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SHORELINE RECESSION: PAST, PRESENT, AND FUTURE, LAKE SAKAKAWEA, NORTH DAKOTA

by
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Bachelor of Science, University of Minnesota-Duluth, 1984

A Thesis
Submitted to the Graduate Faculty
of the
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in partial fulfillment of the requirements
for the degree of
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This thesis submitted by Brian S. Sandberg in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota has been read by the Faculty Advisory Committee under whom the work has been done, and is hereby approved.

John R. Reid
(Chairperson)

Alan E. Kehew

This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

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Title Shoreline Recession: Past, Present, and Future, Lake Sakakawea, North Dakota

Department Geology

Degree Master of Science

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

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ABSTRACT

Shoreline erosion is a major problem at Lake Sakakawea, North Dakota. Instrumentation along the eastern shore was initiated in 1983 to measure shoreline recession and determine the processes responsible, with the ultimate goal being the development of a relatively simple equation to predict the rate of recession which is better than the model currently used by the U.S. Army Corps of Engineers.

For the twenty stations, the present rate of recession ranges from 0.2 to 4.3 m/y. Approximately 78 percent of the yearly recession occurs during the warm months (May-October) due to wave erosion. Erosion over the cold months occurs as a result of thaw failure.

The most important variables associated with shoreline recession include: bank height, effective fetch, offshore slope angle, beach width, mean grain size, percentage of coarse beach clasts, angle between the shoreline and dominant wind, and bank orientation with respect to the sun. These variables, along with the average monthly rate of recession, were submitted to regression analysis.

Because the rates of recession are seasonally dependent a separate equation was developed for warm and cold season recession. The warm season recession equation, in cm/mo, is:

1a) $Rs = 141.53 - [17.2\sqrt{A} + 8.44\sqrt{B} + 25.08\sqrt{C} + 10.4\sqrt{D}]$

where A= angle between the dominant wind and the shoreline, B= bank height, C= offshore slope angle, and D= beach width. This equation exceeds the 95 percent confidence level with an r^2 of 59.3 percent. This equation is preferred to equation 1b:

1b) $Rs=154.9-[18.8\sqrt{A} + 25.12\sqrt{B} + 10.06\sqrt{C} + 6.91\sqrt{D} + 5.03\sqrt{E} + 1.1\sqrt{F}]$ which includes effective fetch (E) and percentage of coarse clasts (F). This equation exceeds the 75 percent confidence level only. Both equations, however, produce similar results.

The cold season rate is:

2) $Rw = Rs\ [(2.05\ (\text{bank height}) + 0.043\ (\text{bank orientation}) - 2)/100$, where bank orientation is with respect to the sun. This analysis exceeds the 99 percent confidence level and produces an r^2 of 46 percent. The yearly rate of recession (cm/yr) is the sum of the warm and cold season recession multiplied by their active months.

$$3)\ Rt = 6(Rs) + 6(Rw)$$

For future bank recession it was assumed that the rate of recession will decrease with time. Thus, an equation was developed that incorporated the present yearly recession rate and the formula for a parabola. Recession calculated from the equations predicts cumulative recession up to 495m over the 500-year life of the reservoir.

Although these equations are a significant improvement over the template method in use by the U. S. Army Corps of Engineers, further testing is necessary to determine their applicability to other inland bodies of water.

INTRODUCTION

In 1953 the Missouri River was dammed near Riverdale, North Dakota, creating Lake Sakakawea (Figure 1). The reservoir was constructed by the Corps of Engineers to help control floods, supply irrigation and potable water, generate power, conserve fish and wildlife, and improve downstream water quality. In 1969 the reservoir first achieved its maximum operating pool level of 564.3m msl. Since then, erosional processes have claimed a substantial amount of shoreline (Figure 2), and created other environmental problems such as diminished reservoir water quality and storage capacity. Earlier attempts to predict ultimate bank recession failed (Cordero, 1982). The assumption made for that model was that material eroded from steep banks would be deposited in the nearshore zone, thereby creating an offshore platform that would reduce wave energy. Consequently, the banks would eventually become stabilized at a reduced angle and recession would cease.

Purpose

The purpose of this study was to develop a better model than the one currently used by the U.S. Army Corps of Engineers to predict bank recession though time. Development of the model was to be based on evaluation of the mechanics, causes, and magnitudes of erosion processes along the eastern shore of Lake Sakakawea, in Mercer and McLean Counties, North Dakota. The primary data were to be obtained from measurement stations installed along the lake (Figure 3). The results of these measurements were then to be analyzed statistically to determine the

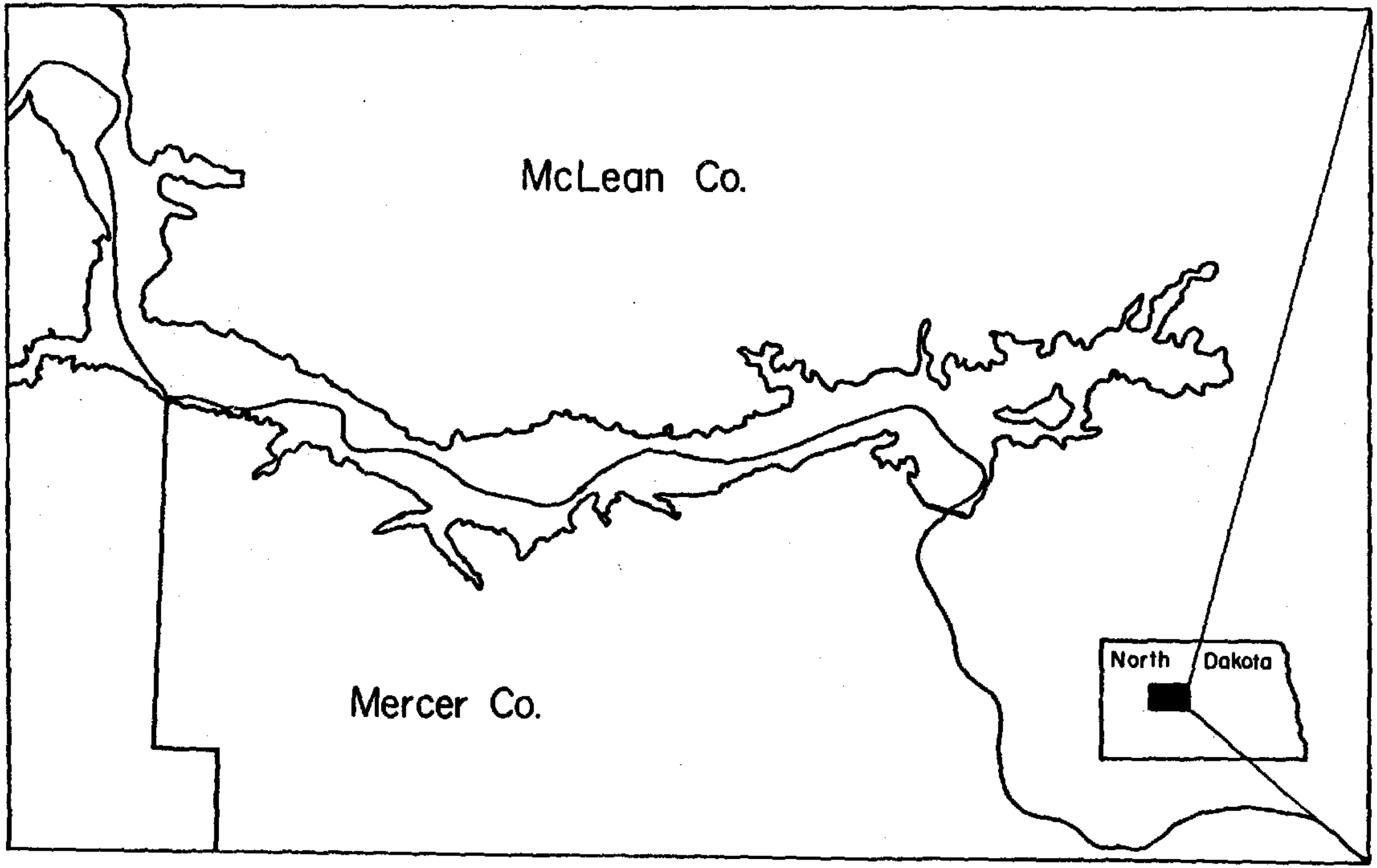

Figure 1 - Location of study area (from Reid and others, 1986).

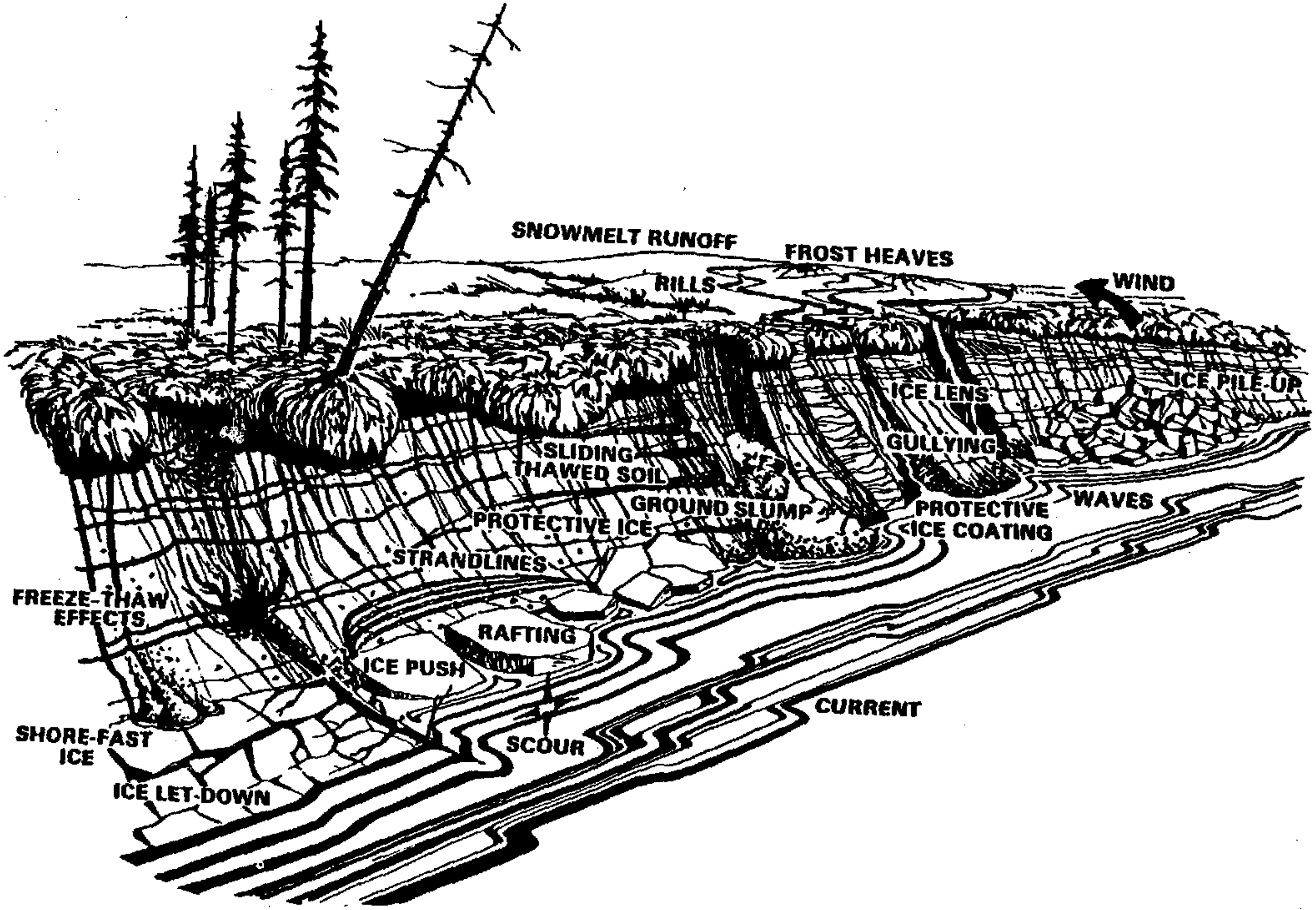

Figure 2 - Erosion processes active in seasonally frozen environments (from Gatto and Doe, 1983).

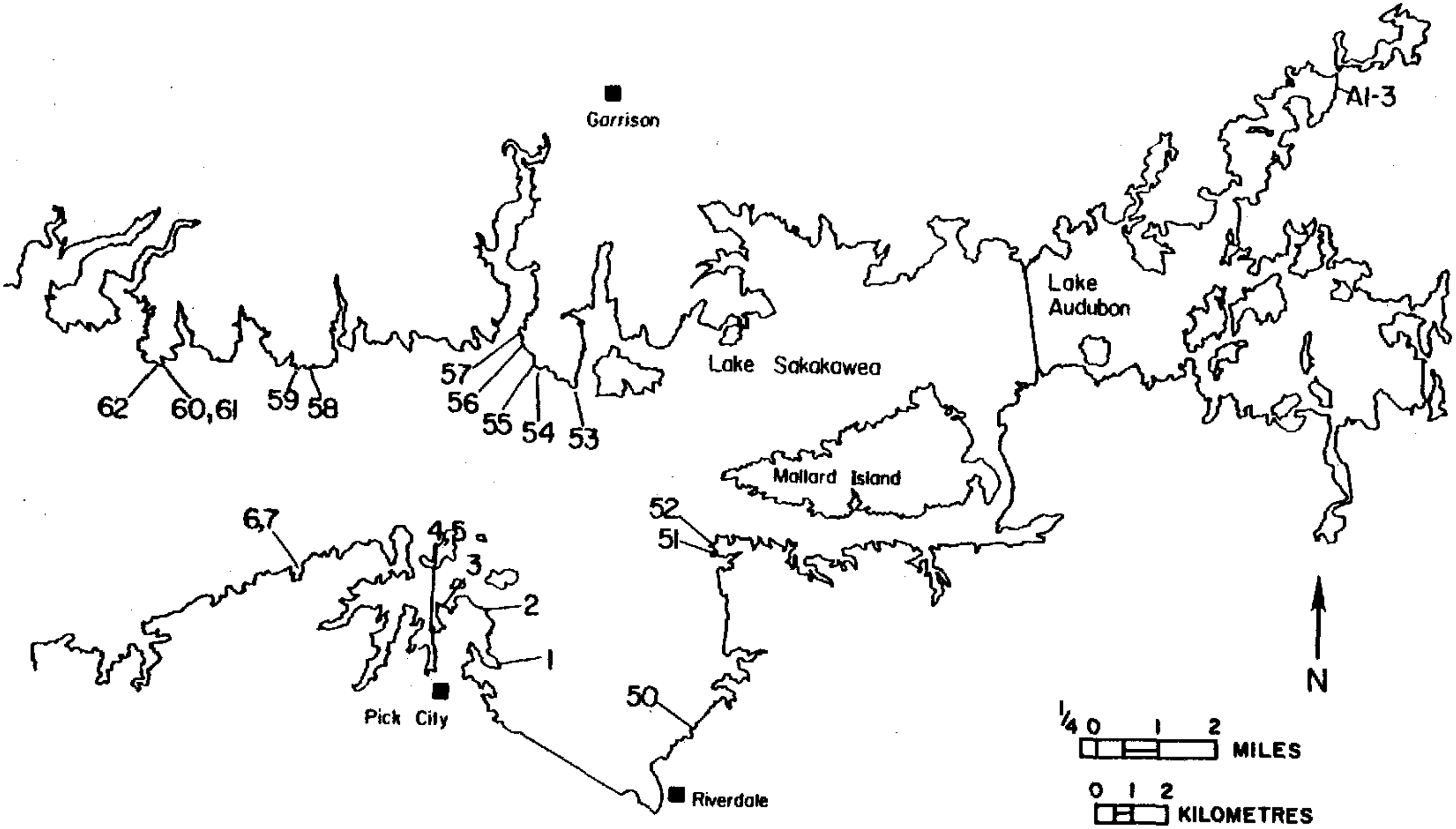

Figure 3 - Bank erosion stations along the eastern shore of Lake Sakakawea, North Dakota (from Reid and others, 1986).

magnitude of their effects on the rates of recession, and to develop a model to predict recession for any point along the shore.

Location

Garrison Dam and Lake Sakakawea are on the Missouri River approximately 121 km upstream from Bismarck, North Dakota. Garrison Dam is one of the largest earthfill dams and the resulting Lake Sakakawea is one of the largest man-made lakes in the world. At maximum pool level, the lake reaches 286 km upstream to just beyond Williston, North Dakota, and has a surface area of approximately 946,000 hectares. Table 1 summarizes some of the physical characteristics of the reservoir.

Climate

The climate of the area is semi-arid and continental, with about 400mm of annual precipitation (Table 2). Spring and Fall are commonly cool with variable precipitation. Summer is warm and generally dry, even though it is the wettest season. Winter is typically cold and dry, with the frost first occurring in early to mid- October and continuing to late April or early May. Over the three-year period of this project, there have been between 77 and 100 days in which the temperature has fluctuated above and below the freezing point. Frost penetration has ranged from 1.0 to 1.5 metres. Climatic data collected over the study period are tabulated in Appendix A.

Geology

The banks along the eastern end of Lake Sakakawea range in height from 2 to 25 metres and typically have near-vertical slopes. The banks consist of Tertiary and Quaternary sediments and sedimentary rocks. Figure 4 is a representative stratigraphic column for this area and Table 3 summarizes the characteristics of the units.

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)
Volum	2.79×10^{10} m^3 (98.7×10^{10} ft^3)
Hydraulic residence time	1.13 years
Mean outlfow	774.3 m^3/s (27,655 ft^3/s)

TABLE 2

Riverdale, North Dakota Weather Summary

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	15.52	394.2	43.0°F (6.1°C)	99°F (37.2°C)	-33°F (-36.1°C)
1985	15.10*	384.6*	43.8°F (6.5°C)	97°F (36.1°C)	-29°F (-33.9°C)

* Through September 1985.

TABLE 3

Stratigraphic Column and Dominant Lithology of Formations in Study Area (from Ulmer and Sackreiter, 1973)

AGE	UNIT NAME		DOMINANT LITHOLOGY
Holocene	Oahe Formation	Riverdale Member	Coarse silt
		Pick City Member	
		Aggie Brown Member	
		Mallard Island Member	
----?-----------	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

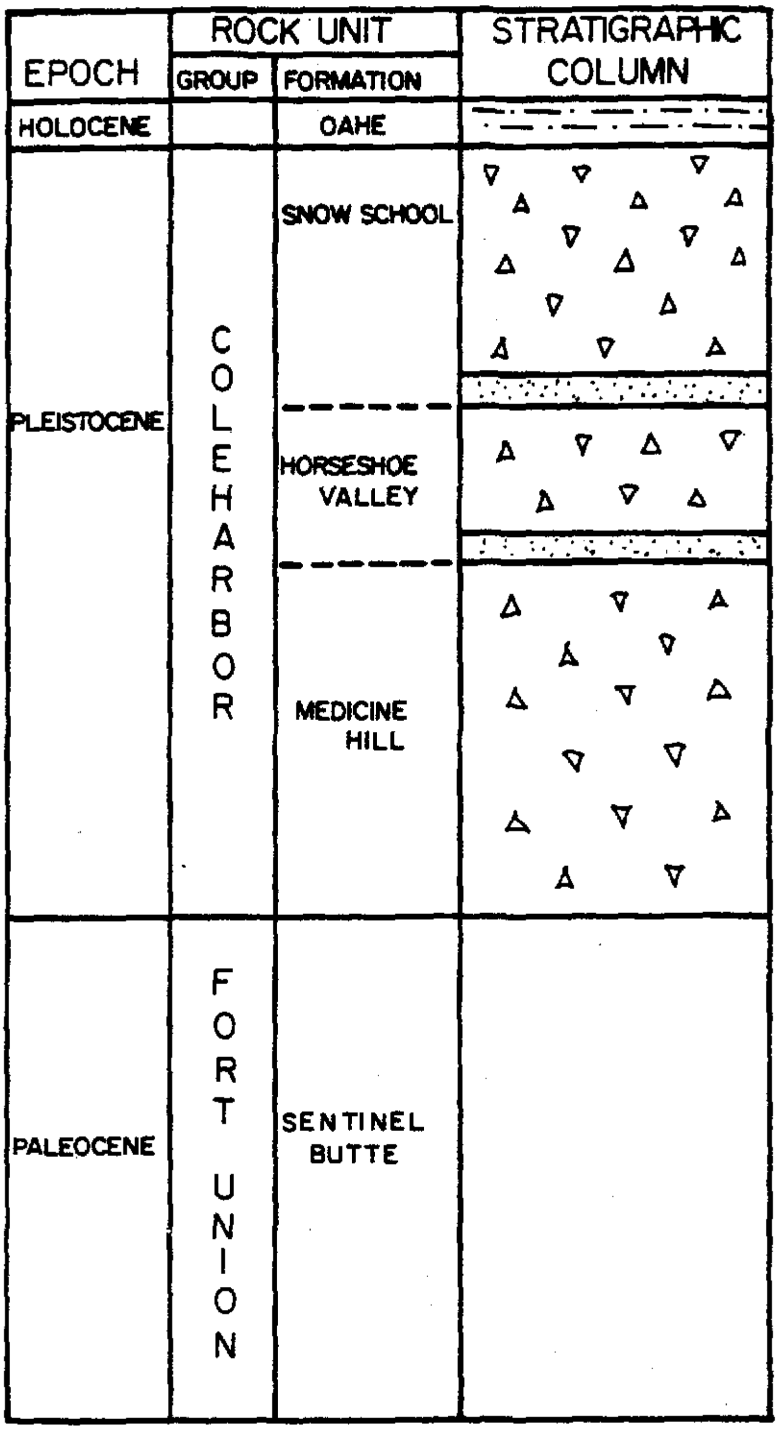

Figure 4 - Geologic column for Lake Sakakawea area, ND (from Reid and others, 1986).

The glacial sediments (till and glaciofluvial deposits) are over 10m thick in places, but the overlying eolian silt is typically less than 0.5m thick. Glacial sediments are the dominate lithology for 13 of the 20 stations at Lake Sakakawea (Figure 5). Tertiary sediments typify two stations; six stations have mixed lithology. Meyer (1979) and Bluemle (1971) have published detailed summaries of the Tertiary and Quaternary geologic history of the area.

Sentinel Butte Formation

The oldest stratigraphic unit exposed in the study area is the Paleocene Sentinel Butte Formation (Ulmer and Sackreiter, 1973). This formation consists of interbedded sandstone, siltstone, mudstone, lignite, and occasional clinker ("scoria"). Poorly consolidated mudstone is the most common lithology in the study area. Changes in color give the formation a banded appearance. Moisture content and density vary greatly.

Textural analyses of 12 samples by Millsop (1985), yielded average sand-silt-clay percentages of 2.2, 47.4, and 50.4, respectively. The average median diameter is 7.7 phi (fine silt). Smectite is the dominant clay.

The bedding of the mudstone is essentially horizontal throughout the area. Joints are well developed both along bedding planes and perpendicular to them (Figure 6). There are also some normal faults developed in the formation, most easily seen by displaced lignite beds. The contact with the overlying unit is always sharp and undulating (Millsop, 1985). The Sentinel Butte Formation is present in the lower parts of most banks and occasionally forms the entire bank. More detailed descriptions of the formation are provided by Jacob (1976) and Crawford (1967).

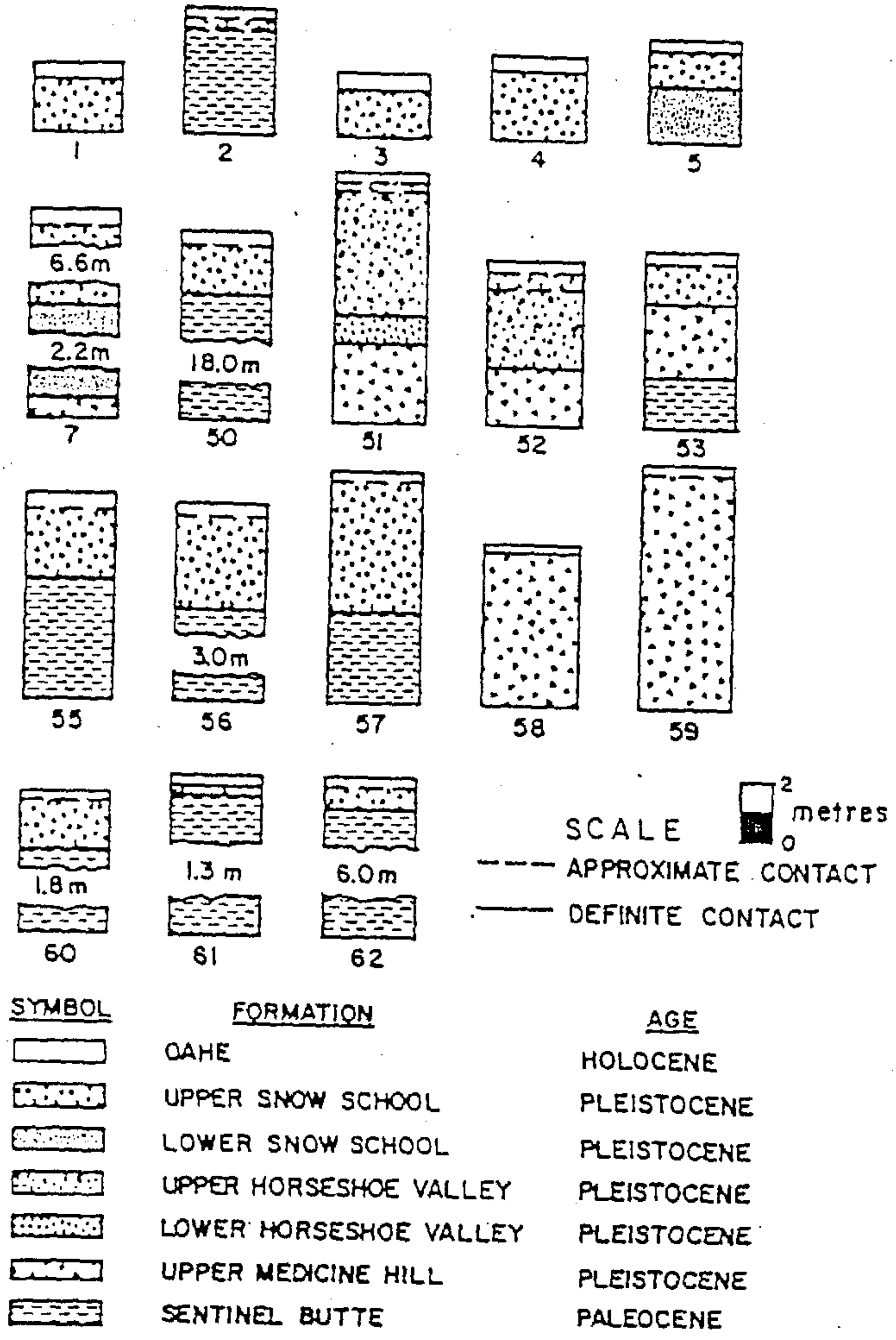

Figure 5 - Stratigraphy of profile sites, Lake Sakakawea, North dakota (from Reid and others, 1986).

Figure 6 - Highly fractured Sentinel Butte mudstone, Station 53 (from Reid and others, 1986).

Pleistocene Formations

Overlying the Sentinel Butte Formation are glacial sediments of the Pleistocene Coleharbor Group (Ulmer and Sackreiter, 1973). The group is divided into three formations: Medicine Hill, Horseshoe Valley, and Snow School (Ulmer and Sackreiter, 1973). Contacts with all the units are sharp and undulating (Millsop, 1985).

Medicine Hill Formation:

The lowermost Pleistocene unit is the Medicine Hill Formation, composed of two distinct members (Ulmer and Sackreiter, 1973). The lower member is not exposed in the study area, but consists of sand, pebbles, and cobbles, and is locally cemented to conglomerate. The upper member is a massive pebble loam (glacial till), and is exposed at numerous erosion stations. The average sand-silt-clay percentages from four samples are 24.7, 45.5, and 29.9, respectively (Table 4). The average median diameter is 5.9 phi (medium silt). The average density is 2.98 gm/cc and the average moisture content is 7.5 percent (Figure 7). For details of the coarse sand composition and mineralogy of all the units see Millsop (1985).

Horseshoe Valley Formation:

The Horseshoe Valley Formation also has two members (Ulmer and Sackreiter, 1973). The lower member is discontinuous and is exposed at only one site in the area, Station 51. There, the lower member consists of interbedded iron-stained conglomerate overlain by a cross-bedded sandy loam unit. Textural analysis of the sand loam yielded sand-silt-clay percentages of 68.4, 14.1, and 17.5, respectively (Table 4). The median grain diameter is 1.8 phi (medium sand).

TABLE 4

Average Texture and Textural Parameters of Glacial Till Units, Lake Sakakawea, ND (modified from Millsop, 1985)

Formation	Number of Samples	% Sand	% Silt	% Clay	Sorting	Median Diameter
Upper Snow School	10	26.4	41.3	32.3	3.415	6.2 phi
Upper Horseshoe Valley	2	32.5	35.0	32.5	3.495	5.7 phi
Upper Medicine Hill	4	24.7	45.4	29.9	3.148	5.9 phi

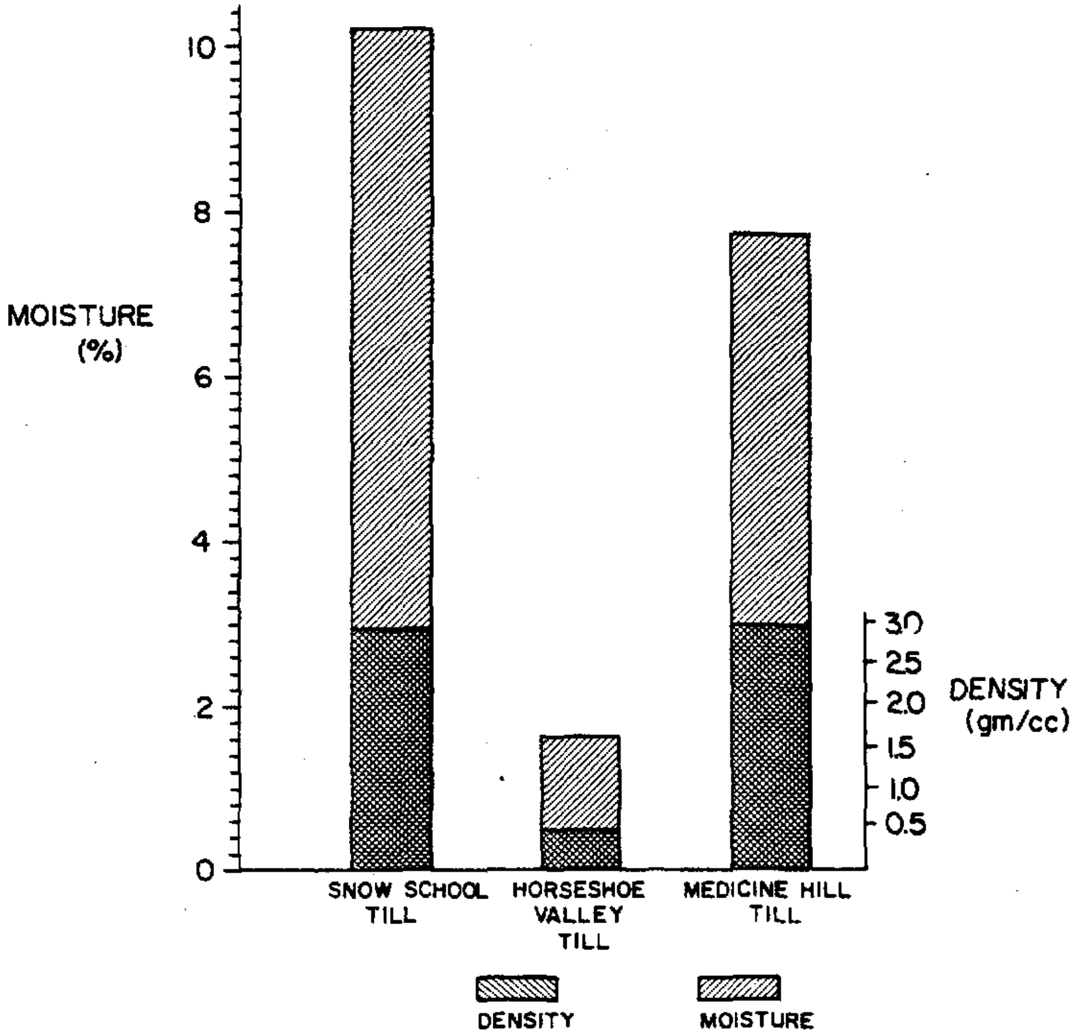

Figure 7 - Density and moisture content of the Snow School, Horseshoe Valley, and Medicine Hill tills (from Reid and others, 1986).

The upper member of the Horseshoe Valley is a pebble loam (glacial till), exposed at only two stations, Stations 51 and 52. The member displays strong columnar jointing, which contributes greatly to its erodibility. The average sand-silt-clay percentages are 32.5, 35.0, and 32.5, respectively (Table 4). The average median diameter is 5.7 phi (medium silt). The average density is 1.64 gm/cc and the average moisture content is 0.5 percent (Figure 7).

Snow School Formation:

The Snow School Formation consists of three members (Ulmer and Sackreiter, 1973). The lowest member is exposed at Stations 4, 5, and 7. It is an iron-stained conglomerate overlain by a flat-bedded and occasionally cross-bedded dirty sand unit. Textural analyses of five samples yielded percentages of sand-silt-clay of 69.1, 19.1, and 11.8, respectively (Table 4). The sand has a median diameter of 2.7 phi (fine sand).

The middle member of the Snow School Formation is not exposed at any erosion station, but has been found in the study area (Ulmer and Sackreiter, 1973). The sediment is classified as a reddish-brown sandy pebble loam (glacial till), and is considered an excellent marker bed (Ulmer and Sackreiter, 1973).

The upper member is a very compact columnar jointed pebble loam (glacial till), and is exposed throughout the study area (Figure 8). Calcium carbonate precipitate is common along joint planes. This member and the Sentinel Butte Formation are the two most commonly exposed units along the eastern end of Lake Sakakawea. The average sand-silt-clay percentages for 10 samples are 26.4, 41.3, and 32.3, respectively (Table 4). The average median diameter is 6.2 phi (fine silt). The average density is 2.94 gm/cc and average moisture content is 10.2 percent

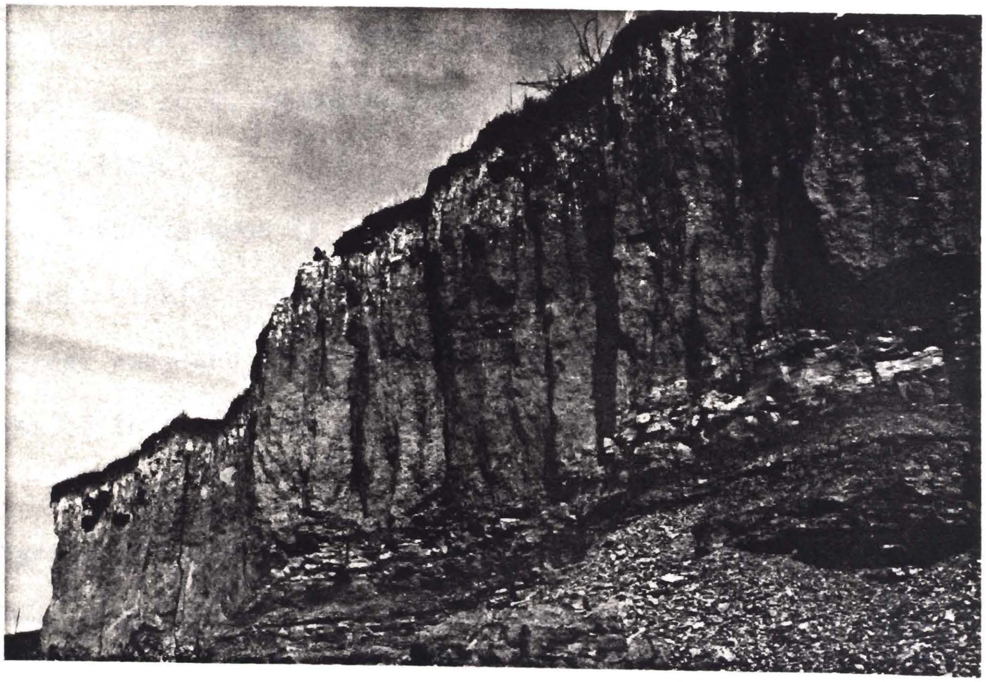

Figure 8 - Vertically jointed Upper Snow School till, Station 55 (from Reid and others, 1986).

(Figure 7). For additional data, such as grain mineralogy and matrix composition, see Millsop (1985).

Oahe Formation

The Oahe Formation is the uppermost stratigraphic unit in the study area. It is interpreted to be wind-blown sediment (loess) (Bickley, 1972). Textural analyses yielded average sand-silt-clay percentages of 7.8, 71.8, and 20.4, respectively. The average median diameter is 6.0 phi (fine silt).

The loess is heavily root-bound which contributes to probably making it the most stable formation in the study area. The underlying tills often break away and leave the loess as an overhang (Figure 9). Thus, failures of this unit are as debris falls or earthfalls.

Previous Work

Earlier attempts to calculate ultimate bank recession at Lake Sakakawea were made by the Corps of Engineers (Corps) (Cordero, 1982). They used a conceptual model based on the conservation of volume (Figure 10). This procedure assumes that the eroded bank material is deposited in the immediate offshore zone. When enough bank material is eroded to form a stable offshore platform that can effectively dissipate approaching waves, bank recession ceases. The problem with this assumption is that the banks are predominantly composed of very fine-grained sediments (e.g., silt and clay) (Table 4) which are carried out into deeper water by wave and current action. Thus, a stable platform is not developed, as yet. Cordero found that within the first 13 years after the maximum pool level had been reached, erosion had already exceeded the projected ultimate limit in 80 percent of the locations measured. Therefore, it

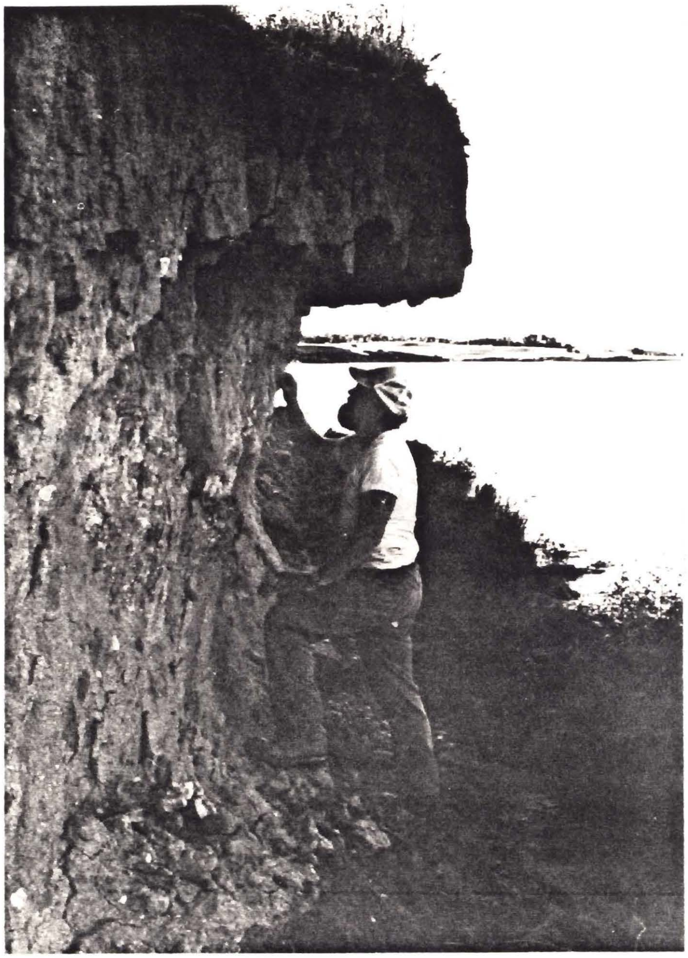

Figure 9 - Overhanging Oahe loess overlying Upper Snow School till, Station 1 (from Reid and others, 1986).

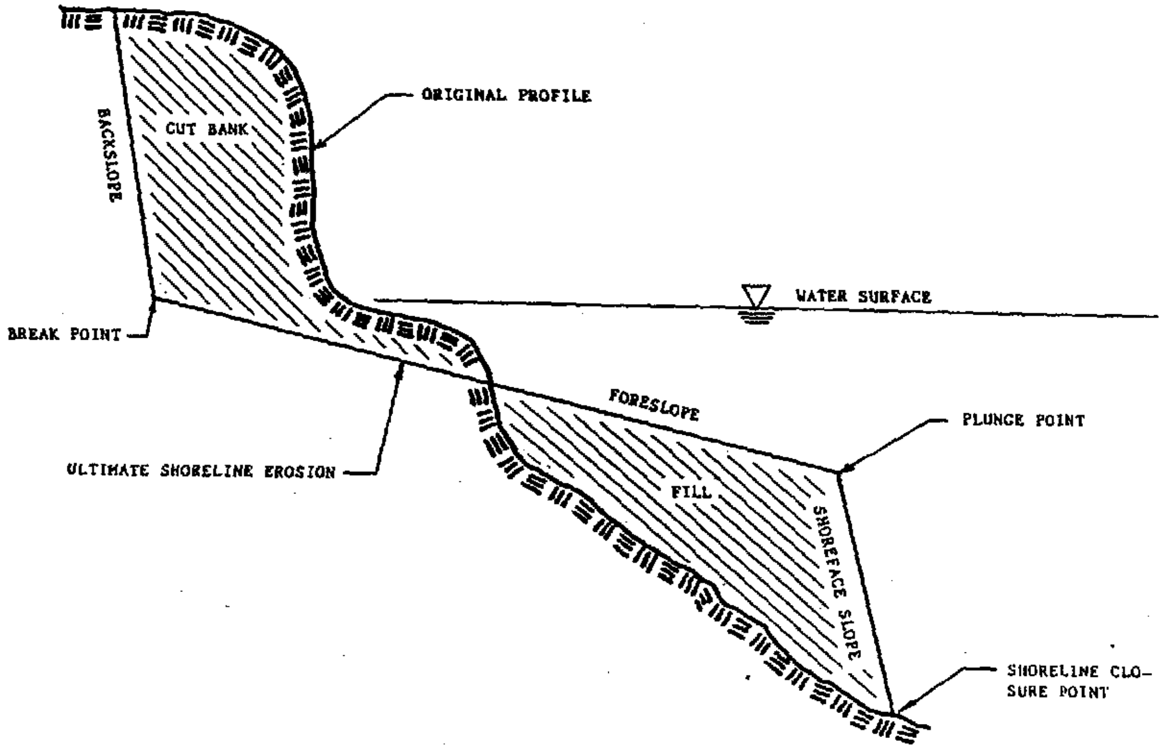

Figure 10 - Conventional procedure used by U.S. Army Corps of Engineers to predict ultimate shoreline recession (from Cordero, 1982).

was concluded that both the conventional technique and ultimate recession estimates needed to be re-evaluated.

Another study related to this thesis was by Gatto and Doe (1983). They calculated bank recession rates during the periods 1958-1966 and 1966-1976. They concluded, from air photo measurements, that bank recession rates for 1958-1966 averaged 4.3m/yr and for 1966-1976 averaged 5.8m/yr. Because of the scale of the photographs these rates were considered approximations at best. They concluded that the primary cause of land loss during 1958-1966 was by reservoir inundation, and for 1966-1976 it was inundation and ensuing wave erosion. They also tested for correlation between measured recession and other variables such as water level, and bank and reservoir characteristics. However, the results did not prove useful in evaluating the erosion processes and bank conditions that contribute to shoreline erosion; significant direct correlations were found with variables that were obviously not important (e.g., duration of ice cover).

Finally, this thesis is the conclusion of a three-year study of bank erosion at Lake Sakakawea. Earlier work on this study was done by Reid and others (1986), Millsop (1985), and Reid and Millsop (1984). Millsop's thesis discussed the establishment of erosion stations, collection of such data as bank recession measurements, and determination of the erosion processes responsible for bank recession. He also determined grain-size distribution and mineral composition of all the formations found along the eastern end of Lake Sakakawea. He concluded that the principal activating cause of bank recession at Lake Sakakawea is wave action. The most important variables responsible for wave erosion included: pool level; wind velocity, direction, and duration; bank orientation; geology; geometry; natural rip-rap; offshore bathymetry; and the presence of nearshore islands. Results indicated that banks shorter than 5m and which face north and northeast, and are composed of well-jointed till or mudstone, have the highest recession rates (Millsop, 1985).

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 chosen as control sites. The purpose of the control sites was to isolate any one independent variable and determine the impact it had on shoreline recession. The eastern end of the Lake Sakakawea was chosen because it was closer to Grand Forks, North Dakota, and because relevant pool and weather data were available at Riverdale. Also, it was assumed that erosion at the eastern end of the lake would be highly active due to long westerly fetch. The stations selected are shown in Figure 3.

Data Collection

Bank Recession Pins

Bank-top recession at each of the stations was measured by inserting a series of pins, 152mm long nails, perpendicular to the shoreline. The pins were set 1.5m and 3m back from the bank edge. Each station had a representative length of shoreline with an average of six sets of pins spaced at 3-metre intervals. Remeasurement of the pins revealed the amount of bank recession over a specific interval. 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. Sixty pins were inserted along north shore banks and seventy-two pins along south shore banks. The pins were measured each time the lake was visited.

Profiles

Beach and bank profiles were measured at each erosion station, using a Brunton compass and 0.8-metre board from the shoreline to the top of the bank. Profiles were measured as often as possible.

Offshore profiles were also measured in conjunction with the onshore profiles during the summers of 1984 and 1985. The profiles were measured with a Raytheon sonar recorder from a boat. A stadia rod attached to the boat was read at about 15m intervals from a transit located onshore at the waterline. Thus, the depth and distance were known and the offshore slope and topography could be plotted. It was hoped that both the onshore and offshore profiles would provide comparative data on changes offshore as well as evidence as to where the eroded sediment was going. If a stable platform is being built, it will help dissipate wave energy before it reaches shore.

Colluvium Volumes

In late May, after spring thaw was complete, the volume of colluvium resulting from thaw failure was determined using three techniques. The most accurate method required excavation of a trench at representative colluvium sections. The colluvium was removed by shovel and placed into a bucket of known volume. When the contacts with the undisturbed bank and beach were reached, the volume of the trench was calculated by multiplying the number of buckets removed by the bucket volume. Using this trench as a standard, the volume of colluvium for an entire section was estimated by pacing along shore. This estimated value was probably a minimum because some 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 colluvium is the result of processes other than thaw failure.

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

The third technique employed trigonometric functions and was applied only to very large colluvium areas. Volumes were calculated by measuring the length of the colluvium apron and its slope angle, and the slope of the bank. From these measurements, the unit area could be determined. The area was then multiplied by the length of shoreline to determine the volume of eroded sediment.

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

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 1985. Wind data were obtained four times daily, except weekends and holidays, from the Riverdale weather station.

Precipitation

Along with pool level and wind data, precipitation events were recorded and incorporated into the data base. Daily work-day meteorological observations from the Riverdale weather station were provided by the Riverdale office of the Corps of Engineers. Because no observations are made over the weekends and holidays, the records were supplemented by data from the volunteer weather observer at Garrison, Mrs. Albert Beierly (until January 1985), and Mr. Herbert Schwarz (since July 1985).

In order to establish a data base to compare north-shore precipitation with that at Riverdale, one additional rain gauge was installed at Fort Stevenson State Park. The park rangers, Tim Thiel and Paula Onufray, kindly recorded each precipitation event there.

Frost Tubes and Thermograph

In order to measure frost depth and duration, frost tubes were installed at Riverdale and Fort Stevenson State Park. Frost depth was measured using a 15mm o.d. polyethlyene tube filled with methlyene blue-dyed water inserted into a PVC casing (35mm o.d.). To measure the frost depth, the tube was lifted up and the thickness of the frozen section was measured, the base being equivalent to the zero-degree isotherm. These tubes are similar to those used by Reid (1985) and Rickard and Brown (1972).

A seven-day thermograph was installed at Fort Stevenson State Park; it was changed weekly by the rangers there. It recorded temperatures throughout the winter, enabling freeze-thaw cycles to be counted.

Field Analyses

The banks at each station were described, sketched, photographed, and measured regularly throughout the project. In the fall of 1983, unweathered samples of the banks were collected for subsequent laboratory analyses of color, texture, coarse sand and clay lithology, and percent carbonate matrix. Joint orientations were also measured at this time. In June 1984, additional samples were collected for moisture content and dry density. The procedures and results of the analyses were discussed by Millsop (1985) and Reid and others (1986).

Along with bank sample collection, offshore samples were collected in July, 1985, to determine grain size distribution. The primary objective was to locate the possible existence of the offshore silt/clay boundary. An Eckman dredge was to used to collect the sediments at specific intervals from shore, directly offshore from the profile pin at the erosion station. Such sites were chosen because the distance from shore could be calculated from offshore profiles made in June 1985. Samples were collected from depths up to 29m and distances of up to 323m from shore. Each sediment sample was placed in a mason jar and labeled.

Finally, the size distribution of beach sediment at each of the station was determined in August, 1985. It was surmised that an abundance of coarse beach clasts forming a beach would effectively impede wave erosion. The distribution was determined by constructing a grid on a representative section of beach. The length of the grid incorporated the entire beach width. At one-metre intervals from the bank face to the water line, particle size was noted at every 10cm mark along a line 80cm wide, parallel to the water line. The data were converted to percentage of area covered by particles of each size class. This method was selected over bulk sampling because it is applicable to large particles and provides a better representative sample for the area in question (Wolman, 1954).

Laboratory Analyses

Laboratory time involved analyzing sediments, calculating wave energy, and performing statistical analyses on possible parameters associated with bank recession. Offshore samples were analyzed for percentages of sand, silt, and clay. Wave energy calculations involved determining effective fetch, which is a parameter that can be used for forecasting waves in inland bodies of water. The procedure for statistical analysis is discussed later.

Offshore Grain-size Analysis

Hydrometer analyses were performed using the standard ASTM (1980) procedures. SediGraph analyses were made on the same samples and compared with hydrometer results. SediGraph sample preparation was as follows. About 15 grams of each sample were soaked in 50 ml of 4 percent Calgon solution (dispersant). After soaking for 24 hours the sample was wet-sieved through a 4-phi screen, using distilled water. Most of the silt and clay passed through the screen. The solution was allowed to settle and then inspected for signs of flocculation. If there was no apparent flocculation the solution was ready to be analyzed. For SediGraph analysis to be valid the solution has to be sufficiently dense, approximately 5gm per 50ml of water. Therefore, water had to be decanted or added accordingly. The SediGraph analyzes the sample using x-rays and produces a cumulative curve for a desired range of phi sizes, in this case coarse silt to fine clay (4 to 12 phi). Both the SediGraph and hydrometer results were then combined to provide a plot for the total sediment range of fine sand to fine clay.

Effective Fetch

Effective fetch is a parameter developed by the Corps of Engineers to more accurately describe the types of wind-generated waves found in restricted bodies of water such as lakes or reservoirs. The procedure for determining effective fetch involves constructing radials at 5° increments up to an angle of 45° on each side of the central radial (the principal fetch) (Saville, 1954). These radials are extended until they intersect the shoreline (Figure 11). A line is then drawn from the point

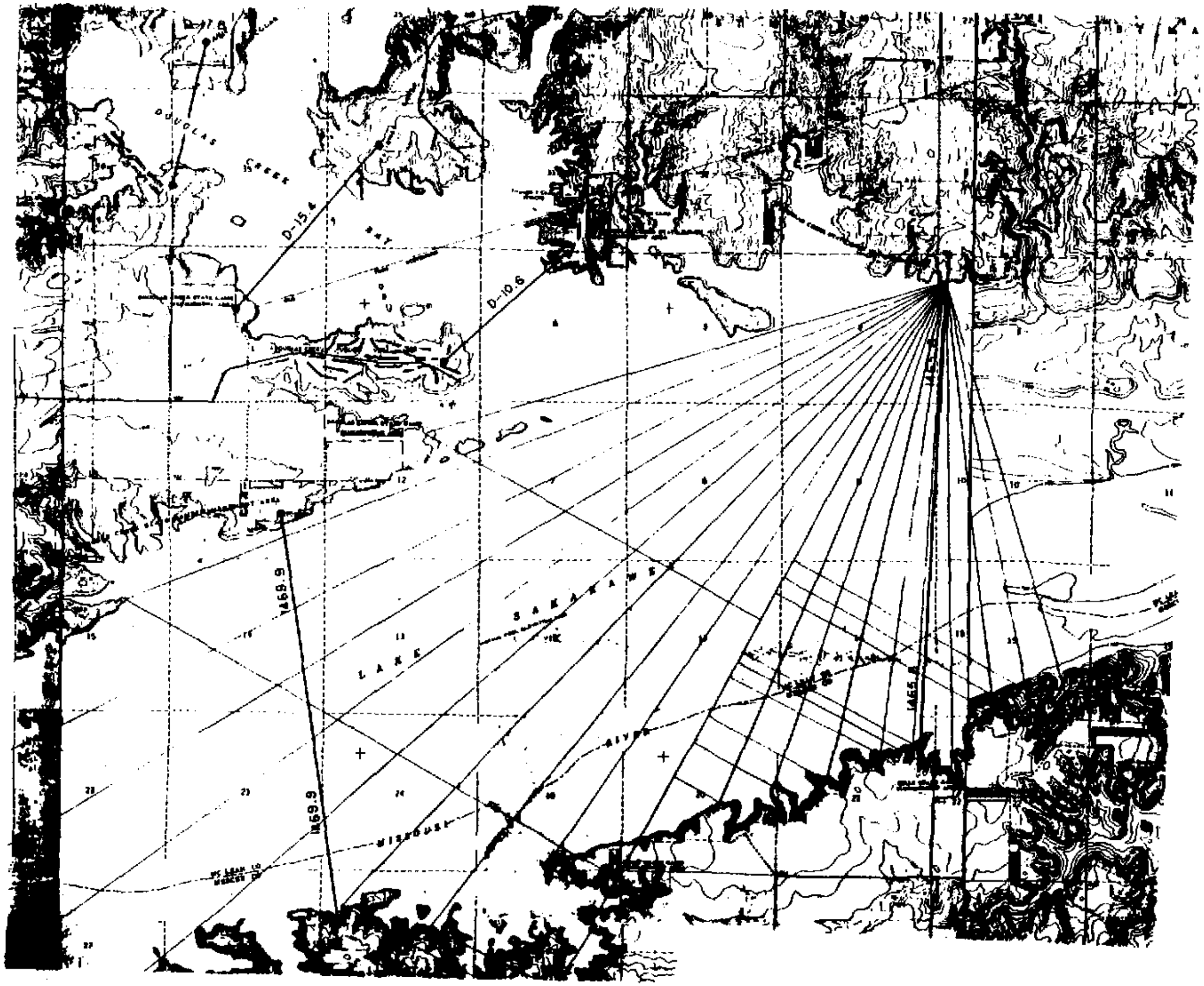

Figure 11 - Method of determination of effective fetch for Station 58, with principal wind from southwest.

of intersection, perpendicular to the central radial. The distance along the central radial from the origin to the line of intersection is measured. Next, the calculated distance is multiplied by the cosine of that particular angle. The resulting products for each radial (distance x cosine) are summed and then divided by the sum of all the cosine angles. Angles up to 45° from the central radial were used for each station at Lake Sakakawea except for Station 53, which required angles up to 90° on each side of the central radial; the station is located on a extended headland that is subjected to wave action from many directions. Effective fetches that are calculated over a 180° sector can lead to values that are too low. This may cause predicted wave parameters to be underestimated (Saville, 1954).

Another consideration was choosing the principal wind direction for each station. This involved identifying the most dominate wind direction in relation to the longest fetch at each station. The station shown on Figure 11, for example, has its principal fetch to the southwest. Strong winds from the south, however, occur more frequently than from the southwest. But if a southern principal fetch were chosen, it would fail to account for the longer fetch to the west. Also, by selecting a principal wind from the south a small effective fetch value would result and cause wave parameters to be underestimated.

Once effective fetch is calculated, it can be applied to a wave forecasting curve that predicts such wave parameters as wave height and wave period. The parameters can then be used in a standard equation that calculates potential deep water wave energy.

RESULTS

Bank Recession

Sites and Measurements

Erosion stations were visited every month from April to October, the most active period of changes in the shoreline geometry. From November to March the sites were visited occasionally to observe changes in shoreline geometry, and study the type of erosion processes active. Also, during this period, measurements of the pins were not always possible because of snow cover. Snow cover also denied road access to some of the stations.

Finally, bank recession pin measurements have proven to be the most valuable technique in the documentation of erosion magnitudes. The cumulative average recession for a measurement interval was determined for each station by summing the bank recession values for all the pins and dividing that by the number of pins measured. The average recession for the 20 stations on Lake Sakakawea is shown on Figure 12. This represents 16 measurements over 26 months of data collection.

Rates: Ranges and Differences

In 1985 bank recession rates were less than 1984, because of the lower pool level (Figure 13). But for each year there is a strong correlation between pool level and the rate of recession. From this, a pool level of 563m msl was determined to be the critical pool level; surface water elevations above this level are high enough for waves to easily reach the banks, especially during storms with strong winds. In

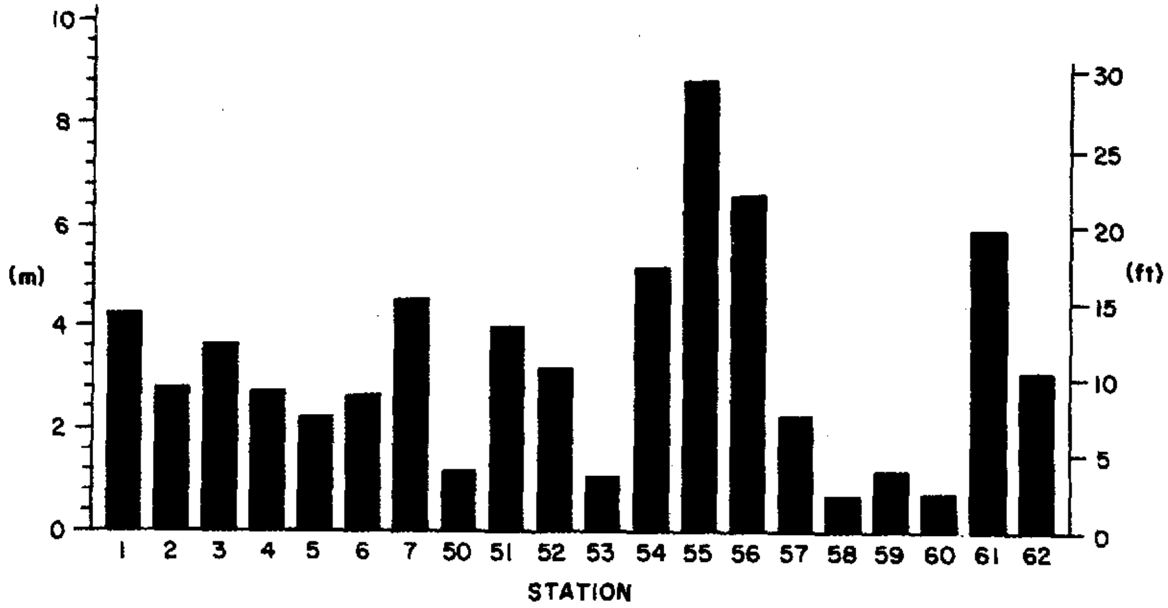

Figure 12 - Cumulative average bank recession 1983-1985 (from Reid and others, 1986).

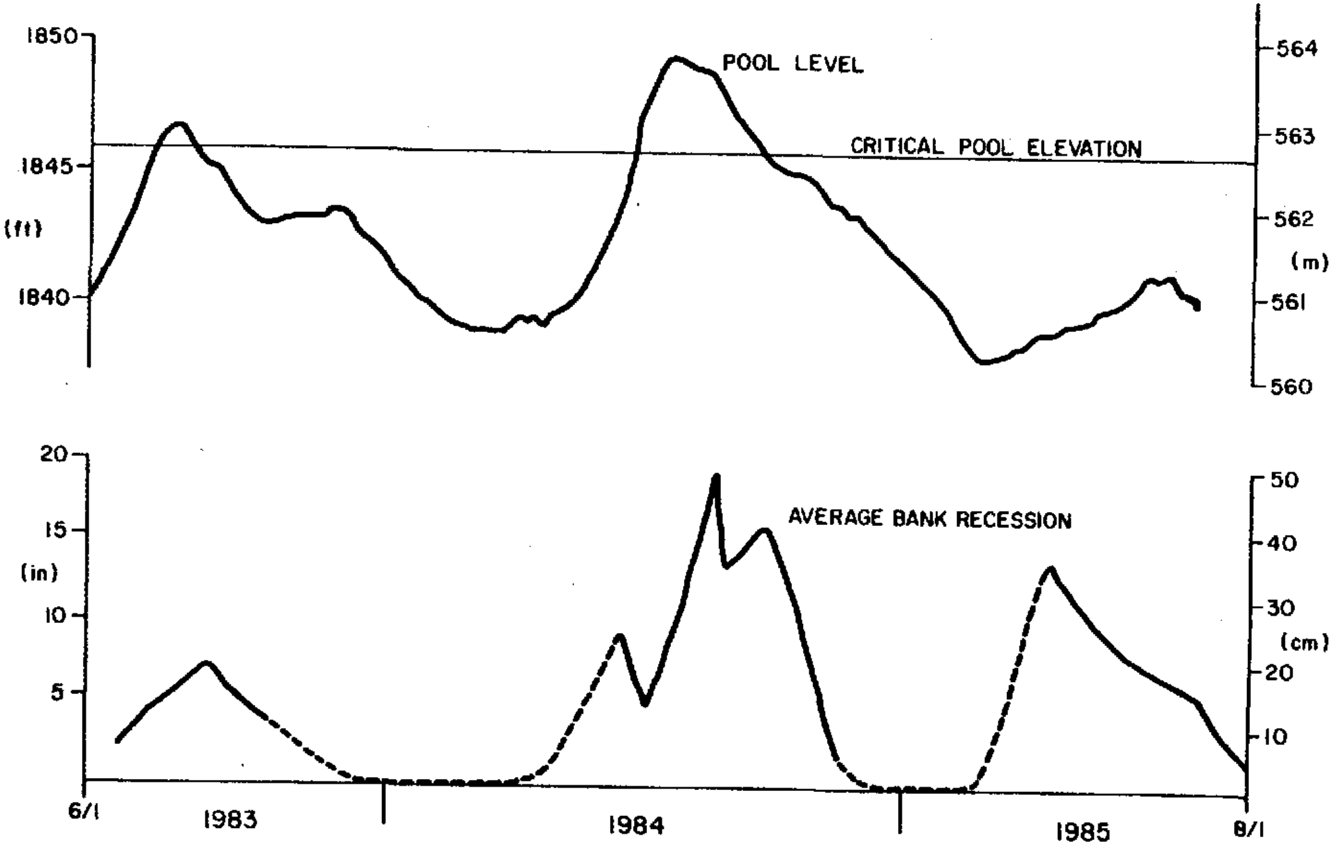

Figure 13 - Comparison of pool levels and average bank recession, 1983-1985 (from Reid and others, 1986).

1984, the pool level was above the critical elevation for a sustained period, while 1985 never reached the critical level.

For the twenty stations, the average yearly rate of recession ranged from 0.34 to 4.34 m/yr. Table 5 lists the stations with their cumulative and yearly recession rates and seasonal percentage. Station 55 had the highest recession rate; Station 58 had the lowest. The average recession rate for all the stations was 1.59 m/yr. Bank recession measurements also show that rates of recession are seasonally dependent. Cumulative warm season recession accounted for approximately 78 percent of the total, a decrease from 87 percent for 1984 (Millsop, 1985). The remaining 22 percent of bank recession occurred during the cold season (Table 5).

Monthly recession rates are high from late May to early October, when wave action is the dominant erosive force. Warm season recession rates, which are controlled by the pool level, peak in July when the highest pool level is attained. After July, downstream demand exceeds upstream input and pool level, and subsequently bank recession, begins to decline. Review of past pool level elevations show that yearly pool levels have alternating high and low years, but the critical pool level (563m msl) is exceeded 50 percent of the time.

Cold season recession accounts for 2 to 50 percent of the total yearly recession. Freeze-thaw, plus other factors, are the driving erosive forces. Recession in the winter does not occur at a continuous rate, but as sporadic events usually in the late winter and early spring when moisture content of the bank material is high. The cumulative recession for each station is presented in Appendix B.

TABLE 5

Cumulative Average Bank Recession at Each Station Lake Sakakawea, June, 1983 through June, 1985

Station	Number of Pins	Cumulative Average Bank Recession m	Warm Weather Recession	Cold Weather Recession	Bank Recession Rate m/y
1	14	4.13	98.5%	1.5%	2.06
2	8	2.77	76.2%	23.8%	1.39
3	6	3.60	94.5%	5.5%	1.80
4	4	2.71	93.7%	6.3%	1.36
5	4	2.25	85.8%	14.2%	1.12
6	3	2.35	76.6%	23.4%	1.18
7	4	4.20	51.7%	48.3%	2.10
50	5	1.03	53.4%	46.6%	0.52
51	12	3.75	85.3%	14.7%	1.88
52	7	3.07	75.6%	24.4%	1.54
53	12	1.03	53.4%	46.6%	0.52
54	5	5.15	87.0%	13.0%	2.58
55	9	8.67	64.7%	35.3%	4.34
56	8	6.02	66.2%	33.8%	3.01
57	8	2.17	60.8%	39.2%	1.09
58	7	0.67	91.0%	9.0%	0.34
59	4	1.02	98.0%	2.0%	0.51
60	1	0.37	91.9%	8.1%	0.19
61	1	5.56	84.7%	15.3%	2.78
62	6	3.01	76.1%	23.9%	1.51
Average	-	3.18	78.2%	21.7%	1.59

Besides seasonal differences, variations in rates were also correlated to many other factors, ranging from the unique geometric characteristics of the shoreline, such as bank height and orientation, to its offshore slope. The significance of these factors will be discussed later.

Bank Failure Mechanisms

A variety of mass movements occurs along the shoreline of Lake Sakakawea. Bank failures, in the forms of falls, topples, slides, and flows, result when stress exceeds strength (Varnes, 1978). Failures of all these classifications were observed at Lake Sakakawea, and are commonly associated with reservoirs (Erskine, 1973). These have been summarized by Millsop (1985).

Attempts to quantify bank failure by these mechanisms were accomplished by recession pin measurements in the warm season and colluvium volume calculations in the spring for cold season recession. Using the methods described earlier, colluvium volumes per metre of shoreline were determined. Volumes ranged from 0.13 m^3/m to 34.8 m^3/m for 1985 (Table 6). The average volume for 1985 was 3.88 m^3/m, whereas 1984 averaged only 0.68 m^3/m. The difference is a reflection of the high warm season recession that occurred the preceding year as result of the unusually high pool level (Figure 13); at the end of 1984, banks along Lake Sakakawea were generally steep and freshly exposed to the weather. In contrast, bank recession in 1983 was less than 1984. Therefore, colluvium from the preceding year remained and protected the underlying bank material from the effects of freeze-thaw and lateral expansion.

TABLE 6

Colluvium Volumes Along Shorelines Near Bank Recession Stations for 1983-1985

Station	Shoreline Length	Volume of Colluvium 1983	1984	1985
	m	m^3/m	m^3/m	m^3/m
1	132	0.58	0.68	0.36
2	73	4.54	0.76	0.82
3	64	9.05	0.18	0.19
4	49	1.54	0.73	0.30
5	33	2.77	0.75	0.13
6	34	21.6	1.12	34.8
7	37	7.6	0.58	10.5
50	70	54.1	3.3	2.0
51	159	12.9	0.39	0.36
52	55	--	0.27	0.53
53	567	0.96	0.79	9.27
54	83	3.0	0.13	0.14
55	64	--	0.72	6.1
56	114	8.1	0.89	3.57
57	109	9.73	0.48	5.8
58	28	8.26	0.33	0.37
59	109	7.57	0.28	1.46
60	58	2.14	0.33	0.22
61	65	3.77	0.59	0.43
62	68	--	0.26	0.20
		Average:	0.68	3.88

Waves

General

A major factor in bank erosion is wind-generated wave action (Carter and Guy, 1983; Quigley and Gelinas, 1976). Previous studies have shown that wave action is the dominant factor in shoreline erosion for lakes (Sterrett, 1980; Mickelson and others, 1976) as well as reservoirs (Reid, 1985; Reid and Millsop, 1984; Gatto and Doe, 1983; Savkin, 1975). For Lake Sakakawea, wave erosion accounted for approximately 78 percent of the total bank recession from June 1983 to August 1985 (Table 5). Because wave action is an important eroding agent, an attempt was made to quantify this factor and incorporate it into a bank recession equation.

Wave Forecasting

The standard method for forecasting waves is not valid for lakes or inland reservoirs because the surface area for the standard equation is considered to be infinitely large. A different method, therefore, had to be developed for water bodies having a limited fetch width. T. Saville, Jr. (1954) first formulated the modification, taking into account the fact that waves are generated not only in the direction of the wind, but also at some considerable angle to it. His method resulted in an "effective" fetch.

Effective fetch is used for width-limited water surfaces, because it was observed that wind velocities over shorter fetches, at angles of 30 to 45 degrees to the longer fetches, produced waves higher than expected. The concept of effective fetch is based on two assumptions (Saville, 1954):

1. The transfer of energy from wind to water surface varies with the cosine of the angle of the wind direction, and

2. waves that impinge on the shoreline are completely absorbed.

Effective fetches for all stations except 3, 4, 5, 60, and 61 are given in Table 7, along with their principal wind direction; the five stations were not included because they are in protected locations, such as bays; these stations, therefore, are affected only when the wind direction is perpendicular to the shoreline. The effective fetch method was applied to the Fort Peck Reservoir, Montana, and Denison Reservoir in Texas and Oklahoma (U.S. Army Corps of Engineers, 1962). Prediction curves were constructed for significant wave height and significant wave period. Significant wave height represents the average height, in feet, of the highest one-third of the waves present, while, the significant wave period is for the highest order, in seconds. The values from the forecasting curves are dependent on the effective fetch and wind velocity. Thus, the effective fetch had to be determined for each site that was evaluated at Lake Sakakawea.

Once the effective fetch is known, values for the significant wave height and period, for a given wind velocity, can be obtained from the forecasting curves. Also, the minimum time duration is given on the curves. Wind velocities of 25, 35, and 45 mph (40, 56, and 72 km/h) were chosen. Winds less than 25 mph will generate small and ineffective waves; winds greater than 45 mph occur infrequently.

Wave Energy

For this study, deep water wave energy was calculated for specified locations where bank recession data were available. The energy of waves determines the potential of work performed on a shoreline, but not whether the work is constructive or destructive; that will depend on wave steepness (H/L) (King, 1972, p.45). The energy in a deep water wave,

TABLE 7

Effective Fetch and Principal Wind
Direction for Lake Sakakawea Stations

Station	Effective Fetch	Wind Direction
1	7.58 km	NE
2	8.21 km	NE
6-7	4.03 km	N
50	7.19 km	NW
51-52	9.11 km	WNW
53	6.96 km	SW
54-55	8.85 km	WSW
56-57	9.15 km	WSW
58-59	7.39 km	S
61	6.13 km	SE

where the depth is greater than half the wavelength, is half potential and half kinetic. The displacement of the wave surface from the stilled water condition gives the wave form a potential energy. At the same time, the orbital motion of the water under the wave constitutes the kinetic energy for the wave (Komar, 1976, p.45). The total energy (E), both potential and kinetic, is calculated according to the equation:

$$E=1/8(w\ L\ H^2),$$

where w is the weight of one cubic foot of water, L is the wavelength, and H is the wave height. Energy is given in foot-pounds per foot of wave crest per wavelength, and is dependent on the wavelength and the square of the wave height. Because the wavelength is not determined from the forecasting curves, the relationship between wave period and wavelength is:

$$L = 5.12\ T^2$$

Once the values of wavelength and wave height are defined, wave energy can be calculated.

Wave energies, along with their respective wind velocities and minimum time durations, are shown in Table 8. These values represent deep water wave energy, and represent the maximum possible wave energy available to do work on the shoreline. These calculations show that for every 10 mph increase in wind velocity the wave energy will increase by a factor of 2 to 3. Also, the time necessary to generate the predicted waves decreases. Small effective fetches limit the amount wave energy generated and indicate that wind/ wave influences are diminished, especially for effective fetches less than 5 km (Hakanson and Jansson, 1983, p.191).

TABLE 8

Wave Characteristics for Various Wind Velocities for Lake Sakakawea Stations

Station	Wind Velocity	td (min)	Hs (m)	T (sec)	Ls (m)	Steepness (Hs/Ls)	Wave Velocity	Energy (Joules)
1	40 km/h	71	0.67	3.15	15.5	.043	4.9 m/s	2,667
	56	62	0.94	3.6	20.2	.046	5.61	6.910
	72	56	1.2	4.1	26.2	.048	6.4	15,679
2	40 km/h	75	0.70	3.2	16.0	.043	5.0 m/s	2,877
	56	65	0.98	3.7	21.4	.046	5.8	7,785
	72	59	1.31	4.1	26.2	.05	6.4	17,246
6-7	40 km/h	45	0.49	2.6	10.5	.046	4.1 m/s	961
	56	39	0.70	3.0	14.1	.05	4.7	2,644
	72	35	0.91	3.4	18.0	.051	5.3	5,778
50	40 km/h	68	0.64	3.1	15.0	.043	4.9 m/s	2,354
	56	58	0.91	3.5	19.1	.48	5.5	6,120
	72	52	1.22	4.0	25.0	.049	6.3	14,230
51	40 km/h	80	0.73	3.3	17.0	.043	5.2 m/s	3,509
	56	68	1.04	3.8	22.6	.046	5.9	9,277
	72	61	1.34	4.3	28.1	.048	6.6	19,402
53	40 km/h	57	0.64	3.1	15.0	.043	4.9 m/s	2,354
	56	58	0.91	3.5	19.1	.048	5.5	6,120
	72	52	1.22	4.0	25.0	.049	6.3	14,230
54-55	40 km/h	79	0.70	3.3	16.5	.043	5.1 m/s	3,103
	56	67	1.01	3.8	22.6	.045	5.5	8,741
	72	60	1.31	4.2	27.5	.048	6.6	18,109
56-57	40 km/h	80	0.73	3.3	17.0	.043	5.1 m/s	3,480
	56	68	1.04	3.8	22.6	.046	5.9	9,277
	72	61	1.34	4.3	28.1	.048	6.6	19,422
58-59	40 km/h	69	0.64	3.1	15.0	.043	4.9 m/s	2.354
	56	61	0.91	3.5	19.1	.048	5.5	6,120
	72	55	1.22	4.0	25.0	.049	6.3	14,230
61	40 km/h	60	0.58	3.0	14.1	.041	4.7 m/s	1,805
	56	52	0.85	3.4	18.0	.047	5.3	5,016
	72	48	1.13	3.8	22.6	.050	5.9	10,987

td = minimum time duration
T = wave period

Hs = significant wave height
Ls = significant wavelength

Freeze-Thaw Effects

General

Studies by Millsop (1985), Reid (1985), Sterrett (1980), and Mickelson and others (1977) have concluded that freeze-thaw effects are important contributors to reservoir and lake bank failure in cool temperate climates.

During the winter, the banks are frozen and relatively stable. Any winter failure that does occur is the result of sublimation of interstitial and lens ice within the frozen sediments. Individual aggregates several millimetres in diameter accumulate at the base of the bank where they remain until acted upon by wave and current action in late spring and summer. When temperatures begin to rise to the freezing point, and ice and snow begin to thaw, massive bank failure begins. Failure occurs as debris flows, mudflows, and planar and rotational slides.

Several factors affect the rate and depth of freezing and thawing of the sediment: soil composition, structure, density, porosity, moisture content, degree of saturation, and temperature (Lawson, 1985). At Lake Sakakawea, frost penetration was measured at Riverdale and Fort Stevenson State Park. Frost penetration ranged from 80 to 100 cm for 1983-84 and was 140 cm for 1984-85. Frost penetration was greater in 1984-85 because of less snow cover on the ground.

The thawing of frozen sediment, which releases meltwater from pore and lens ice, can greatly reduce internal friction and cohesion, thereby decreasing the shearing resistance of bank material (Nixon and Hana, 1979). Excess pore pressures can develop at the ice/sediment interface which reduce or eliminate the shearing resistance of the sediment (McRoberts and Morgenstern, 1974; Nixon, 1973). The frozen horizon prevents free drainage of the water through the soil and the upper horizon, therefore, has a high degree of saturation; this facilitates downslope movement. Gravitational slip or flow failures on slopes as low as 1° to 10° may result (Sterrett, 1980).

Freeze-Thaw Cycles

The depth of freezing is not the most important factor in thaw failure. Instead, the number of fluctuations above and below the freezing point is a more significant factor (Reid, 1985; Trudgill, 1983, p.47). Each fluctuation results in further weakening of the sediment structure (Bryan, 1971). The number of cycles over the past several years at Riverdale is summarized in Figure 14. The numbers represent the daily maximum and minimum air temperatures, not the temperatures at or below the ground surface. Presumably, the latter would be less.

Freeze-thaw cycles, most common in the spring and fall, affect soil properties such as structure, permeability (Chamberlain and Gow, 1979), degree of consolidation, moisture content, density (Johnson and others, 1979), and strength (Broms and Yao, 1964). Broms and Yao (1964), for example, found that cyclic freezing and thawing of clay-rich sediments reduced unfrozen shear strength up to 95 percent, with the largest reduction occurring in sediments that had the highest moisture content before freezing. The repeated freezing and thawing of sediments containing ice lenses will modify soil structure by cracking, dissagregating, separating, and reorienting soil particles and aggregates (Van Vliet-Lanoe and others, 1984).

Frost Heave

Frost heave results from the segregation of ice in the forms of lenses and crystals. The degree of heave is dependent on the direction

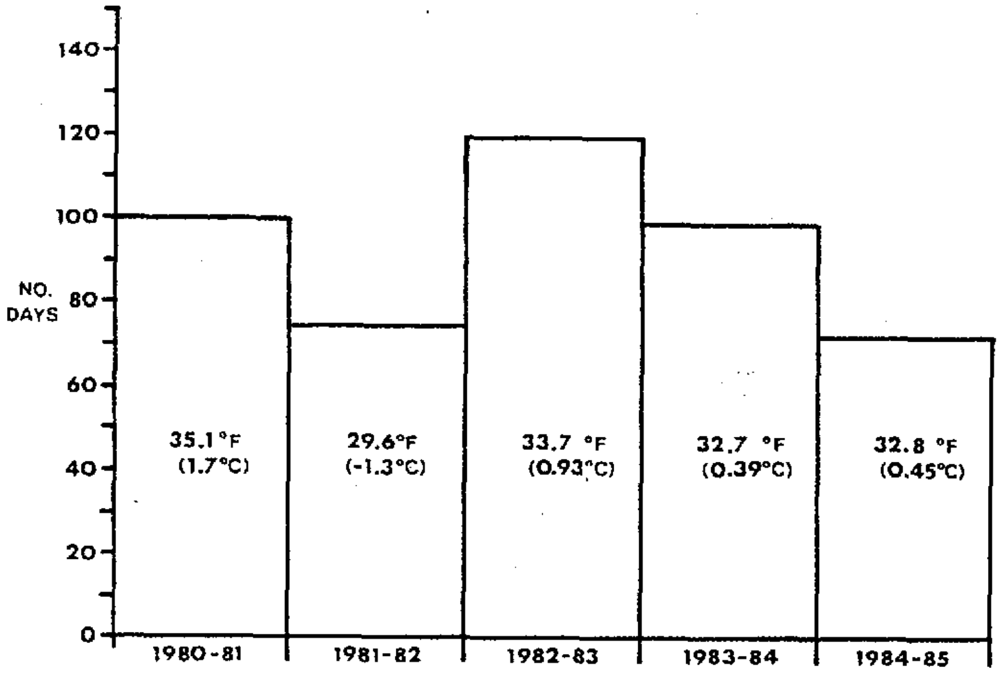

Figure 14 - Yearly freeze-thaw days, 1980-1985, with cold months' temperature.

and dimension of ice growth, and the compressibility of the sediment (Chamberlain and Gow, 1979; Chamberlain and Blouin, 1978; Penner, 1963). The direction of heave is usually in a direction orthogonal to the land surface (Lawson, 1985).

The mechanics of ice segregation and frost heave is not clearly understood although three theories are considered primary ones: capillary, secondary heave, and adsorption force (Chamberlain, 1981). Factors that determine the susceptibility of sediments to frost heave are texture, pore size, moisture content, rate of heat loss, temperature gradient, overburden stress, and the number and duration of freeze-thaw cycles (Chamberlain, 1981). Grain size is typically used as an indicator for frost-susceptible soils and is considered the most important characteristic in identifying the soil's frost susceptibility (Penner, 1976). Soils are classified frost-susceptible if the soil has less than 20 percent clay and greater than 60 percent silt- and sand-size particles (Chamberlain, 1981).

At Lake Sakakawea the sediments are generally considered to be frost- susceptible due to their silty-clayey texture (Millsop, 1985, p.161). However, frost susceptibility will vary from site to site due to the inherent variability of sediment properties and conditions along the reservoir.

Bank Characteristics

General

The banks at the eastern end of Lake Sakakawea are typically of mixed lithology (Figure 5). The banks have near-vertical slopes, primarily because of the large silt-clay composition and high degree of compaction. Various characteristics were studied for their effects on bank recession, especially the bank profiles, geology, structure, and geometry.

Bank profiles were measured as often as possible. From computer-generated profiles, any changes in the bank and beach slope could be observed (Figure 15). Such changes would reflect the degree of stability of the profile. Stabilizing banks, for example, would show a decreasing slope angle. Analysis of the profiles measured over the project period show none of these changes occurring presently. What the profiles do indicate, however, are the effects that lithology and stratigraphy have on shoreline recession.

Bank Geology

Bank geology refers to the geological units and their stratigraphic position. Most of the units have large percentages of silt and clay (Table 4). Because most units are cohesive, their erodibility is primarily a function of the structures present, which better define the mass strength of the lithologic units (Koo, 1982). Of all the lithologic units the massive Medicine Hill Formation is the most resistant to wave erosion, but some of the less fractured mudstones are also resistant to erosion, such as at Station 61. In contrast, Station 58 has an unconsolidated sand exposed at the wave base, yet it experiences little recession (Figure 12). Therefore, an observable correlation between recession rates and dominant bank lithology was not found, despite the fact that lithology does affect erosion rates. It is concluded that insufficient data are available to make such a statistically valid correlation.

Stratigraphic position of the formations is another important factor affecting the rate of recession. Presence of erodible sand units near

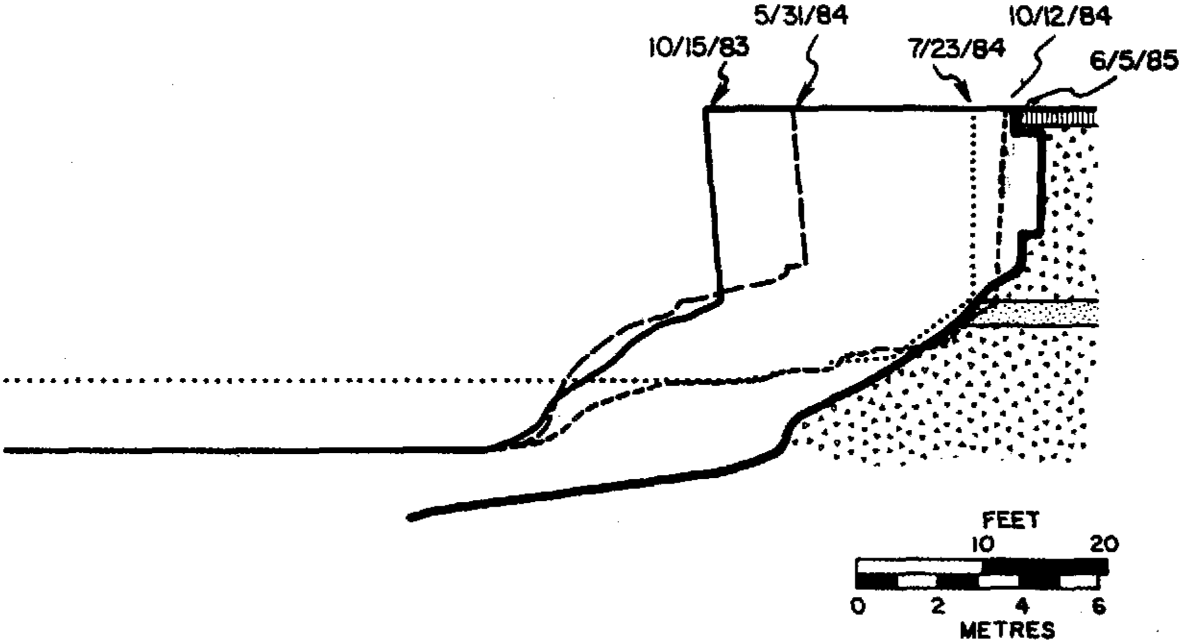

Figure 15 - Sequence of bank profile changes, 1983-1985, Station 51 (from Reid and others, 1986).

the wave base, for example, allows for rapid undercutting of banks such as at Station 51. Removal of sand by wave action oversteepens the bank and increases the shear stress in the overlying jointed glacial till (Figure 15).

Bank Structure

Bank structures, such as joints and faults, were also studied for relationships to rates of recession. As stated earlier, the Sentinel Butte, Upper Horseshoe Valley, and Upper Snow School Formations exhibit ubiquitous jointing. Therefore most of the stations have jointed units in the bank.

The Sentinel Butte Formation has a blocky fracture probably to a large extent because of the repeated loading and unloading of glaciers (Figure 6) (Grisak and Cherry, 1975). The blocks are usually only a few centimetres in length. Normal faults are also found at various locations along the lake, as at Station 55. Such faulting also decreases the mass strength of the bank material.

Glacial till units of the Upper Horseshoe Valley and Upper Snow School Formations exhibit columnar jointing. These tills are rarely found near the wave base zone, but can be weakened greatly by wave undercutting. The joints, which are planes of weakness, detach from the oversteepened bank by gravitational forces combined with lateral expansion or frost heave. Attempts to quantify bank structure, such as joint spacing and frequency, and joint strength, were not done for this project, but would be recommended as a future study.

Bank Geometry

Bank slope angle, length, bank height, and orientation also affect recession rates. Steeper slopes are more unstable than gentler slopes.

At Lake Sakakawea 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 successively low pool levels.

Bank Height: Achievement of slope stability for banks generally requires more time for high banks than for low banks (Buckler and Winters, 1983). At Lake Sakakawea, the taller banks (>9m) recede at a steady rate throughout the year as opposed to the shorter banks (<5m) (Figure 16). But the yearly recession rates for high and low banks are similar (Table 5). This was also found to be true for long-term bank recession rates at Lake Michigan (Buckler and Winters, 1983). The banks in the study area range from 2 to 25 metres in height. Figure 17 shows the relationship between wave-induced bank recession and bank height for Lake Sakakawea; banks less than 5m high were eroded slightly less than banks greater than 9m high. Intermediate banks were found to be eroded the least.

In contrast to this variable relationship, cold season recession is directly related to bank height (Figure 18). Cold season recession, expressed as colluvium, is the greatest for high banks, which, in turn, had ten times more colluvium than banks less than 1.5m high. This should be expected due to the larger surface area of the taller banks.

Bank Slope: Intuitively, the steeper the slope the greater the subsequent erosion. At Lake Sakakawea, most of the banks are nearly vertical and undergoing active erosion. Some slopes less than 25° are stable and vegetated. The stable banks exist because they are located in bays, protected from direct and even indirect wave attack, or have a wide beach.

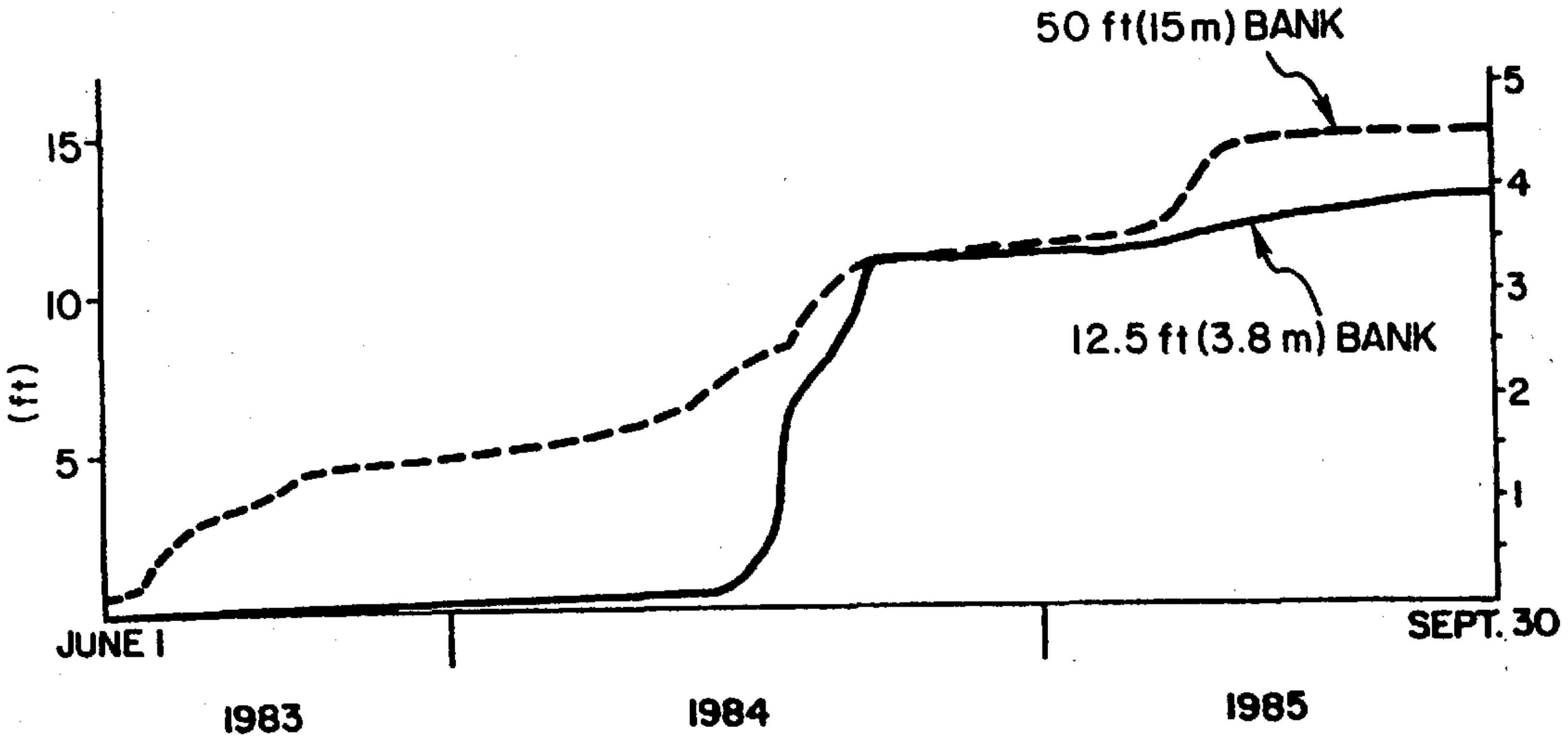

Figure 16 - Comparison of bank recession between a 15m and 3.8m bank (from Reid and others, 1986).

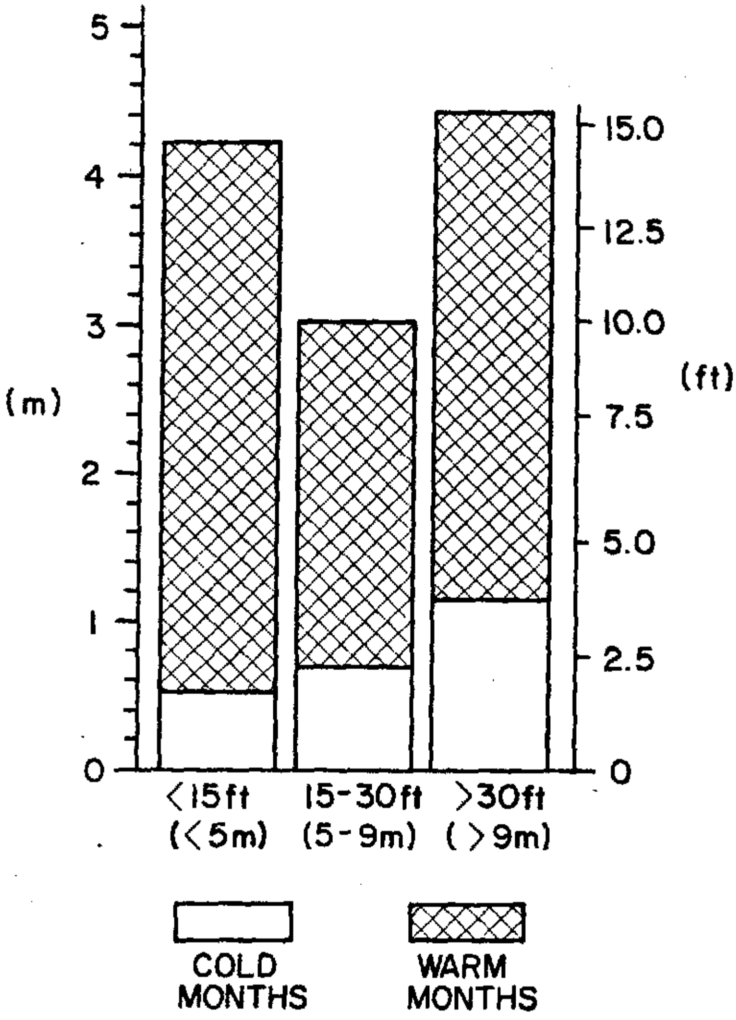

Figure 17 - Comparison of seasonal cumulative average bank recession and bank height (from Reid and others, 1986).

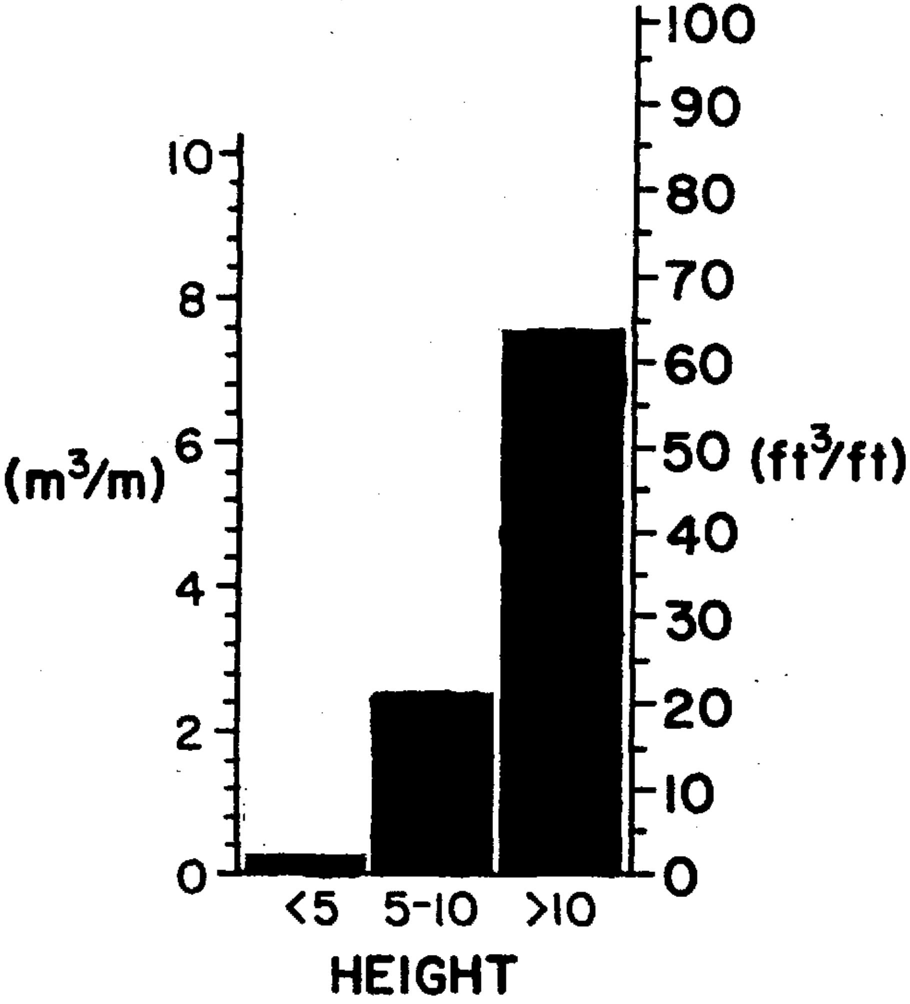

Figure 18 - Relationship between average coluvium and source bank height (from Reid and others, 1986).

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 into the dominant high wind direction. This relationship is especially true during high pool levels (Reid, 1984; Savkin, 1975).

Figures 19 and 20 show the relationship between cumulative average bank recession due to wave erosion according to the various bank orientations. Warm season recession ranged from 2.2m for southwest-facing banks to 0.2m for east-facing banks. North-facing banks showed the second greatest recession but northwest-facing banks showed as much recession as northeast-facing banks and almost as much as west-facing banks. This indicates that wave refraction is important, further justifying the use of effective fetches instead of normal fetches.

Cold season recession is dependent on the orientation of the bank with respect to solar exposure (Figure 21). Recession ranged from 3.2m for southeast-facing banks to only 0.05m east-facing banks. All the northerly-facing banks had equal amounts of recession (0.6m). Finally, west- and south-facing banks are most prone to desiccation-induced jointing because of greater solar exposure during winter.

Offshore Characteristics

Offshore Profile

The composition and geometry of the offshore areas were also evaluated for clues about the present and future stability of the shores. Offshore profiles were determined through continuous fathometric measurements from 91m offshore to the waterline. The profiles were made several times during the summers of 1984 and 1985 so that changes could be

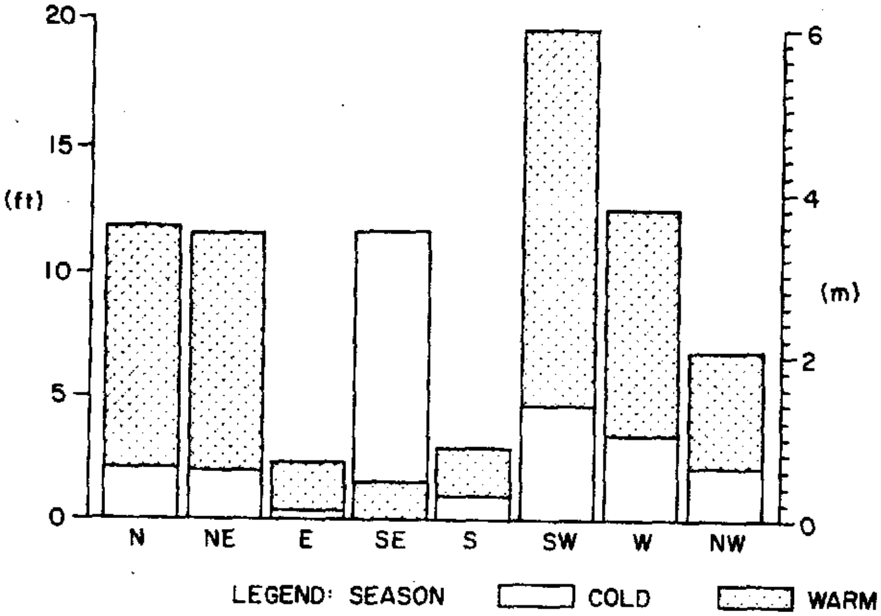

Figure 19 - Comparison of seasonal cumulative average bank recession and orientation (from Reid and others, 1986).

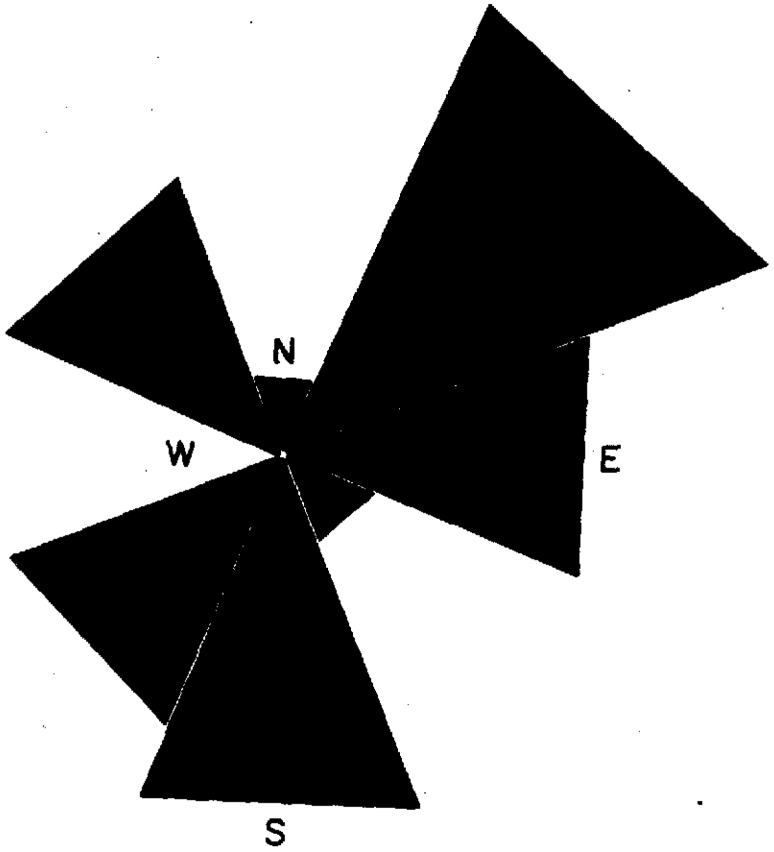

Figure 20 - Average bank recession for given orientations, Lake Sakakawea, ND (from Reid and others, 1986).

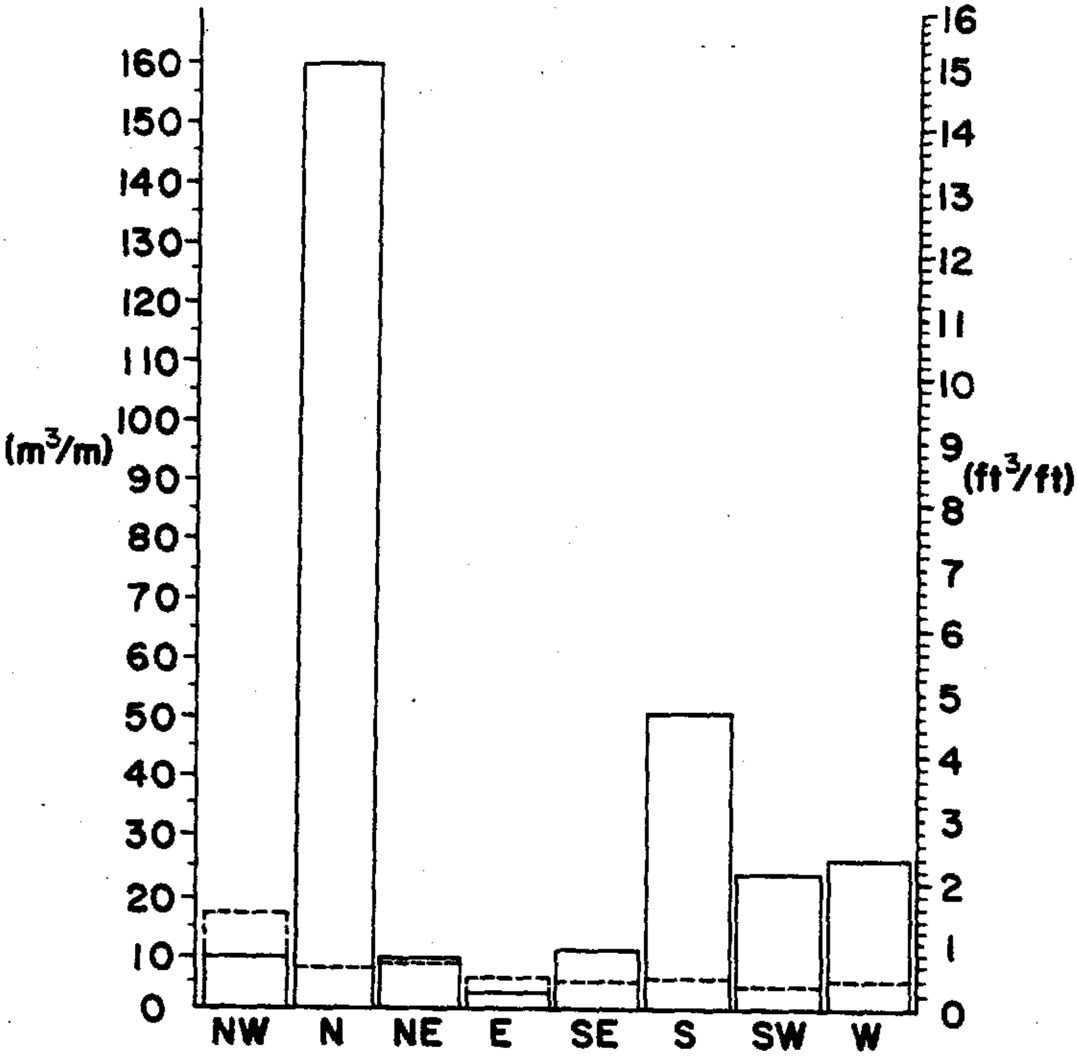

Figure 21 - Comparison of colluvium volumes by orientation for 1984 and 1985 (from Reid and others, 1986).

detected. The results are graphed in Appendix C. An example is shown on Figure 22. From this, and other figures in the Appendix, it can be seen that between July of 1984 and one year later, considerable offshore sediment was eroded, presumably carried into deeper water offshore. This erosion is assumed to have occurred shortly after the July profile was made, as the pool level was still rising then (Figure 13) and several storms struck the area during this time.

If this is any indication of what has occurred over the past 16 years since the reservoir attained its maximum operating pool level, it must be concluded that a stable platform has not yet been constructed.

Offshore Sediment

During the summer of 1985, samples were collected at varying distances and depths along selected offshore profile lines. The purpose was to find a possible silt-clay boundary and possible relationships between bank erosion and offshore sediment sizes. Table 9 lists the results of that survey. The assumption was that if a stable platform is being built it should be reflected in the grain size changes. Specifically, there should be a depth and distance from shore where the sediment is dominantly clay.

Examination of the data reveals that the sediment is mostly silt-size, except at Station 50, which has a substantial percentage of sand nearshore. It must be noted that samples were collected at only 9 locations. Thus, the results must be interpreted as approximations of the conditions along the eastern end of Lake Sakakawea where the samples were collected. Clay-size particles are a minor part of the offshore sediment, even out to depths of 32.6m and as far as 297m from shore. This is the result of two facts: the percentage of clay-size particles in

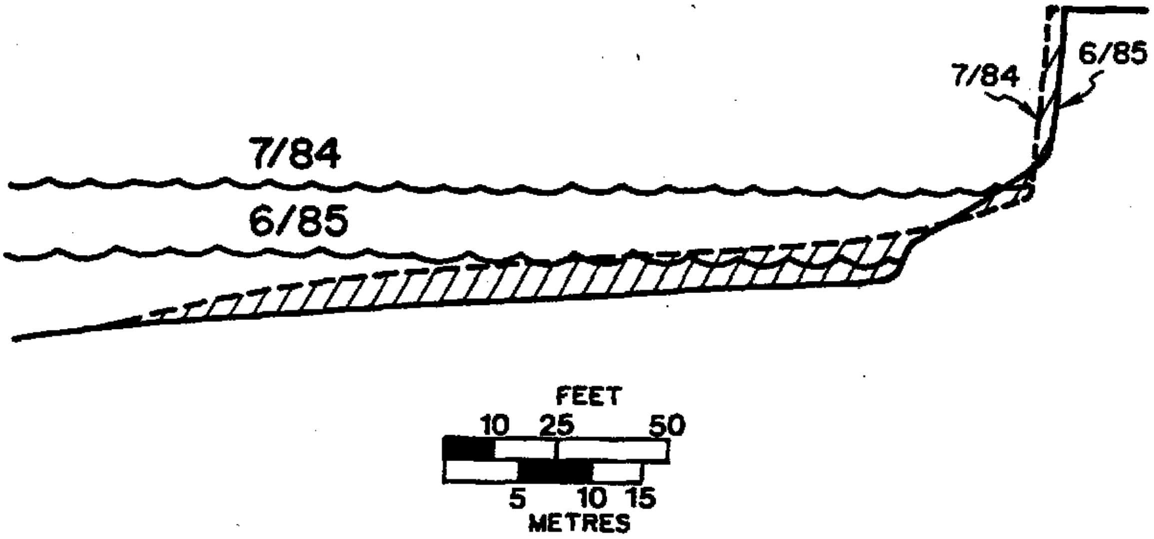

Figure 22 - Bank and offshore profiles at Station 7, 1984 and 1985 (from Reid and others).

TABLE 9

Grain-size Distribution Of Offshore Sediment at Selected Sites Along Lake Sakakawea

Station	Distance from shore (m)	Depth (m)	Slope	Size Distribution (%) sand	silt	clay
1	73.2	5.85	4.5°	24	57	19
	91.5	9.15	5.7°	17	59	24
	106.7	11.3	6.0°	24	48	28
2	53.4	3.7	3.9°	18	62	20
	106.7	8.8	4.7°	4	69	27
	167.7	12.8	4.4°	5	68	27
3	106.7	12.8	6.8°	12	61	27
7	167.7	15.9	5.4°	21	51	28
50	134.0	5.5	2.3°	89	10	1
	289.6	16.5	3.2°	36	42	18
	304.9	18.3	3.4°	0+	74	26
	323.2	19.5	3.5°	14	66	20
53	167.7	10.4	3.5°	13	69	18
	243.9	14.6	3.4°	2	63	35
	274.4	15.5	3.2°	3	68	29
58	45.7	10.4	10.2°	76	18	6
	70.1	11.6	9.4°	12	72	16
	91.5	14.6	9.1°	26	58	16
	152.4	16.2	6.1°	2	71	27
	228.7	19.5	4.9°	17	63	20
	335.4	22.9	3.9°	15	57	28
61-62	198.2	21.0	6.1°	12	70	18
	297.3	32.6	6.3°	12	63	25
E of 60	152.4	19.5	0.0°	45	45	10

the primary materials (tills and mudstone) is less than 35 percent (Table 4) (Millsop, 1985), and secondly, the wave and offshore energy must be high enough to prevent significant accumulation of fine-grain particles nearshore. It would be informative if deep water samples were analyzed.

Beach Characteristics

Beach Width

Another assumption was that wide beaches ought to indicate more stable banks. For this reason, the widths of all the beaches at the erosion stations were measured. Beach width is the distance from the waterline to the bank or colluvium apron. Because beach width is dependent on the pool level, comparable widths were measured from the bank profiles by determining the width above the same elevation. The results are shown in Table 10. Beach widths for 1984 ranged from 4.0m to 85.3m; the same beaches in 1985 were 3.9m and 3.2m, respectively. There was an average of more than 30 percent reduction in beach width in a year's time. Again, this is the result of massive wave erosion during the high pool level of 1984. Adding these observations to those of the offshore platform changes, it is concluded that the profile of the shores where active erosion has been occurring is far from reaching stability.

Beach Composition

Particle sizes of beach sediment adjacent to the erosion stations were also measured. The clast size distribution was defined as the areal percentage of all particle sizes, ranging from boulders to silt/clay. The results of this analysis are in Appendix D. The classes used were silt/clay, sand, pebble, cobble, boulder, and primary material (bedrock or till). Figure 23 shows one station (53) where over 60 percent of the beach is covered by cobbles and boulders. The average annual bank

TABLE 10

Changes in Beach Widths Between 1984 and 1985

Station	June 1984 (m)	July 1985 (m)	Percent Change
1	16.4	15.3	-6.7%
2	17.5	17.3	-1.0%
3	7.6	12.4	+63.4%
7	31.4	1.0	-96.8%
50	20.7	8.8	-57.4%
51	48.0	15.5	-67.7%
52	59.0	27.0	-54.2%
53	27.0	21.8	-19.3%
55	7.0	6.7	-4.3%
56	6.5	2.9	-96.2%
57	20.5	3.5	-82.9%
58	14.2	15.0	+5.6%
59	11.0	11.8	+7.2%
60	15.8	8.2	-48.1%
62	4.0	3.5	-12.2%
		Ave. =	-31.4%

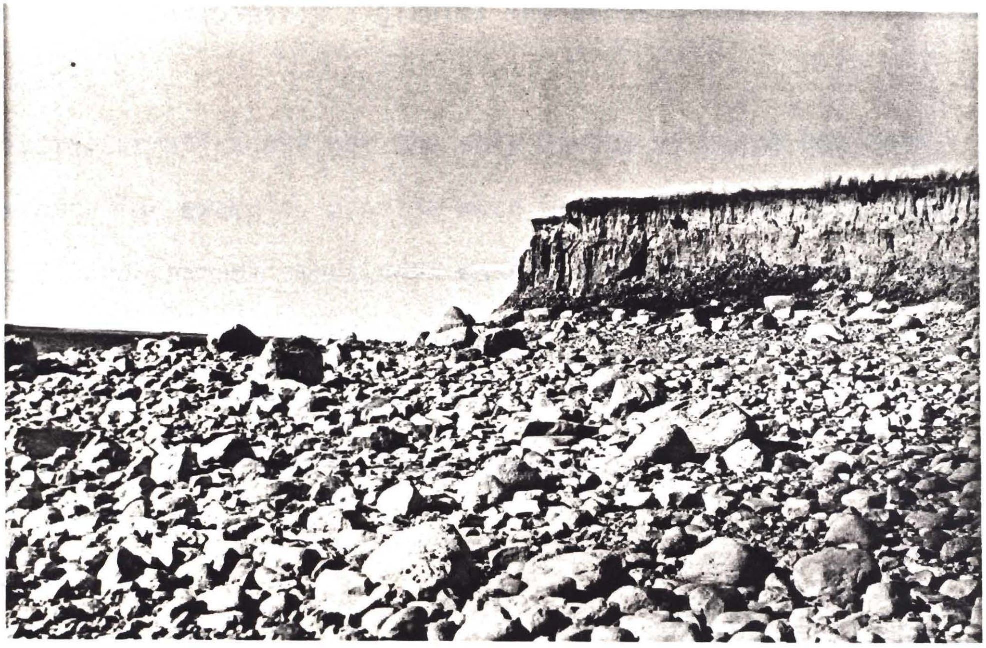

Figure 23 - Lag concentration of glacial erratics, Station 53 (from Reid and others, 1986).

recession for that station is only 0.58 m. The boulders were deposited on the beach by erosion of the banks. But, except for a small percentage, most of the boulders were not derived directly from the bank sediment; most were originally a glacial lag deposit resting on the surface of the land.

Glacial erratics are not the only source of beach boulders. Large concretions, for example, provide much protection from wave impact at Station 50 and channel sandstones masses are also important at the same station (Figure 24). In addition, petrified logs and stumps are common at other sites. All these serve to absorb or dissipate the wave energy and ought to be reflected in lower bank recession rates.

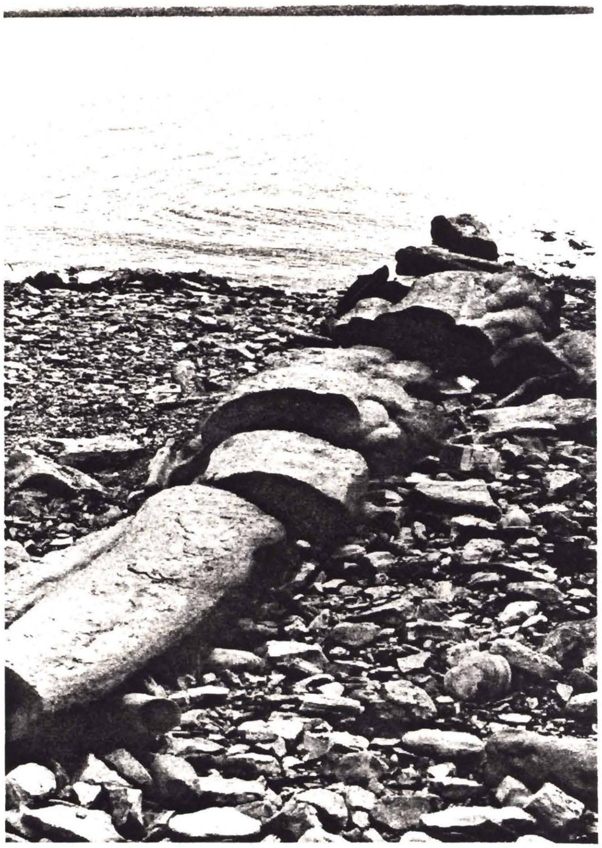

Figure 24 - Channel sandstones protecting Station 50 from wave erosion (from Reid and others, 1986).

DISCUSSION

General

Before discussing the individual factors of bank recession, it is appropriate to summarize seasonal variations of the major erosion processes. From bank recession measurements, it was shown that the rate of bank recession is not continuous throughout the year, with more recession occurring in the summer than the winter. However, substantial cold season recession can occur (Table 5) if certain conditions are met, such as a favorable bank height and orientation with respect to the sun.

The cycle of bank recession at Lake Sakakawea begins during the winter months. The ground freezes to a depth that depends primarily on the air temperature and snow depth. During the three years of this study the frost penetrated between 76 and 155 cm. During the winter of 1984-85 frost penetration was greater than in 1983-84 even though the temperature was slightly warmer; the reason was less snow cover in 1984-85.

More important than frost penetration is the number of freeze-thaw cycles. The actual numbers of such cycles was never satisfactorily determined. Instead, the total number of days the temperature fluctuated above and below the freezing point was recorded. Over the past three winters the number of days of such daily fluctuations ranged from 71 to 121. These fluctuations especially affect bank sediment having a high moisture content; these sediments are more susceptible to the effects of thermal expansion and contraction.

Along the shore, shorter banks may be protected by snow drifts (Figure 25). The high banks (>5m), though, are exposed to the winter

Figure 25 - Low bank at Station 3 protected by Snow drift (from Reid and others, 1986).

cold. As winter progresses, discrete aggregates of failed bank material accumulate at the base of the bank, forming an apron. The amount of material that accumulates is dependent on the bank height and orientation with respect to the sun; tall banks facing northward have the greatest accumulations.

Concurrent with bank failure is development of cracks along the top of the bank (Figure 26). The cracks, which develop sub-parallel to the bank, are associated with the vertically jointed till units. Although some of the cracks are caused by thermal cold contraction of the ground, most are caused by lateral expansion created by the existence of near-vertical banks developed by wave erosion from the previous summer.

Towards the end of the cold season, as the daylight hours increase, the snow begins to melt. Meltwater will infiltrate into the ground, but the amount depends on the antecedent moisture content, permeability of the topsoil, and the depth to the zero-degree isotherm (Granger and others, 1984). The addition of meltwater will increase the total weight of the bank material, which increases the shear stress applied along the vertical joints.

Once temperatures begin to stay above freezing, thaw failure becomes more evident. Masses of sediment and rock fall, slide, and flow to the base of the banks. Northerly-facing banks are more susceptible to thaw failure than banks with other orientations because of the higher moisture content retained over the winter (Figure 21).

By the time thaw-failure has ceased, the pool level usually begins to rise in response to snowmelt from the surrounding plains, and then from the mountains to the west. In a normal year, the pool level reaches a peak height in July, approximately two metres above low pool level in

Figure 26 - Tension joint developed parallel to shore at Station 2, Lake Sakakawea State Park, North Dakota (from Reid and others, 1986).

March. About every other year, the pool level exceeds the 563-metre elevation, an apparently critical level; years in which the level exceeds this elevation are characterized by extensive bank recession.

Erosion by waves in years of relatively low pool level is restricted to beach material and colluvium aprons. The sediment is moved offshore and moved downcurrent by longshore transport. During high pool level, erosion of colluvium, which accumulated along the base of the bank, is removed first, followed by the erosion of primary bank sediment. If the pool level remains high for an extended period, undercutting of the bank occurs, followed by eventual failure. Recession of the bank increases during this period and continues even as the pool level begins to drop (Figure 13). By late fall bank recession essentially ceases, as the pool level drops below the critical level and the ground begins to freeze.

Pool Level

Of all the factors responsible for bank recession on Lake Sakakawea, the height of the pool is the prime one (Millsop, 1985). Typically, the pool level reaches the maximum level in mid-July, after which it declines at a steady rate, and reaches its lowest level in March or April (Figure 13). The height of the pool level determines how close the waves can approach the bank. An increase in the nearshore depth will allow waves to travel closer before breaking. For example, a one-metre increase in the pool level will decrease the beach width by 11.5 metres for a beach with a 5° slope.

Pool-level changes also affect the water table profile and pore water pressure in the bank. Any increase in the pool level will subsequently increase the pore pressure (Costa and Baker, 1981, p.266). The addition of pore water increases the total weight of the bank, and further decreases the bank's stability. When bank material becomes saturated, effective stress, rather than total stress, is the critical factor in failure (Holtz and Kovacs, 1981, p.215; Terzaghi, 1923). Effective stress is the portion of the total stress not borne by the fluid; it is the stress that is actually applied to the grains of the medium. Rearrangement of the sediment grains is caused by changes in the effective stress, not by changes in the total stress (Freeze and Cherry, 1979, p.53). These two stresses are related by the simple equation:

$$\sigma_T = \sigma_e + p,$$

where σ_T is the total stress, σ_e is the effective stress, and p is the pore pressure. The weight of the rock and water remains essentially constant through time, such that $d\sigma_T=0$ and, therefore, $d\sigma_e = - dp$. Under these conditions, if the pore pressure increases, the effective stress decreases by an equal amount. An increase in pore pressure decreases the area of contact between the grains as the grains become supported by pore water.

Another factor is the drawdown rate of the pool level. If the drawdown rate is fast, the water table profile will assume a steep gradient as it slowly adjusts to the change in pool level. The difference in head between the water table and pool level may produce a high pore pressure along a potential slip line. Also, the water flowing back into the reservoir may become concentrated at some point where water exerts a seepage pressure that weakens the toe of the slope and further decreases bank stability (Costa and Baker, 1981, p.267).

Waves

Wave Generation

At Lake Sakakawea wave action is the dominant driving force for bank recession. Most waves are generated by strong winds blowing across a large surface of water (Ritter, 1978, p.513; Bascom, 1964, p.42). The actual process by which winds transfer energy to water is poorly understood (Komar, 1976, p.78). What studies have determined is that the size of the waves are dependent on the wind-speed and duration, fetch, and surface area (Sverdrup and Munk, 1946). Originally, energy was considered to be transferred to waves by two processes: 1) differences in normal pressure on the windward and leeward side of the wavecrest, and 2) tangential stress, which exerts a drag force and increases particle motion at the windward side of the wavecrest.

Since then, other studies have suggested different mechanisms for energy transfer, such as air shear flow, where the rate of energy input is proportional to the curvature of the wind velocity profile (Miles, 1957, 1959). Another study considered the role of pressure fluctuations associated with turbulent velocity eddies, or gusts, within the airstream (Phillips, 1957). Although the degree in which the mechanisms are operative is not known, it can be assumed that the initiation and early evolution are a result of pressure fluctuations upon the surface. Afterwards, shear flow becomes an important mechanism for future growth of the wave (Komar, 1976, p.80).

Shallow Water Waves

In reservoirs that have rapidly deepening waters near the shoreline, plunging and spilling breakers may be expected (Lawson, 1985). Plunging breakers have wave crests that curl over the shoreward face of the waves and strike the surface as a intact mass of water. These breakers are related to steep beaches with intermediate wave steepness. For spilling breakers the wave crest becomes unstable and cascades down the wave front as an irregular foam; these waves are associated with low angle beaches and steep waves (Galvin, 1968; Wiegel, 1964; Patrick and Wiegel, 1955). The effect of waves on vertical cliffs is related to the depth of the water at the base of the cliff. If the depth of the water is sufficiently shallow to allow the breaking wave to trap a pocket of air between the cliff and the breaking water, shock pressures are likely to occur and to cause erosion of the cliff (King, 1972, p.96).

Longshore Currents

As waves enter shallow water, they undergo variations in velocity along their wave crests, causing the waves to bend toward alignment with the depth contours. This bending effect, refraction, depends on the relationship of water depth to wavelength (Komar, 1976, p.110).

Wave refraction has a direct effect on wave energy. For example, refraction combined with shoaling determine such wave parameters as wave height, wavelength, wave period, and direction of movement at a particular water depth for certain deepwater conditions. Therefore, refraction will influence the wave height and the distribution of wave energy along the coast (U.S. Army Coastal Engineering Research Center, 1984). The change in wave direction results in a convergence or divergence of wave energy and determines the amount of force exerted by the waves against structures or cliffs (Komar, 1976, p.110).

Refraction also contributes to changes in the offshore bathymetry and may be another factor in shoreline erosion (Munk and Traylor, 1947). This is especially important in reservoirs within irregular bottom topography. Waves refract and flowlines diverge over deeper waters, as in canyons or submerged river channels; they converge over shallow water, near headlands or ridges. Wave energy is greater in areas of convergence due to an increase in wave height and diminishes in areas of divergence where the wave height is reduced. Therefore, areas of erosion most likely will be correlated with areas of wave convergence. It must also be remembered that shoreline topography is partially controlled by the offshore topography (Fico, 1978).

In reservoirs, where deep water is close to the shoreline, waves are likely to impinge on the beach at an angle to the shoreline. This is important, because wave-induced longshore currents, which transport sediment, are produced by such an oblique wave approach (Komar and Inman, 1970). The velocity of longshore currents depends on the breaker wave height, wave period, beach slope, and angle between the breaking crests and the beach (Putman and others, 1949). Waves in lakes usually have short periods and wavelengths. They, therefore, tend to be steep and not strongly refracted near the shore (Davis, 1976). Subsequently, they can develop strong longshore currents and with them significant sediment transport (Lawson, 1985). An excellent example of longshore transport was observed along the western shore of Fort Stevenson State Park (Stations 53-57). During days with strong northwesterly winds, sediment migrated parallel to the shoreline, downshore towards station 53. At station 53, which is a headland, sediment was either deposited on the extended point of land or carried by refracted waves into the bay.

Offshore Factors

Relationships between waves and the rate of bank recession have been studied by others. Quigley and Gelinas (1976), for example, discovered a linear relationship between historical cliff recession at Lake Erie, over a 150-year period, and the breaking wave energy. From a study along the coast of Japan, Sunamura (1982) concluded that average rate of cliff erosion had a linear relationship with the frequency of waves greater than a "critical" wave height. For Lake Sakakawea, it was determined that no definite relationship exists between the wave energy and the rate of recession. This is especially evident at Station 7, which has an effective fetch of 4.0 km, the smallest fetch calculated, and a cumulative bank recession of 14.6m; at the same time, Station 58, with an effective fetch of 7.4 km, had a cumulative recession of only 2.2m. This further supports the conclusion that no single parameter can completely account for the erosion of a bluff or bank (Lawson, 1985). Other factors involved include bank height, lithology, and orientation, to name a few. Those factors, plus others, determine whether the amount of wave energy reaching the shoreline is increased or diminished.

Factors that can reduce the amount of wave energy reaching the banks are: bottom friction, permeability of the lake bed, offshore bathymetry, and rip-rap. Bottom friction and permeable lake bed effects are minimal to negligible; the effect of frictional drag on energy dissipation is significant only for waves with a long periods (near twelve seconds) and gentle offshore slopes (less than or equal to one degree) (Putnam and Johnson, 1949). This is also true for energy loss due to orbital currents induced into a permeable lake bed (Putnam, 1949). At Lake Sakakawea, such conditions do not exist.

Another factor is the offshore bathymetry. For example, sand bars can effectively reduce wave energy by 78 percent to 99 percent for bar-breaking waves (Carter and Balsillie, 1983). The actual amount of wave reduction is dependent on the bar width and water depth at the bar site. Reformed waves may regain some energy, however, but rarely more than 20 percent of the original amount. The portion of energy transmitted from the incident to reformed wave is dependent on the ratio of wave velocity to the width of the surf zone. No offshore sand bars have been detected at Lake Sakakawea; but submerged river channels, semi-parallel to the shoreline, have been observed and may influence waves similar to that for sand bars.

In contrast to those factors which can decrease offshore wave energy, there are those which cause waves to travel closer to the banks, such as pool-level rises and strong wind effects. The effect of pool-level rise on shoreline recession is well documented (Millsop, 1985; Reid, 1985; Reid and Millsop, 1984). This effect can be confirmed by comparing the amount of bank recession in 1984 and 1985. In 1984, when the pool level was high between late spring and early fall, waves were able to attack the shoreline bluffs directly. In 1985, however, the pool level was 1 to 3 m lower than in 1984, and the effect of wave action was minimal.

When strong winds blow over the water surface they exert a shear stress that drives the water in the direction of the wind. For lakes and reservoirs, this results in water piling up at the windward end of the lake. The change in elevation can be calculated by:

$$S = V^2 F/1400 D,$$

where S is the difference in elevation (in feet) above the still water level, V is the wind velocity (mph), F is the fetch distance (in miles), and D is the depth (in feet). For the eastern end of Lake Sakakawea, the change in elevation under extreme conditions (winds greater than 45 mph) would be less than 0.15m (0.5 feet).

To summarize, wave action is a dominant factor in shoreline erosion at Lake Sakakawea. The erosion of the shoreline by wind-generated waves depends primarily on the wind velocity and duration, effective fetch, nearshore and offshore bathymetry, shoreline morphology, and pool level. Because these factors vary along the shoreline, the rate of the resulting recession also varies. Effective fetches, which account for waves generated by winds at an angle to the principal wind direction, were used with forecasting curves, developed by the Corps, to predict significant wave heights and wave periods at different wind velocities. Wave energy was calculated by the formula:

$$E = 1/8\ w\ L\ H^2.$$

Factors which have an affect on the amount of energy reaching the shoreline are: offshore topography (such as sand bars), pool fluctuations, wind tides, and wave refraction.

Beach Factors

General

Beach material ranges from clay particles to boulders. The material comes from the cliffs behind the beach and the platform beneath, from the land via rivers, and to a lesser degree by wind (King, 1972, p.224).

At Lake Sakakawea, much of the beach material is derived from poorly consolidated cliffs. Longshore transport, however, was found to be an important agent in carrying beach material, as was observed at Fort Stevenson State Park. Along the western shore of the park, silt, sand and pebble-size clasts of "clinker" (baked mudstone) were transported downshore to Station 53. At that point, the sediment was either deposited into the nearby bay or onto the eastern shore by refracted waves. Hence, at Station 53 the western shore was devoid of sand- or pebble-size material except for large glacial erratic boulders, while the eastern shore had well-developed berms of sand- and pebble-size clasts. This was observed at other locations, too, such as near Station 2.

Beach Composition

Beaches with abundant coarse material, pebble-size and larger, impede beach and bank erosion by attenuating wave energy. The waves are dissipated as water percolates into the permeable beach. The rate of percolation is controlled by the degree of sorting and the grain-size distribution (Komar, 1976, p.304); water percolates faster into a gravel beach than a fine sand beach. Beaches composed of sediment with a high clay content, and thinly veneered with coarse beach sediment, are highly impermeable and erodible (Rosen, 1980). At the eastern end of Lake Sakakawea, most of the beaches are impermeable.

Impermeable beaches are highly erodible because of their low swash infiltration, thereby increasing the force of the backwash (Bagnold, 1940). Impermeable beaches may also elevate the water-table, such that a perched water-table may develop in the overlying sand veneer. A perched water-table makes the beach more susceptible to wave erosion (Grant, 1948; Emery and Foster, 1948). A study by Rosen (1980) on the beach erosion susceptibility of Chesapeake Bay, found that 64 percent of the impermeable beaches sampled had perched water-tables. Rosen defined impermeable beaches as beaches with a sand veneer, 1 to 30cm thick, overlying pre-Holocene sediment with a high clay content.

Lake Sakakawea does have some beaches with abundant coarse beach material. The larger beach clasts include lag deposits of glacial erratics, mudstone concretions, channel sandstones, and petrified logs and stumps. If numerous clasts are present, they can effectively breakup waves as they move upshore. For beach locations which have more than 35 percent cobbles and boulders (Stations 50, 58, and 59) (Appendix D), bank recession is less than 1.0 m/y (Table 5). However, not all stations with greater than 35 percent cobbles and boulders will experience minimal recession because other factors such as beach width and gradient are also important. Station 6, which has 42 percent cobbles and boulders (Appendix D), recedes at a rate of 1.2 m/yr, three times faster than Station 58 (Table 5).

From statistical analysis it was found that the areal percentage of boulders and cobbles is weakly correlated to the rate of recession. Therefore, there are either insufficient data to properly correlate this factor or other variables, such as beach width, are more important. Also, the correlation between coarse beach material and the rate of recession may increase with time.

Beach Profile

Beach profile refers to the gradient and length of a beach. The beach profile buffers waves as they move onto shore by dissipating their energy. The beach slope in the wave swash zone is governed by the intensity of the swash, onshore-offshore transport (Komar, 1976, p.303), sand size, and wave steepness (Bascom, 1951).

Several studies indicate that the beach slope increases with increasing coarse particle size distribution (Rosen, 1980; Dubois, 1972; Wiegel, 1964; Bascom, 1951). Thus, coarse particle beaches should have steeper slopes than fine particle beaches. At Lake Sakakawea, beaches with steep slopes are usually found in protected areas such as bays. At

Station 53, the western beach has a lower gradient than the protected eastern beach. Besides grain size, sorting also controls the beach gradient; well-sorted coarse sand beaches have steeper slopes than poorly-sorted coarse sand beaches (Krumbein and Graybill, 1965, pp.351-53).

Beach Width: At Lake Sakakawea, the beach width is a function of the pool level and beach slope. If the pool level increases 1 metre, for example, the beach width decreases 11.5m for a beach with a 5° slope, and 19m for a beach with a 3° slope. A small beach width is unable to buffer incoming waves. Because Lake Sakakawea has a seasonally fluctuating pool level (Figure 13), the beach width changes frequently. An increase in the pool level will also cause erosion of both the shoreline and beach. An eroding beach develops a flatter gradient. The eroded material is carried offshore into deeper water, or it is transported downshore by longshore currents.

Bank Factors

Geology

Bank geology also affects the rate of recession. For Lake Sakakawea, however, significant variation in the rate of recession due to different lithologies was not observed, probably because insufficient data were collected. In another study at Lake Sharpe, South Dakota, again no statistical differences were found between erosion rates and shorelines of different lithologies over a 10-year period (Koopersmith, 1981). A strong correlation, however, was found between lithology and variation in recession along the eastern shore of Lake Michigan (Wilkerson and Gray, 1978). High recession rates occurred at locations with outwash sand and sandy till; low rates were associated with exposure of bouldery till. In those areas, shoreline recession was diminished as the boulders attenuated wave energy and were responsible for the development of a wave-cut bench.

At Lake Sakakawea, the Upper Snow School till is the most erodible unit exposed along the lake, whereas the Upper Medicine Hill is the least erodible. The Sentinel Butte siltstone and mudstone are as erodible as the Lower Snow School, and the Lower Horseshoe Valley is moderately erodible (Millsop, 1985).

Erosional differences between the units are based on more than lithology alone. For example, the Lower Snow School is exposed at only one location, Station 5, which is in a sheltered bay. The stratigraphic position of the unit is also important. For example, although the Lower Horseshoe Valley member at Station 51 is moderately erodible, it is relatively unaffected by wave action unless the pool level is near the maximum elevation (Figure 15). Another factor is the degree of consolidation. The Sentinel Butte Formation, for example, has lenses of well-indurated siltstone and sandstone. If the lenses are located at or slightly above the wave base zone, they will reduce the rate of recession. Station 57 has such massive lenses of siltstone (concretions) at the wave impact zone. Hence, Station 57 recedes at a slower rate than Station 56 even though they each have nearly identical bank characteristics. Finally, the erodibility is governed more by structure than texture.

Structure (i.e., jointing and faulting) is an important variable affecting recession. Jointing is ubiquitous along the eastern end of Lake Sakakawea. The Upper Snow School and Horseshoe Valley members exhibit characteristic columnar jointing, probably due to crustal expansion upon deglaciation (Sterrett, 1980; Grisak and Cherry, 1975). Other joints are caused by desiccation which causes shrinkage and compression of the clay particles (Chamberlain and Gow, 1979). The Sentinel Butte Formation, therefore, has a complex structure of horizontal and vertical jointing (Figure 6). Joints are important because they are avenues for wave exploitation in the summer and for moisture accumulation in the winter. Small caves, for example, often develop in zones of closely-spaced vertical joints.

Faults also exist at Lake Sakakawea, but they are uncommon, and are restricted to the Sentinel Butte Formation. At the fault zone, the bank sediment is typically highly fractured. They are therefore readily exploited by waves.

So, lithology, jointing, and faulting are important variables that affect the rate of recession. However, these variables are difficult to quantify in such a way that they could be used in a statistical analysis.

Engineering Properties: The engineering properties of the bank material also affect bank recession at Lake Sakakawea. The only data available concerning the engineering properties were from the Garrison Dam Embankment Criteria and Performance Report (U.S. Army Corps of Engineers, 1981). Undisturbed samples of glacial tills were analyzed, using the direct shear and the unconsolidated undrained triaxial tests. The report did not specify which till formations were analyzed. Results from the direct shear tests are: dry density, 1.23 to 1.69 g/cm^3, cohesion, 4.78 to 143.64 kPa, and the angle of internal friction, 8° to 34°. The wide range of values given is the result of textural, mineralogical, and structural heterogeneities within the tills. Undisturbed samples of the Sentinel Butte Formation were tested for shear strength, compressive strength, and Atterberg limits. The Atterberg Limits defined a wide range of textural classes, from fine sand to fat clays; the predominant textural class, however, was lean clay. Liquid Limits ranged from 19 to 108; Plasticity Indices ranged from nonplastic to 70. The unconfined compressive strength values were defined by the intrinsic cohesion of the sediment, which is a shear strength parameter. The compressive strength ranged from 191 to 574.6 kPa. The design shear strength, expressed as cohesion, equaled 67 kPa. The angle of internal friction was 20°.

Banks (1972) studied the engineering characteristics of clay-shale slopes in the Fort Union Group, of which the Sentinel Butte is one of the formations. The study included both laboratory analyses and physical measurements of failed and unfailed slopes. The Sentinel Butte Formation was found to have unfailed slopes angles ranging from 18° to 45°. One unfailed slope of that formation, overlain by till, had an angle of 17°. Failed slopes, with or without the overlying till, had considerably lower angles of 7° to 10°.

Factors that affect the slope stability and the mass strength of the bank material include the presence of joints and cyclic freezing and thawing. The presence of joints in both the tills and the Sentinel Butte Formation has already been discussed. Because jointed clays behave more like jointed rocks than massive sediment, their behavior depends on the resistance to sliding along the joints (Esu, 1966). Also, in such cases, traditional slope stability analyses are not applicable because the fissured material is not allowed to reach its peak strength (Skempton, 1964). The strength distribution is dependent on the spacing and orientation of the joints, with the intact strength as the upper limit, and joint strength as the lower limit (Koo, 1982).

Engineering properties are also affected by the internal distribution of ice in the soil. Structures such as cavities occur under repeated freezing and thawing conditions, as result of ice lensing and frost-heave (Van Vliet-Lanoe and others, 1984). Soil volume increases under ice expansion thereby decreasing the density and the shear strength of the material. Simultaneously, the lateral earth pressure increases and additional joint expansion can result (Broms and Yao, 1964).

At Lake Sakakawea, the engineering properties indicate that the bulk strength of the sediment is explained by its cohesive strength. The cohesive strength is best demonstrated by the existence of nearly vertical slopes.

For the Sentinel Butte Formation and tills, the average angle of internal friction was reported as 20° (U.S. Army Corps of Engineers, 1981). However, presumably stable slope angles of 45° were reported for the Sentinel Butte Formation (Banks, 1972). But, any clay-shale slope angles greater than 35° probably represent slopes that are not fully stabilized; stable slopes tend to be covered with vegetation. Therefore, the steeper barren slopes are considered unstable, and will likely fail further. The actual shear strength values calculated by the Corps may be overestimated. Strength tests were performed only on intact masses of sediment without joints. Joints decrease the total strength of the sediment. The measured strength along joints is considered to be equivalent to the residual shear strength of the sediment. The presence of joints decreases the mass strength and wave erosion becomes more effective. At station 51, the differences in strengths of the massive and the jointed till are especially obvious. The massive Upper Medicine Hill till, which is the lowermost unit, forms a resistant protrusion in front of the bank (Figure 15). The vertically jointed Upper Horseshoe Valley till, however, recedes at a substantial rate.

Finally, freeze-thaw cycles affect the moisture that accumulates in joints. The joints are weakened by repeated freezing and thawing to the point that the blocks eventually separate from the bank and fail by sliding, falling, and toppling.

Bank Geometry

The bank slope, height, and orientation each affect the rate of recession. Banks with steep slopes, of course, are more unstable than banks with gentle slopes. At Lake Sakakawea, the banks are nearly vertical. Steep banks are quickly affected by wave undercutting, followed by mass wasting. Bank slopes will eventually evolve to a gentler slope angle. For cohesive sediments, the final slope angle is dependent on several parameters such as bank height, effective angle of internal friction, effective cohesion intercept, and bulk density (Edil and Vallejo, 1980). Other factors that can influence slope stability, and not considered in a standard slope-stability analysis, are: clay properties, structure, and freeze-thaw effects (Costa and Baker, 1981, p.266). As the slope angle decreases, vegetation will develop on the slope; this stabilizes the slope and reduces slope erosion from sheetwash. At Lake Sakakawea, the measured stable slopes had angles less than 25°.

Bank Height: Bank height affects both warm and cold season recession. At Lake Sakakawea the banks vary in height from 2 to 25m. Bank recession due to wave action affects all the banks, with banks less than 5m eroding the most, followed by banks greater than 15m, and intermediate banks eroding the least. This evidence supports the conclusions of

Buckler and Winters (1983) for bluff recession at Lake Michigan. Their study determined that long-term recession rates were unrelated to bank height. But on a short-term basis, high banks (>25m) will show more or less crest recession than low banks. They cite an example of a 50m bluff that experienced several metres of toe erosion since 1968. Yet, the crest has not receded as of 1983. But, in 1982, at an adjacent area of the shoreline, a massive failure occurred that was 60m wide and 15m deep. Because high banks have a greater horizontal distance from crest to base, more time is necessary for the initiation of crest retreat, but when failures occur they tend to be large. These two relationships, then, account for the similarity of long-term recession rates for both high and low banks (Buckler and Winters, 1983). In a study by Edil and Vallejo (1980), higher banks became unstable faster than low banks. In that situation, however, the instability was due to groundwater seepage from a high groundwater table or from a perched aquifer. Groundwater decreases the effective stress, which weakens the sediment, causing failure. At Lake Sakakawea, groundwater seepage is a factor only near the dam spillway by Riverdale, where several rotational slumps have occurred. The lignites, which are interbedded with mudstones in the Sentinel Butte Formation, form perched aquifers. Groundwater discharge from the lignite beds weakens the toe of the slope and facilitates failure. But the cause of the seepage is not due to pool level fluctuations, or major precipitation events; it is likely caused by excessive recharge from Riverdale (Reid and others, 1986). Similar failures have not been observed anywhere else along the lake; the watertable is too low.

For cold season recession, there is a definite correlation with bank height (Figure 18). Taller banks have a larger surface area and are more exposed to climatic factors that cause cold season recession. The smaller banks are often protected by snow drifts (Figure 25). From regression analysis, bank height was found to be the most important variable for explaining cold season recession.

Bank Orientation: The relationship between bank orientation and recession was considered for both warm and cold season recession. For warm season recession, bank orientation with respect to the dominant wind direction was found to be significant. For cold season recession, bank orientation with respect to the solar exposure, was found to be most significant.

Banks facing into the strongest winds are the ones most susceptible to wave erosion along lakes (Buckler and Winters, 1983) and reservoirs (Reid, 1984; Savkin, 1975). It was determined that southwest-facing banks experience the highest recession, followed by north-facing banks, while northeast-, northwest-, and west-facing banks experienced similar amounts of recession (Figures 19 and 20); this indicates that wave refraction is important, as explained by the use of effective fetch.

For cold season recession, north-facing banks experienced the greatest amount of recession (Figure 21). Also, these same banks, Stations 6 and 7, are some of the tallest banks in the study area, which influence the amount of recession, too. South- and west-facing banks also are affected, because of their exposure to the winter sun; the west- and south-facing banks are more prone to desiccation-induced jointing.

Shore Zone Development and Evolution

The purpose of this section is to summarize previously discussed material, and present an evolutionary sequence of changes for the active shore zone. Other studies will also be discussed that have evaluated shore erosion quantitatively, together with some of the problems associated with the resulting models.

Models

Most studies that have quantitatively analyzed beach and bluff erosion have related the amount and rate of recession to the dissipation of wave energy and longshore currents (e.g., Sunamura, 1982; Kachugin, 1980; Black, 1980; Quigley and Gelinas, 1976; Kondratjev, 1966). However, the relationship between wave energy and bluff recession has not yet been positively determined (Edil and Vallejo, 1980).

The model by Kondratjev (1966) proposed a "stable shelf" concept. The concept is similar to Bruun's (1962), which assumes that the eroded bank sediment is deposited in the nearshore zone, developing a protective shoal. Bank erosion is expected to cease after the shelf reaches a calculated width over which all available wave energy is dissipated. Kondratjev's model was applied by van Everdingen (1969) to a river valley reservoir in Canada. He determined the shoreline profile changes for a headland cliff and a gulley. The calculated stable shelf width ranged up to 215m, with a slope of 3°. Also, the most significant changes associated with the shore zone were predicted to occur within 5 to 10 years of the analysis. Unfortunately, it is not known if a post-audit was done to compare the model's accuracy.

The method used by Cordero (1982) is also similar to Kondratjev's model, because they both assume that the most of the eroded bank material will be deposited in the nearshore zone. Both methods, however, ignored other erosional processes, such as freeze-thaw.

Nearshore Zone

Cliff shorelines along lakes and oceans typically have poorly developed beaches (Ritter, 1979, p. 534). As the cliff retreats it leaves behind a beveled surface called a wave-cut platform. The platform can be formed by many processes such as water-layer weathering, solution benching, ramp abrasion, and wave quarrying (Wentworth, 1938). Of these processes, ramp abrasion at the base of the bank is probably most responsible for platform development (Ritter, 1979, p.534).

Corrasion of the cliff by sand particles forms a low gradient platform, with a slope usually near 1°. Platform width largely depends on the depth it can be cut; this depth is less than the depth the sediment can be moved. Bradley (1958) suggested a depth of 10m; his estimated value was based on the degree of abraded pyroxene grains from platforms along the California coast. The length of the platform is also determined by the rate of cliff retreat, which is a function of many factors, which have already been discussed.

Along the eastern shore of Ireland, a study was done on cliff erosion of glacial sediments (McGreal, 1979). That shore is considered a low energy coastline, with a recession rate of 0.3 to 0.4 m/y. Wave-cut platforms were developed in the till. The platforms width ranged up to 100m, with a slope of 1.0° to 1.5°. The active beach zone had an average width of 30m, a slope of 9°, and was composed of pebbles to medium-size sand.

At Lake Sakakawea, it appears that a low angle platform is being developed at some stations (e.g., Station 51) (Appendix C). However, the average offshore slope angle is over 4°. Hence, further leveling of the offshore zone will probably occur.

Besides erosional offshore features, depositional features may also be produced. Depositional features are best developed in areas where waves have a low wave steepness (King, 1972, p.419). At the eastern end of Lake Sakakawea few such depositional landforms have been observed. This is in part due to the existing wave conditions and pool-level fluctuations.

Depositional features, such as offshore bars, develop best in essentially tideless areas, such as the Great Lakes (King, 1972, p.335). At Lake Sakakawea, the tides are replaced by pool-level fluctuations, which can range up to 3m (Figure 13). Thus, any bars developed at high pool level are subsequently destroyed when the pool level is lowered. Also a large a supply of sand in the nearshore area is necessary to develop offshore bars. In Lake Sakakawea very little sand is found offshore (Table 9).

Shore Zone

The final stable slope will be composed of a combination of the primary bank sediment and remolded colluvium. The final slope angle will be a function of the residual strength of the remolded debris material (Sterrett, 1980). Sterrett (1980) compared the bank height and slope angle for stable slopes along Lake Michigan. Stable slopes were defined as being well-vegetated and lacking evidence of recent slope movement. Results indicated that the taller stable banks (>30m) have lower slope angles, ranging from 15° to 32°. For banks less than 18m, stable slopes were established up to 43°.

Stable slopes comprised of the Sentinel Butte Formation and till were reported to have angles of 17° to 20° (Banks, 1972). Previously failed slopes had angles of only about 10°. For this study, it was assumed the stable slope angle will be near 20°, the calculated angle of internal friction (U.S. Army Corps of Engineers, 1981).

To summarize, the active shore zone will evolve through time. For most locations, the cliffs will continue to retreat, with a wave-cut platform forming offshore. The width of the platform is dependent on the wave energy, plus other factors. For some locations, a stable platform width of 100m is possible. In sheltered areas, depositional platforms can develop, provided enough sediment is available. Banks located in depositional areas should become stable quicker than banks behind wave-cut platforms, assuming that depositional platforms will develop quicker than wave-cut platforms.

The beaches will become enriched with sand- and pebble-size clasts as the finer bank sediment is transported into the lake. The addition of coarse beach material will help stabilize the beach and dissipate incoming waves.

Finally, bank recession will continue until wave erosion becomes ineffective. Afterwards, the bank recession will continue as the slope slowly evolves to a more stable angle similar to the angle of internal friction. Typically, the stable bank will be composed of primary bank material and remolded colluvium and will become vegetated.

REGRESSION ANALYSIS

Purpose

The primary objective of this study was to develop a fundamental and relatively simple equation that could relate the present rate of bank recession to other variables representing shoreline types, offshore processes, and other parameters that describe shoreline conditions. One possible method is to use statistical modeling of bank erosion rates. Such statistical analyses have been applied elsewhere to modeling processes responsible for erosion and transport of shoreline sediments (Spoeri and others, 1985; Fox and Davis, 1973; Sonu and James, 1973).

Regression analysis of bank erosion factors at Lake Sakakawea has previously been attempted by Gatto and Doe (1983) and Millsop (1985). Gatto and Doe applied multiple regression analyses to variables associated with historical bank recession, as determined from aerial photographs. Millsop performed stepwise regression analysis to further test his observations and results from field work.

Millsop's stepwise regression analysis was applied to twenty stations over nine measurement intervals. In addition, the stations were tested as a group using one variable value per station, the average cumulative bank recession from 1983 to 1984. Results from the analyses showed that the most important variables associated with bank recession at Lake Sakakawea are, in order of importance: mean pool level, maximum pool level, rainfall, windspeed, and wind direction (Millsop, 1985, p.175).

Millsop was unable to generate any significant models using all the stations. However, regression analysis of individual stations revealed strong correlations with certain variables for Stations 5, 7, 58, and 62. All the stations selected had similar recession curves in which most of the bank recession occurred during the warm season with very little recession occurring over the winter.

Finally, investigations by both Gatto and Doe (1983) and Millsop (1985) failed to define any strong relationships between bank recession and the chosen variables which were applicable to all sites on the lake. In fact, one of the analyses suggested relationships between variables that were highly unlikely, such as a strong direct correlation between the duration of ice cover and bank recession (Gatto and Doe, 1983).

Methodology

Statistical testing was done to assess the possibility that the rate of recession is related to specific physical parameters associated with a given shoreline. The initial step of statistical testing was to formulate an appropriate null hypothesis. Once an hypothesis was selected a decision had to be made to accept or reject it on the basis of the statistical test. If the null hypothesis is rejected when in fact it is true, a type I error has been committed. In contrast, if an incorrect hypothesis has been accepted a type II error has been committed. The probability of committing a type I error is called the level of significance; an acceptable level of significance is usually specified before running the test. In order to minimize the possibility of committing a type II error, which is undefined, the null hypothesis is written so that it will be rejected. For this analysis, the null hypothesis states that

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Multiple regression analysis, the statistical approach used in this study, can be represented in a model equation:

$$Y = Bo + B_1X_1 + B_2X_2 + \ldots + B_nX_n + e,$$

where Y is the dependent variable, B is the regression coefficient, X is the independent variable, and e is the random error. The model states that the dependent variable (Y) is equal to a constant term (Bo), plus the sum of the independent variables (X_i), multiplied by its respective weighting coefficient (B_i), plus a random error. For more detailed discussion of the theoretical and computational essentials of multiple regression see Davis (1973).

Variable Selection and Preparation

Because it has been determined that bank recession is seasonally dependent, two dependent variables were selected for regression analyses: the average monthly warm season recession rate and the yearly percentage of cold season bank recession. The warm season recession data represented the average monthly recession, in centimetres per month, by station, between May and October, from 1983 to 1985 (Table 5). Cold season recession was defined as the percentage of total bank recession occurring between November and April. Originally, it was intended to use a rate measurement as the dependent variable for cold season recession, but monthly measurements were not collected over the winter. Also, cold season recession is much more irregular than warm season recession; a monthly rate would be misleading.

Independent variables selected for multiple regression were based on the following criteria:

1. The variables had to support field observations as being important factors that influence bank recession.
2. The variables had to be easily quantified by either field measurements or by calculations from maps or air photos.

The independent variables finally selected for regression analyses were:

1. Effective fetch (km).
2. Offshore slope angle (degrees).
3. Beach width (m).
4. Areal percentage of coarse beach material.
5. Bank orientation, with respect to the sun.
6. Sine of the angle between the dominant wind direction and orientation of the shoreline.
7. Bank height (m).
8. Mean grain size of lithology at the wave base (phi).

The effective fetch was determined from topographic maps, using the procedure outlined by Saville (1954) and discussed in this report.

The offshore slope angle was determined from offshore profiles, with the profile extending at least 90 m from shore. The slope angle determines how close the waves can approach the shore before breaking. On shore, beach width was measured with respect to a standardized pool elevation; for this study, the elevation chosen was 3 m below the maximum pool level. This presented a problem in some instances where the pool level was above the standard elevation chosen, and the beach width had to be extrapolated from offshore profiles.

The composition of the beach can be determined several ways, but a statistically valid, and relatively quick, method was to construct a grid system, as illustrated in this report. The percentage of the area covered with clasts pebble-size and larger constitutes the value needed for the analyses. Sand-size particles are not included, even though they help identify a stable beach. Larger particles help protect the beach from wave action.

The sine of the angle between the dominant wind direction and shoreline orientation was used to define the station's susceptibility to direct wave attack. For this report, the dominant wind direction was the same principal wind direction used in the effective fetch calculations. For cold season recession, bank orientation was considered with respect to the sun. Values were given on a scale of 0 to 180, with 0 being for banks oriented southeast (the direction of least cold season recession) and 180 being for northwest-facing banks. Banks oriented between the two directions were given values based on the number of degrees on either side of the southeast direction. For example, banks oriented northeast or southwest were given similar values of 90. Grain size was determined from textural analyses of the lithologies located at the wave impact zone. The variables used in the regression analysis are listed in Table 11.

The following regression analyses were tested:

1. (Average rate of recession)$^{1/2}$ vs. independent variable value.
2. Average rate of recession vs. (independent variable value)$^{1/2}$.
3. Average rate of recession vs. independent variable value.

After each test was completed the calculated F-value was compared with the standard F-value to determine its level of significance. For these analyses, the accepted level of significance had to exceed the 90 percent level. This level was chosen because acceptance of a lower level increases the probability of random error affecting the analysis. The goodness

TABLE 11

Variables Selected For Regression Analysis

Y (cm/mo)	X1 (km)	X2	X3 (m)	X4 (m)	X5 (%)	X6 (phi)	X7 (o)
29.75	7.58	0.36	3.7	15.3	0.0	6.5	5.3
17.70	8.21	0.05	7.0	17.3	0.0	7.3	4.4
26.9	4.03	0.74	18.0	3.0	42.0	5.5	6.0
23.4	4.03	0.09	14.5	1.0	31.0	5.5	6.1
4.2	7.19	0.29	20.9	8.8	37.0	6.8	6.3
24.2	9.11	0.31	12.4	15.5	20.0	1.8	1.5
15.2	9.11	0.00	7.0	27.0	15.0	5.9	2.6
7.9	6.96	0.92	9.0	21.8	12.0	5.5	3.4
55.7	8.85	0.00	6.2	10.0	17.0	8.0	3.5
48.0	8.85	0.00	10.5	6.7	13.0	8.0	3.9
29.2	9.15	0.39	11.8	2.9	13.0	8.3	4.7
11.9	9.15	0.39	11.2	3.5	20.0	8.5	5.3
5.1	7.39	0.00	9.1	15.0	45.0	6.5	6.4
11.1	7.39	0.39	8.2	11.8	56.0	6.5	6.2
0.4	6.13	0.67	6.5	7.1	20.0	6.7	6.4

X1 = effective fetch
X2 = sine of angle of dominant wind
X3 = bank height
X4 = beach width
X5 = percentage of coarse beach clasts
X6 = mean grain size
X7 = offshore slope angle

of fit (r^2) was also noted in order to determine what percentage of the variance was explained by the analysis. If the tested F-value did not equal or exceed the 90 percent confidence level, the independent variable with the lowest regression coefficient was removed and the analysis was rerun. This process was continued until the F-value exceeded the 90 percent confidence level, or until the F-value was lower than the previously tested value.

Results

Because it was determined that the rates of recession are seasonally dependent, multiple regression was performed to generate models differentiating both warm and cold season recession. The difference between these analyses and earlier ones (Millsop, 1985; Gatto and Doe, 1983) are: the selection of the dependent and independent variables, the separation of the yearly recession into warm and cold season recession, and, in the case of Millsop's, the addition of another year of data. Another major difference was the assumption of non-linearity of the data. Non-linearity means that the relationship between the rate of recession and the independent variables can be assessed more accurately by introducing exponential functions of the variables into the regression model. This method has been used with other models involving such coastal processes as littoral drift (Komar, 1976, p.196).

Results indicate that the monthly rate of warm season recession is best defined using the square root of the independent variables. The final accepted model used all independent variables except effective fetch, mean grain size, and areal percentage of coarse beach material. The resulting analyses produced a goodness of fit (r^2) value of 0.59; this value represents the amount of variation in recession rates explained by the independent variables. The value would be 1.0 for a perfect fit of all the data with the predictive equation. The F-value, which represents the level of significance or confidence in the analysis, is 3.64 and exceeds the 95 percent confidence level. The regression coefficients for each of the variables and the slope intercept (Bo) are:

1. Offshore slope angle = -25.1
2. Sine of the angle between the dominant wind and the shoreline = -17.2
3. Beach width = -10.4
4. Bank height = -8.4
5. Slope intercept (Bo) = 141.5

For winter recession, the best model found used a linear relationship involving only the bank height and orientation variables. Bank orientation for this analysis was the orientation with respect to the sun. The resulting r^2 value was 0.46, with a F-value of 7.23, exceeding the 99 percent confidence level. The regression coefficients for the independent variables of cold season recession, along with the slope intercept (Bo), are:

1. Bank height = 2.05
2. Bank orientation with respect to the sun = 0.043
3. Slope intercept (Bo) = -2.0

Tests were conducted using other dependent variables, such as the cumulative cold season recession and yearly cold season recession, but none of these tests was able to generate any models that exceeded the 90 percent confidence level.

Subsequently, stepwise regression analyses were done. Stepwise regression is a search procedure that considers all possible combinations of independent variables. Therefore, a dependent variable was tested against each independent variable and with every possible combination of two variables, three variables, and so forth, until every possible combination of independent variables had been considered.

Discussion

Selection of the accepted equations was based on their statistical validity (i.e., exceeding the 90 percent confidence level). For cold season recession, this presented less of a problem, since the accepted equation was the only model generated that surpassed the 90 percent confidence level. A rate measurement would have been preferred instead of using the cold season percentage of yearly recession. It is not inappropriate, however, to use a percentage value as the dependent variable. Bank height, which had the highest correlation, explains the affects that the exposed surface area has upon cold season recession, where a taller bank experiences greater recession (Figure 18). Bank orientation with respect to the sun had a weaker correlation with the dependent variable, as shown by its regression coefficient.

The only drawback to this model was that the goodness of fit value (r^2) is less than 50 percent. This implies that over half of the variance in the data was not explained by this model. But the probability of reproducing these values by random error is less than one percent. The high confidence level was possible because of the few degrees of freedom. As more independent variables are added to the analysis the number of degrees of freedom also increases, and therefore, the amount of variance that has to be explained by the regression analysis increases, too.

The warm season recession model was accepted only on the basis of having the highest level of significance. Another model, which included the effective fetch and percentage of coarse beach material, generated a higher goodness of fit value (0.61) than the accepted model (0.59). The F-value, however, was 2.1 and exceeded only the 75 percent confidence level. The deletion of the two variables increased the confidence level, because the degrees of freedom, which determined the standardized F-value, were lowered. Yet the goodness of fit value was not significantly changed; this implies that the two additional variables are not strongly correlated with the rate of recession.

This presents a problem, as the effective fetch and percentage of coarse beach material should, intuitively, be important variables that control bank recession. For Lake Sakakawea, however, strong correlation between effective fetch and cumulative bank recession was not indicated (Table 12). Therefore, the susceptibility of bank recession by wave action was more accurately described by the offshore slope angle and the angle of orientation between the dominant wind direction and shoreline orientation. The percentage of coarse beach material may be implicitly reflected in the beach width, where a wider beach will have a greater possibility of having a higher percentage of coarse beach material.

Other independent variables that should be considered for future analysis might include beach height, and coarse beach material cobble-size or larger. Also, a variable that quantitatively describes joint structure should be attempted in future study. If the model is applied to other reservoirs an attempt should be made to separate lithologies by their engineering properties.

To summarize, the independent variables that best describe bank recession at Lake Sakakawea are: offshore slope, sine of the angle between the dominant wind direction and shoreline orientation, bank

TABLE 12

Effective Fetch and Associated Bank Recession for Lake Sakakawea Stations

Station	Effective Fetch (km)	Cumulative Bank Recession (metres)
1	7.58	4.1
2	8.21	2.8
7	4.03	4.5
50	7.19	1.2
51	9.11	4.0
53	6.96	1.0
54	8.85	5.5
55	8.85	8.7
56	9.15	6.2
57	9.15	2.2
58	7.39	0.7
59	7.39	1.1
61	6.13	5.6

height, beach width, and bank orientation with respect to the sun. The dependent variables defined were the average monthly recession (cm/mo) for the warm season and percentage of yearly recession during the cold season.

Two separate models were generated that explain both warm and cold season recession. The accepted warm season recession model used all the independent variables, except effective fetch, percentage of coarse beach material, and bank orientation with the respect to the sun. The generated model exceeded the 95 percent confidence level and had a goodness of fit value (r^2) of 0.59. Another model was generated that included effective fetch and coarse beach material, but was rejected because it did not exceed the 90 percent confidence level, although its goodness of fit value was larger (0.61).

Cold season recession used bank height and bank orientation with respect to the sun as its independent variables. The model generated a goodness of fit value of 0.46, and a F-value that exceeded the 99 percent confidence level.

Finally, statistical tests can demonstrate with specified probabilities only what things are not and not what they are. In other words, statistical analysis can determine only what relationships do not exist between two or more variables. It must be understood, though, that the predictive accuracy of a statistical model does not represent its primary role. "Instead, it provides a method to quantitatively assess and assure consistency within and between concepts of the governing processes and data describing the relative coefficients" (Konikow, 1986, p.183). Therefore, this model should help to improve our understanding of factors controlling bank recession.

ULTIMATE BANK RECESSION

General

In order to determine the most probable bank recession, it is first appropriate to set boundaries to the system. For this reason, a minimum and a maximum recession distance, along with a probable ultimate recession distance, have been defined.

Minimum Ultimate Recession

The minimum ultimate recession is the most conservative prediction, and is based on four assumptions:

1. Wave action immediately becomes an ineffective eroding agent.
2. The stable slope angle is equivalent to the angle of internal friction.
3. The bank height remains constant.
4. The existing bank slope is 90 degrees.

For wave action to become ineffective, the pool level would have to remain below the critical pool elevation of 563m; below this elevation, wave erosion of the colluvium and the primary bank material is minimal, as it was in 1982, and 1985. By elimination of the wave erosion factor, bank erosion would be restricted to thaw and creep failure and overland erosion.

The stable slope angle selected was 20 degrees. This is the average angle of internal friction calculated for the Sentinel Butte Formation and the overlying tills units (Banks, 1972). The angle also represents the probable slope angle for a stabilized slope which has a high percentage of silt- and clay-size sediment (Holtz and Kovacs, 1981, p.543). The bank height selected is the maximum height at each station.

The equation used to derive the minimum recession used basic trigonometric functions. The method considers the bank as part of a right triangle in which the existing bank slope is 90°. At Lake Sakakawea, most banks fulfill this requirement. The resulting minimum bank recession, then, is the distance the top would have to retreat, without toe erosion, before the bank face reached a 20° slope. This is the product of the bank height, multiplied by the cotangent of 20°. The calculated distances using this procedure are listed in Table 13. The values range from 10 m for Station 1 and 57 m for Station 7. Station 1 has the lowest bank, and Station 7 the highest. Thus, the minimum recession distance in this calculation is a function of the bank height, only.

Once the minimum recession distance was calculated for each station, the time required for each bank to reach this stable position was determined by dividing the distance by the present average yearly rate of bank recession for that station. The range was from 5.2 years for Station 1, to 112.9 years for Station 50, which also has a tall bank, but a lower recession rate (Table 5).

This method differs from the template used by Cordero (1982) (Figure 10) in that the colluvium accumulation is ignored; it is assumed that the sediment eroded from the banks is transported out to the deep water. In either case, both methods produce ficticious results. It would presumptuous and incorrect to assume that this minimum ultimate recession value will not be exceeded. The primary reason for this is that the pool level is expected to exceed the critical level an average of every other year at Lake Sakakawea (Figure 13). The resulting wave action affects the

TABLE 13

Minimum Ultimate Recession Along the Eastern End of Lake Sakakawea

Station	Bank Height (m)	Minimum Ultimate Recession Distance (m)	Present Rate of Recession (m/yr)	Year to Minimum Ultimate Recession
1	3.7	10.2	1.95	5.2 yrs
2	7.0	14.3	1.39	13.9
3	3.8	10.5	1.85	5.6
4	4.5	12.4	1.28	9.7
5	5.0	13.7	1.05	13.1
6	18.0	44.4	1.24	39.8
7	14.5	39.9	1.99	20.0
50	20.9	54.4	0.51	112.9
51	12.4	34.1	1.75	19.4
52	7.0	19.3	1.47	13.1
53	9.0	24.7	0.48	51.6
54	6.2	17.0	2.30	7.4
55	10.5	28.8	3.99	5.9
56	11.8	32.4	3.09	10.5
57	11.2	30.7	1.04	29.6
58	9.1	25.0	0.31	74.5
59	8.2	22.5	0.51	44.2
60	7.9	21.7	0.33	65.9
61	6.5	17.8	2.65	6.7
62	12.1	33.3	1.46	22.8

bank profile. Also, it is assumed that the bank recession rate will decrease with time, with the development of a stable offshore platform.

Maximum Ultimate Recession

Maximum ultimate recession is the other end member for ultimate shoreline recession. The calculated value is basically a function of the geographic location of the shoreline. For maximum ultimate recession, it is assumed that most of the eroded sediment will continue to be carried offshore, and a stable depositional platform will not be developed. The remaining sediment would be transported by longshore currents into sheltered areas such as bays. This is analogous to oceans, such that given enough time the shoreline will become straight. For Lake Sakakawea, which is infinitely smaller, the reservoir will begin to fill with sediment. As more sediment is introduced, a stable platform will certainly be constructed and bank recession rates will decrease.

Determination of the maximum recession also assumed that the greatest bank recession will continue to occur at the eastern end of the lake, due to the long westerly fetch. Erosion at the eastern end will be characterized by headland erosion, such as at Fort Stevenson State Park, with some deposition by longshore transport into adjacent bays. Yet, even within a certain area there will be different rates of recession, depending on geographic factors such as position with respect to offshore islands and the maximum fetch.

The maximum recession values were calculated from standard 7.5-minute U.S. Geological Survey topographic maps. The maximum recession value determined from the maps was approximately 1km, with an average maximum recession of 245m. The calculated recession value of 245m is an average; headlands, for example, will more likely recede a greater distance.

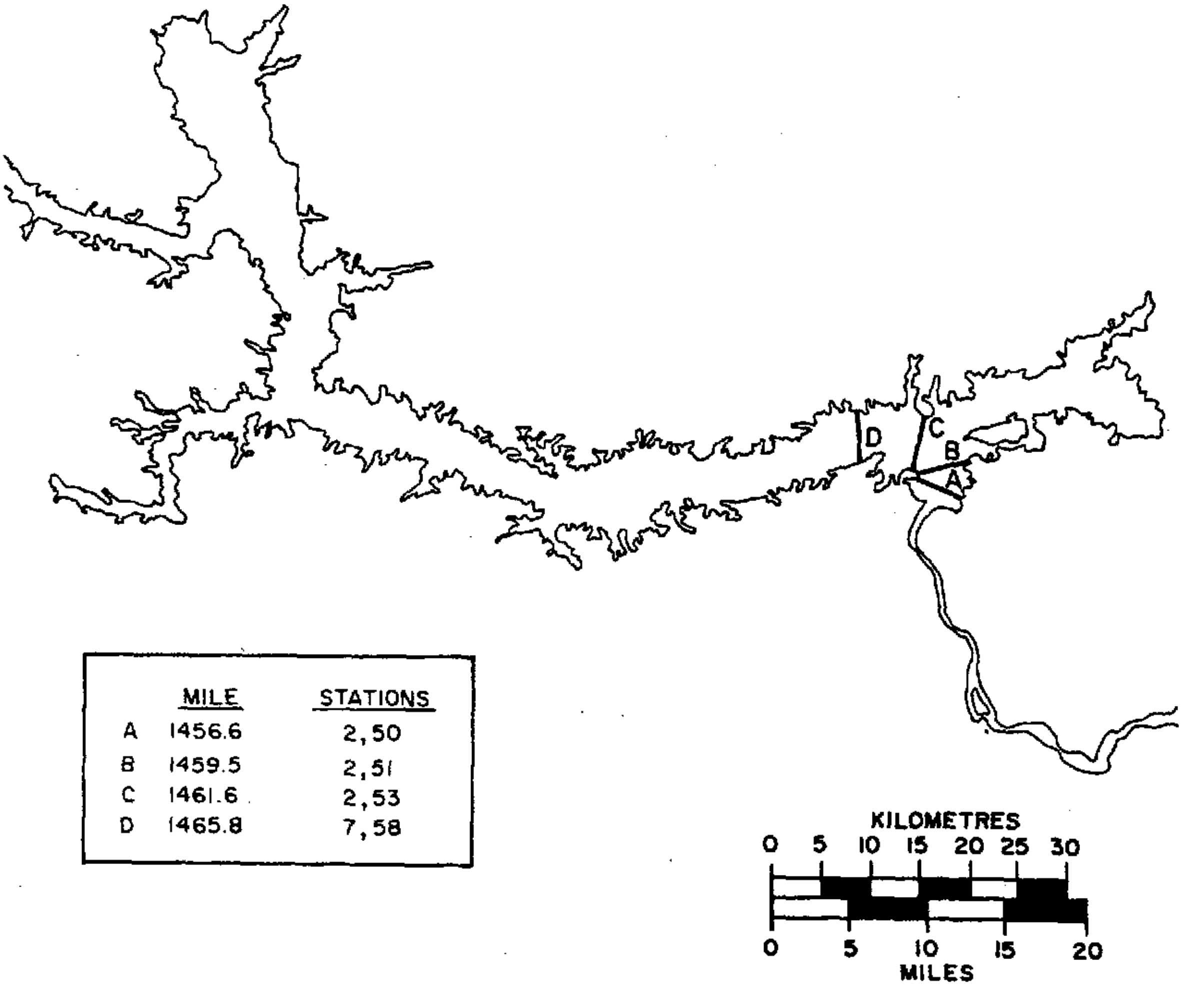
Obviously, this attempt at predicting ultimate recession is conjecture, and certainly not statistically valid. The most probable ultimate recession value should lie somewhere between the minimum and maximum values. Consequently, any valid prediction of bank recession must consider all the variables affecting erosion. This method has been used for the determination of the probable ultimate recession.

Probable Ultimate Recession

The probable ultimate recession represents the best estimation of bank recession for the lifetime of the reservoir, 500 years. Two different methods were used to estimate probable ultimate recession, trend analysis and statistical analysis. Trend analysis used only historical data available from the Corps sediment rangeline surveys. Statistical analysis, in contrast, used physical parameters that were found to be statistically significant to shoreline erosion. Both methods assumed that the rate of recession will decrease with time.

Trend Analysis

Trend analysis is an attempt to predict ultimate bank recession using historical data from the Corps sediment rangeline surveys. These rangelines are located all along the shoreline (Figure 27). The purpose of the rangelines is to determine the changes in the configuration of the reservoir. Five of the rangelines coincided with erosion stations (Stations 2, 50, 51, 53, and 58) so that both current and historic recession could be examined. From the surveys, it was possible to measure the cumulative recession from 1969 to 1979. In 1969, the reservoir attained its operating level; land lost prior to 1969 was primarily



	MILE	STATIONS
A	1456.6	2,50
B	1459.5	2,51
C	1461.6	2,53
D	1465.8	7,58

Figure 27 - Location of U.S. Army Corps of Engineers sediment range lines along Lake Sakakawea (from Reid and others, 1986).

by inundation and not by wave erosion. Estimation of cumulative recession from 1979 to 1984 was done by assuming that the present average yearly rate of recession has remained constant since 1979. The average yearly rate was multiplied by 5 years and added to the 1979 cumulative recession. These two cumulative recession values, therefore, are two known points on a recession curve.

For trend analysis, it was assumed that the rate of recession would decrease with time, such that the recession curve would have the shape of a parabola on its side. The equation for a parabola on its side that passes through the origin is $y = ax^2 + bx$, where y is the cumulative bank recession, x is the time projected into the future, and a and b are constants calculated from the historical data, the cumulative recession for 1979 and 1984.

The trend analysis curve was extended to 500 years into the future, the expected lifetime of the reservoir. The projected results are given in Table 14. These results show that Stations 53 and 58 will experience little recession, while Station 51 is expected to have a 500-year cumulative recession of 585 m. These predicted trends are approximations, only. Another method was needed, however, by which these trends could be further evaluated, and by which all the stations could be included. For this, statistical correlation was done using the past 2 1/2 years of data from erosion stations at the eastern end of Lake Sakakawea.

Statistical Analysis

One of the original intentions of this study was to develop a bank recession equation that does not require any historical data, so that the equation could be applied to other reservoirs which have not been studied before. As discussed earlier, regression analyses were done with all the

TABLE 14

Ultimate Recession: From Historical and Current Rates (metres)

Station	1969	1979	1984	2069	2169	2469AD
2	0	14.3	21.3	121.6	215.0	426.0
50	0	17.7	20.7	46.0	63.4	98.2
51	0	54.9	64.9	151.2	210.3	327.4
53	0	26.2	28.6	34.1	47.9	75.0
58	0	0.4	2.1	4.1	5.5	8.2

stations, except Stations 3, 4, 5, 60, and 62; these stations are located in such protected areas as bays. The purpose of the regression analyses was to determine what independent variables are best related to both warm and cold season monthly recession. From regression analysis, the following independent variables were determined to be statistically relevant for warm season recession: sine of the angle between the wind and shoreline, bank height, offshore slope angle, and beach width. For cold season recession, bank height and bank orientation with respect to the sun were selected.

The warm season recession equation uses the respective regression coefficients of the independent variables and the slope intercept calculated from the accepted analysis. The warm season equation is:

1) $Rs = 141.53 - [17.2\sqrt{A} + 8.44\sqrt{B} + 25.08\sqrt{C} + 10.4\sqrt{D}]$,

where Rs is the monthly warm season recession rate (cm/mo), A = angle between the wind and shoreline, B = bank height, C = offshore slope angle, and D = beach width. This equation exceeds the 95 percent confidence level with a goodness of fit value (r^2) of 59.28.

The cold season recession rate is:

2) $Rw = Rs\ [(2.05\ (\text{bank height}) + 0.043\ (\text{bank orientation}) - 2)/100]$,

where the orientation is the value between 0° to 180°, with 0° being the direction of the lowest cold season bank recession, in this case, southeast. Again, the values 2.05 and 0.043 are the regression coefficients calculated from regression analyses, and 2 is the slope intercept. The analysis produced an r^2 value of 0.46. The F-value exceeded the 99% confidence level. The rate is in cm/month.

The total value, bank height and orientation, is divided by 100. This gives a decimal value which is then multiplied by the warm season recession rate (Rs). Having the cold season rate dependent on the warm season rate is appropriate; if a station has a high warm season recession rate the banks will become oversteepened and allow for the cold season driving forces to be more effective. Also, this was the only relationship generated from regression analyses that was statistically valid (i.e., surpassed the 90 percent confidence level).

These two equations were combined to produce a yearly rate of recession, the sum of the warm and cold season rates multiplied by their active months is:

$$3)\quad Rt = 6(Rs) + 6(Rw)$$

For Lake Sakakawea, six months is applicable because wave action is the dominant force from May through October and freeze-thaw is active from November through April. The resulting value will be in cm/year, or in/year, depending on the units used. Yearly results predicted from the above equations are compared with the observed yearly rates in Table 15. The predicted and observed recession rates were next subjected to regression analysis to determine their correlation. The two rates compare favorably, with an r^2 of 0.54.

Originally, the following equation (1b) was developed that included all pertinent variables, including effective fetch and percentage of coarse beach material:

$$1b)\quad Rs=154.9-[18.81\sqrt{A}+25.12\sqrt{B}+10.06\sqrt{C}+6.91\sqrt{D}+5.03\sqrt{E}+1.1\sqrt{F}]$$

where A = sine of the angle between bank orientation and the dominant wind direction, B = offshore slope angle, C = beach width, D = bank height, E = effective fetch, and F = areal percentage of coarse beach material. The effective fetch must be determined from available map or air photographic coverage, using the procedure outlined by Saville

TABLE 15

Comparison Between Observed and Predicted Yearly Recession Rates

Station	Observed Yearly rate (m/yr)	Predicted* Yearly Rate (m/yr)
1	2.06	1.10
2	1.39	1.35
6	1.18	1.00
7	2.10	2.58
50	0.52	0.03
51	1.80	2.34
52	1.54	1.75
53	0.52	0.36
54	2.58	2.80
55	4.34	2.81
56	3.01	2.32
57	1.09	1.95
58	0.34	0.88
59	0.59	0.52
61	2.78	1.00

* Using equations 1a, 2, and 3

(1954) and illustrated in this report. The composition of the beach can be determined several ways, but the easiest way was to lay out a section of known width, e.g., 10 m, extended from the base of the bank to the waterline, and count the number of points intersected on the grid by the clasts of the various sizes. This provides an area percentage, a more relevant unit than volume percentage. The percentage of the area covered with the clasts of pebble-size or larger constitutes the value needed for the equation. Sand-size particles are not included, despite the fact that they frequently help identify a stable beach. The numbers associated with the variables are regression coefficients and 154.9 is the slope intercept. The r^2 value is 0.61. The F-value exceeds the 75 percent confidence level.

This equation (1b) was rejected, because it did not exceed the 90 percent confidence level. Despite this, the predicted results from this equation are comparable to the accepted equation, which ignores effective fetch and coarse beach material. Comparison between the observed and predicted yearly rates using equation (1b), with all the variables, is shown in Table 16. These rates were also subjected to regression analysis and produced an r^2 value of 0.55. Therefore, although this equation is comparable to the equation using only four variables, the confidence level is below the accepted 90 percent level. The confidence level is lowered because of the addition of two more independent variables. These additional variables change the degrees of freedom, which help determine the confidence level. By adding more variables to the equation the probability for error to occur increases (i.e., the confidence level is decreased). If statistical validity is secondary, this equation, 1b, can be used in place of equation 1a, as it predicts almost as accurately and

TABLE 16

Comparison Between Predicted and Observed Yearly Recession Rates using Equations 1a and 1b

Station	Observed Yearly Rate (m/yr)	Predicted* Yearly Rate (m/yr)	Predicted** Yearly Rate (m/yr)
1	2.06	1.26	1.10
2	1.39	1.63	1.35
6	1.18	1.12	1.00
7	2.10	2.79	2.58
50	0.52	0.04	0.03
51	1.80	2.28	2.34
52	1.54	1.74	1.75
53	0.52	0.42	0.36
54	2.58	2.71	2.80
55	4.34	2.82	2.81
56	3.01	2.20	2.32
57	1.09	1.78	1.95
58	0.34	0.88	0.88
59	0.59	0.30	0.52
61	2.78	0.96	1.00

* using equations 1a, 2, and 3

** using equations 1b, 2, and 3

uses the intuitively important parameters of effective fetch and beach clast percentage. These two variables may become more significant through time, but this can be proven only by the collection of additional bank recession data.

For projection into the future the most important assumption is that recession will decrease with time, such that if the cumulative recession were plotted on a graph with respect to time the graph would have the shape of a parabola on its side. As in the case of the trend projection, the equation for a parabola must be incorporated into the future recession equation. The parabola equation selected is:

$$y^2 = ax,$$

where y is the cumulative recession, x is the number of years, and a is the constant that must be determined. Because one of the initial assumptions for the equation is that historical data are not available, the present yearly rate must be determined. This rate, which is a segment of the parabola, is the difference in cumulative recession over a one-year period, or y_2-y_1. Because "a" must first be defined, the equation is rearranged to a = y^2/x, or a = y_2^2/x_2, and y_1^2/x_1^1. By defining y_2 in terms of y_1 and Rt, the constant a is now equal to $y_1^2/x_1 = (y_1^2 + Rt)^2/x_2$. By cross-multiplying and setting the equation equal to zero, a quadratic equation is developed such that:

$$y_1^2x_1 + 2y_1Rtx_1 + Rt2x_1 - y_1^2x_2 = 0.$$

Now y1 can be solved using the quadratic formula, where the constants a, b, and c are $(x_1 - x_2)$, $2Rtx_1$, and $Rt2x_1$, respectively. Once y_1 is determined, the constant a can be solved and future recession can be determined. Application of these equations to the control bank recession stations reveals an ultimate recession ranging from only 5.3m (Sta. 50) to 495m (Sta. 55) (Table 17). For Station 50 the predicted ultimate recession is obviously incorrect because the predicted yearly rate is too low. The yearly rate is a function of the numerical values of the independent variables and their respective coefficients. Anomalous values for predicted rates can be explained only by variance in the analysis. Thus, for Station 50 the ultimate recession value from trend analysis should be used instead. For sites without historical data, minimum ultimate recession values should replace predicted ultimate values if the predicted ultimate values are lower than the minimum values.

Comparison between the statistical and trend analysis show that Station 51 has a predicted ultimate recession of 412m and 585m, respectively, whereas, Station 2 has a predicted recession of 76m from statistical and 238m from trend analysis. It was hoped that both analyses would produce comparable results. Unfortunately, due to the many possible errors and assumptions made for both methods similar results were not possible. However, additional data might reduce the differences.

In conclusion, the equation that best relates bank recession rates to the causative variables for Lake Sakakawea involves exponential relationships. Whether or not the equations are applicable to other reservoirs needs to be tested. Regardless, either equation should provide a predictive method for determining bank recession that is many times more accurate than the template presently in use.

TABLE 17

Predicted Cumulative Bank Recession For Stations at Lake Sakakawea

Station	Rt m/yr	100 Years (m)	200 Years (m)	500 Years (m)
1	1.10	87	123	194
2	1.35	107	151	238
6	1.00	79	111	176
7	2.58	203	287	454
50	0.03	2.4	3.3	5.3
51	2.34	184	260	412
52	1.75	136	195	308
53	0.36	57	80	127
54	2.80	220	312	493
55	2.81	221	313	495
56	2.32	183	258	408
57	1.95	154	217	343
58	0.88	69	98	155
59	0.52	41	58	92
61	1.00	79	111	176

* Using equations 1a, 2, and 3

RECOMMENDATIONS FOR FURTHER STUDY

From this study has come an appreciation of the importance of further research. Although two and a half years of data have been collected it would be presumptuous to believe that all the necessary information has been accumulated. Furthermore, it would be naive to state that the collected data are statistically representative of the long-term rates of recession; further data are obviously needed. Therefore, it is recommended that five years of data be collected to provide a stronger foundation for statistical analysis. Further collection of data could continue with minimal cost and time. Also, with continued data collection variables such as effective fetch and percentage of coarse beach clasts might become more significant.

Additional field work might be useful both to this study and to the Corps. Deep water sediment samples, for example, could be collected during the winter with a piston core sampler. Analysis of the samples should reveal the sedimentation rate for Lake Sakakawea. Also, testing the different lithologies, especially the till formations, for engineering properties such as cohesion, residual shear strength, and compressive strength would provide other variables that could be tested.

The resulting equations need further testing. Other variables should also be measured and tested, such as beach height, joint strength, sediment cohesion, and longshore current velocity. Then, the equations should be applied to other locations along the lake, such as the sediment range lines; the results should be compared with the measured historical recession. The equations should also be tested at other reservoirs such as Oahe.

CONCLUSIONS

In 1983 a detailed study began to determine which parameters define bank recession at Lake Sakakawea, North Dakota, and from the resulting data to develop a relatively simple equation that can predict present bank recession rates, and project them into the future.

Previous work involved the establishment of erosion stations, textural analysis of bank sediment, and description of the erosional processes. The collected bank recession data represent 26 measurements over a two and a half year period at 20 sites along the eastern end of Lake Sakakawea. The parameters analyzed included basin-wide factors, such as climate and pool-level fluctuations; offshore factors, such as slope, composition, and wave energy; beach factors, such as composition and width; and bank factors, such as geometry, lithology, stratigraphy, and geographic location.

At present, bank recession rates range from 0.2 to 4.3m/y, averaging 1.6m/y. Approximately 78 percent of the total bank recession occurs during the warm months (May - October); wave action is the principal erosion agent. During the cold months (November - April), recession is caused directly or indirectly by freeze-thaw processes.

Fifteen stations were statistically analyzed using variables that are associated with the rate of recession. The remaining five stations were ignored because they are located in sheltered areas such as bays. Separate analyses were done for both warm and cold season recession.

The variables selected for analyses were: effective fetch, bank height, beach width, areal percentage of coarse beach clasts, offshore slope, mean grain size, sine of the angle between the shoreline and dominant wind, and bank orientation with respect to the sun.

1. Effective fetch, a parameter used in wave forecasting for lakes and reservoirs, has a direct relationship to wave energy.
2. Bank height was found to be an important factor for both warm and cold season recession; shorter banks experienced faster recession in the warm months as a result of wave action. In the cold months the same short banks were usually protected by snow drifts. The tall banks (>9m), however, were exposed to the processes related to freeze-thaw.
3. Beach width represents the distance the broken wave must travel to reach the bank.
4. The areal percentage of coarse beach clasts defines the effectiveness of cobble- and boulder-size material in breaking up approaching waves.
5. Offshore slope, which had the highest correlation with warm season recession, defines how close the waves can approach the shore before breaking.
6. The angle between the wind and shoreline accounts for the changes in wave energy due to wave refraction.
7. Bank orientation with respect to the sun was used only in the cold season analysis. North-facing banks experienced greater cold season recession as a result of the high antecedent moisture content.

Based on these results, two sets of seasonal recession equations were developed. The warm season recession rate, in cm/month, is:

1a) $Rs = 141.53 - [17.2\sqrt{A} + 25.08\sqrt{B} + 10.43\sqrt{C} + 8.37\sqrt{D}]$, where A= sine of the angle between bank orientation and dominant wind direction, B= offshore slope angle, C= bank height, and D= beach width. The numbers associated with each of the independent variables are regression coefficients and 141.53 is the slope intercept. This equation was accepted in preference to another equation (1b):

1b) $Rs=154.9-[18.8\sqrt{A} + 25.12\sqrt{B} + 10.06\sqrt{C} + 6.91\sqrt{D} + 5.03\sqrt{E} + 1.1\sqrt{F}]$ which included the variables effective fetch (E) and areal percentage of coarse beach clasts (F). Equation 1a exceeded the 90 percent confidence level and had an r^2 value of 0.59, whereas equation 1b exceeded the 75 percent confidence level only. Both equations (1a and 1b) produced similar results, though.

Cold season recession is explained by:

2) $Rw = Rs\ [(2.05(\text{bank height}) + 0.043(\text{bank orientation}) - 2)/100]$.

Again, 2.05 and 0.043 are regression coefficients and 2 is the slope intercept. Bank orientation is with respect to the sun, with a higher value given for north-facing banks. The cold season recession equation exceeded the 99 percent confidence level and had an r^2 value of 0.46. The two seasonal rates are then multiplied by the respective months their erosional processes are active to give the resulting yearly rate (cm/yr):

3) $Rt = 6(Rs) + 6(Rw)$.

For calculating future recession, it was assumed that the bank recession rates will decrease with time, such that the recession curve will have the shape of a parabola. Therefore, that equation uses the formula $y^2= ax$, where y is the cumulative recession, x is the years projected into the future, and a is a constant calculated from the quadratic equation.

These equations are the first to be developed that are statistically valid. In addition, they can be used to estimate the present yearly rate of recession in areas without current or historic recession data. Once the present yearly recession rate is calculated, it can be projected into the future to predict the total bank recession which can be anticipated in the absence of extensive field work. It is a significant improvement over the template method used by the U. S. Army Corps of Engineers. However, further testing is necessary to determine its applicability to other reservoirs.

APPENDICES

APPENDIX A

METEORLOGICAL DATA FOR LAKE SAKAKAWEA AREA
(from Reid and others, 1986)

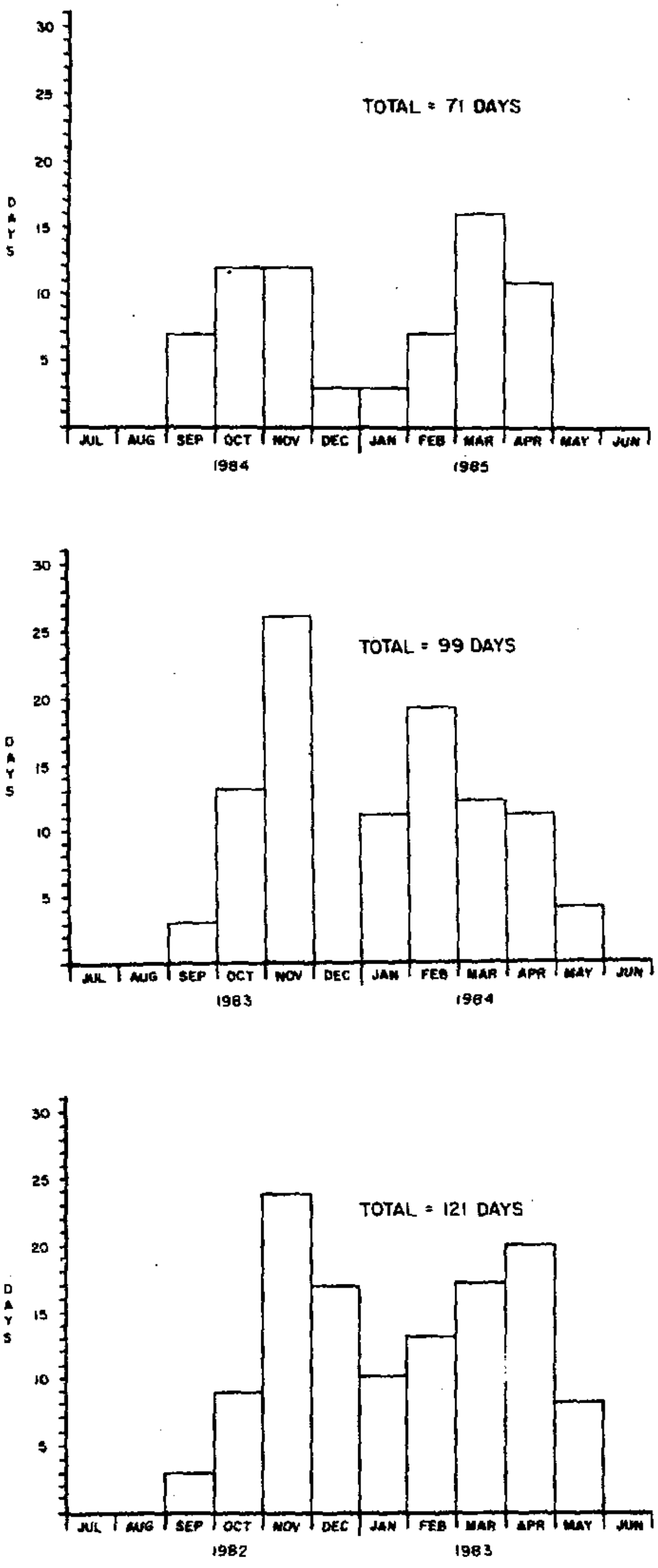


Figure 28 - Number of freeze-thaw days/month, Riverdale, ND, 1982-1985.

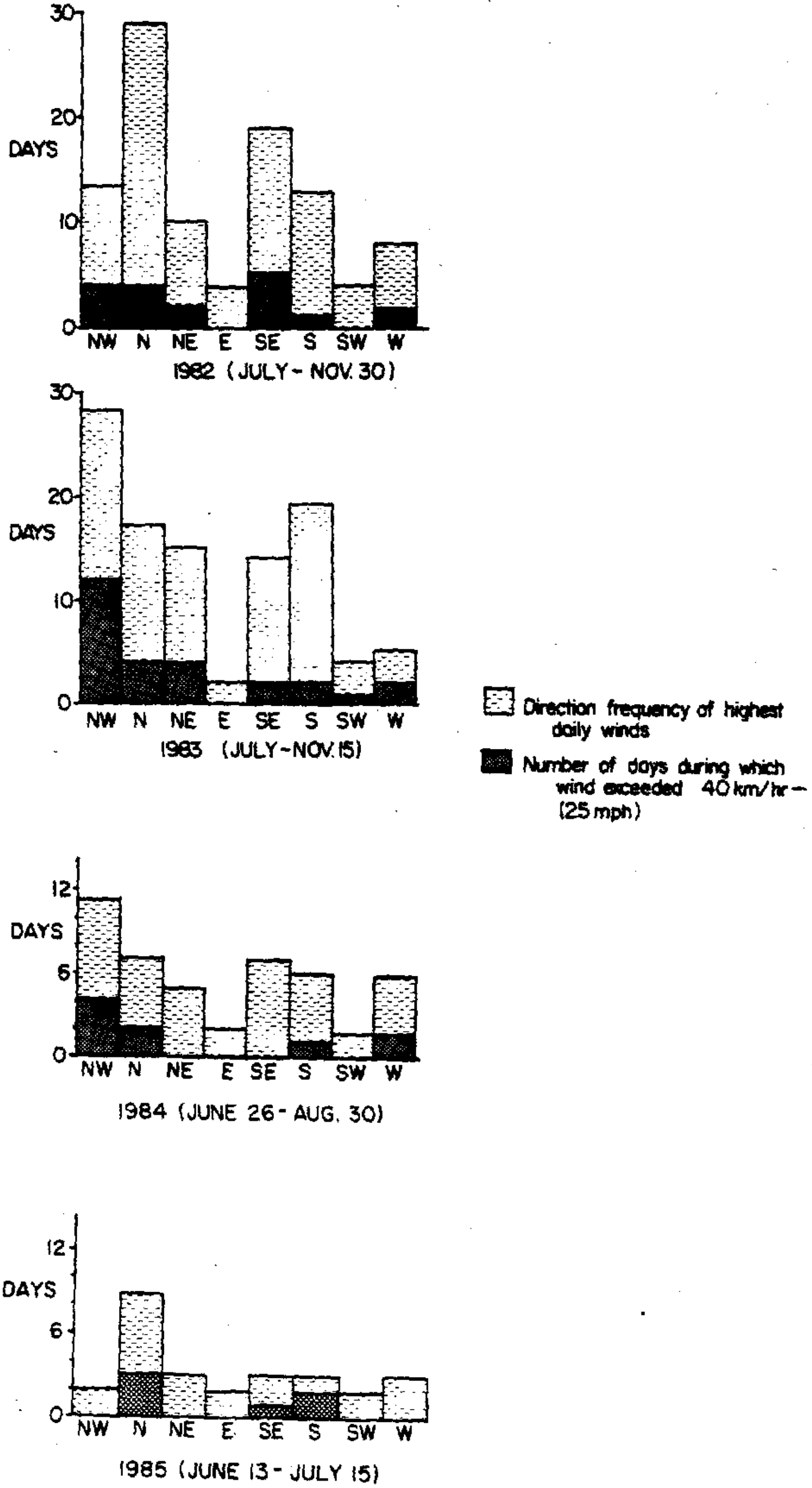


Figure 29 - Direction and frequency of winds on Lake Sakakawea during the summmer highest pool levels, 1982-85.

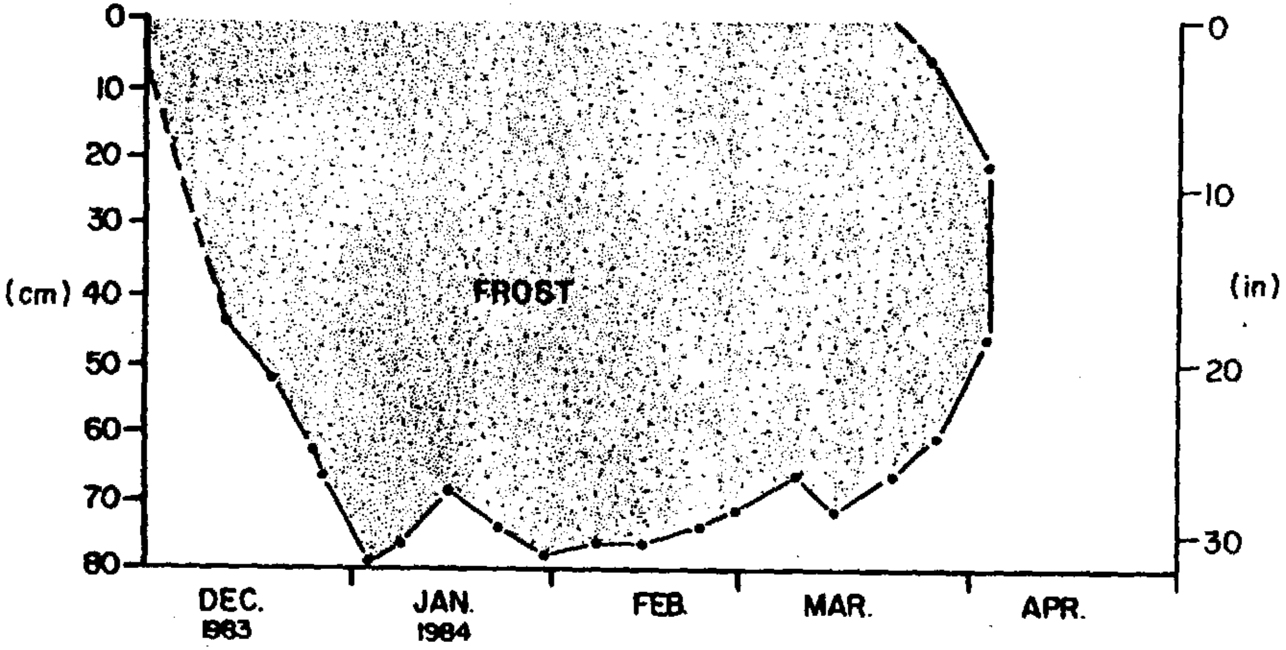


Figure 30 - Frost penetration at Riverdale, ND, 1983-84.

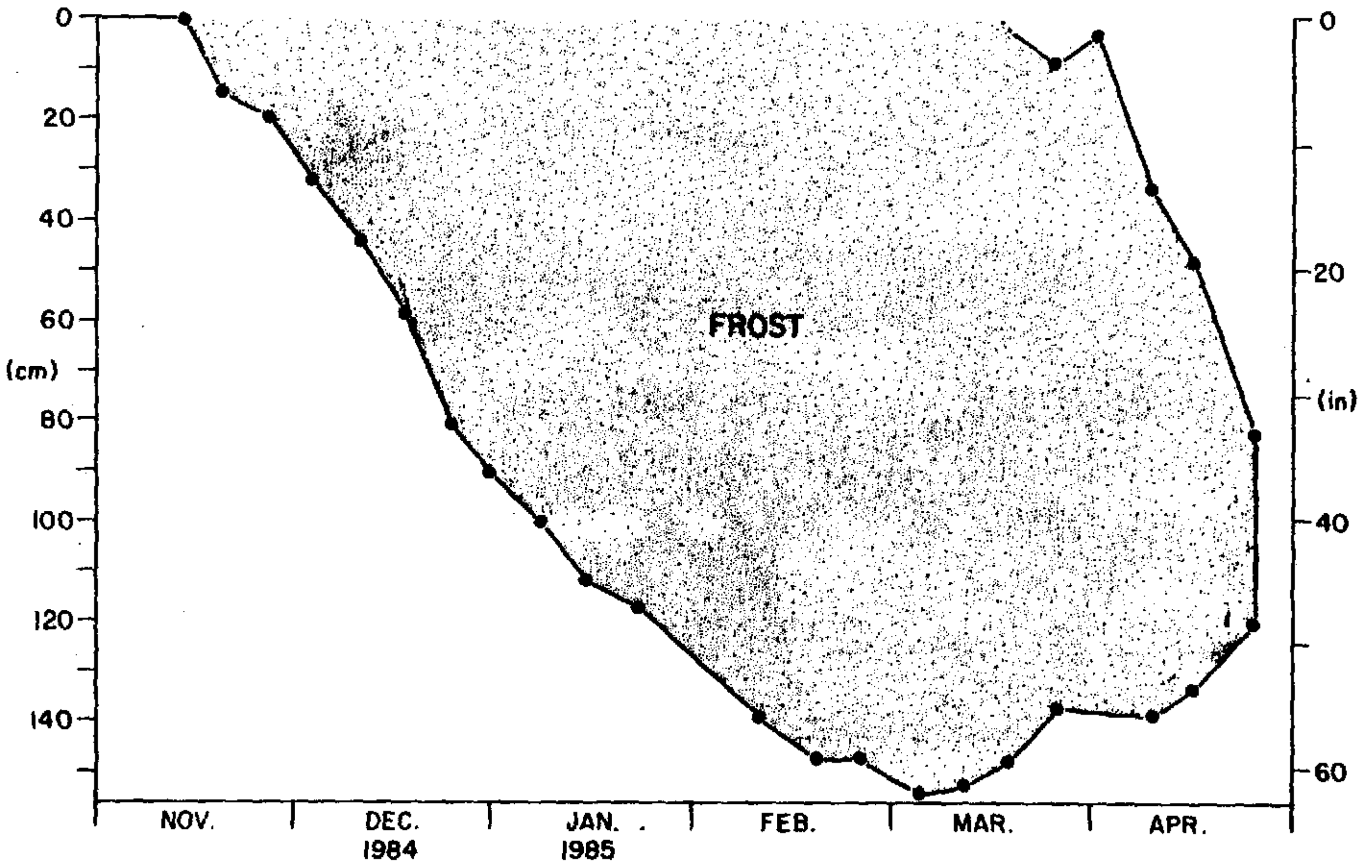


Figure 31 - Frost penetration at Riverdale, ND, 1984-85.

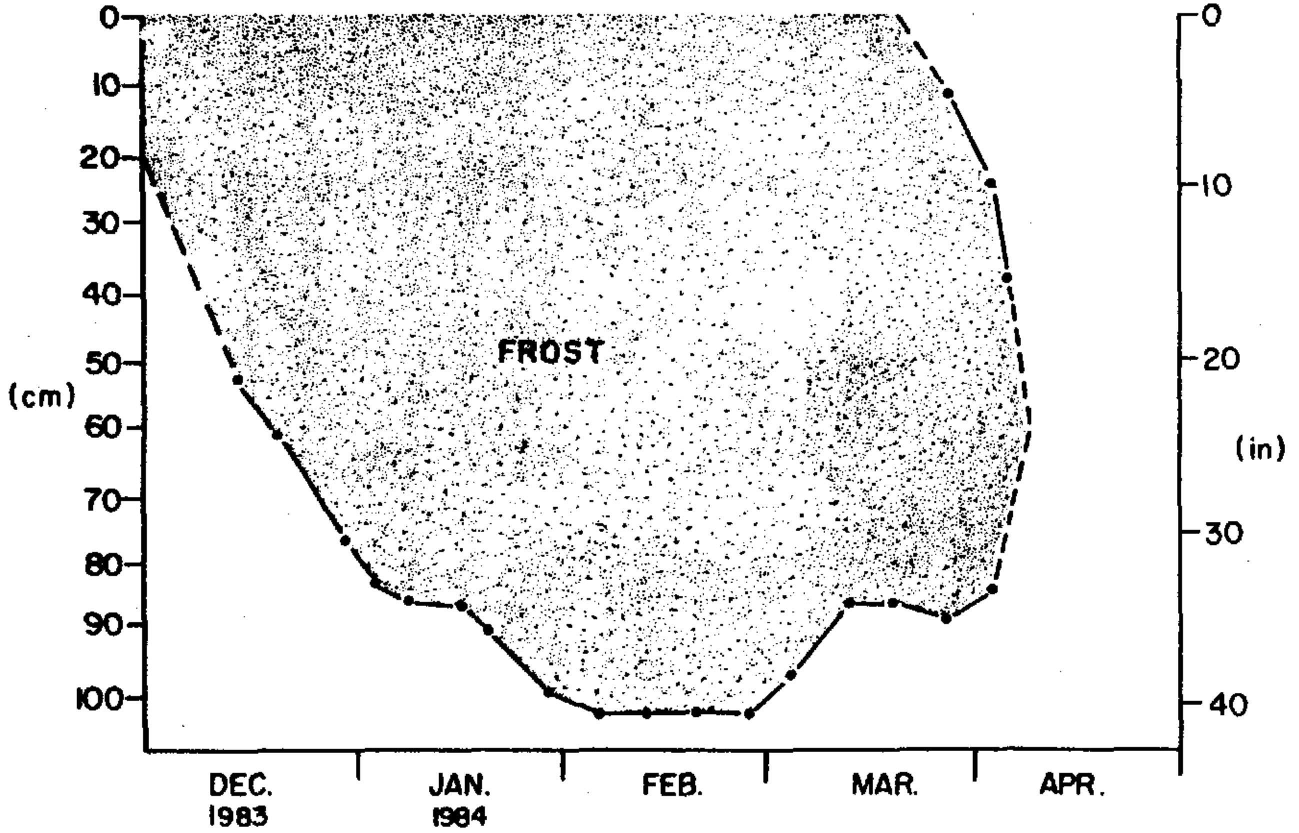


Figure 32 - Frost penetration at Fort Stevenson State Park, ND, 1983-84.

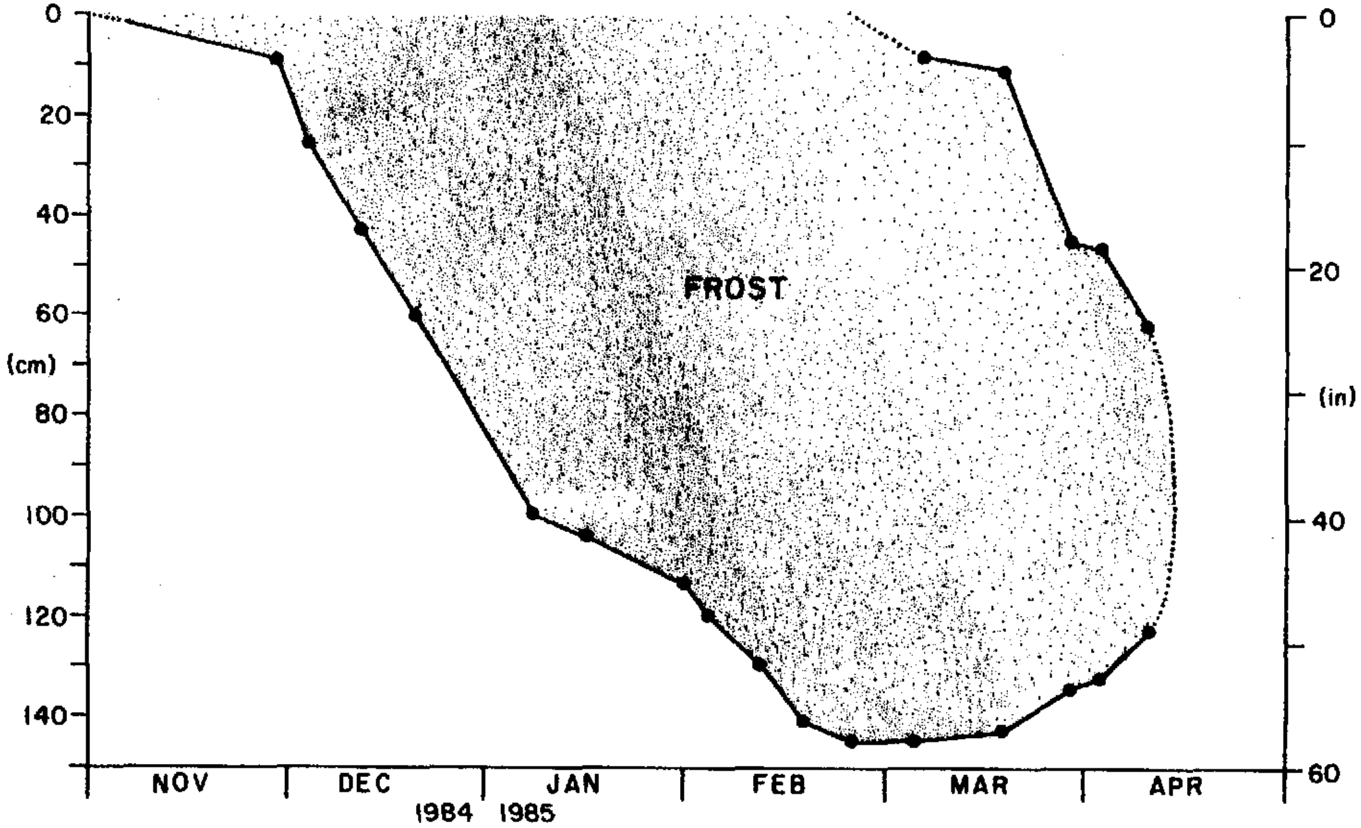


Figure 33 - Frost penetration at Fort Stevenson State Park, ND, 1984-85.

APPENDIX B

CUMULATIVE BANK RECESSION FOR LAKE SAKAKAWEA
(from Reid and others, 1986)

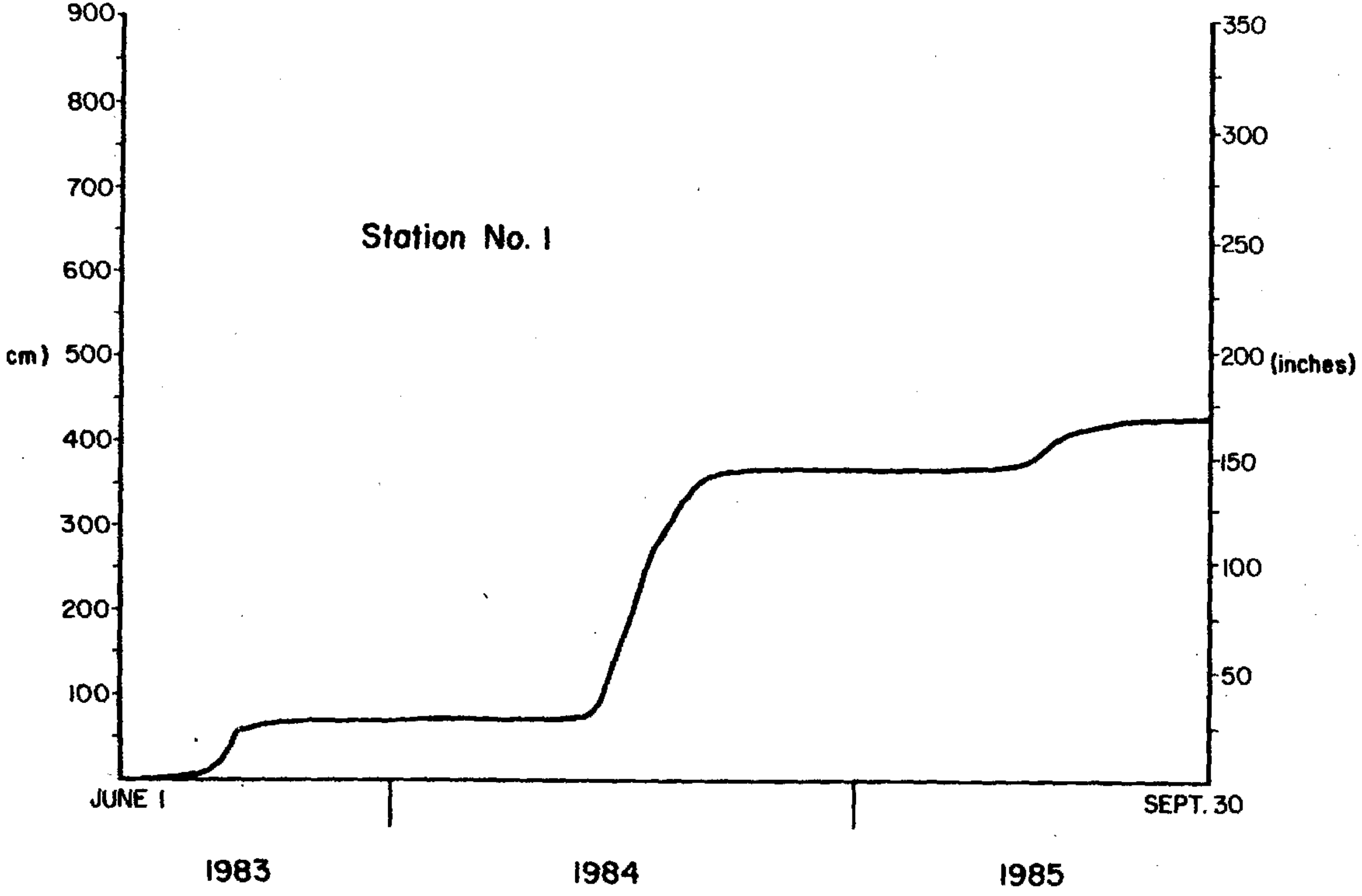


Figure 34 - Cumulative bank recession, Station 1.

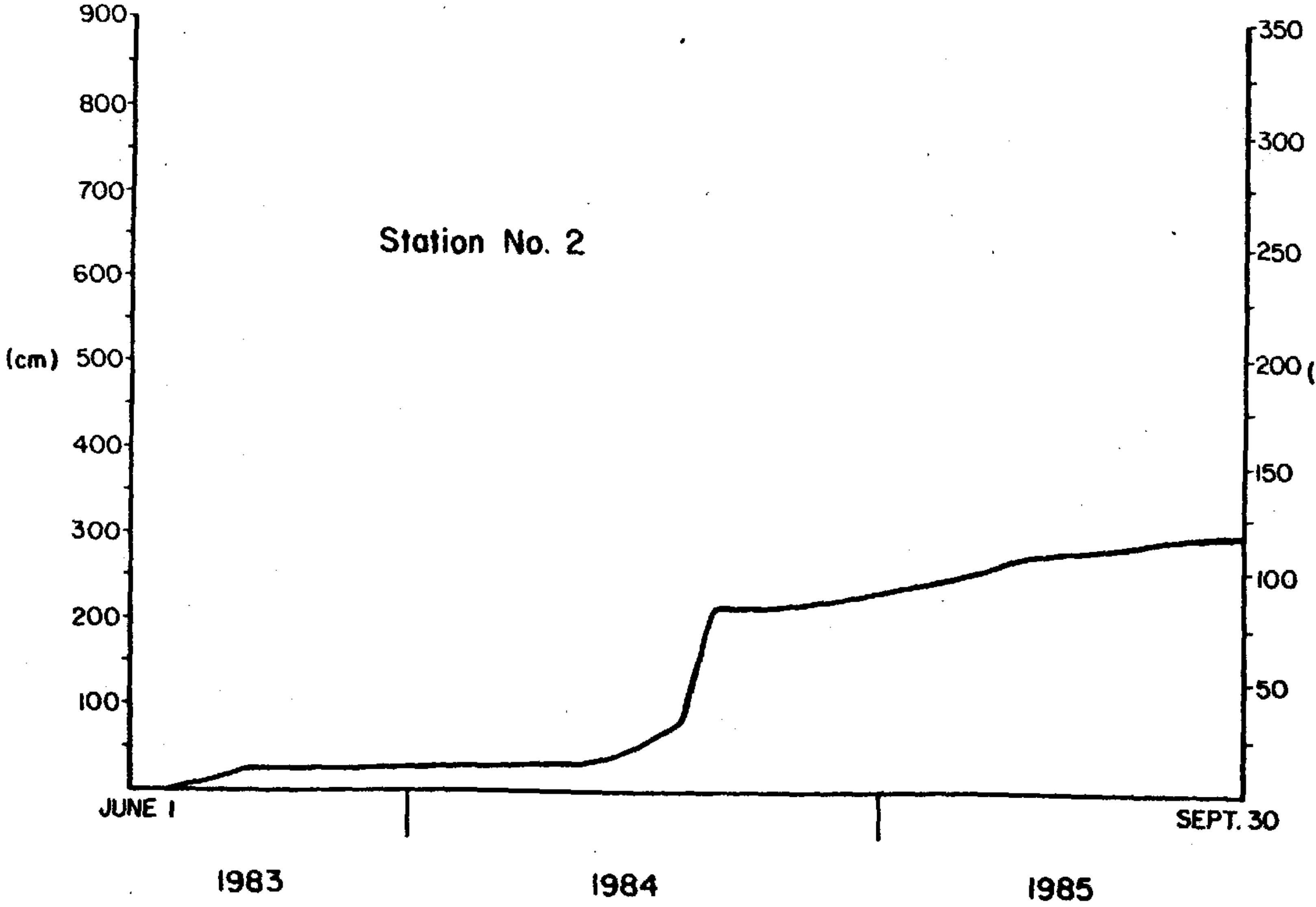


Figure 35 - Cumulative bank recession, Station 2.

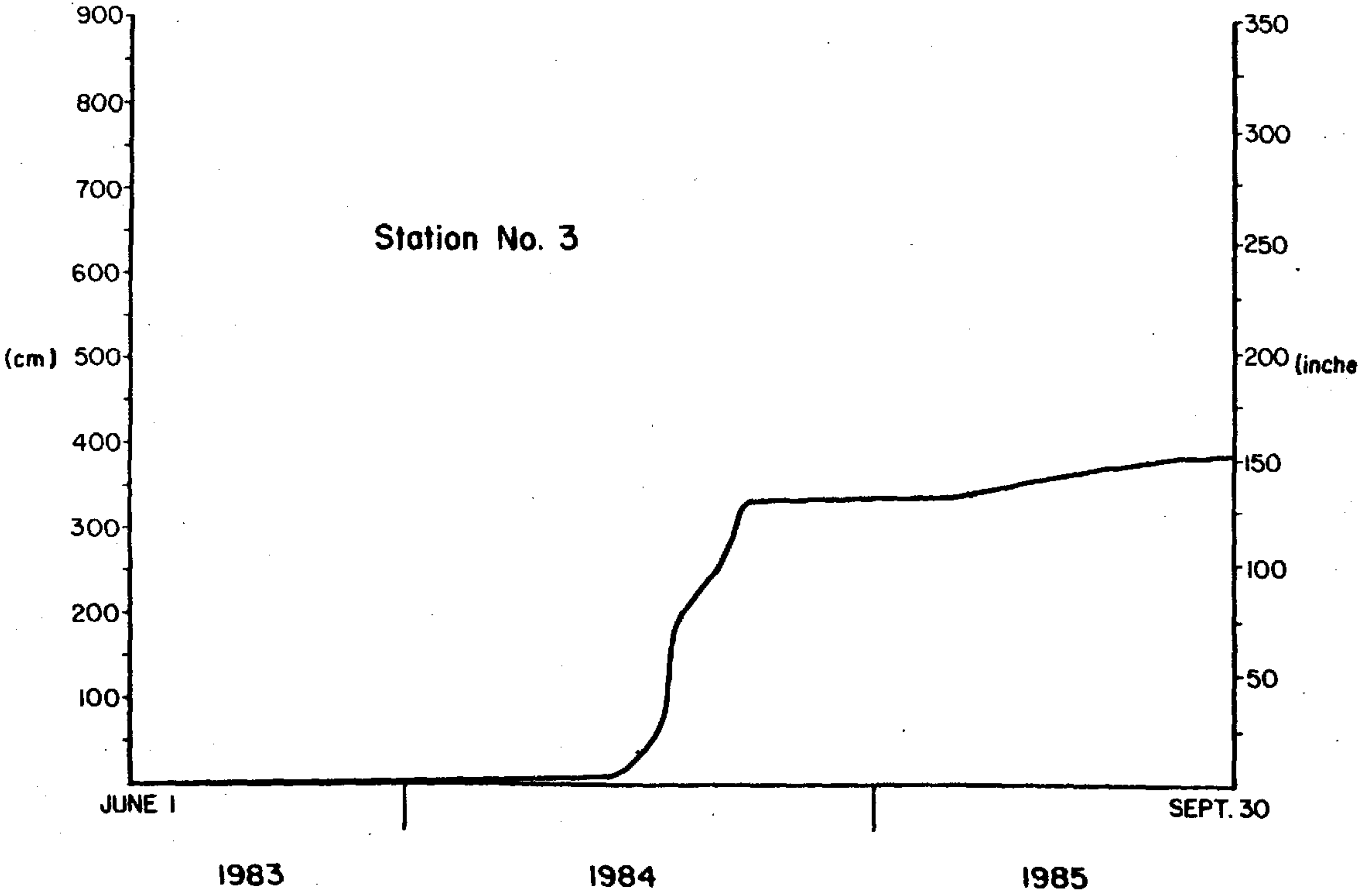


Figure 36 - Cumulative bank recession, Station 3.

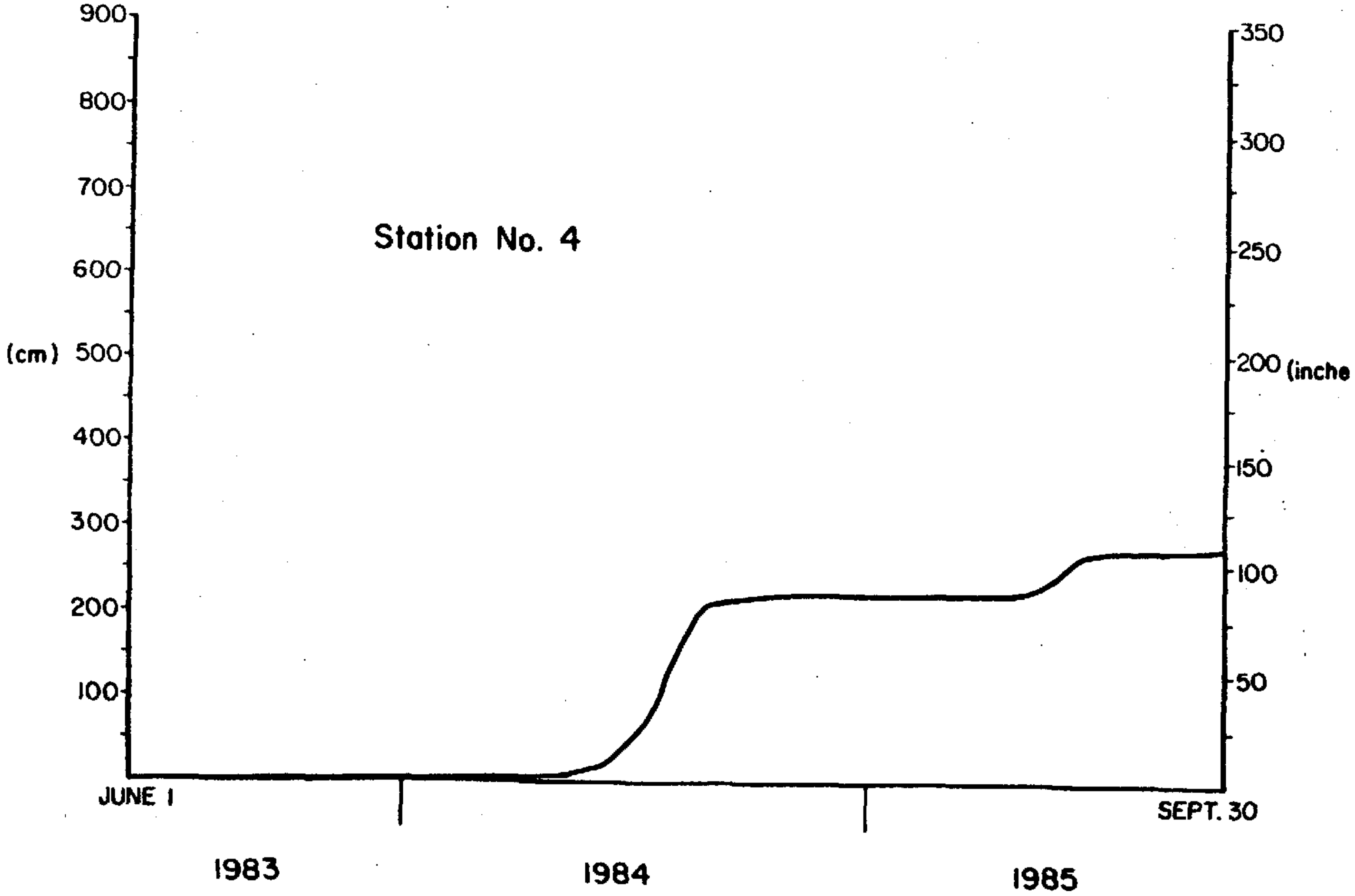


Figure 37 - Cumulative bank recession, Station 4.

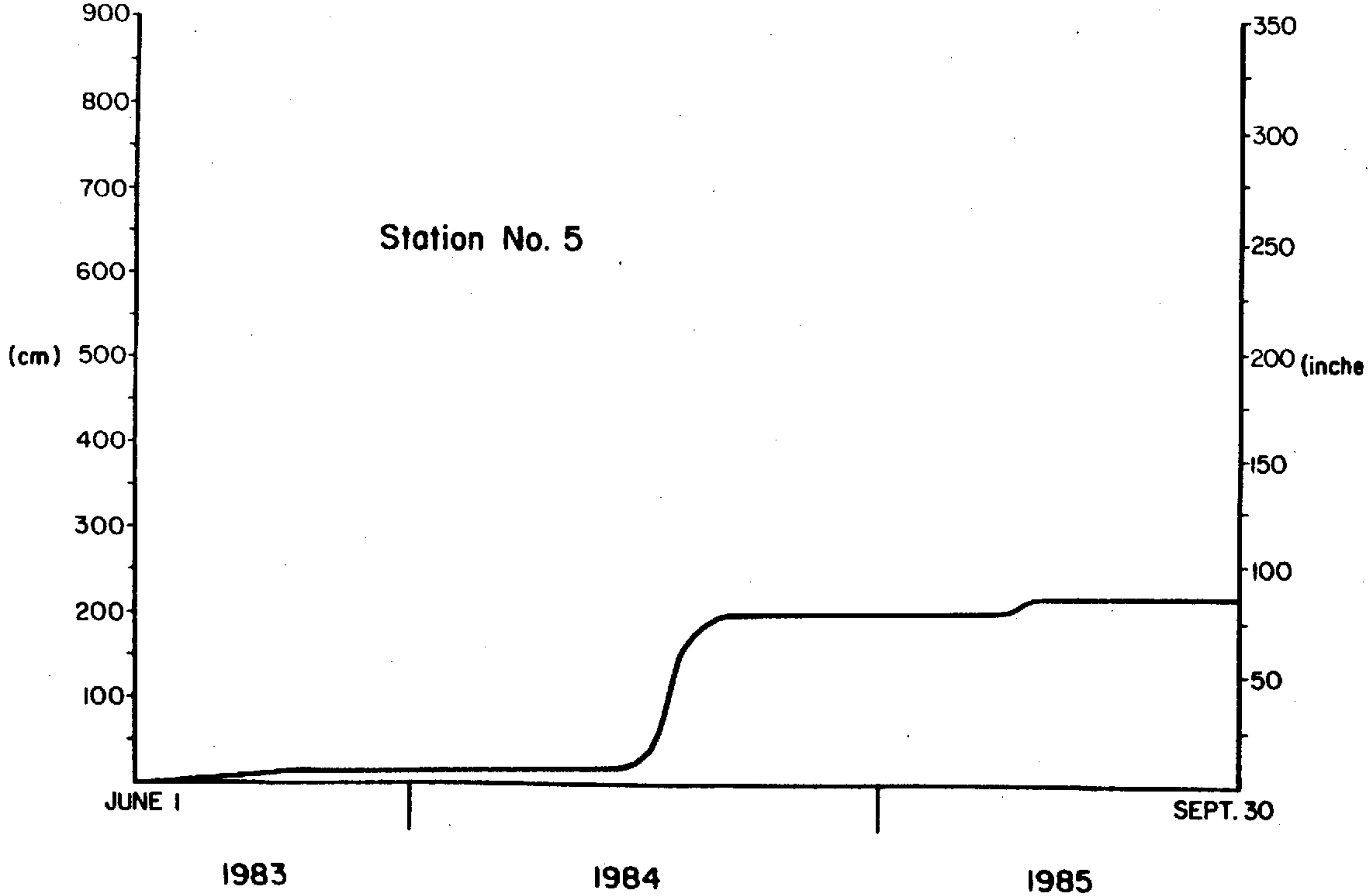


Figure 38 - Cumulative bank recession, Station 5.

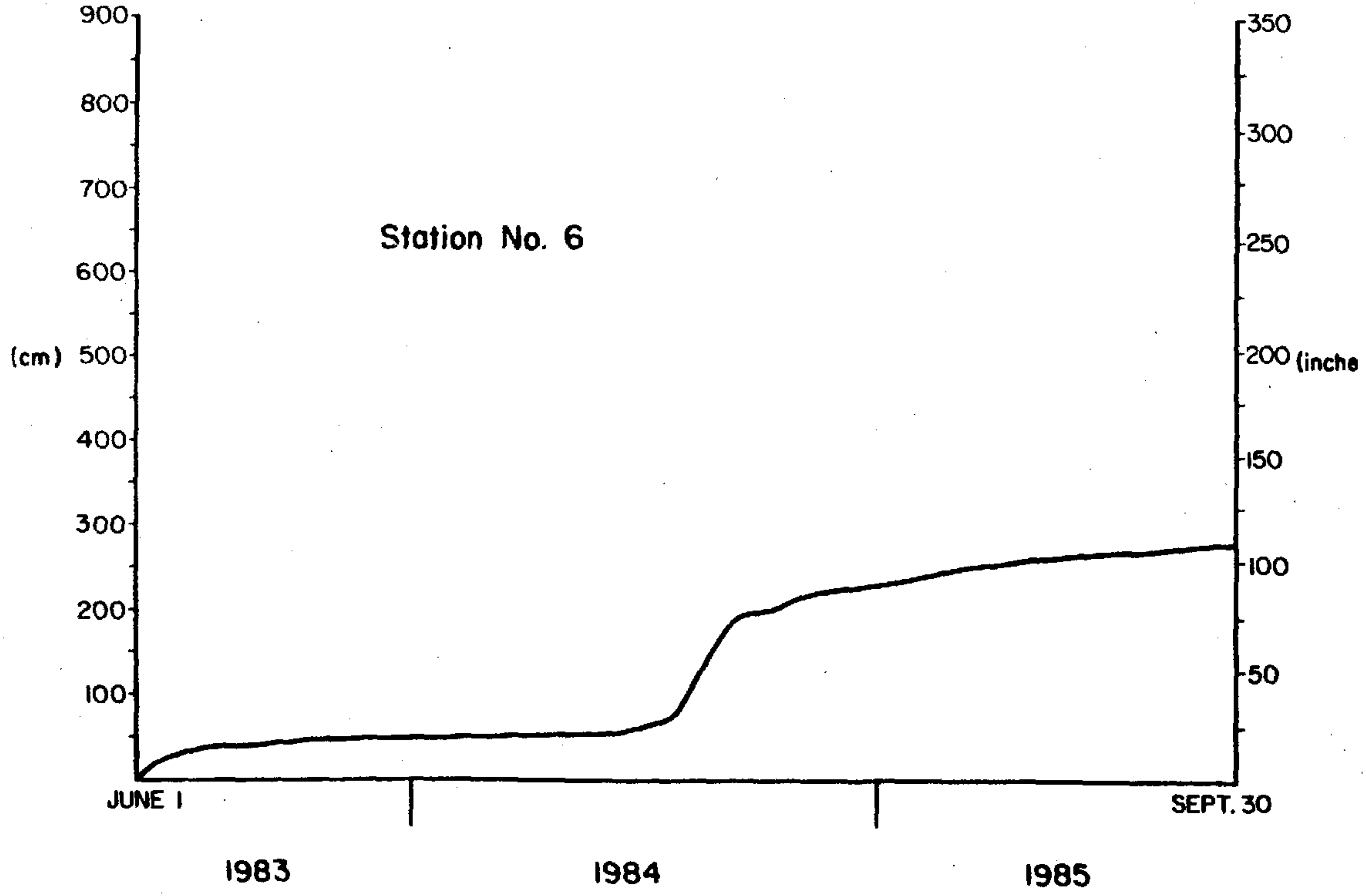


Figure 39 - Cumulative bank recession, Station 6.

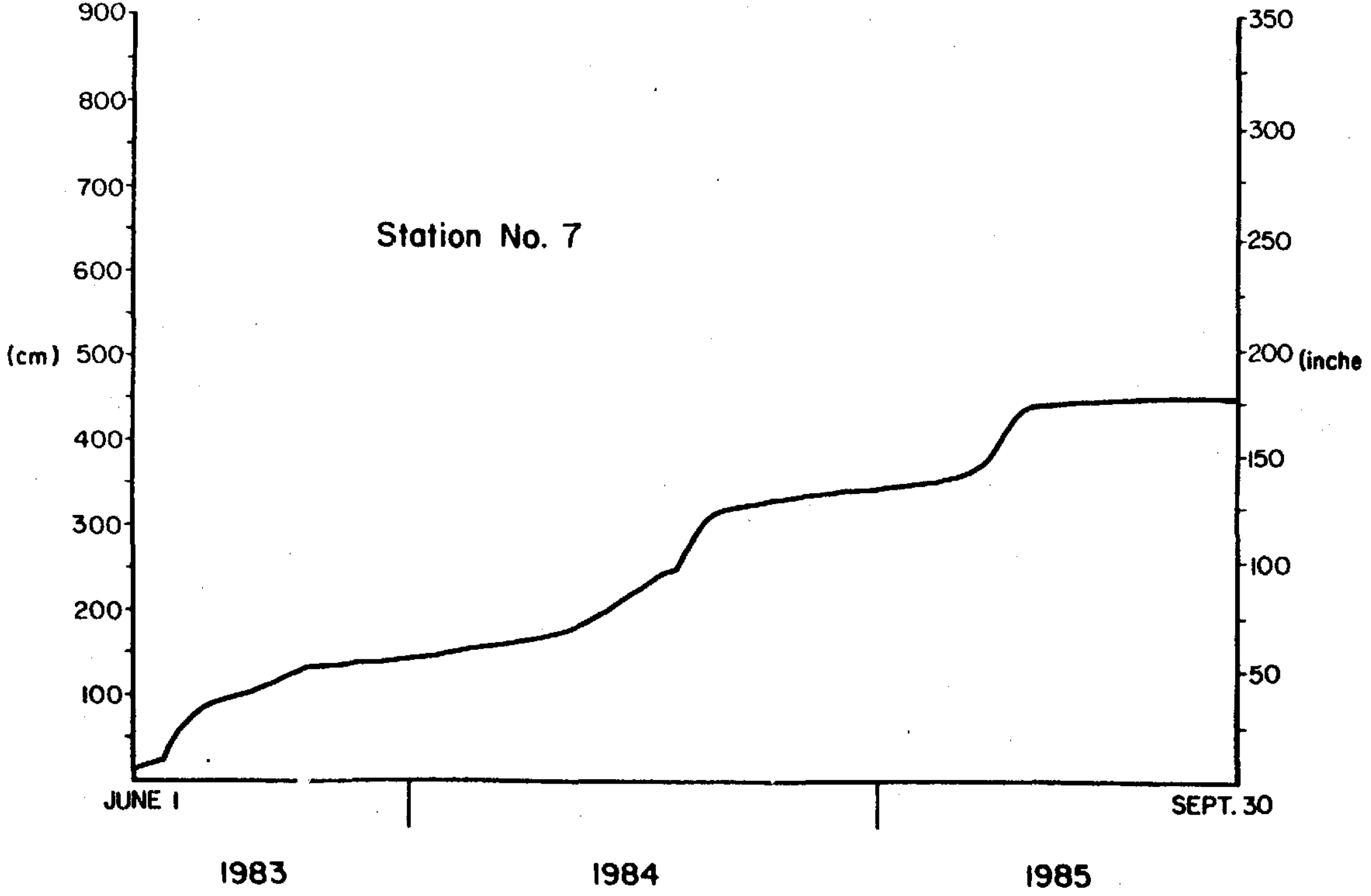


Figure 40 - Cumulative bank recession, Station 7.

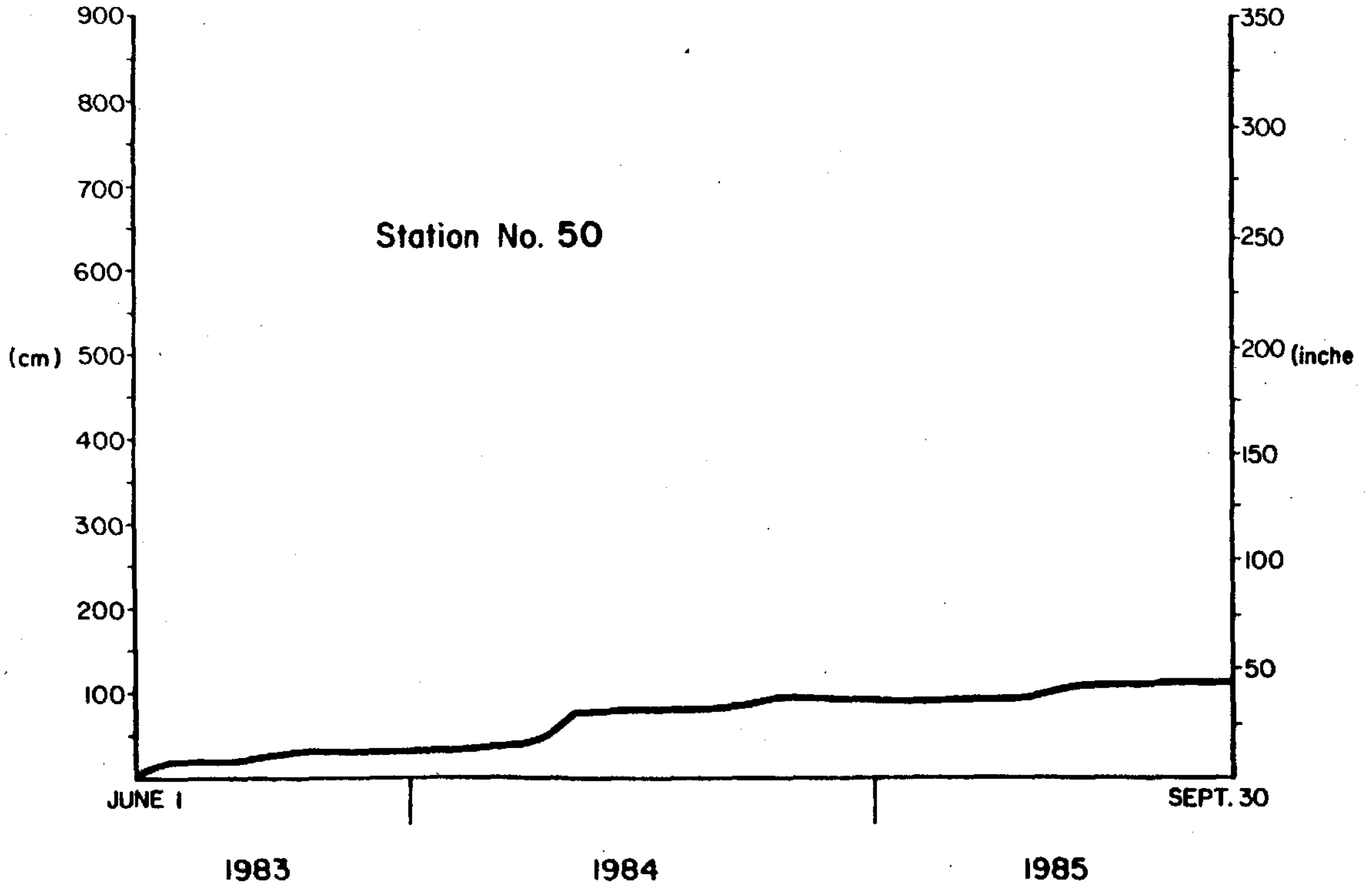


Figure 41 - Cumulative bank recession, Station 50.

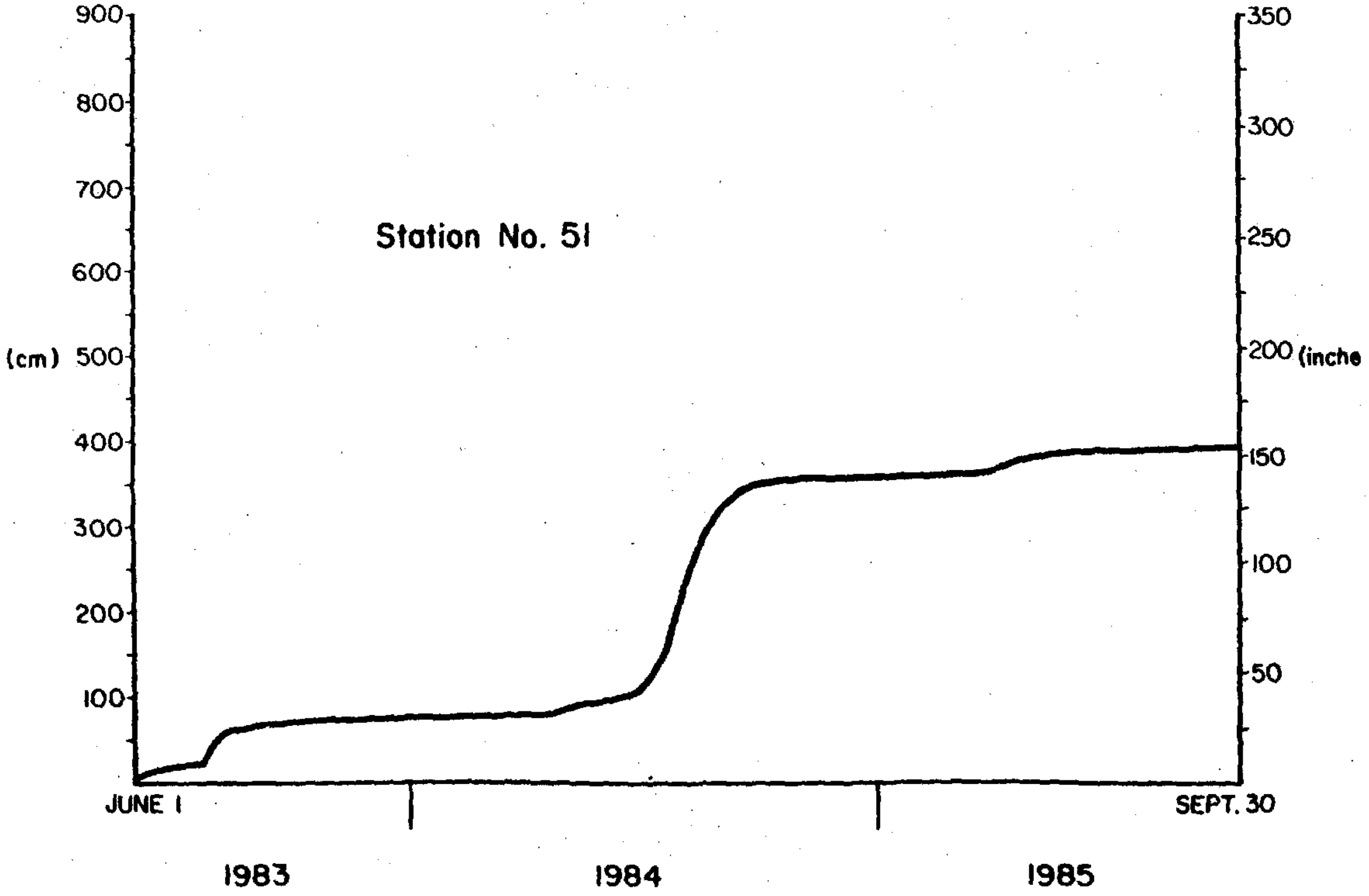


Figure 42 - Cumulative bank recession, Station 51.

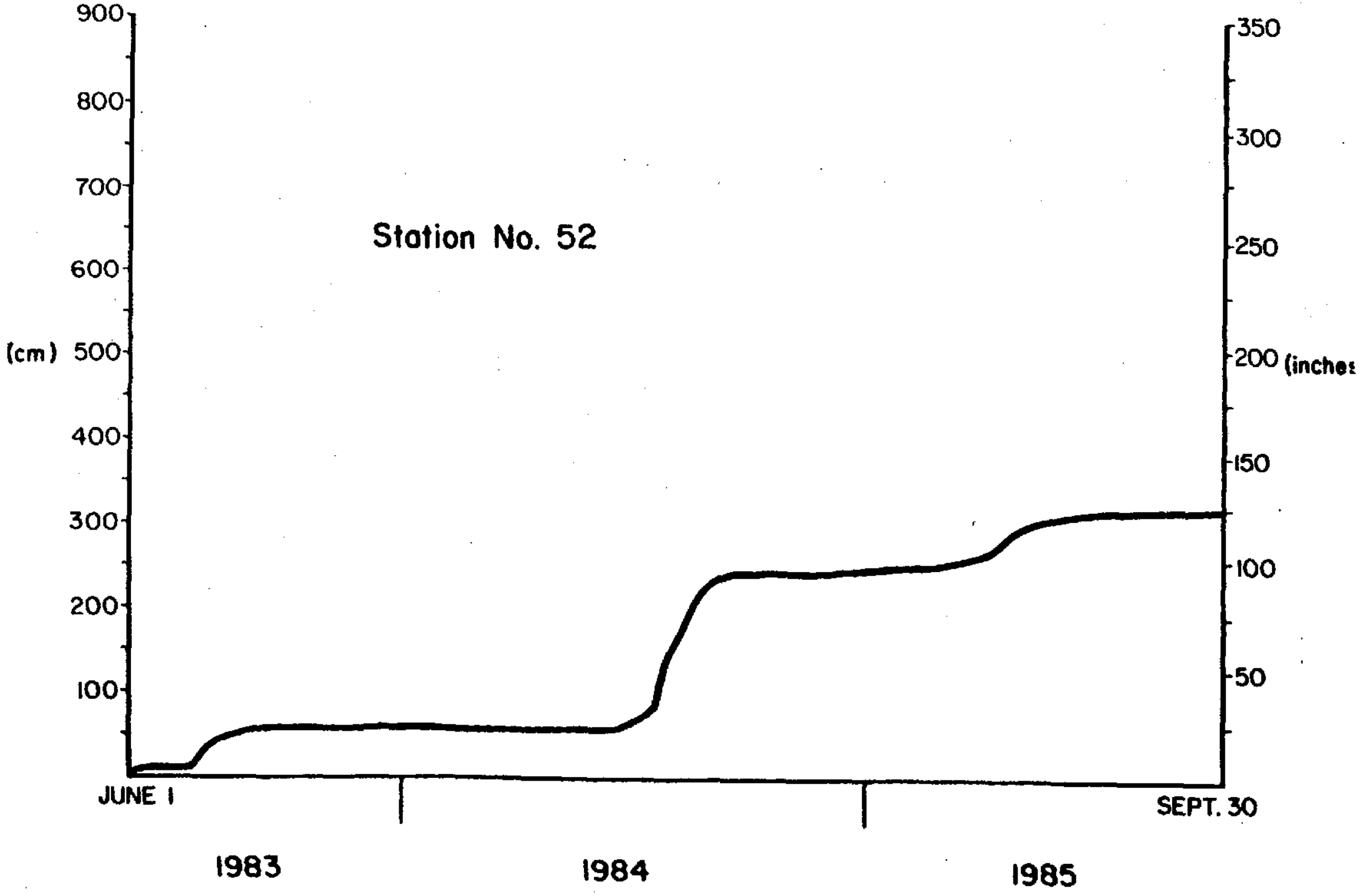


Figure 43 - Cumulative bank recession, Station 52.

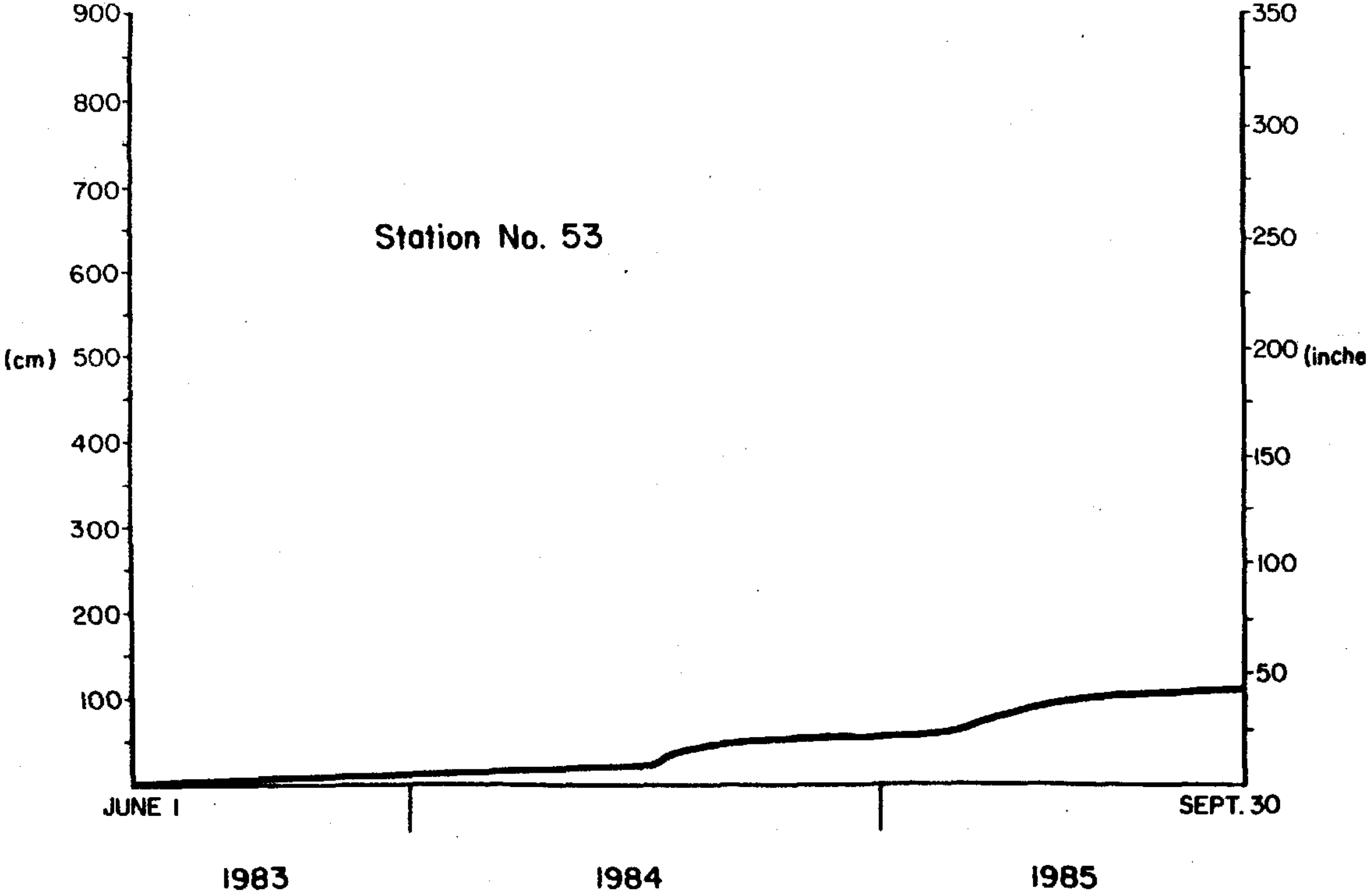


Figure 44 - Cumulative bank recession, Station 53.

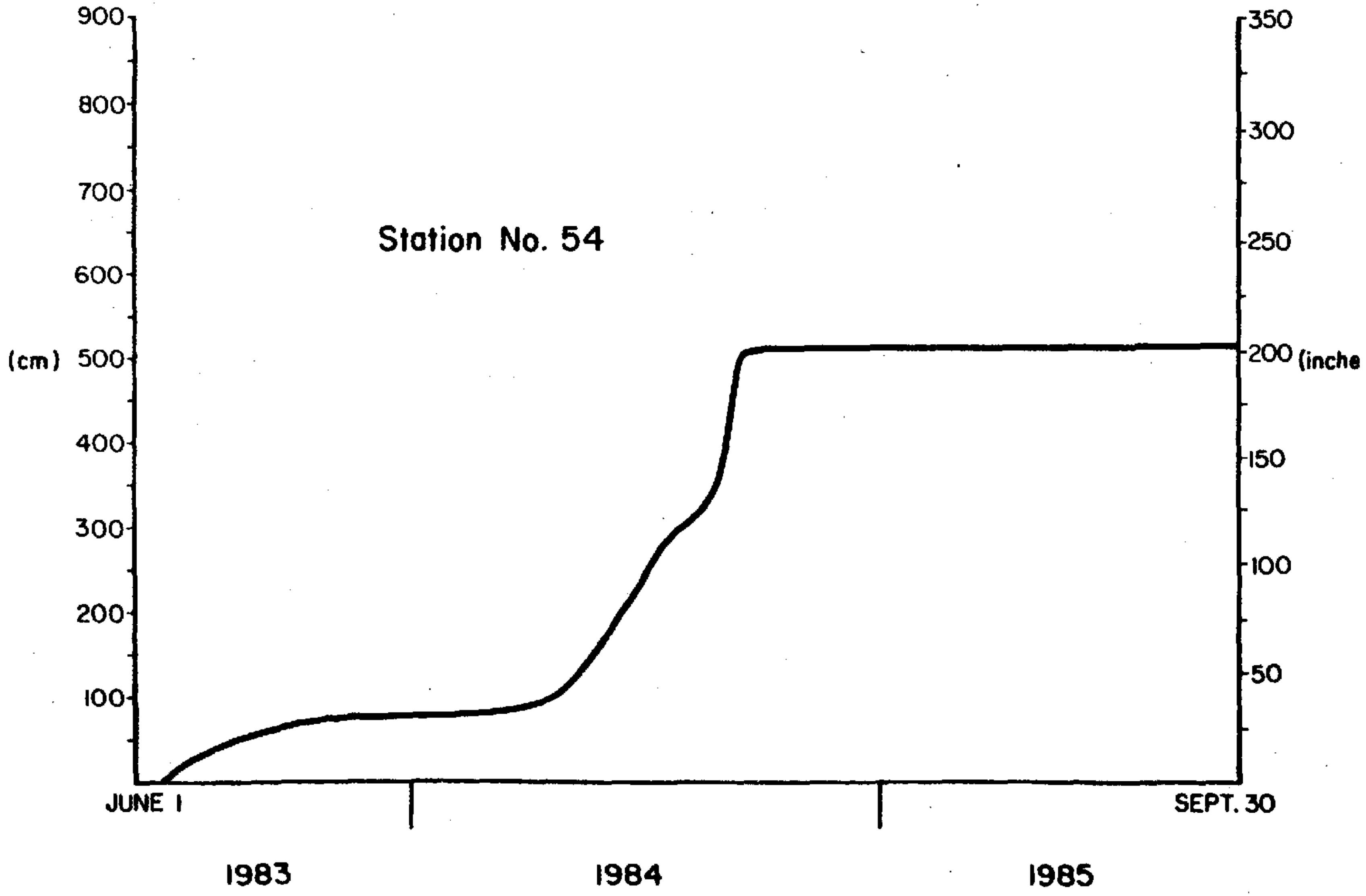


Figure 45 - Cumulative bank recession, Station 54.

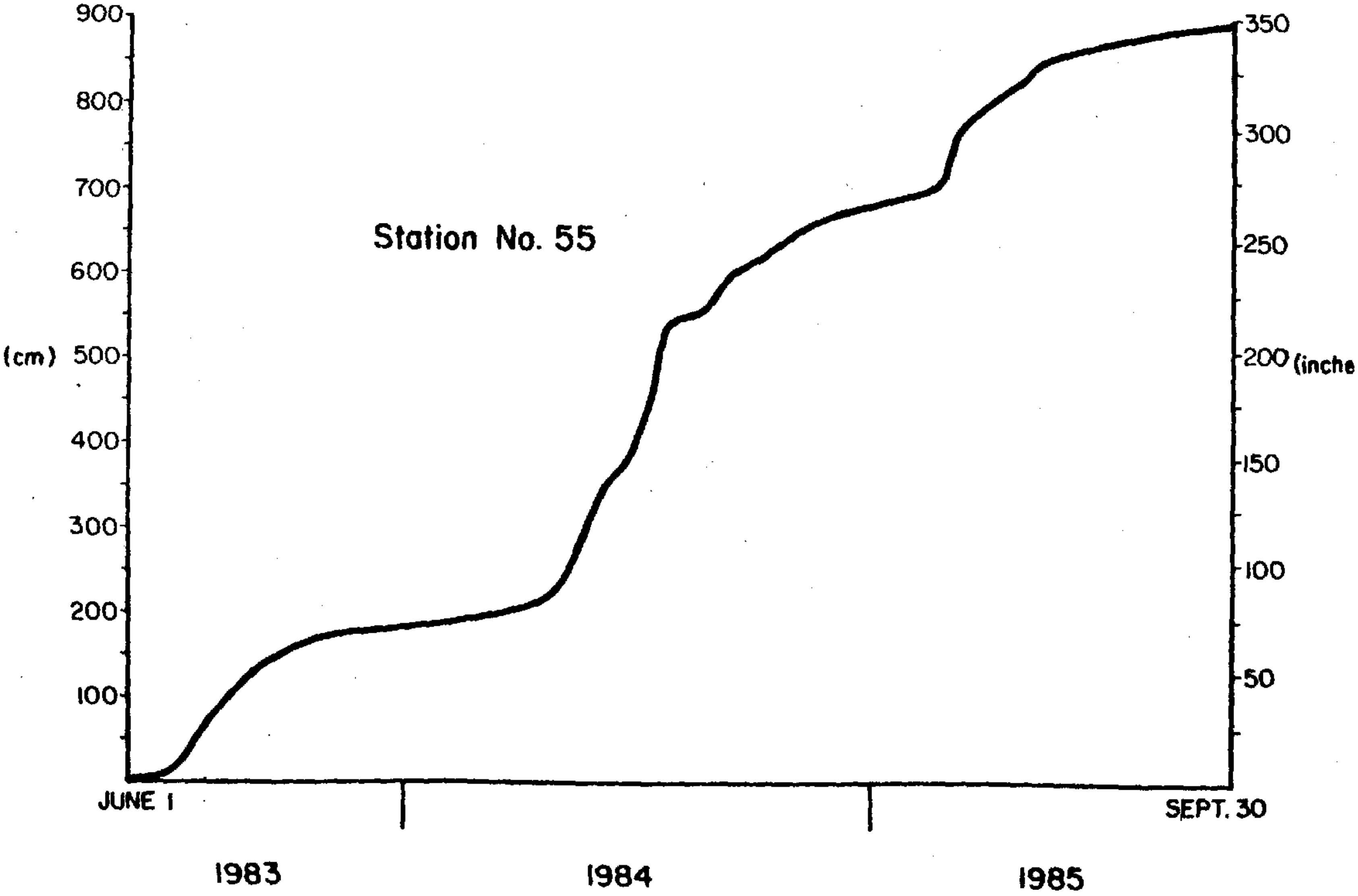


Figure 46 - Cumulative bank recession, Station 55.

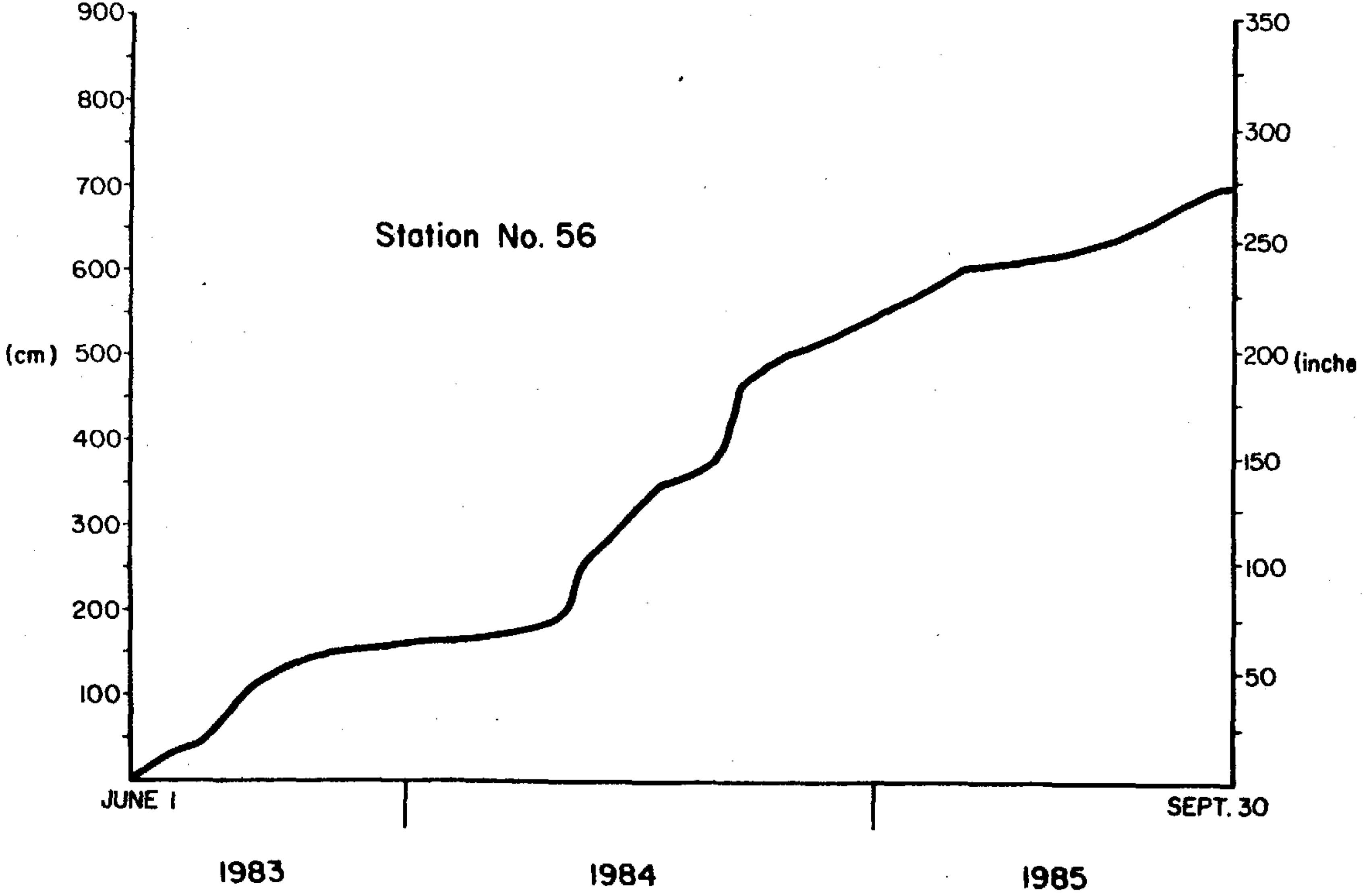


Figure 47 - Cumulative bank recession, Station 56.

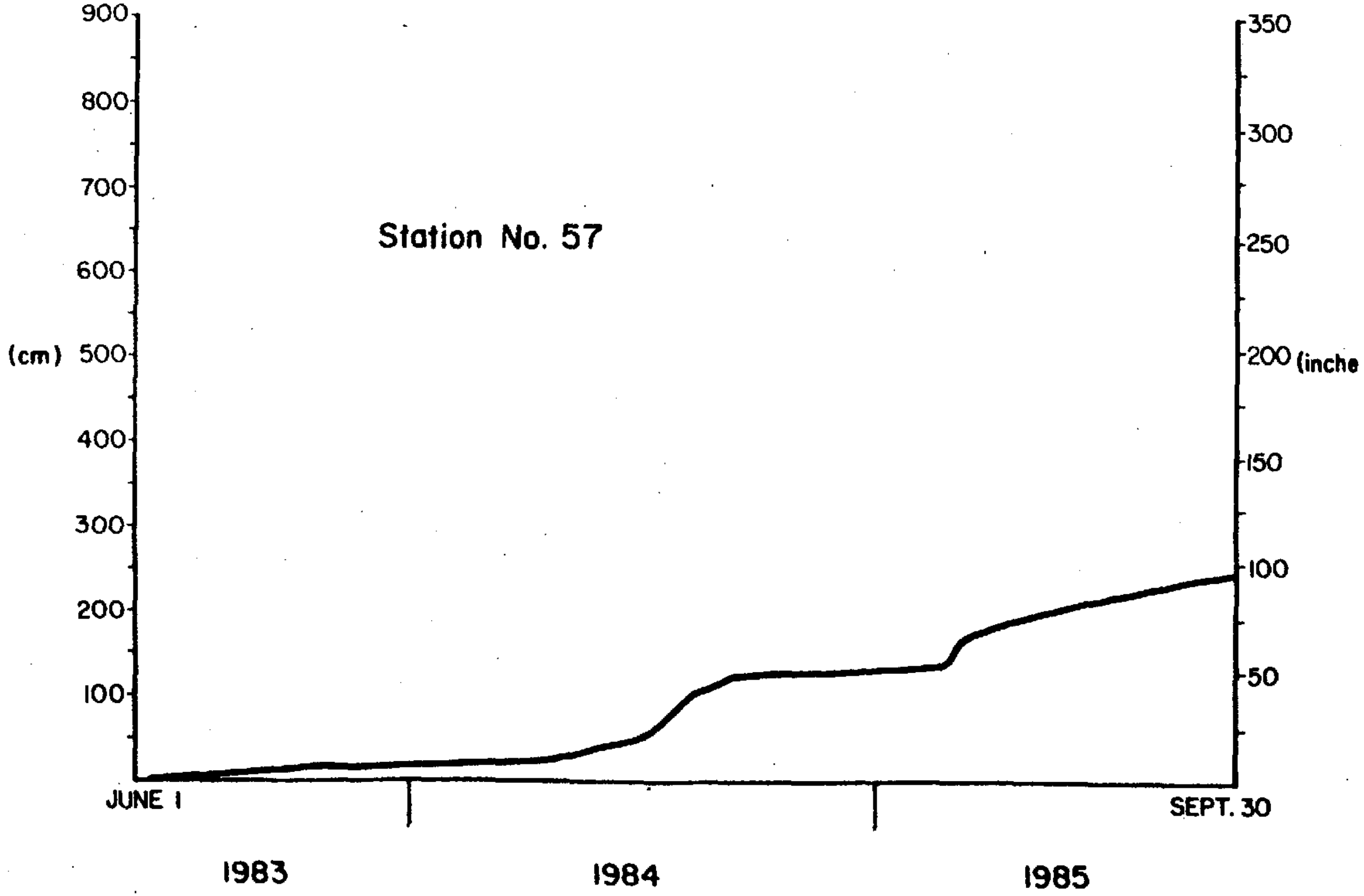


Figure 48 - Cumulative bank recession, Station 57.

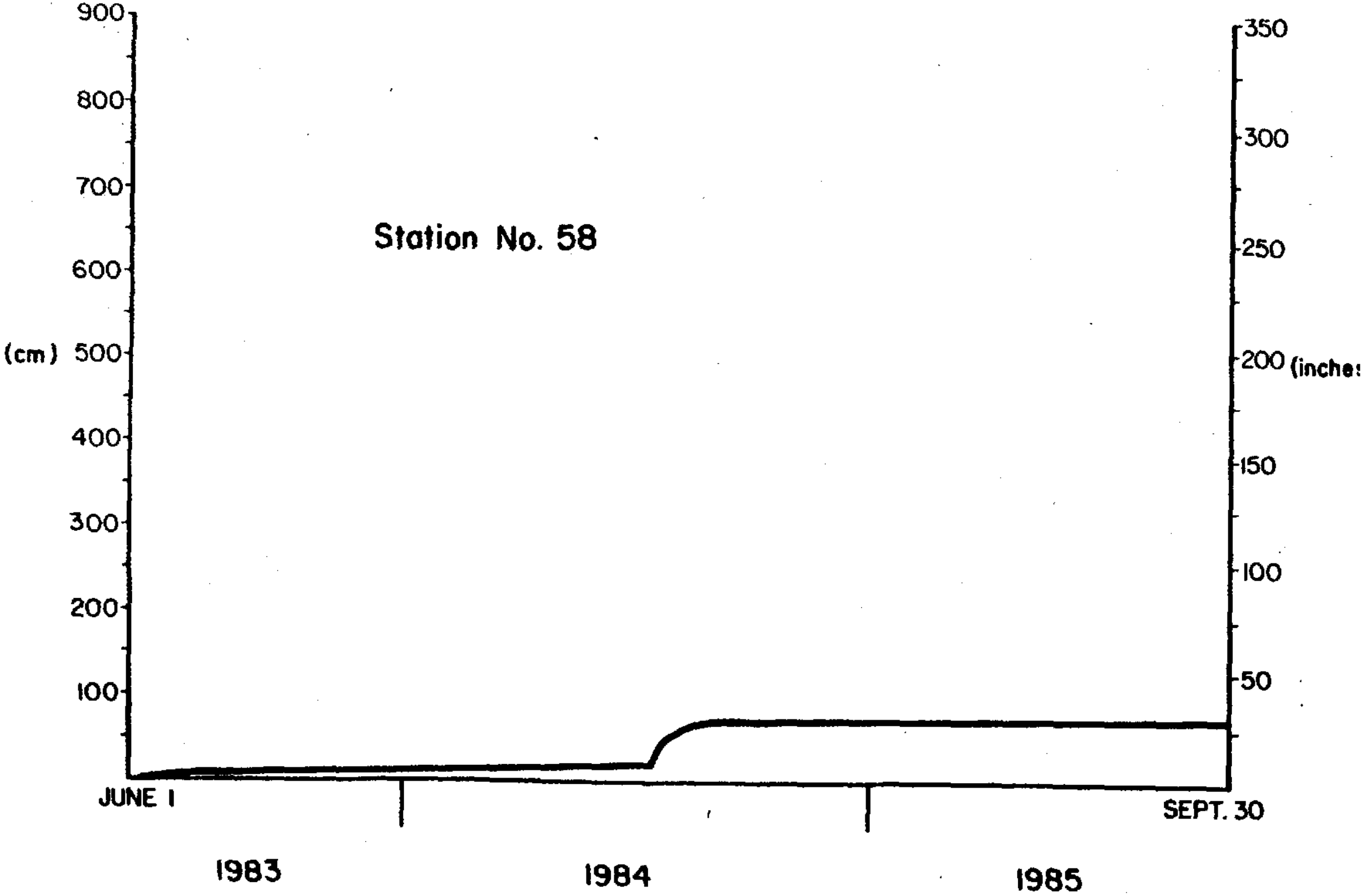


Figure 49 - Cumulative bank recession, Station 58.

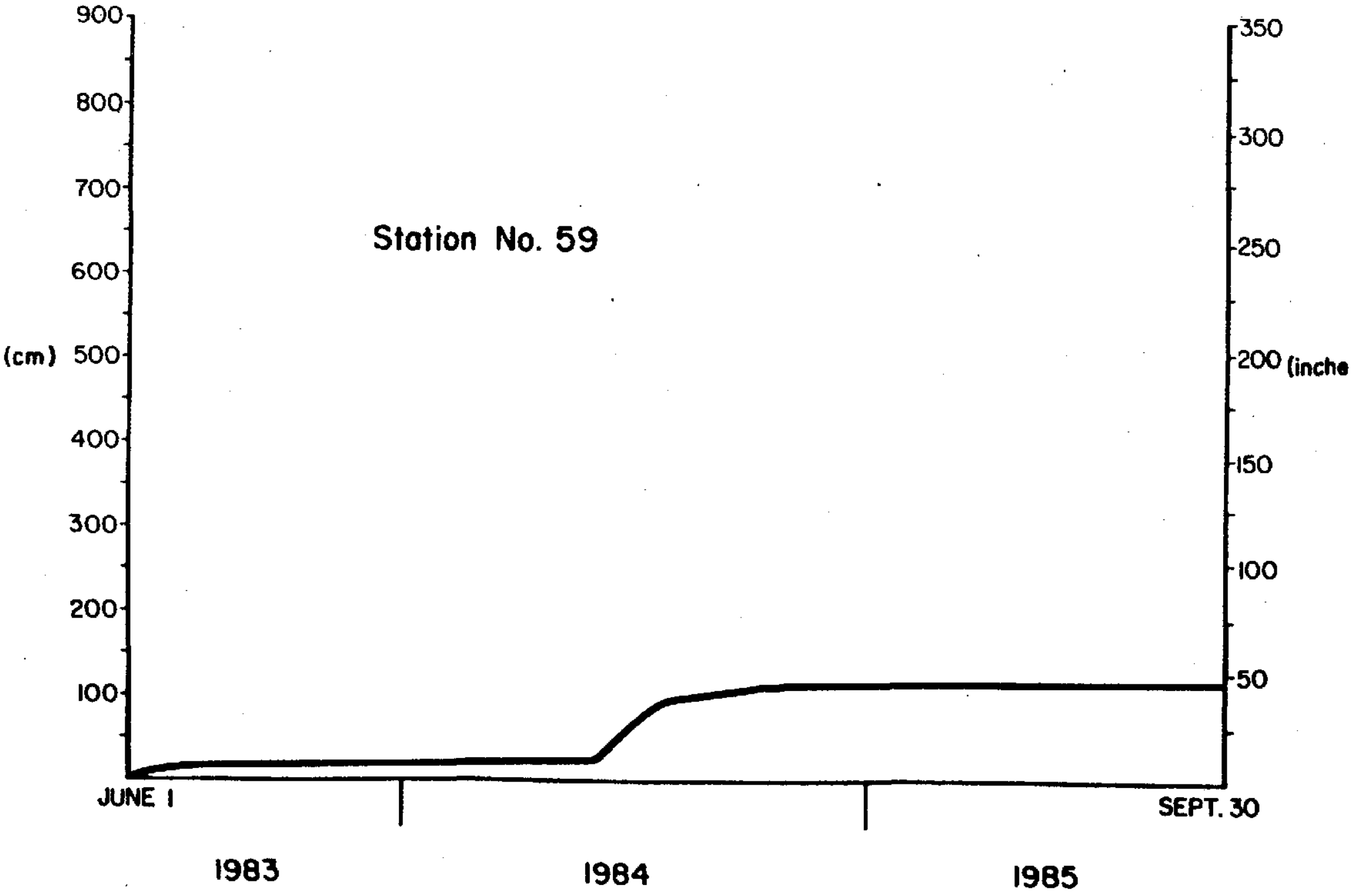


Figure 50 - Cumulative bank recession, Station 59.

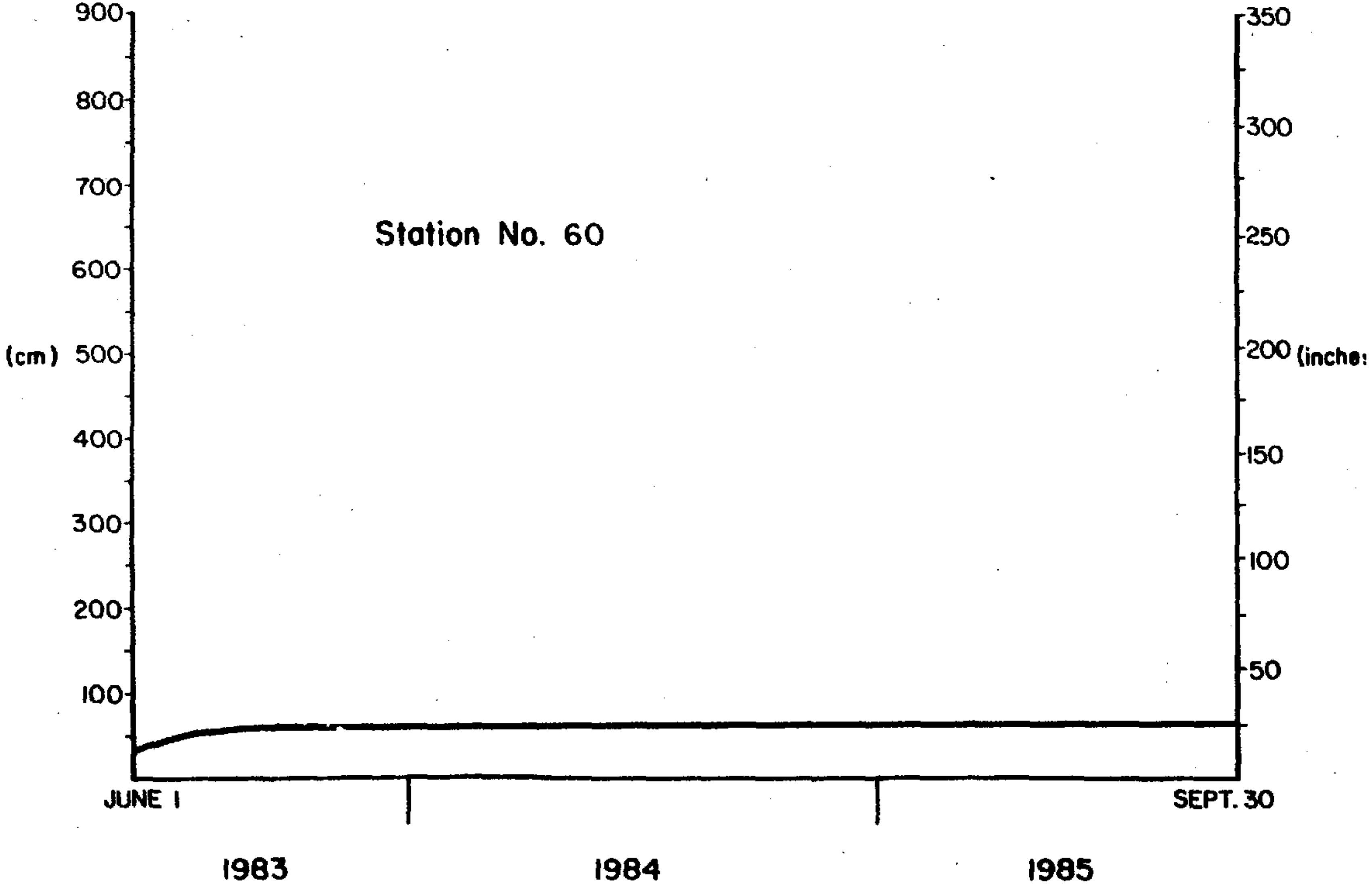


Figure 51 - Cumulative bank recesssion, Station 60.

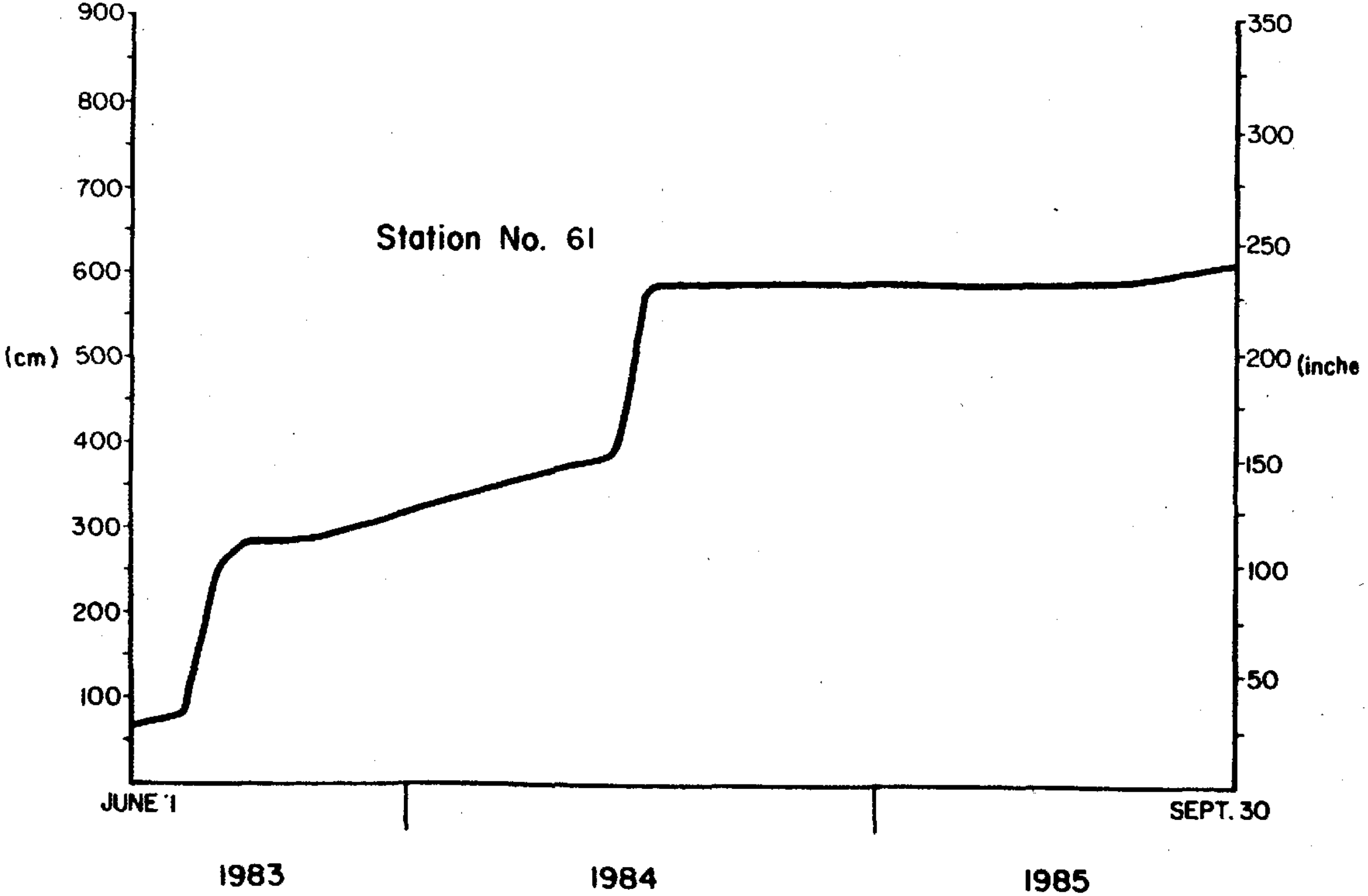


Figure 52 - Cumulative bank recession, Station 61.

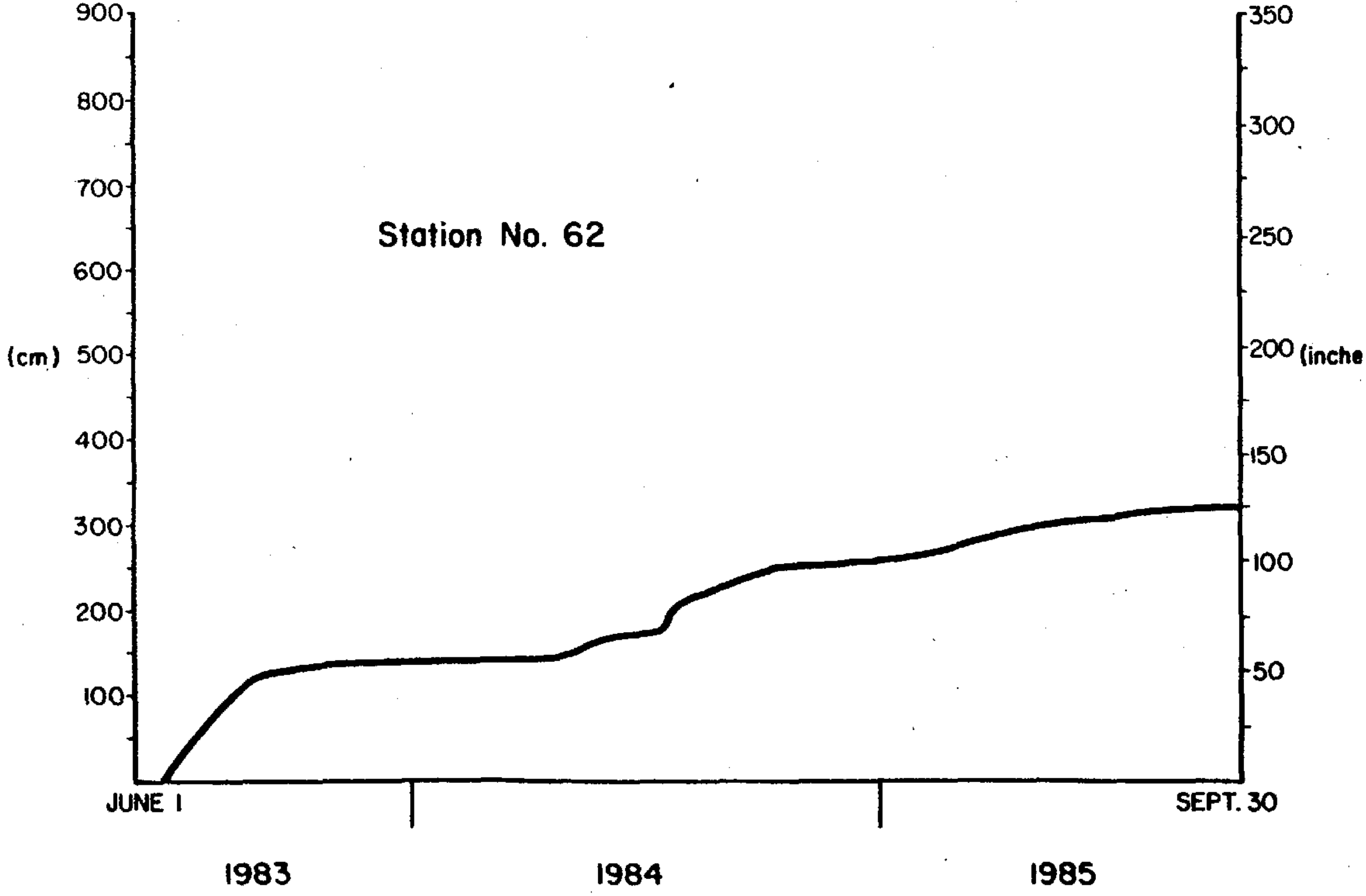


Figure 53 - Cumulative bank recession, Station 62.

APPENDIX C

BANK PROFILES OF LAKE SAKAKAWEA STATIONS
(from Reid and others, 1986)

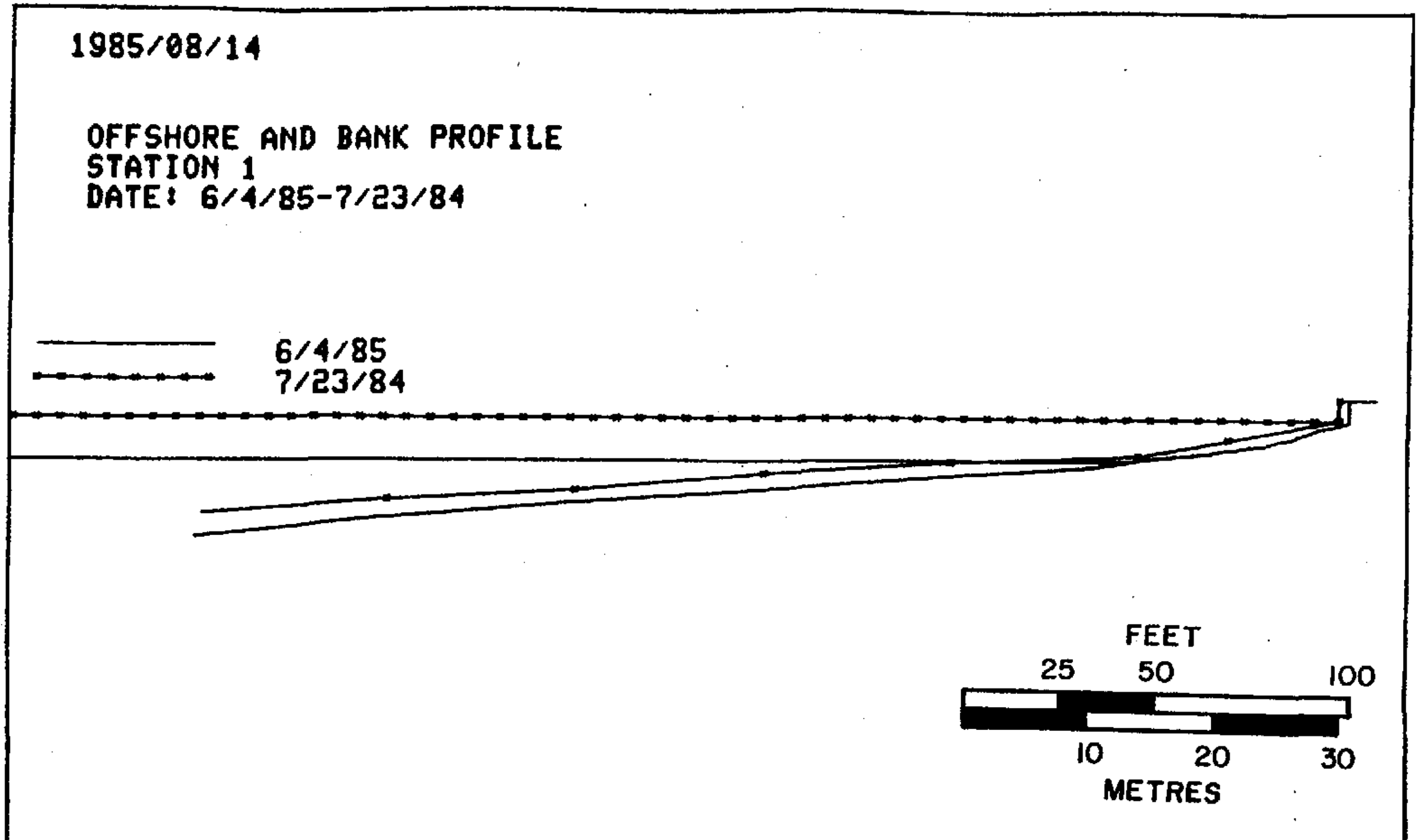


Figure 54 - Offshore and bank profile, Station 1.

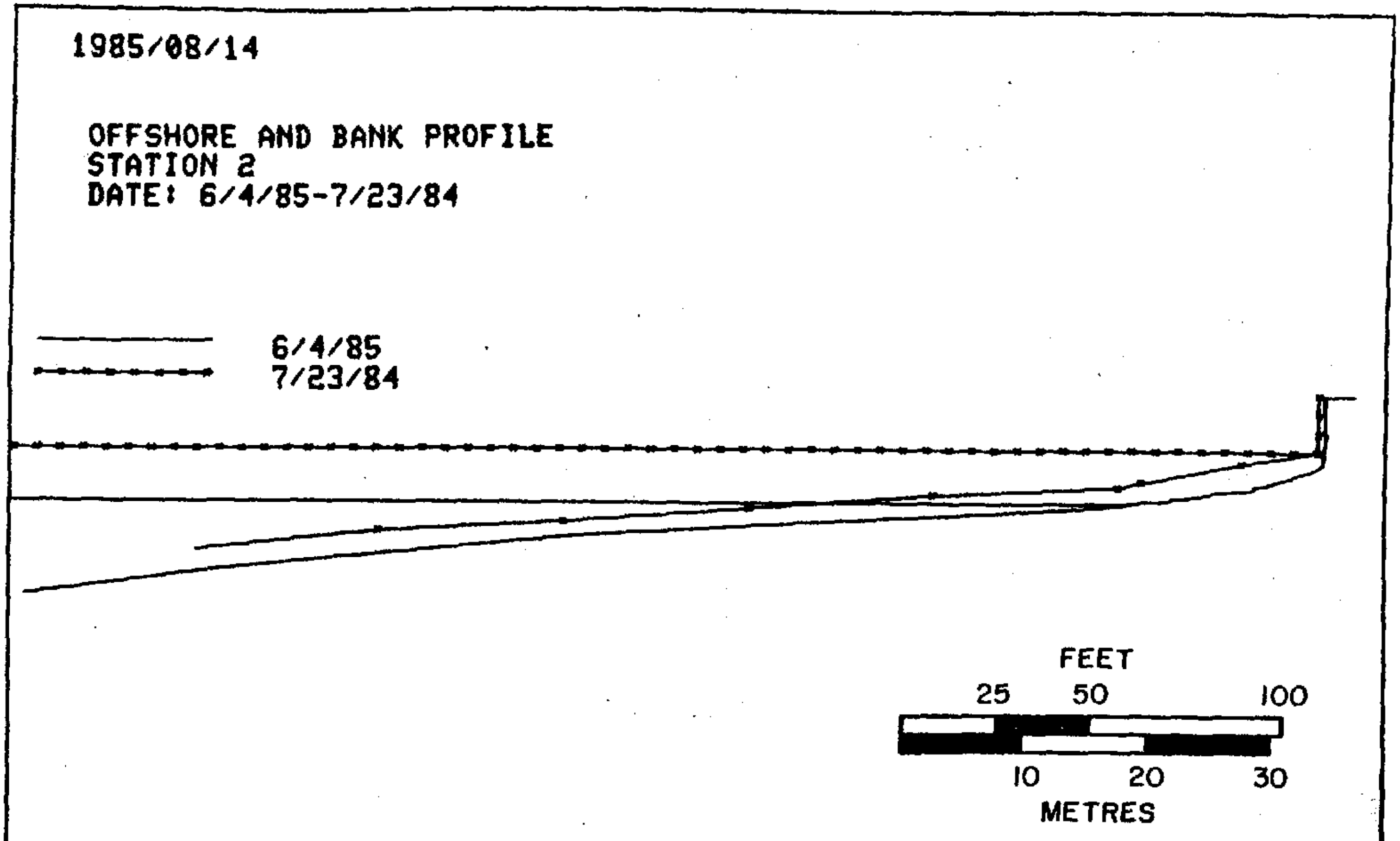


Figure 55 - Offshore and bank profile, Station 2.

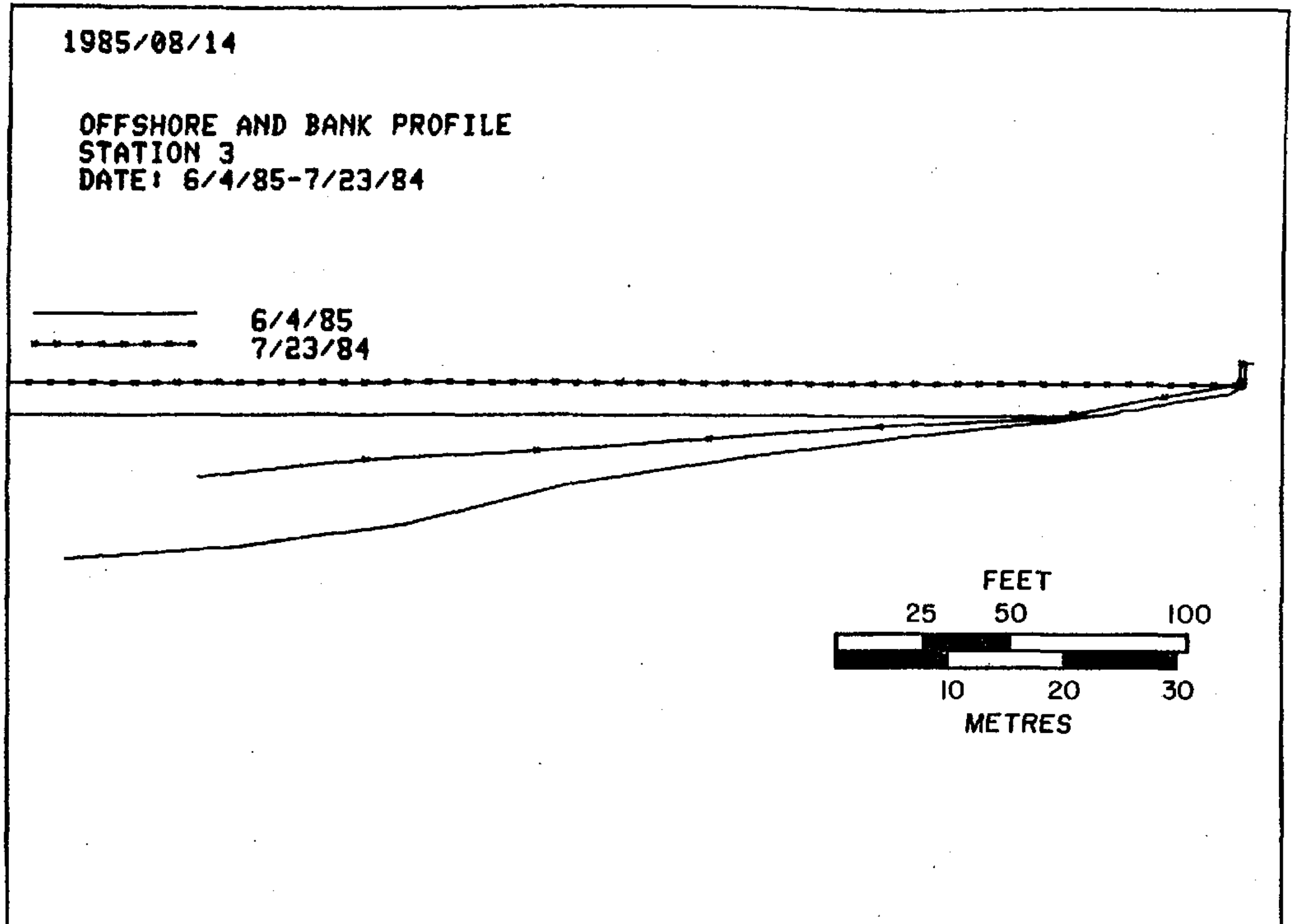


Figure 56 - Offshore and bank profile, Station 3.

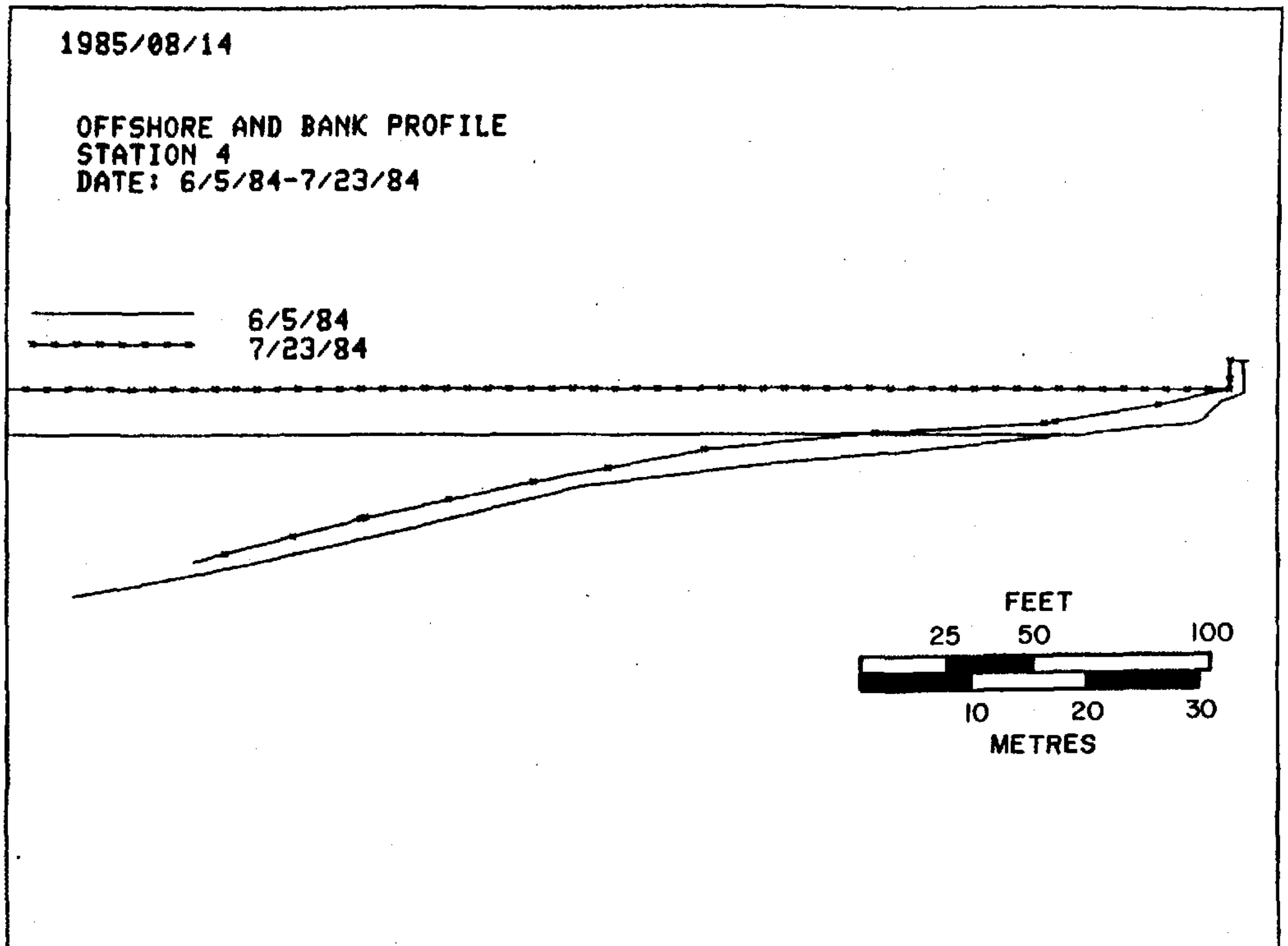


Figure 57 - Offshore and bank profile, Station 4.

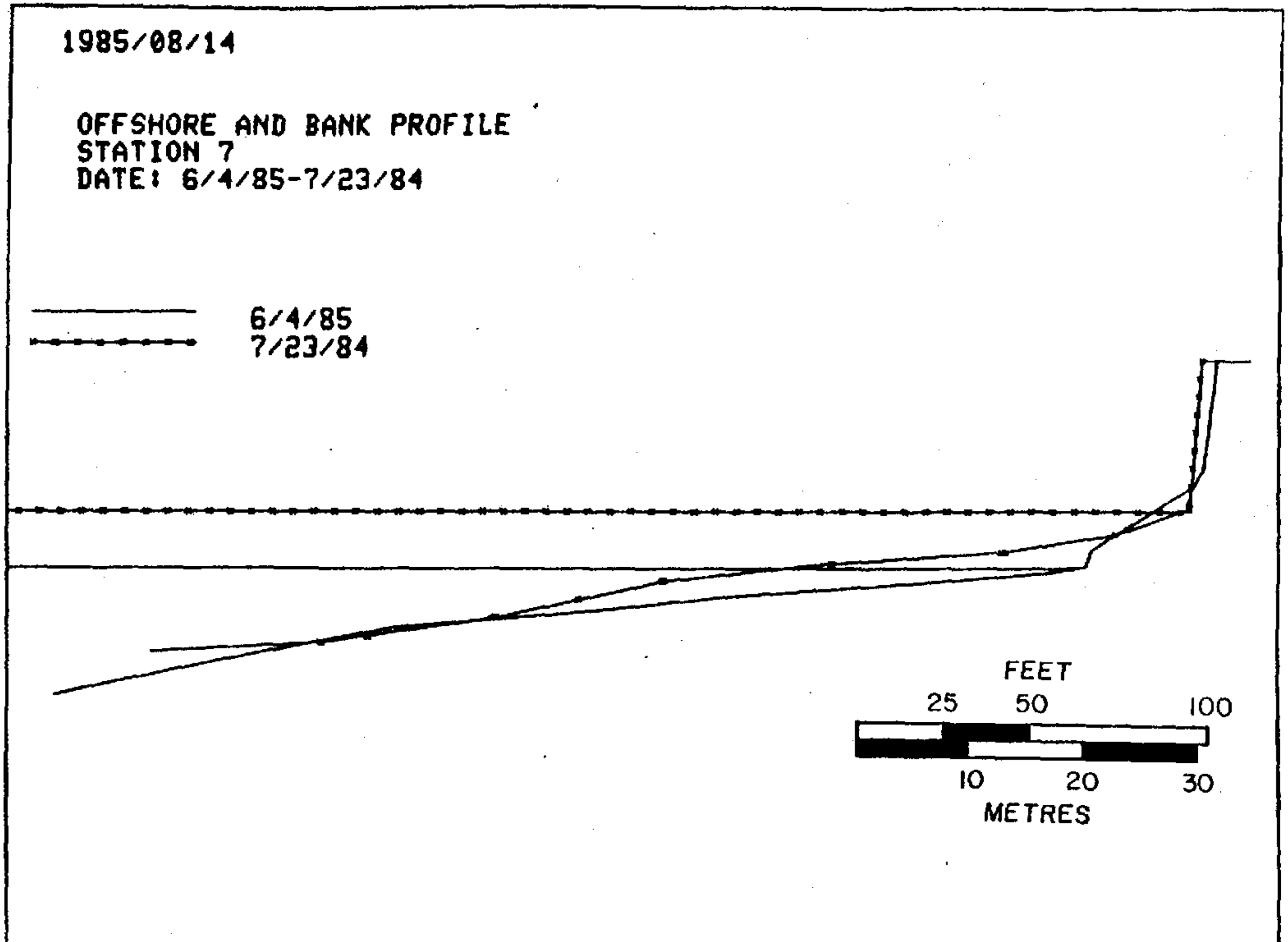


Figure 58 - Offshore and bank profile, Station 7.

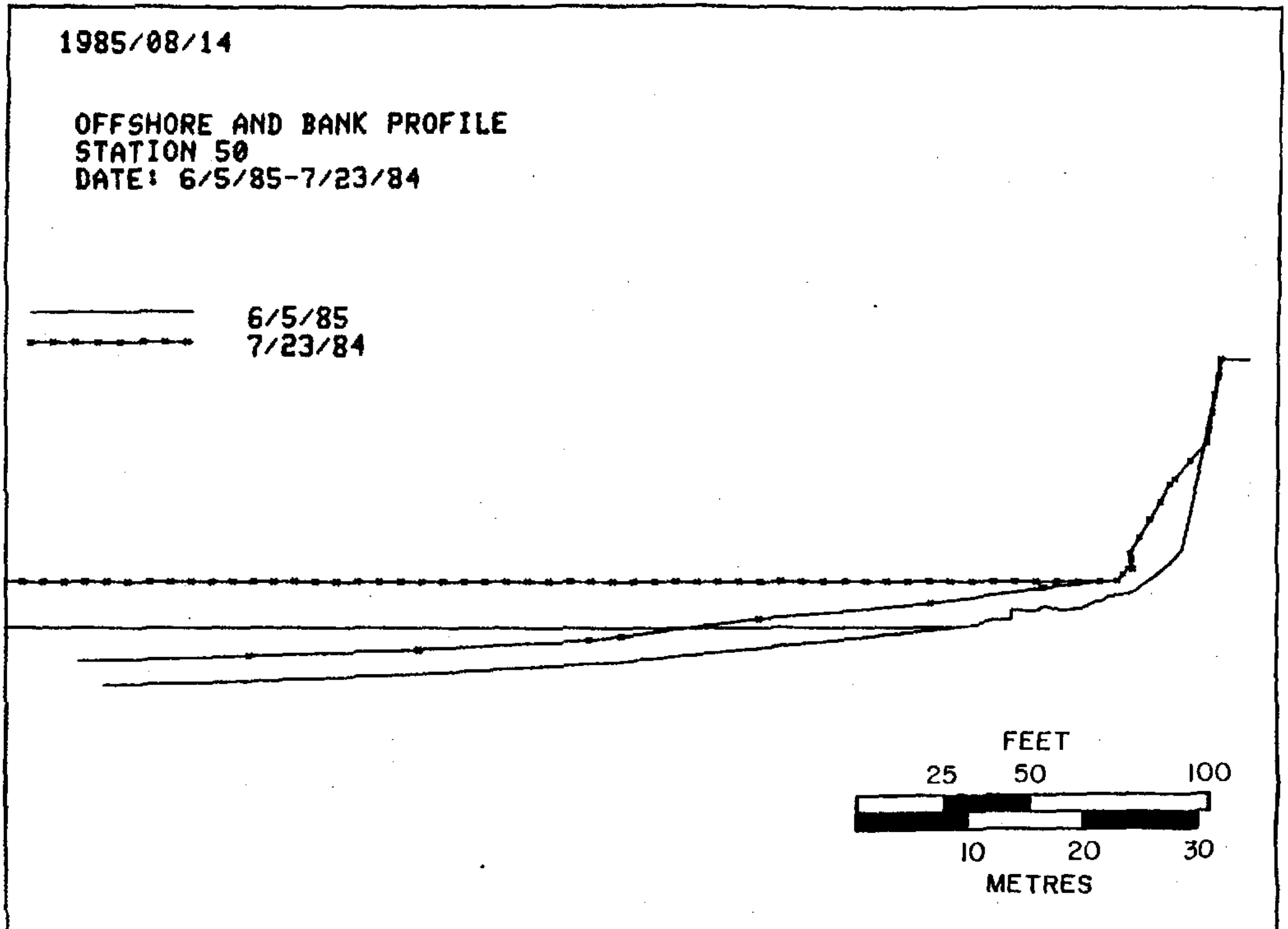


Figure 59 - Offshore and bank profile, Station 50.

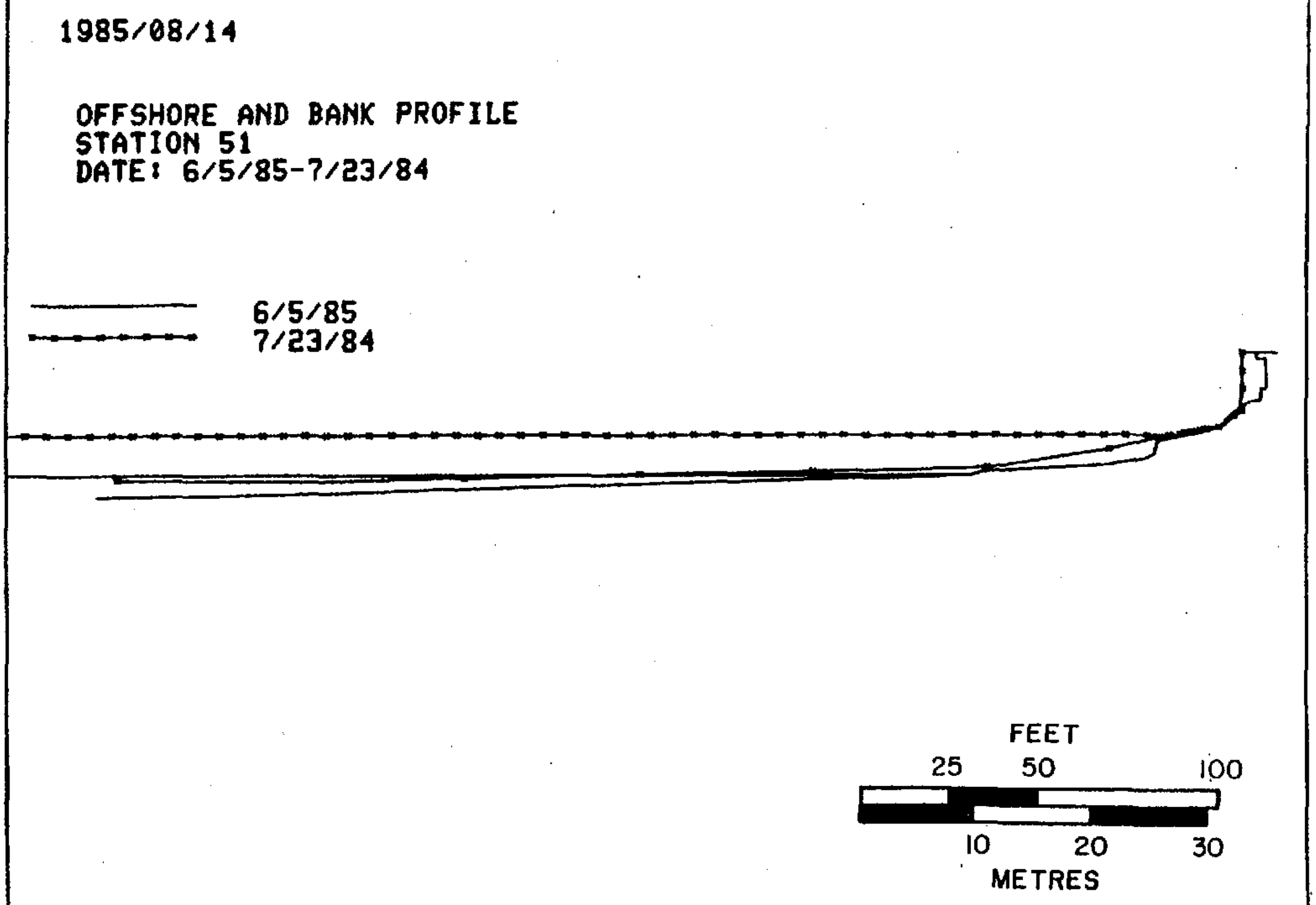


Figure 60 - Offshore and bank profile, Station 51.

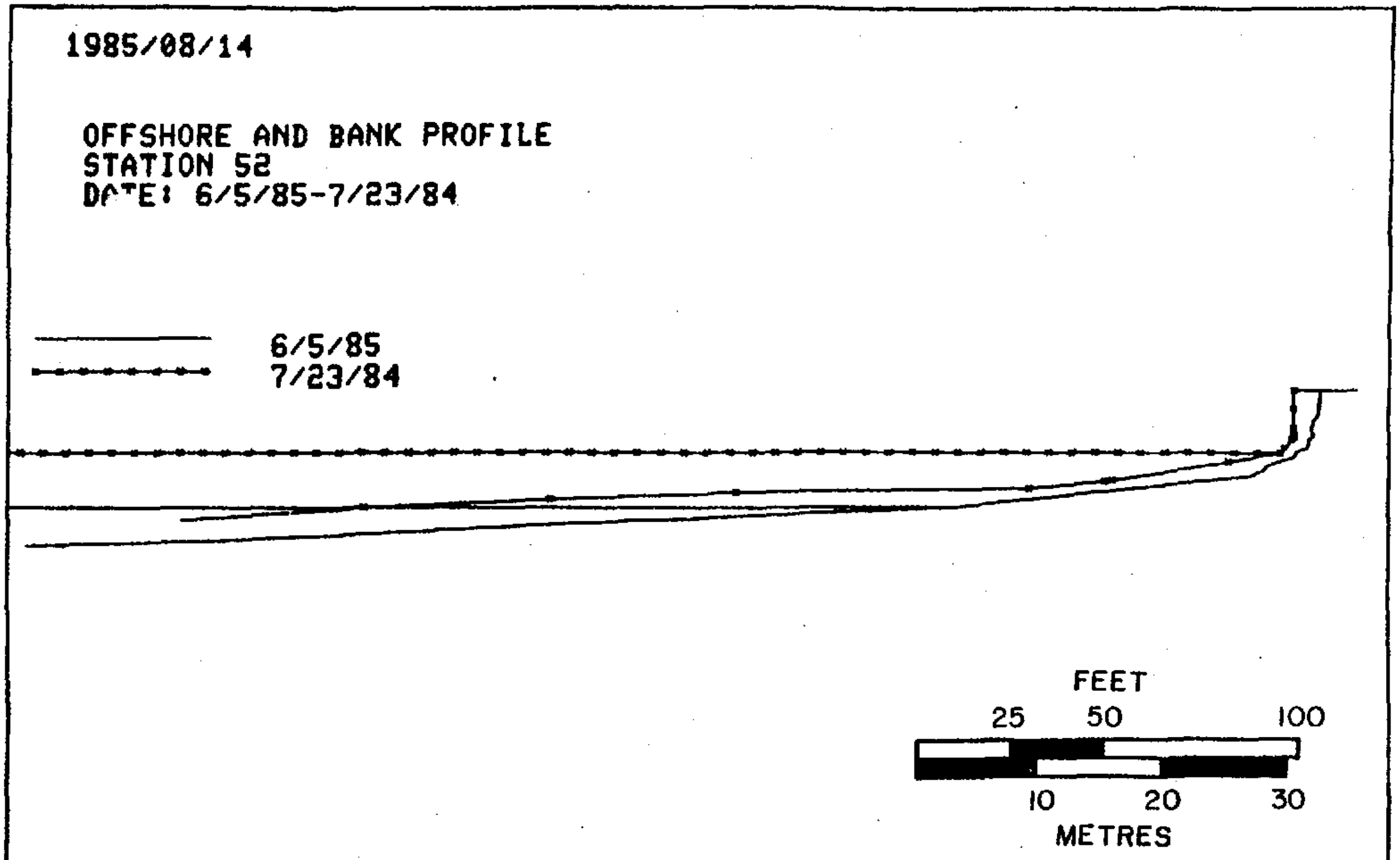


Figure 61 - Offshore and bank profile, Station 52.

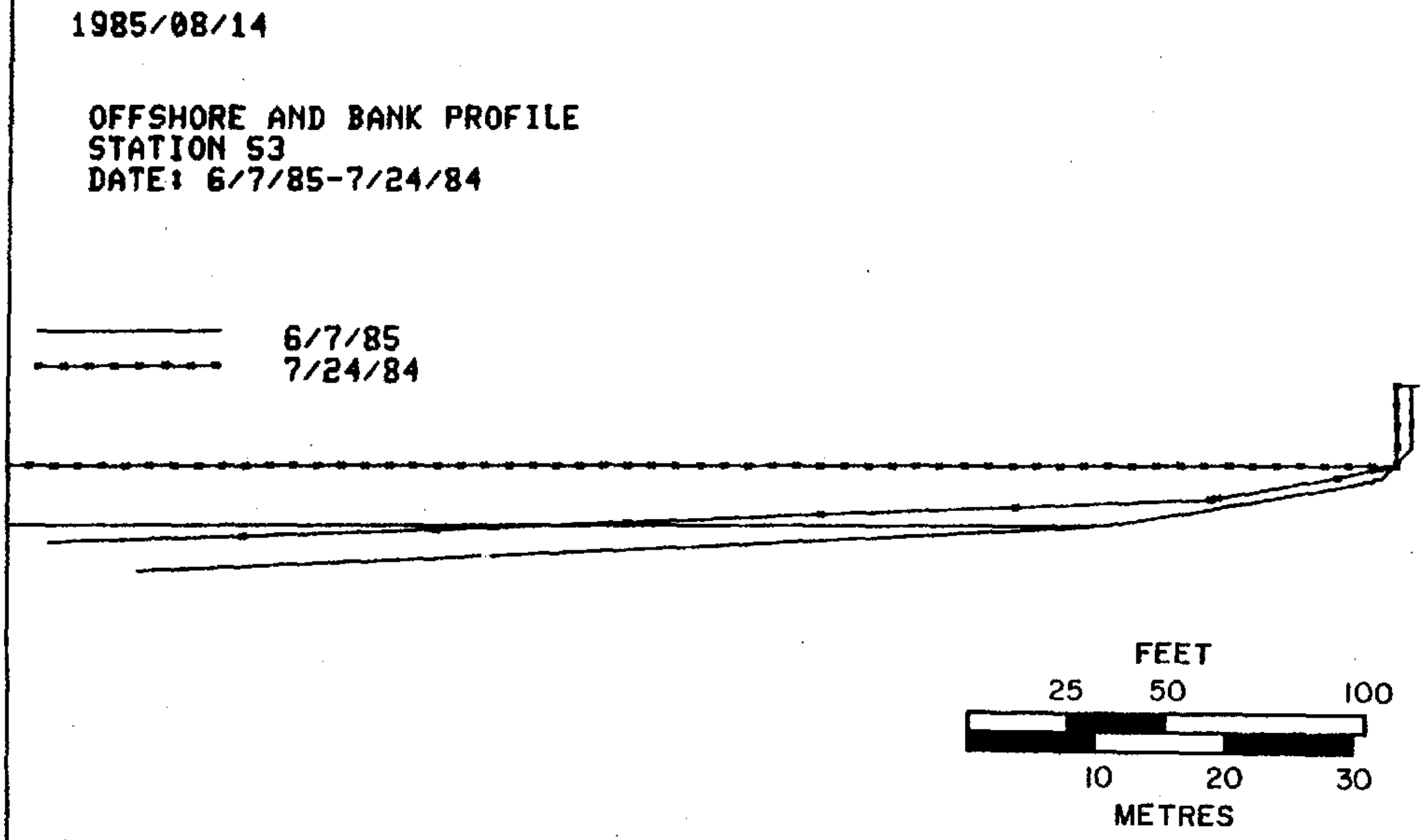


Figure 62 - Offshore and bank profile, Station 53.

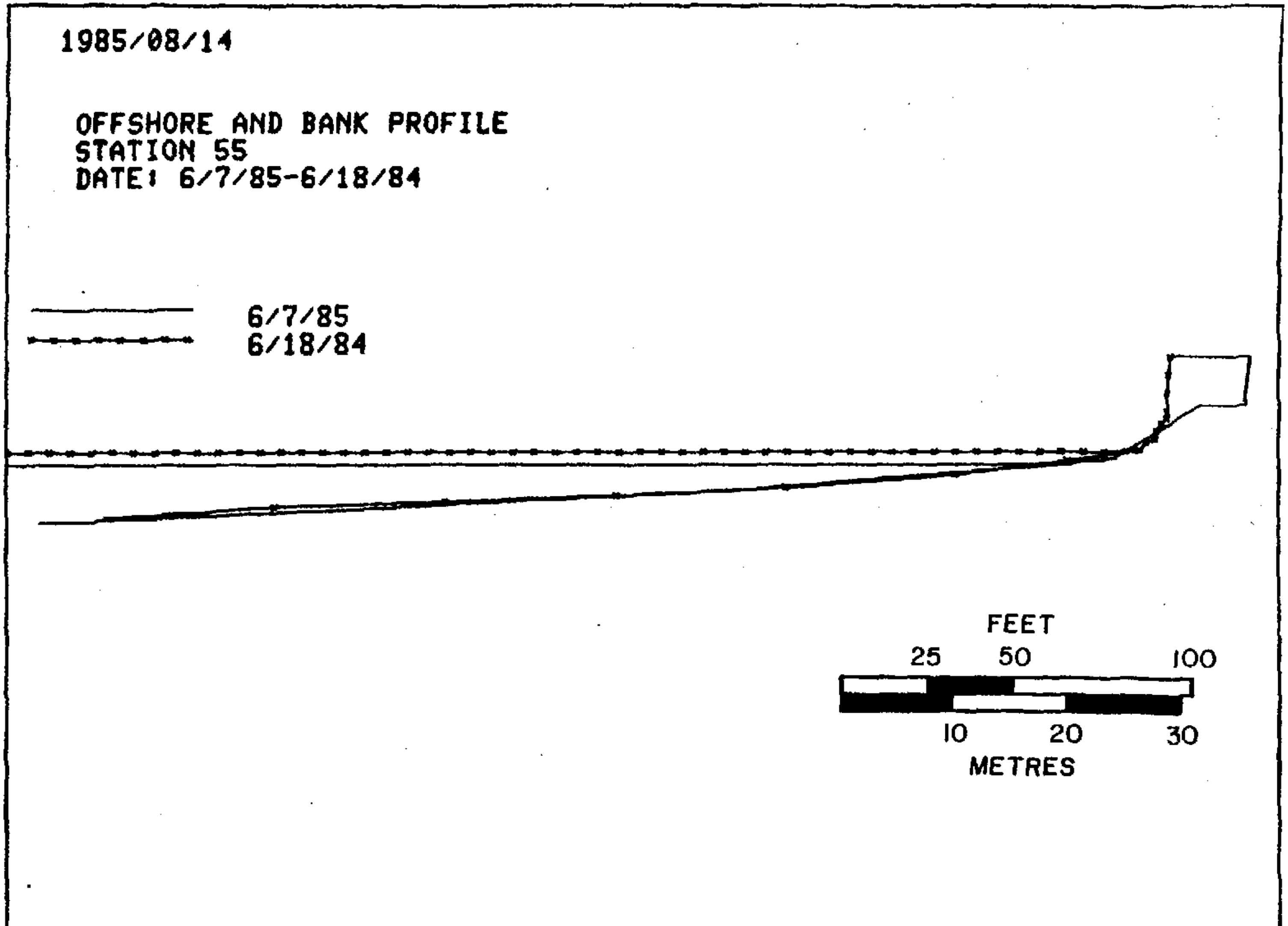


Figure 63 - Offshore and bank profile, Station 55.

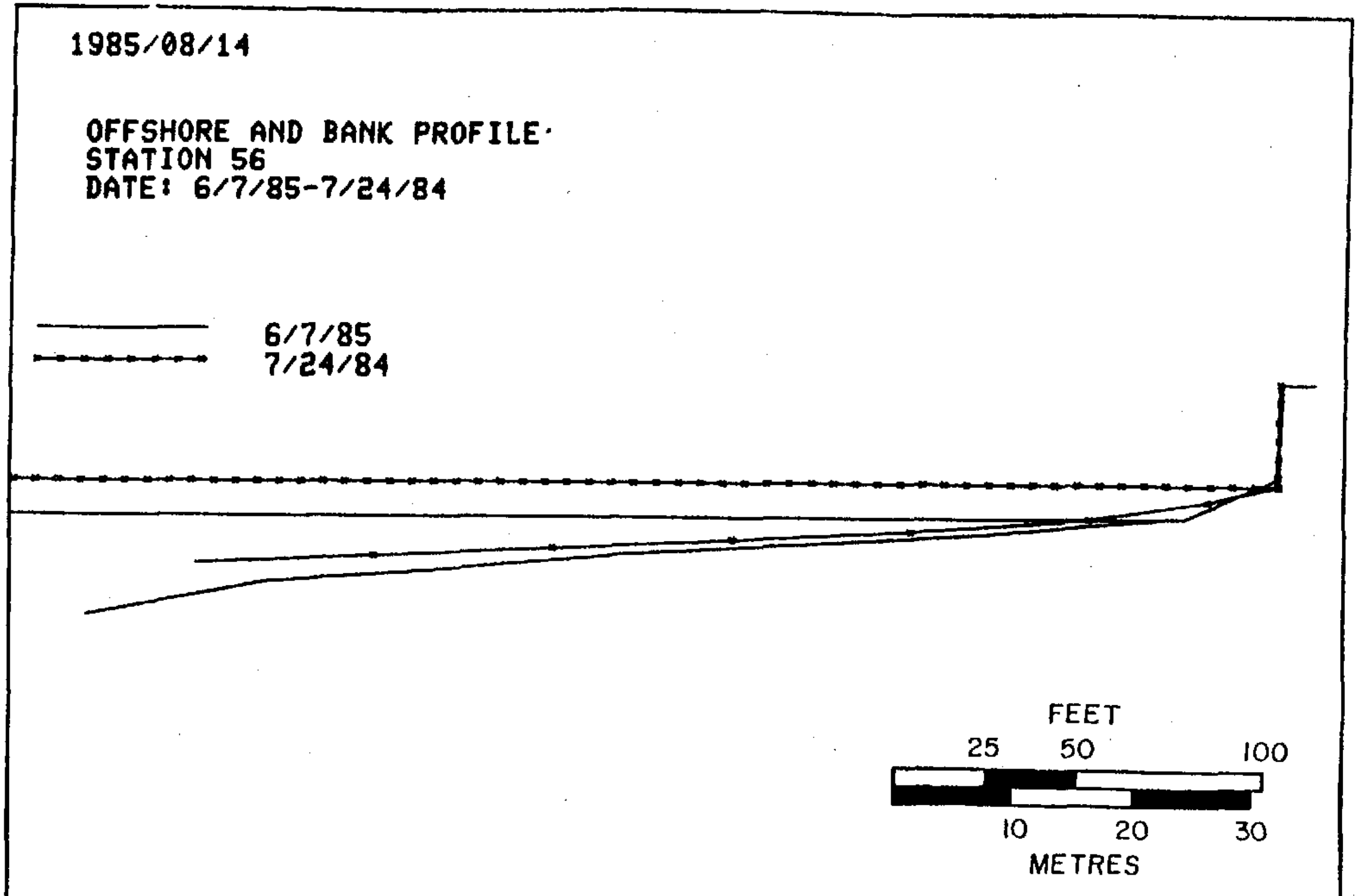


Figure 64 - Offshore and bank profile, Station 56.

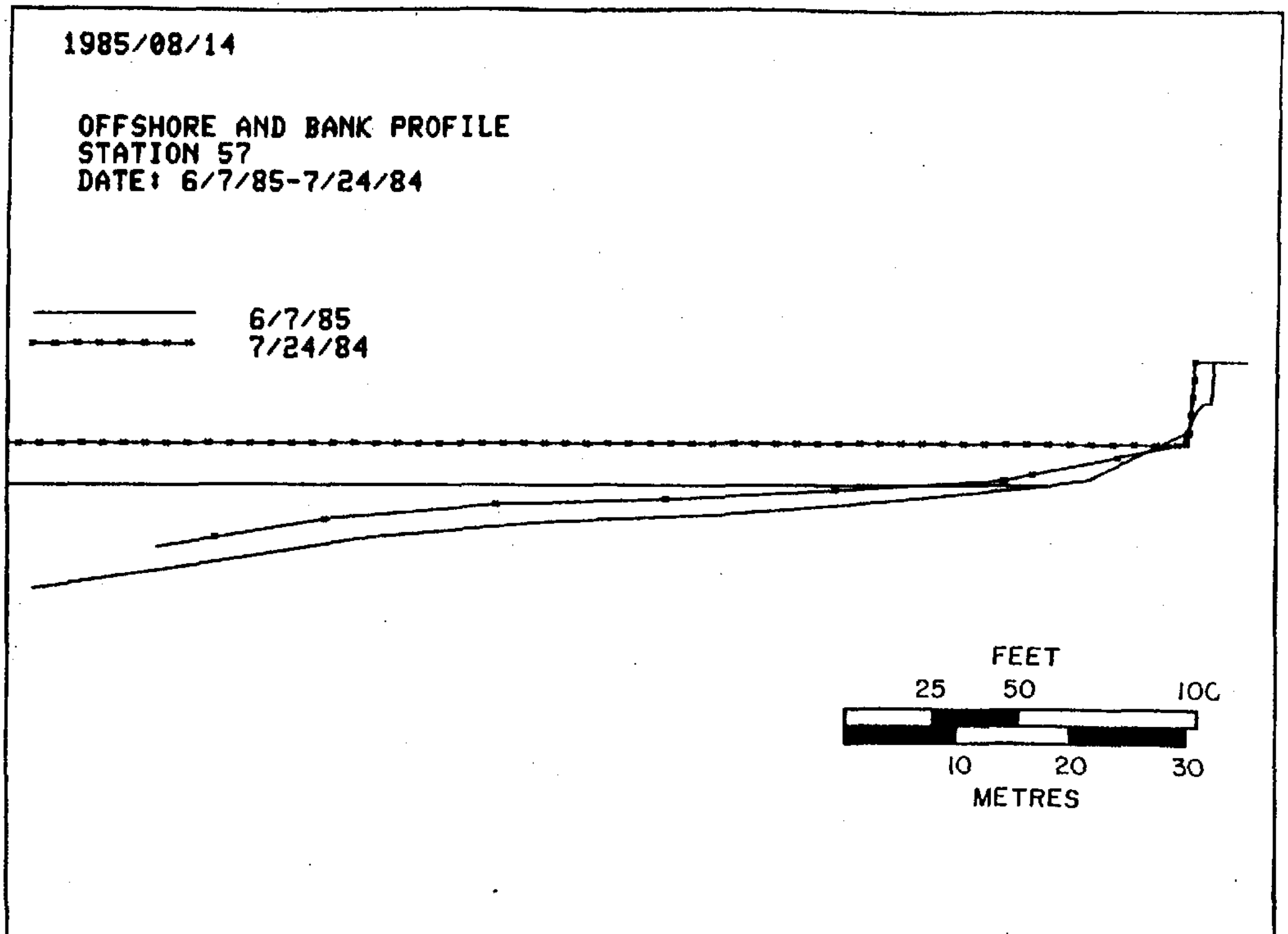


Figure 65 - Offshore and bank profile, Station 57.

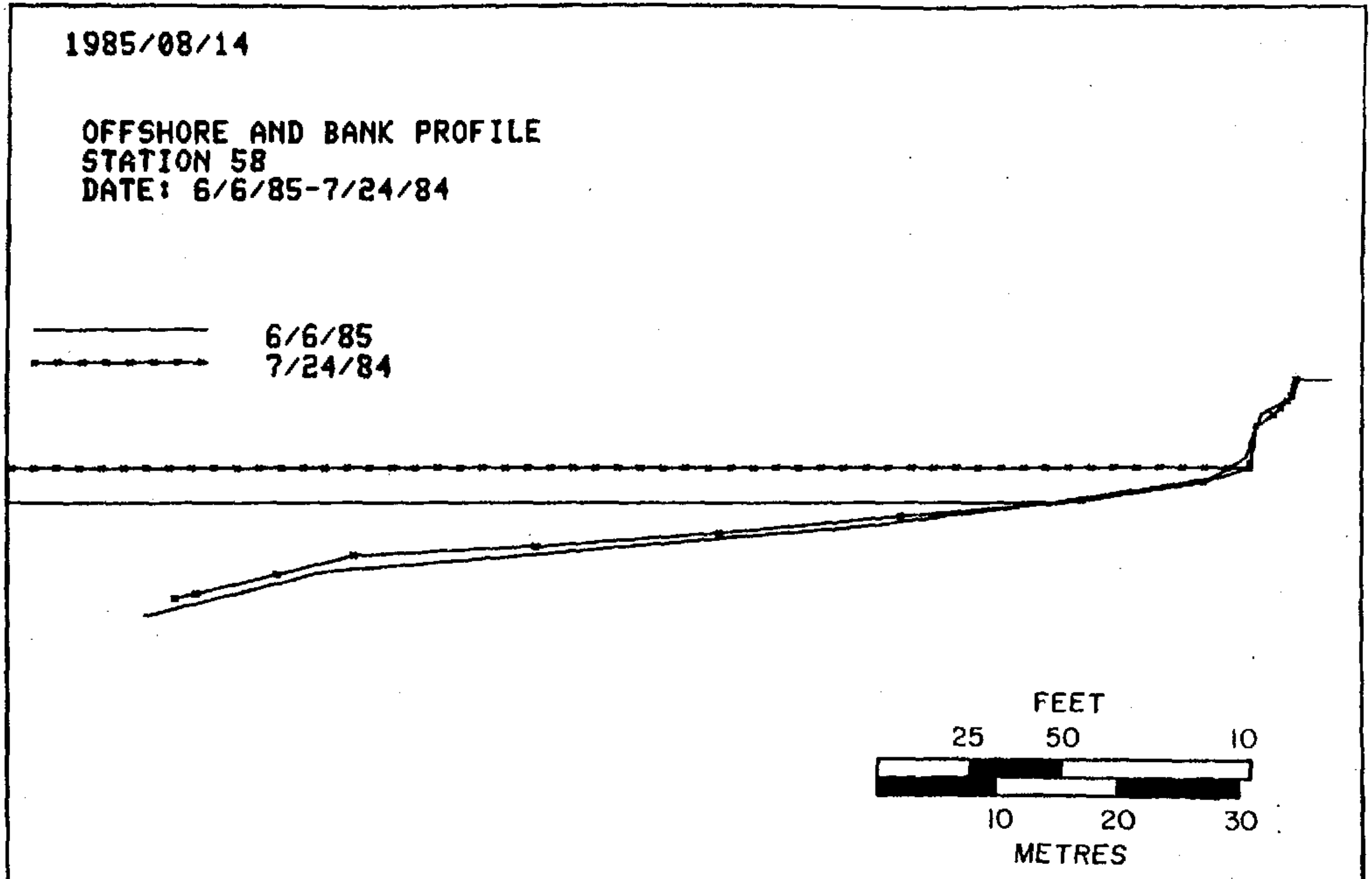


Figure 66 - Offshore and bank profile, Station 58.

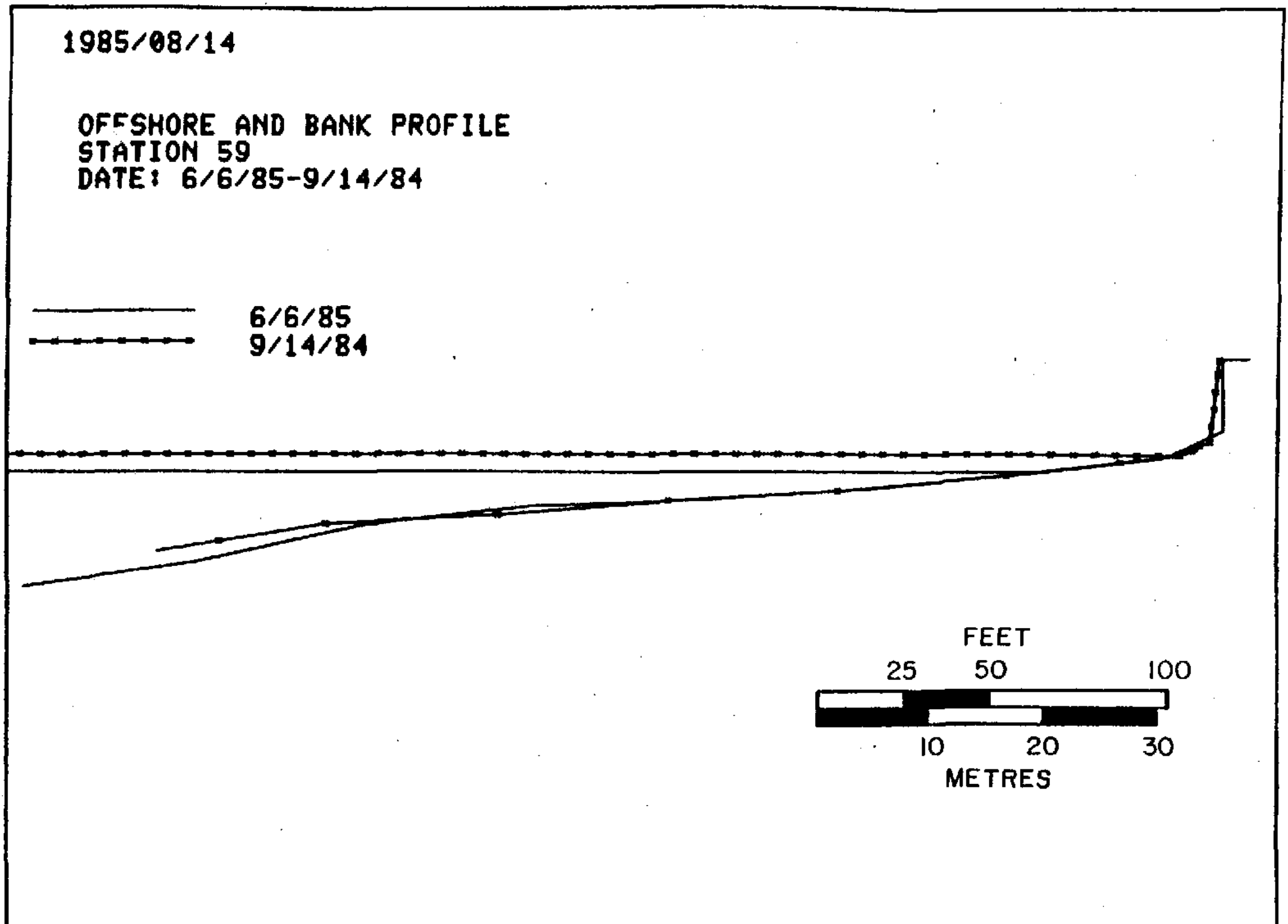


Figure 67 - Offshore and bank profile, Station 59.

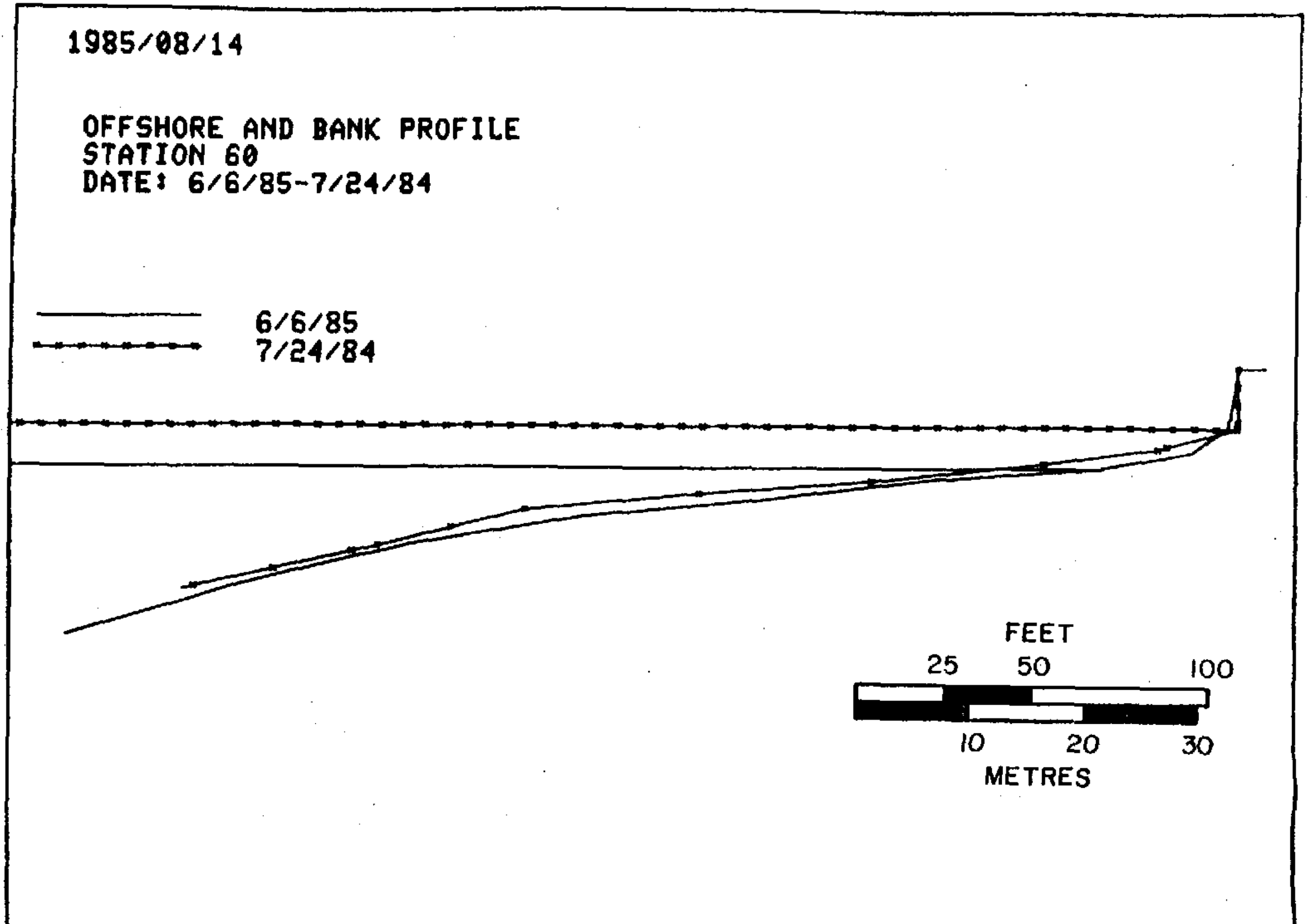


Figure 68 - Offshore and bank profile, Station 60.

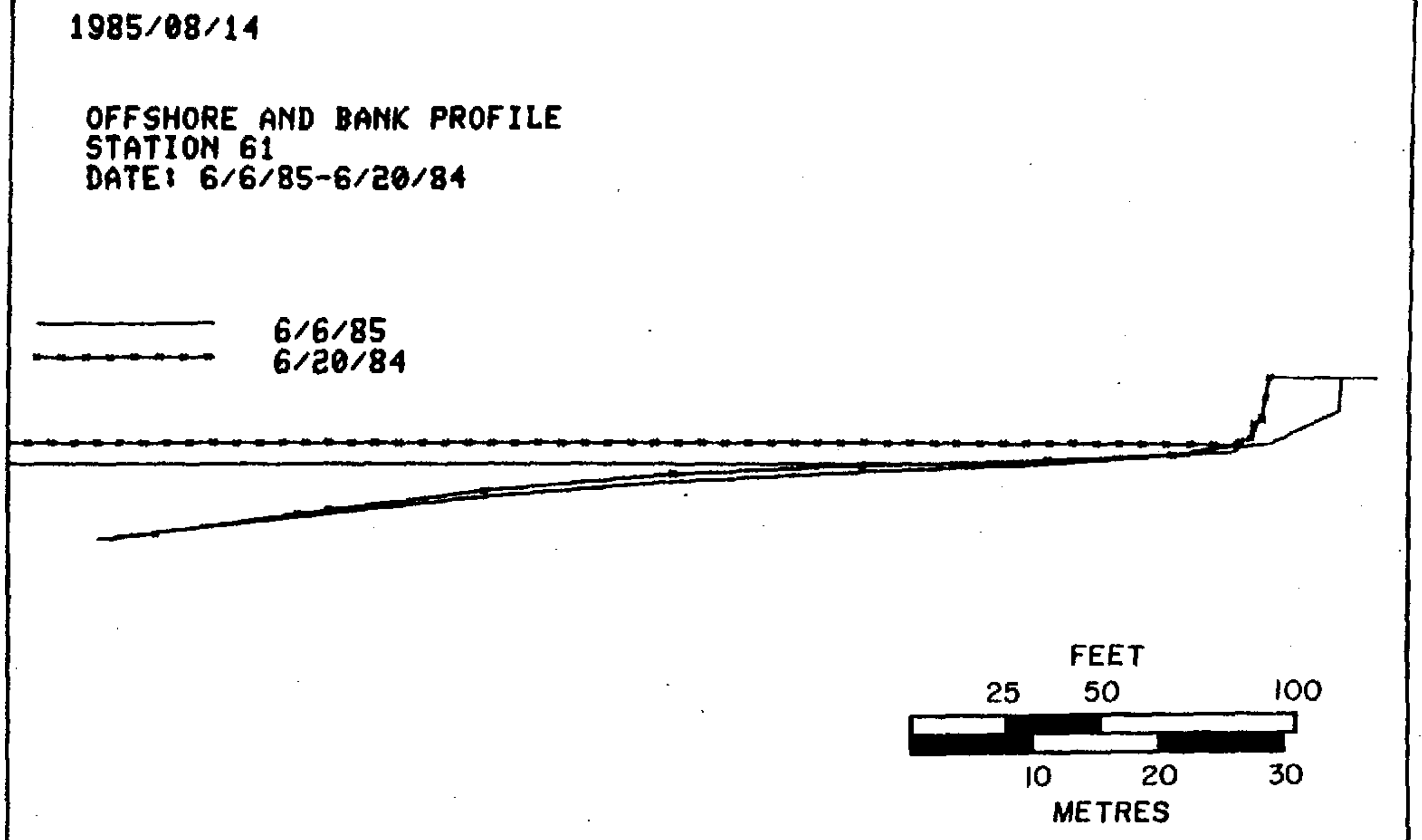


Figure 69 - Offshore and bank profile, Station 61.

APPENDIX D

BEACH CLAST PERCENTAGE AT LAKE SAKAKAWEA EROSION STATIONS
(from Reid and others, 1986)

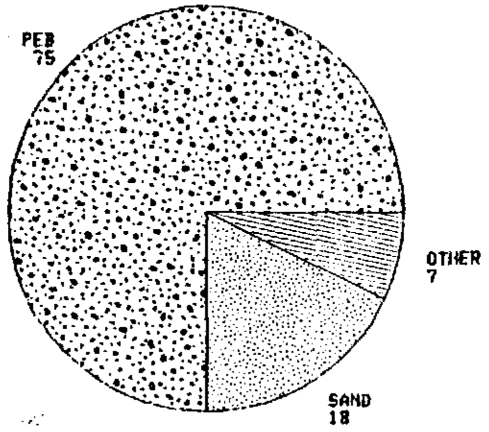


Figure 71 - Beach clast percentage, Station 1.

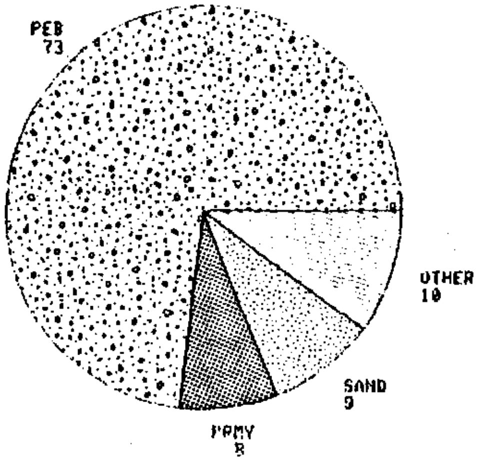


Figure 72 - Beach clast percentage, Station 2.

☐ Silt &/or clay
▨ Sand
▨ Pebble
▨ Cobble
▨ Boulder
■ Primary
▨ Other

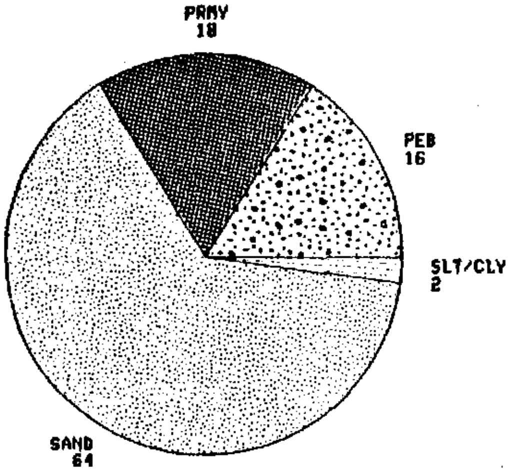


Figure 73 - Beach clast percentage, Station 3.

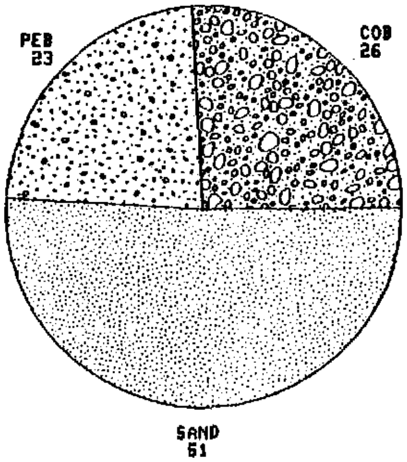


Figure 74 - Beach clast percentage, Station 4.

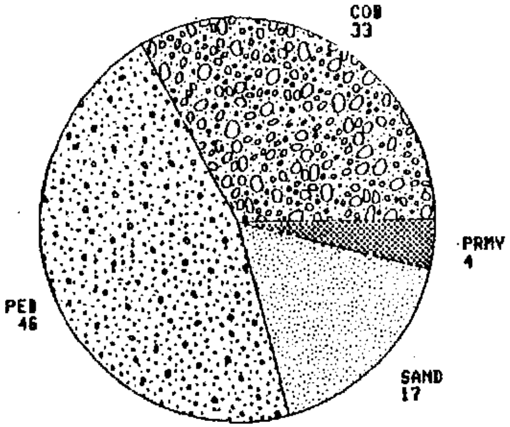


Figure 75 - Beach clast percentage, Station 5.

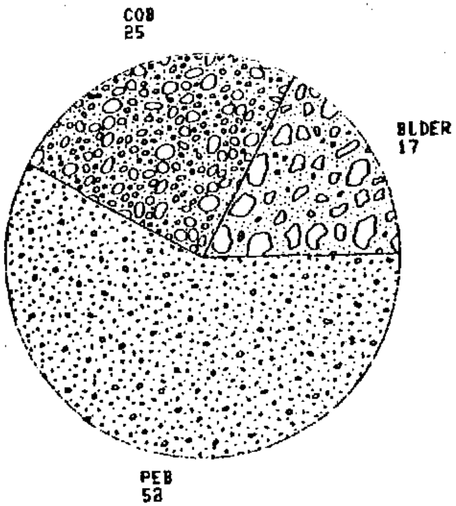


Figure 76 - Beach clast percentage, Station 6.

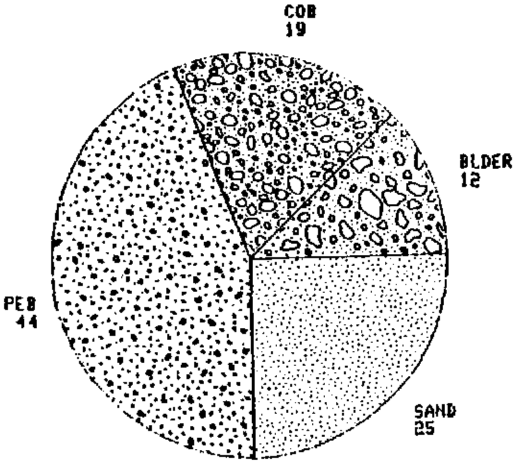


Figure 77 - Beach clast percentage, Station 7.

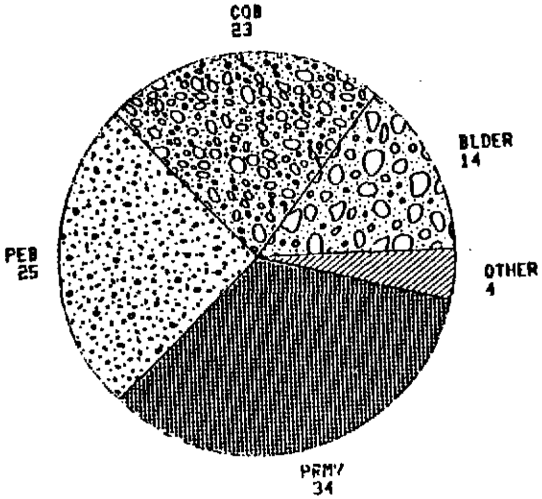


Figure 78 - Beach clast percentage, Station 50.

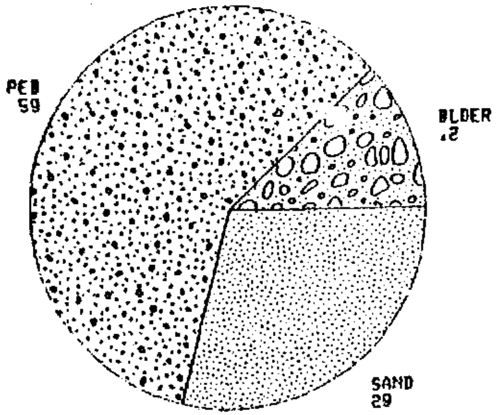


Figure 79 - Beach clast erpcentage, Station 53.

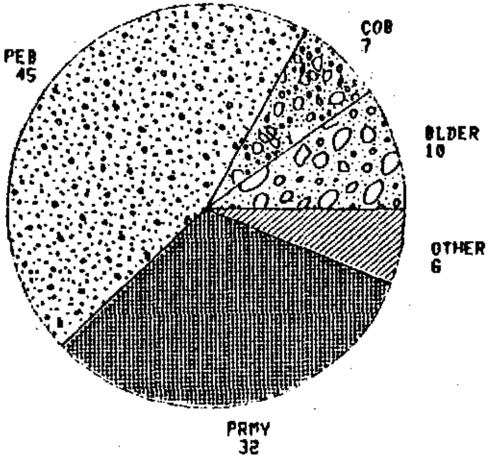


Figure 80 - Beach clast percentage, Station 54.

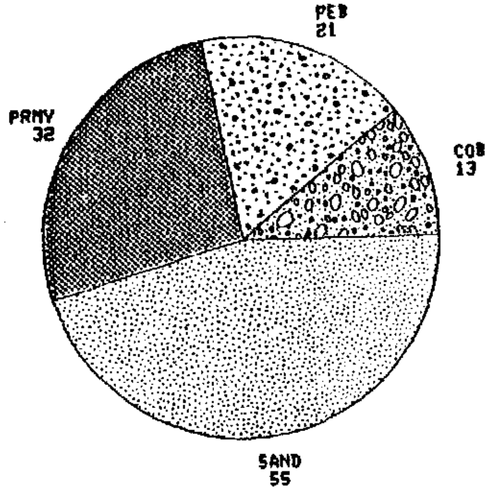


Figure 81 - Beach clast percentage, Station 55.

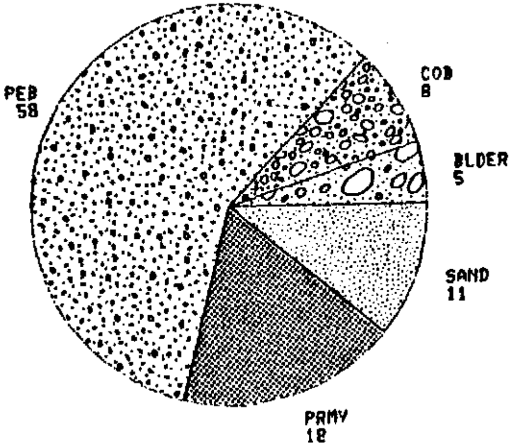


Figure 82 - Beach clast percentage, Station 56.

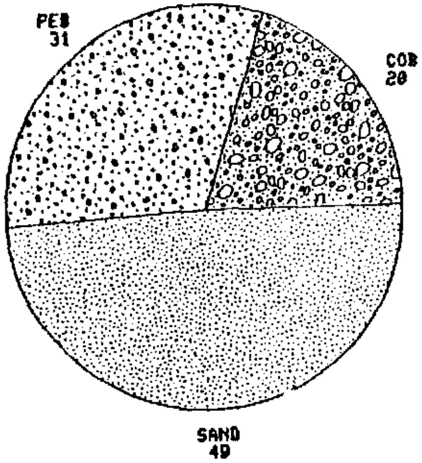


Figure 83 - Beach clast percentage, Station 57.

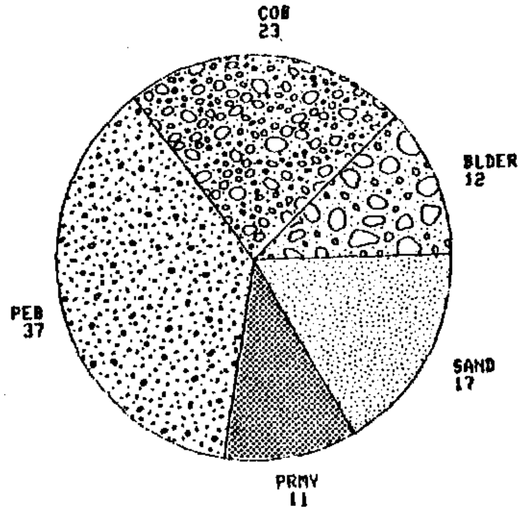


Figure 84 - Beach clast percentage, Station 58.

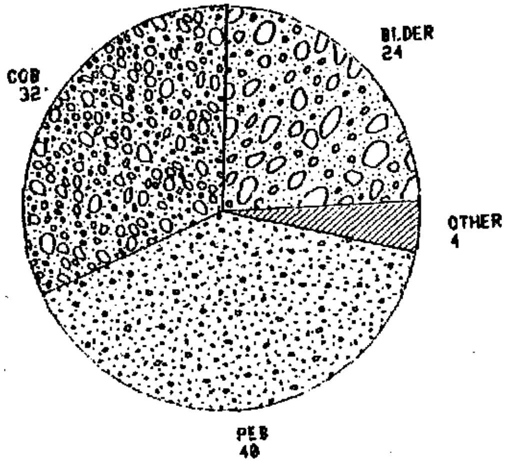


Figure 85 - Beach clast percentage, Station 59.

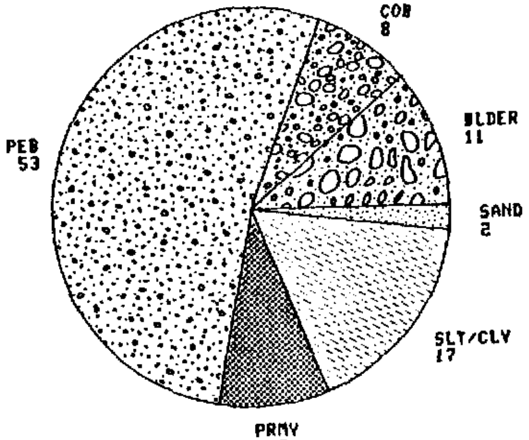


Figure 86 - Beach clast percentage, Station 60.

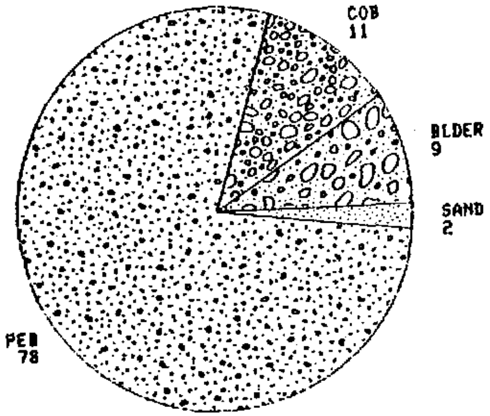


Figure 87 - Beach clast percentage, Station 61.

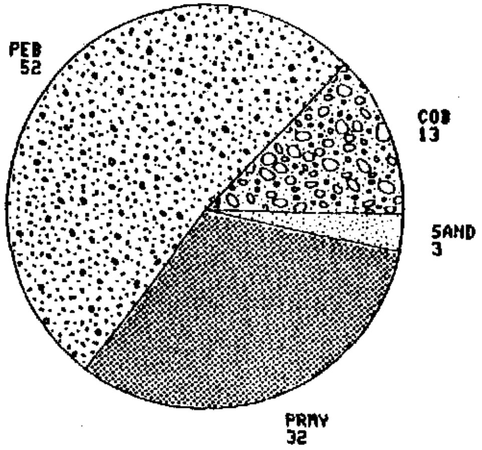


Figure 88 - Beach clast percentage, Station 62.

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