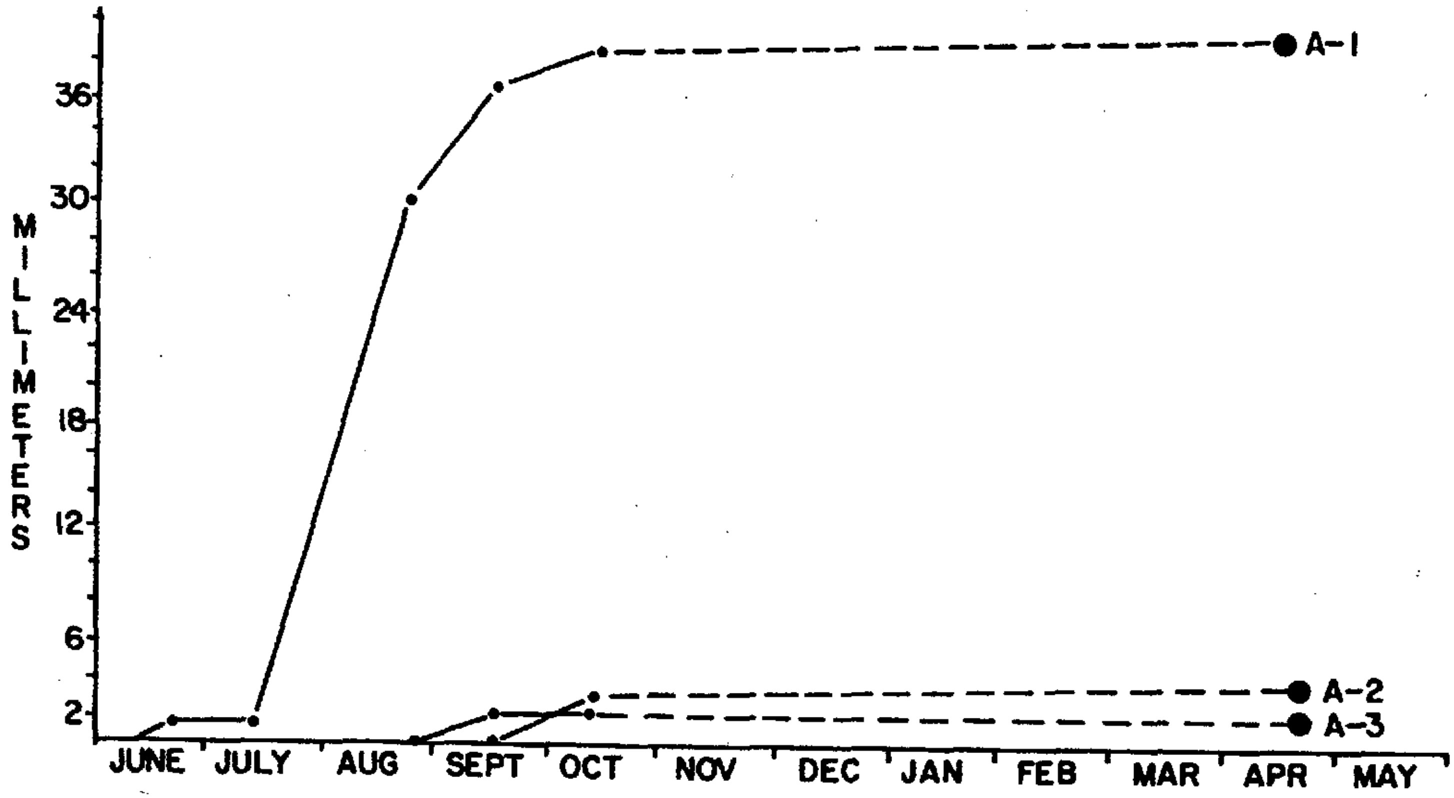

MILLIMETERS
36
30
24
18
12
6
2
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
A-1
A-2
A-3

Figure 29. Rills developed as a result of rainsplash and runoff in colluvium. Wide angle photo of station 50, August 22, 1983.

Wind/Bank Orientation

Wind velocity, direction and duration determine the speed and the direction of the rainfall. The most frequent directions of strong winds at Lake Sakakawea in 1983 were northwest and north (Figure 17). Not surprisingly then, the most bank slope erosion occurred on northwest- and north-facing slopes (Figure 30, and Table 37, Appendix F).

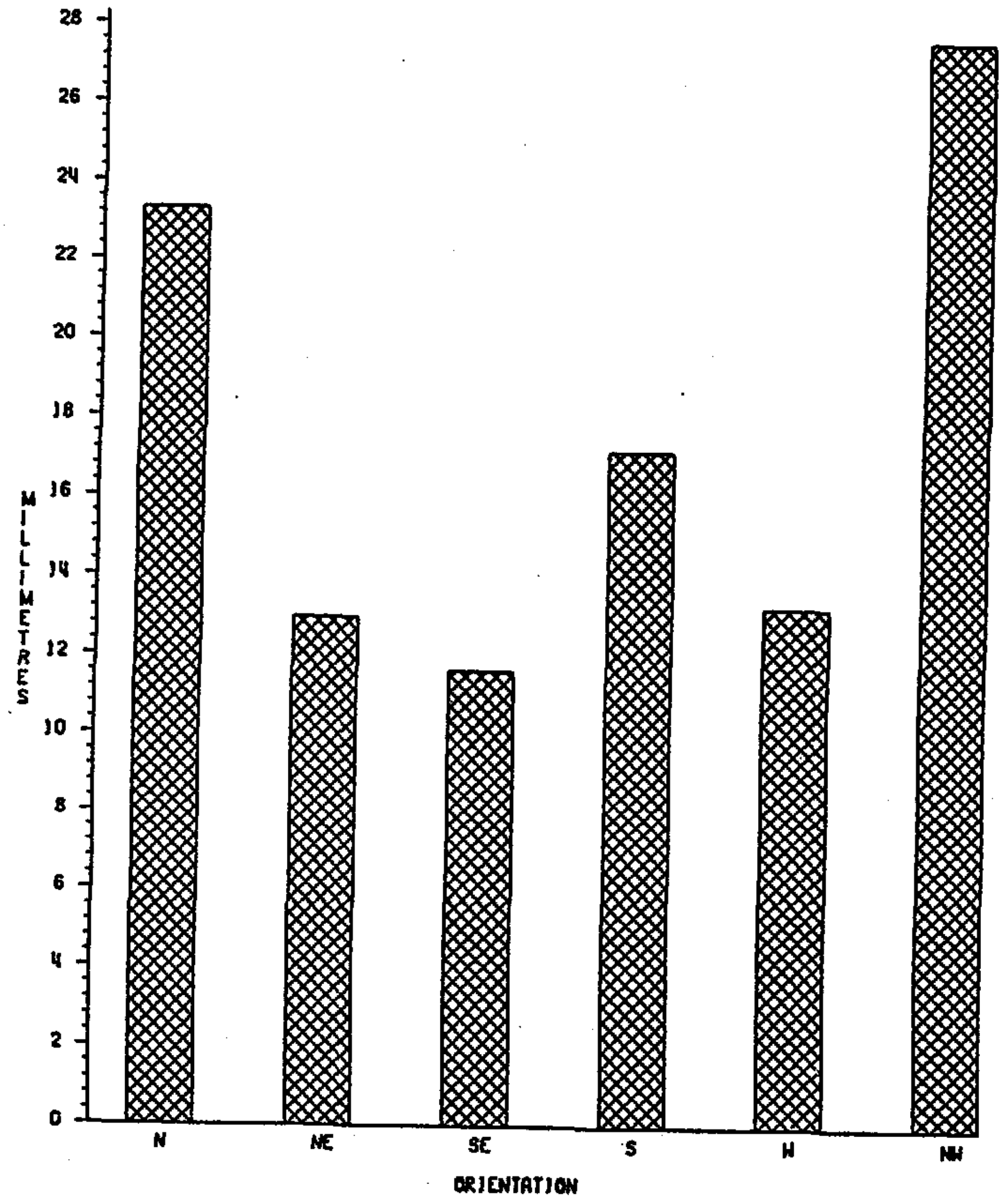
Surface Conditions

Another variable is the condition of the surface at the time of precipitation. For example, the pre-existing moisture content is a significant factor in the effectiveness of subsequent rain erosion (Reid, 1984). Thus far, the moisture content of the units has been determined only once, in June 1984 after two days of precipitation. The moisture content of the samples is listed in table 26 (Appendix A). The values ranged from 0.5 to 30.0 percent and appear to be related to lithology as well as depth. For example, the Upper Horseshoe Valley Formation contained much less moisture than either of the other two tills, no matter what depth.

North-facing banks generally have the highest moisture content because of minimum exposure to the sun (Churchill, 1982; Birkeland, 1974, p.184). It was noted earlier that banks facing north or northwest had the highest amounts of overland erosion. However, the soil moisture will have to be measured more times in order to ascertain its relationship to erosional processes at Lake Sakakawea.

Other important factors affecting surface conditions are surface crusting and water-stable aggregate (WSA) formation. Surface crust formation involves the disaggregation of sediment aggregates which are then either carried by runoff or forced by raindrop impact into available

Figure 30. Relationship of 1983 average overland erosion to bank orientation.


28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MILLIMETRES
N
NE
SE
S
W
NW
ORIENTATION

pore spaces (Luk, 1979). The presence of surface crusts on the banks at Orwell Lake affected the degree of rainsplash and runoff erosion (Reid, 1984). Although the relationship has not been studied, surface crusts observed on Lake Sakakawea banks certainly affect overland erosion there. Fine-grained sediment is typically eroded as aggregates rather than as individual particles, so water-stable aggregates >0.5mm in diameter are important because they maintain their size and shape upon wetting (Bryan, 1974, 1976). An increase in the percentage of WSA >0.5mm in diameter should result in an increase in stability and, thus, a reduction in rainsplash entrainment and bank slope erosion (Reid, 1984). The presence of smectite in the Lake Sakakawea bank sediments also contributes to WSA stability because it expands and closes the boundaries between aggregates (Bryan, 1974).

Finally, the amount and type of vegetation is also important. It helps to decrease slope erosion by: 1) increasing storage capacity by acting as a water pump; 2) protecting the surface from raindrop impact; 3) helping to bind the sediment together; 4) increasing the hydraulic roughness of the surface; 5) reducing the effective slope steepness by forcing the flow to meander; and 6) absorbing flow shear forces (Meyer, 1976). Unfortunately, the vegetative cover on most Lake Sakakawea banks is minimal due to periodic inundation and, especially, to wave-induced oversteepening and mass wasting. However, where vegetation is present, it certainly plays a role in decreasing the overland erosion at the site.

Bank Geometry

A fourth factor that affects the quantity of overland erosion at a site is slope length (Evans, 1980). It is important because runoff is accumulative as it proceeds downslope, which increases the effective water depth and, thus, basal shear. Therefore, the rate of soil loss should increase with an increase in slope length (Smith and Wischmeier, 1957), especially on the lower parts of slopes. For example, station 50 (Figures 27 and 29) had the longest colluvium slope of any of the stations, which is one of the reasons why that slope experienced the most erosion.

A factor that obviously affects slope length is bank height. Generally, the higher the bank is, the longer the bank slope will be. Slope erosion for 1983 was analyzed with respect to bank height. The results, shown in figure 31, and table 38 (Appendix F), show a definite trend; the higher the bank, the more bank slope erosion.

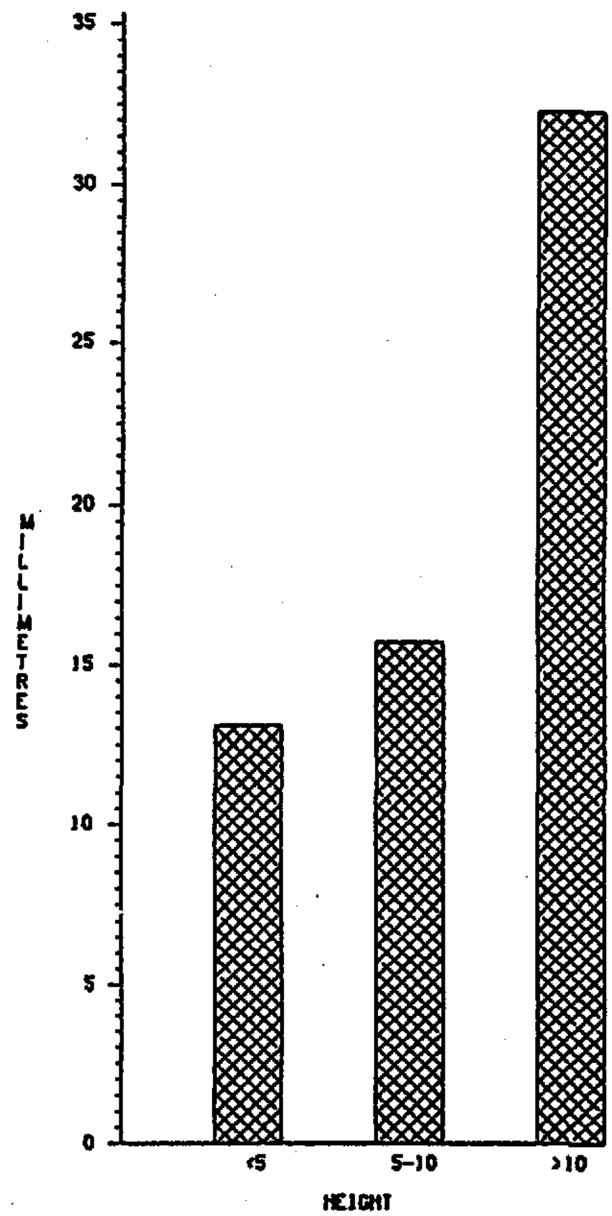
Slope erosion also tends to increase with increasing slope angle up to a point, and then decrease (Bryan, 1979). At Orwell Lake, erosion on gentle slopes (average 34 degrees) was almost twice that of steeper slopes (Reid, 1984). Although this relationship was not studied quantitatively at Lake Sakakawea, observations indicate it is important. Because of the nearly vertical banks produced by wave erosion, the effects of rain on the primary sediment and bedrock are minor. Most of the 2-52mm of bank slope erosion recorded at each lake occurred in the gentler-sloping colluvium at the toe of the banks.

Groundwater

General

Groundwater can greatly influence bank erosion along reservoirs (Gatto and Doe, 1983; Doe, 1980; Kachugin, 1980) and lakes (Sterrett, 1980; Mickelson and others, 1977; Hadley, 1976). Groundwater generally flows toward the level of large water bodies, where it discharges. Thus, reservoir and lake banks are usually effectively drained (Doe, 1980).

Figure 31. Relationship of 1983 average overland erosion to bank height.



35
30
25
20
15
10
5
0
MILLIMETRES
<5
5-10
>10
HEIGHT

However, groundwater in the bank can lower bank stability and contribute to failure in several ways:

1. By producing pore water pressures which reduce effective stresses, thereby lowering shear strength (Freeze and Cherry, 1979, p.471-472; Cedergren, 1977, p.340). Water table and pore pressure fluctuations are usually controlled by infiltration from rainfall and snowmelt, but for reservoirs, pool level fluctuations play an important role (Murphy and Kehew, 1984; Doe, 1980). Increases in rainfall, snowmelt or pool level lead to rises of the water table and, therefore, pore pressures. Also, rapid drawdown of pool level creates a pore pressure differential because drainage of water from the banks is slower than the rate of drawdown (Doe, 1980), and the lateral support has been removed.
2. By generating hydrostatic pressures as tension joints are filled from runoff. This may trigger slides or topples (Chandler, 1977).
3. By reducing or eliminating cohesive strength, especially if the cohesion is due to the existence of a soluble binder (Cedergren, 1977, p.340). This is particularly characteristic of loess (Terzaghi, 1950). Also, leaching of salts from clays results in a decrease of shear strength (LaRochelle, Chagnon and LeFebvre, 1970).
4. By increasing bank weight and, thus, increasing shear stress (Carter and Guy, 1983; Carson, 1971). This can trigger slides, topples, falls or flows.

5. By producing horizontal and vertical seepage forces (Doe, 1980; Sterrett, 1980). Horizontal seepage, especially important where perched water tables exist, may result in sapping and subsequent bank failure. This process most often occurs in sands underlain by clay-rich sediments and is common along Great Lakes shorelines (Sterrett, 1980; Mickelson and others, 1977; Hadley, 1976).

The main factors affecting groundwater-induced bank failure are: topography (Patton and Hendron, 1974); bank geometry and materials (Buckler and Winters, 1983); type, abundance and orientation of joints and faults (Sterrett, 1980); rate of reservoir pool level fluctuations (Doe, 1980); and, the amount of rainfall and/or snowmelt (Chandler, 1977).

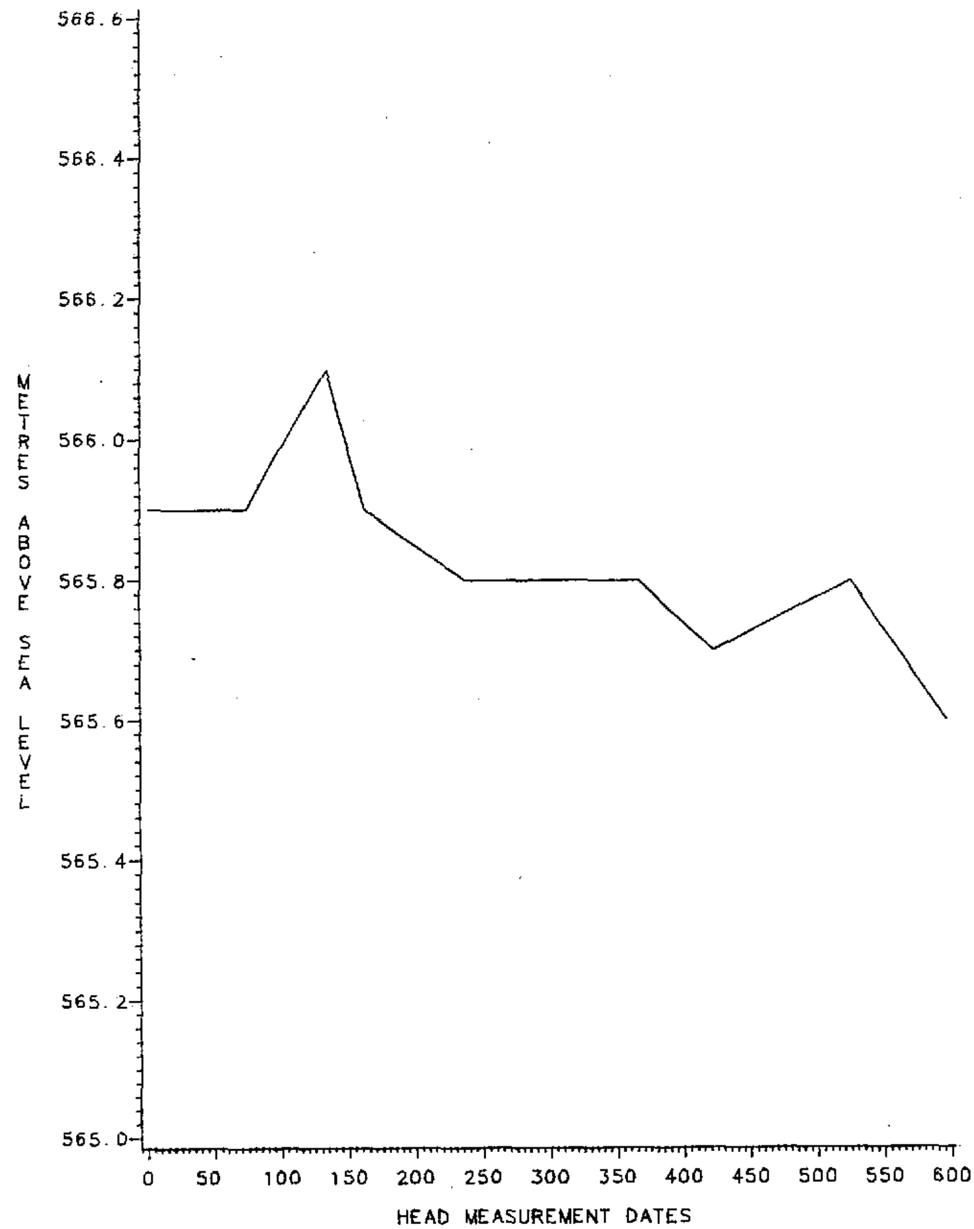
Lake Sakakawea

Groundwater-induced failure appears to occur infrequently, but, as at Orwell Lake, it is likely to have caused the largest bank failure in the study area: the slump and accompanying earthflow below the maintenance buildings at Riverdale in the spring of 1983 (Figure 32). This failure appears to have been along an arcuate surface, resulting in a slump block with the characteristic downward and backward rotation of the mass. The displaced sediment at the toe was shoved up and subsequently, failed by flowage. The site continues to experience minor additional failures.

The direct cause of the slump is probably related to an increase in pore pressures caused by an increase in groundwater level (Figure 33) which was most likely due to snowmelt. The increase in pore pressures decreased the effective stresses and, thus, the shear strength of the

Figure 32. Slump/earthflow failure below Riverdale. The irregular mass extending from bottom left to the center is the toe of the slump which subsequently failed by flowing. May 16, 1983.

Figure 33. Head fluctuations, piezometer 010, December 13, 1982 to August 1, 1984. (Measurement Day 1 = December 13, 1982, Day 135 = April 2, 1983, and Day 600 = August 1, 1984.)


566.6
566.4
566.2
566.0
565.8
565.6
565.4
565.2
565.0
METRES ABOVE SEA LEVEL
0 50 100 150 200 250 300 350 400 450 500 550 600
HEAD MEASUREMENT DATES

sediment. Also, the added weight in the bank caused an increase in shear stress. The failure occurred when the shear stress exceeded the shear strength along the failure plane.

Data from a piezometer above the slump show a sharp increase in head between February 25, 1983 and April 2, 1983 (Figure 33). The next reading, taken May 25, 1983, revealed that the head had returned to the same level it was at on February 25th. Therefore, the failure probably took place between early April and late May. However no information could be found to ascertain exactly when.

The passive cause of the failure is related to stratigraphy. The exposure is characterized by almost 10m (33 ft) of glacial sediments (till and sand) overlying about 10m (33 ft) of Sentinel Butte mudstone. Within the mudstone is a thin lignite bed from which groundwater preferentially discharges; springs were observed to flow from that bed even in mid-winter 1983/84. Therefore, it is hypothesized that the plane of failure was probably along that lignite bed.

The importance of groundwater at other sites is unknown. However, sites at which it may be particularly important are those where the Lower Horseshoe Valley and Lower Snow School sands crop out. For example, at station 51, the Lower Horseshoe Valley sand is underlain by the massive Medicine Hill till (Figure 14). Thus, that sand unit could be very susceptible to groundwater sapping, especially upon rapid drawdown of the reservoir pool. Although no springs or seeps have been observed except at the Riverdale slump, groundwater can influence bank stability in many ways and should be considered further in future studies at Lake Sakakawea.

Frost-Thaw

General

Recent studies by Reid (1984, 1985), Sterrett (1980), and Mickelson and others (1976) have concluded that frost heave and thaw failure are primary contributors to reservoir and lake bank failure in cool-temperate climates.

Frost heave in sediments is caused by ice segregation as moisture migrates toward the freezing plane (Chamberlin, 1981). Preferential growth of ice crystals is more important to frost heave than is volume increase upon freezing (Penner, 1963). In order for frost heave to take place, subfreezing temperatures (Chamberlin, 1981), a sufficient amount of moisture (Ritter, 1979, p.135) and a frost-susceptible sediment (Chamberlin, 1981) must exist. When frost heave occurs, it causes sediments to expand, resulting in disruption (Carter and Guy, 1983), jointing, or bank failure (Reid, 1984, 1985).

Although none of the present theories for ice segregation and frost heave is universally accepted, each is in general agreement on the factors which affect frost heave: sediment texture (Reid, 1984; Nixon, 1973), pore size (Chamberlin, 1981; Yong and Osler, 1971), moisture content (Ritter, 1979, p.135), number of freeze-thaw cycles (Trudgill, 1983, p.47), rate of heat removal (Penner, 1972), temperature gradient (Gorle, 1980), and overburden stress (Chamberlin, 1981). At Orwell Lake, Reid (1984, 1985) also found snow depth, bank slope and bank orientation to be important.

As temperatures rise above freezing, and thaw of ice and snow occurs, bank stability may be significantly affected (McRoberts and Morgenstern, 1974). Water that is generated may cause many types of flows (Reid, 1984; McRoberts and Morgenstern, 1974). Also, soil aggregates (Harrison, 1970) and joint planes (Reid, 1984) which had been strengthened by ice formation may be weakened sufficiently such that falls, topples or slides may occur. Even if bank failure does not occur, thaw processes significantly weaken the bank making it more susceptible to other erosion processes (Carter and Guy, 1983).

The most important factors affecting thaw failure at Orwell Lake are moisture content, number of freeze-thaw cycles, bank slope angle and orientation, and sediment texture and structure (Reid, 1984, 1985). Other important factors are pore pressures (Nixon, 1973), the thermal properties of the sediment (Morgenstern and Smith, 1973; Nixon and McRoberts, 1973) and the depth (McRoberts and Morgenstern, 1974) and rate of movement of the thaw front (Nixon and McRoberts, 1973).

Relatively few workers have quantified erosion due to frost-thaw processes. In the only relevant study along reservoirs, Reid (1984, 1985) used erosion pins, bank recession pins and colluvium excavations to measure the amount of frost-thaw failure. Erosion pins were also used by Hooke (1979) and Hill (1973) to quantify frost-thaw failure along river banks.

Lake Sakakawea and Lake Audubon

Frost-thaw processes are the second most important cause of bank erosion at Lake Sakakawea, as they are at Orwell Lake. During the winter, the banks are frozen and relatively stable. Little mass movement takes place until late winter, when segregation ice, which develops during the numerous freeze-thaw cycles, undergoes sublimation. This releases the previously bound sediment, resulting in accumulation of aggregates along the base of the steep banks (Figure 34) (Reid, 1984; Harrison, 1970).

Once thaw begins, however, rapid bank failure follows. Falls, planar slides, and topples along previously bound joints (Figures 35 and 36), and various types of flow failure (Figures 36 and 37) succeed one another through the end of the thaw period, typically near the end of April. For another brief interval, the banks of Lake Sakakawea become relatively stable. Only as the pool level of Lake Sakakawea begins to approach its maximum level does the water again impinge upon the toes of the banks. Wave action accompanying these high pool levels removes some or all of the sediment (colluvium) that has accumulated because of thaw-failure.

Frost-thaw failure is relatively insignificant at Lake Audubon because the short banks commonly are all but completely buried by winter snow drifts. The drifts reduce the number of freeze-thaw cycles, as well as the penetration of the zero degree isotherm.

Colluvium Volumes

The measurement of colluvium volumes is highly relevant, because, to a large extent, the volumes reflect the amount of spring thaw failure. The determined volumes are minimum values, however, because any colluvium which came to rest on the ice sank when the ice melted. The total length of Lake Sakakawea shoreline included in this study was 1.97km (1.22 mi). Only 79.3m (260.1 ft) of shoreline were studied along Lake Audubon.

Because the high pool levels of 1982 were relatively low, little colluvium was removed by the waves then; hand excavation of the colluvium in the late spring and early summer of 1983 revealed an abundance of colluvium at the stations around Lake Sakakawea (Table 18). Only upon

Figure 34. Accumulation of aggregates at the base of a steep till bank. Particles were released upon sublimation of interstitial ice. Station 7, April 10, 1983.

Figure 35. Blocks of till and loess resulting from thaw failure. Station 56, May 17, 1983.

Figure 36. Mudstone and lignite fragments, and mudflow resulting from thaw failure. Riverdale slump site, February 25, 1984.

Figure 37. Debris flow resulting from saturation of clay-rich sediment re-entrant. Station 56, February 25, 1984. (These failures also can be the result of rainwater runoff.)

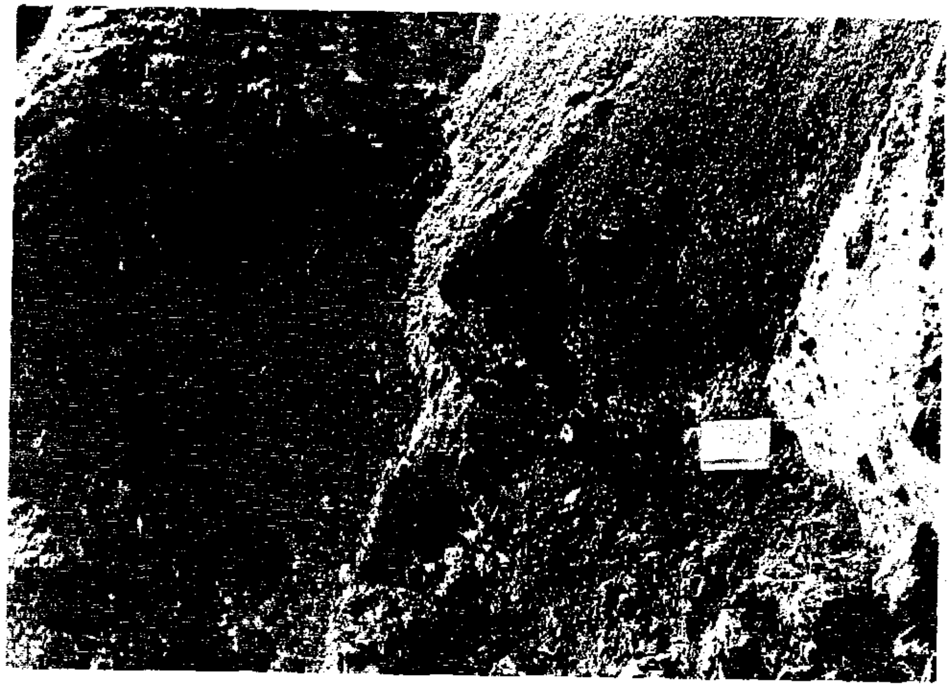


TABLE 18

Colluvium Volume for Each Site at Lake Sakakawea, and Lake Audubon, North Dakota, 1983 and 1984
(* 1983 volumes include both old and recent colluvium; 1984 volumes include only that colluvium added since June 1983.)

Station	Length of Shore (m)	Date (1983)	Volume* (m^3)	Date (1984)	Volume (m^3)	Volume (m^3/m)
Lake Sakakawea						
1	131.9	6/14	77	6/12	90.3	0.68
2	72.8	6/14	331	6/12	52.7	0.72
3	63.7	6/21	577	6/12	11.5	0.18
4	49.1	6/21	76	6/13	35.7	0.73
5	32.8	6/15	91	6/13	24.7	0.75
6	33.7	6/21	729	6/13	37.6	1.12
7	37.3	6/21	285	6/13	21.8	0.58
50	70.0	6/7	3,787	6/13	230.9	3.30
51	159.3	6/23	2,051	6/13	62.3	0.39
52	54.9	-	-	6/13	14.9	0.27
53	566.7	6/28	536	6/13	440.9	0.78
54	82.8	6/9	246	6/14	10.5	0.13
55	64.1	-	-	6/14	46.4	0.72
56	113.8	6/9	927	6/14	101.3	0.89
57	109.2	6/28	1,063	6/14	52.1	0.48
58	28.2	6/24	233	6/14	9.4	0.33
59	109.2	6/24	827	6/14	31.0	0.28
60	58.2	6/23	125	6/14	19.3	0.33
61	64.6	6/23	243	6/14	38.4	0.59
62	68.3	-	-	6/14	18.0	0.26
Total	1,970.6				1,349.7	avg = 0.68
Lake Audubon						
A1	42.7	-	-	5/31	77.8	1.82
A2	18.3	-	-	5/31	12.2	0.67
A3	18.3	-	-	5/31	13.6	0.74
Total	79.3				103.6	avg = 1.31

observing the rate of colluvium accumulation over the next few months did it become apparent that those excavation volumes represented more than one year of accumulation. The measurements for the spring and early summer of 1984 therefore included only new colluvium, i.e. that which accumulated since the spring of 1983 (Table 18). Of all the stations, station 50 had the greatest colluvium accumulation per metre of shoreline ($3.30m^3/m$), whereas station 54 had the least ($0.13m^3/m$). The intense wave erosion during the summer of 1984 was so great that even much of the colluvium that had accumulated prior to 1983 was removed by waves. This was especially evident at station 50 (Figure 82, Appendix C).

Lake Audubon had a higher average colluvium accumulation per metre of shoreline than did Lake Sakakawea (Table 18). However, most of this accumulated upon failure of banks weakened by ice-shove and not thaw failure.

Bank Recession and Joint Propagation

The amount of bank recession interpreted to be due to frost-thaw processes is likely to be slightly over-estimated by recession amounts for the cold weather months (October 16, 1983 to May, 31, 1984) (Table 9); the recession for that interval includes some caused by wave erosion, but most of it probably was a result of frost-thaw failure. Then, as seen in table 9, bank recession due to frost-thaw accounts for a maximum of 13 percent of the total bank recession at Lake Sakakawea. It ranged from 0.01 to 1.13m (0.01 to 3.72 ft) and averaged 0.30m (0.98 ft). Shorter banks (stations 1-5) experienced both the least bank recession and the lowest percentage due to frost-thaw, whereas higher banks generally experienced high recession. Station 50 had the highest percentage of bank recession due to frost-thaw. This was partly a result of its great height, and consequent greater area. However, the main reason it had a higher percentage of its bank recession due to frost-thaw rather than wave erosion was because of the small amount of wave erosion of the primary sediment; it was protected by a large colluvium slope.

Besides being an important activating factor of bank recession, cold weather and frost-thaw processes can be important to joint propagation and/or expansion. Less than 20 percent of the extension joints measured at Lake Sakakawea first appeared and/or failed over the cold weather months (Figures 6 and 7). Although joint initiation and failure due to frost-thaw processes was relatively minor, those processes were instrumental in widening and weakening existing joint planes.

Again, at Lake Audubon, it is unknown how much of the total bank recession can be accounted for by frost-thaw processes because of the large amount of erosion of ice-shoved materials. However, because of the very low banks, the amount of bank recession at Lake Audubon due to frost-thaw processes is probably minor.

Area Eroded

For the 11 profile sites analyzed between October 1983 and October 1984, only about 16 percent of the erosion occurred between October 1983 and June 1984 (Table 19). Interpreted to be primarily the result of thaw, the areas eroded ranged from 0.02 to $11.09m^2$ (0.22 to 119.37 ft^2) and averaged $2.87m^2$ (30.89 ft^2).

There appears to be no trend to these data. For example, short banks (stations 1, 3 and 4) showed as much erosion as tall banks (stations 60, 61 and 62). Also, profile sites at stations 51 and 52 have similar heights, orientations and freeze-thaw induced recession amounts

TABLE 19

Area Eroded at Lake Sakakawea Bank Profile Sites During the Cold Weather Months

Station	Measurement Interval	Area Eroded (m^2) and % of Total Area Eroded for that Site
1	10/16/83 - 05/30/84	1.41 (20.6%)
2	10/16/83 - 05/30/84	11.09 (51.3%)
3	10/16/83 - 05/30/84	0.99 (18.2%)
4	10/16/83 - 05/30/84	1.45 (16.3%)
5	10/16/83 - 05/30/84	0.11 (1.6%)
7	----	----
50	----	----
51	10/15/83 - 05/31/84	10.30 (18.6%)
52	10/15/83 - 05/31/84	0.02 (0.1%)
53	----	----
55	----	----
56	----	----
57	----	----
58	----	----
59	10/15/83 - 06/01/84	3.57 (36.6%)
60	10/15/83 - 06/01/84	1.35 (14.6%)
61	10/15/83 - 06/01/84	0.12 (1.0%)
62	10/15/83 - 06/01/84	1.17 (3.9%)
Average		2.87 (16.6%)

but their areas eroded are much different (Table 19). Thus, from these data it appears the variables affecting frost-thaw processes must be highly interrelated.

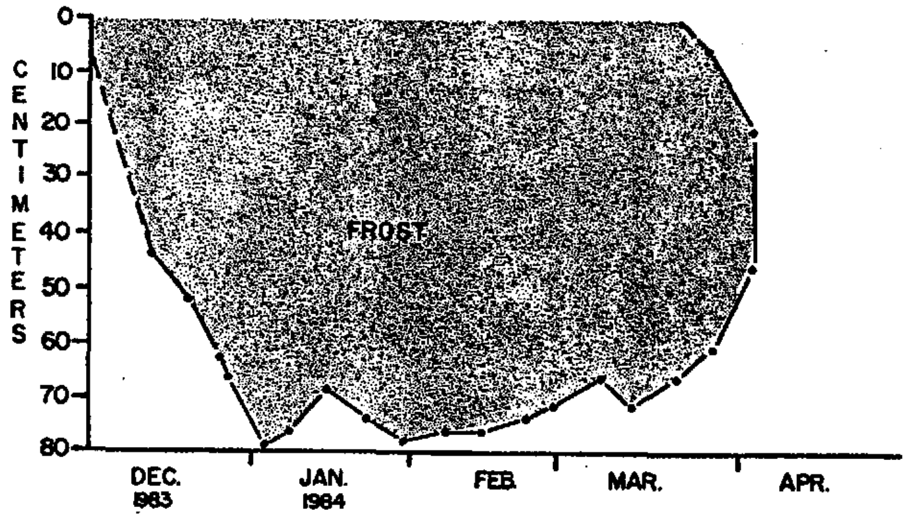
Frost

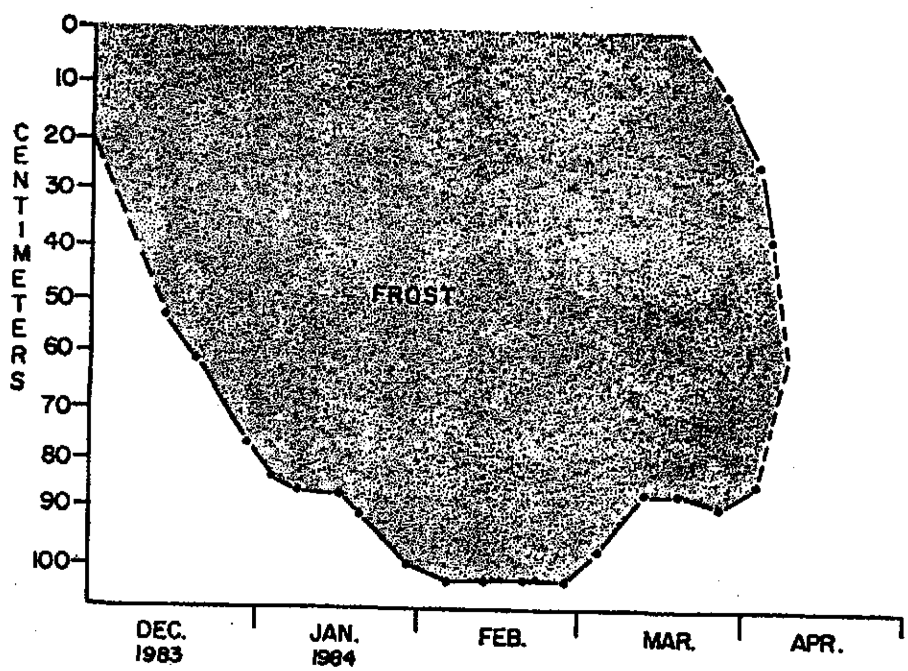
The depth and duration of frost are critical factors affecting frost-thaw failure (Reid, 1984; Chamberlin, 1981; McRoberts and Morgenstern, 1974). Frost penetration is generally deepest closest to exposed banks (Reid, 1984). During the winter and spring of 1984, evidence of frost weakening was abundant at Lake Sakakawea; joints were pushed apart by ice growth (Table 10), and the surfaces of the bank materials were disrupted.

Only three of the frost tubes installed in the fall of 1983 provided data useful to the project, one each at Lake Sakakawea State Park and Fort Stevenson State Park, and one within the Corps of Engineers weather station just northeast of Riverdale. The data from the tube at Lake Sakakawea State Park showed rates of penetration of the zero degree isotherm similar to the other two sites, even though the site was insulated by a deeper snow cover. Because a deep snow cover is not typical for this area, only the graphs of the remaining two frost tubes (Riverdale and Fort Stevenson, Figures 38 and 39) are presented. As can be seen, the shapes of the two curves are similar, with the ground first freezing in late November and then thawing in late March to early April. The curves also show the characteristic melting from both top and bottom, as at Orwell Lake (Reid, 1984). Although the difference in maximum depth of frost penetration between the two Sakakawea sites is about 20cm, it is important to note that up until January 1, 1984 the frost depth at the two sites was almost identical. The first week of January experienced

Figure 38. Frost penetration, winter 1983-1984, Riverdale, North Dakota.

Figure 39. Frost penetration, winter 1983-1984, Fort Stevenson State Park, North Dakota.


CENTIMETERS
0
10
20
30
40
50
60
70
80
FROST
DEC. 1983
JAN. 1984
FEB.
MAR.
APR.


CENTIMETERS
0
10
20
30
40
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60
70
80
90
100
FROST
DEC. 1983
JAN. 1984
FEB.
MAR.
APR.

temperatures up to +9°C (48°F). The accompanying decrease in frost depth during that week was rapid at the Riverdale site; at Fort Stevenson the penetration merely ceased for that time. For this reason, it was concluded that the thermal properties at the two sites are different. The surface sediment at Riverdale is till (disturbed); the surface at Fort Stevenson is vegetation-covered, which acts as an insulation blanket, subduing temperature fluctuations at depth and allowing cold to continue moving downward even after the surface temperatures increase.

In conclusion, frost heave is important in triggering some bank failures but it is especially important in weakening the banks by expanding joints and disrupting sediment structure.

Freeze-Thaw Cycles

The depth of freezing is not the most significant factor in thaw failure. More important is the number of fluctuations above and below the freezing point (Reid, 1985; Trudgill, 1983, p.47). Each cycle results in a weakening of the sediment structure (Bryan, 1971). Table 20 summarizes the number of cycles over the past several years at Riverdale, North Dakota. The number varies greatly; during colder winters there are fewer fluctuations above and below the freezing point. Warmer winters are characterized by frequent fluctuations, freezing at night and melting during the day. It must be remembered, though, that these records are from daily maximum and minimum thermometer readings. The readings are taken from a standard weather shelter placed 1.2 to 1.5m (4 to 5 ft) above the ground surface. The temperatures at and below ground level fluctuate much less. The table, therefore, represents a maximum number of fluctuations that might occur at ground level. Exactly what this means with regard to thaw failure at Lake Sakakawea or Lake Audubon is

TABLE 20

Winter Freeze-Thaw Cycles at Riverdale, North Dakota

Winter (Oct. - April)	Number of Cycles
1976-77	83
1977-78	54
1978-79	51
1979-80	70
1980-81	100
1981-82	71
1982-83	97
1983-84	99

not yet known. However, it can be hypothesized that the more freeze-thaw cycles there are, the more thaw failure there will be. Insufficient data have been collected to determine whether or not the amount of thaw failure during the late winter/early spring of 1984 was greater than usual.

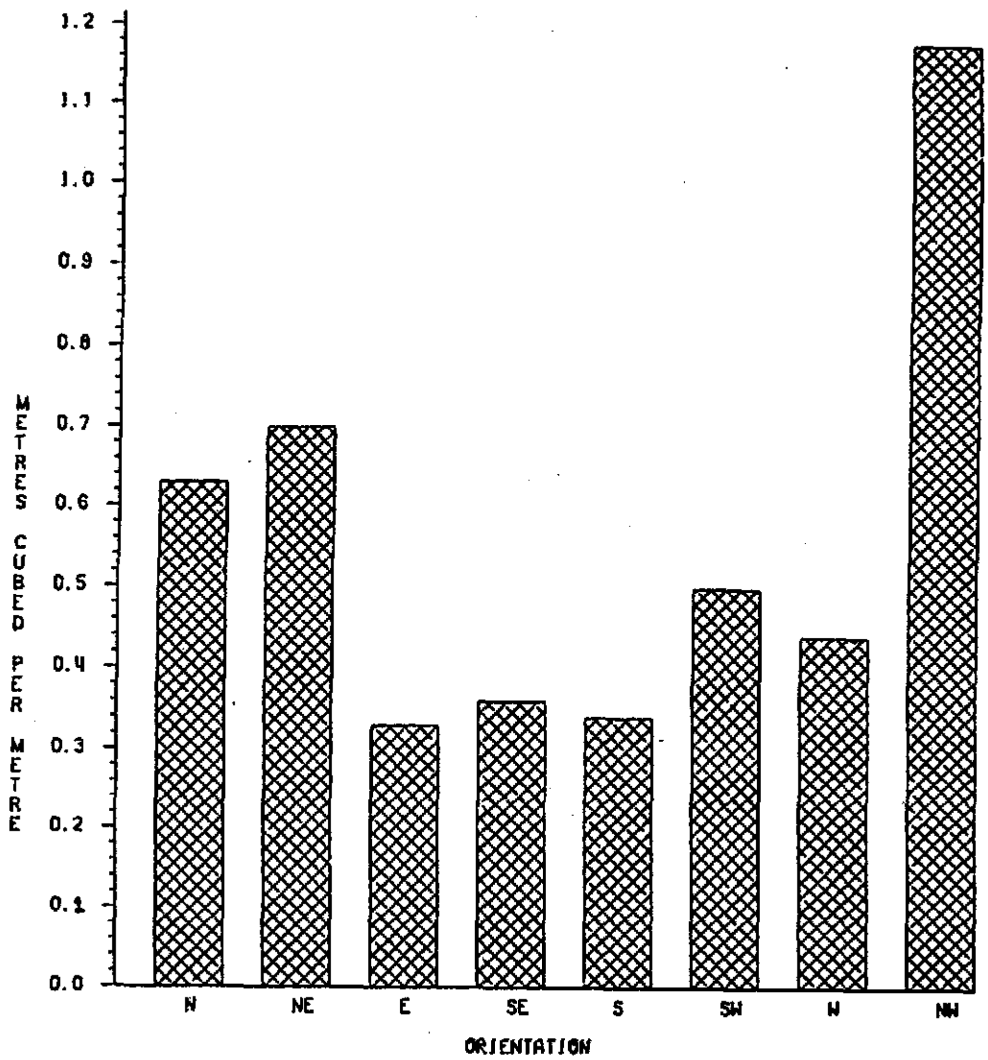
Snowmelt

Although snowmelt is primarily important because of its effect on pool level, it can also contribute to thaw failure (Reid, 1984, 1985). Most of the surfaces above the banks at Lake Sakakawea are fairly level or slope toward the lake. It appears this is true of Lake Audubon also. Where a lakeward slope exists, meltwater can infiltrate and flow along the contact of the upper thawed zone and the underlying frozen zone. This contributes additional water to the banks and may cause various types of debris flows, earthflows and mudflows (Figure 37).

Bank Orientation

Bank orientation also affects the quantity of frost-thaw failure (Reid, 1984, 1985). Figure 40, and table 39 (Appendix G), show the relationship of bank orientation to thaw-derived colluvium volumes calculated for the winter and spring of 1983 and 1984. The values ranged from 0.33 to 1.18m^3/m (3.55 to 12.71 ft^3/ft). Banks facing northwest, northeast and north had the highest volumes of thaw-derived colluvium, whereas the east-, south- and west-facing banks all had much lower volumes. This difference is probably due to a higher remnant moisture content in the north-facing banks (Reid, 1984, 1985) because they are less desiccated by solar energy over the winter. These same factors affect joint initiation and failure, and, in fact, joint data strongly support the colluvium data (Figures 6 and 7); primarily joints both

Figure 40. Relationship of 1984 thaw-derived colluvium to bank orientation.



1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
METRES CUBED PER METRE
N
NE
E
SE
S
SW
W
NW
ORIENTATION

initiated and failed in north- and northwest-facing banks. Bank recession data, on the other hand, show strikingly opposite results (Figure 41, and Table 33, Appendix E); north- and northwest-facing banks showed less recession than south- and west-facing banks. These relationships reflect the importance of bank geometry to thaw failure.

Bank Geometry

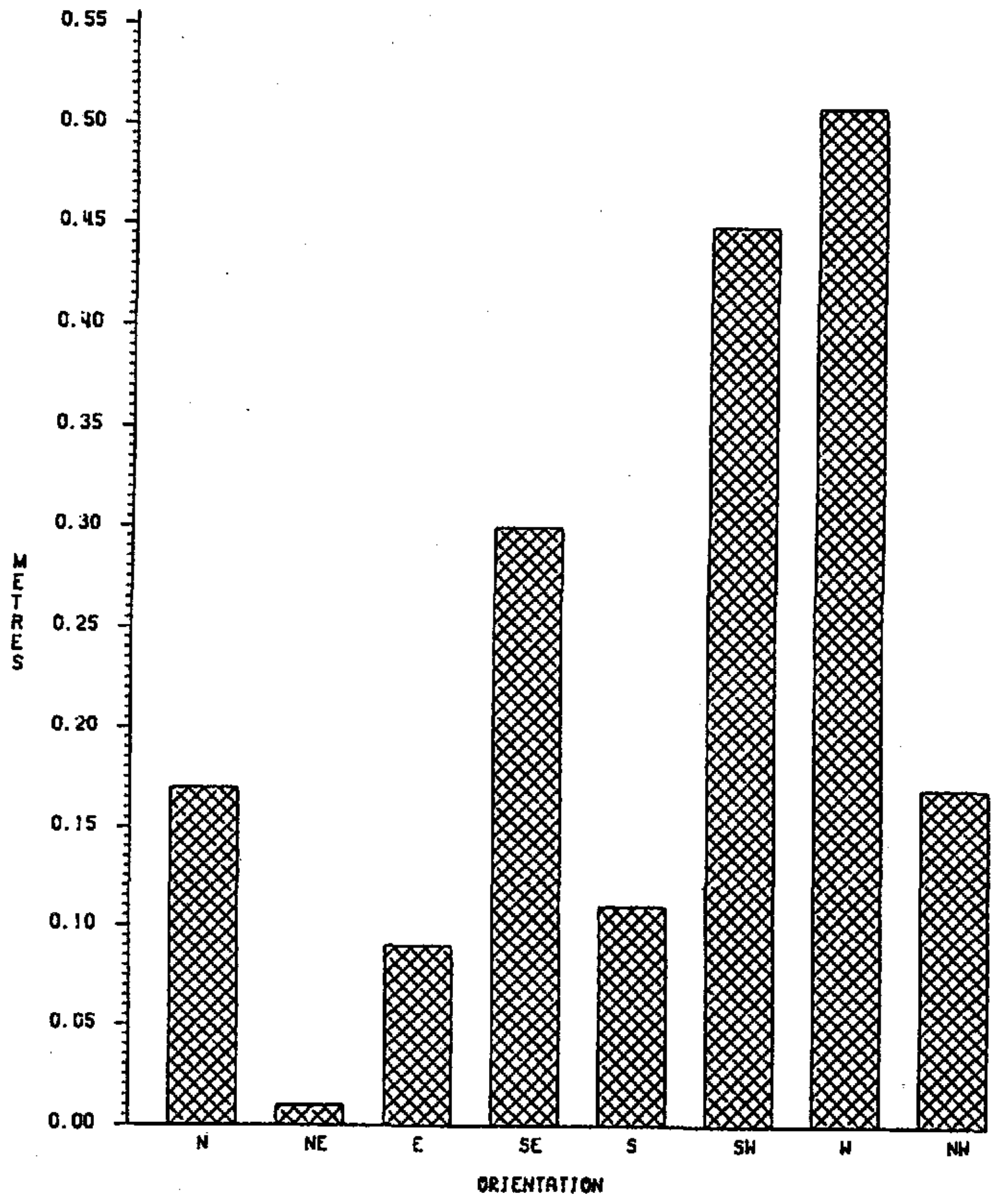
The higher the bank is, the more bank material there is available for colluvium. The apparent anomaly in the bank recession/orientation relationship mentioned above may be explained by differing bank heights. The north-facing banks include stations 6, 7 and 50 (Table 4), the tallest banks in the study area. Large amounts of thaw failure may occur on a taller, gentler sloping bank without much bank-top recession, whereas comparatively lesser amounts of thaw failure may occur on a shorter, steeper bank but cause more recession. Thus, even though the taller, north facing banks receded a relatively small amount, they still produced the most colluvium.

The relationship of bank height to thaw-derived colluvium and bank recession at Lake Sakakawea is depicted in figures 42 and 43, and summarized in tables 41 and 36 (Appendices G and E). As expected, both data sets illustrate the dominance of thaw failure for the eight stations with banks >10m high. The lower banks not only have less available material for colluvium, but also are protected and temporarily stabilized by snow banks.

Bank Geology

The texture, clay mineralogy and structure of the bank sediments also affect frost-thaw (Reid, 1984, 1985). For example, clay and silt

Figure 41. Relationship of cold weather cumulative average bank recession to bank orientation.



0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
METRES
N
NE
E
SE
S
SW
W
NW
ORIENTATION

Figure 42. Relationship of 1984 thaw-derived colluvium to bank height.

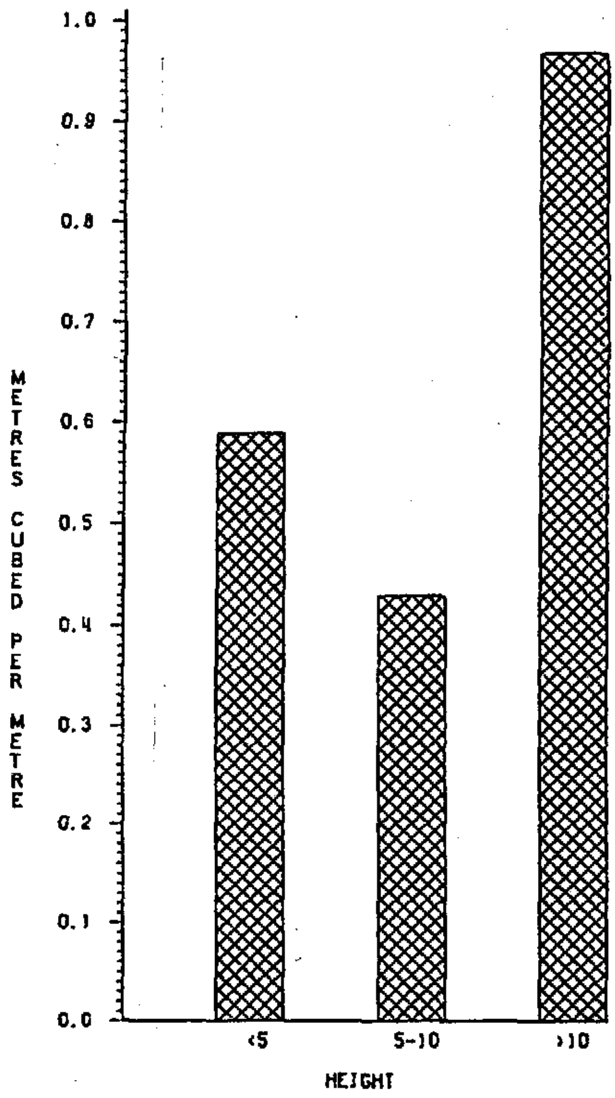
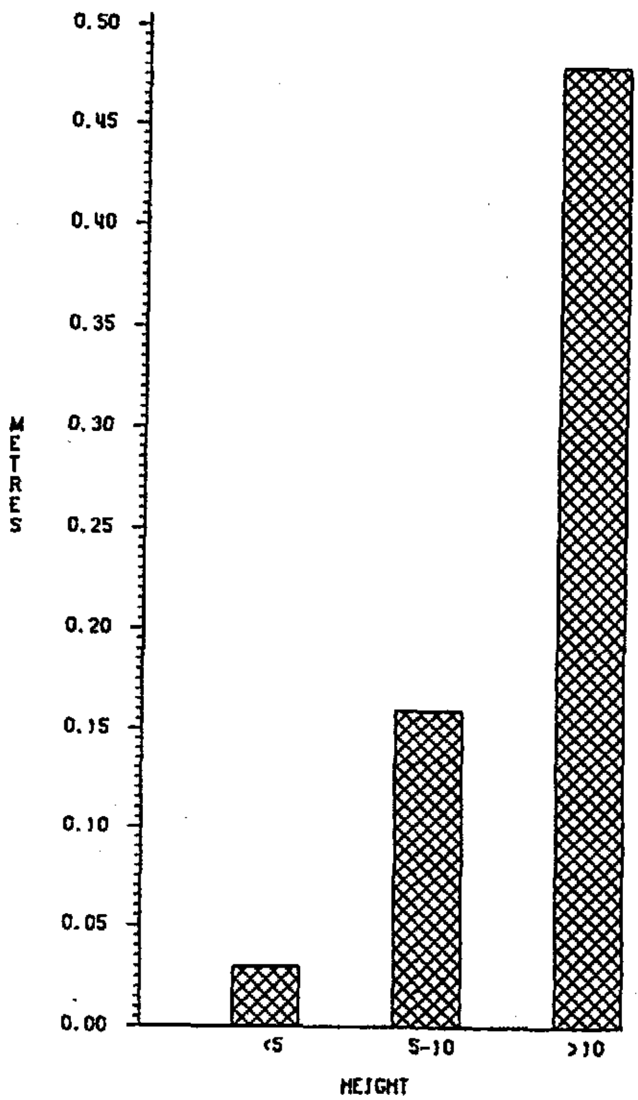

METRES CUBED PER METRE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
<5
5-10
>10
HEIGHT

Figure 43. Relationship of cold weather cumulative average bank recession to bank height.



0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
METRES
<5
5-10
>10
HEIGHT

generally expand much more than sand and gravel (Journeaux and Coutard, 1972). The tills at Lake Sakakawea would be termed frost-susceptible by most definitions because of their typical clayey-silt texture. Clay mineralogy is important because clays are the minerals most susceptible to expansion during freezing (Reid, 1984). This factor is relevant at Lake Sakakawea because most of the clays in the sediments are smectites. Structure may be the most vital of the geologic factors. For example, jointed tills are more susceptible to thaw failure than are massive tills (Hill, 1973) because joints act as planes of exploitation and reduce the shear strength of the till.

The relationship between structure and thaw failure appears to be a significant one at Lake Sakakawea (Figures 44 and 45, and Tables 40 and 35, Appendices G and E). The massive Upper Medicine Hill till is associated with the three lowest average amounts of colluvium and two of the four lowest average bank recession amounts, whereas the jointed Upper Snow School till is associated with the two highest average amounts of colluvium and the two highest average bank recession amounts. The jointed Upper Horseshoe Valley till, and Sentinel Butte siltstones and mudstones also are susceptible to thaw failure.

In conclusion, then, bank geology, along with bank height, bank orientation, frost depth, freeze-thaw cycles and snowmelt runoff are the most important variables affecting thaw failure at Lake Sakakawea.

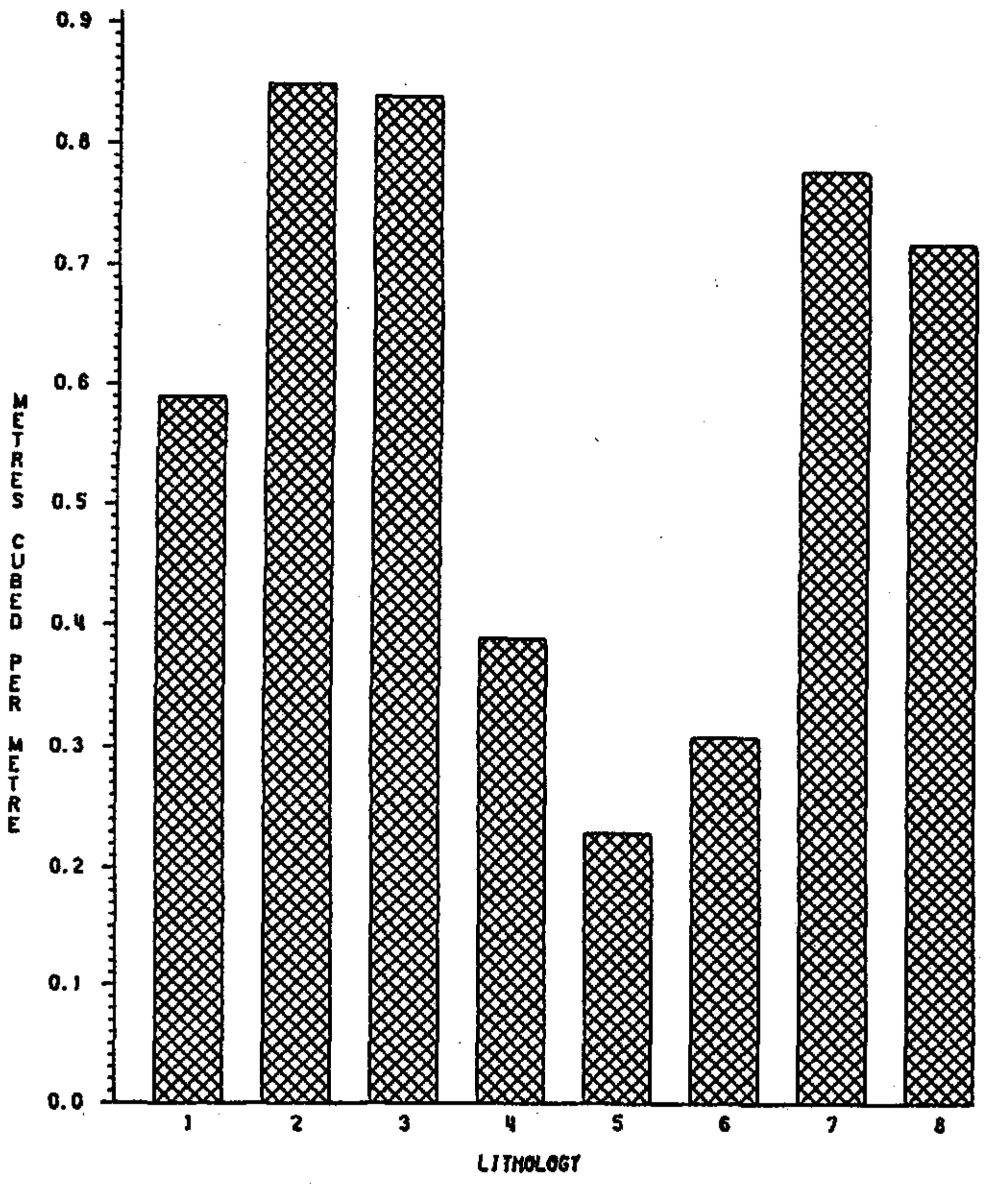
Lake Ice

Lakes Sakakawea and Audubon freeze over during most winters. Ice can protect reservoir and lake banks by reducing the effects of winter waves and currents but it can also erode the banks if the pool level is high enough for the ice to shove the bank sediment directly (Gatto, 1982;

Figure 44. Relationship of 1984 thaw-derived colluvium to bank lithology.

Key to bank lithologies on horizontal axis are as follows:

1= Oahe and Upper Snow School Formations
2= Oahe, Upper Snow School, Lower Snow School and Upper Medicine Hill Formations
3= Oahe, Upper Snow School and Sentinel Butte Formations
4= Oahe, Upper Horseshoe Valley, Lower Horseshoe Valley and Upper Medicine Hill Formations
5= Oahe, Upper Horseshoe Valley and Upper Medicine Hill Formations
6= Oahe and Upper Medicine Hill Formations
7= Oahe, Upper Medicine Hill and Sentinel Butte Formations
8= Oahe and Sentinel Butte Formations

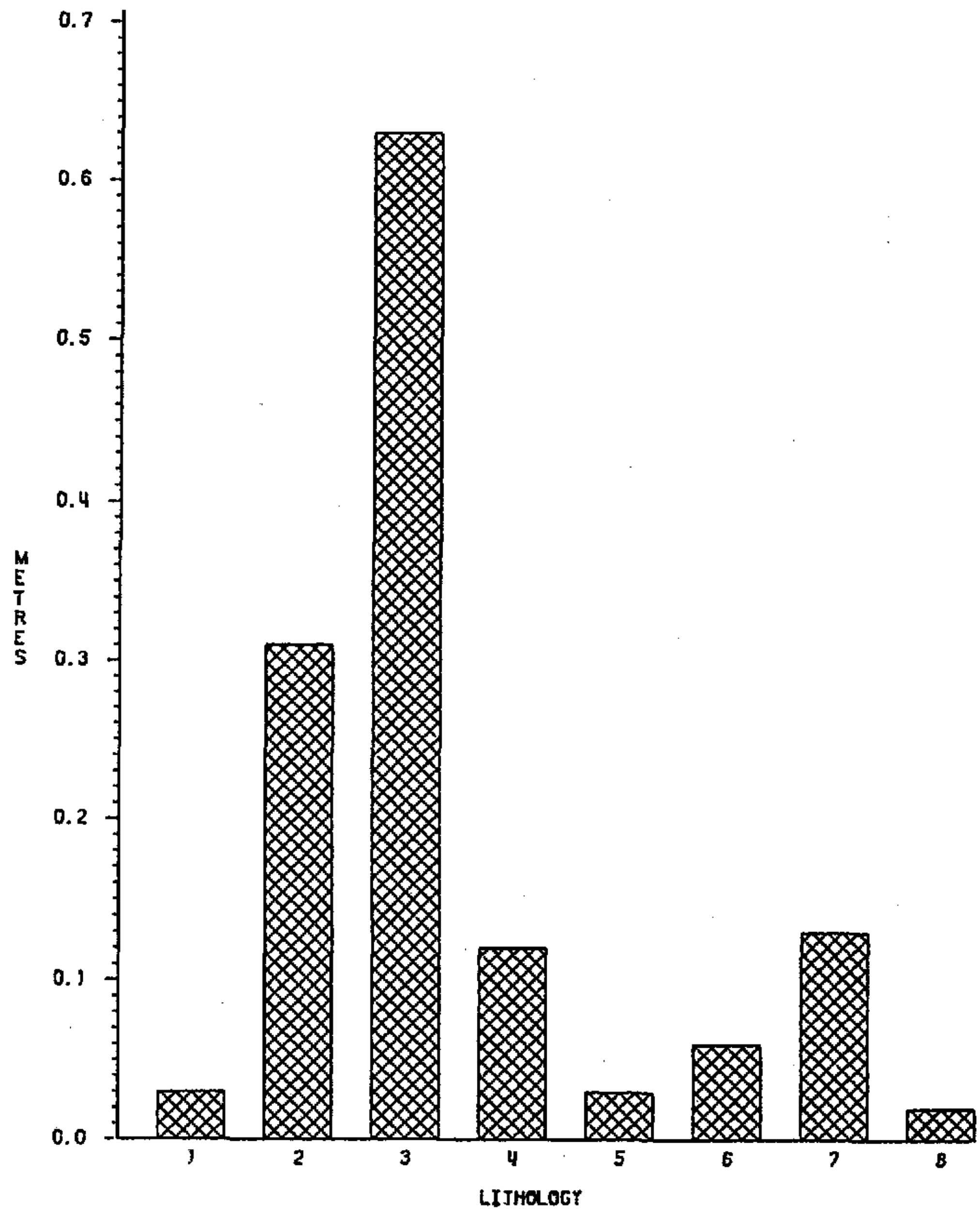


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
METRES CUBED PER METRE
1
2
3
4
5
6
7
8
LITHOLOGY

Figure 45. Relationship of cold weather cumulative average bank recession to bank lithology.

Key to bank lithologies on horizontal axis are as follows:

1 = Oahe and Upper Snow School Formations
2 = Oahe, Upper Snow School, Lower Snow School and Upper Medicine Hill Formations
3 = Oahe, Upper Snow School and Sentinel Butte Formations
4 = Oahe, Upper Horseshoe Valley, Lower Horseshoe Valley and Upper Medicine Hill Formations
5 = Oahe, Upper Horseshoe Valley and Upper Medicine Hill Formations
6 = Oahe and Upper Medicine Hill Formations
7 = Oahe, Upper Medicine Hill and Sentinel Butte Formations
8 = Oahe and Sentinel Butte Formations



METRES
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
LITHOLOGY

Hadley, 1976). Even if the pool level is low enough that the ice is not in direct contact with the bank, the ice can still remove beach and nearshore sediment and, thus, steepen the offshore profile. Many lakes experience ice-shoving as the ice contracts during cold snaps and the infilling water freezes and expands laterally (Pessl, 1969; Kovacs, 1983). Additional ice-shove may occur in the spring when wind-driven ice blocks are blown onto the shores.

At Lake Sakakawea, however, these mechanisms merely redistribute off-shore sediment because the pool level is low during that time. However, at Lake Audubon, winter ice-shove was the dominant cause of bank recession in 1984. The pool level that winter was maintained higher than usual and the expanding lake ice impinged directly on the banks. Ice-shove ridges resulted, especially along the east end where the erosion stations were located. Figure 46 shows one such ridge along a low area between stations A1 and A2. The ice effectively weakened the bank such that even slight wave action was sufficient to cause bank failure. If future pool levels are kept high during the winter at Lake Audubon additional rapid bank recession can be expected.

Snow

Snow also affects bank erosion. The amount of snow on a bank slope and top influences bank stability in three ways. First, the weight of the snow may increase the shear stress of the bank enough to trigger failure (Varnes, 1978). Secondly, the snowcover thickness is a factor in the rate and depth of freezing (Reid, 1984). Finally, the amount of water produced upon melt may greatly affect bank stability (McRoberts and Morgenstern, 1974).

Figure 46. Ice-push ridge of grass, tree saplings and till at east end of Lake Audubon. Between stations A1 and A2, May 31, 1984.

The amount of snowfall in the winter of 1983-1984 at Lake Sakakawea was small. There were some isolated drifts and, at times, a light 3 to 8cm (1 to 3 in) blanket on the ground which may have had some effects, although minor overall, on freezing rate and meltwater production.

Human and Animal Activity

Finally, human and animal activity also can weaken banks. Fisherman, beachcombers and even geologists climb on the banks, releasing colluvium into the water and loosening primary sediment and bedrock. Also, in a few places, trails leading down a slope have diverted runoff, causing increased erosion, creating small gullies. Finally, many birds and animals use the banks as their home. Their burrowing, tunneling and other activities locally weaken the banks considerably.

REGRESSION ANALYSES

Purpose

According to D.P. Hauser (1974, p.149), "Stepwise regression may be regarded essentially as a search procedure to identify which independent variables, previously thought to be of some importance, actually appear to have the strongest relationship with the dependent variable." Regression analysis can be applied to predict or explain the relationships between variables in many aspects of geology. For example, it can be used to define the most important variables associated with shoreline, or bank erosion. Both Hooke (1979) and Hill (1973) used this technique to analyze river bank erosion in Great Britain.

The purpose of regression analyses in this study was to define statistically the importance of some of the variables associated with bank erosion at Lake Sakakawea. This was already attempted by Gatto and Doe (1983) who applied multiple regression to analyze some variables they thought to be associated with historical bank recession. However, they concluded that their results were unreasonable because they "suggested relationships between the variables that are contradictory to accepted results of related studies." For example, bank recession had a strong correlation with the duration of ice cover but no correlation with wind direction or bank sediment type.

The danger of research by correlation rather than by analysis of mechanisms and processes has been pointed out by Quigley (1976). In this study, stepwise regression is used only to further test observations and results of field work.

Variable Selection and Preparation

The dependent variables used in the regression analyses were: 1) average bank recession per measurement interval; and, 2) cumulative average bank recession. (The former was used in regression analyses of individual stations, whereas the latter was used in the regression analysis of all stations.) Average bank recession was calculated for each measurement interval. The sum of the recession amounts for all the pins at a given station was divided by the number of pins. This yielded the average bank recession for that station during that interval. Cumulative average bank recession values for each station during the study are listed in table 9.

Variables which could be quantified and which were observed to influence bank recession were chosen as independent variables. Variables used in the regression analyses are listed in tables 21 and 22. The data for each variable are listed in Appendix H.

The variables must be quantified in such a way that they are relevant or meaningful. One problem was interval length. The measurement intervals varied from 10 to 207 days. In order to alleviate this irregularity, any values of variables affected by interval length were divided by the interval length to yield daily averages. Those variables affected were average bank recession, rainfall and freeze-thaw cycles. Other problem variables were wind direction and lithology at the zone of wave impact. Wind direction was finally measured as the angle between the wind direction and the bank face. The lithology at the zone of wave impact was given a value based on relative erodibility by waves.

Next, Statistical Analysis Systems (SAS) normal distribution and collinearity tests were performed on each variable to help ensure the

TABLE 21

Variables Used in Regression Analyses of Individual Stations and Results of Normal Distribution and Collinearity Tests

	Variable	Normal (N) or Not Normal (NN)	Collinear Variables (C)
Y :	Average bank recession (cm/day)	N	
X 1:	Maximum pool level (m)	N	C(1,2)
X 2:	Mean pool level (m)	N	C(2,1)
X 3:	Rainfall (mm/day)	N	
X 4:	Freeze-thaw cycles (number/day)	NN	
X 5:	Maximum frost depth (cm)	NN	
X 6:	Mean high wind speed (km/hr)	N	
X 7:	Dominant wind direction (< with bank face)	N/NN	
X 8:	Duration of ice cover (months)	NN	
X 9:	Maximum bank height (m)	NN	
X10:	Lithology at wave impact zone (erodibility)	NN	
X11:	Station orientation (compass degrees)	NN	
X12:	Northward fetch (km)	NN	
X13:	Northeastward fetch (km)	NN	
X14:	Eastward fetch (km)	NN	
X15:	Southeastward fetch (km)	NN	
X16:	Southward fetch (km)	NN	
X17:	Southwestward fetch (km)	NN	
X18:	Westward fetch (km)	NN	
X19:	Northwestward fetch (km)	NN	

TABLE 22

Variables Used in the Regression Analysis of All Stations and Results of Normal Distribution and Collinearity Tests

Variable	Normal (N) or Not Normal (NN)	Collinear Variables (C)
Z : Cumulative average bank recession (cm)	N	
X 9: Maximum bank height (m)	N	
X10: Lithology at wave impact zone (erodibility)	N	
X11: Station orientation (compass degrees)	N	
X12: Northward fetch (km)	NN	
X13: Northeastward fetch (km)	NN	
X14: Eastward fetch (km)	NN	
X15: Southeastward fetch (km)	N	
X16: Southward fetch (km)	N	
X17: Southwestward fetch (km)	N	
X18: Westward fetch (km)	NN	
X19: Northwestward fetch (km)	NN	

best possible results from stepwise regression. A normal distribution is important because it is an underlying assumption of the F-test used in regression analysis (Davis, 1973). If the variable's skewness was between +1 and -1 and/or the probability statistic was 0.05 or greater, the data were assumed to be normally distributed. If a variable was not normally distributed, the log of the values was taken and the variable was re-tested. If it was still not normally distributed, it was deleted. Results of the normal distribution tests for individual stations are given in table 21. Table 22 lists the results for variables for all the stations together.

If two independent variables are collinear, higher standard errors and biased coefficient estimates may result (Hauser, 1974; Gunst and Mason, 1980). For the Sakakawea data, if two variables had correlation coefficients of 0.8 or greater (Hauser, 1974), they were tested further with a collinearity procedure. Their eigenvalues, condition indices, and portions explained were analyzed and if a high condition index existed which explained the majority of both variables, the variables were declared collinear (SAS Statistics User's Guide, 1982). The variable with the lowest R^2 value was deleted from the particular analysis. The only two variables that were collinear in any of the tests are maximum pool level (X1) and mean pool level (X2) (Tables 21 and 22).

After performing the tests, the variables Y, X1 or X2, X3, X6, and sometimes X7, were the only ones available for regression analyses of the individual stations (Table 21). Only Z, X9, X10, X11, X15, X16, and X17 were available for regression analysis of all the stations together (Table 22).

Stepwise Regression Analysis

All 20 stations were individually analyzed over nine measurement intervals in separate stepwise regression analyses (nine variable values/station). In another analysis, the stations were analyzed as a group over the entire study period (one variable value/station). Again, SAS procedures were utilized to compute the models that best explained bank recession at the stations. The FORWARD and MAXR options of PROC STEPWISE were used. (See the SAS Statistics User's Guide (1982) for description of these procedures). Critical F-values for 95 percent confidence limits used are listed in Davis (1973).

Results

The results of the individual station stepwise regression analyses are summarized in table 23. Mean pool level (X2) is the one variable which best explains average daily bank recession at station 1; it explains about 69 percent of the bank recession. Mean pool level (X2), together with wind direction (X7), explain about 72 percent of the bank recession. This explanation of the results can be extrapolated to table 23 for each of the stations. Unfortunately, there were no significant models generated from regression involving all the stations together.

Discussion

Stepwise regression analyses have defined statistically the most important variables associated with bank recession at Lake Sakakawea. They are, in order of apparent importance: mean pool level (X2), maximum pool level (X1), rainfall (X3), wind speed (X6), and wind direction (X7) (Table 24). Overall, pool level (X1 + X2) is the most important variable in explaining the amount of bank recession at most stations. As stated

TABLE 23

Results of Stepwise Regression
for Individual Stations

Station	1-Variable Model/R^2	2-Variable Model/R^2	3-Variable Model/R^2
1	X2/0.687	X2, X7/0.716	---
2	X2/0.696	X2, X3/0.814	---
3	X2/0.485	---	---
4	X1/0.508	---	---
5	X1/0.916	X1, X3/0.922	X1, X3, X6/0.922
6	---	---	---
7	X3/0.738	X3, X6/0.899	X3, X6, X1/0.918
50	---	---	---
51	X2/0.447	---	---
52	X2/0.713	X2, X7/0.808	---
53	X2/0.723	X2, X7/0.780	X2, X7, X3/0.825
54-56	---	---	---
57	X6/0.670	X6, X3/0.726	---
58	X2/0.818	X2, X3/0.896	X2, X3, X6/0.926
59-61	---	---	---
62	X2/0.842	X2, X7/0.895	X2, X7, X3/0.945

TABLE 24

Summary of Regression Model Placings for Each Variable

Variable	1-Variable Model	2-Variable Model	3-Variable Model
X1	2	1	2
X2	8	6	3
X3	1	5	5
X6	1	2	3
X7	0	4	2

earlier, results of field study have indicated that wave erosion is responsible for over 87 percent of the bank recession at the stations. The most important variable affecting wave erosion is pool level, with wind direction, wind speed, bank face orientation, bank lithology and structure also important. Thus, the regression analyses do indeed support field observations and measurements.

The results for the individual stations, depicted in table 23, vary considerably. For example, significant R^2 values for one-variable models cover a broad range, from 0.447 to 0.916. Also, stations 5, 7, 53, 58 and 62 have significant 1-, 2-, and 3-variable models, whereas stations 50, 54-56 and 59-61 have no significant models at all. These variations are due to the timing of bank failure events and reflect the erosion processes acting upon the banks of Lake Sakakawea. An examination of the cumulative average bank recession curves for stations 1 and 56 best explain the situation. The curve for station 1 (Figure 51, Appendix B) is nearly horizontal during the late fall and winter, reflecting the relatively small amount of bank recession due to freeze-thaw failure, and shows sharp rises over the late spring and summer, reflecting the significance of wave erosion. The other stations that have models significant at the 95 percent confidence level have cumulative curves similar to station 1. Thus, bank recession (Y) increases during the summer, as does pool level (X1 and X2) ard rainfall (X3). These values correlate positively at various levels for each station and significant regression equations are generated.

The cumulative curve for station 56 (Figure 64, Appendix B) shows a significant rise during the late fall and winter, and sharper rises during the late spring and summer. Two possible reasons for this are:

1) delayed bank failure, due to wave erosion, but activated by another process after the last measurement prior to freeze-up; and, 2) significant thaw failure before the first spring measurement date. The latter is probably the case at station 56, because in March 1984, a large amount of colluvium was observed on the lake ice at that station (Figure 47). Thus, there was no strong positive correlation between bank recession (Y) and the dependent variables used, and no significant models were generated.

The results of this analysis also indicate that rainfall (X3) is relatively significant. However, observations and field measurements have indicated that bank recession due directly to rainfall (rainsplash and rainwash) is insignificant. But, the regression analyses results are obviously due to a positive correlation between rain events and bank recession events. Rainfall may be an important activating factor, ultimately causing the failure of undercut or jointed banks. Four possible ways rainfall can activate bank failure are: 1) through saturation of the soil on top of the bank (this increases the weight of the bank top); 2) through increasing pore pressures, and reducing effective stress; 3) through vibrations caused by heavy rainfall or associated thunderstorms; and, 4) through flushing and widening of extensional joints.

Finally, there were no significant models generated in the regression analysis using all the stations. That is, none of these variables appears to be statistically important in explaining bank recession for the entire set of stations. However, observations indicate otherwise. For example, lithology at the zone of wave impact (X10), station orientation (X11), and fetch direction (X12 through X19) are all important in affecting the quantity of wave erosion (and thus, bank recession)

Figure 47. Colluvium apron on ice resulting from frost-thaw. The mode of failure was probably toppling. Station 56, March 31, 1984.

that will occur at a particular site (See Waves in DISCUSSION OF RESULTS AND OBSERVATIONS).

In conclusion, after evaluation and preparation of the variables, stepwise regression analyses were used to define statistically the most important variables associated with bank erosion, or recession, at Lake Sakakawea. Results reveal that pool level is the most important variable and, also, that the magnitude of erosion processes varies from station to station. These results support field observations and measurements.

HISTORICAL BANK RECESSION

Procedures

United States Department of Agriculture vertical aerial photographs of parts of the study area were gathered for the purpose of measuring historical bank recession. These photographs were taken between May 19, 1958 and August 21, 1976.

The selection process for choosing appropriate aerial photographs was controlled largely by the availability of photographs. Photographs of most of the erosion stations were available for the years 1958, 1966 and 1976 (Appendix I). To minimize photographic distortions, the stereo-pairs used were those with a site closest to the center of the photograph.

The nominal scales for the selected aerial photographs were either 1:20,000 or 1:40,000. The smaller scale (1:40,000) photographs were much more difficult to measure precisely. The actual scale of each photograph varies due to distortions (e.g., radial, relief and tilt) within the photograph (Tanner, 1978; Wolf, 1974). Because of the variation in scale, the average scale was determined for the site portion of each photograph (Wolf, 1974). First, stable reference points (e.g., buildings, road intersections, etc.) were located on both the aerial photograph and the corresponding U.S. Geological Survey topographic map (scale of 1:24,000). Next, distances between like points were measured on both the photograph and the map. Then, the scale for that portion of the photograph was calculated by using the following formula: scale = (photo distance/map distance) x (map scale). Three scales of measurement were made from the site portion of each photograph and, thus, three scales were obtained. Those three scales were then averaged for the site portion of the aerial photograph.

Measurements were made using dividers and the 60th scale of an engineer's scale under stereoscopic magnification. Readings were made to the nearest 0.21mm. This corresponds approximately to the strict limit of measurement which the human eye can accurately measure, as defined by Tanner (1978). He listed in table form the "smallest field distance measurable" for various scales using the strict (0.2mm) limit. The minimum measurable distance (mmd.) was calculated for each photograph, using the table. Because two photographs were used to find the change in distance at a site, their respective mmd.'s were combined (Tanner, 1978).

Before any measurements could be made, however, the bluffline at each erosion site had to be located on the photographs. Once this was done, the distance along each transect from a known point (usually a road intersection) to the erosion station bluffline was measured on the photograph. This distance was measured twice. The average of the two measurements was then converted to an equivalent ground distance using the average photograph scale. These measurements were made for each year for which photographs were available. The shortening of the distance, then, equaled the total amount of land lost due to inundation and/or bank erosion. This value was then compared to the combined mmd. of the photographs. If the measured distance exceeded the combined mmd., the value was considered to be significant.

Because the reservoir was filling until 1969, when it first reached the maximum normal pool level of 564.3m (1850 ft) msl., most of the land lost between 1958 and 1966 was due to inundation. However, for the period 1966 to 1976, it was assumed most of the transgressional inundation had taken place. Although seasonal (1-3m; 3-10 ft) fluctuations occur annually, the water will never rise above the 564.3m (1850 ft) level because that is the control level of the dam. Using the appropriate U.S. Geological Survey topographic maps (complete with contours mapped before reservoir closure) the distance from the same known point that was used on the aerial photograph to the 1850-foot contour was measured. This distance was then converted to an equivalent ground distance and compared to the ground distance from the known point to the bluffline on the photograph. If it was greater than the distance to the bluffline on the photograph, the difference (if larger than the combined mmd.) was recorded as bank recession. This was done for both intervals but was more useful for the period of 1966 to 1976 because prior to 1966 there was little bank recession.

Results

The results of aerial photograph measurements are given in table 25. Bank recession rates for 1966 to 1976 ranged from 1.2 to 4.3m/y (3.9 to 14.1 ft/y) and averaged 2.2m/y (7.2 ft/y). These values correspond very well to the rates determined from bank recession pin measurements (Table 9). Thus, it may be concluded that bank recession rates have been relatively uniform from 1966 to 1984.

Rates for the same years, as calculated by Gatto and Doe (1983), are much different, ranging from 1.8 to 13.1m/y (5.9 to 43.0 ft/y) and averaging 5.8m/y (19.0 ft/y). This discrepancy between the two studies reflects: 1) the inaccuracy of measuring small scale changes on small scale aerial photos; and/or, 2) the variability of erodibility for each shoreline segment because of changing orientation, bank materials, etc.;

TABLE 25

Results of Aerial Photograph Analysis
(Actual Bank Recession is defined as the change beyond the 564.3m contour.)

	1958 - 1966				1966 - 1976				1958 - 1976		
Station	Total Change (m)	Actual Bank Recession (m)	Combined MMD (m)	Minimum Bank Recession Rate (m/y)	Total Change (m)	Actual Bank Recession (m)	Combined MMD (m)	Minimum Bank Recession Rate (m/y)	Total Change (m)	Total Bank Recession (m)	Bank Recession Rate (m/y)
1	184.5	25.0	8.1	3.1	42.7	42.7	12.0	4.3	227.2	67.7	3.8
2	96.6	7.6	8.1	<1.1	21.9	21.9	12.0	2.2	118.5	29.5	1.6
3	195.9	4.1	8.1	<1.1	18.0	18.0	12.0	1.8	213.9	22.1	1.2
4	52.6	0	8.1	0	6.9	4.0	12.0	<1.2	59.5	4.0	0.2
5	39.0	0	8.1	0	15.0	7.3	12.0	<1.2	54.0	7.3	0.4
50	174.5	0	8.2	0	55.9	24.4	12.1	2.4	230.4	24.4	1.4
51	77.4	0	8.2	0		NOT AVAILABLE				NOT AVAILABLE	
52	135.3	0	8.2	0		NOT AVAILABLE				NOT AVAILABLE	

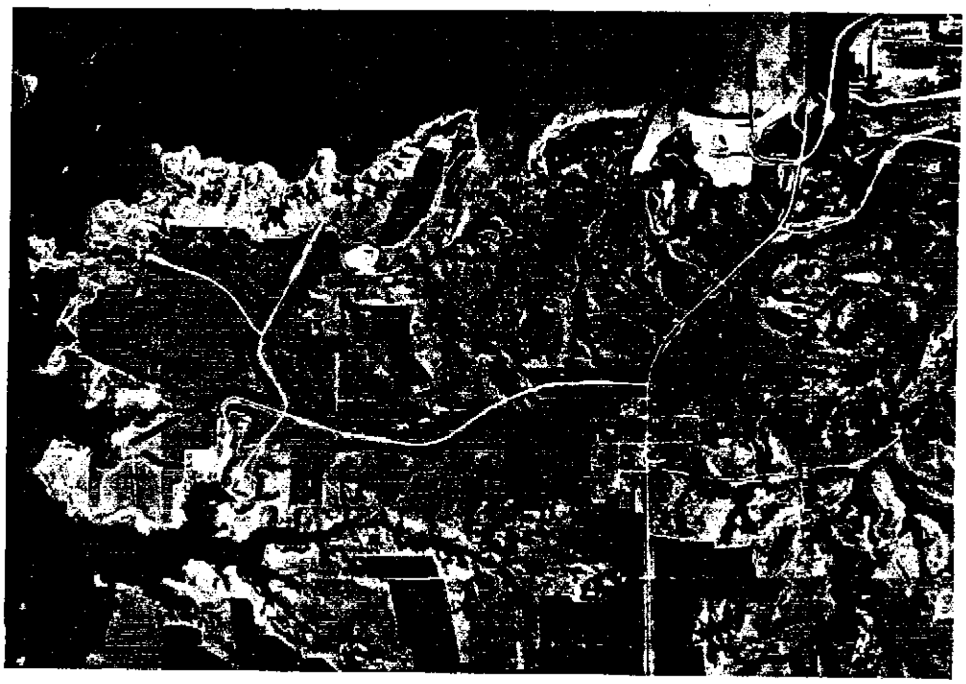
	1958 - 1976			
Station	Total Change (m)	Actual Bank Recession (m)	Combined MMD (m)	Minimum Bank Recession Rate (m/y)
53	227.0	23.8	12.3	1.3
54	142.8	0	12.3	0
55	95.3	41.0	12.3	2.3
56	196.6	31.5	12.3	1.8
57	201.5	54.0	12.3	3.0

and/or, 3) the lack of proper differentiation between inundation and bank recession.

In summary, figures 48, 49 and 50 illustrate the dynamic changes which occurred at Lake Sakakawea State Park between 1958 and 1976.

Figure 48. Aerial photograph of Lake Sakakawea State Park, July 1, 1958.

Figure 49. Aerial photograph of Lake Sakakawea State Park, September 14, 1966. Note the amount of change since 1958 due to inundation.



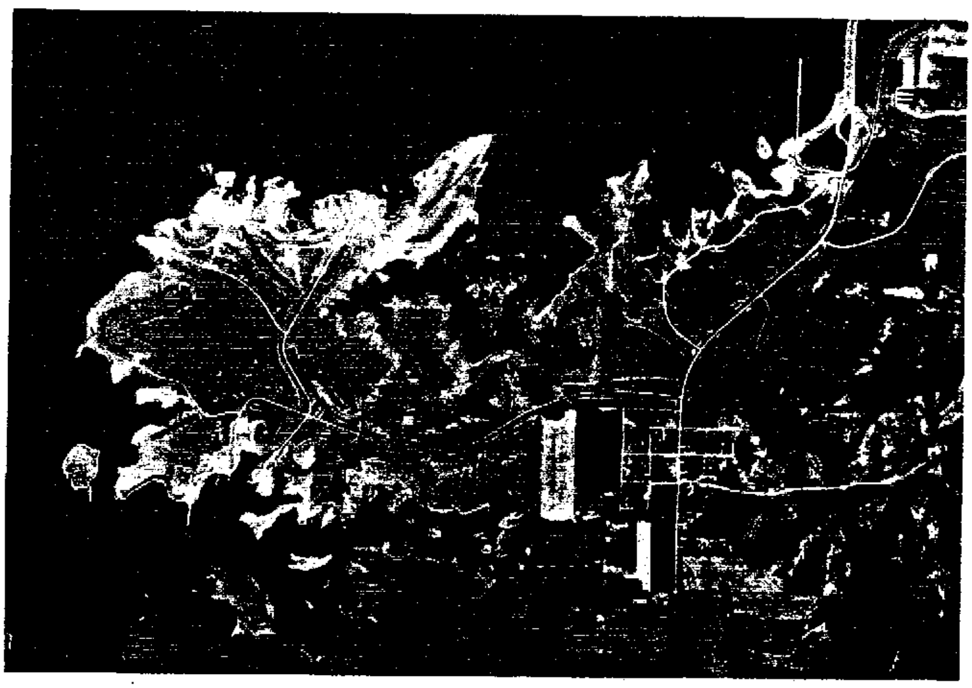


Figure 50. Aerial photograph of Lake Sakakawea State Park, July 14, 1976. Note the amount of change since 1966. This was probably primarily due to shoreline erosion by waves.

BANK EVOLUTION AND ULTIMATE BANK RECESSION

Another purpose of this study was to lay the foundation for predicting the (probable) ultimate bank recession rates along the eastern end of Lake Sakakawea. Although much more data must be collected before reliable predictions can be made, the data accumulated during this study have laid that foundation. But how does one predict ultimate recession?

A necessary step is the evaluation of the modes of bank evolution. The majority of the banks along eastern Lake Sakakawea basically evolve the same way as the majority of till banks along the Great Lakes (Carter and Guy, 1983; Sterrett, 1980; Mickelson and others, 1977; Quigley and others, 1977; Hadley, 1976; Quigley and Gelinas, 1976). This dominant mode of bank evolution at Lake Sakakawea is illustrated by bank profiles from stations 3 and 51. The cycle begins in late fall as the pool level is lowered and the lake begins to freeze; the sites have steep upper banks, possibly with gentler colluvium slopes at the toe (Figures 75 and 81, Appendix C). Varying degrees of thaw failure over the winter and spring causes more colluvium to accumulate at the toe and, by late spring, the banks tend to become relatively stable (Figures 75 and 81, Appendix C). Then, the pool level typically rises rapidly in response to the influx of snowmelt. Accompanying wave erosion removes toe colluvium and may even attack the primary bank material, causing undercutting and subsequent upper bank failure (Figures 76, 77, 82 and 83, Appendix C). Finally, in late summer or early fall, the pool level is lowered again and the banks once again become more stable as the colluvium slope expands toward the top of the banks (Figures 78 and 84, Appendix C).

There are various methods for predicting bank evolution and bank recession. They include computer modeling and bank stability analyses.

Computer Applications

Ahnert (1971) developed a program which predicts slope profile development based on several user-defined variables (e.g., lithology, structure). A modified version of such a program (including variables like pool level, and bank orientation vs. wind direction) may be useful at Lake Sakakawea. Another computer modeling procedure involves generating equations by using multivariate regression. These can be used to predict the bank recession at a site, within certain confidence limits, based on key dependent variables. Each of these computer techniques may be applicable to Lake Sakakawea, but more data are needed before either can be attempted, because the variables first must be defined statistically. Although they reflect the rates for the study period, the data collected thus far are only by coincidence statistically representative of long term erosion rates and causes.

Bank Stability Analysis

Another commonly used method for predicting bank evolution involves analyzing bank stability. The distribution of principal stresses in a slope is typically skewed, which causes planes of shear failure, or slip surfaces, to be curved (Carson and Kirkby, 1972, p.150). Methods of analyzing the stability of slip surfaces in slopes have been discussed by Fredlund and Krahn (1977), Patton and Hendron (1974), Sowers and Sowers (1970), and Terzaghi and Peck (1967). The most common methods derive the safety factor (SF) which is the ratio of measured shear strength to calculated shear stress. Theoretically, when the SF is less than one, failure will occur. Limit equilibrium methods, consisting largely of variations of methods of slices, and which use effective stresses, are the most commonly used techniques for computing the SF (Fredlund and Krahn, 1977). Because these methods take into consideration complex geometry and the reduction in soil strength along the slip surface due to pore pressures, they are the ideal techniques to use when measuring the SF for slumping in saturated, cohesive banks. However, as Patton and Hendron (1974) point out, pore pressure distributions should be evaluated carefully because they are often grossly underestimated.

Edil and Haas (1980), Mickelson and others (1977), and Edil and Vallejo (1980), have successfully used modified versions of Bishop's method of slices to calculate the SF along Great Lakes shorelines. They showed that slope evolution in coastal bluffs can be predicted with successive applications of the analysis.

In some cases the method of slices may be inadequate and analysis of other failure mechanisms may be necessary. This is especially true of wave-cut, overhanging banks, where the critical failure mechanisms commonly are translational shear, tensile failure or beam failure. Thorne and Tovey (1981) analyzed these types of failures and produced dimensionless stability charts which may be used to calculate the SF for each of the three failure mechanisms. They also developed stability equations for blocks that have previously fallen on slopes. Bank angle was found to be the most important parameter.

Finally, bank stability analyses may be useful in analyzing slope evolution at Lake Sakakawea but most methods do not account for wave erosion, overland erosion or thaw failure, which must also be considered in determining the ultimate stability of a bank. Because of the lack of geotechnical data, bank stability analyses could not be computed for Lake Sakakawea banks.

Other

A third technique for estimating ultimate recession involves using both erosion measurements and field observations. An example is the conventional technique used by the Corps of Engineers (Figure 4). However, as discussed earlier, this procedure did not work for the majority of range lines; the original ultimate recession predictions have been exceeded. But in the summer of 1984, during reconnaissance along the eastern end of Lake Sakakawea, it was observed that some range lines are characterized by relatively low, vegetated, stable banks. Therefore, further investigation of the range lines may provide better insight as to what are the important variables affecting ultimate recession at Lake Sakakawea.

By using field observations and analyzing profiles, aerial photographs, and bank recession data, an approximation of bank recession rates can be calculated for particular sites. Using these rates, bank recession or bank stability maps may be delineated. Given similar pool levels and wind parameters, this type of map should be generally accurate perhaps for up to five years but they would need to be updated as more data become available and shoreline conditions change. These maps can be used to plan land-management or to identify areas which should be artificially stabilized. For example, if a map of this type were delineated for Fort Stevenson State Park, it would be apparent that the banks south and west of the maintenance area are highly susceptible to erosion (bank recession rates are >3m/y, Table 9) and serious consideration should be given to stabilizing those banks.

Black (1981) also used recession maps in conjunction with an extended beach slope evolution model to predict the time in which a bank would ultimately stabilize. The model is similar to the Corps of Engineers technique and appears to be working for some sites at Rathbun Lake, Iowa.

In conclusion, although some of the data collected so far have provided a basis for evaluating bank erosion, much more data are needed and many factors must be considered before a serious attempt at predicting ultimate bank recession at Lake Sakakawea can be made. Some of these factors are: bank recession, profile and historical data, geotechnical data, stability analyses, statistical models, sedimentation rates, changing shoreline geology and geometry due to erosion, and future plans for the reservoir, including both upstream and downstream reaches. However, one fact is clear, ultimate bank recession at Lake Sakakawea depends primarily upon the amount of wave energy that reaches the unprotected banks. As long as the present pool management continues, the beaches and banks will not stabilize and bank recession will continue.

BANK STABILIZATION ALTERNATIVES

Protection of the bank toe from wave erosion is imperative to bank stabilization along most of the eastern end of Lake Sakakawea. The easiest way to prevent such erosion would be to keep the pool level at or below about 562.0m (1843.4 ft) msl. This would greatly reduce toe erosion and allow the banks to begin to stabilize. Bank recession would continue for many years but the rate and ultimate magnitude would be much less than if higher pool levels were maintained. The problem with this procedure is that a critical percentage of reservoir capacity would be lost.

Many alternative methods are available. A widely used approach is to protect the bank directly with rock fill, rip-rap, retaining walls, bulkheads or revetments (U.S. Army Corps of Engineers, 1980; Hadley, 1976). These methods are costly, though, and would be impractical for some of the higher banks. The use of groins and breakwaters should be restricted; although they can be successful, they must be well planned to avoid causing erosion by altering littoral drift and sediment deposition processes (Mickelson and others, 1977).

Regrading banks (Hadley, 1976) may be another viable alternative. This involves removing material from the top of the bank and regrading to an adequately stable profile. Of course, if the toe is not protected from further wave erosion, this method is impractical.

Another method involves artificial beach widening and nourishment (Carter and Guy, 1983). However, if not coupled with pool level regulation, this would be only a temporary protective measure because waves and currents would eventually remove the sediment.

Another solution may lie in the construction of diversion canals along the Missouri and Yellowstone rivers, and Lake Sakakawea. Excess water could be discharged into these canals rather than increasing pool level above 562.0m (1843.4 ft) msl. Besides helping to stop bank erosion at Lake Sakakawea, these canals would also supply water for farmers and municipalities. Unfortunately, the canals would undoubtedly create serious political problems.

Finally, various types of fast-growing, well-rooted vegetation could be used for protecting the base of some banks (Hoffman, 1978). Again, though, without concurrent pool level regulation, this method would be only a temporary deterrent at best.

In conclusion, the easiest, least expensive, and ultimately the most aesthetically pleasing method for promoting bank stabilization is pool level regulation at or below about 562.0m (1843.4 ft) msl. However, because this is probably not viable, the best methods for protecting and stabilizing problem areas would be: 1) armoring the toe of the bank with rip-rap or rock fill, or construction of revetments, retaining walls or bulkheads or, 2) a combination of regrading the bank, armoring the toe, and planting vegetation on the unprotected upper slope. Both of these methods may also require periodic sediment nourishment to prevent undercutting of the protective structure at the toe.

SUMMARY

1. Bank erosion is an important environmental problem at Lake Sakakawea and Lake Audubon. Not only is land lost, but water quality is adversely affected and reservoir storage capacity is decreased.
2. A typical sequence for erosion at Lake Sakakawea begins in late winter as frost, binding some of the sediment, undergoes sublimation. The loosened aggregates accumulate as a thin apron at the foot of steep banks. Spring thaw results in slab failures, followed by earthflows and mudflows. As summer approaches, the lake rises because of the snowmelt influx until the maximum pool level is reached sometime in mid-summer. Waves, generated by strong winds, easily erode the loose colluvium along the base of the banks. However, not all of the colluvium is eroded every year; sometimes the pool level does not reach the base of the banks and at other times, duration of high pool level is too brief for the removal of all the colluvium. But, if all the colluvium is eroded (as was the case during the summer of 1984), the waves can remove the primary sediment or bedrock, effectively undercutting the banks. At the top of such banks, extensional joints are initiated. The joints expand until bank failure releases the stresses. If the pool level is still high enough, the blocks tumble into the water. Otherwise, they accumulate along the base of the bank. Bank failure continues until a relatively stable profile has formed. Finally, late summer to late winter is an extended period of relative quiescence, after which time release of aggregates by sublimation again occurs.

3. The most important activating factor at Lake Sakakawea is wave erosion. It is responsible for about 87 percent of the total bank recession, which ranges from 0.6 to 5.9m (0.5 to 4.6m/yr). Measurement of aerial photographs for 1966 to 1976 yielded similar recession rates (1.2 to 4.3m/yr). Results indicate that banks with the highest recession rates are shorter than 5m, are composed of well-jointed till or mudstone, and face north or northeast. Also, regression analyses confirm the relationship between pool level and bank recession at Lake Sakakawea.
4. Thaw failure accounts for most of the remaining 13 percent of total bank recession at Lake Sakakawea. It is greatest for those banks facing west or northwest and which are composed of well-jointed till or mudstone.
5. At Lake Audubon, the most important activating factors are lake ice-shove and subsequent wave erosion. Those factors caused most of the 0.8 to 1.4m (0.69 to 1.22m/yr) of recorded bank recession there.
6. Ultimate bank recession at Lake Sakakawea depends primarily upon the amount of wave energy that reaches unprotected banks. As long as the present pool management continues, beaches and banks will not stabilize and, therefore, bank recession will continue.
7. The processes at the two lakes, but especially Lake Sakakawea, are similar in importance to those processes acting along the banks of Orwell Lake, Minnesota (Reid, 1984, 1985).

RECOMMENDATIONS FOR FURTHER STUDY

1. Although much information has been gathered about erosion rates and causes in the past 15 months, there are some voids in the data and, perhaps more important, there is little appreciation for the statistical validity of the data. To assume that the data collected are representative of typical long term rates of erosion for the two lakes is statistically without foundation. Therefore, any addition to the data would help to evaluate how representative they are. Also, future studies should be expanded farther west on both lakes. From casual observations and the study of aerial photographs, it is apparent that the conditions (e.g., maximum fetch and glacial till thickness) farther west along Lake Sakakawea are different from those in the study area. Furthermore, the range lines established by the Corps of Engineers should be further investigated and evaluated.
2. The interrelationship of the erosion variables needs to be assessed further. Control sites should be chosen such that two or three variables are held constant. To investigate the significance of bank geology to wave erosion, for example, sites which have similar bank orientation, bank geometry, and offshore conditions but different stratigraphy should be sought and studied. However, this may be more easily said than done because of problems in identifying and reaching such sites.

3. The significance of erosion variables which were not studied (or only very briefly studied) needs to be evaluated. These include the following:

   a) Wave energy and wave types: How much wave energy is generated by winds during high pool levels and, how does that relate to bank erosion? How important is fetch and refraction in affecting wave energy at Lake Sakakawea? Do certain types of waves cause more erosion than others when they break against the banks?

   b) Offshore sediments: How does the type and amount of offshore sediment that is available for corrasion affect erosion magnitudes? How does the type and amount of offshore sediments affect the offshore bathymetry?

   c) Offshore bathymetry: Where is the eroded sediment going; are stable offshore platforms being built or is the sediment being transported into deep water? If offshore platforms are being built, how does their size affect wave energy? How closely related are variations in bank recession and the interaction of storm waves with the offshore bathymetry and sediment system?

   d) Precipitation: How do differences in precipitation around the lake affect the magnitudes of overland erosion and the moisture content of sediments?

   e) Moisture content: How does the antecedent moisture content of the different lithologies at Lake Sakakawea affect the magnitude of erosion processes?

   f) Frost: How does the depth of frost at specific sites affect the quantity of thaw-induced failure at those sites?

g) Freeze-thaw cycles: Do more freeze-thaw cycles indeed cause more thaw failure?

h) Stratigraphy: How will the stratigraphy change at a site as the bank recedes? If it does change, how will it affect erosion rates? (Also, much more work needs to be done on correlation and interpretation of the glacial stratigraphy.)

4. The role of groundwater needs to be evaluated. Piezometers should be installed at certain sites to assess groundwater flow, groundwater fluctuations due to pool level fluctuations (especially rapid drawdown), and the role of groundwater in slope stability. Detailed analysis of the large slump below Riverdale may provide insight into the role of groundwater at that site.

5. Expansion of the analysis of geotechnical properties, as well as bank stability analyses should be undertaken. Although detailed analyses of texture, structure and mineralogy have been completed, other properties are also important to bank stability. These include: the amount of water stable aggregates, unconfined compressive strength, Atterburg limits, angle of internal friction, cohesion, and, because most bank failures occur along joint planes, the shear strength along joint planes. Also, the depth of secondary joints in relation to bank height may be another important factor to consider in bank stability analyses.

6. Regression analyses should be repeated and erosion prediction equations should be generated when adequate data are collected to ensure statistically valid equations.

7. Probable ultimate bank recession maps should be made using historical data (aerial photo and range line), slope stability analyses,

statistical techniques, field measurements, observations, sedimentation and reservoir-use projections, and other pertinent data.

8. Using bank recession predictions, etc., particularly susceptible sites should be identified and stabilization alternatives should be studied.

APPENDICES

APPENDIX A

Physical Characteristics of Bank Samples

EXPLANATION

In the following tables the samples analyzed are defined by a letter which is preceded by the station number (Figure 2). The letters refer to the stratigraphic position at the sites. The letter A defines the lowest visible unit, irrespective of its actual age.

The formations are abbreviated in the following tables (and following appendices) as follows:

O. = Oahe Formation

U.S.S. = Upper Snow School Formation

L.S.S. = Lower Snow School Formation

U.H.V. = Upper Horseshoe Valley Formation

L.H.V. = Lower Horseshoe Valley Formation

U.M.H. = Upper Medicine Hill Formation

L.M.H. = Lower Medicine Hill Formation

S.B. = Sentinel Butte Formation

TABLE 26

Color, Moisture Content and Dry Density of Bank Samples, Lakes Sakakawea and Audubon, North Dakota

Sample	Predominant Dry Color	Moisture Content (%) and Depth (m)	Dry Density (gm/cc)	Formation
Lake Sakakawea				
1A	gray (10 YR 5/1)	--	--	S.B.
1B	lt. brownish gray (2.5 Y 6/2)	16.8 (1.3)	2.56	U.S.S.
1C	dk. grayish brown (10 YR 4/2)	--	--	O.
2A	gray (5 Y 6/1)	1.1 (3.0)	1.99	S.B.
2B	lt. gray (2.5 Y 7/2)	--	--	S.B.
2C	lt. gray (5 Y 6/1)	--	--	U.S.S.
2D	grayish brown (10 YR 5/2)	--	--	O.
3A	pale brown (10 YR 6/3)	11.6 (0.6)	2.82	U.S.S.
4A	lt. brownish gray (2.5 Y 6/2)	--	--	L.S.S.
4B	lt. yellowish brown (2.5 Y 6/4)	13.8 (2.0)	2.61	U.S.S.
5A	red (2.5 Y 5/8)	--	--	L.S.S.
5B	lt. gray (2.5 Y 7/2)	5.8 (1.5)	3.02	L.S.S.
5C	lt. brownish gray (2.5 Y 6/2)	2.3 (1.0)	2.83	U.S.S.
7A	grayish brown (2.5 Y 5/2)	11.3 (6.0)	3.22	U.M.H.
7B	pale brown (10 YR 6/3)	--	--	L.S.S.

TABLE 26 (continued)

Sample	Predominant Dry Color	Moisture Content (%) and Depth (m)	Dry Density (gm/cc)	Formation
Lake Sakakawea				
7C	lt. brownish gray (2.5 Y 6/2)	--	--	U.S.S.
50A	lt. brownish gray (2.5 Y 6/2)	11.9 (6.1)	2.37	S.B.
51A	lt. yellowish brown (2.5 YR 6/4)	--	--	L.H.V.
51B	lt. brownish gray (2.5 Y 6/2)	0.5 (5.3)	1.42	U.H.V.
52A	lt. brownish gray (2.5 Y 6/2)	10.0 (4.5)	3.18	U.M.H.
52B	lt. yellowish brown (2.5 Y 6/4)	0.4 (4.0)	1.86	U.H.V.
52C	dk. grayish brown (2.5 Y 4/2)	--	--	O.
53A	lt. yellowish brown (2.5 Y 6/4)	--	--	S.B.
53B	lt. gray (2.5 Y 7/2)	4.6 (2.5)	2.43	U.M.H.
56A	lt. gray (5 Y 7/1)	--	--	S.B.
56B	lt. brownish gray (2.5 Y 6/2)	--	--	S.B.
56C	lt. yellowish brown (2.5 Y 6/4)	--	--	U.S.S.
57A	pale olive (5 Y 6/3)	--	--	S.B.
57B	lt. brownish gray (2.5 Y 6/2)	7.0 (5.5)	2.87	S.B.
57C	pale yellow (2.5 Y 7/4)	2.3 (5.4)	2.55	S.B.
57D	pale olive (5 Y 6/3)	2.8 (5.0)	3.61	U.S.S.

TABLE 26 (continued)

Sample	Predominant Dry Color	Moisture Content (%) and Depth (m)	Dry Density (gm/cc)	Formation
Lake Sakakawea				
57E	lt. gray (5 Y 7/2)	--	--	O.
58A	lt. gray (10 YR 7/1)	3.9 (6.0)	3.09	U.M.H.
60A	lt. brownish gray (2.5 Y 6/2)	--	--	U.S.S.
61A	pale olive (5 Y 6/3)	11.1 (5.0)	1.70	S.B.
61B	lt. brownish gray (10 YR 6/2)	30.0 (1.3)	4.51	S.B.
Lake Audubon				
1A	lt. brownish gray (2.5 Y 6/2)	13.8 (0.4)	3.19	U.S.S.

TABLE 27

Texture of Bank Samples, Lakes Sakakawea and Audubon, North Dakota

Sample	% Sand	% Silt	% Clay	Textural Name	Sorting	Skewness	Kurtosis	Median Diameter	Formation
Lake Sakakawea									
1A	0.7	41.2	58.1	silty clay	1.647	-0.003	0.964	8.2 Ø	S.B.
1B	18.7	53.4	27.9	silty clay loam	2.770	-0.078	1.195	6.5 Ø	U.S.S.
1C	9.7	72.4	17.9	silt loam	1.934	0.222	1.556	5.8 Ø	O.
2A	0.3	43.1	56.6	silty clay	1.653	4.828	1.112	8.3 Ø	S.B.
2B	0.9	67.5	31.6	silty clay loam	2.551	0.176	0.662	7.3 Ø	S.B.
2C	27.0	39.1	33.9	clay loam	2.884	-0.148	0.882	6.8 Ø	U.S.S.
2D	7.0	58.2	34.8	silty clay loam	3.172	-0.147	1.104	7.4 Ø	O.
3A	24.9	47.6	27.5	clay loam	2.960	0.175	0.639	5.4 Ø	U.S.S.
4A	80.9	10.1	9.0	loamy sand	2.003	0.577	4.971	2.1 Ø	L.S.S.
4B	24.8	42.4	32.8	clay loam	3.735	-0.137	0.767	6.8 Ø	U.S.S.
5A	64.7	24.4	10.9	sandy loam	2.072	0.736	1.807	3.3 Ø	L.S.S.
5B	70.2	14.5	15.3	sandy loam	2.132	0.797	4.134	2.8 Ø	L.S.S.
5C	31.7	32.7	35.6	clay loam	3.233	0.179	0.501	5.8 Ø	U.S.S.
7A	28.5	46.9	24.6	loam	3.500	0.045	0.918	5.5 Ø	U.M.H.
7B	58.4	31.0	10.6	sandy loam	2.546	0.677	1.642	3.2 Ø	L.S.S.
7C	24.2	42.2	33.6	clay loam	3.233	0.080	0.927	6.3 Ø	U.S.S.
50A	1.4	70.0	28.6	silty clay loam	2.141	0.360	0.922	6.8 Ø	S.B.
51A	68.4	14.1	17.5	sandy loam	2.741	0.612	1.388	1.8 Ø	L.H.V.
51B	31.3	36.4	32.3	clay loam	4.074	0.069	0.731	5.8 Ø	U.H.V.
52A	22.7	51.3	26.0	silt loam	3.148	-0.077	0.982	5.9 Ø	U.M.H.
52B	33.6	33.5	32.9	clay loam	2.916	0.237	0.522	5.5 Ø	U.H.V.
52C	7.2	82.0	10.8	silt	1.640	0.357	1.567	5.4 Ø	O.
53A	9.6	18.9	71.5	clay	2.142	0.493	1.304	5.5 Ø	S.B.
53B	20.9	45.4	33.7	clay loam	2.542	0.074	0.990	5.8 Ø	U.M.H.
56A	0.1	28.0	71.9	clay	2.983	0.102	0.552	8.3 Ø	S.B.
56B	2.2	52.0	45.8	silty clay	2.754	-0.890	0.597	8.0 Ø	S.B.
56C	30.7	37.6	31.7	clay loam	3.937	0.029	0.988	5.1 Ø	U.S.S.

TABLE 27 (continued)

Sample	% Sand	% Silt	% Clay	Textural Name	Sorting	Skewness	Kurtosis	Median Diameter	Formation
Lake Sakakawea									
57A	0.6	47.8	51.6	silty clay	1.835	0.128	0.923	8.5 Ø	S.B.
57B	1.8	33.1	65.1	clay	1.998	0.133	1.234	8.2 Ø	S.B.
57C	0.5	48.9	50.6	silty clay	1.730	0.070	0.977	8.5 Ø	S.B.
57D	31.3	35.3	33.2	clay loam	3.563	-0.012	0.844	5.6 Ø	U.S.S.
57E	7.5	74.6	17.9	silt loam	1.756	0.432	1.385	5.4 Ø	O.
58A	26.7	37.9	35.4	clay loam	3.403	-0.001	0.817	6.5 Ø	U.M.H.
60A	25.1	39.5	35.4	clay loam	3.898	-0.054	0.781	7.7 Ø	U.S.S.
61A	0.2	58.1	41.7	silty clay	1.828	0.121	0.946	7.8 Ø	S.B.
61B	7.6	59.8	32.6	silty clay loam	2.978	0.204	0.714	6.7 Ø	S.B.
Lake Audubon									
1A	25.4	43.3	31.3	clay loam	3.937	-0.166	0.845	6.5 Ø	U.S.S.

TABLE 28

Average Clay Mineral Ratios for the Sentinel Butte Formation, Lake Sakakawea, North Dakota

Number of Samples	Kaolinite	Chlorite	Illite/ Muscovite	Smectite
9	.08	.08	.18	.66

TABLE 29

Comparison of Clay Mineral Ratios for Glacial Till Samples, Lakes Sakakawea and Audubon, North Dakota

Sample	Kaolinite	Chlorite	Illite/ Muscovite	Smectite	Formation
Lake Sakakawea					
1B	.06	.02	.11	.81	U.S.S.
2C	.16	.09	.35	.40	U.S.S.
3A	.11	.04	.24	.61	U.S.S.
4B	.09	.04	.27	.60	U.S.S.
5C	.13	.10	.35	.42	U.S.S.
7A	.30	0	.27	.43	U.M.H.
7C	.11	.09	.35	.45	U.S.S.
51B	.12	.10	.22	.56	U.H.V.
52A	.11	0	.12	.77	U.M.H.
52B	.20	0	.20	.60	U.H.V.
53B	.30	.25	.28	.17	U.M.H.
56C	.11	.02	.13	.74	U.S.S.
57D	.13	.10	.22	.55	U.S.S.
58A	.08	.05	.17	.70	U.M.H.
60A	.09	.09	.13	.69	U.S.S.
Lake Audubon					
1A	.11	.08	.29	.52	U.S.S.

TABLE 30

Matrix Dolomite and Calcite Percentages for Glacial Till Samples, Lakes Sakakawea and Audubon, North Dakota

Sample	% Dolomite	% Calcite	% Total Carbonate	Formation
Lake Sakakawea				
1B	10.5	9.2	19.7	U.S.S.
2C	7.1	3.4	10.5	U.S.S.
3A	14.0	6.8	20.8	U.S.S.
4B	11.3	2.7	14.0	U.S.S.
5C	12.6	12.2	24.8	U.S.S.
7A	11.1	5.5	16.6	U.M.H.
7C	8.2	15.9	24.1	U.S.S.
51B	10.0	5.9	15.9	U.H.V.
52A	10.6	3.6	14.2	U.M.H.
52B	11.9	4.3	16.2	U.H.V.
53B	9.8	4.0	13.8	U.M.H.
56C	13.5	6.3	19.8	U.S.S.
57D	14.0	2.9	16.9	U.S.S.
58A	9.7	3.5	13.2	U.M.H.
60A	12.3	6.0	18.3	U.S.S.
Lake Audubon				
1A	11.3	9.6	20.9	U.S.S.

TABLE 31

Coarse Sand Lithology of Glacial Till Samples, Lakes Sakakawea and Audubon, North Dakota

Sample	% Dolomite	% Limestone	% Crystalline	% Quartz & Feldspar	% Shale	% Sandstone	% Other	Total Number of Grains	Formation
Lake Sakakawea									
1B	5.2	6.1	30.0	15.0	12.2	31.5	0	213	U.S.S.
2C	12.9	4.3	18.3	39.8	10.7	14.0	0	93	U.S.S.
3A	9.5	10.2	19.7	36.1	19.7	13.3	1.9	274	U.S.S.
4B	9.0	10.3	15.5	27.5	28.7	6.4	2.6	233	U.S.S.
5C	9.2	9.8	27.2	29.2	16.4	6.2	2.0	305	U.S.S.
7A	3.8	6.9	5.4	8.8	21.1	14.0	40.0	317	U.M.H.
7C	12.4	16.3	7.8	23.5	30.1	6.5	3.3	153	U.S.S.
51B	16.1	12.9	16.1	30.4	18.6	5.4	0.7	280	U.H.V.
52A	4.7	9.9	10.4	13.7	47.6	9.0	4.7	212	U.M.H.
52B	6.3	5.7	38.8	18.3	18.0	11.1	1.8	333	U.H.V.
53B	9.1	10.4	11.7	28.6	22.1	18.2	0	77	U.M.H.
56C	12.1	6.6	30.0	26.9	17.2	6.9	0.3	290	U.S.S.
57D	12.2	6.9	18.3	36.6	17.2	4.1	4.7	344	U.S.S.
58A	6.4	7.6	7.2	14.7	51.8	11.5	0.8	251	U.M.H.
60A	9.6	10.5	34.3	19.7	15.5	9.6	0.8	239	U.S.S.
Lake Audubon									
1A	12.5	8.2	27.6	29.2	13.6	8.9	0	257	U.S.S.

APPENDIX B

Cumulative Average Bank Recession for Each Station

EXPLANATION

Measurement dates are at inflection points.

Day 1 = April 9, 1983
Day 267 = January 1, 1984
Day 503 = August 24, 1984

FIGURE 51.

CUMULATIVE AVERAGE BANK RECESSION, STATION 1

TOTAL=3.709M PINS=14 LENGTH=115.9M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=NE
MAXIMUM BANK HEIGHT=3.7M

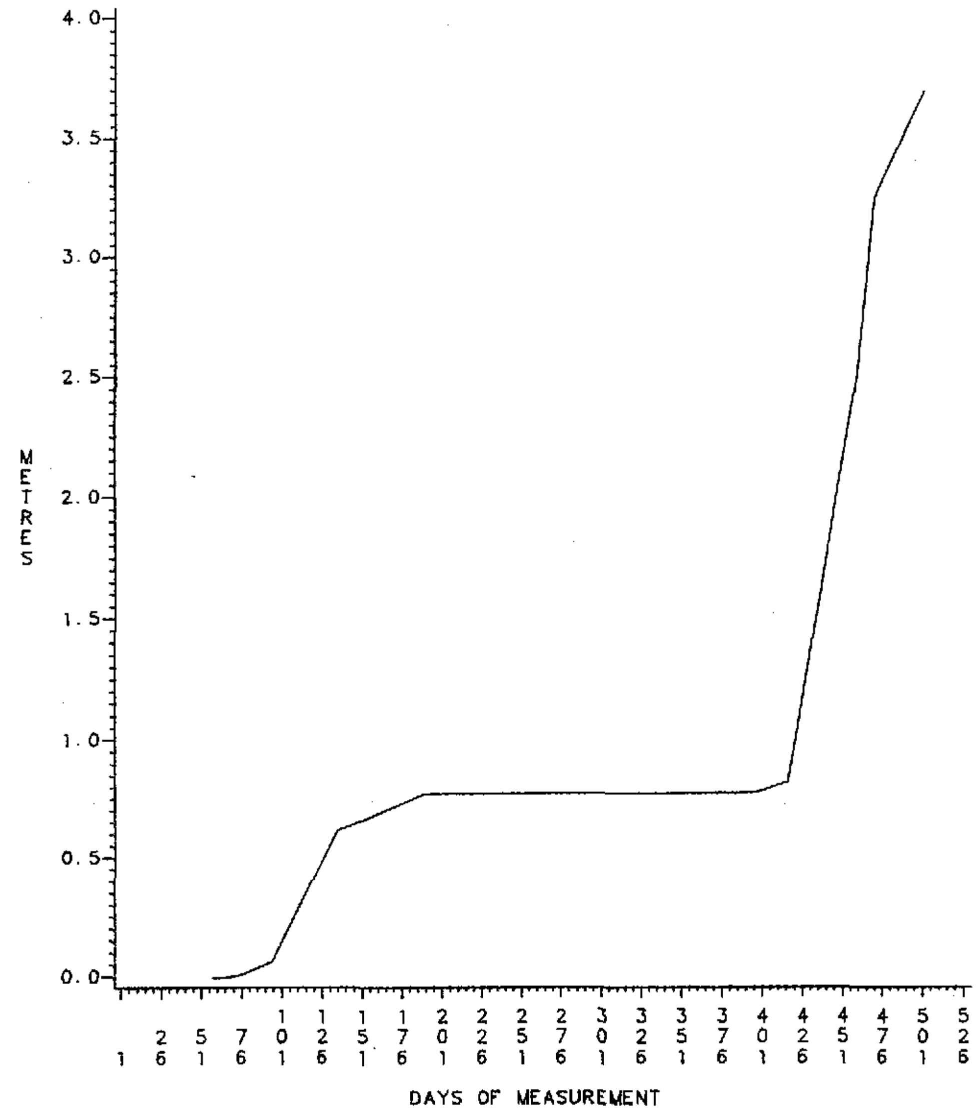


FIGURE 52.

CUMULATIVE AVERAGE BANK RECESSION, STATION 2

TOTAL=1.945M PINS=8 LENGTH=47.0M
PREDOMINANT LITHOLOGY=MUDSTONE AVERAGE ORIENTATION=NE
MAXIMUM BANK HEIGHT=7.0M

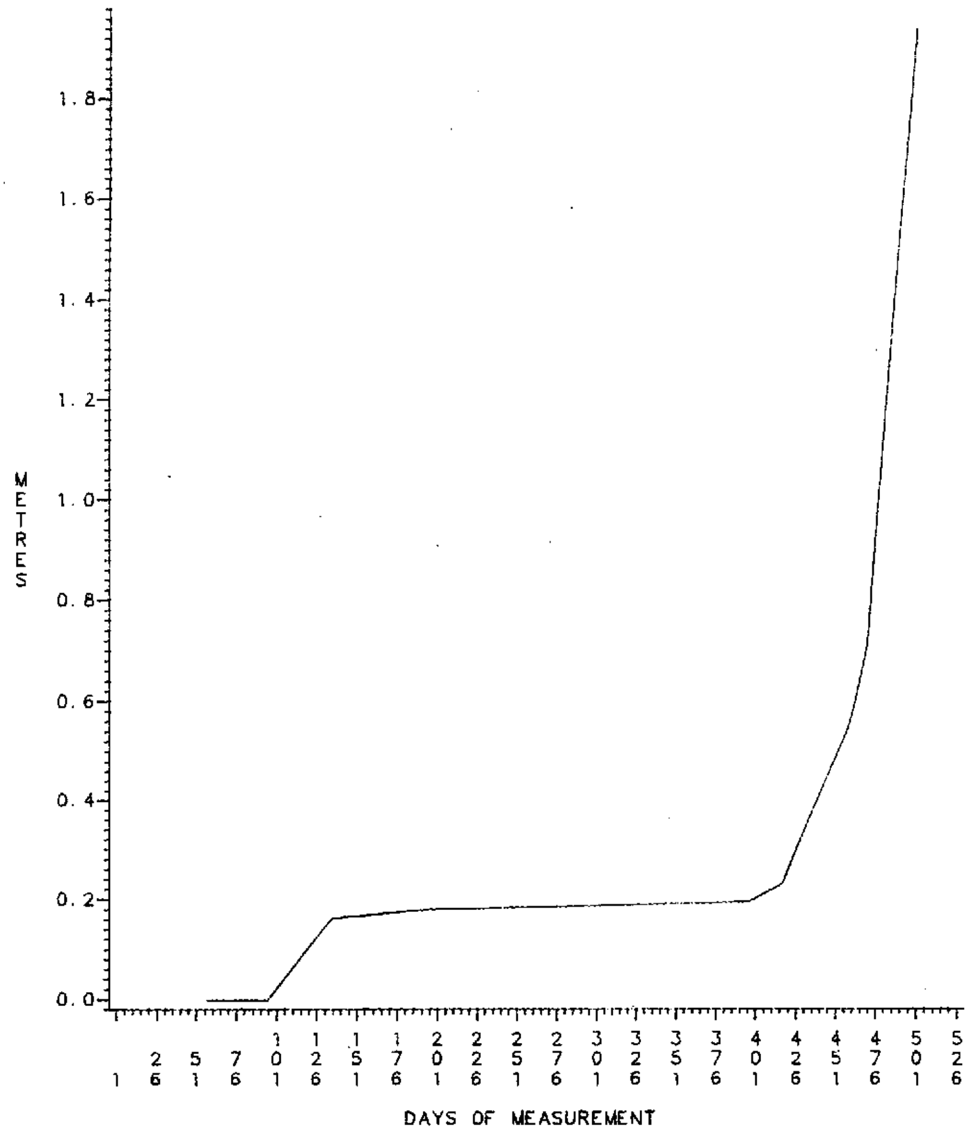


FIGURE 53.

CUMULATIVE AVERAGE BANK RECESSION, STATION 3

TOTAL=2.499M PINS=6 LENGTH=61.0M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=N
MAXIMUM BANK HEIGHT=3.8M

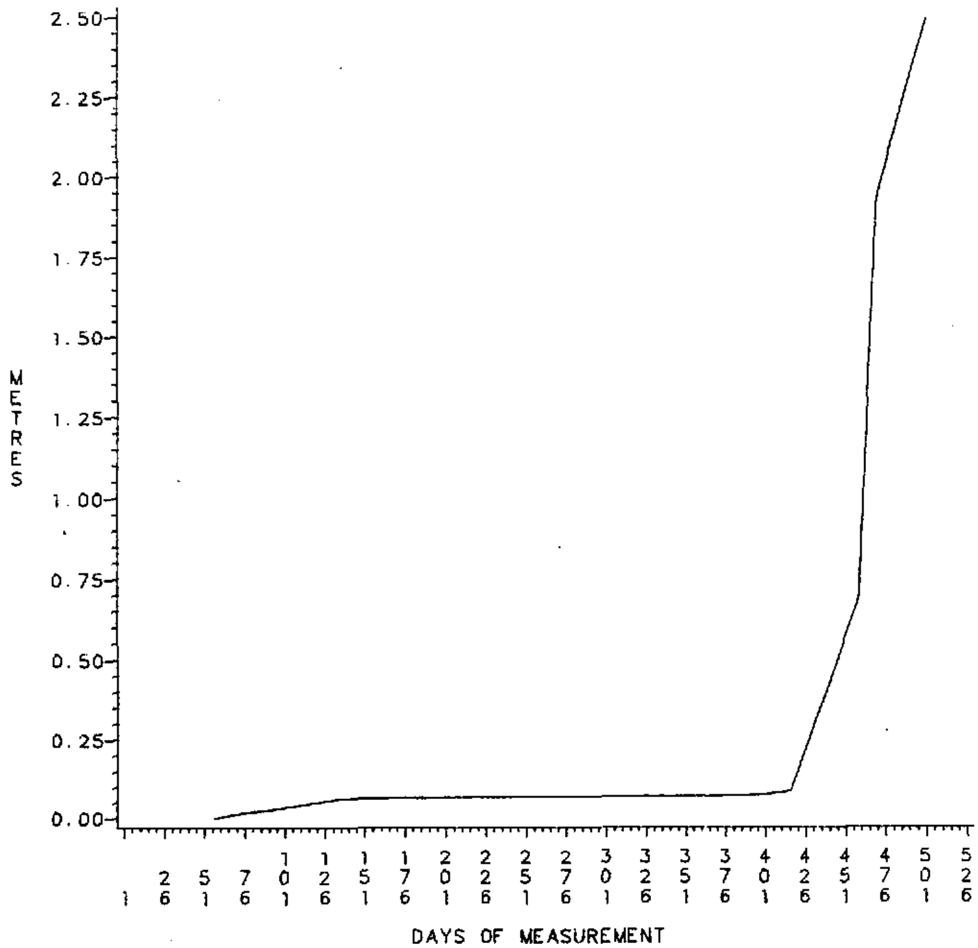


FIGURE 54.

CUMULATIVE AVERAGE BANK RECESSION, STATION 4

TOTAL=2.136M PINS=4 LENGTH=36.6M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=NW
MAXIMUM BANK HEIGHT=4.5M

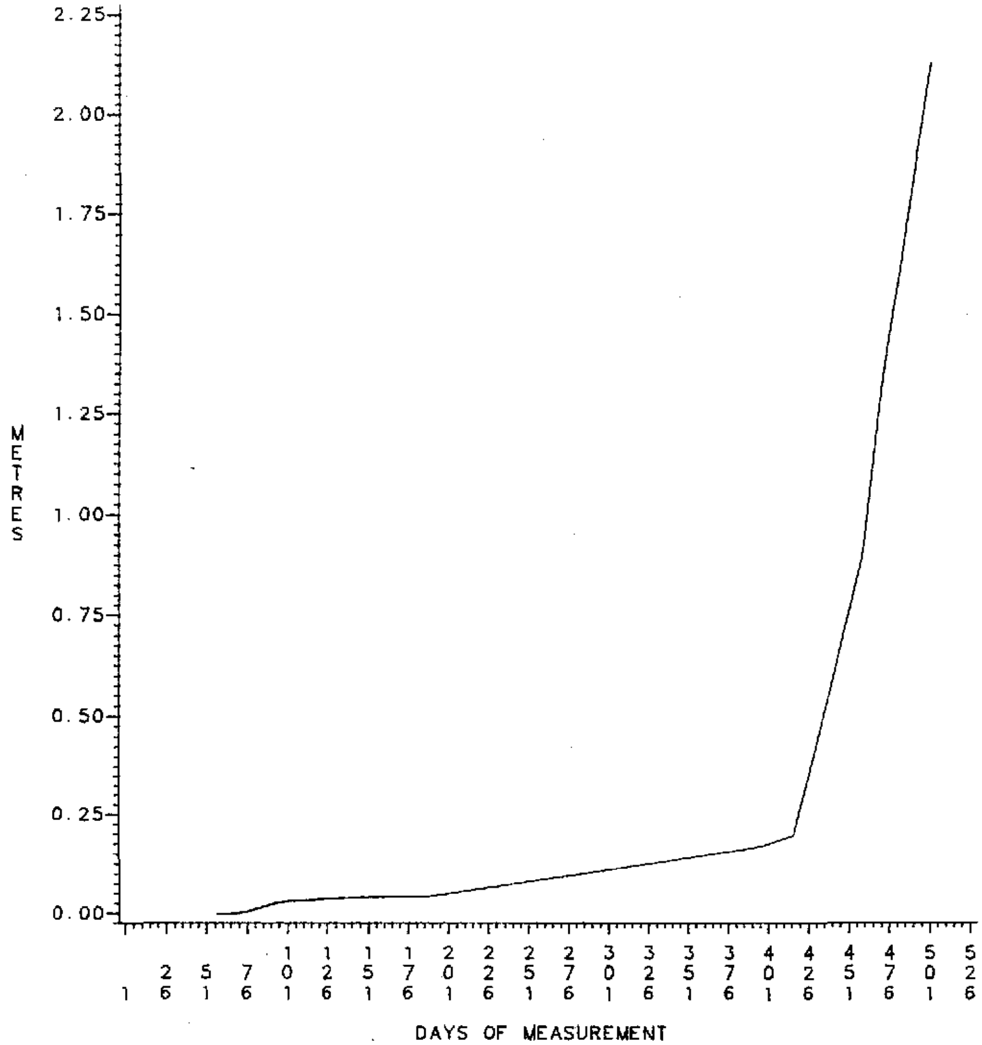


FIGURE 55.

CUMULATIVE AVERAGE BANK RECESSION, STATION 5

TOTAL=1.933M PINS=4 LENGTH=18.3M
PREDOMINANT LITHOLOGY=TILL/SAND AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=5.0M

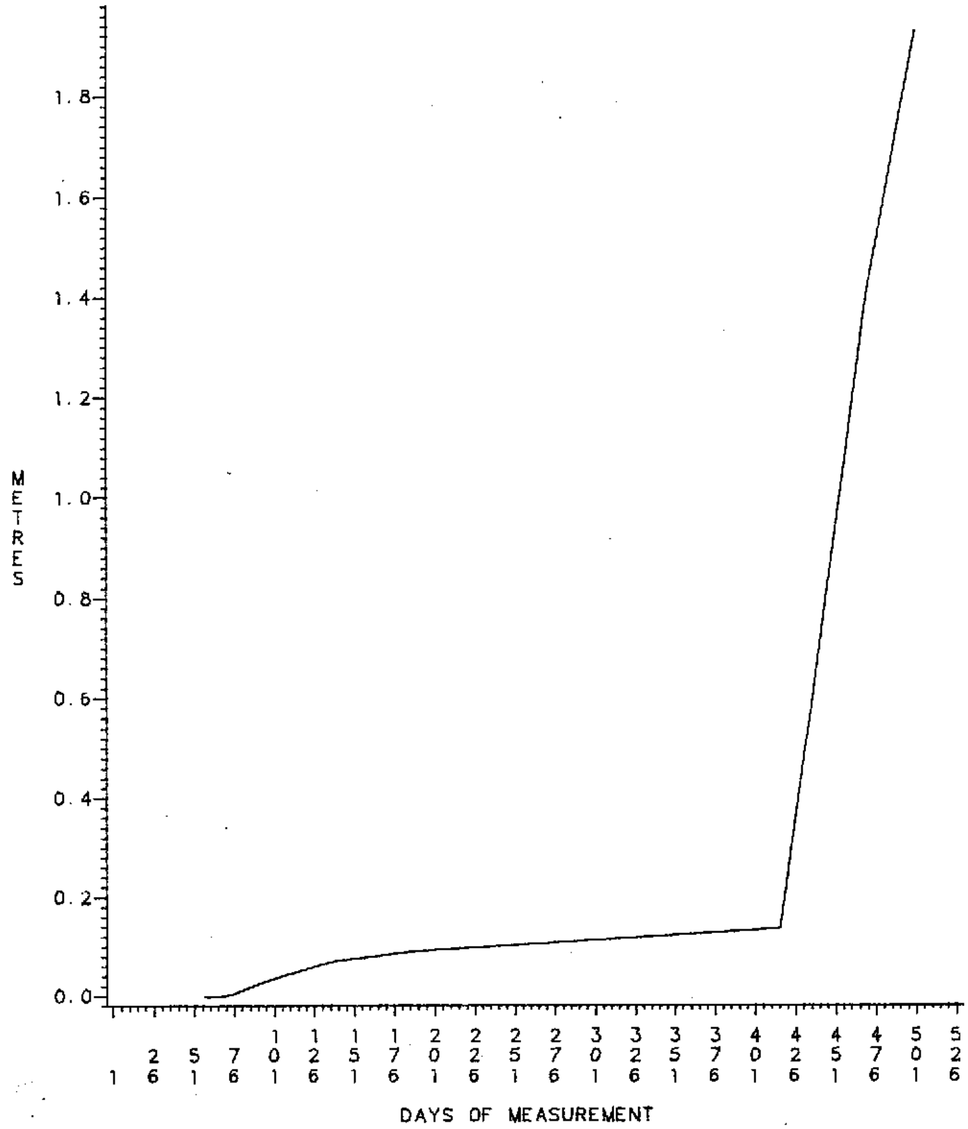


FIGURE 56.

CUMULATIVE AVERAGE BANK RECESSION, STATION 6

TOTAL=0.872M PINS=3 LENGTH=18.3M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=N
MAXIMUM BANK HEIGHT=18.0M

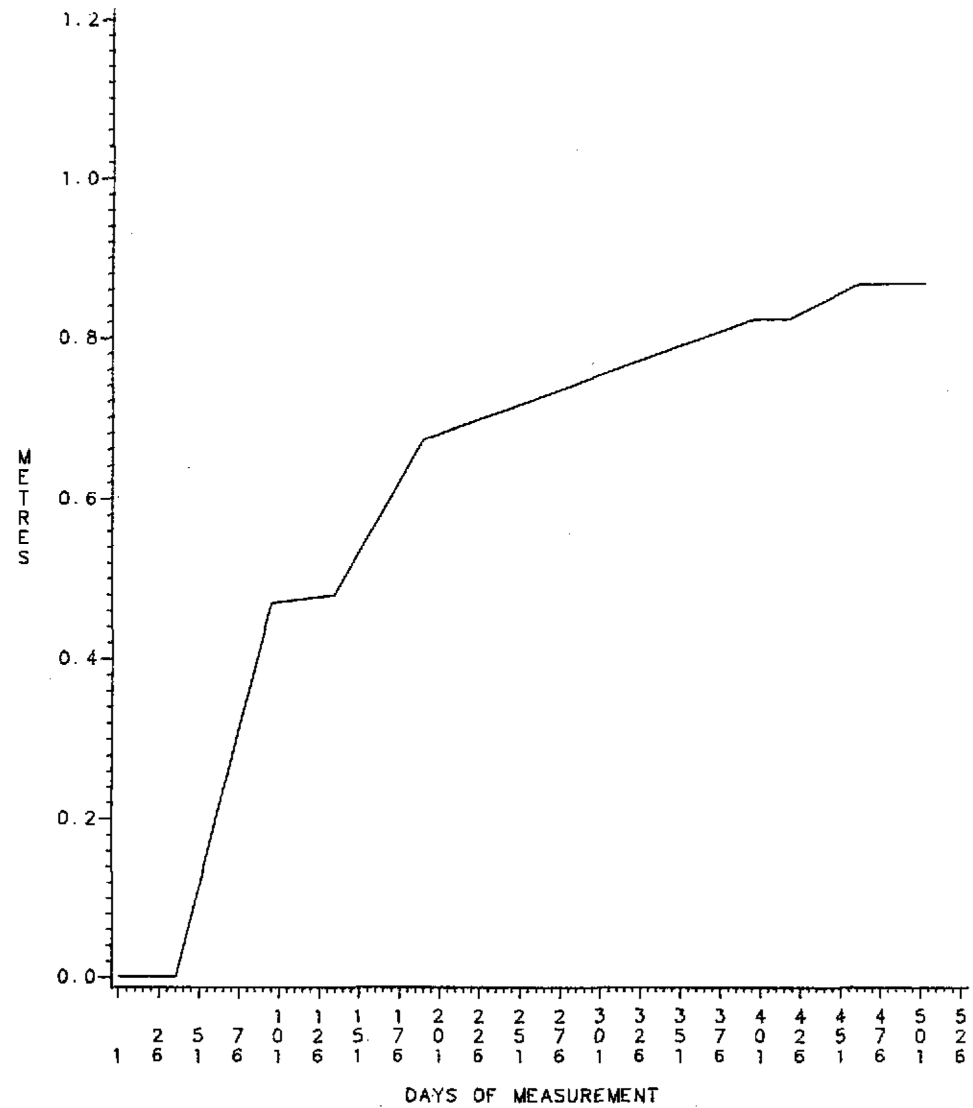


FIGURE 57.

CUMULATIVE AVERAGE BANK RECESSION, STATION 7

TOTAL=3.190M PINS=4 LENGTH=27.5M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=N
MAXIMUM BANK HEIGHT=14.5M

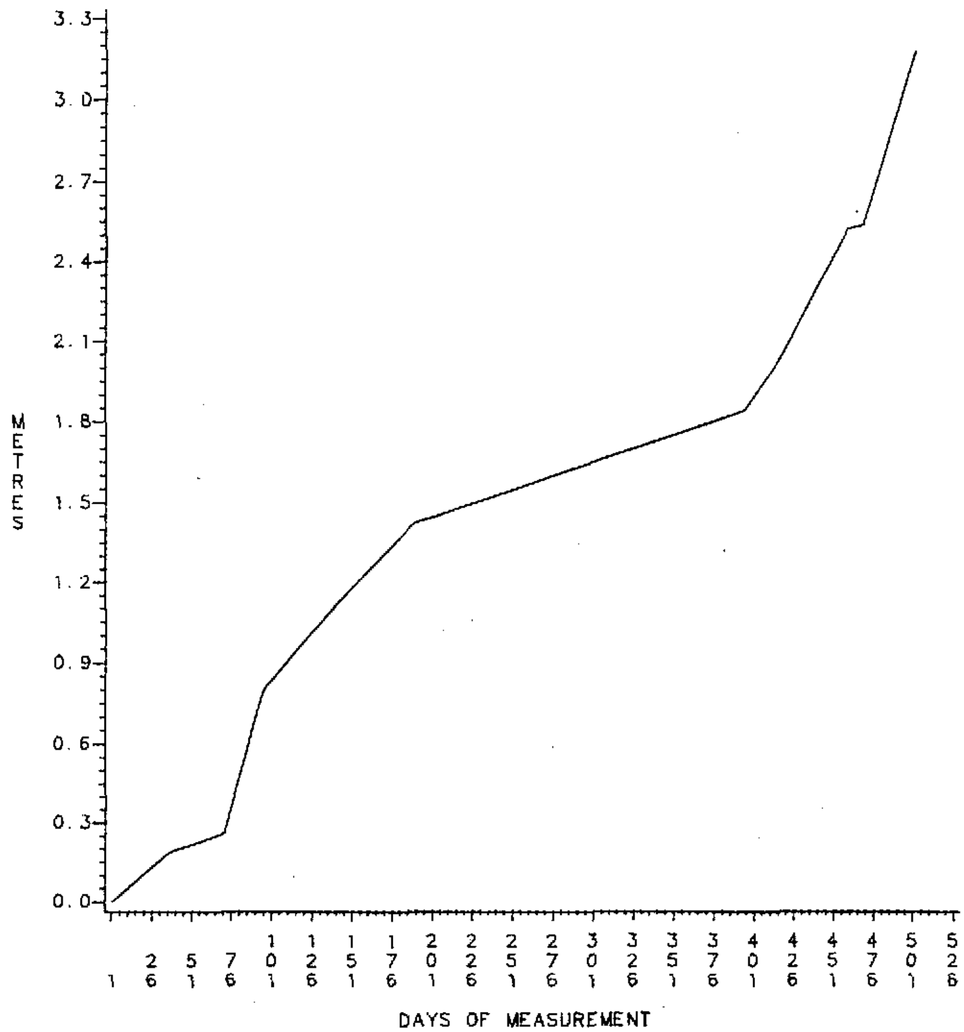


FIGURE 58.

CUMULATIVE AVERAGE BANK RECESSION, STATION 50

TOTAL=1.012M PINS=5 LENGTH=24.4M
PREDOMINANT LITHOLOGY=TILL/MUDSTONE AVERAGE ORIENTATION=NW
MAXIMUM BANK HEIGHT=20.9M

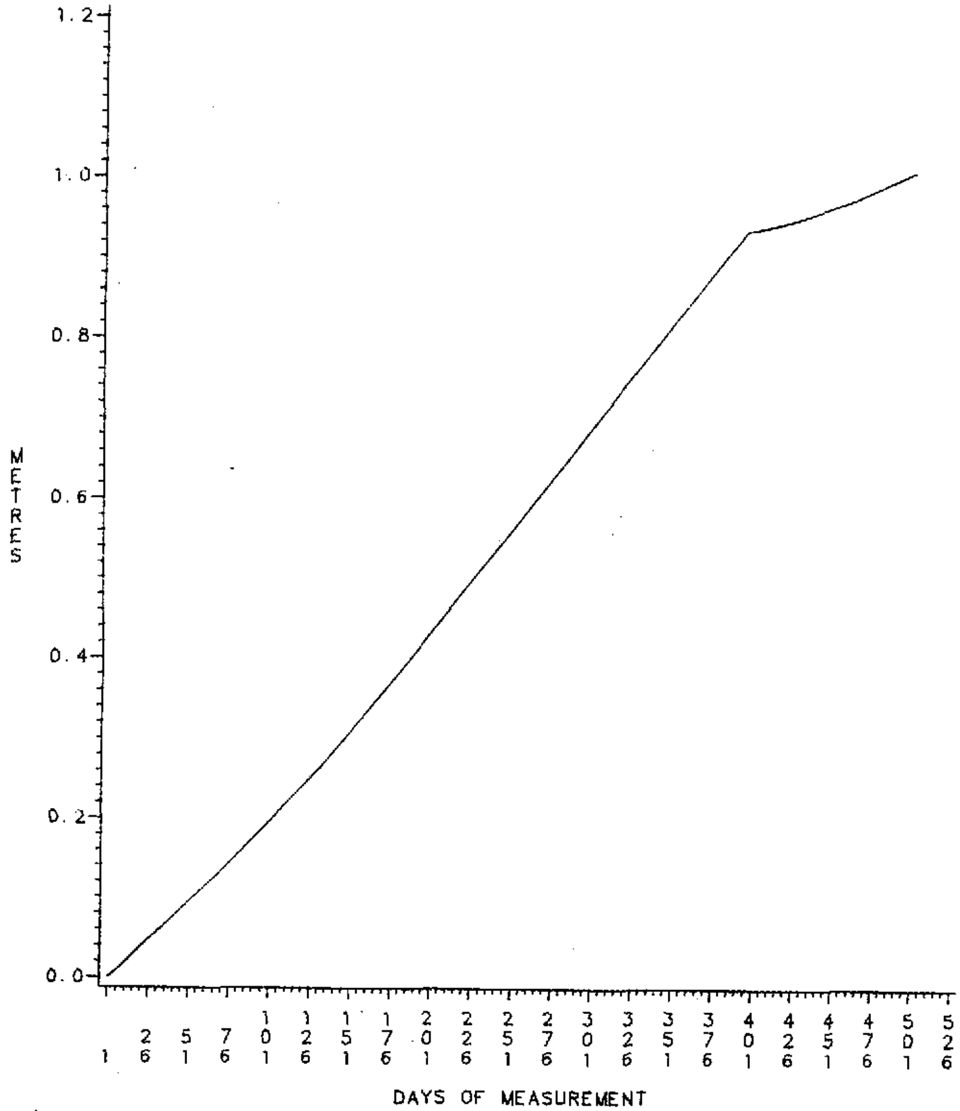


FIGURE 59.

CUMULATIVE AVERAGE BANK RECESSION, STATION 51

TOTAL=2.801M PINS=12 LENGTH=83.9M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=12.4M

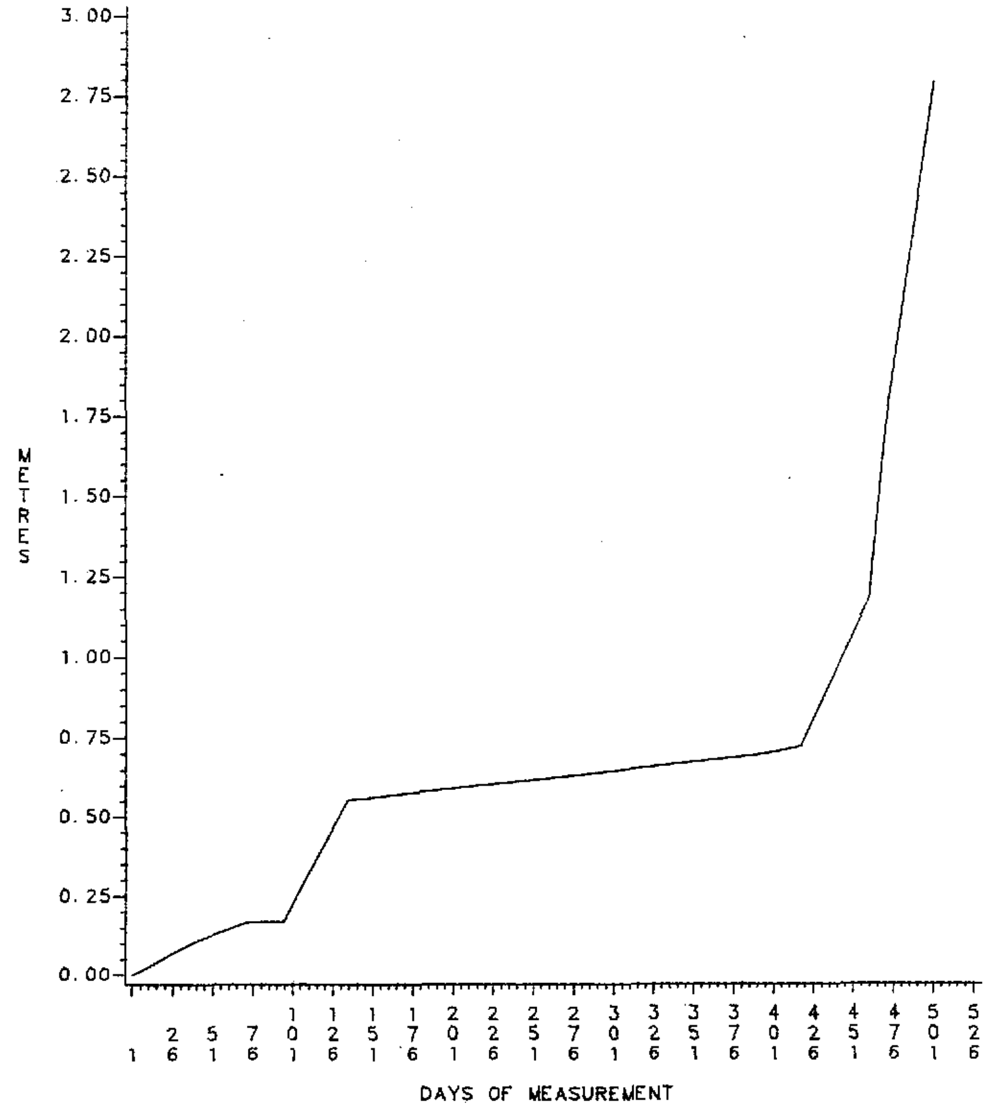


FIGURE 60.

CUMULATIVE AVERAGE BANK RECESSION, STATION 52

TOTAL=2.389M PINS=7 LENGTH=54.9M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=7M

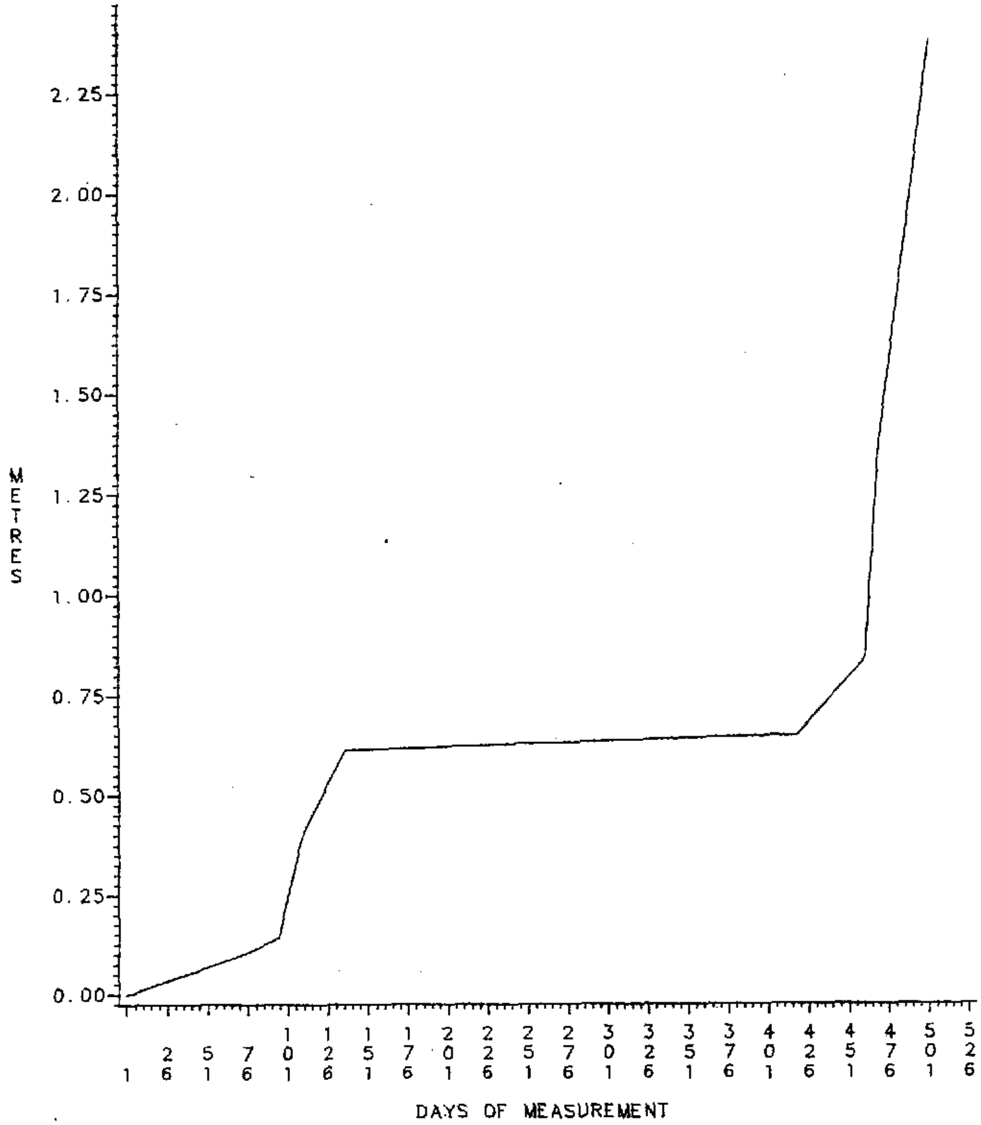


FIGURE 61.

CUMULATIVE AVERAGE BANK RECESSION, STATION 53

TOTAL=0.63M PINS=12 LENGTH=134.2M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=S
MAXIMUM BANK HEIGHT=9.0M

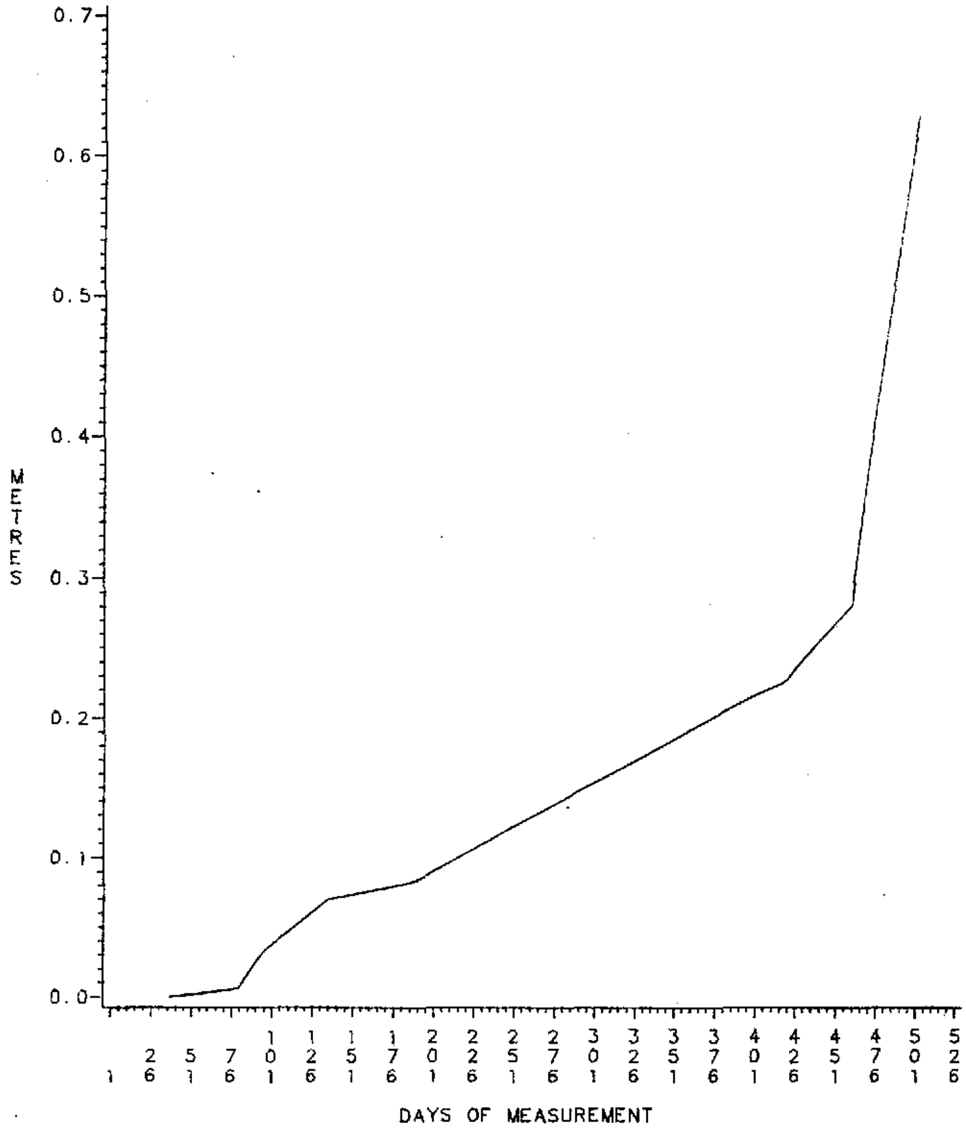


FIGURE 62.

CUMULATIVE AVERAGE BANK RECESSION, STATION 54

TOTAL=3.167M PINS=5 LENGTH=24.4M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=SW
MAXIMUM BANK HEIGHT=6.2M

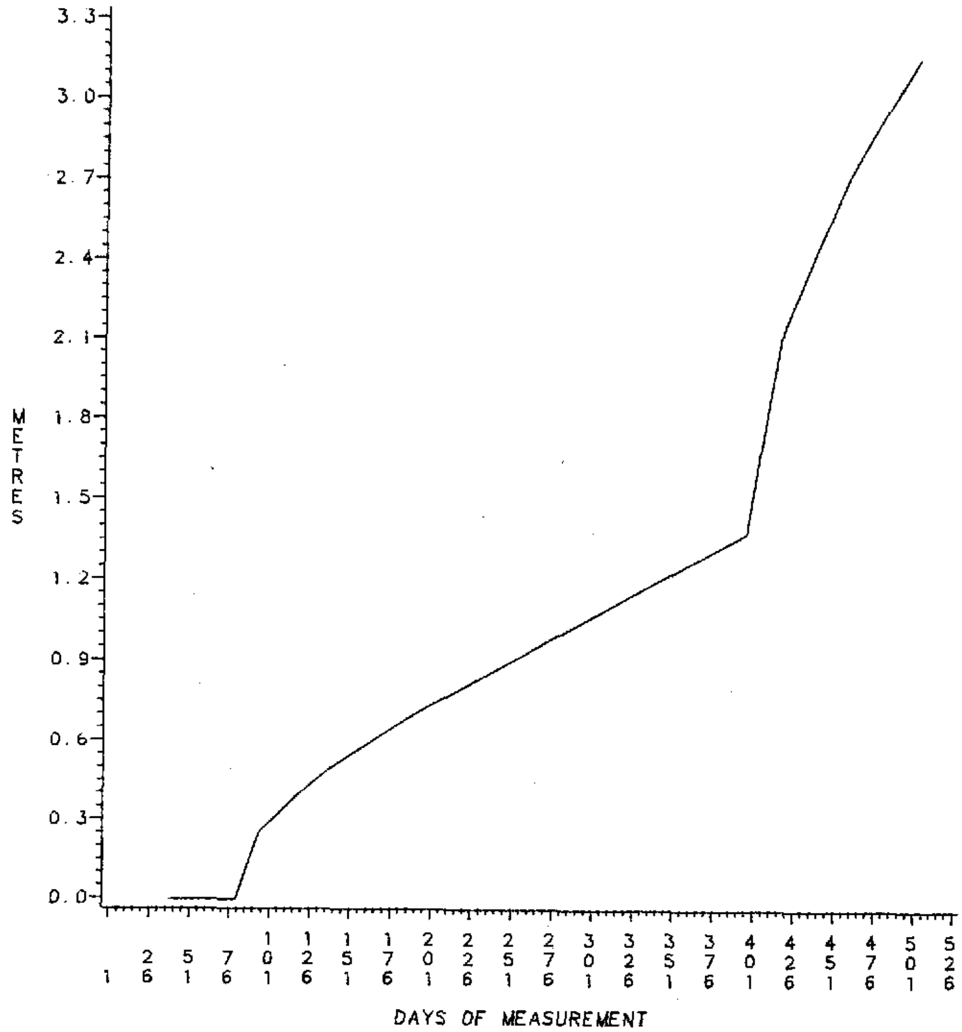


FIGURE 63.

CUMULATIVE AVERAGE BANK RECESSION, STATION 55

TOTAL=5.869M PINS=9 LENGTH=60.0M
PREDOMINANT LITHOLOGY=TILL/MUDSTONE AVERAGE ORIENTATION=SW
MAXIMUM BANK HEIGHT=10.5M

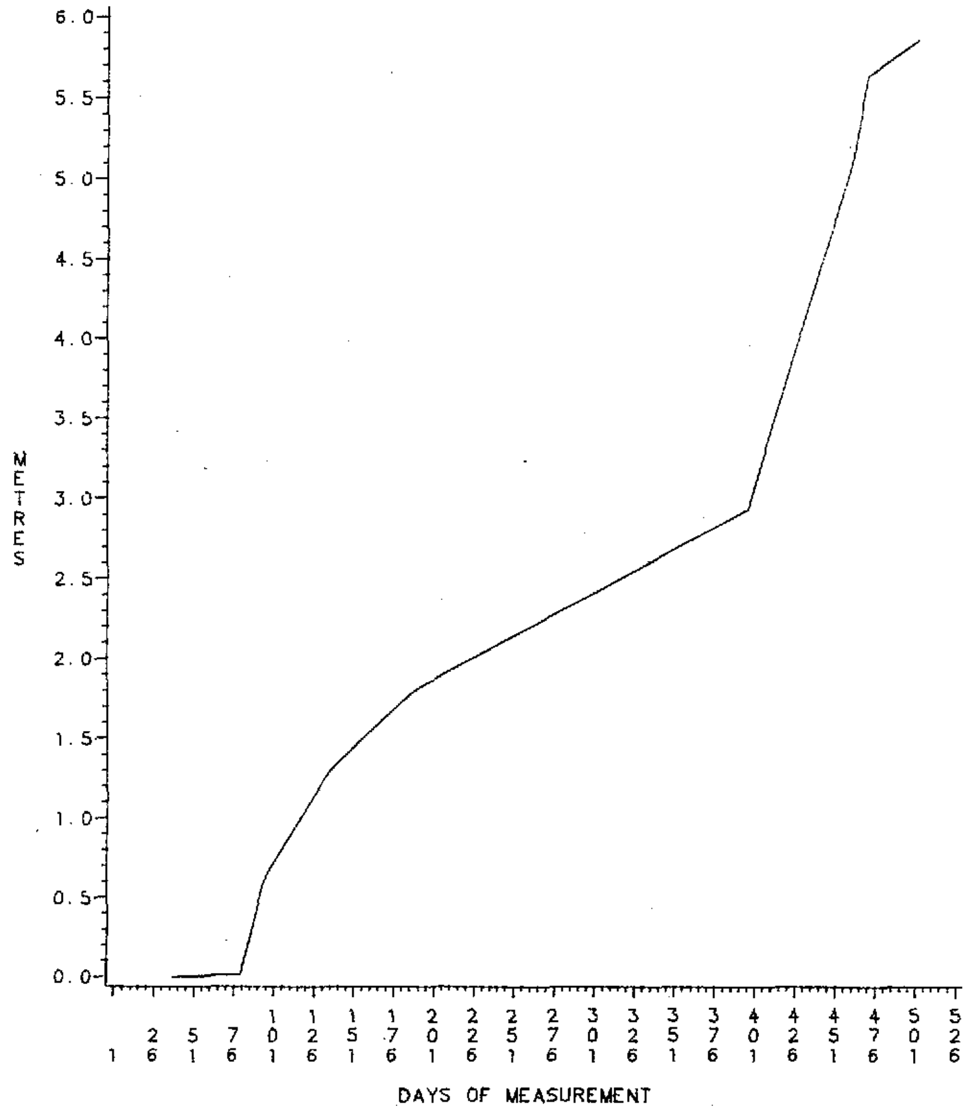


FIGURE 64.

CUMULATIVE AVERAGE BANK RECESSION, STATION 56

TOTAL=3.568M PINS=8 LENGTH=36.6M
PREDOMINANT LITHOLOGY=TILL/MUDSTONE AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=11.8M

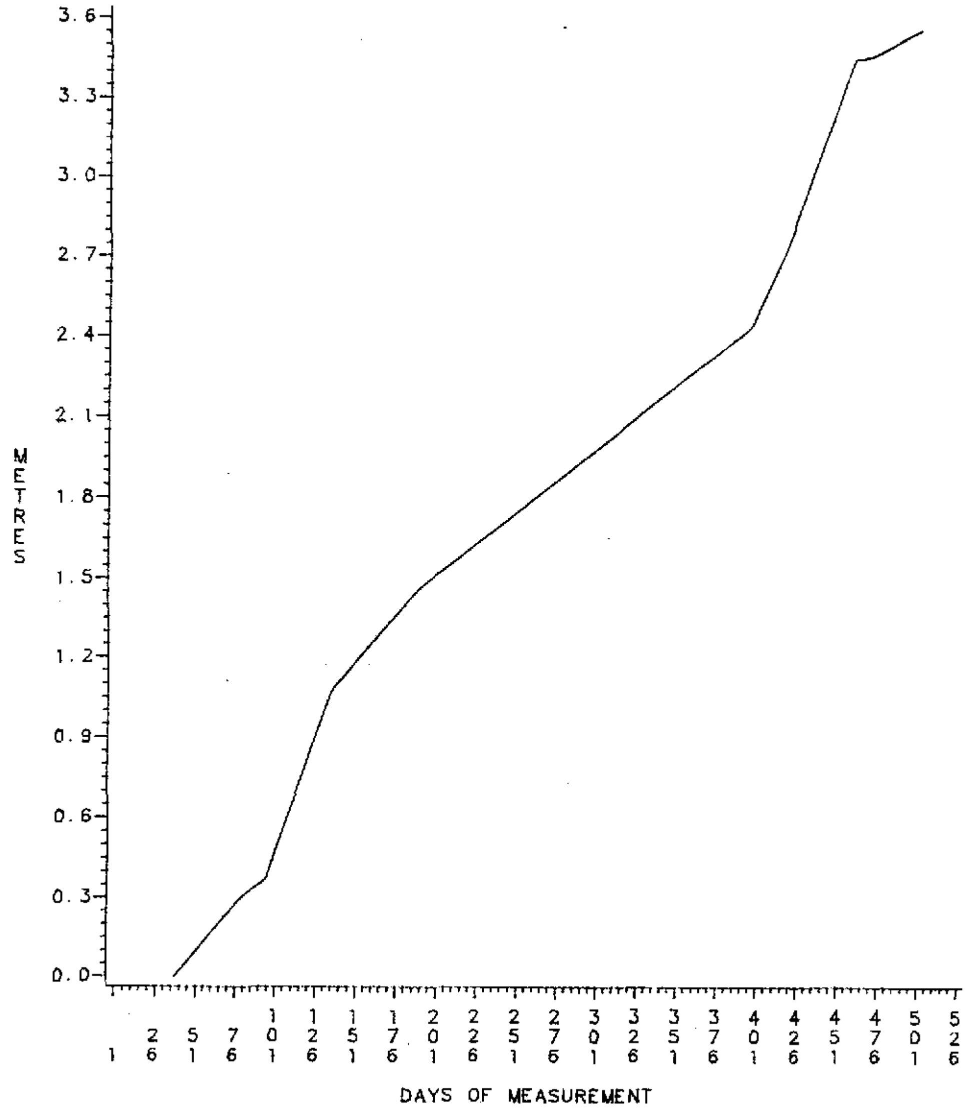


FIGURE 65.

CUMULATIVE AVERAGE BANK RECESSION, STATION 57

TOTAL=0.773M PINS=8 LENGTH=42.7M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=11.2M

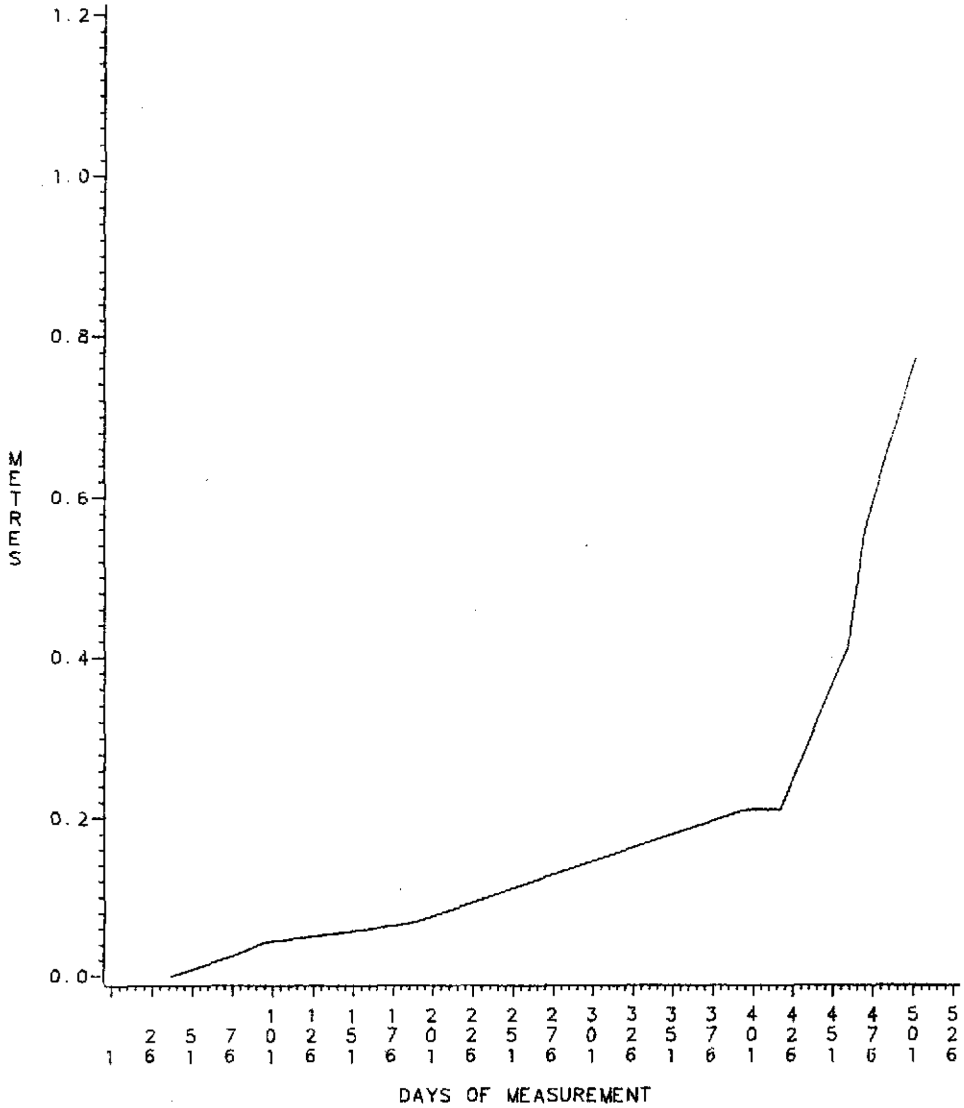


FIGURE 66.

CUMULATIVE AVERAGE BANK RECESSION, STATION 58

TOTAL=0.777M PINS=7 LENGTH=36.6M
PREDOMINANT LITHOLOGY=TILL/SAND AVERAGE ORIENTATION=S
MAXIMUM BANK HEIGHT=9.1M

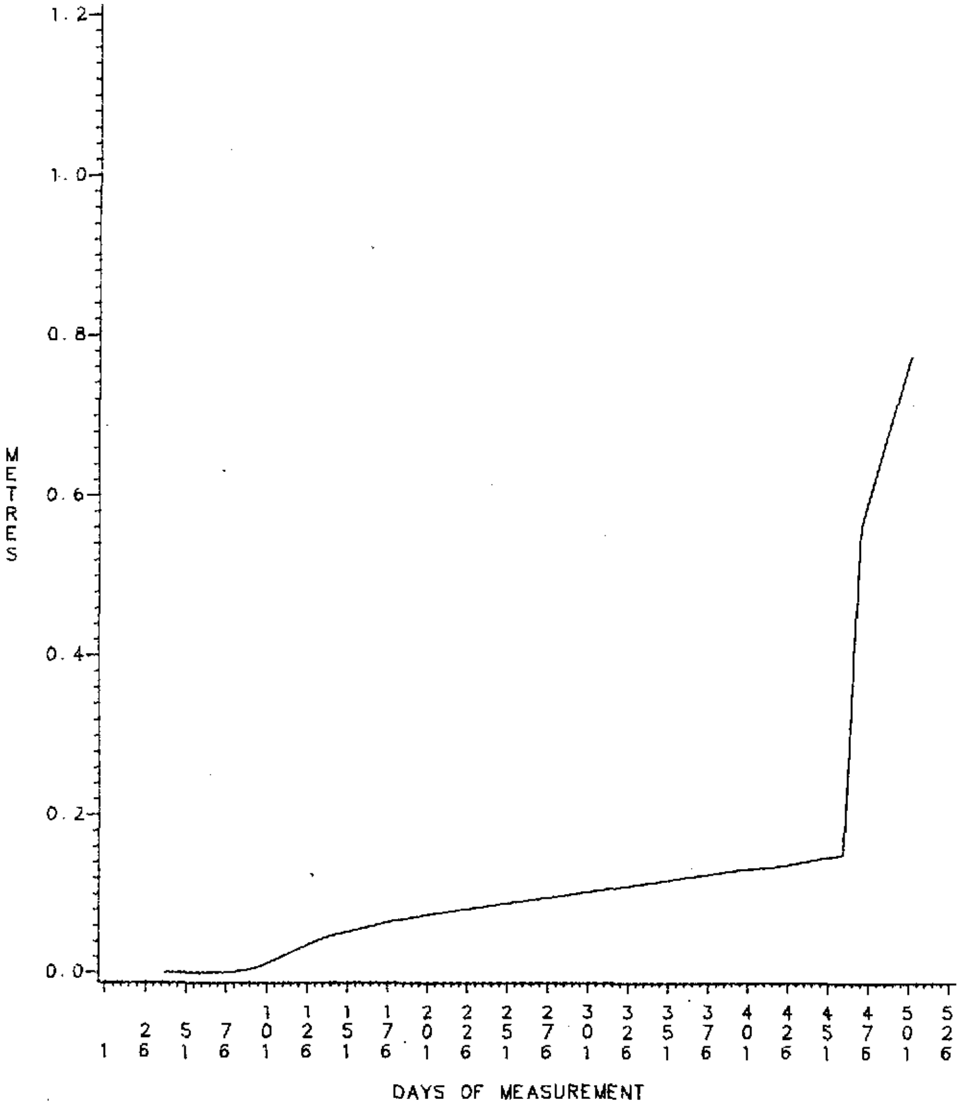


FIGURE 67.

CUMULATIVE AVERAGE BANK RECESSION, STATION 59

TOTAL=0.960M PINS=4 LENGTH=22.9M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=S
MAXIMUM BANK HEIGHT=8.2M

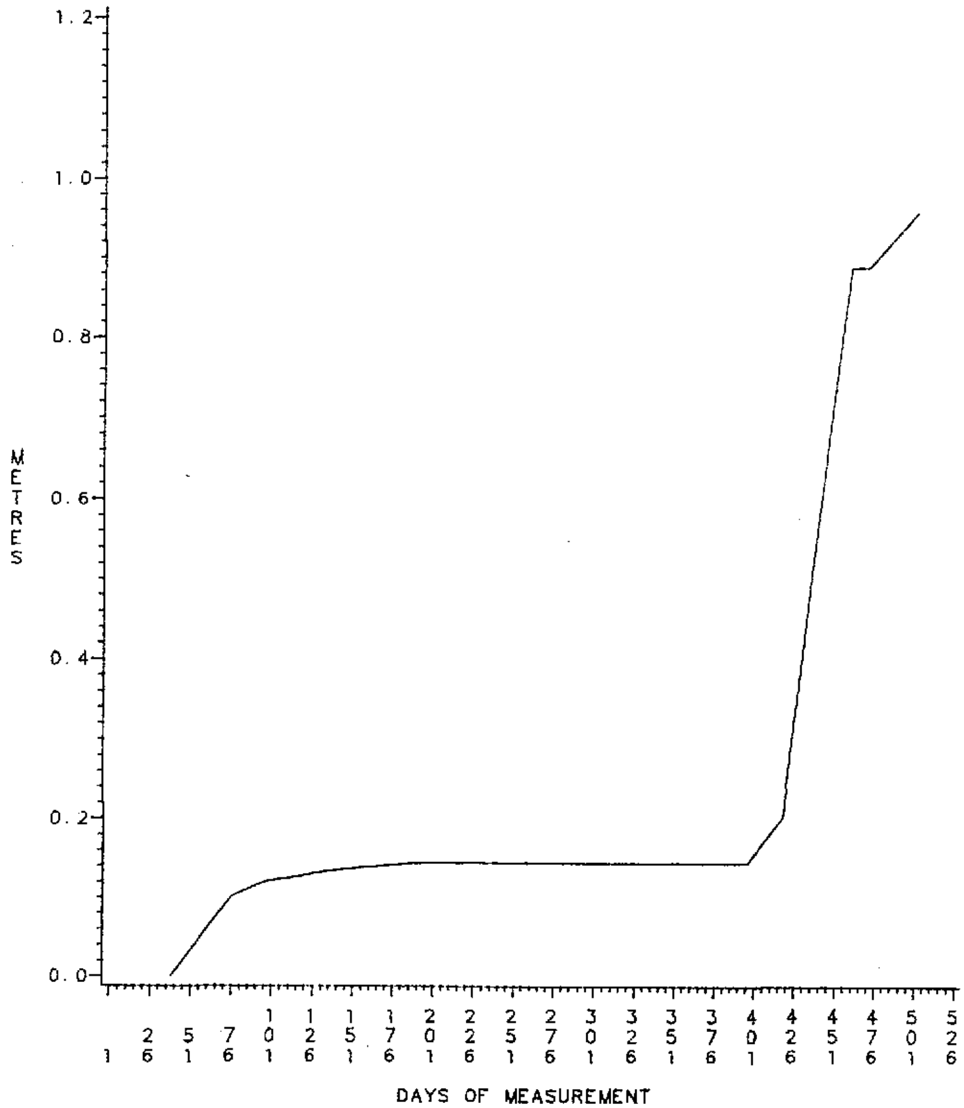


FIGURE 68.

CUMULATIVE AVERAGE BANK RECESSION, STATION 60

TOTAL=0.710M PINS=1 LENGTH=1.0M
PREDOMINANT LITHOLOGY=TILL/MUDSTONE AVERAGE ORIENTATION=E
MAXIMUM BANK HEIGHT=7.9M

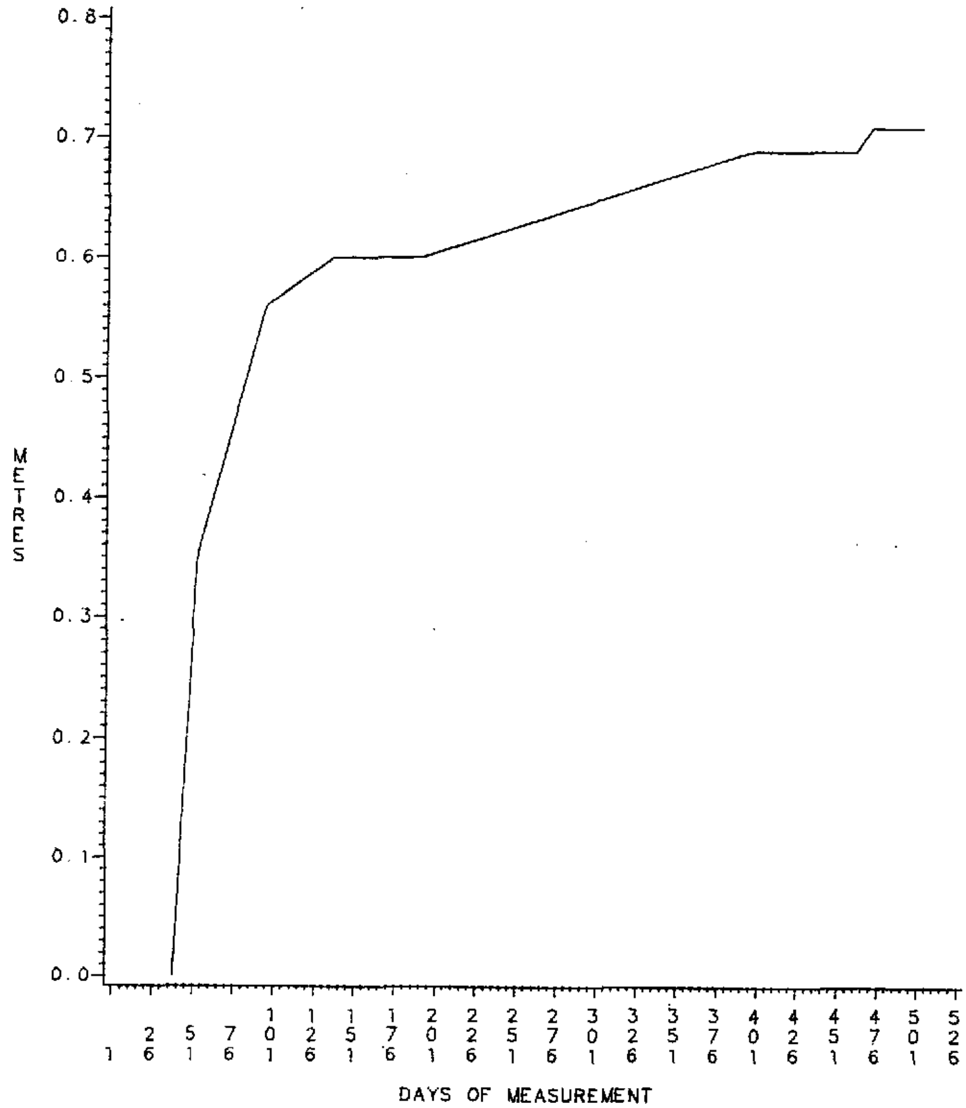


FIGURE 69.

CUMULATIVE AVERAGE BANK RECESSION, STATION 61

TOTAL=5.775M PINS=1 LENGTH=1.0M
PREDOMINANT LITHOLOGY=TILL/MUDSTONE AVERAGE ORIENTATION=SE
MAXIMUM BANK HEIGHT=6.5M

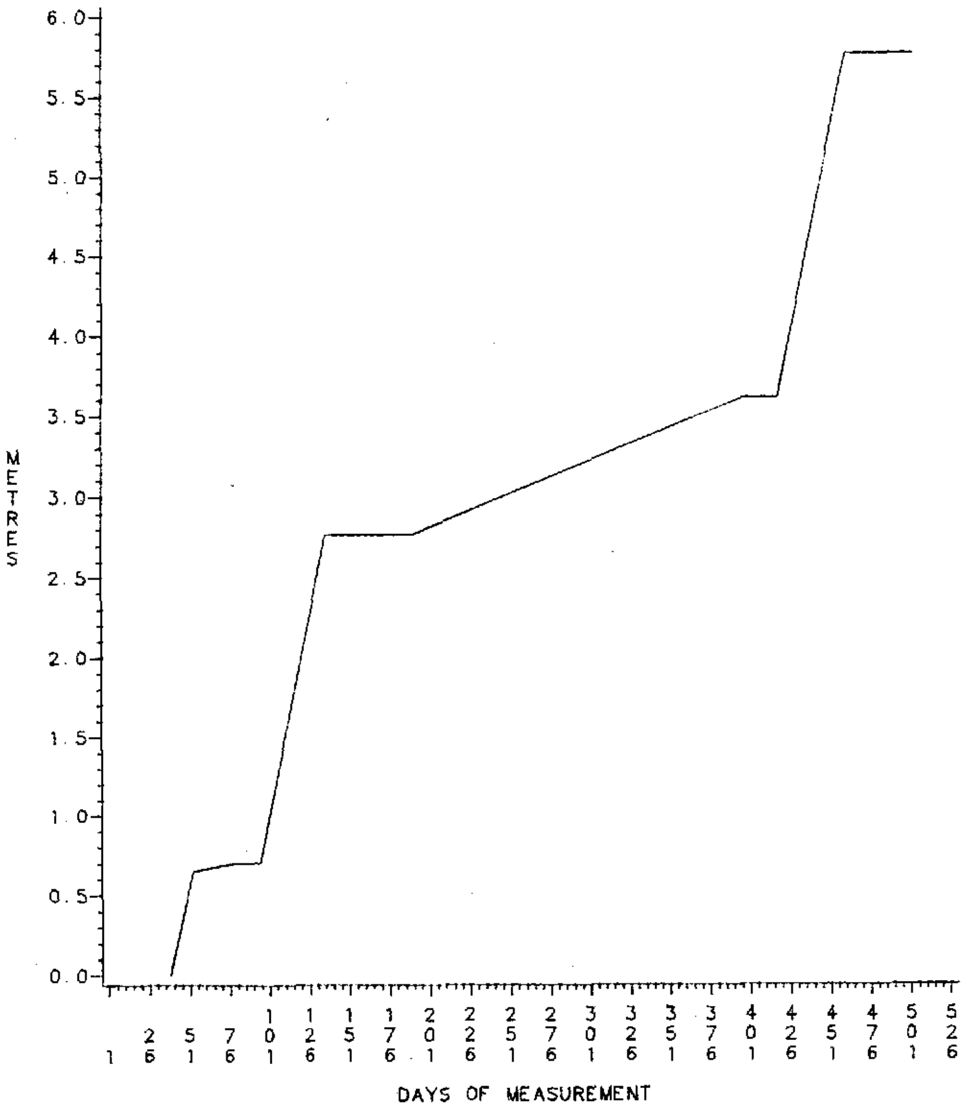


FIGURE 70.

CUMULATIVE AVERAGE BANK RECESSION, STATION 62

TOTAL=1.130M PINS=6 LENGTH=24.4M
PREDOMINANT LITHOLOGY=TILL/MUDSTONE AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=12.1M

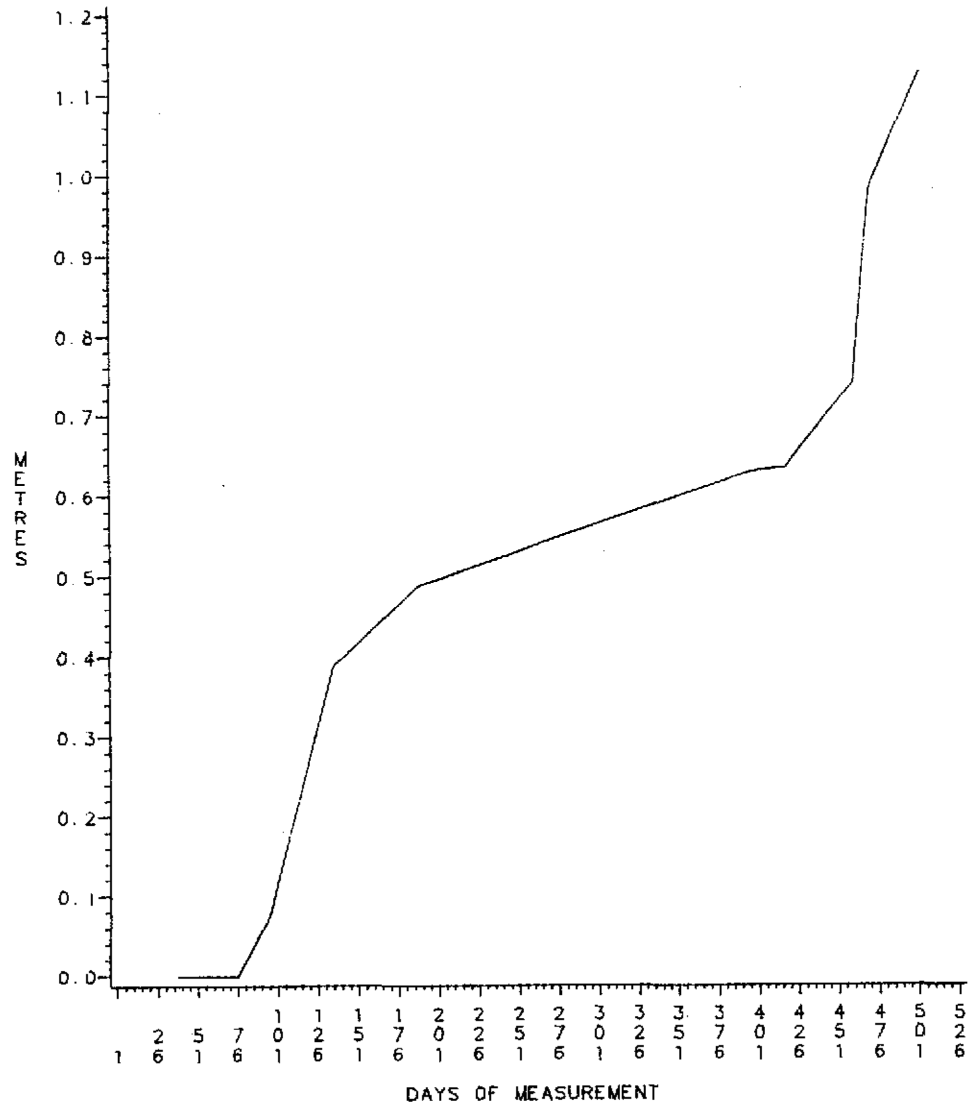


FIGURE 71.

CUMULATIVE AVERAGE BANK RECESSION, STATION A1

TOTAL=1.437M PINS=8 LENGTH=42.7M

PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=W

MAXIMUM BANK HEIGHT=1.7M

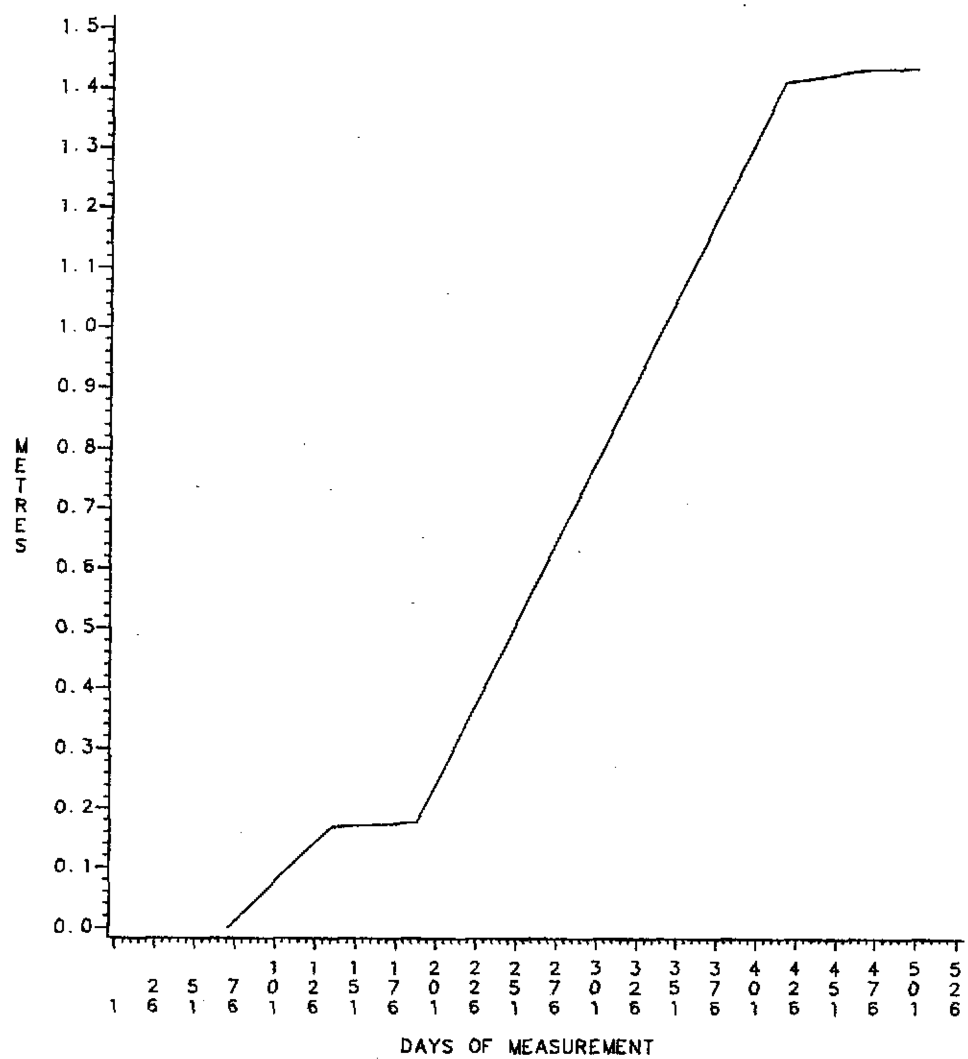


FIGURE 72.

CUMULATIVE AVERAGE BANK RECESSION, STATION A2

TOTAL=1.079M PINS=4 LENGTH=18.3M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=W
MAXIMUM BANK HEIGHT=1.5M

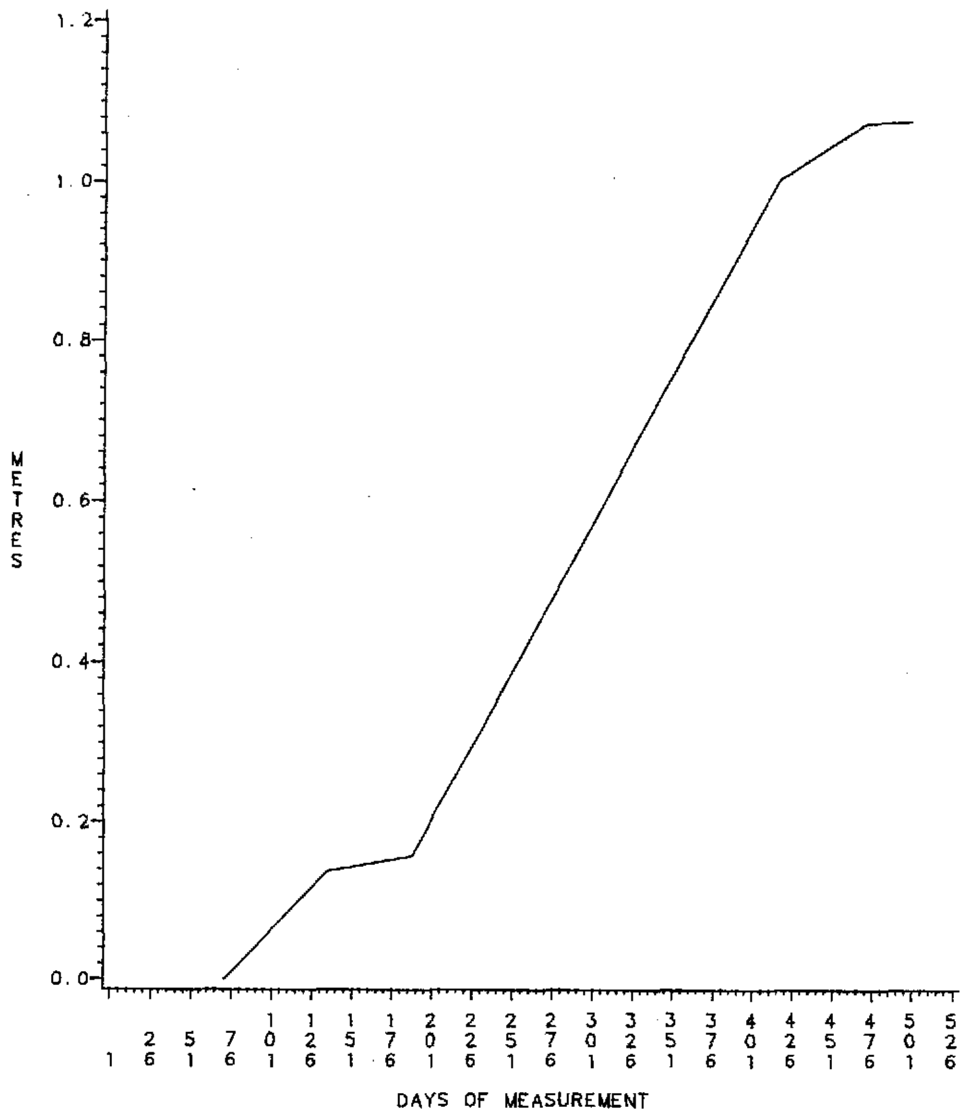
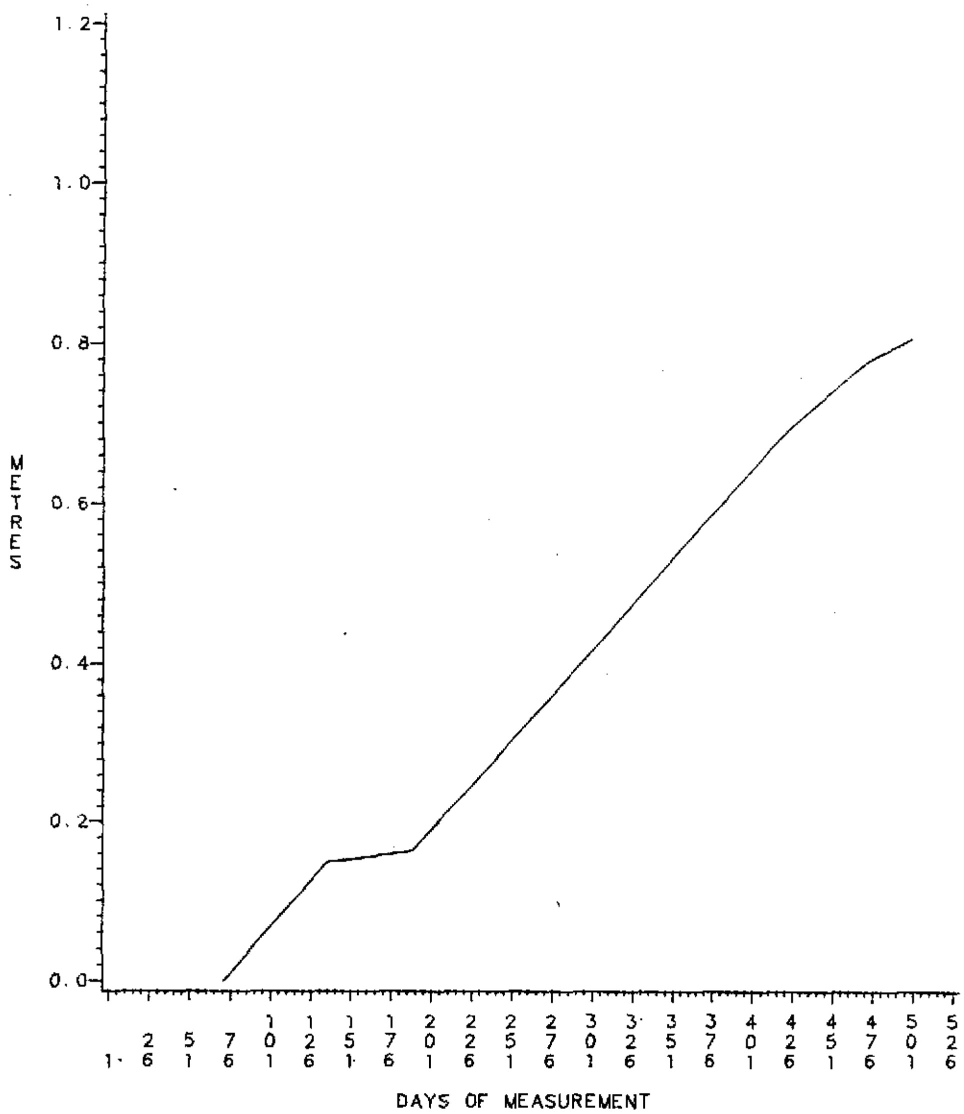


FIGURE 73.

CUMULATIVE AVERAGE BANK RECESSION, STATION A3

TOTAL=0.808M PINS=4 LENGTH=18.3M
PREDOMINANT LITHOLOGY=TILL AVERAGE ORIENTATION=NW
MAXIMUM BANK HEIGHT=1.0M



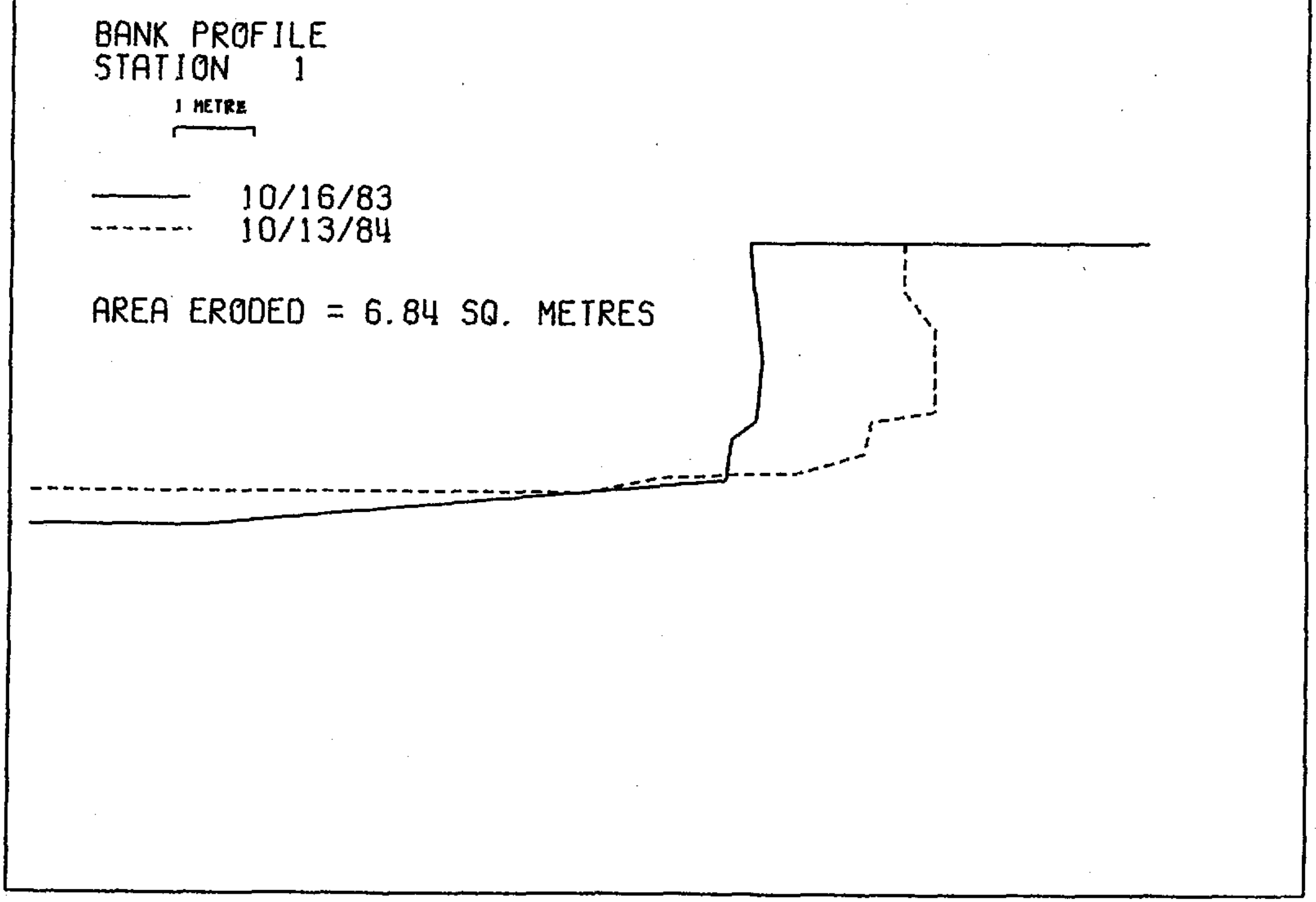
APPENDIX C

Selected Bank and Offshore Profiles,
Lake Sakakawea

EXPLANATION

Each figure defines the profile at the site and the relative pool level for two respective dates. The pool levels are indicated by the lines which extend across the figure and are parallel to the bank top.

FIGURE 74.


BANK PROFILE
STATION 1
1 METRE
10/16/83
10/13/84
AREA ERODED = 6.84 SQ. METRES

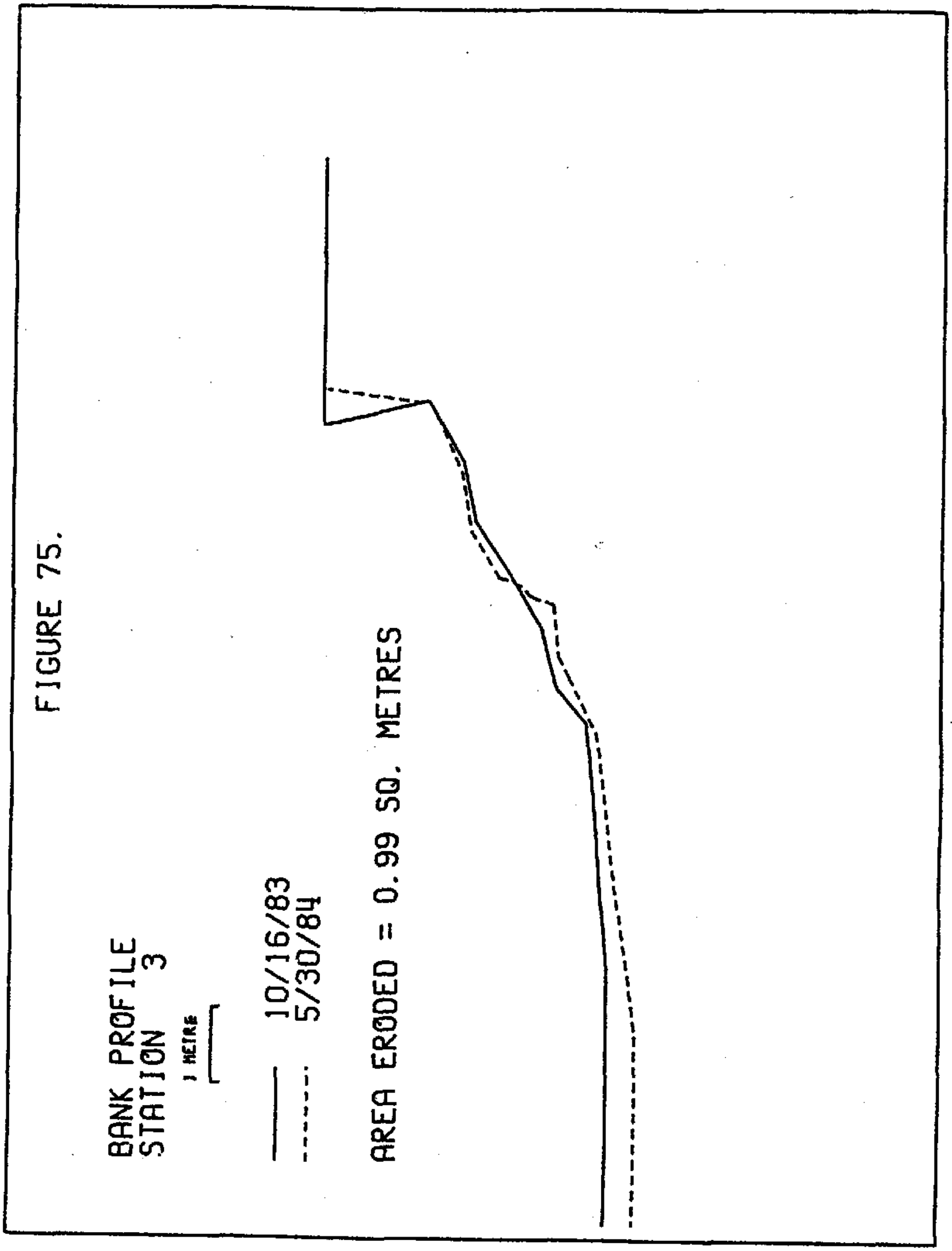

BANK PROFILE
STATION 3
1 METRE
10/16/83
5/30/84
AREA ERODED = 0.99 SQ. METRES

FIGURE 75.

FIGURE 76.

BANK PROFILE
STATION 3

1 METRE

——— 10/16/83
------- 7/23/84

AREA ERODED = 4.03 SQ. METRES

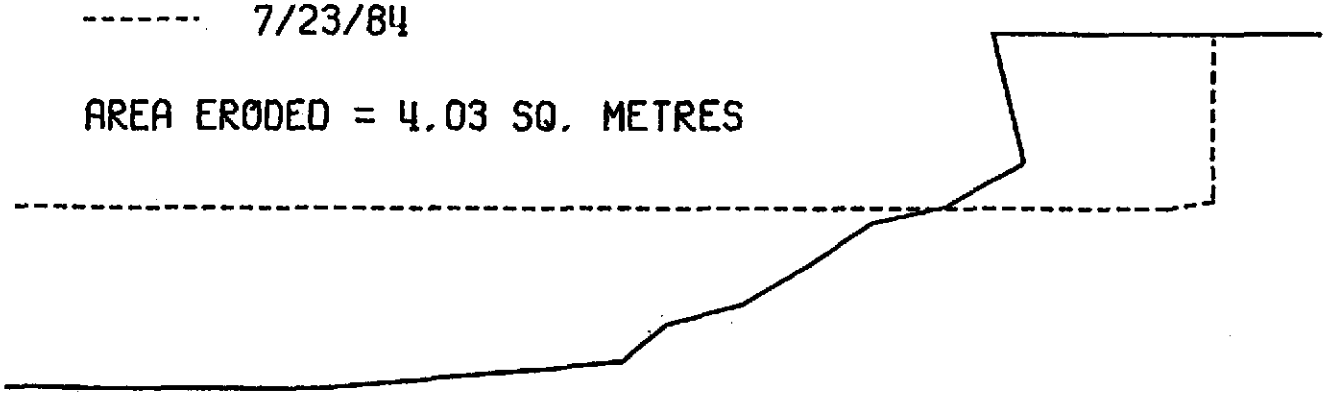


FIGURE 77.

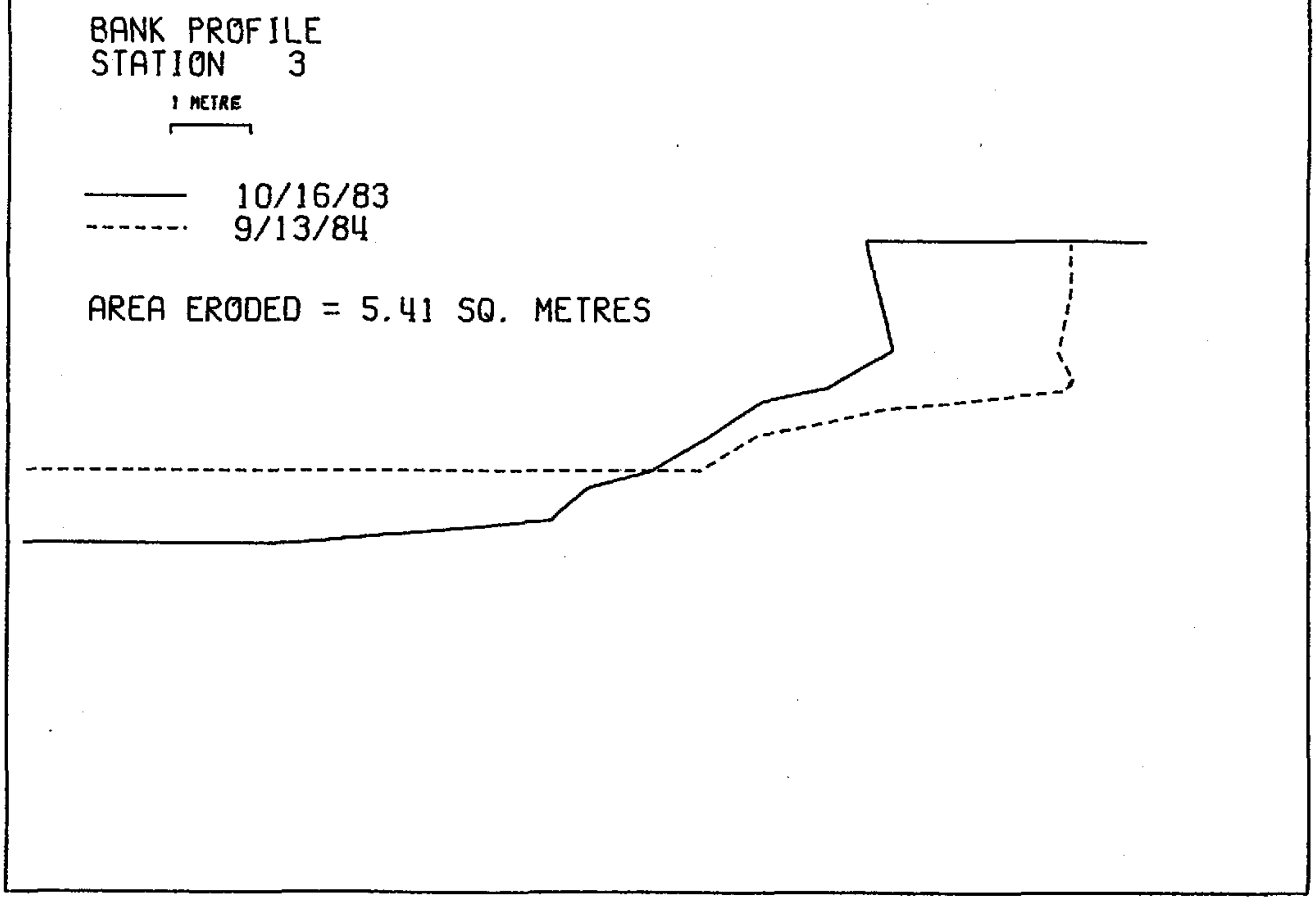
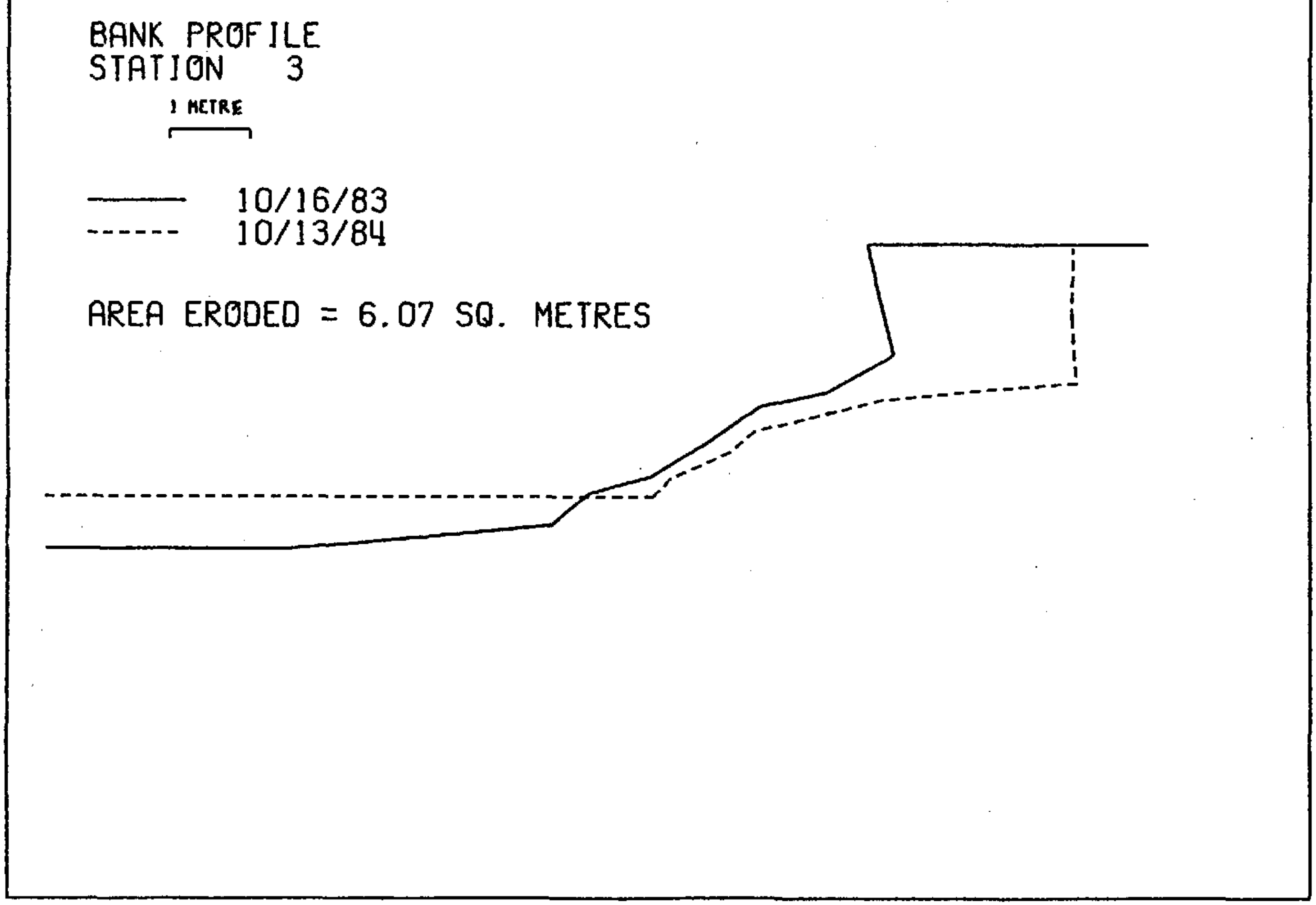

BANK PROFILE
STATION 3
1 METRE
10/16/83
9/13/84
AREA ERODED = 5.41 SQ. METRES

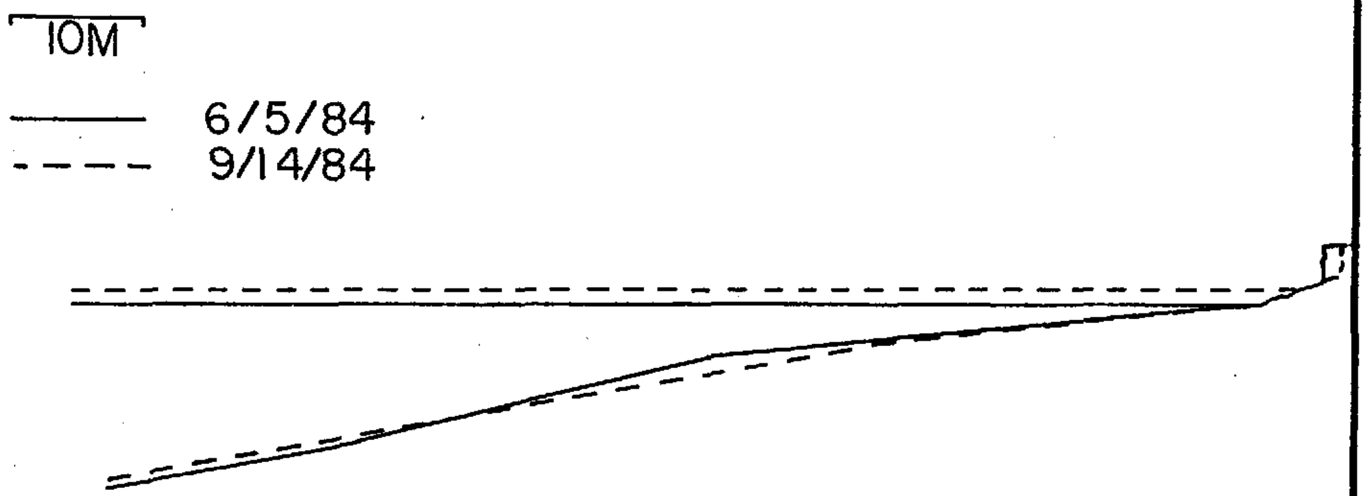
FIGURE 78.



BANK PROFILE
STATION 3
1 METRE
10/16/83
10/13/84
AREA ERODED = 6.07 SQ. METRES

FIGURE 79.

OFFSHORE AND BANK PROFILE
STATION 4



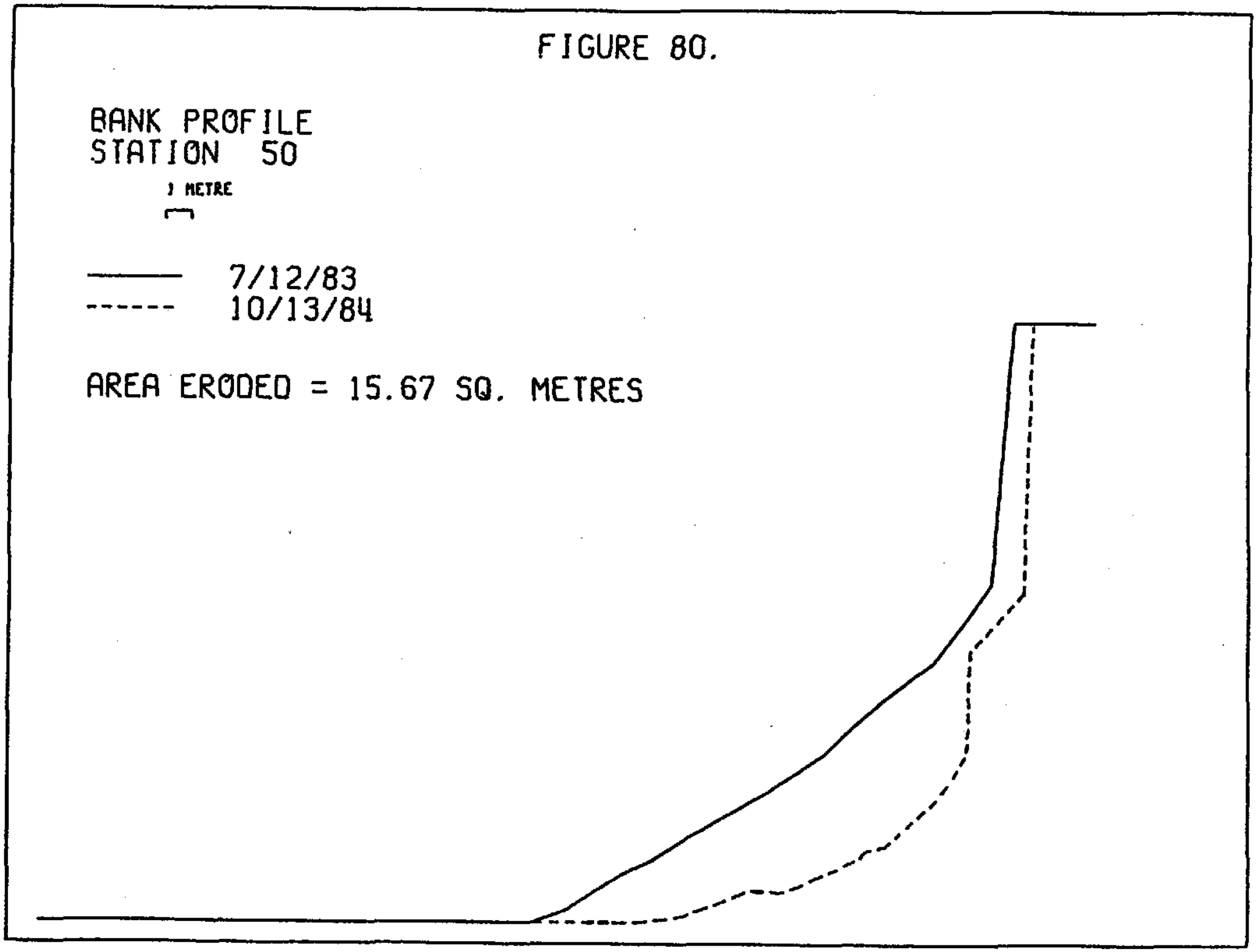

BANK PROFILE
STATION 50
1 METRE
7/12/83
10/13/84
AREA ERODED = 15.67 SQ. METRES

FIGURE 80.

FIGURE 81.

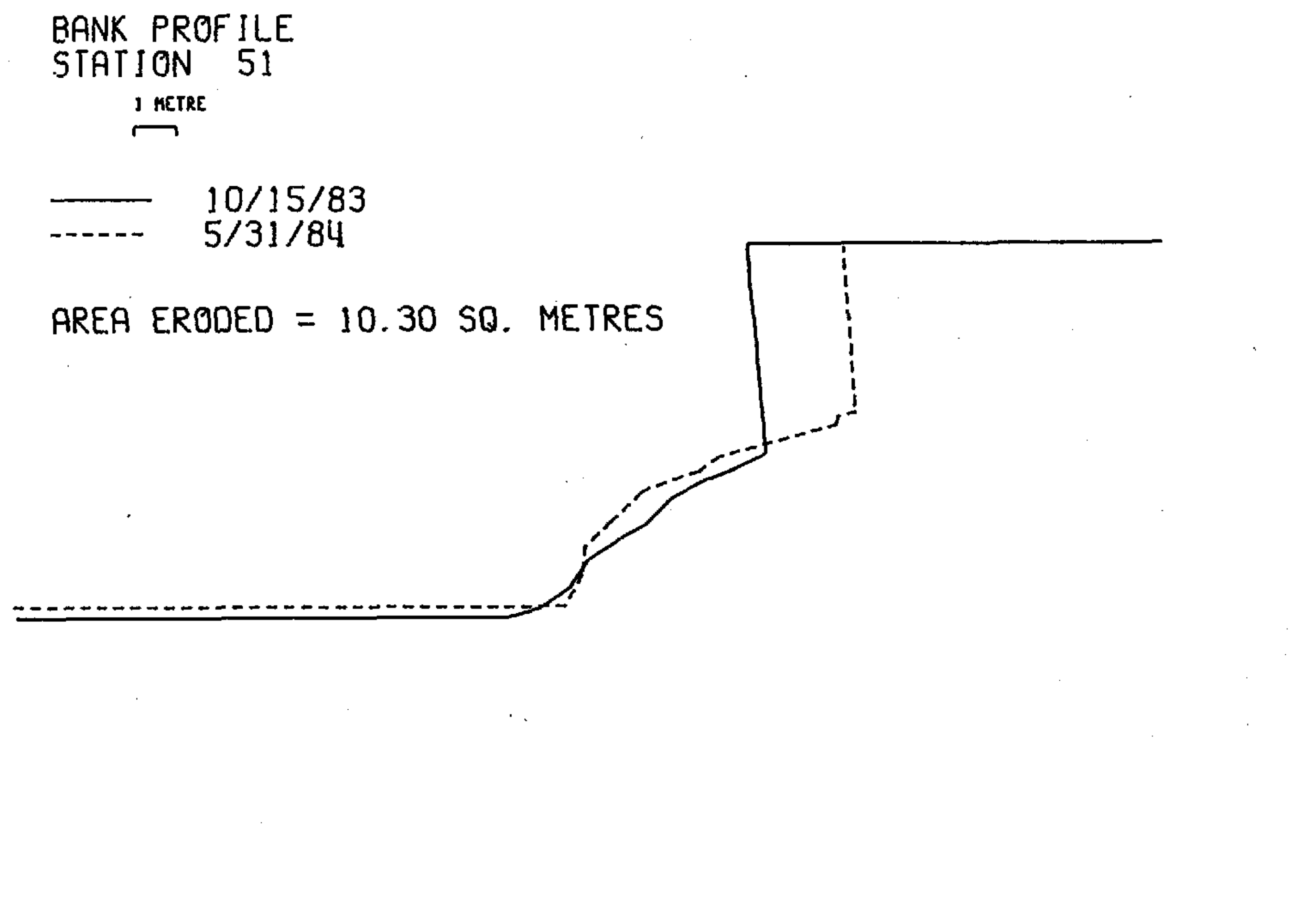

BANK PROFILE
STATION 51
1 METRE
10/15/83
5/31/84
AREA ERODED = 10.30 SQ. METRES

FIGURE 82.

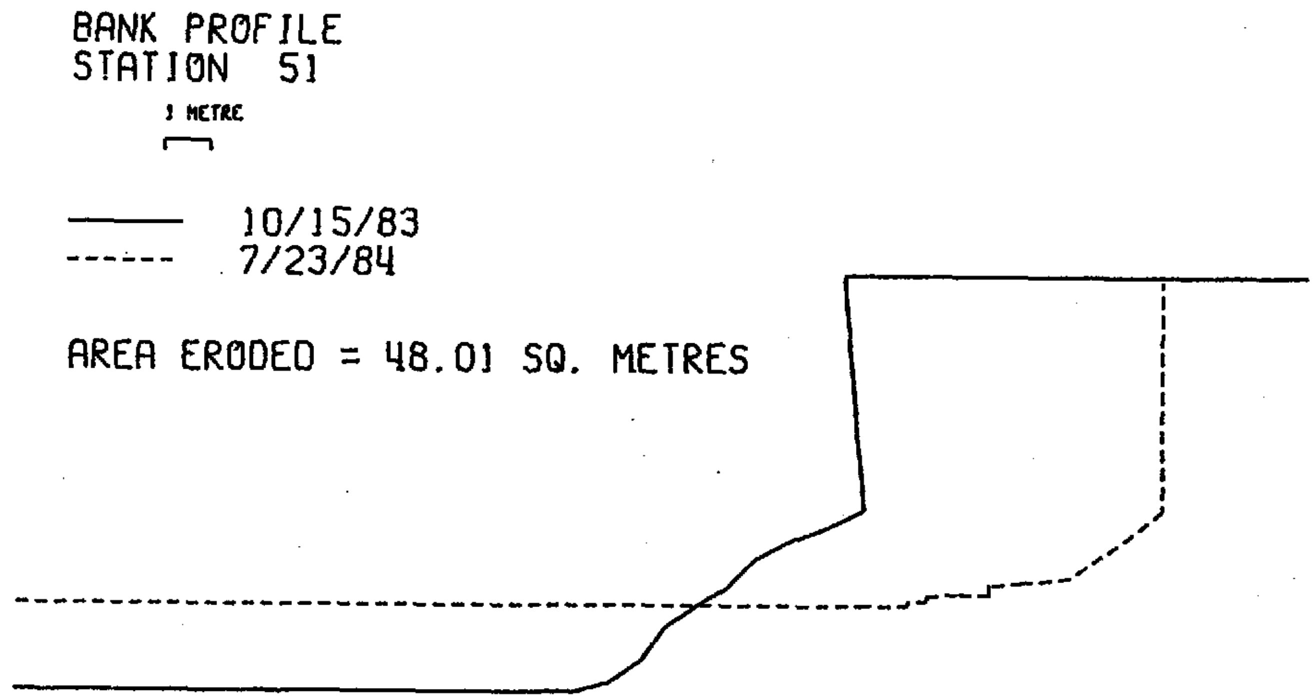
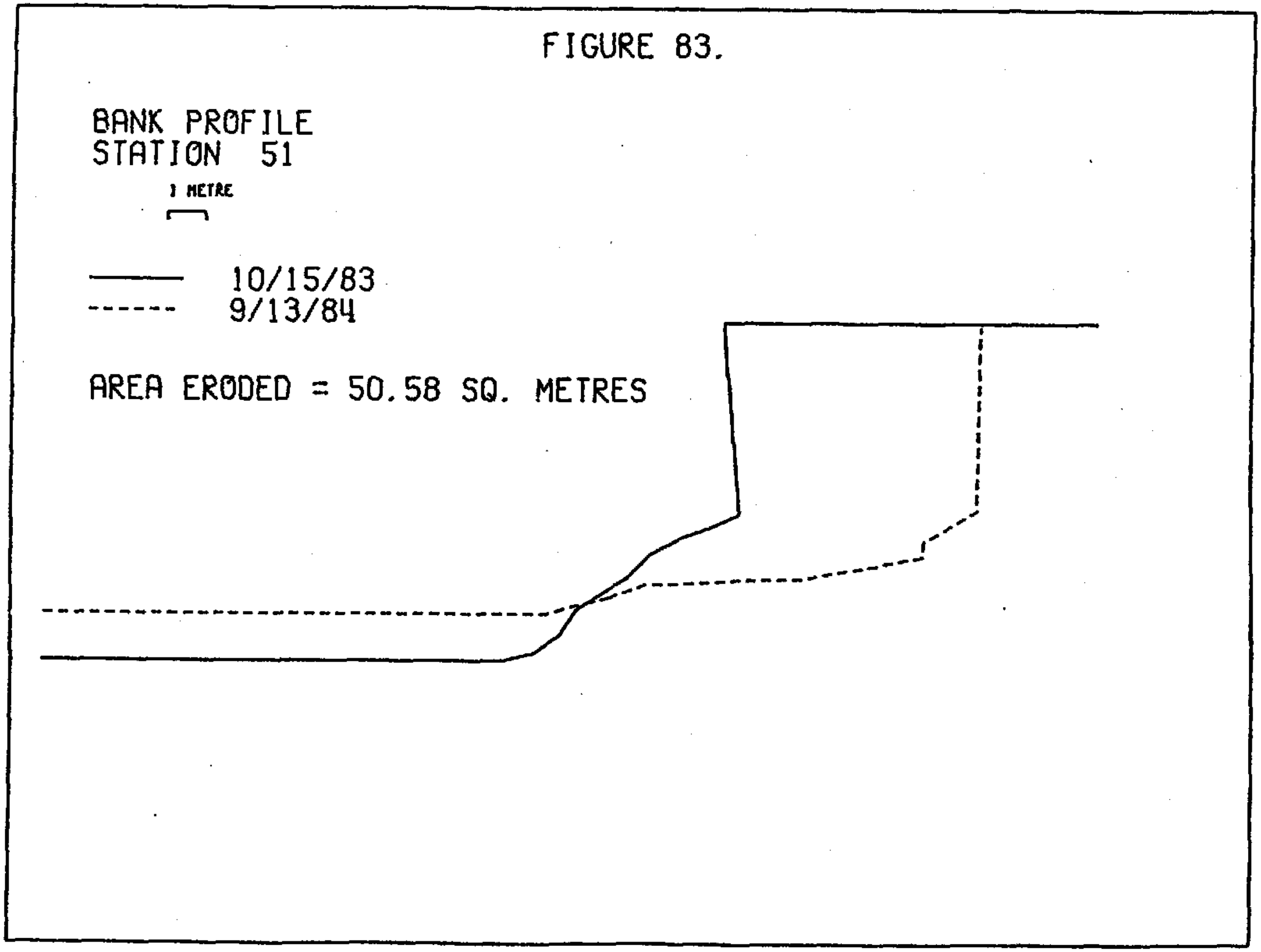

BANK PROFILE
STATION 51
1 METRE
10/15/83
7/23/84
AREA ERODED = 48.01 SQ. METRES

FIGURE 83.


BANK PROFILE
STATION 51
1 METRE
10/15/83
9/13/84
AREA ERODED = 50.58 SQ. METRES

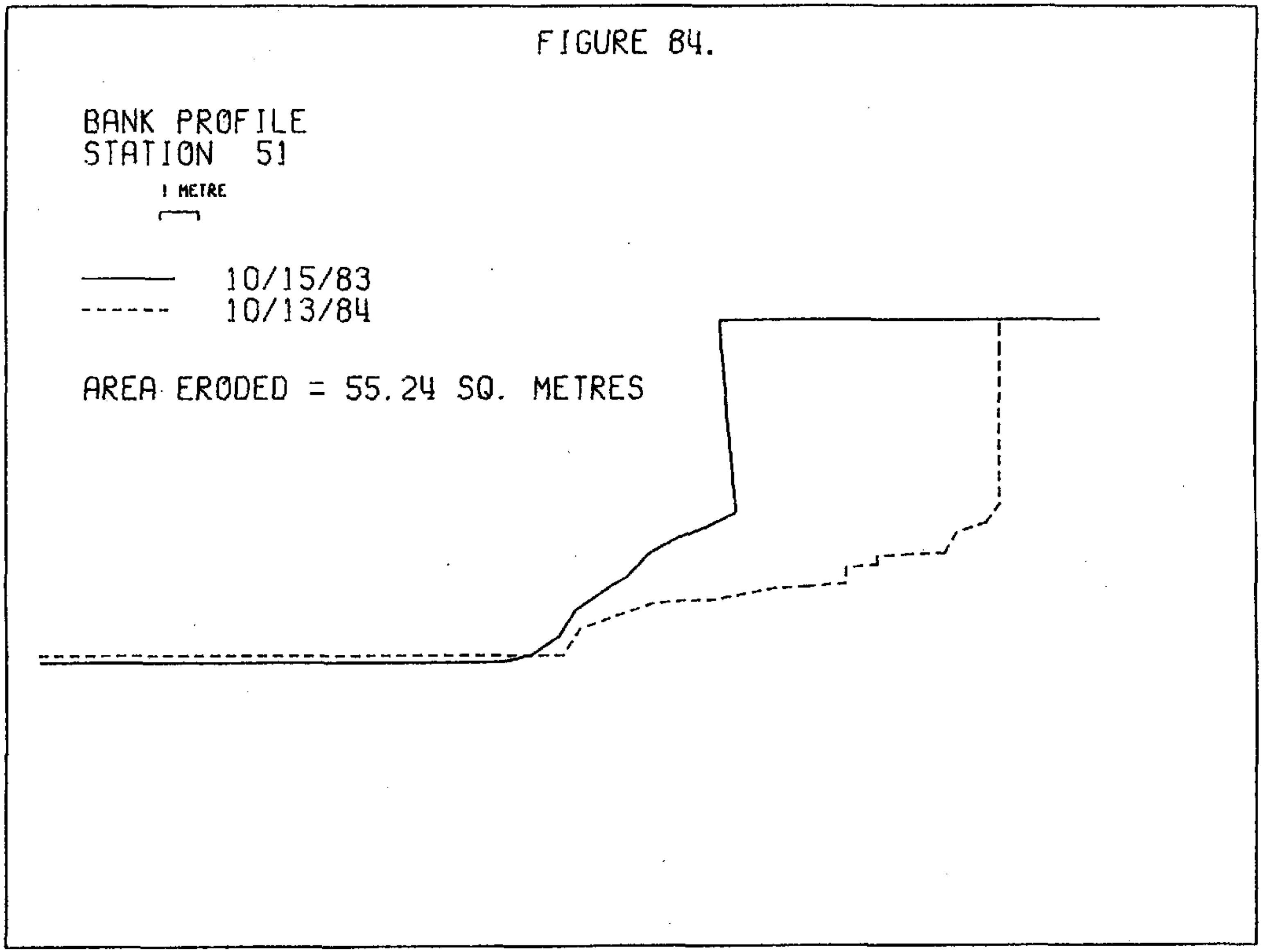

BANK PROFILE
STATION 51
1 METRE
10/15/83
10/13/84
AREA ERODED = 55.24 SQ. METRES

FIGURE 84.

FIGURE 85.

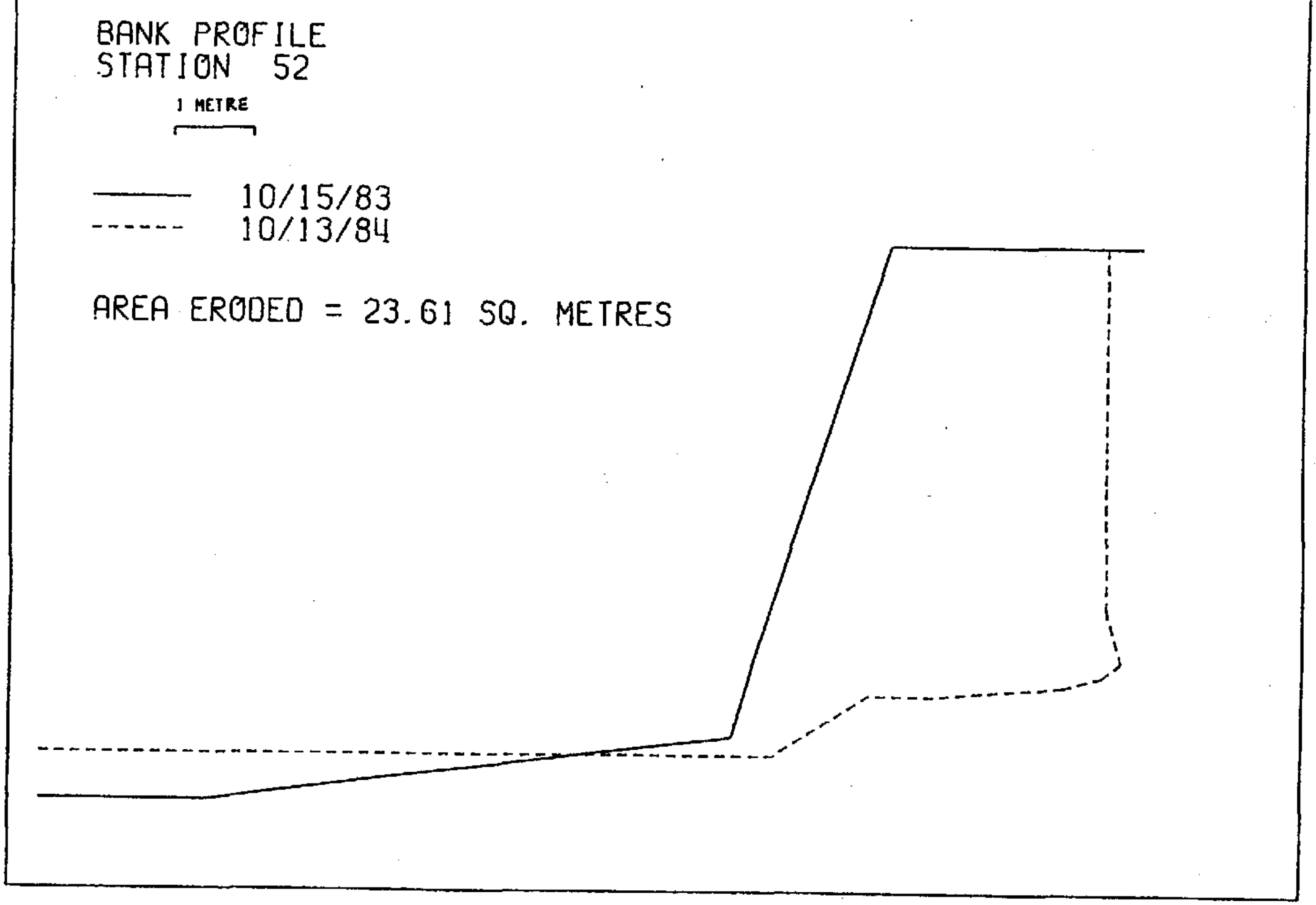

BANK PROFILE
STATION 52
1 METRE
10/15/83
10/13/84
AREA ERODED = 23.61 SQ. METRES

FIGURE 86.

OFFSHORE AND BANK PROFILE
STATION 53

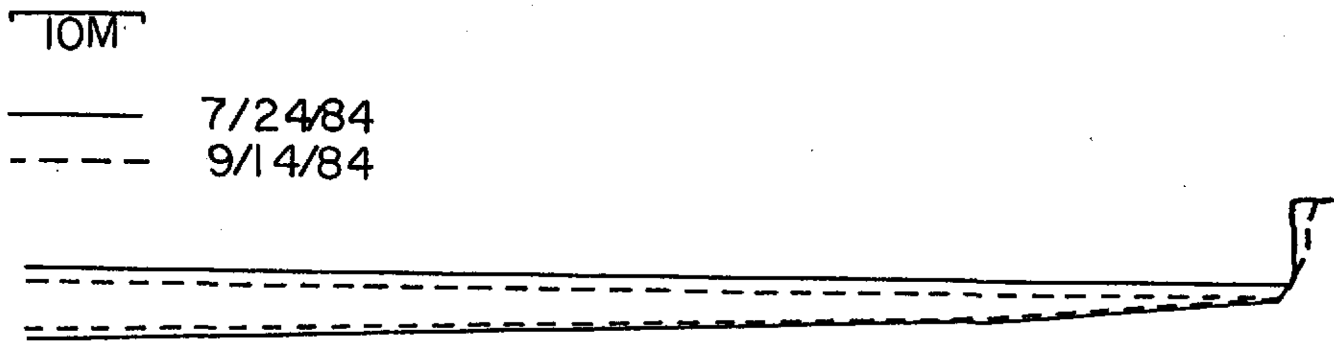


FIGURE 87.

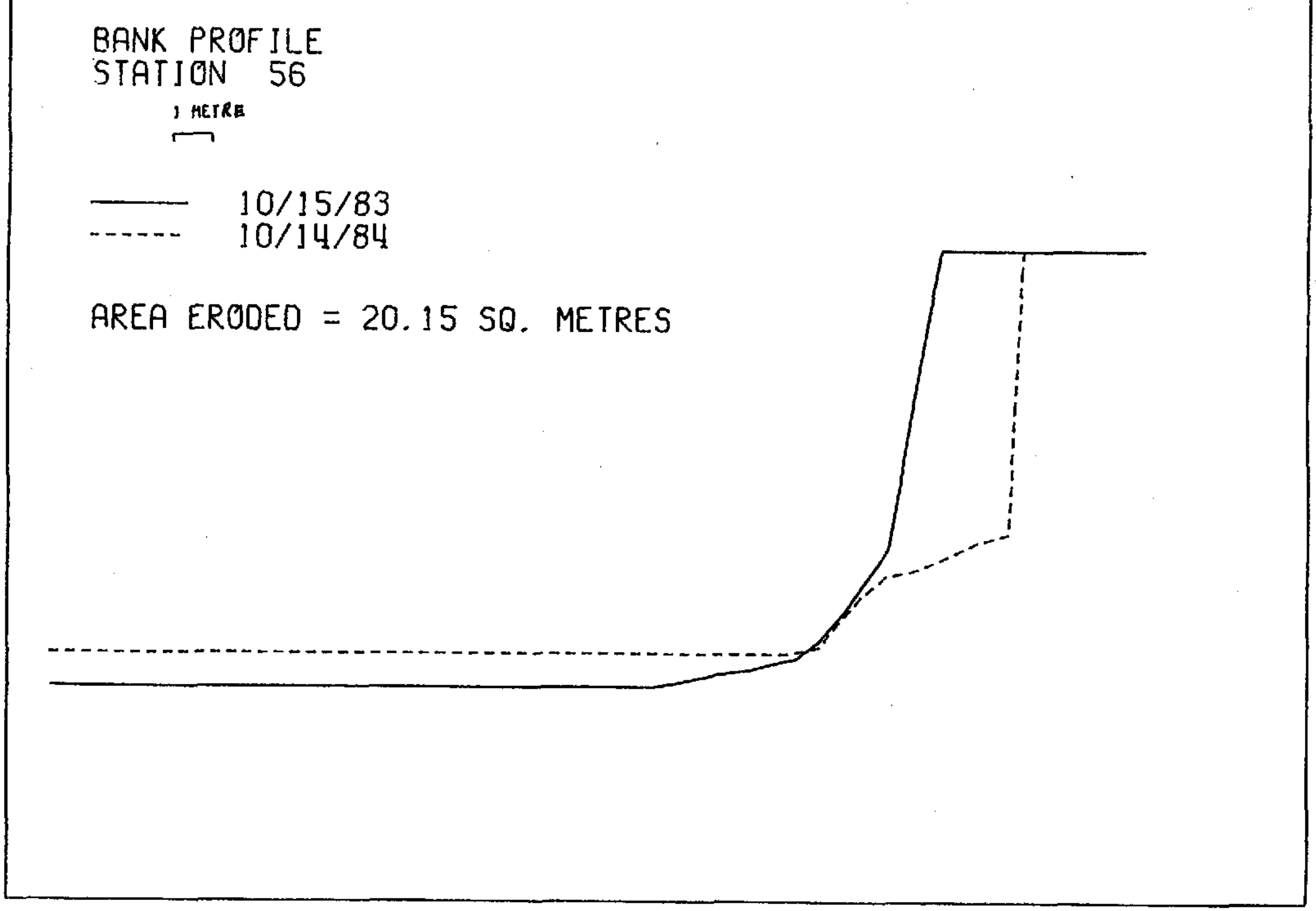

BANK PROFILE
STATION 56
1 METRE
10/15/83
10/14/84
AREA ERODED = 20.15 SQ. METRES

FIGURE 88.

OFFSHORE AND BANK PROFILE
STATION 56

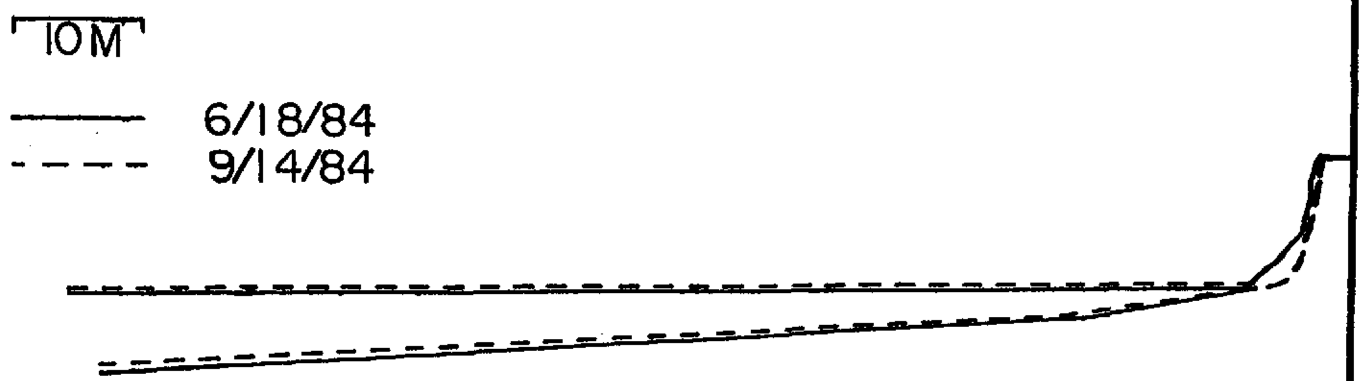


FIGURE 89.

OFFSHORE AND BANK PROFILE
STATION 61

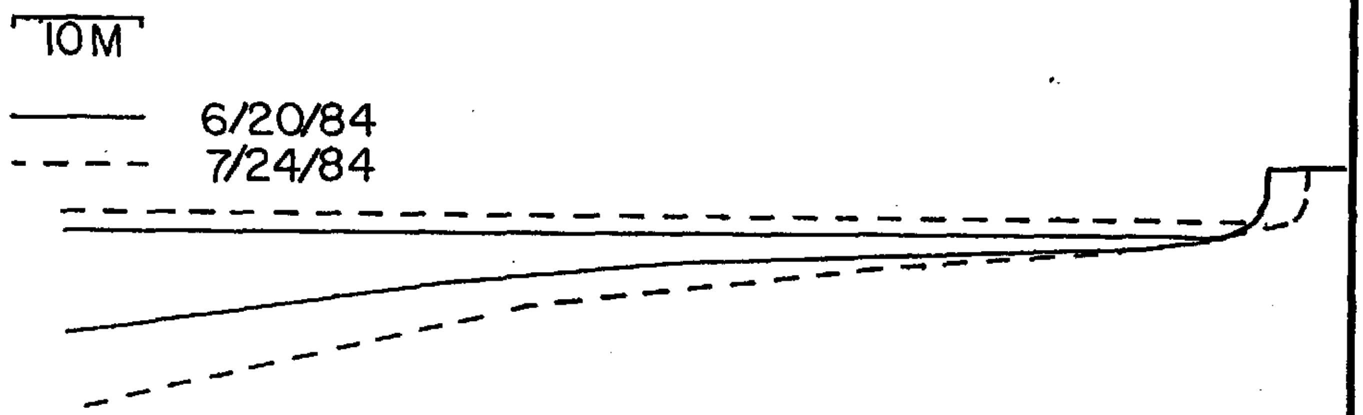
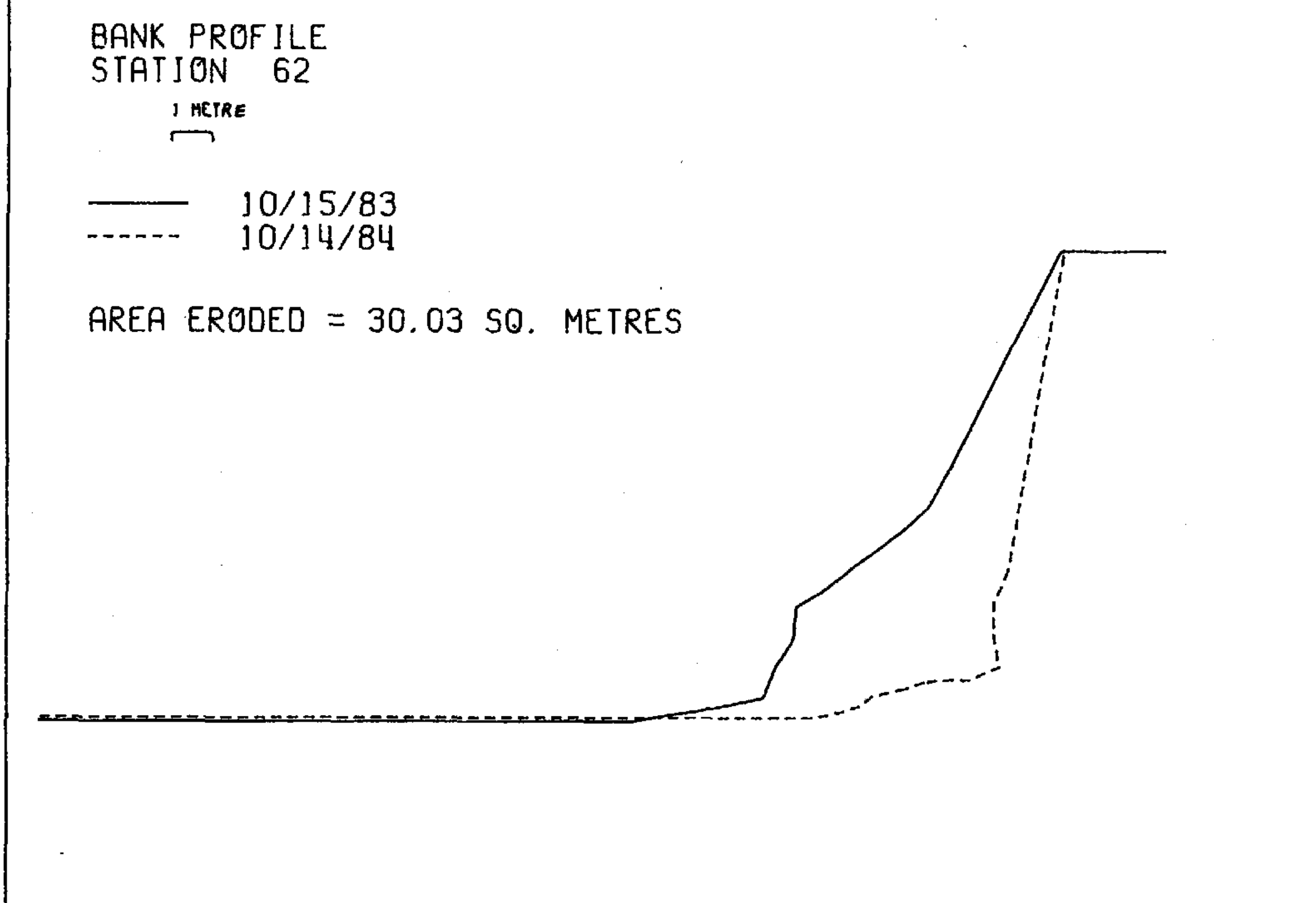


FIGURE 90.


BANK PROFILE
STATION 62
1 METRE
10/15/83
10/14/84
AREA ERODED = 30.03 SQ. METRES

APPENDIX D

Maximum Fetches for Lake Sakakawea Stations

TABLE 32

Maximum Fetch Distances (km)
for Lake Sakakawea Stations
(as measured from topographic maps)

Station	Fetch Direction							
	N	NE	E	SE	S	SW	W	NW
1	9.76	15.36	5.80	5.52	1.70	0	0	0
2	7.39	12.48	5.60	0	0	0	0	0
3	0.32	1.28	0	0	0	0	0	0.16
4	1.76	0.26	0.32	0.16	0	0	0.27	1.76
5	0.16	0	0	0	0	0.32	0.16	0.40
6	5.28	0.32	0.16	0	0	0	0.13	0.14
7	5.28	0.32	0.16	0	0	0	0.13	0.14
50	11.20	1.00	0	0	0	1.00	3.00	5.50
51	0	0	0	0.56	3.84	6.24	6.40	7.60
52	0	0	0.10	0.14	0.14	6.40	6.40	0
53	0	0	0	5.44	9.10	5.30	12.40	0.32
54	0	0	0	0	9.28	7.20	4.96	1.42
55	0	0	0	0	9.31	6.72	5.00	1.31
56	0	0	0	0	0	7.10	1.30	0.90
57	0	0	0	0	9.66	8.96	0.80	0.70
58	0	0	6.21	6.85	4.80	9.17	2.62	0
59	0	0	6.26	6.98	4.94	9.20	2.75	0
60	0.16	0.16	0.80	5.92	5.78	0	0	0
61	0	0	0.83	6.29	5.76	2.38	3.63	0
62	0	0	0	0	5.97	2.43	0.10	0

APPENDIX E

Relationship of Cumulative Average Bank Recession to Erosion Variables

EXPLANATION

Cumulative average bank recession (CABR) during warm weather or highest pool levels is defined as that recession for the periods May 1983 to October 16, 1983 and June 1, 1984 to August 24, 1984. CABR during cold weather or low pool levels is defined as that recession for the period October 17, 1983 to May 31, 1984. Because station 59 was not measured at the end of May 1984 it was only used for the warm weather CABR calculations.

TABLE 33

Relationship of Cumulative Average Bank Recession (CABR) to Bank Orientation
(* Station 59 was not measured over cold weather interval)

Orientation	Pins Used (Station, pins)	Total CABR (m)	Warm Weather CABR (m)	Cold Weather CABR (m)
N	3, all; 6, all; 7, all	2.34	2.17 (92.8%)	0.17 (7.2%)
NE	1, all; 2, all	3.07	3.06 (9.7%)	0.01 (0.3%)
E	60, all	0.71	0.62 (87.3%)	0.09 (12.7%)
SE	53, 1-3; 59*, 1-2; 61, all	1.64	1.50	0.30
S	51, 1-9; 58, all; 59*, 3-4	2.15	2.05	0.11
SW	5, 1-2; 53, 4-12; 54, all; 55, 1-6	2.45	2.00 (81.5%)	0.45 (18.5%)
W	52, 1-2; 55, 7-9; 56, all; 57, all; 62, all	2.10	1.59 (75.7%)	0.51 (24.3%)
NW	4, all; 5, 3-4; 50, all; 51, 10-12; 52, 3-7	1.85	1.68 (91.0%)	0.17 (9.0%)

TABLE 34

Relationship of Cumulative Average Bank Recession (CABR) to Bank Lithology at the Wave Impact Zone (only important during warm weather months)

Bank Lithology (Formation)	Stations	Warm Weather CABR (m)
U.S.S.	1, 3, 4	3.15
L.S.S.	5	1.89
L.H.V.	51	2.69
U.M.H.	6, 7, 52, 58, 59	1.55
S.B.	2, 50, 53, 54, 55, 56, 57, 60, 61, 62	1.90

TABLE 35

Relationship of Cold Weather Bank
Recession to Overall Bank Lithology
(Data was unavailable for station 59)

Bank Lithology (Formation)	Stations	Average Bank Recession (m)
O.-U.S.S. (Stations 4 and 5 also have L.S.S.)	1, 3, 4, 5	0.03
O.-U.S.S.-L.S.S.-U.M.H.	6, 7	0.31
O.-U.S.S.-S.B.	50, 54, 55, 56, 57, 60, 61, 62	0.63
O.-U.H.V.-L.H.V.-U.M.H.	51	0.12
O.-U.H.V.-U.M.H.	52	0.03
O.-U.M.H.	58	0.06
O.-U.M.H.-S.B.	53	0.13
O.-S.B.	2	0.02

TABLE 36

Relationship of Cumulative Average Bank Recession (CABR) to Bank Height
(Data for station 59 was unavailable for cold weather months)

Bank Height (m)	Stations	Total CABR (m)	Warm Weather CABR (m)	Cold Weather CABR (m)
<5	1, 3, 4, 5	2.97	2.94 (99.1%)	0.03 (0.9%)
5-10	2, 52, 53, 54, 58, 59*, 60, 61	1.59	1.44	0.16
>10	6, 7, 50, 51, 55, 56, 57, 62	2.70	2.22 (82.3%)	0.48 (17.7%)

APPENDIX F

Relationship of 1983 Average Overland Erosion to Erosion Variables

TABLE 37

Relationship of 1983
Average Overland Erosion (AOE)
to Bank Orientation

Orientation	Stations	AOE (mm)
N	7	23.33
NE	1, 2	13.00
E	--	--
SE	53A	11.67
S	53B, 58, 59	17.25
SW	--	--
W	51	13.33
NW	4, 5, 52, 50	27.84

TABLE 38

Relationship of 1983
Average Overland Erosion (AOE)
to Bank Height

Bank Height	Stations	AOE (mm)
<5m	1, 4, 5	13.11
5-10m	2, 52, 53A-B, 58, 59	15.74
>10m	7, 50, 51	32.33

APPENDIX G

Relationship of Thaw-Colluvium to Erosion Variables

TABLE 39

Relationship of Thaw-Colluvium to Bank Orientation

Orientation	Stations (*partial)	Colluvium (m^3/m)
N	3, 6, 7	0.63
NE	1, 2	0.70
E	60	0.33
SE	53*, 59*, 61	0.36
S	51*, 58, 59*	0.34
SW	5*, 53*, 54, 55	0.50
W	52*, 56, 57, 62	0.44
NW	4, 5*, 50, 51*, 52*	1.18

TABLE 40

Relationship of Thaw-Colluvium to Overall Bank Lithology

Bank Lithology (Formation)	Stations	Colluvium (m^3/m)
O.-U.S.S.	1, 3, 4, 5	0.59
O.-U.S.S.-L.S.S.-U.M.H.	6, 7	0.85
O.-U.S.S.-S.B.	50, 54, 55, 56, 57, 60, 61, 62	0.84
O.-U.H.V.-L.H.V.-U.M.H.	51	0.39
O.-U.H.V.-U.M.H.	52	0.23
O.-U.M.H.	58, 59	0.31
O.-U.M.H.-S.B.	53	0.78
O.-S.B.	2	0.72

TABLE 41

Relationship of Thaw-Colluvium to Bank Height

Bank Height (m)	Stations	Colluvium (m^3/m)
<5	1, 3, 4, 5	0.59
5-10	2, 52, 53, 54, 58, 59, 60, 61	0.43
>10	6, 7, 50, 51, 55, 56, 57, 62	0.97

APPENDIX H

Data Used in Regression Analyses

TABLE 42

Data Used in Regression Analyses for Variables Common to All the Stations
(See Appendix B for interval definitions.)

Variables	Interval								
	1-76	76-96	96-137	137-190	190-397	397-419	419-461	461-472	472-503
Maximum Pool Level (m)	562.0	562.8	563.2	562.9	562.3	561.8	564.1	564.1	564.0
Mean Pool Level (m)	561.2	562.4	563.1	562.4	561.4	561.5	562.8	564.1	563.9
Rainfall (mm/day)	0.54	3.49	1.31	0.16	0	0.38	2.56	0	2.65
Freeze-Thaw Cycles (number/day)	0	0	0	0	0.48	0	0	0	0
Maximum Frost Depth (cm)	0	0	0	0	79.5	0	0	0	0
Mean High Wind Speed (km/hr)	35.6	26.8	34.4	34.0	30.5	42.6	23.8	25.8	27.5
Duration of ice cover (months)	0	0	0	0	4.2	0	0	0	0

TABLE 43

Dominant Wind Direction (angle with bank face) Data Used in Regression Analyses
(See Appendix B for interval definitions.)

Station	Interval								
	1-76	76-96	96-137	137-190	190-397	397-419	419-461	461-472	472-503
1	24	-21	24	-21	-21	-21	21	-24	-21
2	45	0	45	0	0	0	0	-45	0
3	90	45	90	45	45	45	-45	-90	45
4	70	65	70	65	65	65	-65	-70	65
5	45	90	45	90	90	90	-90	-45	90
6	90	45	90	45	45	45	-45	-90	45
7	85	50	85	50	50	50	-50	-85	50
50	24	-21	24	-21	-21	-21	21	-24	-21
51	-10	35	-10	35	35	35	-35	10	35
52	-10	35	-10	35	35	35	-35	10	35
53	-58	-13	-58	-13	-13	-13	13	58	-13
54	-30	15	-30	15	15	15	-15	30	15
55	-30	15	-30	15	15	15	-15	30	15
56	-5	30	-5	30	30	30	-30	5	30
57	-5	30	-5	30	30	30	-30	5	30
58	-90	-45	-90	-45	-45	-45	45	90	-45
59	-20	-25	-20	-25	-25	-25	25	20	-25
60	24	-21	24	-21	-21	-21	21	-24	-21
61	-45	-90	-45	-90	-90	-90	90	45	-90
62	-20	25	-20	25	25	25	-25	-20	25

TABLE 44

Data for Constant Variables Used in Regression Analyses
(See Table 32 for maximum fetches and Table 4
for maximum bank heights and orientations.)

Station	Relative Erodibility of Lithology at Wave Impact Zone (1-10; 10 = most erodible)
1	7
2	2
3	7
4	7
5	9
6	5
7	5
50	2
51	8
52	5
53	2
54	2
55	2
56	2
57	2
58	5
59	5
60	2
61	2
62	2

TABLE 45

Average Bank Recession (cm/day) Data Used in Regression Analyses
(See Appendix B for interval definitions.)

Station	Interval								
	1-76	76-96	96-137	137-190	190-397	397-419	419-461	461-472	472-503
1	0.01	0.31	1.35	0.29	0.001	0.21	3.99	6.84	1.45
2	0	0	0.41	0.03	0.01	0.17	0.77	1.36	3.97
3	0.11	0.06	0.09	0.002	0.003	0.07	1.41	11.32	1.80
4	0.02	0.13	0.03	0.005	0.06	0.13	1.62	4.10	2.54
5	0.02	0.13	0.10	0.04	0.02	0.02	2.25	2.75	1.66
6	0.40	0.81	0.03	0.35	0.07	0	0.10	0.01	0.01
7	0.38	2.24	0.70	0.64	0.21	0.84	1.16	0.15	2.02
50	0.19	0.22	0.22	0.25	0.26	0.05	0.06	0.09	0.09
51	0.23	0.01	0.96	0.06	0.06	0.10	1.07	5.38	3.48
52	0.14	0.20	1.12	0.02	0.01	0	0.45	5.61	3.17
53	0.01	0.17	0.09	0.02	0.06	0.05	0.13	0.88	0.81
54	0	1.73	0.56	0.40	0.33	3.45	1.43	1.01	1.01
55	0.04	4.05	1.66	0.95	0.55	3.40	3.29	5.29	0.70
56	0.73	0.42	1.73	0.72	0.47	1.33	1.72	0.12	0.32
57	0.07	0.10	0.02	0.03	0.07	0	0.49	1.35	0.67
58	0	0.04	0.09	0.05	0.03	0.01	0.04	3.73	0.70
59	0.28	0.09	0.03	0.02	0	0.26	1.64	0.05	0.21
60	2.50	0.50	0.10	0	0.04	0	0	0.18	0
61	1.94	0.05	5.01	0	0.41	0	5.14	0	0
62	0	0	0.89	0.23	0.08	0.03	0.30	2.58	0.54

APPENDIX I

Aerial Photograph Data

TABLE 46

Aerial Photographs Used in Analysis
of Historical Bank Recession
(The Average Scales are as measured near the stations)

Stations	Frame No.	Date	Average Scale
1-5	BAO-5V-85	July 1, 1958	1:19,919
	BAO-1GG-107	September 14, 1966	1:20,418
	38057-176-155	July 14, 1976	1:39,553
50	BAQ-2V-60	May 19, 1958	1:20,616
	BAQ-4GG-185	August 25, 1966	1:20,535
	38055-376-136	July 17, 1976	1:40,003
51-52	BAQ-2V-124	May 19, 1958	1:20,478
	BAQ-4GG-37	August 25, 1966	1:20,649
53-57	BAQ-3V-14	May 22, 1958	1:21,219
	38055-576-66	August 21, 1976	1:40,447

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