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Shoreline erosion processes
Orwell Lake, Minnesota

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Shoreline erosion processes
Orwell Lake, Minnesota

John R. Reid

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Orwell Lake, in west-central Minnesota, is a flood-control, water-management reservoir first impounded in 1953. Subsequent erosion of the shoreline and a lack of knowledge of slope erosion processes in this region prompted this study to identify and quantify the processes there. The processes were measured at selected sites between June 1980 and June 1983. Erosion of the banks is primarily caused by three processes: rain, frost thaw, and waves. The first two processes tend to move sediment to the base of the steep slopes, forming a relatively gentle surface of accumulation. Wave action then tends to move this sediment into the lake. Analysis of the data collected over three years has confirmed that wave action is the dominant erosion process, providing almost 77% of the erosion during the 1981-82 study year. During the 1981 high pool level, 2,089 Mg of sediment, mostly colluvium, was removed from the lower

20. Abstract (cont'd)

slopes by wave action striking the 1.62 km of eroding shoreline. More than 4,300 Mg was eroded by waves accompanying the higher pool levels of 1982. During years in which the pool level does not exceed 325.5 m in elevation, the colluvium slope builds up at the expense of the steeper slope. But during successive years with higher pool levels, the resulting thin colluvium is quickly eroded. Erosion of the primary sediment, a compact till, then occurs, forming the typical nearly vertical banks. In winter the upland surface adjacent to the lake freezes to a depth of between 1 and 2 m, depending on the surface temperature, the snow cover, and the distance from exposed banks. In late winter soil aggregates, released by the sublimation of interstitial ice within the banks, begin to accumulate at the base of the slopes, often veneering snowbanks there. Once thaw begins, slab failure of bank sediment is followed by mudflows and earthflows. Thaw failure at Orwell Lake in the winter of 1981-82 accounted for over 20% of the erosion; in the spring of 1982, 824 Mg was eroded by this process and 746 Mg the following spring. Such slope failure is most intense along north-facing banks and considerably less intense on south-facing banks, where more effective desiccation and sublimation reduce the soil moisture content. Summer rainfall is responsible for the remaining 3% of the total erosion, amounting to 102 Mg in 1981 and 208 Mg in 1982. Because the banks are steep and relatively short, rainwash is infrequent; rainsplash is the most consistent process during the summer, but the infrequent storms during which rainwash occurs cause greater total erosion. Erosion by rain has increased in each of the past three summers, largely because of increased precipitation. Infrequent massive slope failures (slumps) have occurred at the east end of the lake where a buried clay-rich unit is stratigraphically and topographically positioned to favor such failures. Drought years followed by heavy spring rains probably will result in additional slope failures of this type at the east end. Unless changes are made, the banks at Orwell Lake will continue to recede. Restriction of the pool level to less than 325.5-m elevation is the least expensive solution to the problem.

PREFACE

This report was prepared by Dr. John R. Reid, Professor, Geology Department, University of North Dakota, Grand Forks, North Dakota. Funding for the research described in this report was provided by Corps of Engineers Civil Works Project 31568, *Erosion Potential of Inland Shorelines and Embankments Subject to Freezing and Thawing.*

Lawrence Gatto and Michael Ferrick of CRREL technically reviewed the manuscript of this report. From the beginning, Dr. Jerry Brown, Dr. Daniel Lawson and Lawrence Gatto have been most cooperative in providing advice and assistance. Their concern and generous help is sincerely appreciated. An additional starter grant was awarded for project supplies and technical support by the Engineering Experiment Station, University of North Dakota. The North Dakota Geological Survey provided use of their mobile drill rig and the Giddings soil probe, and Mark Stadum and later, Dan Pyle, operated the rigs. Because of their expertise and careful attention to the task the necessary holes were completed quickly and with excellent results.

Piezometer pipe was donated to the project by the U.S. Army Corps of Engineers, St. Paul District, through the efforts of Arlee Keys, in charge of the Baldhill Dam, Lake Ashtabula, and Levane Dempsey, of the St. Paul District office. Mr. Keys was formerly the dam tender at Orwell Lake and he was very helpful during the early phases of the project in reviewing the history of the reservoir and providing leads to appropriate documents. Mr. Dempsey arranged to have these and other documents made available. He also provided a set of infrared photographs of the lake taken in September 1979. These were especially helpful in identifying critical research sites. The Corps also permitted free access to the office-storage building at Orwell Dam which was used to store equipment and supplies between trips and for shelter during several night storms. Gratitude is expressed to the St. Paul District Corps of Engineers for their cooperation and encouragement.

The author thanks Dennis Johnson, a U.S. Army Corps of Engineers employee assigned to Orwell Dam. Dennis was always ready to assist in pulling vehicles out of the mud, to help launch and retrieve the boat, and to warn of predicted storms when a radio was not available. Dennis also agreed to read the instrument stations on call. He faithfully carried out this important task on his own time. Bruce O'Neel, the subsequent dam tender at Orwell Lake, has continued in this cooperative spirit, always being ready to assist in this project in innumerable ways.

Finally, the author is most indebted to the student assistants who labored on this project: Gary Winbourn (1980), Stephen Thompson (1981), and Robert Meek (1982). Each suffered through severe storms, wood ticks, mosquitoes and summer heat. The first two assisted in the collection of data during the cold winter. Without their dedication and perseverance this project could not have been successful.

CONTENTS

ILLUSTRATIONS

Tables

SUMMARY

Bank erosion along lakes often destroys valuable land and the resulting sediment accumulation in lakes reduces their capacity to store water or to support recreational activities. Most recent studies of bank erosion have determined recession rates for specific sites, but most have not determined the amount of erosion caused by the various contributing processes. Some studies have even concluded that this "is very difficult, if not impossible" (Ouellet and Baird 1978). This project was done to define and quantify bank erosion processes along Orwell Lake, a flood-control and water-management reservoir impounded in 1953 and operated by the U.S. Army Corps of Engineers. Perhaps an awareness of the variability and the magnitudes of each process will aid in the management and development of lakes in this part of the upper Midwest.

Orwell Lake is located along the Otter Tail River approximately 10 km south-southwest of Fergus Falls, Minnesota. Native vegetation in the area is typical of a tall grass prairie. Regional climate is cool-temperate subhumid. Winters are cold and dry, springs cool and variable, summers warm, with characteristic late afternoon and evening thunderstorms, and falls again cool and variable. Sediments around the lake are of Late Wisconsinan and Holocene age. They are mostly of Barnesville formation till with an interbedded lake silt unit; an overlying partly collapsed lake silt and sand unit form the upper boundary of the Barnesville formation. Beneath the Barnesville formation is a well-sorted sand unit resting on collapsed till of the Dunvilla formation. Overlying all units is eolian silt in which a deep mollisol (chernozem) soil has formed. The geotechnical properties of the tills are significant factors in the amount and type of erosion modifying the reservoir banks.

Since Orwell Lake was first impounded, a considerable amount of bank erosion has occurred. During the summer of 1980 Federal land had to be traded for private land along the southern shore where erosion was active. Prior to that a large slump occurred along the eastern shore in spring, 1977. The U.S. Army Corps of Engineers (St. Paul District) has been concerned about the causes of bank erosion and the ways to mitigate the erosion. Some causes, such as wave erosion, were expected to be important, but no data had been collected to assess the magnitude, frequency and significance of this or any other process.

Other than the following, no published reports are known for Orwell Lake. Previous work addressed the geology and engineering properties of the dam site (U.S. Army Corps of Engineers 1979 and 1981), the changes in sediment profile surveys, the operation procedures of the reservoir (Falk et al. 1975) and historical bank recession (Doe 1980). The survey results show a maximum cumulative bank recession of 0.8 m from 1954 to 1964, with the cumulative average less than 0.5 m. Historical recession reported from the analysis of aerial photographs was much higher than recession measured from the profile surveys or in the field during this study.

As a first step in this study all the banks surrounding Orwell Lake were closely examined and representative sections were scraped to fresh sediment, measured, sketched, sampled and photographed. Some sites were cored to analyze detailed stratigraphy. Based on the types of sediments in the banks and on the apparent significance of exposure direction to resulting erosion, 11 erosion stations were established at first. Two stations were added later in the project. All sites were along the 1.62 km of shoreline (10% of the total) where erosion appeared to be active. The remainder of the shoreline was either very gentle and grass-covered or steeper and covered by trees and shrubs.

Each station consisted of between 4 and 13 erosion pins, 155 mm long, inserted normal to the bank surface. The change in the bank surface along the pins provided data on the amounts of erosion or deposition that resulted from overland processes (i.e. rainsplash, sheet wash, rill wash). Measurements were frequent during the summer when storms passed through the area and only occasional during the winter when little change occurred. During 1980-81, measurements were made 24 times, 26 times the following year, and from June to October 1982, 13 times.

Bank profiles at each erosion station were measured several times to determine the amount of bank sediment eroded by waves during high water periods. The amount of bankline recession was measured from a series of pins installed 3 m inland from the bank crest.

Nine frost tubes were installed landward of the bank crest and on the bankface to measure frost depths. The depths were measured at regular intervals from the time of first freeze to the time of complete thaw each year. Two 80-mm PVC pipes for frost heave measurement were installed with wings glued to the bottom to inhibit heaving. Changes in the ground surface were measured along these pipes and all other access tubes (piezometer, soil moisture, and frost) throughout the winter in the hope that they would record at least the minimum heave at each site.

In late fall sheets of polyethylene were laid along the base of selected banks and anchored. After all thaw failure had occurred, the volume of sediment on the sheets was measured. The annual amount of thaw failure for all the eroding banks along the lake was calculated by using the estimated volume of thaw accumulation for each section.

Piezometers were installed to determine the effect of reservoir water level fluctuations on ground water levels, to measure piezometric fluctuations in a discharging aquifer at the east end of the lake and to attempt to discern a possible relationship between aquifer head pressures and occasional massive slumping. The piezometers were read periodically during the project.

Soil samples of standard volume were collected from erosion station sections immediately before a storm and then immediately after to define soil moisture content. Four soil moisture access tubes were also installed to below the expected frost line. A neutron probe was used to determine the water contents at 25-cm spacings from the surface to the bottom of each tube. Soil moisture at the surface at the time of precipitation is a significant factor in erosion and heave.

The results of the three years of data analysis have provided insights into the magnitudes of various erosion processes. Wave action is the dominant process. It caused over 76% of the total erosion in 1981–82 and 88% in 1982–83. During years when the reservoir water level does not exceed 325.5 m, sediment accumulates along the base of the banks. Any year that the pool reaches its maximum level, waves remove this sediment and transport it to deeper parts of the lake. After two successive years of high water, this accumulated sediment would be thin and waves would quickly remove it; the waves would directly erode the more resistant, in-situ till. The amount of wave erosion is dependent on water level and wind direction, velocity and duration.

The second most effective erosion process along Orwell Lake is thaw failure, which caused over 20% of the total erosion in the spring of 1982 and about 10% the following spring. Thaw failure begins with slab slips along joints in the in-situ till that have been enlarged by frost action, and mud and earthflows then occur when thaw has progressed. Erosion accompanying thaw is relatively minor along south-facing banks where winter sublimation, which significantly reduces soil moisture, is more intense. In the spring of 1982 more than 74% of total thaw failure occurred along north-facing banks.

Erosion by rainsplash and overland flow (rill and interrill wash) occur for the longest time during the year but cause only about 3% of the total erosion. Erosion by rainsplash was evenly distributed around the lake in the summer of 1981, but was more intense on north-facing banks the following summer. The variation in erosion by rainsplash and rill and interrill wash is high from event to event, depending mostly on the condition of the sediment at the time of rainfall.

Erosion by mass wasting of soil aggregates that have been loosened by sublimation of interstitial ice during winter also occurs. It results in an accumulation of soil particles at the base of steep banks that often buries snowbanks. The volume of soil eroded in this manner is only a fraction of 1% of the total erosion in any year. No large slumps were observed during the three years of this study, but future massive rotational slumping could occur following droughts, especially at the east end of the lake where clay-rich lacustrine sediment lies between tills. Erosion by wind (deflation) was also insignificant because the primary till is compact and the secondary sediment is fine.

The ultimate result of bank erosion is bank recession. The average yearly retreat of the bank crest at one station was 0.8 m, and 0.36 m was the average for all the stations. These are probably good approximations of future rates, provided the reservoir level fluctuates as in the past. It is important to emphasize that the erosion processes modifying reservoir banks can vary greatly from place to place and from year to year. Long-term studies are required to understand these processes more fully.

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SHORELINE EROSION PROCESSES
Orwell Lake, Minnesota

John R. Reid

CHAPTER 1. INTRODUCTION

Banks bordering streams and lakes are produced primarily by the hydraulic forces acting near their bases, the water actively scouring or weakening the banks for subsequent erosion by other processes. Erosion of stream banks often destroys valuable land, threatens communities, and sometimes drastically alters the hydraulic geometry of the channels, causing subsequent flooding to increase or be directed into areas previously untouched by flooding. Then, too, the eroded sediment is deposited elsewhere, often causing even greater problems. As recently as 1969 it was estimated that 2% of the 7×10^6 miles of stream banks in the United States were characterized as having serious erosion problems (Piest and Bowie 1974). With the recent increase in the flooding of major streams in the Missouri-Mississippi River basin it is probable that this percentage has increased.

In the case of lakes, similar problems exist; valuable land is destroyed or threatened, and the resulting sediment accumulation reduces the capacity of the lake to store water or to support recreational activities. In lakes, the dominant erosional process is generally the action of waves whose directions are controlled by the wind.

Perhaps the two most studied lakes are those in the U.S.S.R., created for the generation of hydroelectric power, and the Great Lakes of the United States. Bank and bluff erosion along Lake Michigan, for example, has received much attention this past decade. Although most recent lake erosion studies have adequately addressed the seriousness of bank erosion and have determined the recession rates for specific shoreline sections or sites, most have been unable to separate the processes. Some have even concluded that this "is very difficult, if not impossible" (Ouellet and Baird 1978), mostly because of the existing differences in relief and the inhomogeneity of the bank material.

Despite this, there have been successful attempts to separate and quantify shore erosion processes. An excellent example is the stream bank study by Hill (1973) in northern Ireland. As in the case of the Orwell Lake study, upper and lower slopes were measured separately, and several techniques were used to differentiate erosion by rain, streamflow, and frost action. Even though the climates of the two studies are very different, erosion processes and their relative values are similar. Part of the problem in addressing shoreline erosion, whether along streams or lakes, is the lack of understanding of shoreline erosion. As noted by Shur et al. (1978), "Even specialists are often mistaken as to the real extent of the erosion process and are inclined to consider shoreline collapses as unique and grandiose events unrelated [to] common processes of erosion."

This report is an attempt to define and quantify bank erosion processes along the shore of a reservoir impounded in 1953. Perhaps an awareness of the variability and the magnitudes of each process will aid in the management and development of lakes in this part of the upper Midwest.

Location

Orwell Lake is approximately 10 km south-southwest of Fergus Falls, Otter Tail County Minnesota (Fig. 1) The lake is about 10 km west of the eastern margin of the Glacial Lake Agassiz Plain, in the Big Stone Moraine complex. Although the native vegetation is that of a tall grass prairie, the boundary of the forest ecotone is not far to the east.

The climate of the area is cool-temperate subhumid. The average temperature for 1981 was 6.2°C and the total precipitation was 544 mm, with more than 60% falling as thunderstorms during the growing season (Table 1). Winters are severe; the average January temperature for 1982 was -20°C. The first frost normally occurs in early October and the last in early May. The simplest description of the weather at Orwell Lake is that winters are cold and dry, springs cool and variable, summers warm, with characteristic late afternoon and evening thunderstorms, and falls again cool and variable.

Orwell lake is an artificially dammed section of the Otter Tail River, which joins with the Bois de Sioux River at Breckenridge, Minnesota, to form the Red River of the North. The river at the site of the lake has cut into sediments of Late Wisconsinan and Holocene age. The banks of the reservoir are mostly Barnesville formation till with an interbedded lake silt unit and an overlying partly collapsed lake silt and sand unit which form the upper boundary of the Barnesville formation. Beneath the Barnesville formation is a well-sorted sand unit resting on collapsed till of the Dunvilla formation. Overlying all units is eolian silt in which a deep mollisol (chernozem) soil has formed. The lower sand unit is at high pool level in one section of the shore and this certainly has affected erosion there. Otherwise, the geotechnical properties of the tills are significant factors in the amount and type of erosion acting to modify the shoreline of Orwell Lake.

Orwell Lake is a flood-control and water-management reservoir, operated by the U.S. Army Corps of Engineers since 1953. The pool level fluctuates between 320 m (m.s.l.), usually in late winter, to about 326 m, usually in the fall (Table 2). The pool level is decided at the St. Paul District Office, Corps of Engineers. To accomplish its flood-control objective, the pool is lowered over the winter to provide storage capacity for the anticipated snowmelt runoff. The water-management objective is to guarantee flowing water downstream, especially during the cold, dry winter, both for meeting municipal needs and to minimize fish kills. The filling of the pool in late summer and early fall is intended to provide this need over the winter. At maximum pool level the lake contains between 14.1 and 20 ha^3 of water and at minimum pool level only about 1 ha^3. At the same time, the area covered during maximum pool levels is about 450 ha, but only 85 ha at low levels. The configurations of the lake at a typical level (323 m) and at the high level (326 m) are shown in Figures 2 and 3, respectively.

Figure 1. Location of Orwell Lake, Minnesota.

Table 1. Weather summary for Orwell Lake, Minnesota, 1980-1982.

	1980		*1981*		*1982*	
Month	*Avg temp (°C)*	*Total precip (mm)*	*Avg temp (°C)*	*Total precip (mm)*	*Avg temp (°C)*	*Total precip (mm)*
Jan	−12.4	20.8	−9.4	2.8	−20.3	22.4
Feb	−12.3	9.4	−7.1	12.7	−11.9	11.9
Mar	−6.1	9.4	0.9	14.5	−3.1	31.8
Apr	+8.8	1.5	8.1	45.7	4.9	13.2
May	15.8	18.8	15.4	31.8	14.9	41.9
Jun	18.5	84.1	17.5	118.6	15.2	41.7
Jul	21.3	78.5	17.3	154.2	22.1	106.2
Aug	19.1	119.6	20.3	50.6	20.3	119.9
Sep	12.0	41.4	14.1	12.2	14.2	85.1
Oct	5.8	25.9	6.8	72.6	7.8	115.6
Nov	2.2	1.3	2.2	11.4	−3.5	12.2
Dec	−9.1	2.0	−11.2	14.7	−6.0	6.9
	5.3	412.75	6.22	543.81	5.16	608.7

Table 2. Physical characteristics of Orwell Lake.

Drainage area		
Total	4,714 km^2	(1,820 miles^2)
Effective (below main lake region)	635 km^2	(245 miles^2)
Elevation		
Spillway	328 m	(1,075 ft) m.s.l.
Normal full pool	326 m	(1,070 ft) m.s.l.
Normal low pool	320 m	(1,048 ft) m.s.l.
Lake dimensions		
Area:		
Normal full pool	450 ha	(1,110 acres)
Normal low pool	85 ha	(210 acres)
Length: Normal full pool	6.4 km	(4.0 miles)
Width: Normal full pool	1.6 km	(1.0 mile)
Capacity:		
Normal full pool	14.1 ha^3	(14,100 acre-ft)
Normal low pool	1.0 ha^3	(1,000 acre-ft)
Discharge		
Maximum (17 June 1953)	48 m^3/s	(1,710 ft^3/s)
Minimum (5 August 1970)	0.02 m^3/s	(0.7 ft^3/s)
Average depth		
Normal full pool (326 m)	5.3 m	(17.4 ft)
High pool (325.5 m)	5.1 m	(16.8 ft)
Maximum depth		
Normal full pool (326 m)	9.4 m	(31 ft)
High pool (325.5 m)	8.8 m	(29 ft)

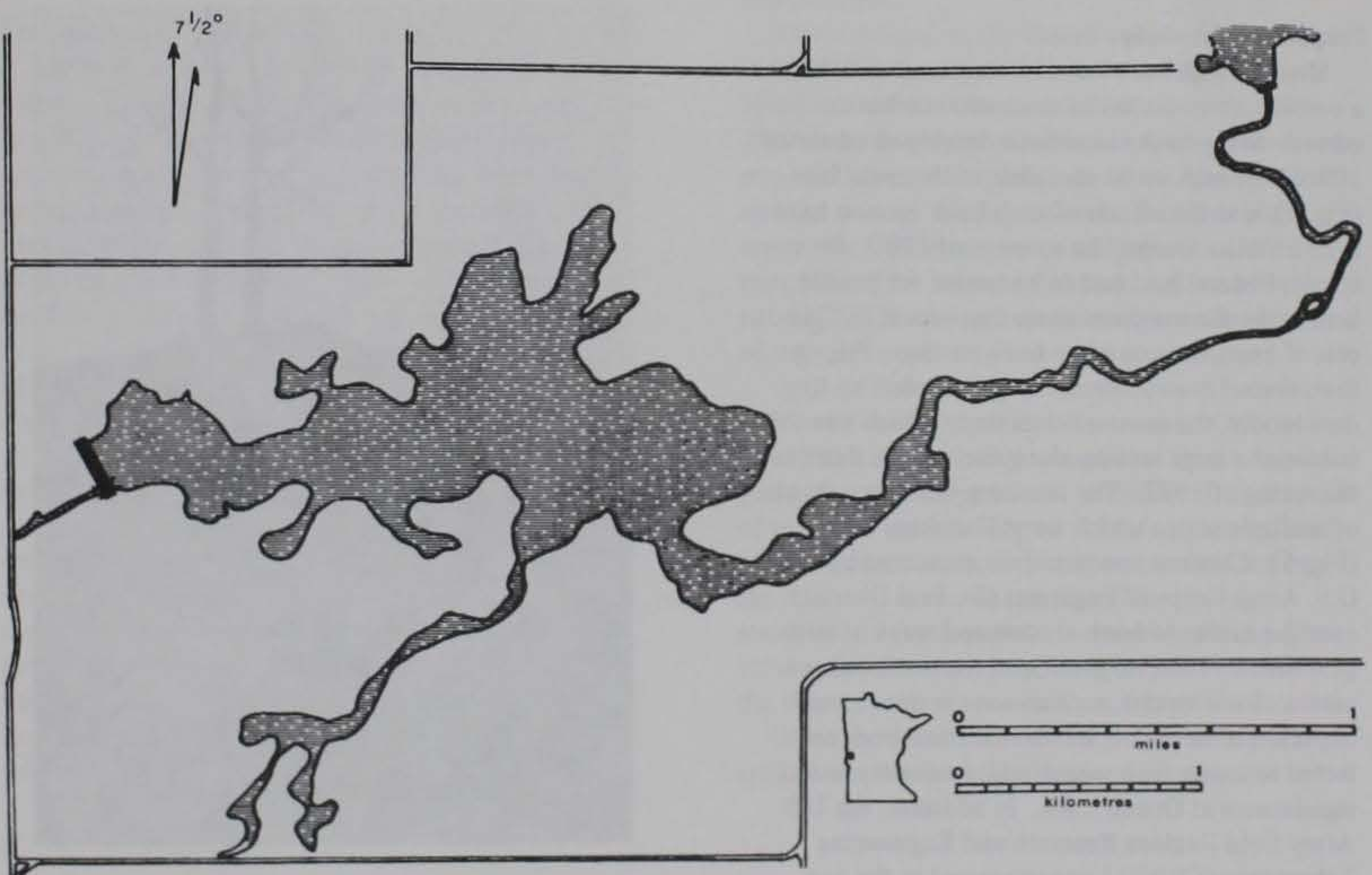


Figure 2. Orwell Lake, Minnesota, 323-m level.

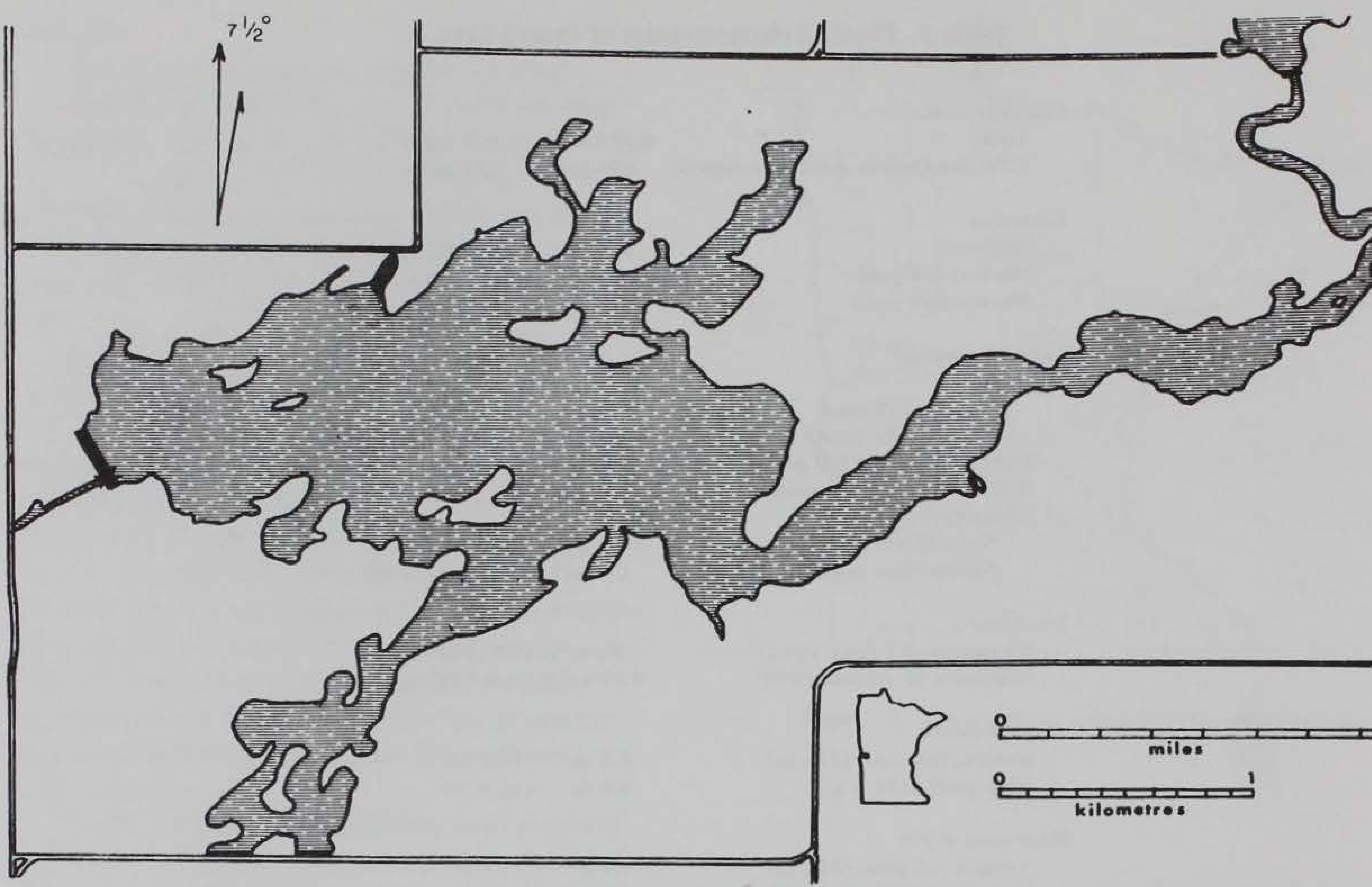


Figure 3. Orwell Lake, Minnesota, 326-m level.

Purpose of the study

Since Orwell Lake was first impounded in 1953, a considerable amount of shore erosion has occurred. Steep banks have been developed on about 10% of the high water shoreline of the main lake (Fig. 4), and the effects of such bank erosion have been serious. During the summer of 1980, for example, Federal land had to be traded for private land along the southern shore that was in the process of being destroyed by bank erosion. Prior to that, several erosion events were recorded by the dam tender, the most noticeable of which was the failure of a large section along the eastern shore in the spring of 1977. The resulting slump consisted of multiple scarps which are still striking today (Fig. 5). Concern was therefore expressed by the U.S. Army Corps of Engineers (St. Paul District) over the causes of bank erosion and ways to mitigate the rates and magnitude of the erosional processes. Some causes, such as wave erosion, were expected to be active, but no data had been collected to assess their magnitude, frequency and significance at Orwell Lake. In addition, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) was interested in the processes of erosion unique to such cold climate regions as west-central Minnesota. This project

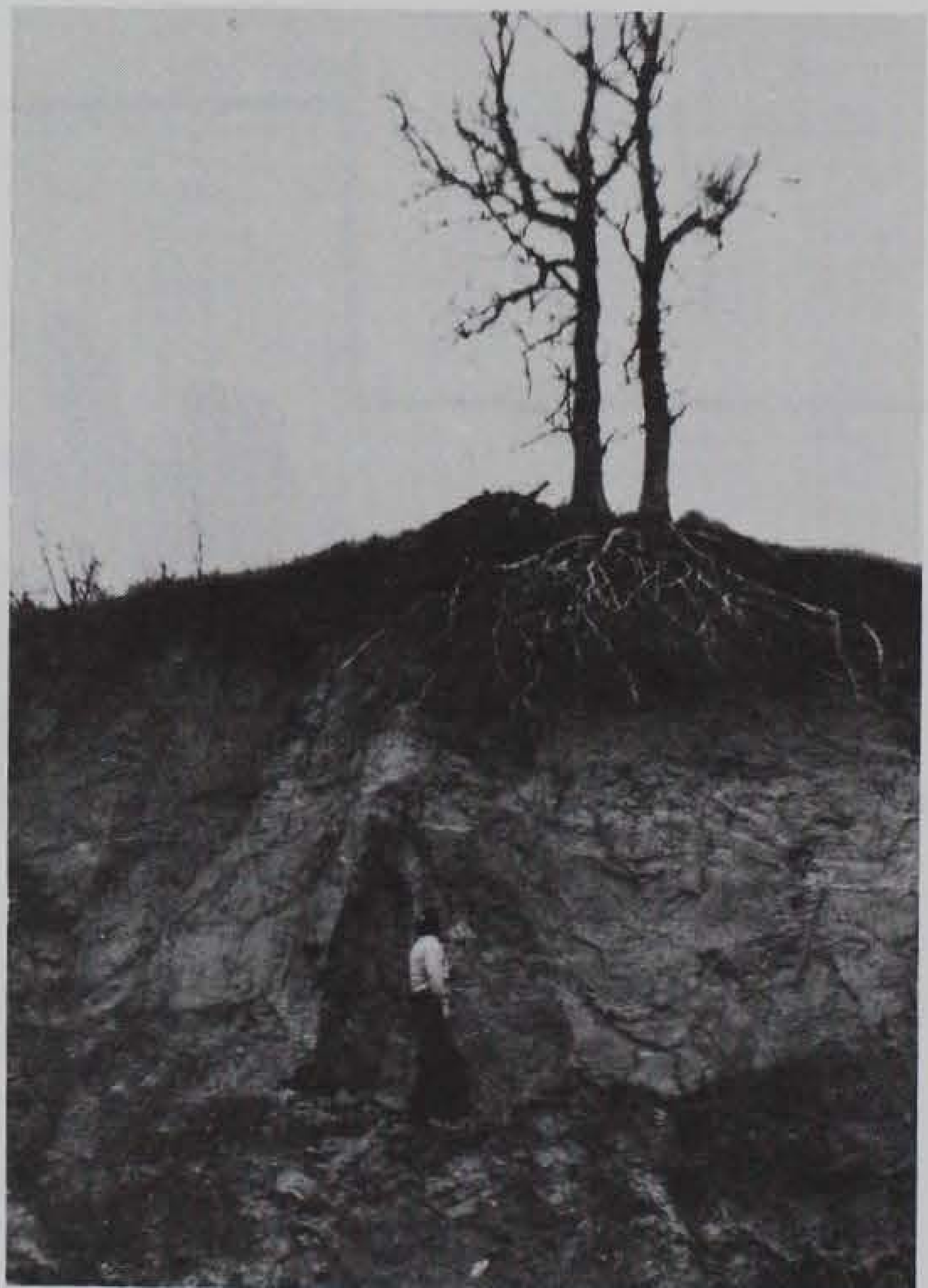


Figure 4. Steep erosional bank showing a recent slab failure, erosion station 8, March 1982.

Figure 5. Massive slope failure (slump) at east end of Orwell Lake.

was therefore organized to identify and quantify the erosional processes at Orwell Lake. The initial procedure was to first identify both critical and control areas, and to begin to collect the relevant data.

Previous work

Other than reports by the U.S. Army Corps of Engineers on the geology and engineering properties of the dam area (1979 and 1981) and some sediment profile surveys, little work has been done on this reservoir basin. The reports confirm a complex sequence of glacial, fluvial, and lacustrine units at the dam end of the lake. Water under artesian head has resulted in mud boils adjacent to the dam in the reservoir, causing concern about the safety of the dam. Piezometer nests were installed and are being monitored on a regular basis.

The unpublished sediment transect surveys were made in 1954 and again in 1964. The results were generally compatible with what would be expected: erosion along the margins (maximum of less than one meter, with an average of about 300 mm) and deposition in the deep parts of the basin. Some parts of the transects, however, denoted erosion where deposition would be expected, and deposition where erosion would be expected. The surveys were not highly accurate, explaining some of the apparent discrepancies. According to these surveys, the maximum cumulative bank recession over the 10-year period was 0.8 m and the cumulative average was less than 0.5 m. One section showed a net *progression* of the bluff of 0.2 m during that 10-year interval.

Other studies on the Orwell area include an environmental impact statement, evaluating the operation procedures of the reservoir (Falk et al. 1975). This study was based almost entirely on generalized pre-existing data and did not address bank erosion and the geology of the reservoir. Based on that report the U.S. Army Corps of Engineers (1975) noted that "the areas of shoreline that are alternately inundated and exposed are generally devoid of vegetation and subject to some wave action."

A more recent study of reservoir bank recession addressed sites along Berlin Reservoir in Ohio and Orwell Lake (Doe 1980). Airphotos from several years allowed comparison to be made. The amounts of recession reported (up to 4.3 m/year) were much higher than recession measured in the field during the study. It is concluded that either the photo scales were not adequate to measure bank changes accurately, or more likely, that the pool levels at the time of each photo were not taken into account.

Other than these studies, no published reports are known for Orwell Lake.

CHAPTER 2. METHODOLOGY

Geology

All the banks surrounding Orwell Lake were examined in detail early in the project. Representative sections were scraped to fresh sediment, measured, sketched, sampled and photographed. Subsequent coring at various sites around the lake over the next two summers added to the understanding of the stratigraphy of the area. New exposures resulting from intense wave erosion in the fall of 1981 further clarified the interpretation of the geologic history of the sediments.

Overland erosion

On the basis of the knowledge of the types of sediments in the banks and on the apparent significance of exposure direction to resulting erosion, 11 erosion stations were established in June 1980 at selected sites along the banks of Orwell Lake. All sites were along the 1.62 km of shoreline exposed by erosion, representing about 10% of the total shoreline. The remainder of the shoreline was either very gentle and grass-covered or steeper and characterized by trees and shrubs. By the end of the year, additional stations were installed as results from the first stations became apparent. At the close of the project data were being collected from 13 such stations (1-12A, 7A and 8A were destroyed) (Fig. 6).

Each station consisted of between 4 and 13 spikes ("pins"), 155 mm long, inserted normal to the bank surface. The number of pins used per station depended on the length of the slope being measured. Pins inserted into the upper part of the banks were usually flush with the surface (Fig. 7); those lower down were left protruding about 10 mm so that the pins would not be completely buried if sediment accumulated there. The pins were reset when needed. Each pin was inserted through a washer, and erosion would cause the washer to settle; deposition would be recorded by burial of the washer. The height of the pin head above the bank surface was always measured on the same side, as significant differences sometimes existed from one side of the pin to the other. Measurements were frequent during the summer when storms passed through the area and only occasional during the winter when little change occurred. During the 1980-81 study year (June 1980-June 1981) 24 readings were taken; 26 readings were taken the following year, and from June 1982-October 1982 an additional 13 readings were recorded.

Whenever possible, attempts were made to record changes immediately after a storm. This was accomplished the first two years by camping at the lake during the storm period and the following year by having an assistant living within a short driving distance from Orwell Lake.

During the summer of 1981 another method was designed to determine overland flow erosion and to compare the results with those of adjacent erosion stations. Two lines of garden edging 1-2 m apart were set into the sediment at erosion station 2 (Fig. 8), extending downward from the break in slope immediately below the vertical bank face. The lines converged farther downslope to convey all overland flow into a funnel leading into a bucket (Emmett 1970). This system was designed to channel all runoff through the funnel and into a bucket. However, on three occasions the funnel became plugged with sediment and overflowed, and on at least three other occasions the bucket overflowed. Therefore, the results of the 19 recorded events represented a minimum measure of the sediment removed from the bank by storm erosion at this location because the sediment that overflowed could not be measured.

A second runoff station was installed farther up the lake at erosion station 4, but wave erosion (October 1981) destroyed both stations as it eroded most accumulation slopes around the lake. No appropriate sites could be identified the summer of 1982 and no runoff stations were established.

Wave erosion

The existence of steep banks surrounding Orwell Lake reflects the importance of wave erosion there. Early attempts to measure the degree of such erosion failed because of the underestimation of the intensity of this process; early erosion stakes and lines of boulders were completely destroyed, eliminating any chance of measurement. Prior to the high lake level of October 1981, numerous "rebar" rods were placed vertically into the sediment at the very base of banks. Most, however, were destroyed when masses of bank collapsed onto the rods, bending them and making them more

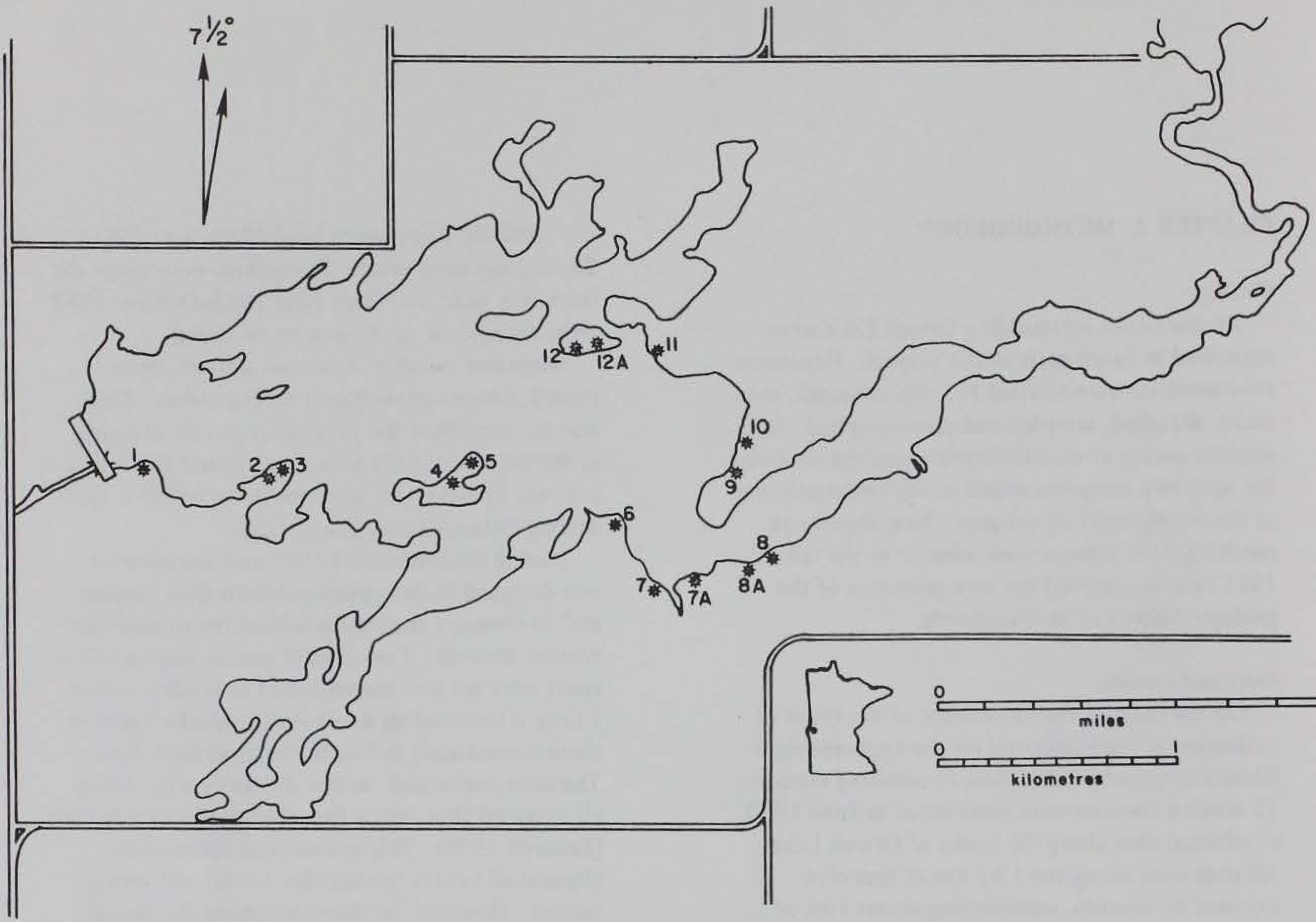


Figure 6. Orwell Lake, Minnesota with locations of erosion stations.

Figure 7. Erosion pin with washer inserted flush with a steep slope surface.

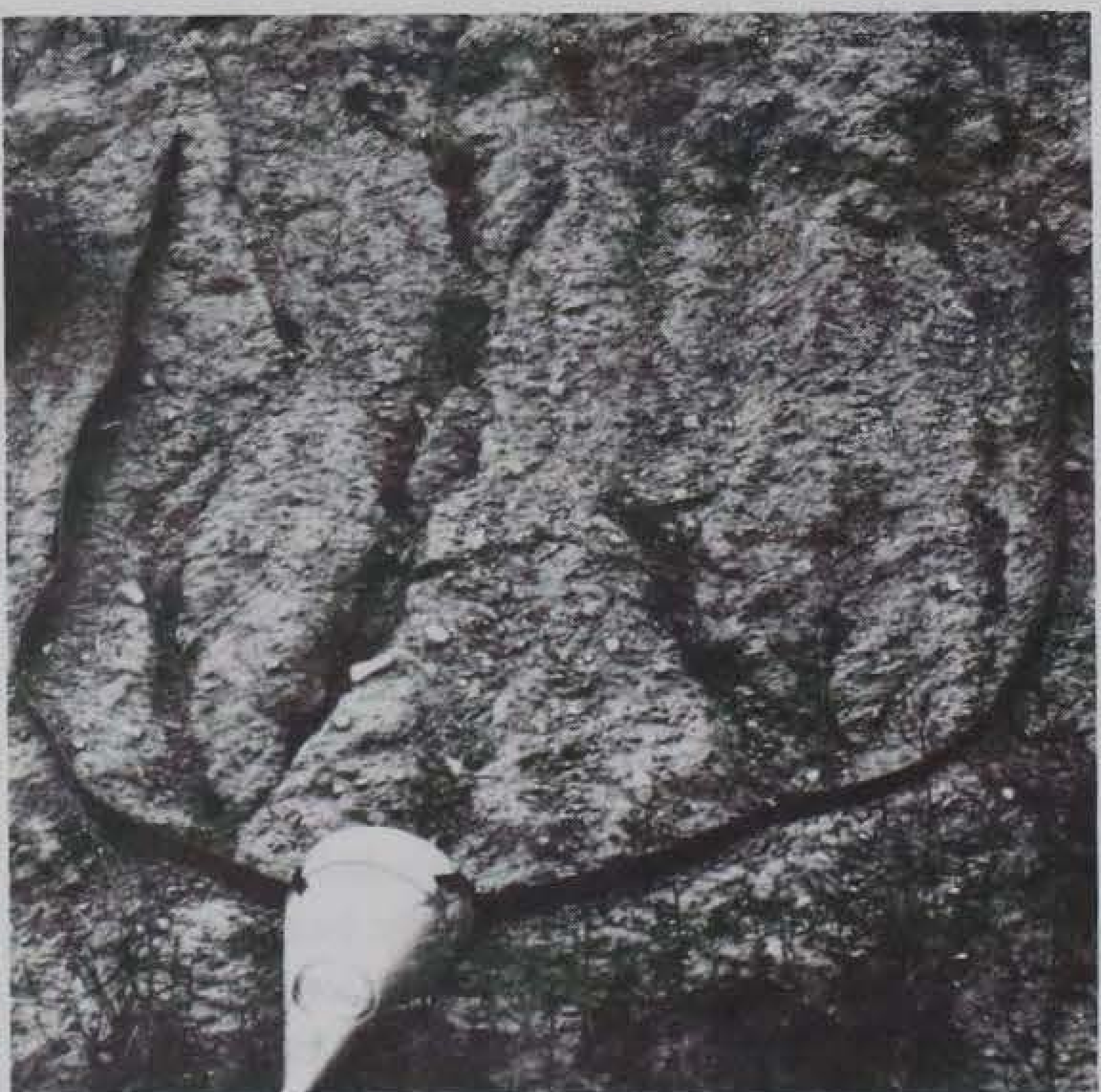


Figure 8. Runoff station 1; the garden edging leads into the funnel.

susceptible to concurrent wave erosion. In anticipation of this problem the bank profiles at each erosion station were measured in the summer of 1981 by determining the average slope angle over 0.7-m intervals from the bank base to the top. Remeasurement of the profiles after the lake level dropped allowed the calculation of the volume of bank removed by this process. In addition, "rebar" rods were installed prior to the high pool levels of October 1982.

Frost penetration and heave

During the summer of 1980 nine holes were drilled for the purpose of installing frost tubes (Fig. 9). At each site a 35-mm-i.d. PVC casing tube was installed to below the expected frost line. Inside was a 15-mm-o.d. polyethylene tube filled weth methylene blue-dyed water. At each reading the tube was lifted out of the casing tube and the depth of freezing was measured as the bottom of the frozen mixture, correcting for the distances between the top of the tube and the ground level.

One set of four tubes was installed at increasing distances from a bank face to measure the effect of the exposed face on the depth of freezing. Two additional tubes were installed at an angle into a bank, one north-facing, and the other south-facing (Fig. 10). The rest were on level ground away from exposed banks. The frost level was measured at regular intervals from the time of first freeze to the time of complete thaw each year.

Attempts to measure frost heave were more difficult. The final solution was to install an 80-mm diameter PVC pipe to below the frost line. Wings were glued to the bottom to inhibit the frost from lifting the entire pipe. The surface was marked and the heaving of the ground measured, as frost penetrated.

A second tube was installed at an angle into a steep bank, but packing of sediment around it was unsuccessful. All other access tubes (piezometer, soil moisture, and frost) were also marked and measured through the winter in the hope that they would record at least the minimum heave at each site.

Thaw failure

Following the active wave erosion of the banks in October 1981, sheets of polyethylene were laid with one edge at the base of the newly eroded banks

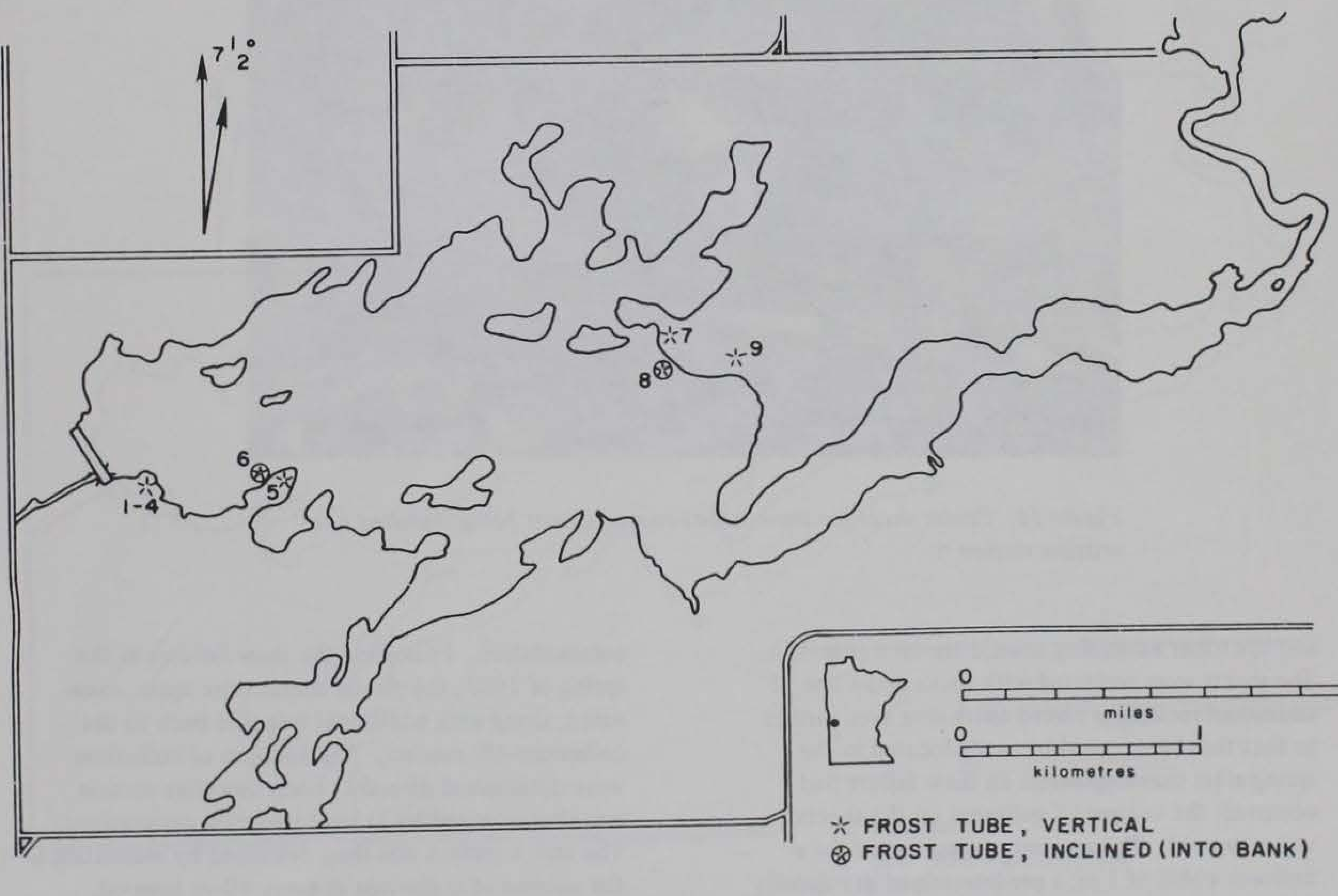


Figure 9. Locations of frost tubes at Orwell Lake.

Figure 10. Frost tube 8 inclined into bank erosion station 11. The top of the liquid-filled inner tube is even with the ground surface.

Figure 11. Plastic sheet for thaw failure measurement being installed near erosion station 6.

and the other extending toward the lake (Fig. 11). The sheets were weighted with rocks and a line of additional rocks was placed extending even farther so that the sheets could be easily located in the spring after thawing. After all thaw failure had occurred, the volume of sediment on the sheets was measured. The amount was corrected for a uniform width of 1 m; a predetermined dry density of 1.54 g/cm^3 was used to calculate the mass of the accumulation. Following the thaw failures in the spring of 1983, the plastic sheets were again excavated, along with additional trenches back to the colluvium-till contact. The volumes of colluvium were determined directly. Each shoreline section was characterized by at least two such excavations. The entire section was then described by estimating the volume of colluvium at every 10-m interval, using the results of the excavation sites as a standard.

The total amount of thaw failure for the lake was then calculated from measurement of the length of shoreline and the estimated volume/weight of thaw accumulation for each section.

Bank recession

Early in the second year of the study (February 1982), a series of pins was set about 3 m from the bank edges, prior to any thaw, because most of the upper bank erosion appeared to be the result of thaw failure. The pins were remeasured in May and again in late fall. In addition, airphotos were examined to determine the feasibility of using them to determine bank erosion since 1954.

Ground water

Five piezometers were installed in the summer of 1980 for three purposes:

1. To determine the effect of pool level fluctuations on the ground water table.
2. To measure piezometric fluctuations in a discharging aquifer at the east end of the lake.
3. To attempt to discern a possible relationship between aquifer head pressures and the occasional massive slumping, also at the east end of the lake.

Data from the piezometers could be used to measure potentiometric levels of various aquifers that might be involved in slope failure (Fig. 12). The position of the screened intervals within each piezometer was determined from the interpretation of the stratigraphy at the time of drilling. The sections immediately below and above the screens were sealed with cement or bentonite, as was the part surrounding the top. In the summer of 1982 two additional piezometers were installed, one to monitor a known discharge site near a recent slump area, and the other to measure aquifer transmissivity and response time to pool level fluctuations. The piezometers were read periodically over the three-year period. Appendix C includes the installation data for each piezometer.

Soil moisture

The moisture condition (infiltration capacity) of the soil surface at the time of precipitation is a significant factor in erosion. The Antecedent Precipitation Index (Gregory and Walling 1973) is one method used to define this moisture condition, but it does not apply to site-specific stations. Consequently, soil samples of standard volume had to be collected from erosion station sections

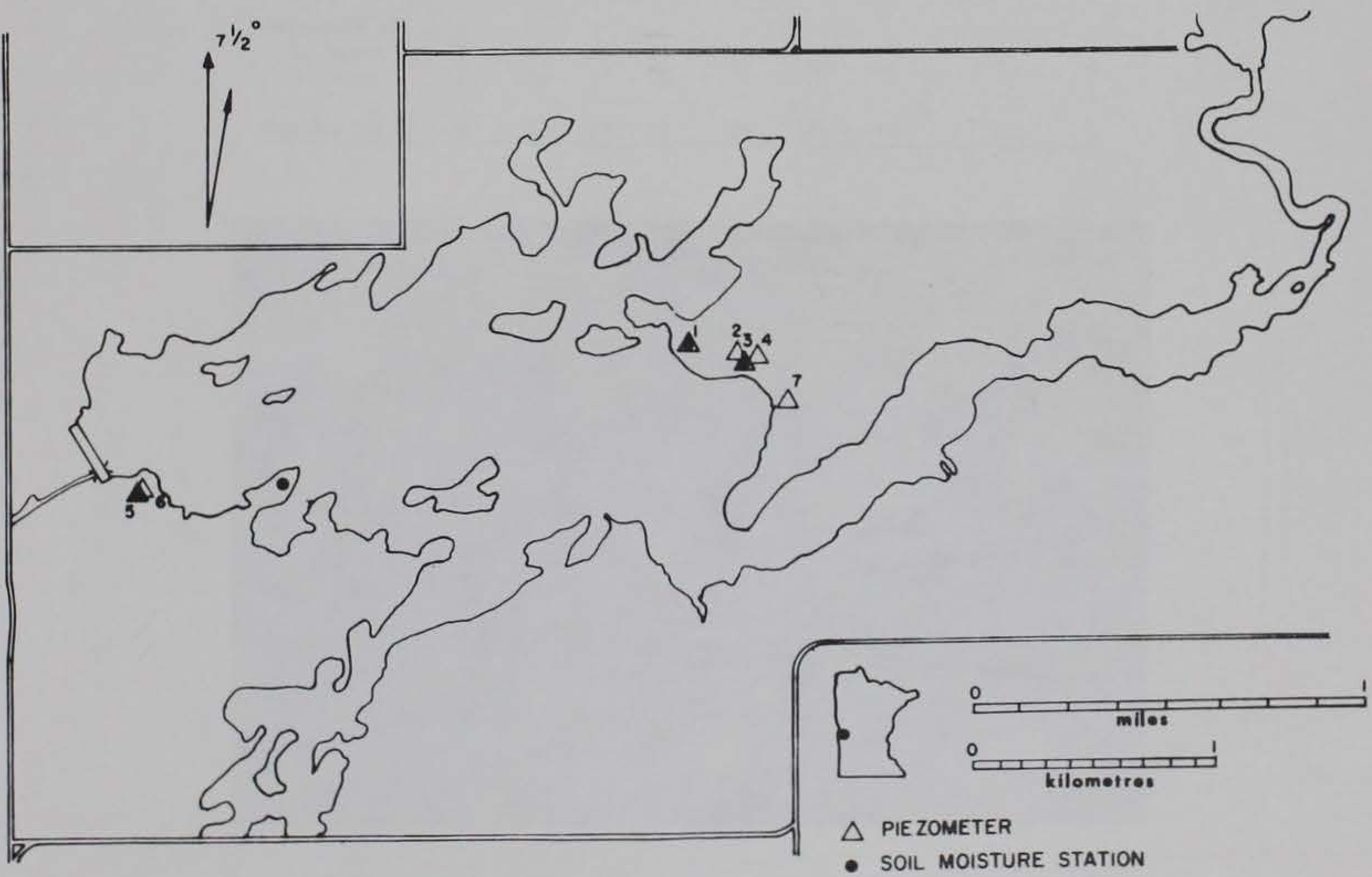


Figure 12. Location of piezometer and soil moisture stations.

immediately before a storm and then immediately after to define soil moisture content.

The moisture content also is a factor in the amount of subsequent frost heave. Therefore, four soil moisture access tubes were installed to below the expected frost line (Fig. 12). A Campbell Pacific Nuclear Corporation model 503A neutron probe was used to determine the water contents at 25-cm spacings from the surface to the bottom of each tube. The readings were calibrated with samples collected at the time of the reading at Orwell Lake and with samples from a test site in western North Dakota.

CHAPTER 3. RESULTS

Geology

Dunvilla formation

The sediments composing the banks of Orwell Lake were deposited during, and subsequent to, the Late Wisconsinan glaciation of the area (Moran et al. 1976). Two distinctly different tills are exposed there. The lower till is correlated with the Dunvilla till, first defined and described by Anderson (1976). The till is typically a dark gray and compact pebbly, silty and clayey sand (Table 3). The very coarse sand-size fraction is high in shale and characteristically contains lignite fragments. Larger clasts of lignite are scattered through this till.

The Dunvilla till has been correlated with the Dahlen till on the North Dakota side of the Lake Agassiz Plain, largely on the basis of the high shale content, but also because of its geographic and stratigraphic position (Anderson 1976). It is interpreted to have been deposited between 13,500 and 14,000 years B.P. (Clayton and Moran 1982).

Immediately above the Dunvilla till is a well-sorted sand unit (Fig. 13), lacustrine silts, or a sheared zone in which the Dunvilla till is incorporated into the younger Barnesville till (Fig. 14). All units, except the sheared zones are included

Table 3. Texture and lithology of till units at Orwell Lake.

Unit	Texture				Very coarse sand lithology				
	Gravel	*Sand*	*Silt*	*Clay*	*Mineral grains*	*CO_3*	*Shale*	*Sandstone*	*Lignite*
Barnesville Till									
b. upper	2	15	58	25	35	28	24	13	0
a. lower	2	25	47	26					
Dunvilla Till	6	42	30	22	28	21	48	0	2

Figure 13. Contact of partly collapsed sands (unit B) and overlying Barnesville till (unit C) at erosion station 5.

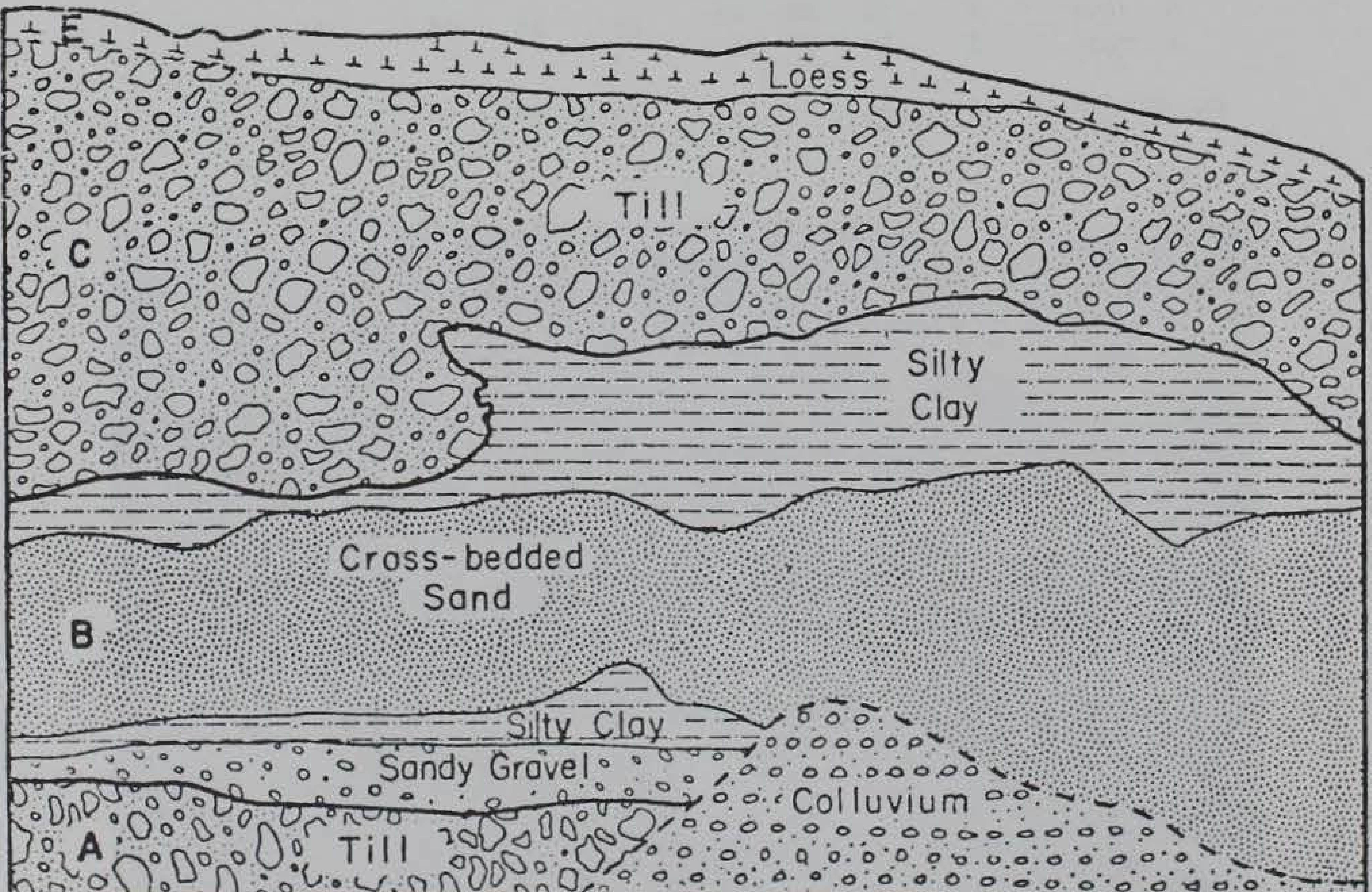
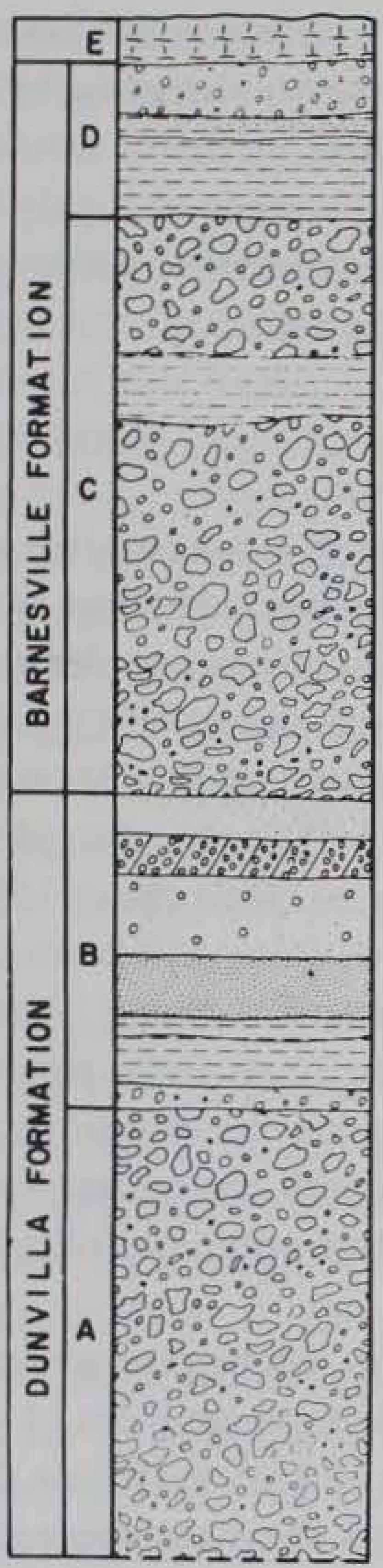


Figure 14. Photograph and interpretive sketch of bank exposure near erosion station 8, showing lithologic units and structures (see Fig. 15 for description of units).



Unit E - Silt (loess) dark brown, organic-rich.

Unit D - Gravel, sand, silt, clay (fluvial and lacustrine); highly variable. Shows same range of sediment characteristics as Unit B.

Unit C - Pebble loam (till); yellowish-brown (10 YR 5/4) unsorted and unbedded mixture of clay-size to boulder-size sediment; matrix averages 25% sand, 48% silt, and 27% clay; moderately jointed, with blocky structure. A thin lacustrine silt separates two till phases of this formation along the entire south shore of the lake.

Unit B - Gravel, sand, silt clay (fluvial and lacustrine); highly variable; the coarser beds are moderately to well-sorted fine- to coarse-grained sand, sandy gravel, and gravel, with vague plane bedding to planar and trough-shape cross beds. The silt and clay beds are moderately sorted, unbedded pebbly silt and clay to well-sorted clay and laminated silt and clay.

Unit A - Pebble-loam (till); light yellowish-brown (2.5 Y 6/4) to dark grayish-brown (10 YR 4/2); unsorted and unbedded mixture of clay-size to boulder-size sediment; matrix averages 42% sand, 36% silt, and 22% clay.

Figure 15. Composite geologic column of the banks of Orwell Lake, Minnesota. (For scale, unit B averages about 1 m thick.)

in the Dunvilla formation. Figure 15 is a composite section of the units exposed at Orwell Lake. Examination of the piezometer holes, described in a later section, will show that this figure is greatly simplified.

Barnesville formation

The Barnesville formation includes the till and associated lake and river sediments deposited immediately prior to inundation by glacial Lake Agassiz about 11,000 years ago (Clayton and Moran 1982). At Orwell Lake the formation is composed of two till units, separated by a collapsed proglacial lacustrine unit (Fig. 16), and overlain by a discontinuous sand and gravel and a lacustrine sequence. The lowermost of the two till units is a pebbly, clayey, sandy silt (about 2% gravel, 25% sand, 47% silt, and 26% clay). The upper till is significantly siltier (about 2% gravel, 15% sand, 58% silt, and 25% clay). The higher silt content is presumably a result of incorporation of the proglacial lake sediments during the minor readvance here.

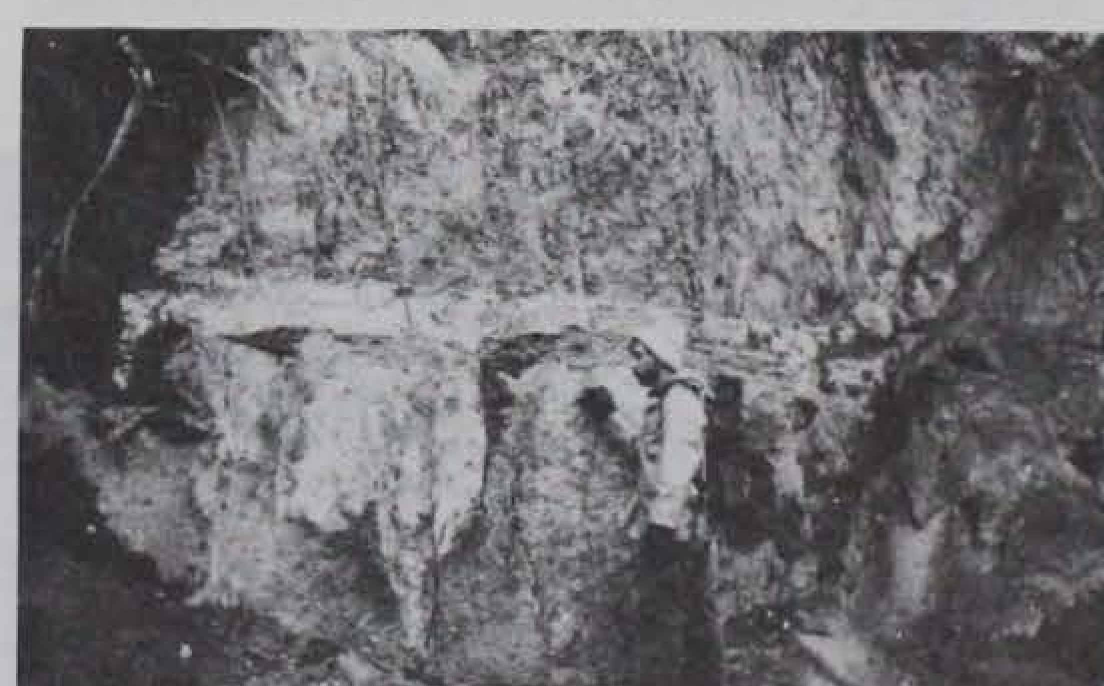


Figure 16. Lacustrine silt unit separating the upper and lower Barnesville tills at erosion station 9.

The average of the very coarse sand-size lithology is distinctly different from that of the Dunvilla till; about 35% are crystalline or mineral grains, 28% are carbonates, 24% are shale, and 13% are sandstone and siltstone grains (Table 3). Lignite fragments are rare in the Barnesville till.

The uppermost unit at Orwell Lake is an eolian silt, correlated with the Oahe formation of North Dakota.

Geotechnical properties

The geotechnical properties of the sediments composing the banks of Orwell Lake determine, to a large extent, the effectiveness of erosion processes on the banks. The textural and lithologic characteristics of the two tills, the Dunvilla and the Barnesville, have already been discussed (Table 3).

Jointing

Another obvious characteristic, however, is the structure; all of the till units are highly jointed, the lower Barnesville, especially so (Fig. 17). Three sets of joints are present, two almost vertical, trending S 55° W and the other N 30° W, and the third set almost horizontal. The spacing of the primary vertical joints is about 15 cm, whereas the horizontal joints are only about 1 cm apart. It is probable that the vertical joints are the result of the shear stresses at the base of the former glacier. The horizontal joints are probably due primarily to glacial unloading, although dehydration of the sediments must also have contributed to secondary jointing. The upper Barnesville till unit does not display the same degree of jointing as the lower unit, but this may partly be due to obscuring by surface processes. Of course, the loading factor would be less, too. Regardless, the presence of highly jointed sediment in the banks contributes to subsequent failure, especially during thaw.

Moisture content

Several types of measurements were made to determine the moisture content of the bank sediment. Standard volume samples were collected of the bank sediment immediately prior to and following a storm. The dry sediments averaged about 4% water by weight. The samples collected immediately after a storm averaged about 16% water. Other samples collected from drill cores from above the water table averaged between 13 and 18% water. Data from the neutron probe measurements showed the degree to which the moisture content varies with depth and with season, as expected. Waves of increased moisture could be followed to depth after precipitation.

If these waves can be disregarded, the moisture content tends to increase from 11 or 12% to about 15% at a depth of 1.75 m (below the normal frost line). In all cases the measurements reflect the moisture content of the Barnesville till, the primary sediment of the banks. No measurements were made during the height of the thaw season as the probe was not then available. Due to the presence of frozen sediment at depth, however, the moisture content must have been appreciably greater during

Figure 17. Highly jointed lower unit of the Barnesville till at erosion station 5.

the thaw season, contributing to the flow failure of the sediments in the banks.

Density

The dry density of the surface sediment varied from site to site, but averaged about 1.54 g/cm^3. Due to the overburden load both now, and especially at the time of initial deposition, sediment at depth has a higher density (Table 4). The Barnesville till, at a depth of between 5 and 6 m, for example, has a dry density of 1.85 g/cm^3. With the addition of moisture, the bulk density increases significantly. The Barnesville till has a subsurface moist density of about 2.71 g/cm^3 (15.3% water). All calculations of mass eroded by any of the processes measured assumed a dry density of 1.54 g/cm^3.

Other engineering properties

Samples from four stratigraphic units obtained from near piezometer stations 2 and 4 were submitted to the Omaha District Office of the Corps of Engineers for engineering testing. Some of the results are summarized in Table 4. Only the Barnesville till and the underlying lacustrine unit are included, as the data for these units were the most relevant and the analyses were also more complete. Results of the Atterberg limit determinations indicate that both units are probably overconsolidated, with a plasticity index of 15 for the Barnesville till and only 6 for the underlying lacustrine sandy clay. The angle of internal friction for both samples is unusually high; the unconfined compressive strength for the Barnesville till is exceedingly high (84,000 kgf/m^2) and for the lacustrine unit, very high (21,800 kgf/m^2). A problem exists in interpreting why the till unit has a lower angle of internal friction than the lacustrine unit, but a significantly higher compressive strength. Apparently the lacustrine unit had a higher water content than the till at the time of deposition and was not as affected by the glacial loading as the till even though under a higher total stress. Removal of the respective samples from the core tubes caused a greater relaxation (expansion) of the till, causing it to have a lower angle of internal friction.

Table 4. Geotechnical characteristics of units, Orwell Lake.

	Barnesville till	*Sandy clay (lacustrine)*
Depth	5.2–6.1 m (17.20 ft)	7.2–7.9 m (23.5–26 ft)
Moisture content	15.3%	18.6%
Void ratio	0.46	0.56
Saturation	90%	90%
Dry density	1.85 g/cm^3 (115.4 lb/ft^3)	1.73 g/cm^3 (107.9 lb/ft^3)
Liquid limit	33	24
Plastic limit	18	18
Plasticity index	15	6
Unconfined compressive strength	84,000 kgf/m^2 (8.61 tons/ft^2)	21,800 kgf/m^2 (2.24 tons/ft^2)
Angle of internal friction (ϕ)	33°	36.5°

In summary, the till, the typical sediment of the banks at Orwell Lake, is well consolidated, explaining why so many banks are relatively stable even though almost vertical. These geotechnical properties do not explain, however, the occasional failure by slumping, as has occurred at the east end of the lake (Fig. 5). The failure of these sites must be due to pore-water pressure changes, as controlled by the structure and stratigraphy of the area. The presence of highly jointed till resting on a sandy clay unit (lacustrine), which becomes exposed upon truncation by waves along the shore, sets up at least one of the passive conditions favoring failure. The activating cause appears to be controlled by the climate.

Overland erosion

The amount of erosion of the banks of Orwell Lake was determined primarily by measurement of erosion pins. Supplementary data were obtained from a runoff station established adjacent to erosion station 2. The resulting data for each station, presented in the appendices include

1. Cumulative *net changes*, an average of all pins for each slope segment (steep and relatively gentle) for each station, 15 June 1980 through 14 June 1981 (App. A1).
2. Cumulative *net changes* of each station, disregarding differences in slope angle, for the three years of measurements (App. A2 and A3).
3. Cumulative *average erosion* for each station, without regard to slope angle, for the three years of measurements (App. A4-A6).

The variation in degree of erosion on the two slopes is clearly shown in Figure 18. Although the trends of erosion are almost identical for this station, the more gentle slope shows greater erosion, perhaps in response to a greater depth of the sheet of runoff water downslope. This graph shows that erosion occurred mainly during the rainy season at station 2 in 1980-1981. Essentially no erosion occurred during the months of September through January. The erosion in February is the result of thaw failure (see *Freeze-Thaw Phenomena*).

The separate measurements of the two slope segments ceased in late 1981 after waves removed most and, in some cases, all of the lower slopes at the stations. The data for the first year and subsequent years were, therefore, recalculated to consider the entire slope at each station as a single unit (Fig. 19). Finally, accumulation data were ignored and only erosion measurements were averaged for each station for each date in order to display cumulative average erosion for the year (Fig. 20).

Most of the sites show periods during the year when there is apparent net accumulation on the slopes; erosion station 1 is typical (Fig. 19). Technically, net accumulation is impossible without material being added from outside the system. Three explanations are presented for this anomaly. First, sediment on the slope is always in some stage of transit down the slope. Because the pins are between 50 and 100 cm apart, at any one instant a wave of sediment might reach one or more pins rather than be between pins. An average of the pins at a given station might, therefore, record an erroneous increase in the average surface level. Over a long period of time, e.g. one year, such aberrations

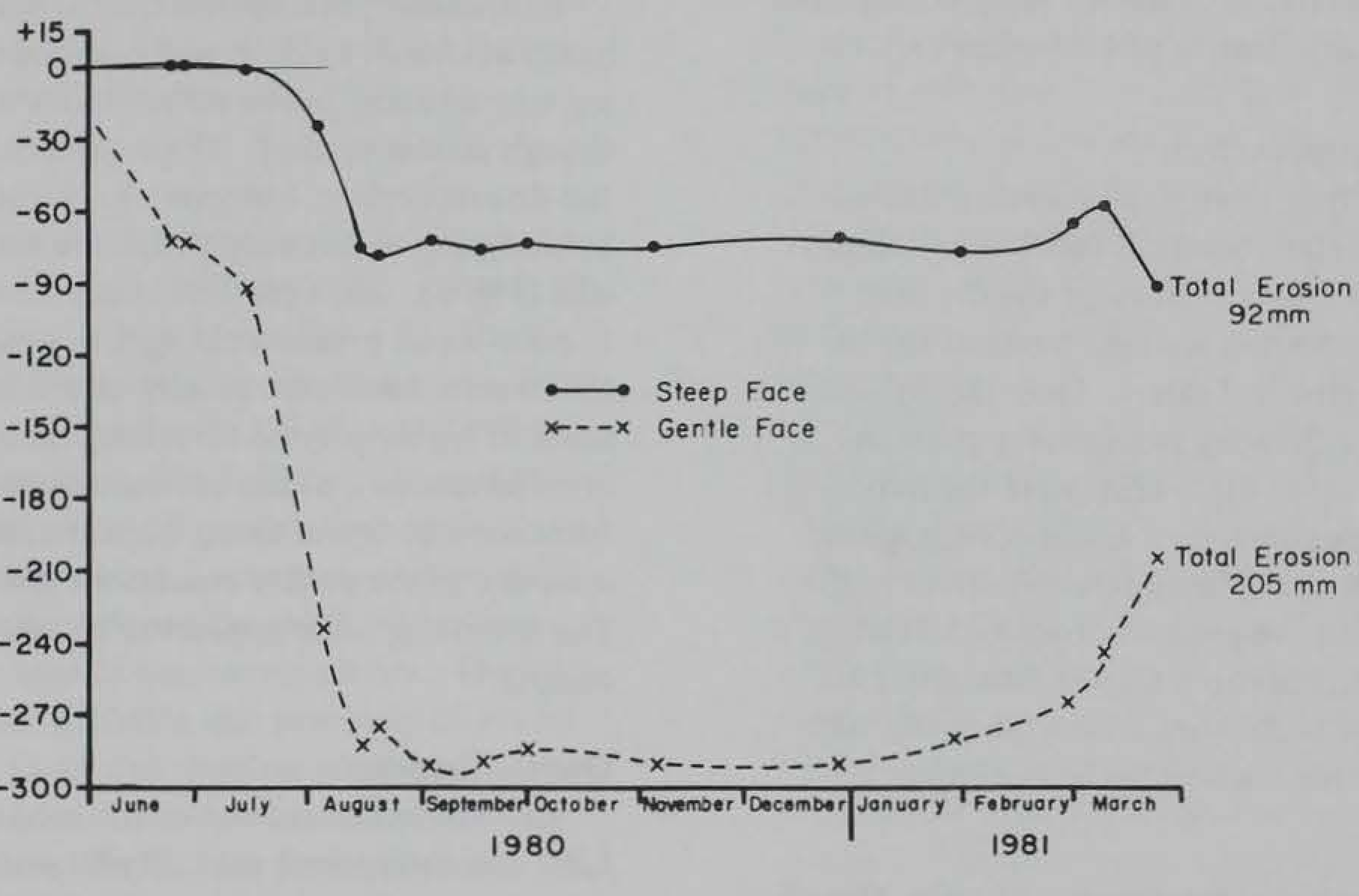


Figure 18. Cumulative net change for steep and gentle slope, erosion station 2, 1980-81.

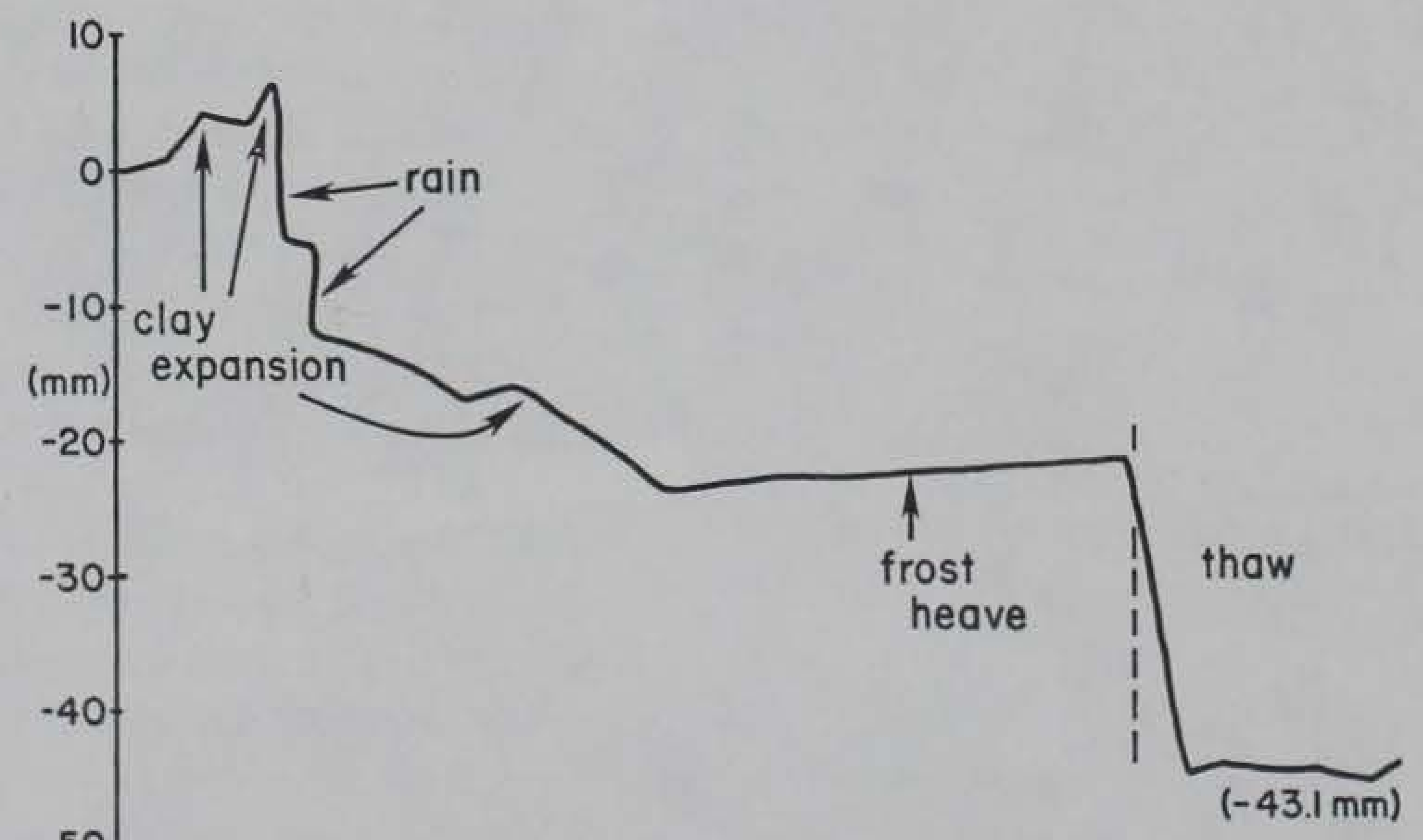


Figure 19. Cumulative net change, erosion station 1, 1981-1982.

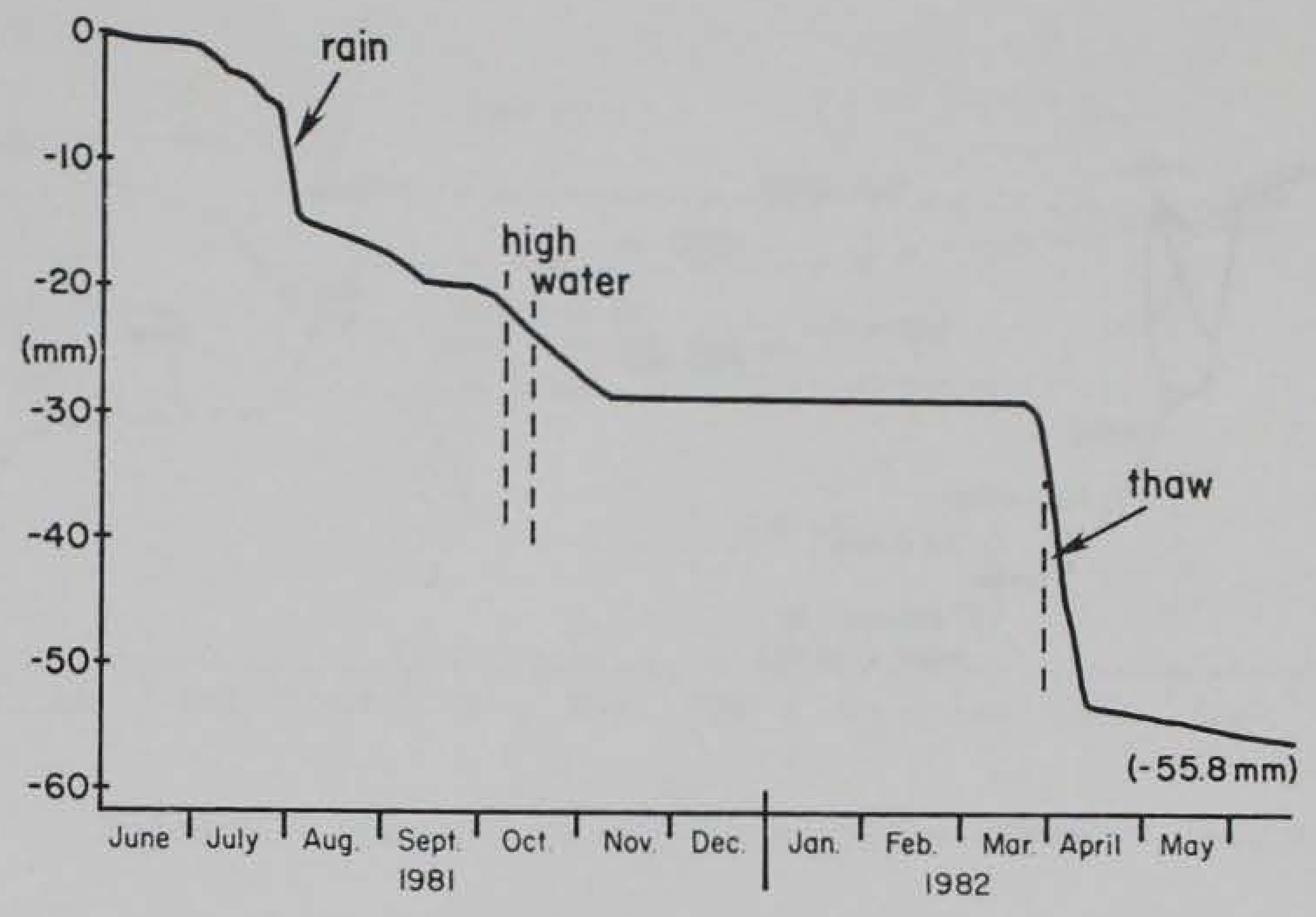


Figure 20. Cumulative average erosion, erosion station 1, 1981-1982.

Table 5. Comparison of seasonal processes on in-situ bank and accumulation slopes, 1980-1981, Orwell Lake, Minnesota. Interpreted from Appendix A; see Table 12 for slope angle data.

	In-situ bank slopes				*Accumulation slopes*			
	(Summer)	*(Spring)*	*(Winter)*	*(Summer)*	*(Summer)*	*(Spring)*	*(Winter)*	*(Summer)*
Erosion station	*Overland erosion (mm)*	*Thaw failure (mm)*	*Frost heave (mm)*	*Clay swell (mm)*	*Overland erosion (mm)*	*Thaw failure (mm)*	*Frost heave (mm)*	*Clay swell (mm)*
2	-21	-14.4	c. 0.6	c. 0.2	-40	-5.5	c. 0.2	1
3	-13	-2.0	c. 0.3	1	-11	-3.0	1 (snow cover)	*
4	-23.5	c. -2.0	c. 0.2	c. 0.2	-9	-8	c. 0.2 (snow cover)	*
5	-8.5	-7.0	c. 0.2	c. 0.1	-8	0	(snow cover)	*
6	-1.0	0	c. 0.1	1	-6	-10	(snow cover)	1
7	-7.0	0	c. 0.2	c. 0.1	-13.5	-6	c. 0.2	*
8	-6	-2	c. 0.1	c. 1.5	-13	-10	c. 0.3	*
9	-4.8	0	0	0	-17	-5	*	*
10	-3.5	-1	1	1.5	-22	-1	1	*
12	-1.2	0	-0	-0	-12	0	*	*

*No measurable amount

would be smoothed out and the true value of change would be recorded. A second explanation relates to the mineralogy of the sediment. Between 65 and 79% of the clay-sized sediment is montmorillonite and most of that is the highly expandable Ca- and Na- type. It is concluded that some of the apparent "accumulation" events are due to expansion of the clay minerals upon wetting by rain. The approximate amount of clay swelling was measured directly from the net changes graphs, such as from Figure 19. Table 5 summarizes the values, which do not exceed about 2 mm. The third cause of apparent accumulation is frost heave, also summarized in Table 5.

Data for three stations, 5, 9, and 12, have been selected to illustrate erosion events and trends for the three years of measurements. These stations, three of the 12 to 14 stations measured, are north-

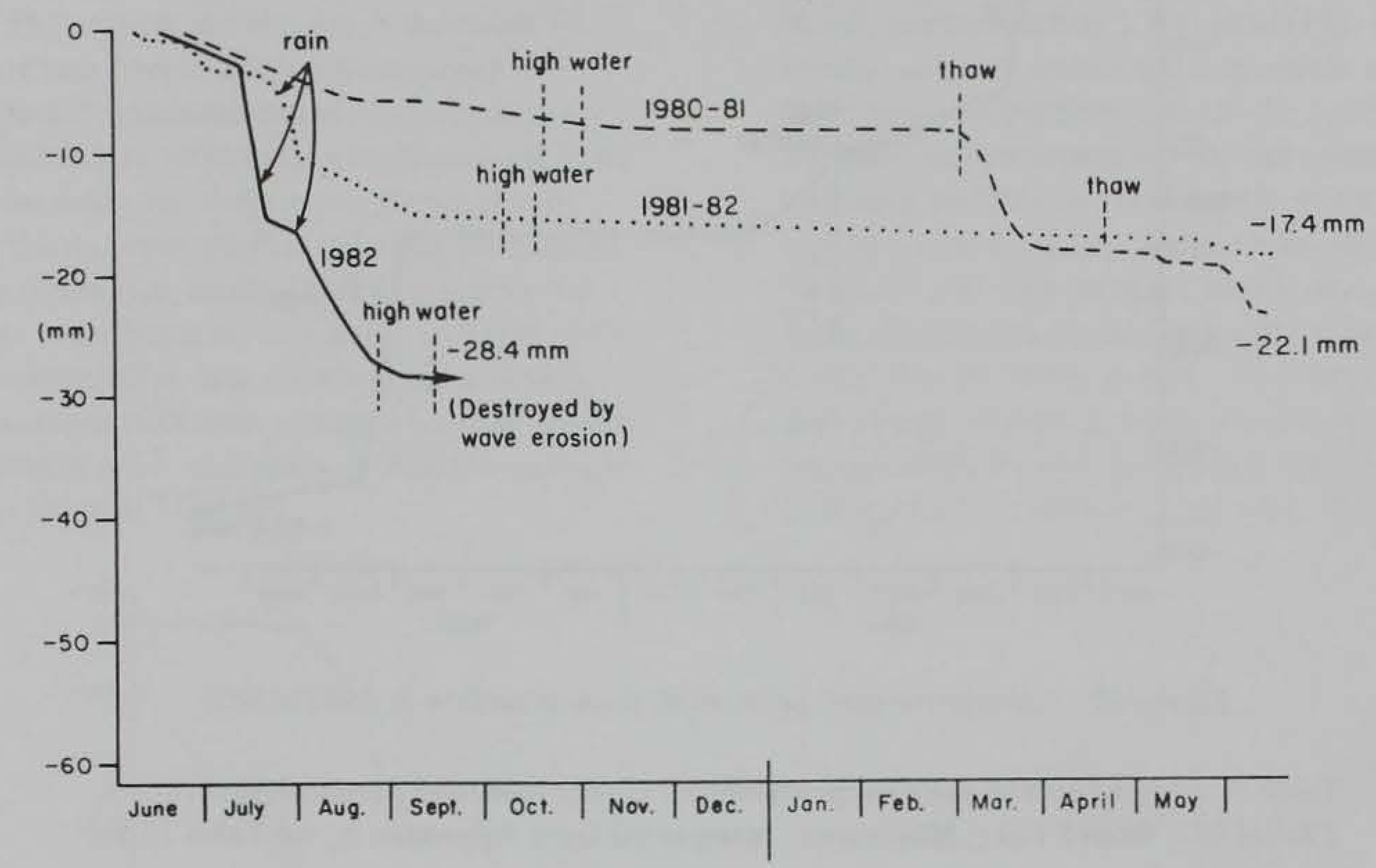


Figure 21. Cumulative average erosion at overland erosion station 5, 1980–1982.

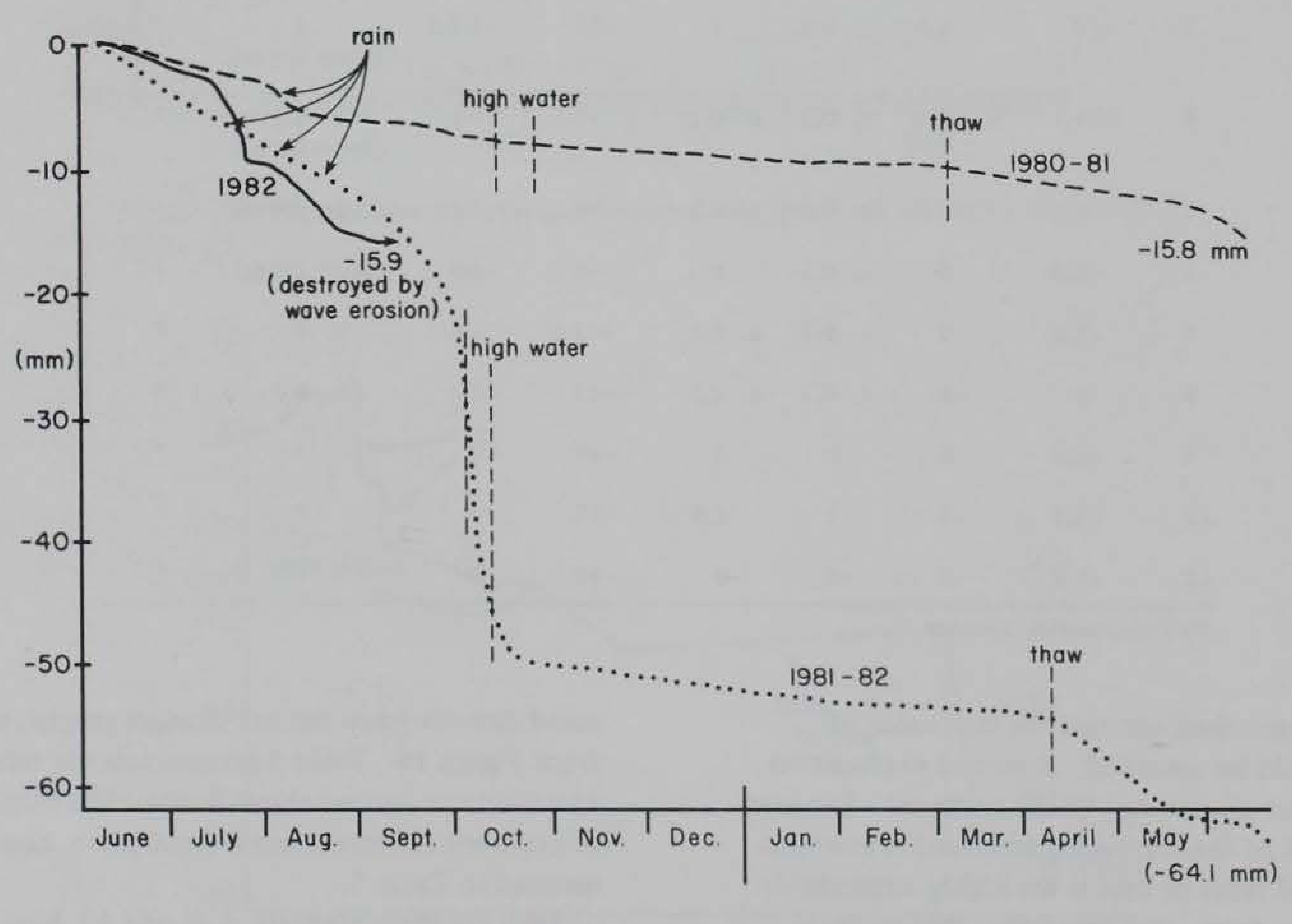


Figure 22. Cumulative average erosion, erosion station 9, 1980–1982.

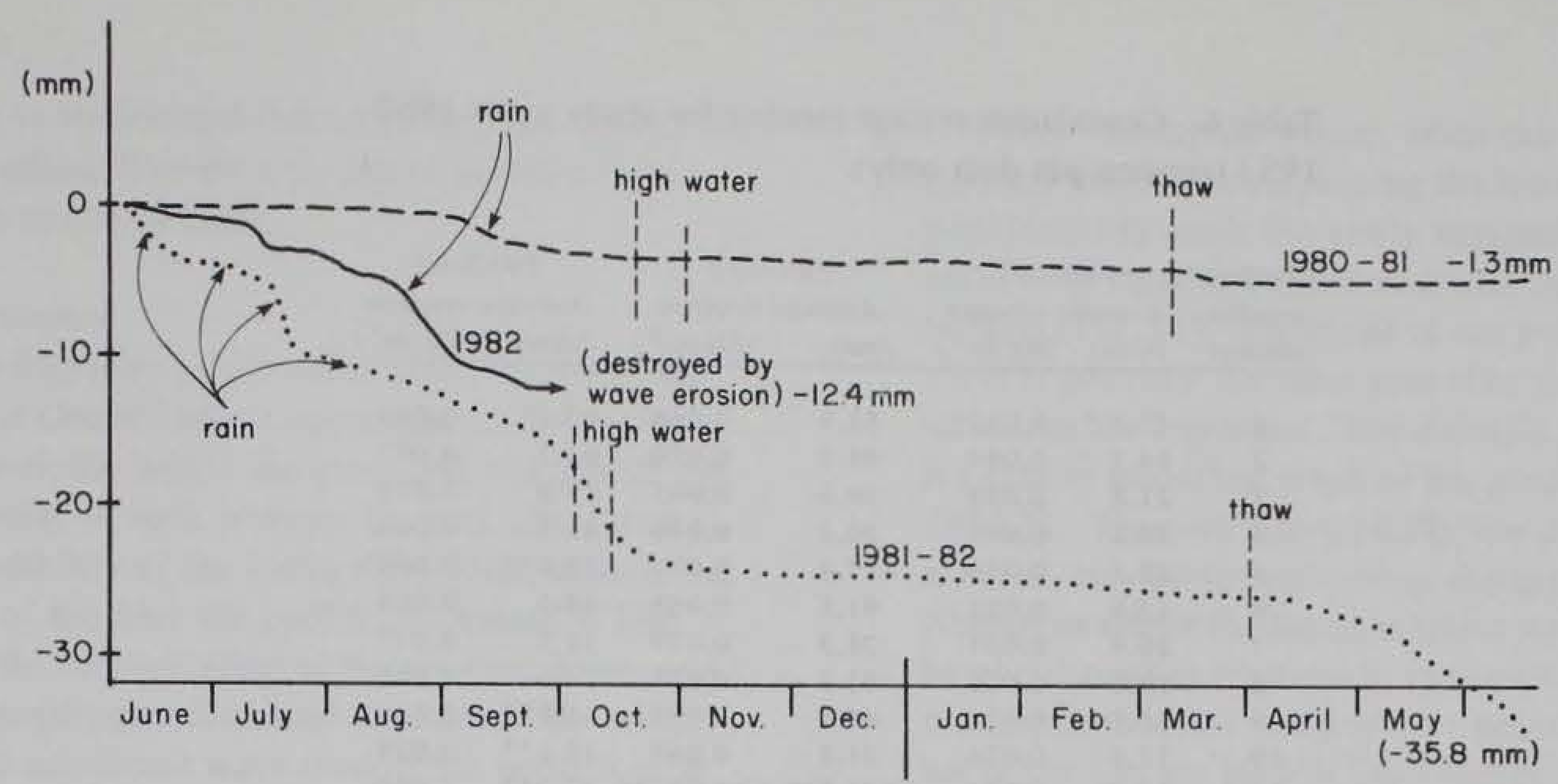


Figure 23. Cumulative average erosion, erosion station 12, 1980-1982.

facing, west-facing, and south-facing, respectively (Fig. 6). There were no east-facing stations. The resulting curves (Figs. 21-23) reflect erosion by all three processes: rain, waves, and thaw failure. Several observations can be made:

1. Except for the thaw failure at station 5 (Fig. 21) erosion at the three stations in 1980-1981 was negligible. This is especially true for station 12 (Fig. 23), where only 1.3 mm of erosion occurred over the 12 months of measurement.
2. Erosion during the following year, 1981-82, was significantly greater, again disregarding the thaw failure at station 5. This was due largely to the greater amount of erosion accompanying wave action that year, but erosion by rain was also significantly greater.
3. Erosion at two of these three stations was greater during the summer of 1982 than for the same periods the previous two years.

From the data from each station, the resulting cumulative depths of erosion were converted to equivalent masses (Table 6). Because complete data exist for only two years, only those are included. The erosion during the 1980-81 study year ranged from 2 kg/m^2 for station 12 to 84 kg/m^2 for station 2; for 1981-82 the range was from 27 kg/m^2 for station 5 to 99 kg/m^2 for station 9. For the 1982-83 year the erosion (as recorded just by erosion pins) ranged from 19 kg/m^2 for station 12, which was destroyed by wave action and therefore did not record erosion over the entire year, to 97 kg/m^2 for station 2 (Table 6).

These data ignore some important facts. First of all, the values are all minimum ones because many pins were completely removed by wave erosion in the fall of 1981 (and again in the fall of 1982). The erosion pin data were therefore a measurement of the average erosion of the *remaining* pins. To assume that an amount equal to the remaining length of the pins was eroded would have brought the average closer to actuality, but this would have been only an approximation. For this reason, only an average of the measurements of the remaining pins was used.

Secondly, additional pins were lost by burial during thaw failure. Attempts to locate the missing pins by excavation were sometimes successful. But unless new pins were quickly installed at those sites any intervening erosion would go unmeasured. It is concluded that the amount of such intervening erosion was minimal, however, and that the average erosion, based on the remaining pins, is close to the true value.

The average cumulative erosion values for each station and for each interval ignore any measured accumulation on the pins. Accumulation readings were counted merely as sites of no erosion and included into the average for that reading period. Table 6 summarizes the results for three study years* and Table 7 is a summary of data for rain (overland) erosion for two successive summers.

The data from each station were next extrapolated to those adjacent shoreline sections also characterized by erosion. It must be understood that by defining overland erosion as that occurring only between June and September ignores the rain erosion occurring in April, May, and October (at least in some years). Precipitation records, together with the data collected at the erosion stations over the three years of the study, suggest that the values recorded between June and September are a close

*Study year—began on 1 June; beginning of measurements to determine the amount of erosion by various processes during a year.

Table 6. Cumulative average erosion for study years 1980–1983 (erosion pin data only).

Overland erosion station	*1980–81 Average erosion (mm)*	*(Mg/m²)*	*1981–82 Average erosion (mm)*	*(Mg/m²)*	*1982–83 Average erosion (mm)*	*(Mg/m²)*
1	(7.8)*	0.012*	55.8	0.086	43.9*	0.068
2	54.7	0.084	45.5	0.070	63.2	0.097
3	21.8	0.033	29.0	0.045	55.8	0.086
4	30.2	0.046	36.3	0.056	41.1	0.064
5	22.1	0.034	17.4	0.027	28.4**	0.044
6	13.8	0.021	41.1	0.063	35.3	0.054
7	20.4	0.031	25.3	0.039	51.5	0.079
8	18.6	0.026	42.2	0.065	51.6	0.080
9	15.8	0.024	64.1	0.099	15.9**	0.025
10	15.8	0.024	31.1	0.048	18.6**	0.029
11	15.3	0.024	(>36.8)†	(>0.057)†	32.2**	0.050
12	1.3	0.002	35.8	0.055	12.4**	0.019
7A	–	–	(>36.0)†	(>0.055)†	–	–
8A	–	–	(>12.9)†	(>0.020)†	–	–

* Station reinstalled April 1981; earlier data invalid.

† Station destroyed, November 1981, by wave erosion and consequent mass wasting. Minimum values only.

**Station destroyed, October 1982, by wave erosion and consequent mass wasting. Minimum values only.

Table 7. Average overland erosion for summers of 1981 and 1982 (June–September), Orwell Lake (erosion pin data only).

Erosion station	*1981 Average erosion (mm)*	*(Mg/m²)*	*1982 Average erosion (mm)*	*(Mg/m²)*
1	21.3	0.033	46.3	0.072
2	17.3	0.027	60.7	0.094
3	10.6	0.016	33.5	0.052
4	20.5	0.003	48.2	0.075
5	16.9	0.026	29.2	0.045
6	31.6	0.049	22.3	0.034
7	13.0	0.020	39.7	0.061
8	14.0	0.022	43.3	0.067
9	17.4	0.027	24.9	0.039
10	6.8	0.010	26.7	0.041
11	18.6	0.028	32.7	0.051
12	11.3	0.017	22.8	0.035
7A	1.7	0.003	–	–
8A	11.3	0.017	–	–

approximation of the total rain erosion at Orwell Lake.

To test the accuracy of the erosion pin method for measuring overland erosion a runoff station (as described in Chapter 2) was established in the summer of 1981. Between 12 May and 26 September, 19 collections were made of the sediment removed from that site. A total of 31.26 kg (dry weight) accumulated either in the funnel or the lower-placed bucket in this interval. The area of the station was 4.2 m^2, resulting in a net erosion of 7.4 kg/m^2, or an average of 4.8 mm for the entire runoff station surface. At the same time, there were 19.1 mm of sediment eroded at the adjacent erosion station (2). The difference between the two values is significant. The explanation lies in the design of the funnel system.

As previously mentioned, the funnel occasionally became plugged and the bucket overflowed so that some sediment was lost. In addition, changes in surface hydraulics occasioned by diverting runoff into the funnel apparently reduced the normal erosion by increasing perimeter friction. Previous field studies using this system (Emmett 1970) involved a much longer slope and the terminal area in which the sediment was channeled into a funnel was a much smaller percentage of the system. The conclusion that erosion was reduced by this installation at Orwell Lake became apparent toward the end of the test; the surface at the runoff station was higher than the adjacent surfaces, whereas before the test the slopes on either side were even with the runoff station surface.

The runoff station results, then, represent a minimum approximation of overland erosion at that site. The value of the test is that the data do support the results obtained by the erosion pins, as both sets of data are within an order of magnitude of each other. Despite the recognized limitations of the runoff station technique for this site, the test reinforces the validity of the erosion pin method.

Erosion by overland flow at Orwell Lake is, therefore, a measurable and predictable process. The absolute value of the erosion does vary from station to station and from year to year. Rainsplash and overland flow are only minor causes of bank erosion at Orwell Lake.

Wave erosion

The degree to which waves erode the shoreline banks at Orwell Lake is dependent mostly on the pool level; the higher the pool level, the greater the probability of such erosion. Factors, other than the erodibility of the banks themselves, include the length of the time the pool is maintained at high levels, the configuration of the reservoir basin, and the strength, direction, and duration of the wind.

That significant wave erosion can occur is such a small lake as Orwell is unusual. The lake is defined as being 6.4 km long at normal full pool level (Table 2) but the effective length of the lake, the length over which the wind can blow undisturbed, is only 3 km. The maximum depth of the lake is about 9.4 m at normal full pool level, and the average depth within the main basin is only 5.3 m. Large erosive waves are not characteristic of lakes with such a short fetch and shallow depth.

An added consideration is that the wind coming off the prairie is virtually unobstructed; the wind at times is therefore strong. Erosion of the colluvium at the base of the banks was witnessed on many occasions during individual storms and especially during the day or so in advance of intense cold fronts. During such events the waves vigorously attacked the base of the banks for long periods, undercutting tham and causing active collapse of the upper banks.

Except during the winter, when the lake is frozen, any storms accompanying the lowering of the pool level will erode the newly exposed offshore sediments, forming a series of strand lines and terraces (Fig. 24). The shape of the pool level curve is generally the same year after year, but variations are important. For example, Figure 25 is a greatly smoothed graph of the pool levels for 1980-81. The pool was typically low during the summer, late winter and spring, and high in the fall. Numerous minor fluctuations (most not shown here) occurred in response to extended dry periods, thunderstorms, and to the power-generating schedule of the Dayton Hollow Dam immediately upstream from Orwell Lake. The rise in level during the fall of 1980 was rather steady, the pool reaching a maximum level of about 325.5 m, and then dropping at a more gradual rate over the late fall and early winter. Erosion by waves that season was minor; the only site noticeably affected was at erosion station 6 (Fig. 6).

In contrast, the pool level trend the following (1981-82) was characterized by a steeper rise, reaching a maximum level about 1 m higher than the previous year, followed by a sharp decline (Fig. 26). Despite the brief period at this peak, considerable erosion resulted. On the basis of the measurement of wave stakes only, only 15 kg of sediment eroded over a 1-m-wide segment of shoreline at erosion station 3. Farther up the lake, at station 6, however, between 0.62 and 0.77 Mg was removed for the same unit length of shore; across the lake at station 12 between 2.17 and 4.93 Mg/m

Figure 24. Erosion station 6, showing steep active bank and terraces formed as pool was lowered (June 1982).

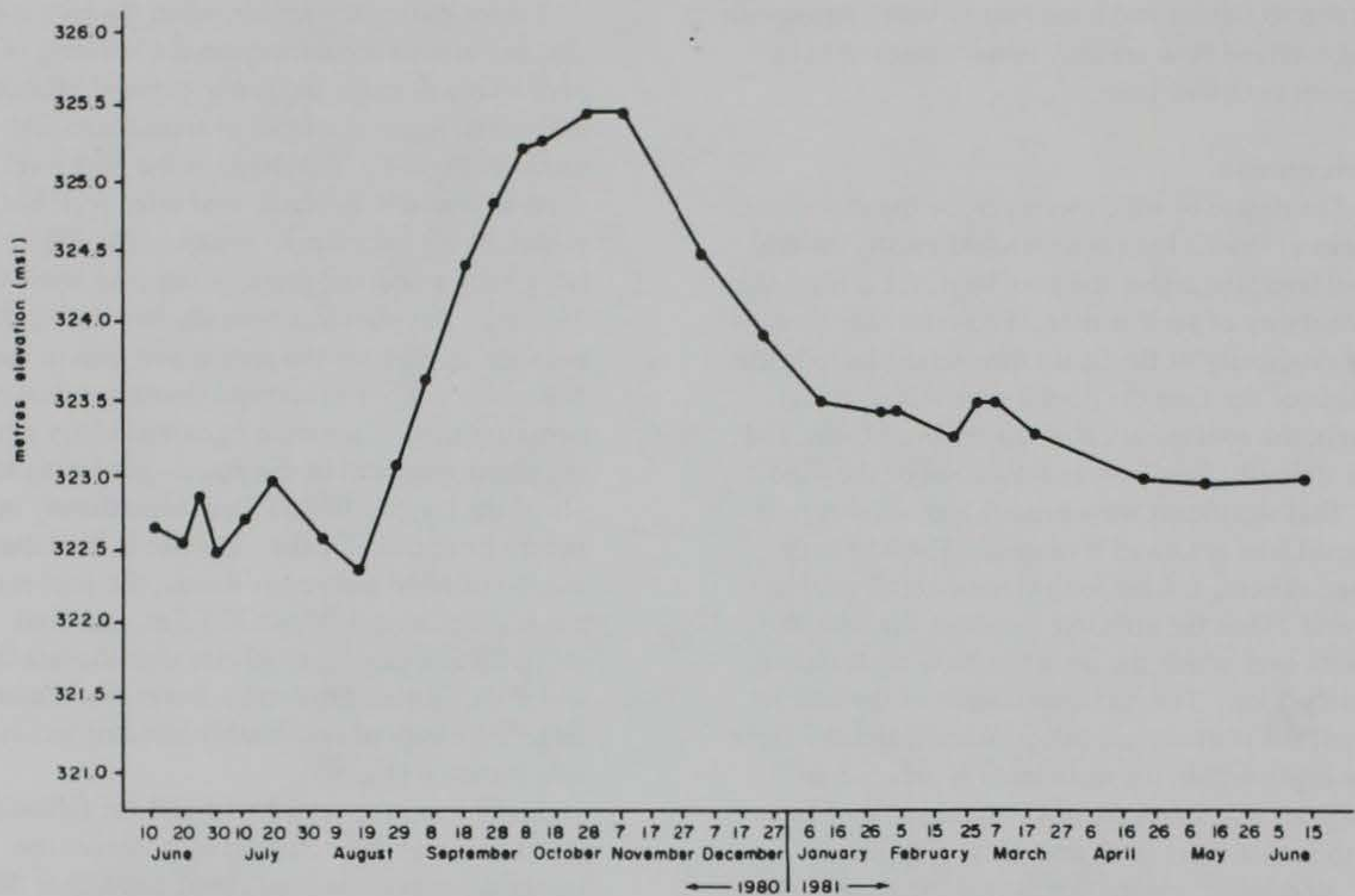


Figure 25. Orwell Lake pool levels 1980–1981.

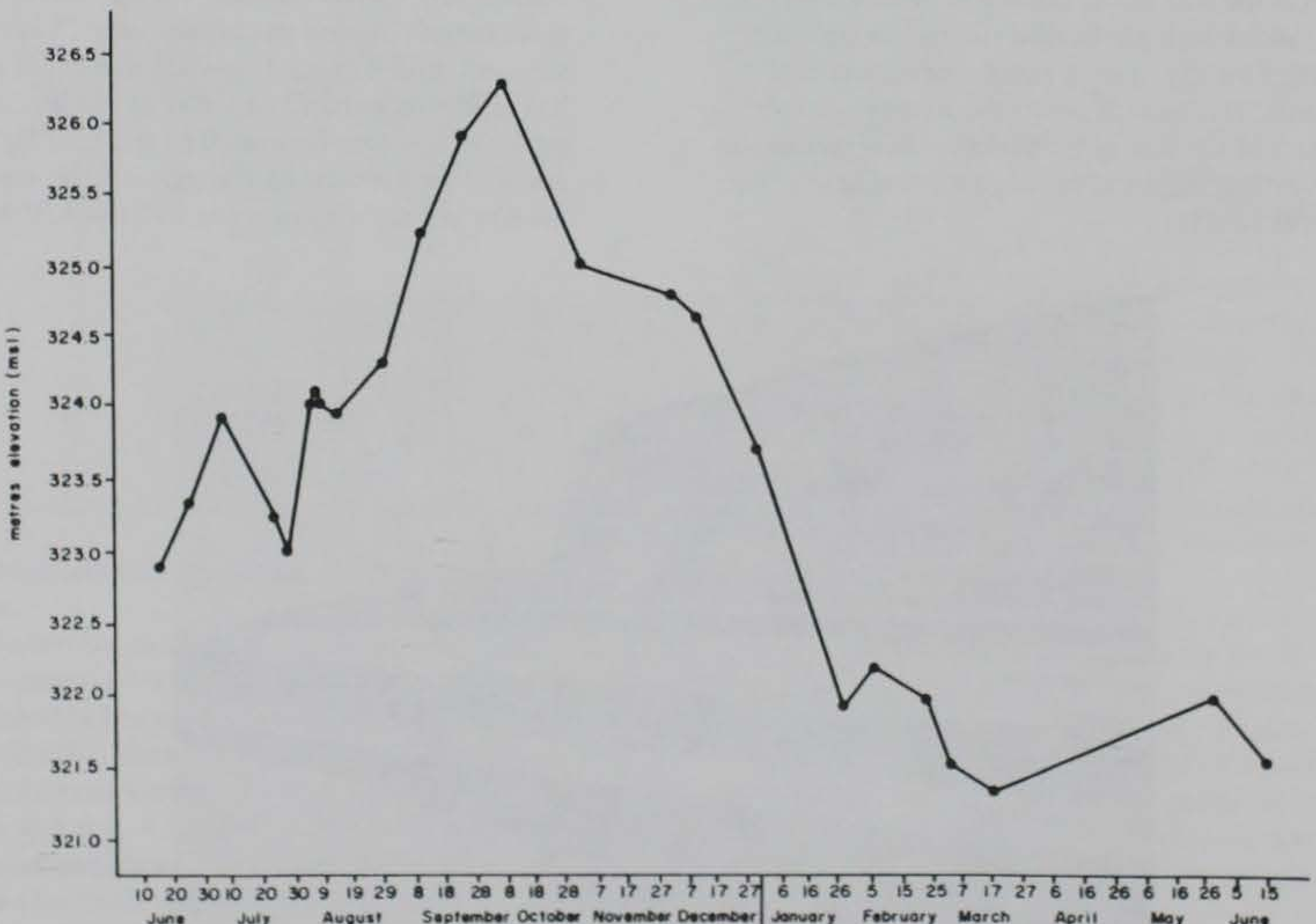


Figure 26. Orwell Lake pool levels 1981–1982.

were removed. This converts to 238 Mg removed by wave erosion for the 195.1-m-long stretch of shoreline at station 12 (see Table 8).

The more useful technique was to determine the profiles of the banks before such erosion and compare the same profiles afterwards. The assumption was that the upper parts of the banks would not be directly affected by the wave erosion at the base, at least not immediately. The results are shown in Figure 27; the shaded sections represent the cross-sectional area eroded by waves during the high pool levels of October 1981. In each case the resulting profile at the base was a vertical bank (Fig. 28), an unstable situation for any material.

In the fall of 1982 the pool level was raised to 326.4 m, where it remained for several days (Fig.

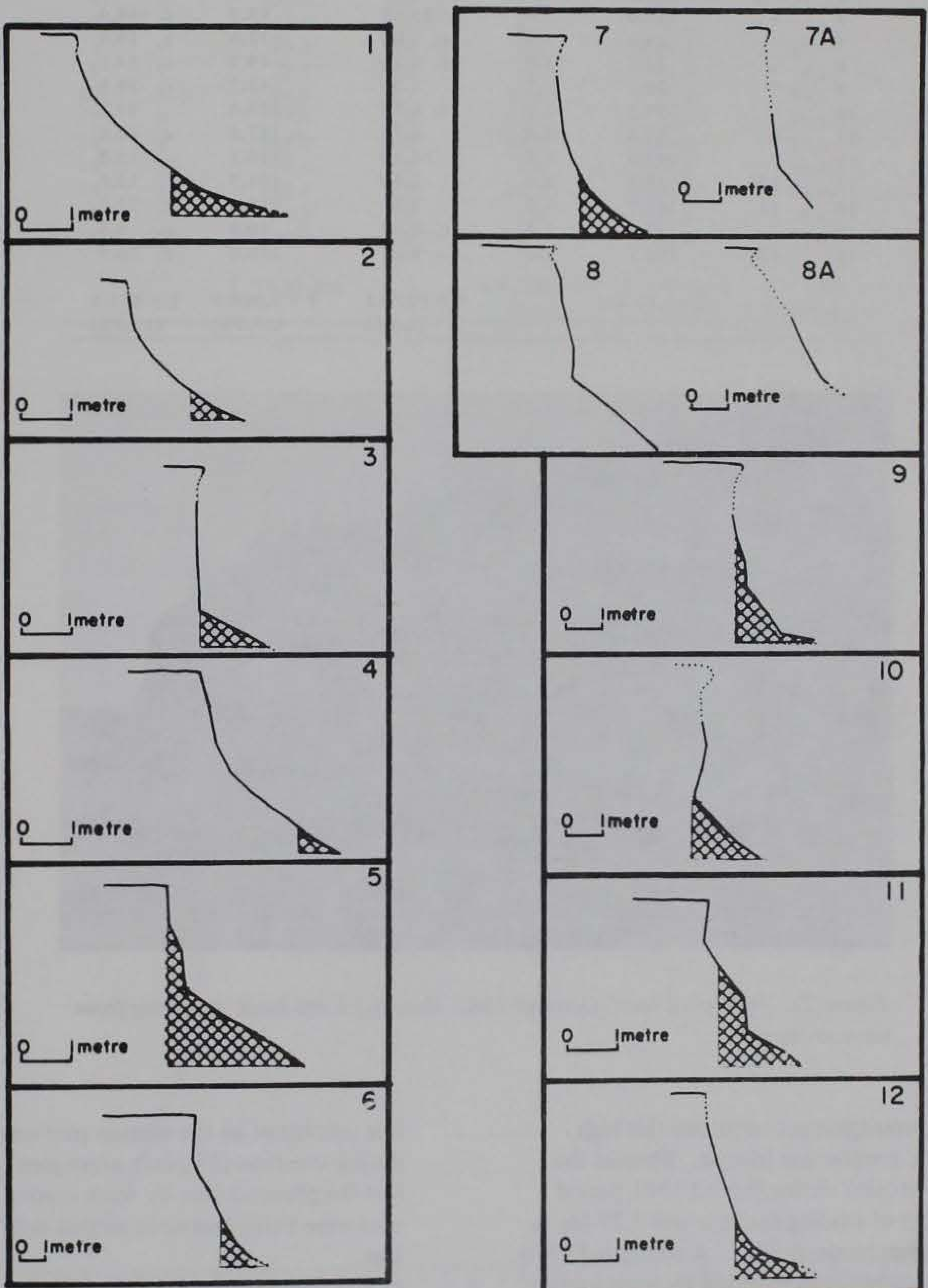


Figure 27. Profiles of Orwell Lake banks at overland erosion station sites before and after wave modification in October 1981. The patterned area was removed by lake erosion. (See Fig. 6 for location of stations.)

Table 8. Shore erosion summary, 1981-1982 season (total erosion by each process for each shoreline section) for Orwell Lake.

Section	Erosion station	Section length (m)	Average height (m)	Summer Overland erosion (Mg)	Fall Wave erosion (Mg)	Spring Thaw failure (Mg)
1	1	82.3	2.0	5.43	c. 36.2	c. 12.9
2	2,3	163.1	2.0	8.81	88.9	25.6
3	–	70.1	1.0	c. 1.12	c. 32.2	c. 11.0
4	–	45.7	1.5	c. 0.21	c. 14.1	c. 7.2
5	4,5	274.3	2.9	11.53	623.1	278.3
6	6	157.0	3.0	23.08	93.3	c. 168.4
7	–	29.0	3.5	c. 2.03	>32.5	c. 29.4
8	–	53.3	3.0	c. 3.20	>59.7	c. 54.1
9	7	38.1	1.7	1.30	42.7	c. 38.6
10	–	97.5	3.2	c. 6.86	c. 221.4	99.0
11	8	51.8	4.0	4.56	c. 117.8	c. 16.6
12	9	105.0	5.0	14.18	128.1	15.8
13	10	79.8	3.0	2.40	101.7	12.0
14	11	141.7	2.0	7.94	218.8	c. 21.0
15	–	33.1	1.2	c. 0.68	c. 40.4	c. 5.0
16	12	195.1	2.8	9.29	238.0	c. 28.9
		T = 1.62 km		T = 102.62 (3.4%)	T = 2,088.9 (69.3%)	T = 823.8 (27.3%)

Figure 28. High pool level, October 1982, showing steep bank resulting from wave erosion.

29). Wind storms again accompanied this high stage and bank erosion was intense. Whereas the average wave erosion during the fall 1981 period was 1.27 Mg/m of eroding shore, it was 3.77 Mg/m during the higher levels of 1982. A calculated 4376 Mg of bank sediment was removed by wave impact and transported into the deeper parts of Orwell Lake that fall (Table 9). The extra-high pool level, together with a long period at that level, allowed for much more erosion to occur than usual. Forty-five percent of all the erosion pins were destroyed during this time (37 pins); more pins (45) were lost the previous year by wave erosion, but more pins were being measured so that only 35% were lost.

Careful observation of the wave erosion, as it was occurring, and the examination of the shoreline segments afterwards, revealed that the waves normally do not erode much till; it is too compact to be readily eroded this way. The mass removed by

Table 9. Shore erosion summary, 1982-1983 season (total erosion by each process for each shoreline section) for Orwell Lake.

Section	Erosion station	Section length (m)	Average height (m)	Summer Overland erosion (Mg)	Fall Wave erosion (Mg)	Spring Thaw failure (Mg)
1	1	82.3	2.0	11.9	114.1	20.6
2	2,3	163.1	2.0	23.8	5.0	36.6
3	–	70.1	1.0	5.1	48.6	17.6
4	–	45.7	1.5	4.1	24.3	10.0
5	4,5	274.3	2.9	43.1	12.3	232.6
6	6	157.0	3.0	16.1	326.4	33.2
7	–	29.0	3.5	6.2	70.3	8.6
8	–	53.3	3.0	9.8	110.8	20.6
9	7	38.1	1.7	4.1	22.9	4.2
10	–	97.5	3.2	20.9	4.8	78.6
11	8	51.8	4.0	13.9	73.4	31.8
12	9	105.0	5.0	20.5	323.0	77.8
13	10	79.8	3.0	9.8	147.5	44.4
14	11	141.7	2.0	14.5	1008.2	44.0
15	–	33.1	1.2	1.4	141.3	8.2
16	12	195.1	2.8	3.3	1943.3	77.6
		T = 1.62 km		T = 208.2 (3.9%)	T = 4376.2 (82.1%)	T = 746 (14.0%)

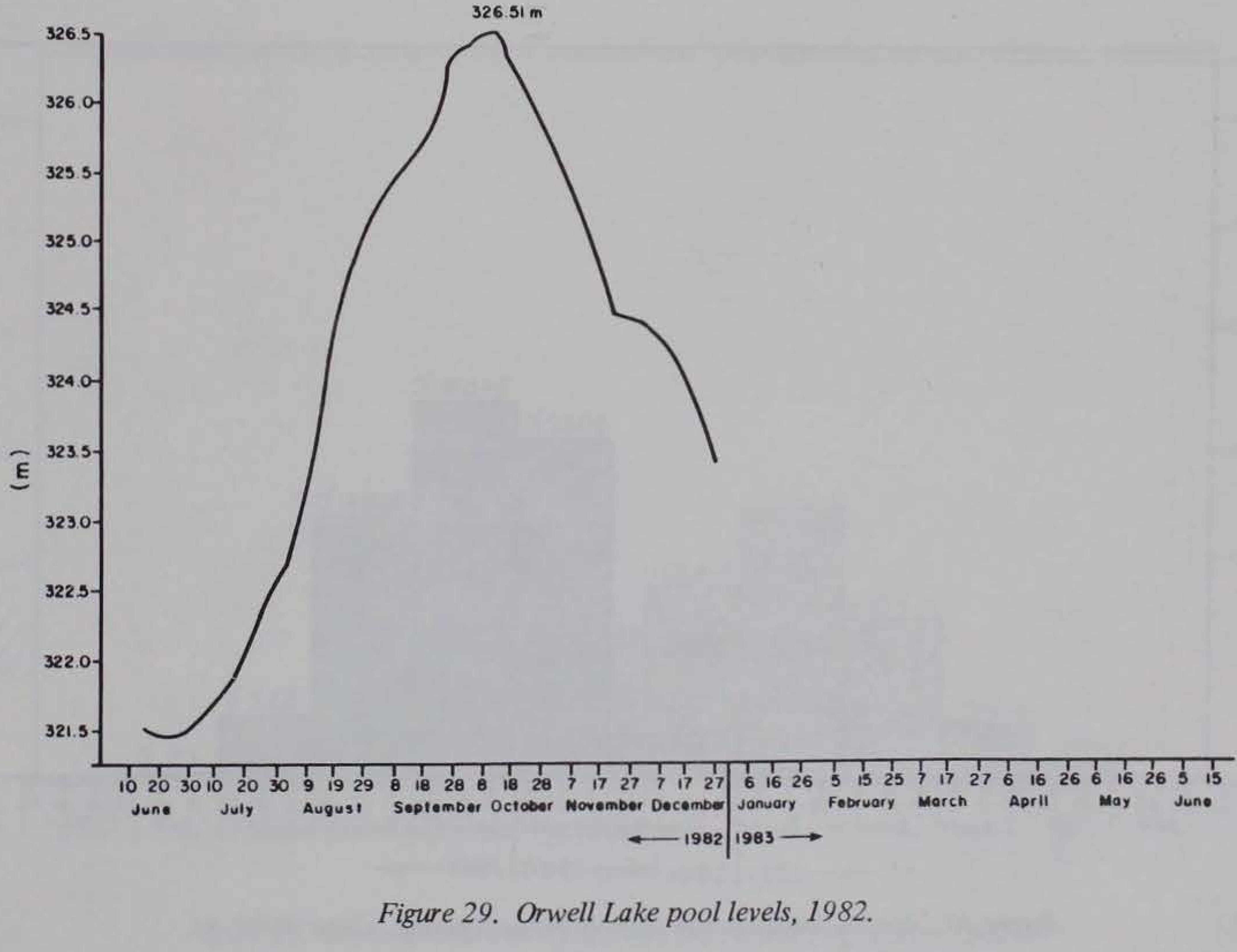


Figure 29. Orwell Lake pool levels, 1982.

such wave action is almost entirely the colluvium deposited at the base of the banks by rainsplash and interrill erosion, and by various processes of mass wasting, although some till must be removed, were to maintain the near-vertical banks (as were formed at station 12 in 1982). Wave-worn masses of till, up to cobble size, were collected near erosion station 5 in the fall of 1981, but were seen nowhere else. It is concluded that the primary result of wave erosion is the translocation of colluvium into the deeper parts of the lake, thereby making room for the renewed deposition of more colluvium.

Freeze-thaw phenomena

Frost penetration

The winter of 1980-81 was relatively warm. The average temperature of the cold season (September through April) was -4.5°C, with the first persistent frost occuring on December 1. There were, as a result, 122 days in which the temperature fluctuated above and below the freezing point (Table 10). The 1981-82 cold season began two weeks earlier, on November 15; the average winter temperature was almost 6°C lower and the temperature fluctuated above and below the freezing point during only 75 days. The third winter, 1982-83, was warm again, with an average temperature of +0.3°C and 103 days in which the temperature fluctuated above and below the freezing point. In the 1980-81 winter there were 980 freezing degree days (FDD) (Fig. 30) (Hill 1973). The next winter had 1,495 FDD (Fig. 31). The 1982-83 winter was characterized by only 778 FDD (Fig. 32). Despite the considerably colder winter, the maximum penetration of the zero isotherm during the 1981-82 winter was the same or only slightly more than in 1980-81, because of a

Table 10. Winter weather summary (September through April) Orwell Dam Station.

	1980-81	*1981-82*	*1982-83*
Average temperature	-4.5°C (23.9°F)	-10.2°C (13.7°F)	+0.3°C (32.5°F)
Total precipitation	32.5 mm (1.28 in.)	94.7 mm (3.73 in.)	270 mm (10.64 in.)
First persistent frost	1 Dec.	15 Nov.	4 Nov.
Maximum frost penetration	1.4 m	1.4 m	1.0 m
Number of fluctuations above/below freezing	122 days	75 days	103 days
Cumulative average freezing degree days	980	1,495	778

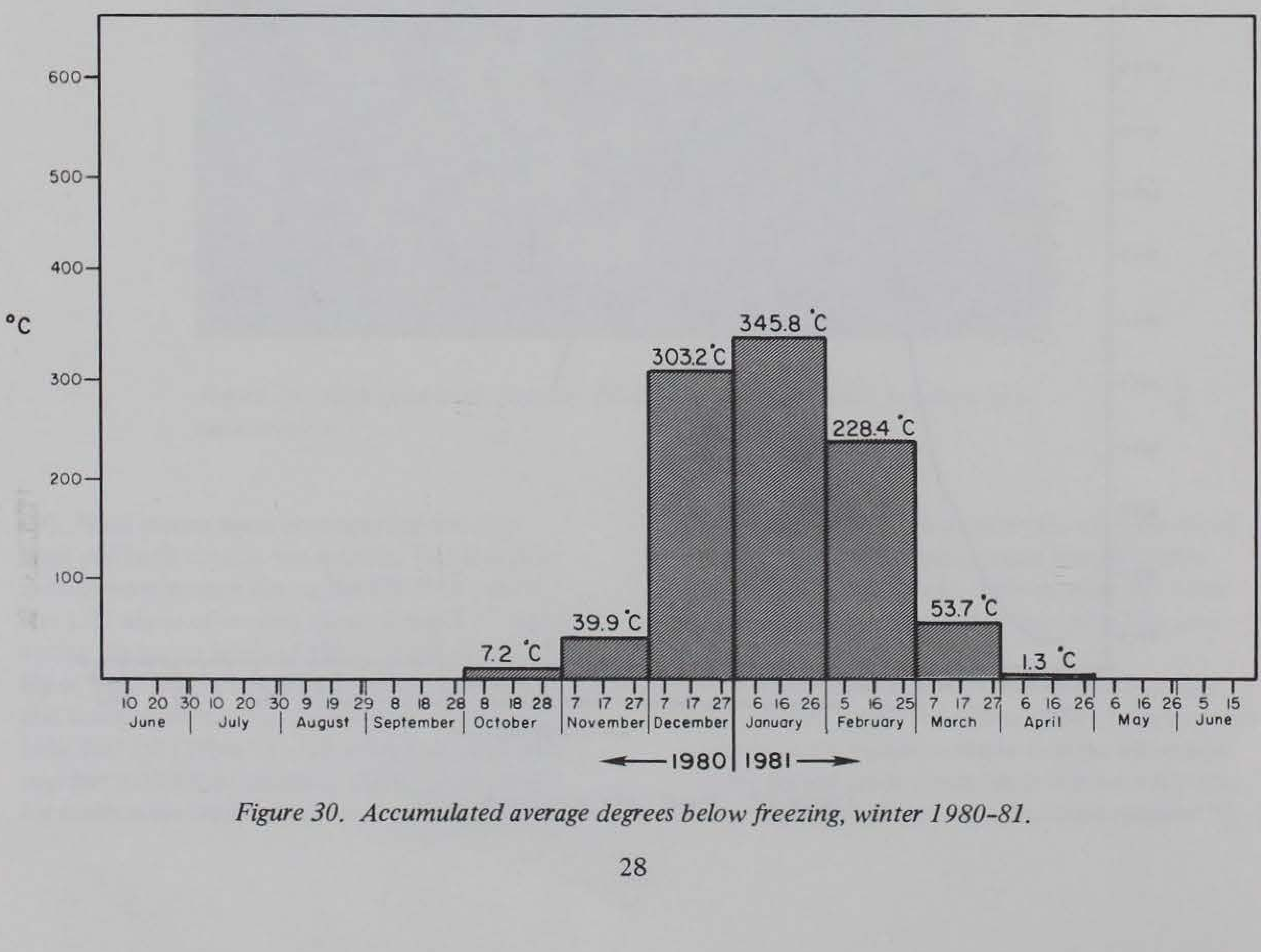


Figure 30. Accumulated average degrees below freezing, winter 1980-81.

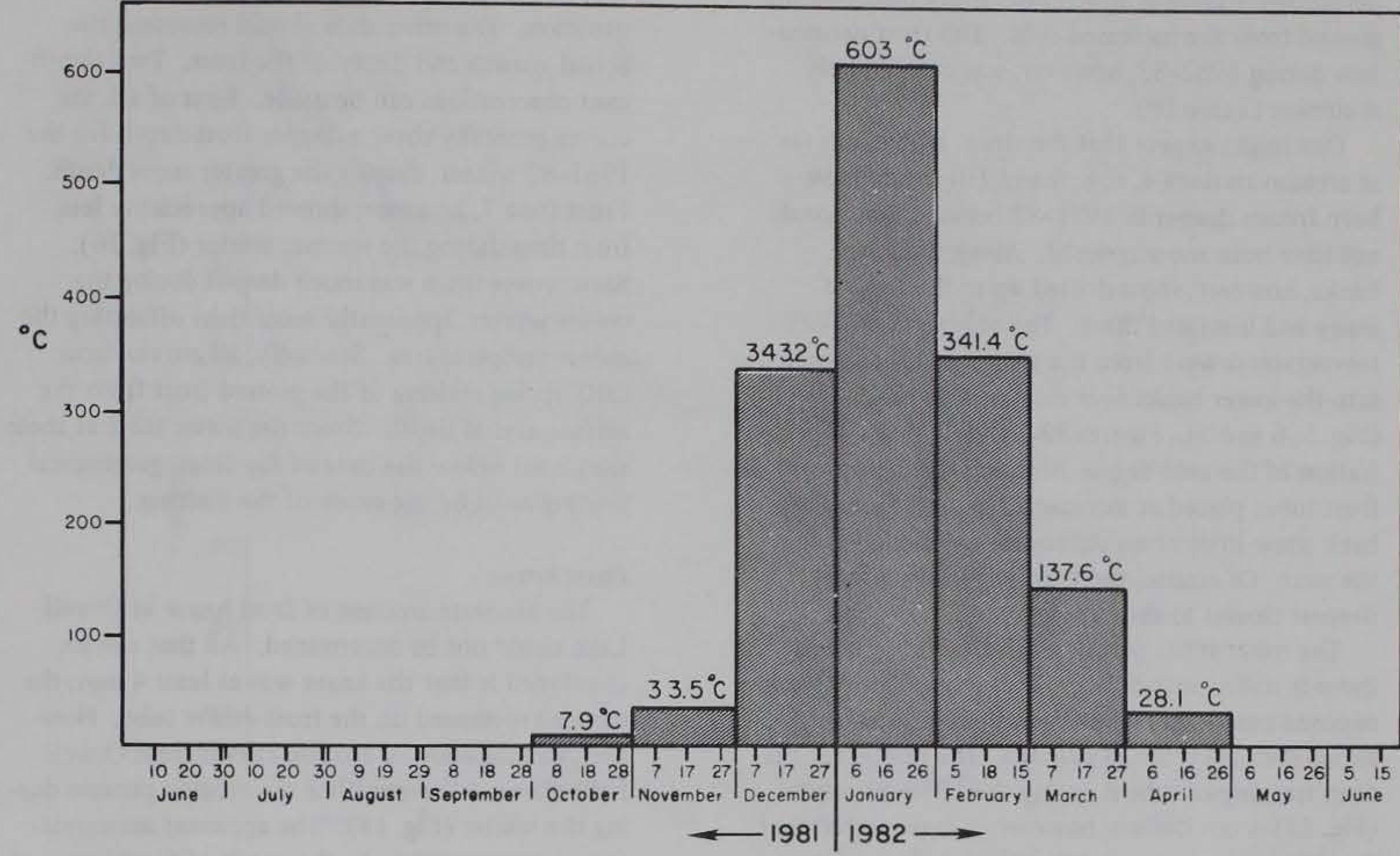


Figure 31. Accumulated average degrees below freezing, winter 1981–82.

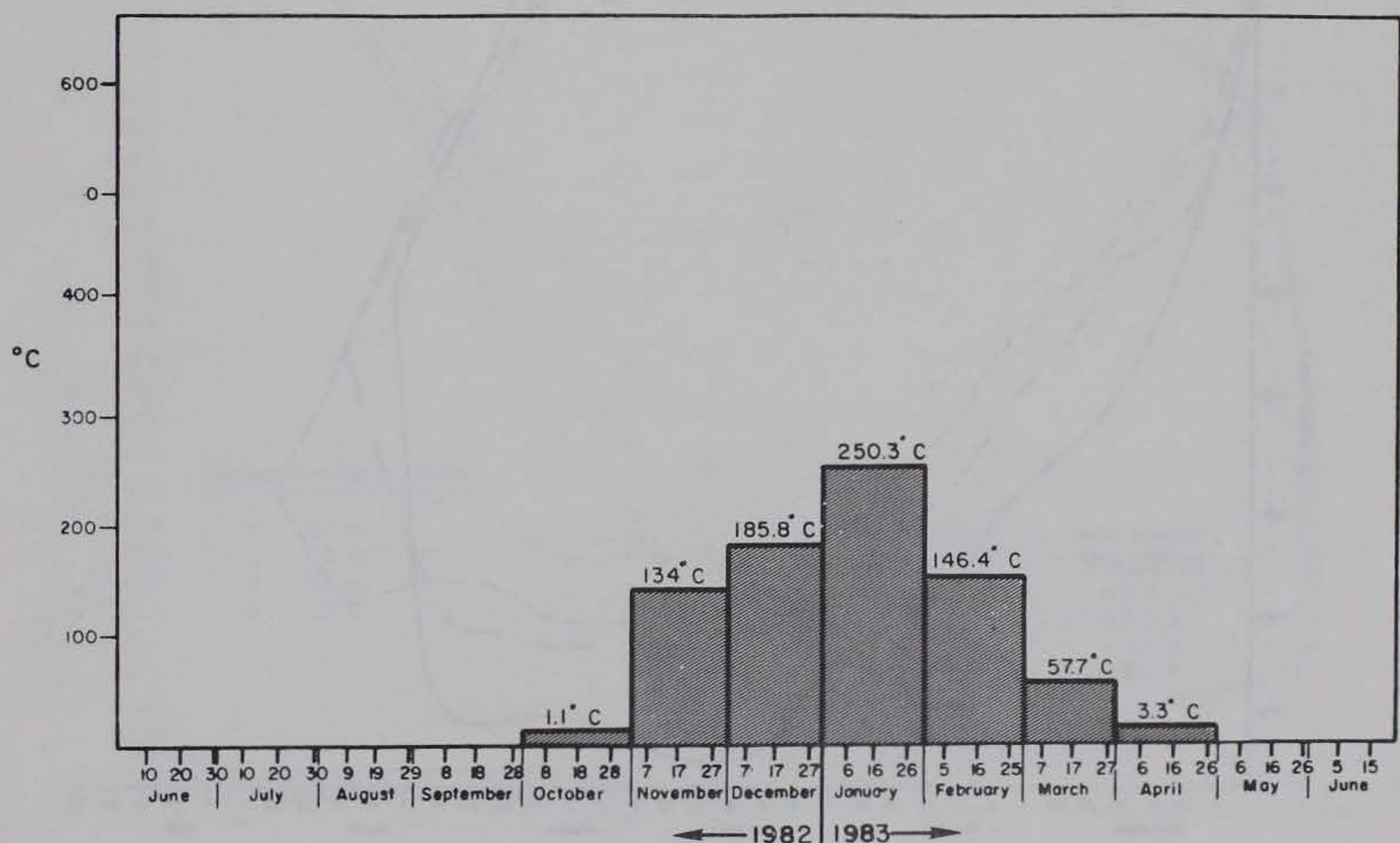


Figure 32. Accumulated average degrees below freezing, winter 1982–83.

deeper snow blanket which effectively insulated the ground from the increased cold. The frost penetration during 1982-83, however, was considerably shallower (Table 10).

One might expect that the steep, high banks (as at erosion stations 4, 6, 8, 9 and 10) would have been frozen deeper in 1981-82 because they would not have been snow covered. Along the lower banks, however, snow drifted up to the tops of many and insulated them. The only data on bank temperatures were from the two frost tubes inserted into the lower banks near erosion stations 2 and 11 (Fig. 5, 6 and 9). Figures 33-38 show that the penetration of the zero degree isotherm for the set of frost tubes placed at increased distances from the bank show little or no difference from one year to the next. Of course, the frost penetration was deepest closest to the exposed bank.

The other tubes permit a comparison between those installed vertically on level ground away from exposed banks, and those two tubes inserted into exposed banks (Fig. 34 and 36). The reason for the deep freezing of tube 8 during the 1980-81 winter (Fig. 34) is not known; however, it is suspected that the tube was open to the air between the readings of 26 December and 28 January. The resulting curve, therefore, does not reflect the undisturbed situation. The other data should represent the actual growth and decay of the frost. Two significant observations can be made. First of all, the curves generally show a deeper frost depth for the 1981-82 winter, despite the greater snow depth. Frost tube 7, however, showed appreciably less frost than during the warmer winter (Fig. 36). Snow cover there was much deeper during the colder winter, apparently more than offsetting the colder temperatures. Secondly, all curves show early spring melting of the ground frost from the surface *and* at depth. Since the water table at these sites is far below the base of the frost, geothermal heating must be the cause of the melting.

Frost heave

The absolute amount of frost heave at Orwell Lake could not be determined. All that can be concluded is that the heave was at least 4 mm, the amount measured on the frost-heave tube. However, examination of erosion curves from Orwell Lake shows a "reversal" of the erosion process during the winter (Fig. 18). The apparent accumulation is interpreted to be the result of frost heave of the bank surface around the erosion pins. Again,

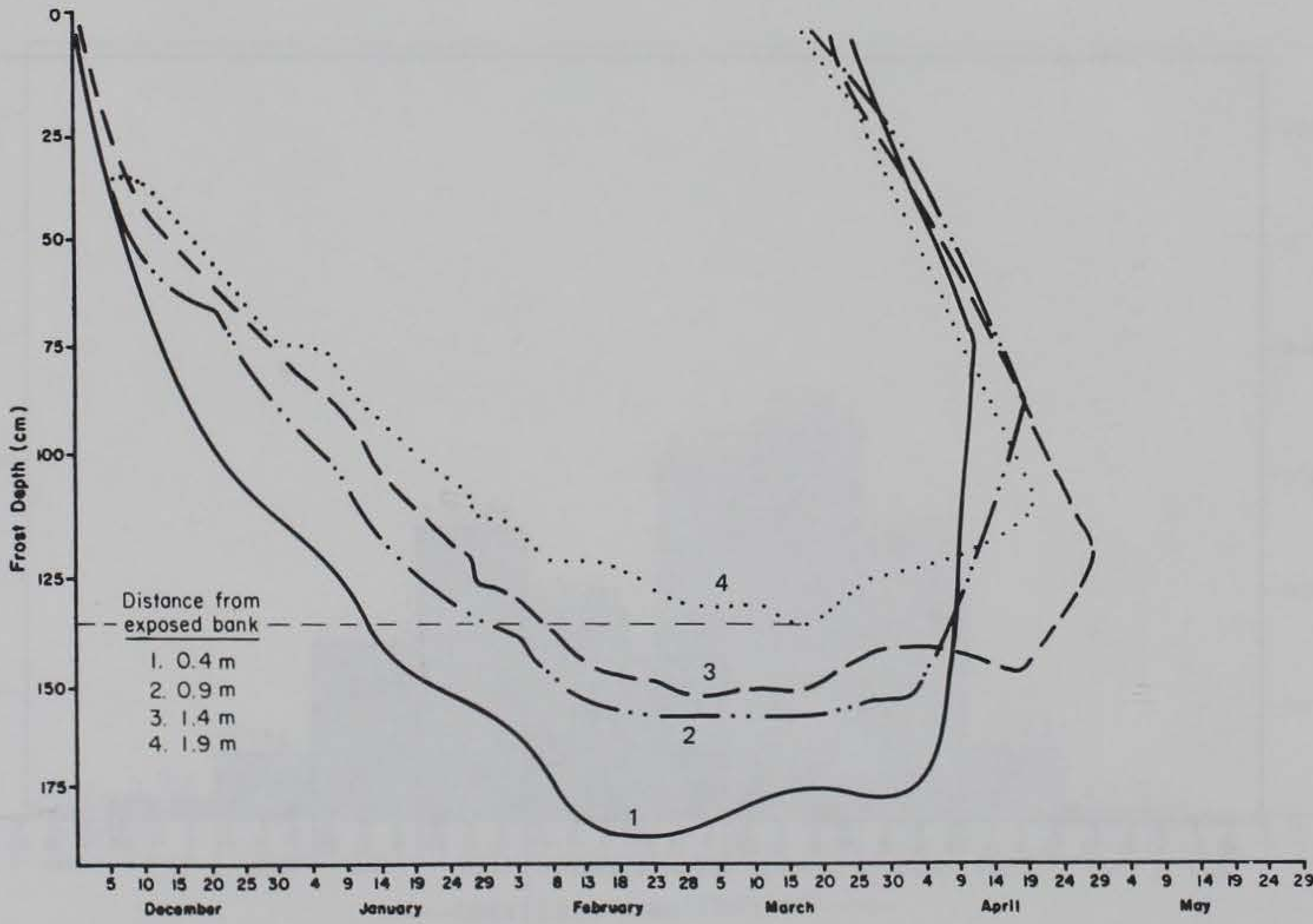


Figure 33. Penetration of frost (winter 1980–81), tubes 1–4.

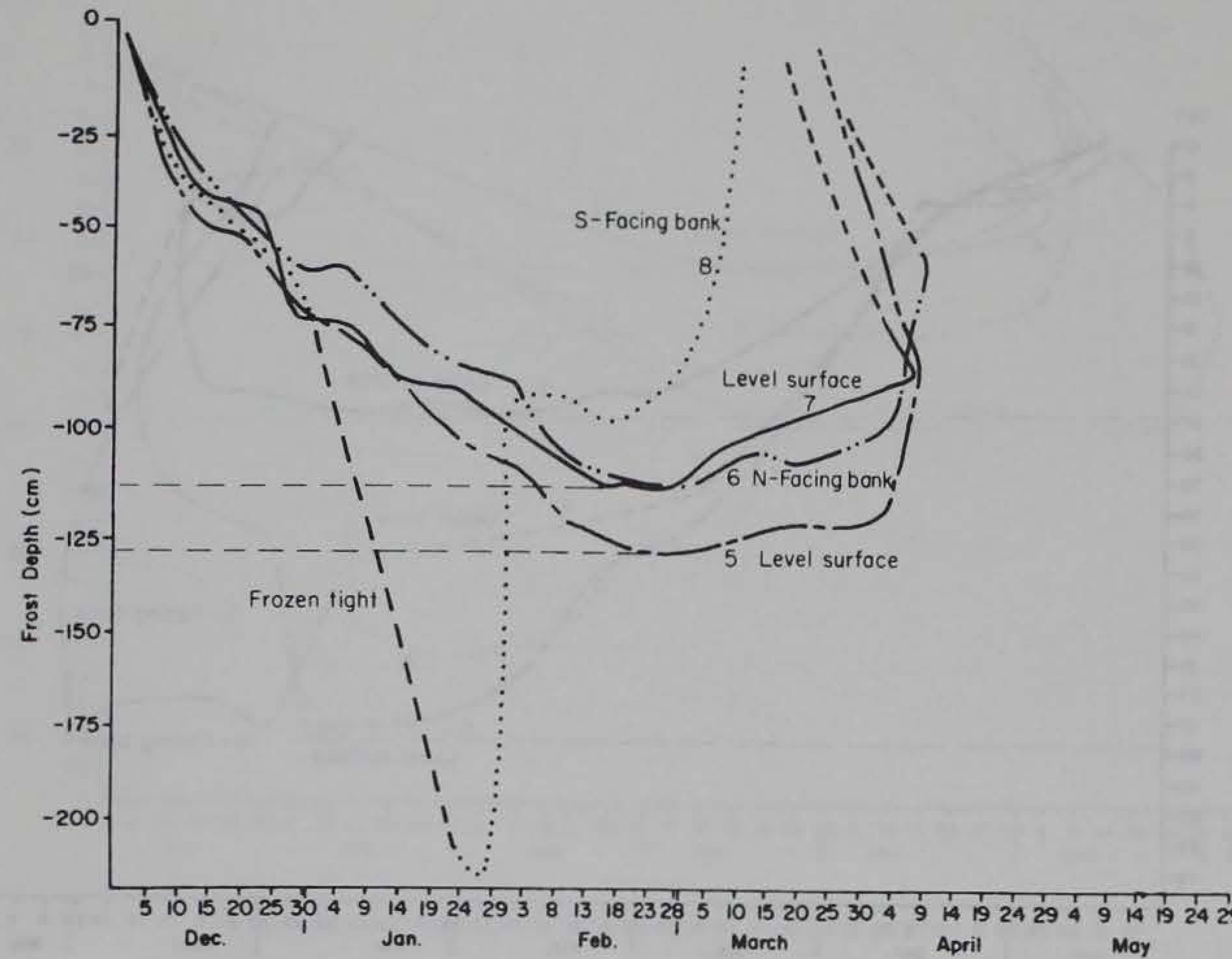


Figure 34. Penetration of frost (winter 1980–81), tubes 5–8.

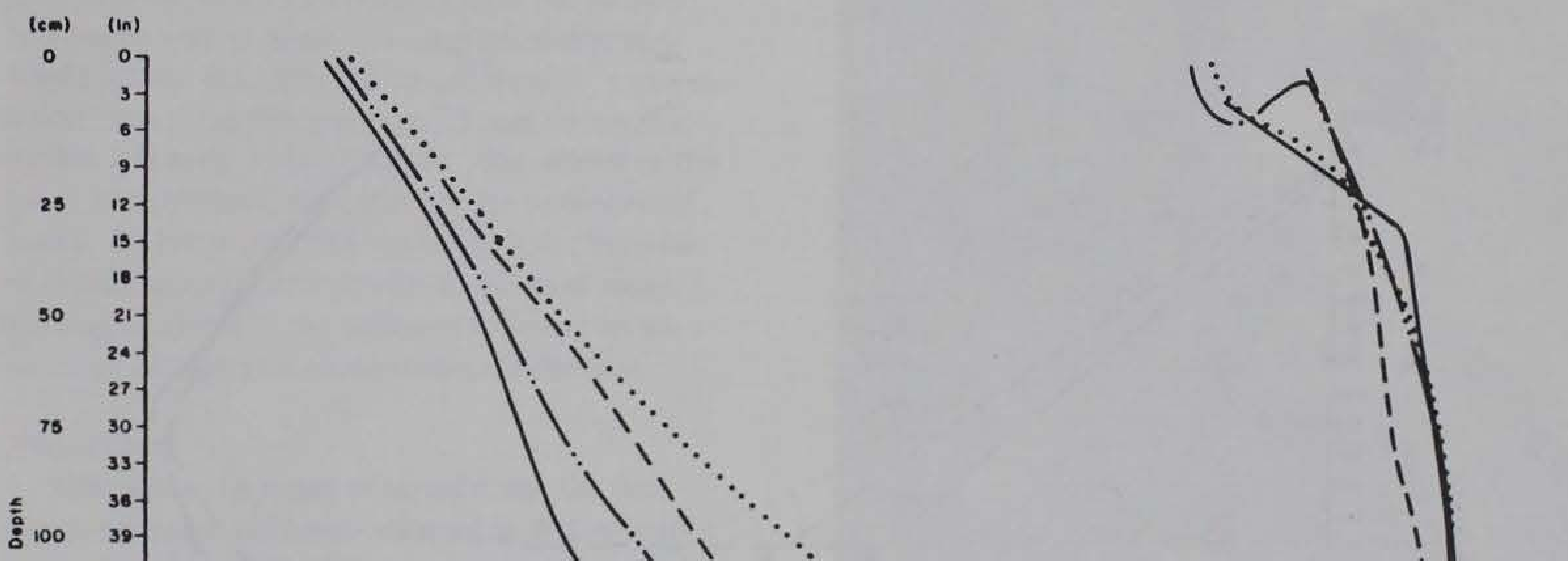


Figure 35. Penetration of frost (winter 1981–82), tubes 1–4.

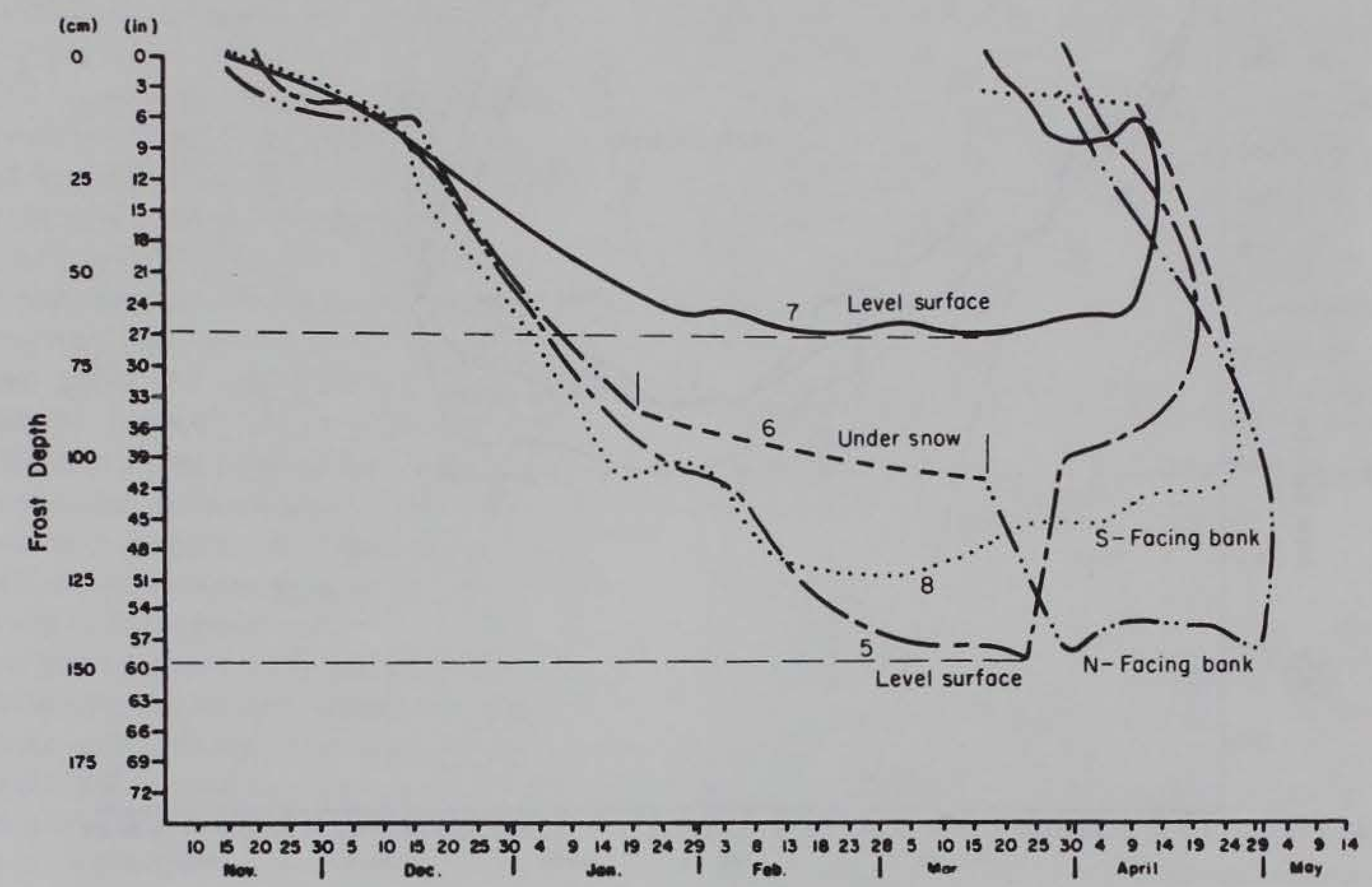


Figure 36. Penetration of frost (winter 1981-82), tubes 5-8.

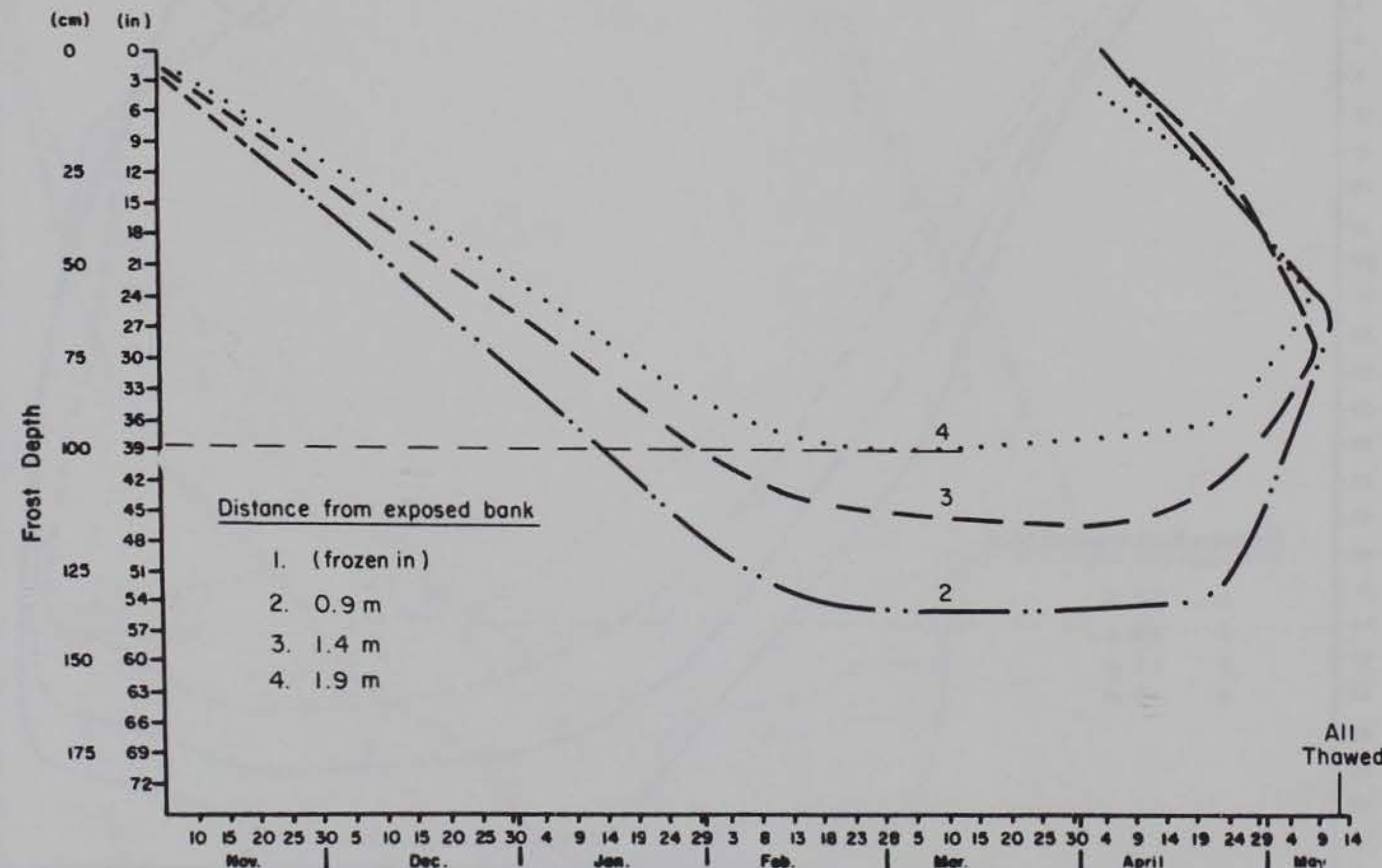


Figure 37. Penetration of frost (winter 1982-83), tubes 2-4.

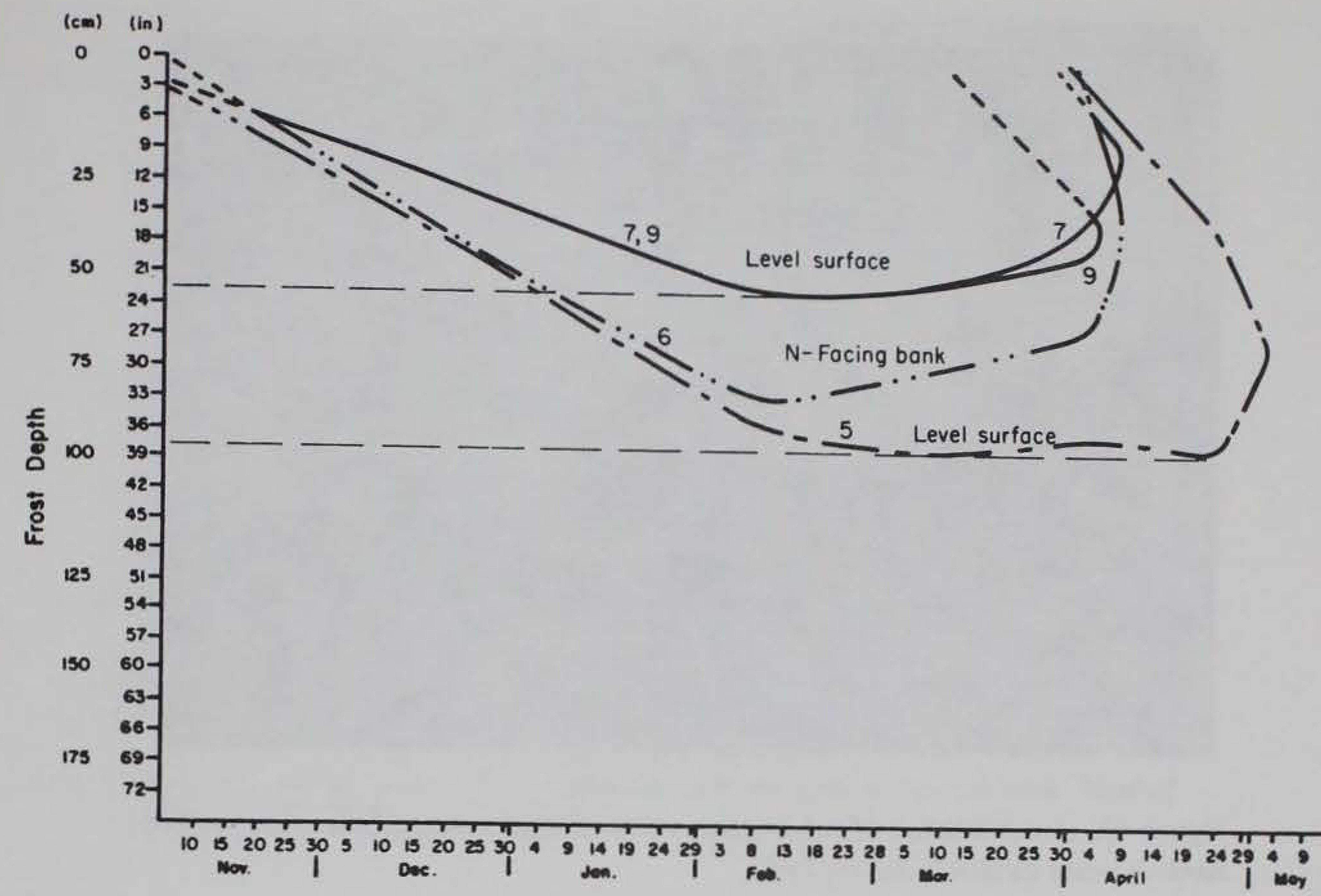


Figure 38. Penetration of frost (winter 1982-83), tubes 5-9.

this amount should represent a minimum value for frost heave at these sites because once the ground had frozen a short depth the subsequent freezing would lift the pin. The maximum average "accumulation" measured this way was 5.5 mm for erosion station 2 in early 1981 (Table 5). The effects of the heave were obvious, especially on the near-vertical banks. By late winter the banks displayed myriads of closely spaced joints parallel to the bank faces. Spalling of sheets of the sediment followed an initial stage of aggregate accumulation at the base.

Thaw failure

Although not a result of actual thaw, the first failure of frozen sediment occurred in mid-winter as interstitial ice in the frozen sediment began to sublimate in response to the cold, dry air. Individual aggregates several millimeters in diameter began to accumulate at the base of the banks. In the winter of 1980 the aggregates were very obvious as they veneered the snowbanks below (Fig. 39). The next year, late January 1981, and again the following winter, the accumulation was clearly measurable in the absence of snow (Fig. 40) and plastic sheets, set at the base of banks in the winter of 1982 to measure thaw failure, soon became veneered with sediment. The amount of sediment removed from the exposed bank faces by this process is comparatively minor, certainly much less than 1% of the total

Figure 39. Accumulation of sublimation-released aggregates onto snowbank at erosion station 4, February 1980.

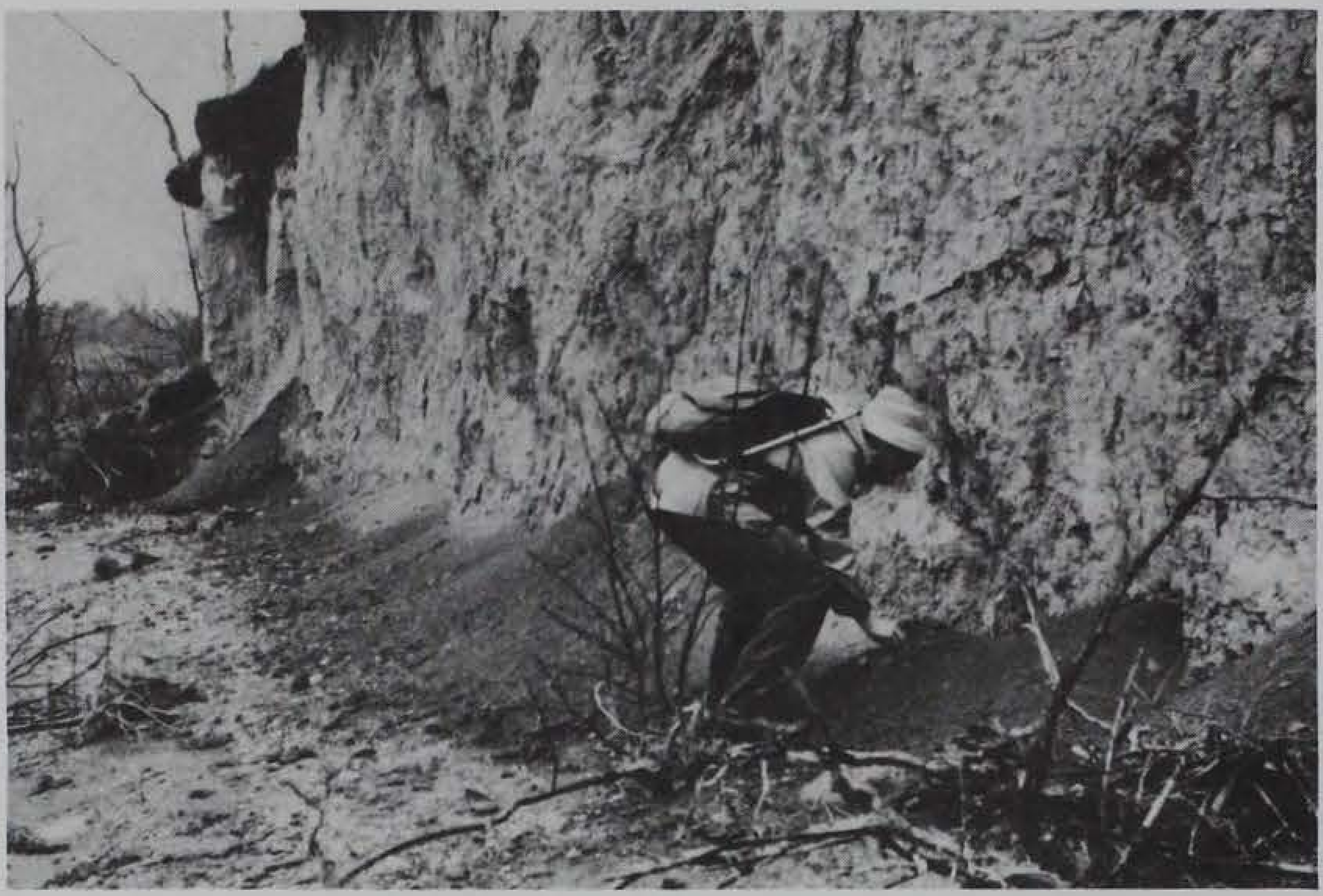


Figure 40. Accumulation of sublimation-released aggregates at base of snow-free bank; erosion station 9, March 1982.

erosion at each site. Release of aggregates from steep banks has been reported by others (Harrison 1970, Wolman 1959, Hooke 1979).

Once temperatures began to rise above the freezing point, massive slope failure also began. The failure was manifested in planar slipping along frost-expanded joints in the till, followed by flow of the surface sediment. As expected, the south-facing banks began to fail first. Figure 41 shows a small mudflow that extended onto a residual snowbank. Such flows were rare. More commonly, the mud flowed as sheets (rather than as lobes) that spread over the remnant snow (Fig. 42). This photograph near erosion station 12 reveals the effects of the melting of the formerly mud-veneered snow. Collapse and desiccation have left an irregular and cracked surface.

The first attempt to quantify the amount of thaw failure was by use of erosion pins. Depending on the station, the measured thaw failure was either the amount eroded around the pins, or the amount accumulated on them. Pins high up on the slopes, of course, tended to measure erosion; thawed sediment would come to rest at the base of the banks, burying the lower pins. So, the results of the first year were evaluated on the basis of steeper vs more gentle sections of the stations (Fig. 18, Table 11, and App. A1). As can be seen from the table, measured thaw failure is almost always less than summer overland erosion, whether the slopes are steep or gentle (the gentle slope at erosion station 6 is the exception)

Figure 41. Small mudflow onto remnant snowbank at erosion station 11, February 1981.

Figure 42. Sheet flows of mud deposited over snowbank, now melted. West of erosion station 12, March 1982.

Table 11. Comparison of thaw failure amounts on steep and gentle slopes, spring 1981, Orwell Lake (data from erosion pins only).

Erosion station	Bank height (m)	Total average thaw failure for steeper slope (mm)	(kg)	(kg/m²)	Bank height (m)	Total average thaw failure for gentler slope (mm)	(kg)	(kg/m²)
2	0.92	14.4	20.4	22	2.72	5.5	23.0	8
3	2.67	2	8.2	3	1.38	3	6.37	5
4	2.72	2	8.4	3	1.41	8	17.37	12
5	2.03	7	21.9	11	2.79	–	–	–
6	6.10	–	–	–	1.41	10	21.71	15
7	3.34	–	–	–	2.69	6	24.86	9
8	3.59	2	11.1	3	2.80	10	43.12	15
9	3.51	0	–	–	1.98	5	15.25	8
10	3.55	1	5.5	2	2.03	1	3.13	2
11	–	–	–	–	–	–	–	–
12	3.36	0	–	–	0.69	–	–	–

because the procedure is designed more to measure erosion than accumulation. The graphs in Appendix A reflect average changes from one date to another, but some pins along the lower parts of the stations were occasionally lost by burial and could not be located. Such pins were omitted from the subsequent calculations, effectively skewing the results toward less thaw accumulation. The results of the first year, therefore, were an underestimation of the degree of thaw failure at Orwell Lake.

The most accurate measurement of thaw failure was for the 1982 spring when thawed sediment accumulated onto sheets of plastic set at the base of representative sections prior to the winter freeze and following the drop in pool level in the fall (Fig. 11). The toes of the banks were excavated after all thaw had ceased. The volume of sediment resting on the sheets was the amount accumulated from thaw. Although the significance of thaw failure had been surmised from the results of the first spring thaw, the actual mass and variability between stations was, until this measurement, unknown. The results are presented on Tables 8 and 9. The stations where accurate measurements were made are listed with positive values; extrapolation between stations is shown by values that are approximate, e.g. section 1, c. 12.9 Mg. A total mass eroded by thaw failure at Orwell Lake amounted to 823.8 Mg for the 1.62 km of shoreline characterized by active erosion (Appendix B). Of greatest significance is that this represents 27.3% of all erosion occurring here in the spring of 1982, but only 14% in the spring of 1983.

The difference in total mass for the two years was less dramatic, 824 Mg in 1982 and 746 Mg in 1983 (Tables 8 and 9).

Ground water fluctuations

The locations of the piezometer wells and their interpreted stratigraphy are noted on Figures 12 and 43, respectively. The units in the stratigraphic columns for each well correspond to those described in Figure 15, units A and B being the Dunvilla and Barnesville formations, respectively. The position of the screened interval and an average head level are also shown.

The results of measuring these wells (Fig. 44 and 45) reveal that the topographically lower areas are characterized by a piezometric head that fluctuates with the pool levels. This is especially true for wells 1, 5 and 6. It is concluded that the aquifers at these wells are hydraulically connected to the lake interface. (Compare the pool level fluctuations with the piezometric heads for these wells.)

Piezometer 7, positioned slightly lower than 5 and 6, was expected to fluctuate much like the other three wells; such was not the case. This well was installed upslope from a discharge zone to the south of piezometer 4 (Fig. 12). The head for this well is considerably greater than for the other three wells at a similar elevation, perhaps because there is a larger area of higher ground behind it than at the other sites. The aquifer for these four wells is stratigraphic unit B and recharge is probably through the highly jointed Barnesville till.

The remaining three piezometers (2–4) were installed at the head of an extensive slump zone that first began to fall in the spring of 1977. Ground water pressures are believed to have been the triggering mechanism for this failure. Monitoring of the piezometric heads at three separate aquifer levels was undertaken to gather clues about the ground water system there. Figures 44 and 45 show that very little change occurred in these wells over the two years of measurements. The initial rapid rise of water in well 4 (Fig. 44) reflects the fact that the well did not reach equilibrium until 12 August. The other wells reached equilibrium quickly. Of significance is the observation that so little change did occur in these wells even over extended dry periods, e.g. the winter months. These aquifers are, therefore, believed to be recharged slowly through the overlying till aquitards.

Because no slumping occurred during this study, an analysis of hydrostatic pressures as a cause of such failures could not be made.

It is concluded that ground water was not an important cause of erosion anywhere in the lake during the three years of study. Occasionally, however, it becomes a significant cause of massive bank failure.

Other slope failures

Historical slope failures have sometimes been dramatic. The entire eastern end of Orwell Lake is marked by slump and earthflow topography. Although these are not the result of any processes

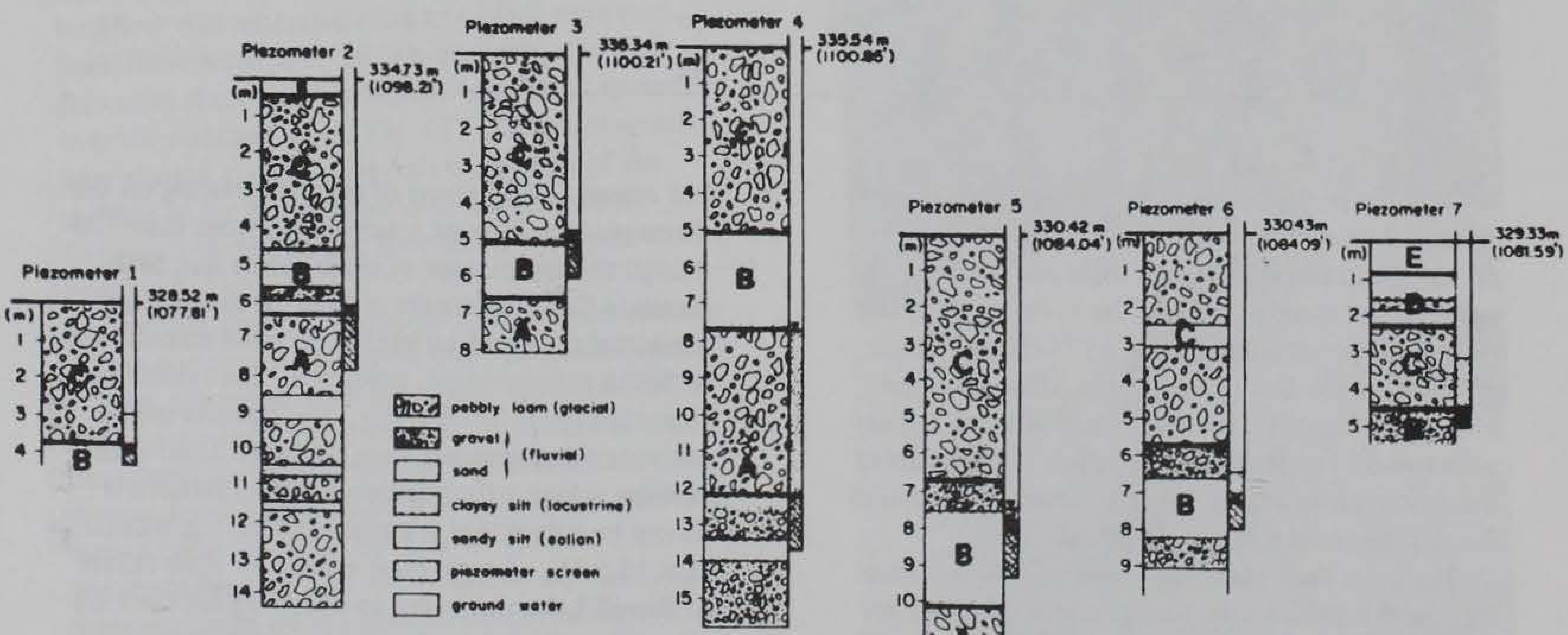


Figure 43. Lithologies and interpreted stratigraphy at the piezometer stations, showing the position of the screen and the water table for each site.

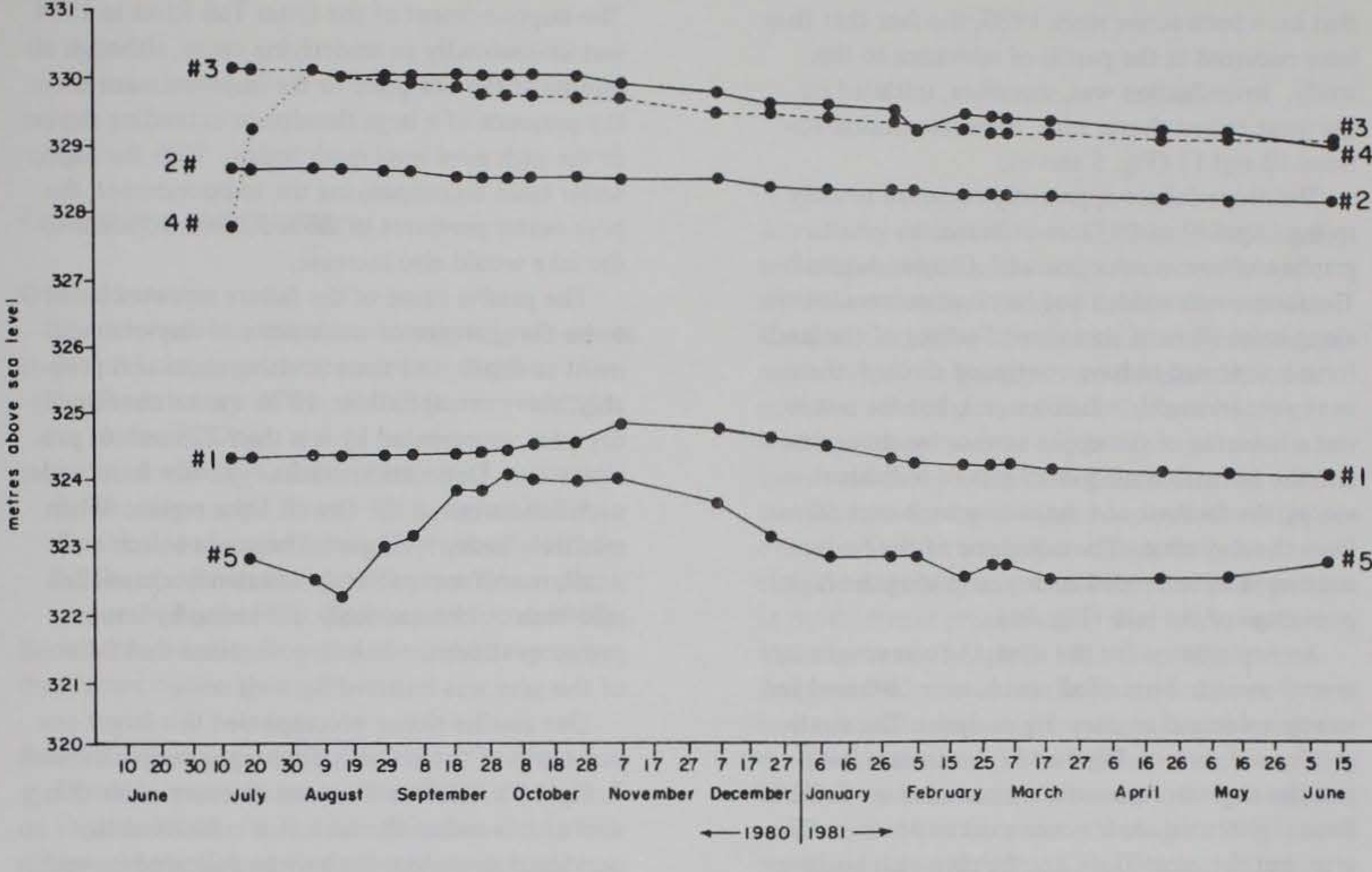


Figure 44. Piezometric head fluctuations, 1980–81.

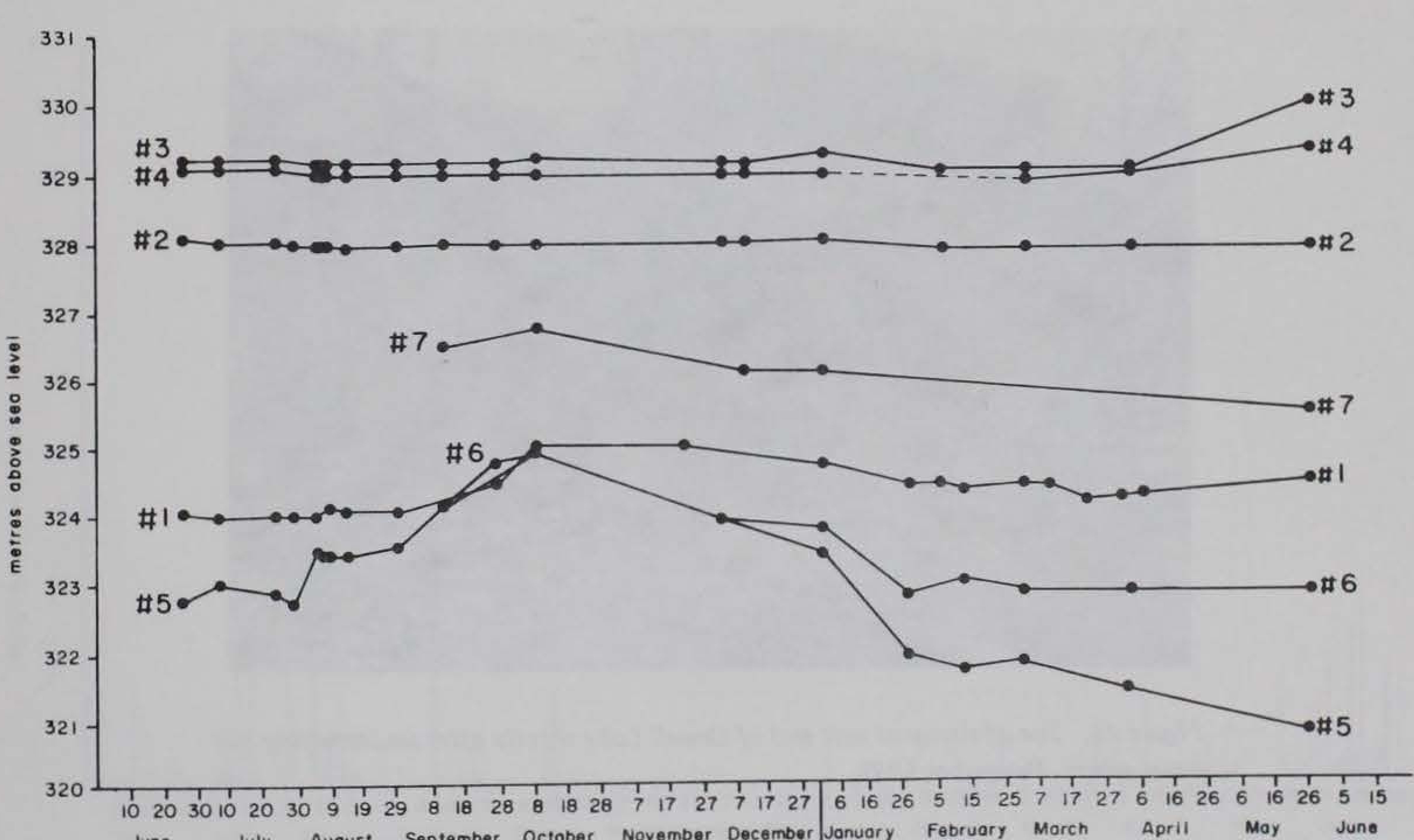


Figure 45. Piezometric head fluctuations, 1981–82.

that have been active since 1980, the fact that they have occurred in the past is of relevance to this study. Investigation was, therefore, initiated on the most recent slump zone, between erosion stations 10 and 11 (Fig. 5 and 6).

This slope failure apparently occurred in early spring (April ?) of 1977, as indicated by photographs and communication with Charles Adams*. The failure was sudden and involved movement along some 98 m of shoreline. Settling of the landform is reported to have continued through the next year (probably much longer), but the result was a lowering of the upper surface by about 3 m and the formation of over 13 sets of individual scarps, the farthest one extending back over 50 m from the shoreline. The raised toe of the feature continued to be eroded each year during the high pool stage of the lake (Fig. 46).

An explanation for the slumping was sought by several means. First of all, cores were obtained for stratigraphic and engineering analysis. The stratigraphy is shown on Figure 43 (piezometer 2–4) and the engineering results are included on Table 4. Several potential shear zones exist at depth in this area, but the most likely are the clay-rich horizons associated with unit A in the Dunvilla Formation.

The impoundment of the Otter Tail River in 1954 was undoubtedly an underlying cause, although airphotos of the site prior to the impoundment show the presence of a large floodplain extending almost to the high pool level mark today. With the higher water table accompanying the impoundment, the pore-water pressures in the sediments adjacent to the lake would also increase.

The passive cause of the failure was concluded to be the presence of weak units of clay-rich sediment at depth, and the activating cause was probably heavy precipitation. 1976 was an abnormally dry year, represented by less than 228 mm of precipitation. Desiccation cracks typically form under such conditions in the Orwell Lake region. When relatively heavy spring rains began in March and April, runoff was probably selectively channelled into such cracks, suddenly increasing hydraulic pressures at depth. It is hypothesized that failure of this area was initiated by such rains.

One smaller slump accompanied this larger one just south of the artesian discharge site (piezometer 7, Fig. 12). Because there are so many older slump sites at this end of the lake, it is concluded that periods of drought will likely be followed by such slope failures in this area.

Figure 46. Toe of slump at east end of Orwell Lake shortly after undercutting by wave action, December 1981.

*Charles Adams, U.S. Army Corps of Engineers, Baldhill Dam, Valley City, North Dakota, personal communication, 22 July 1981.

CHAPTER 4. DISCUSSION

Overland erosion

The amount of erosion accompanying rain events at Orwell Lake depends upon several factors:

1. The intensity of the rainfall (Kirkby 1980, Hudson 1971),
2. Wind velocity and direction,
3. The slope angle (Evans 1980, Bryan 1979),
4. The slope length (Evans 1980, Maddy 1974),
5. The condition of the surface prior to a rain event (Bryan 1976, Epstein and Grant 1967).

Because the eroding slopes are devoid of vegetation, that factor can be ignored.

Rainfall intensity

The daily precipitation at Orwell Lake is shown on Figures 47–49. That there is a cause-and-effect relationship between summer precipitation and erosion of the slopes cannot be denied, but attempts to determine a correlation coefficient were abandoned after initial evaluations. Perhaps the most serious problems in assessing such a coefficient were the occasional delays between the events and the time that either the erosion measurements were made or the rain gauges read. On more than one occasion several storms struck the area between readings; an assessment of which storm caused the most erosion, or when during the storm the erosion occurred could not be made. It was apparent, however, from direct observation, that the greatest erosion did not always occur during periods of greatest or most intense precipitation. For example, the thunderstorm of 31 July 1981 (Fig. 48), which dropped 74.7 mm of rain intermittently over a two-hour period caused only low to moderate erosion at the erosion stations; water infiltrated and ran off without much erosion. In contrast, the one-third smaller precipitation event of 3 August 1981 caused significant erosion (App. A3). This is contrary to Hudson's (1971) conclusion that only storms with precipitation greater than 25 mm/hr are important

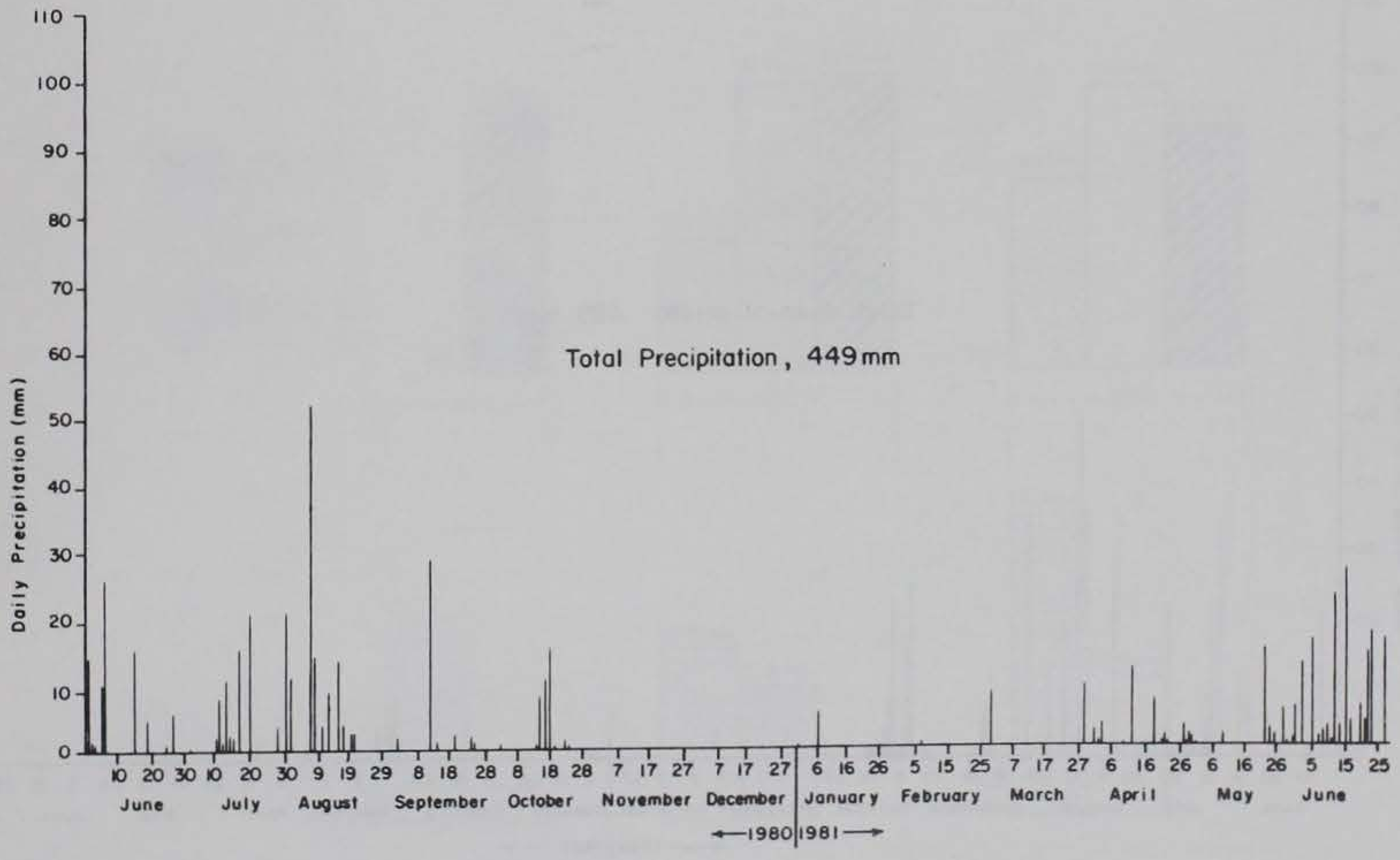


Figure 47. Daily precipitation, Orwell Lake, 1980–1981.

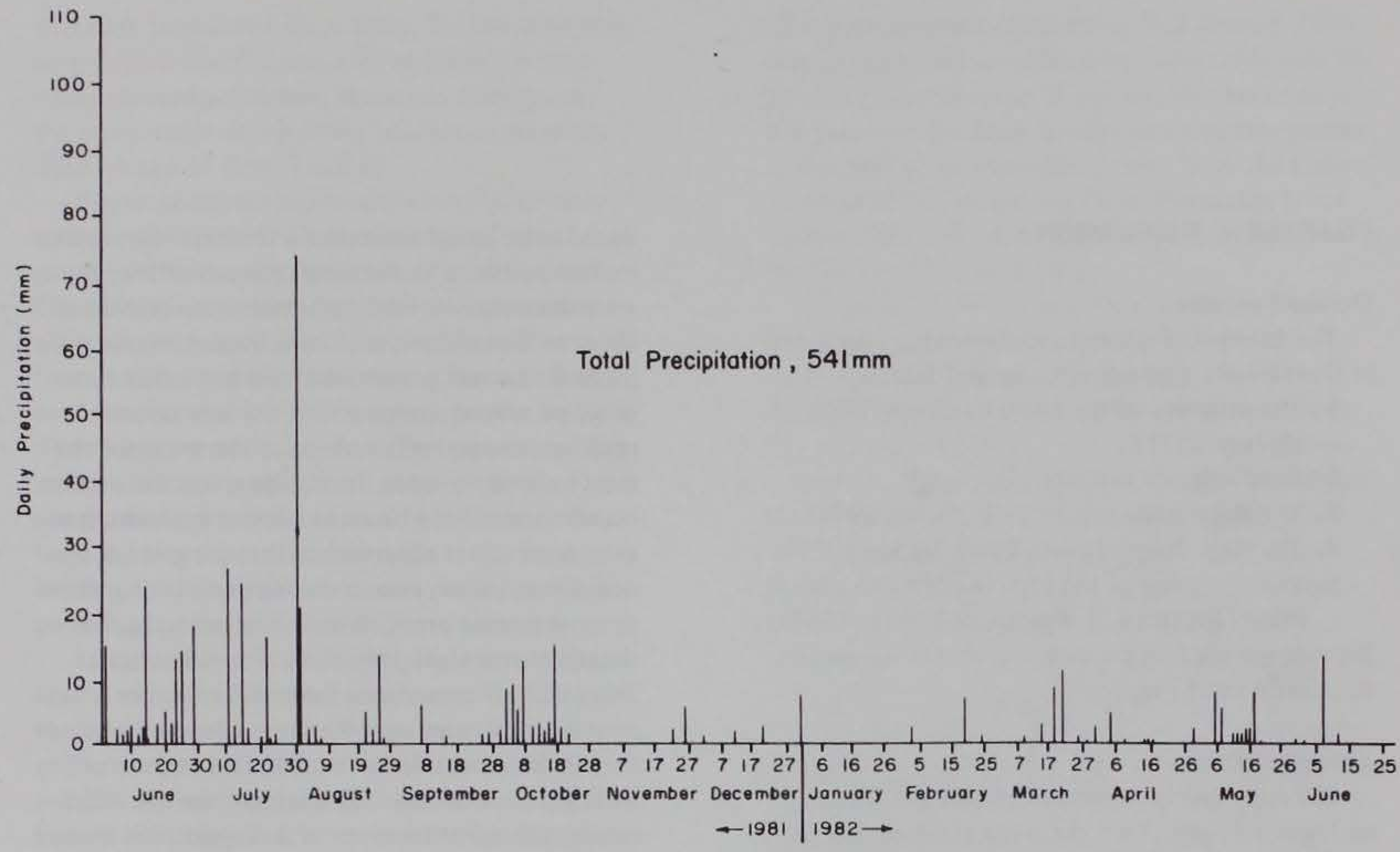


Figure 48. Daily precipitation, Orwell Lake, 1981–1982.

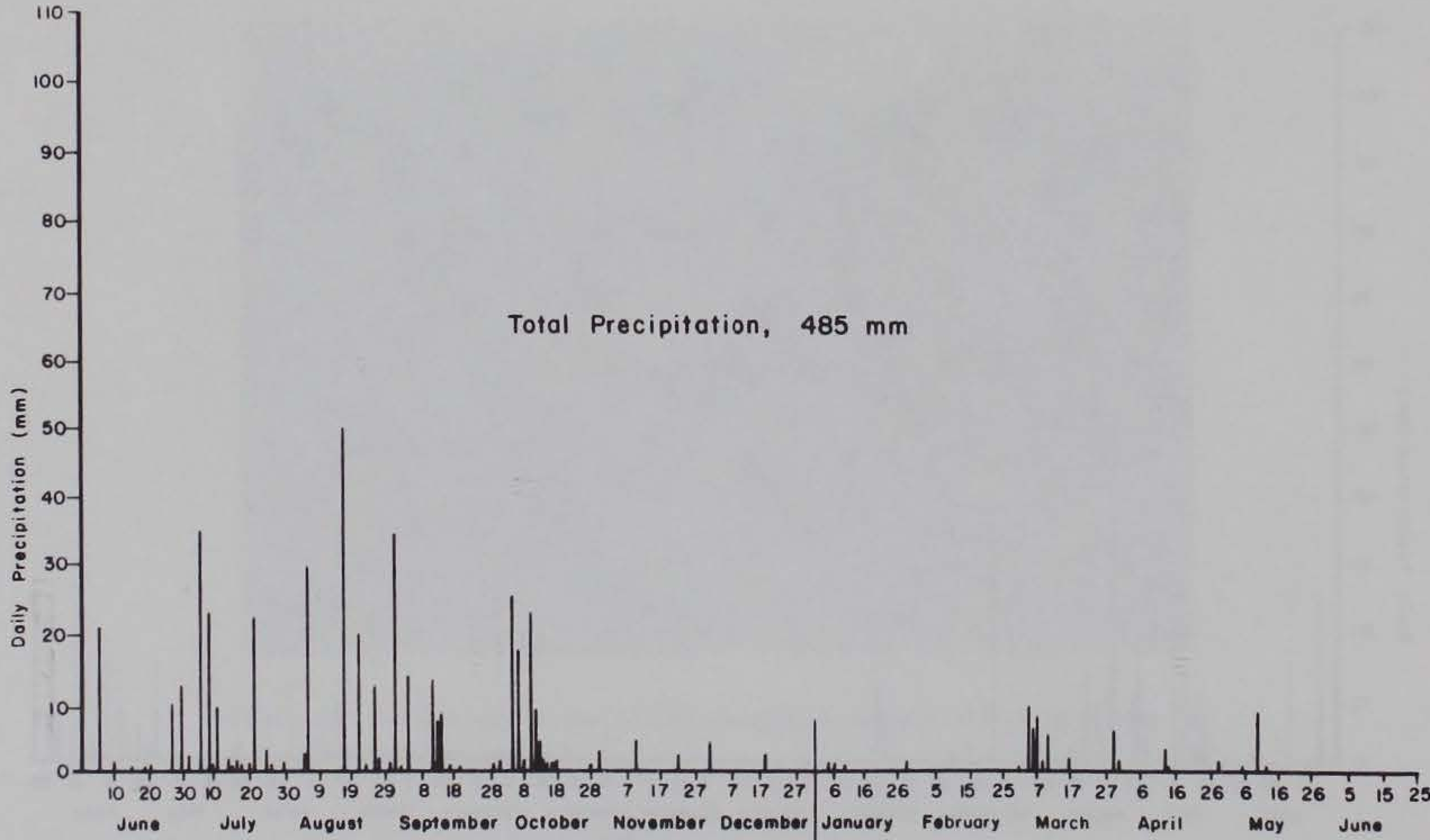


Figure 49. Daily precipitation, Orwell Lake, 1982–1983.

in causing erosion. Obviously, around Orwell Lake other factors are involved.

The intensity of the rain events at Orwell Lake was not measured with statistical validity. The Orwell Dam weather station does have an automatic recording gauge but data from this were less than satisfactory; the times of greatest summer precipitation in 1981, for example, were times when the instrument was not recording properly. In the summer of 1982 two tripping bucket gauges were installed to complement the field cylinder gauges installed the previous year. One set of gauges was located on the north shore (station 11) and the other on the south shore (station 2). Data from all four gauges were compared with data from the dam station (Fig. 50). The gauges on the north-facing shore almost always recorded less precipitation than those on the opposite shore because the summer rains are accompanied by winds from the south for much of the time. The north-facing gauges at station 2, intentionally positioned close to the bank surface and below the top of the bank to measure the rain actually reaching the bank face, were thus effectively sheltered. The amount of rain intercepted by the south-facing gauges and at the dam station were similar, but the relationship between the rainfall and the resulting erosion was reversed. The south-facing shore, with higher precipitation, had *less* erosion than the opposite shore (Fig. 50). The condition of the surface appears to be an important factor here (see *Surface Condition* section).

Wind and bank orientation

The task of relating erosion events to the actual wind direction accompanying storms is difficult; most severe storms, having a high rainfall intensity, were characterized by sharply changing wind directions during the storm. Without being at a station during each storm it is impossible to know at what stage the maximum erosion occurred. This factor cannot be evaluated with existing information because wind data are not included in the Orwell Dam weather observations. Wind velocity and direction as factors in erosion at Orwell Lake were observable, though. One effect was the creation of "stripewash" on windswept slopes during storms accompanied by high winds (Fig. 51). Such resulting erosion along paths of wind-directed runoff was not uncommon at Orwell Lake. Usually such events were brief and the amount of sediment eroded rather minor. On the other hand, because the overland erosion at Orwell Lake is non-isotropic and because other physical characteristics of the banks are relatively uniform, wind is a significant factor in erosion

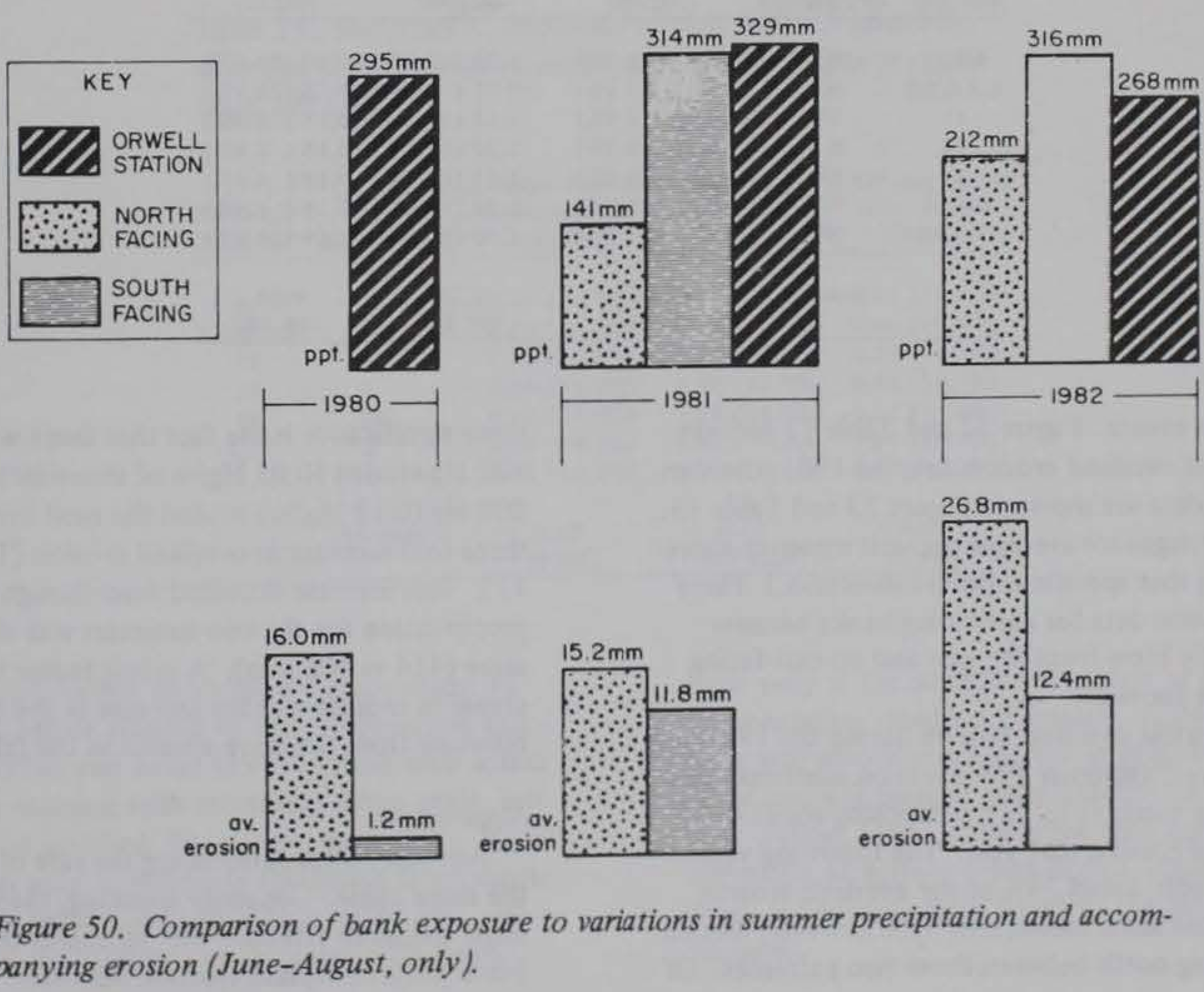


Figure 50. Comparison of bank exposure to variations in summer precipitation and accompanying erosion (June-August, only).

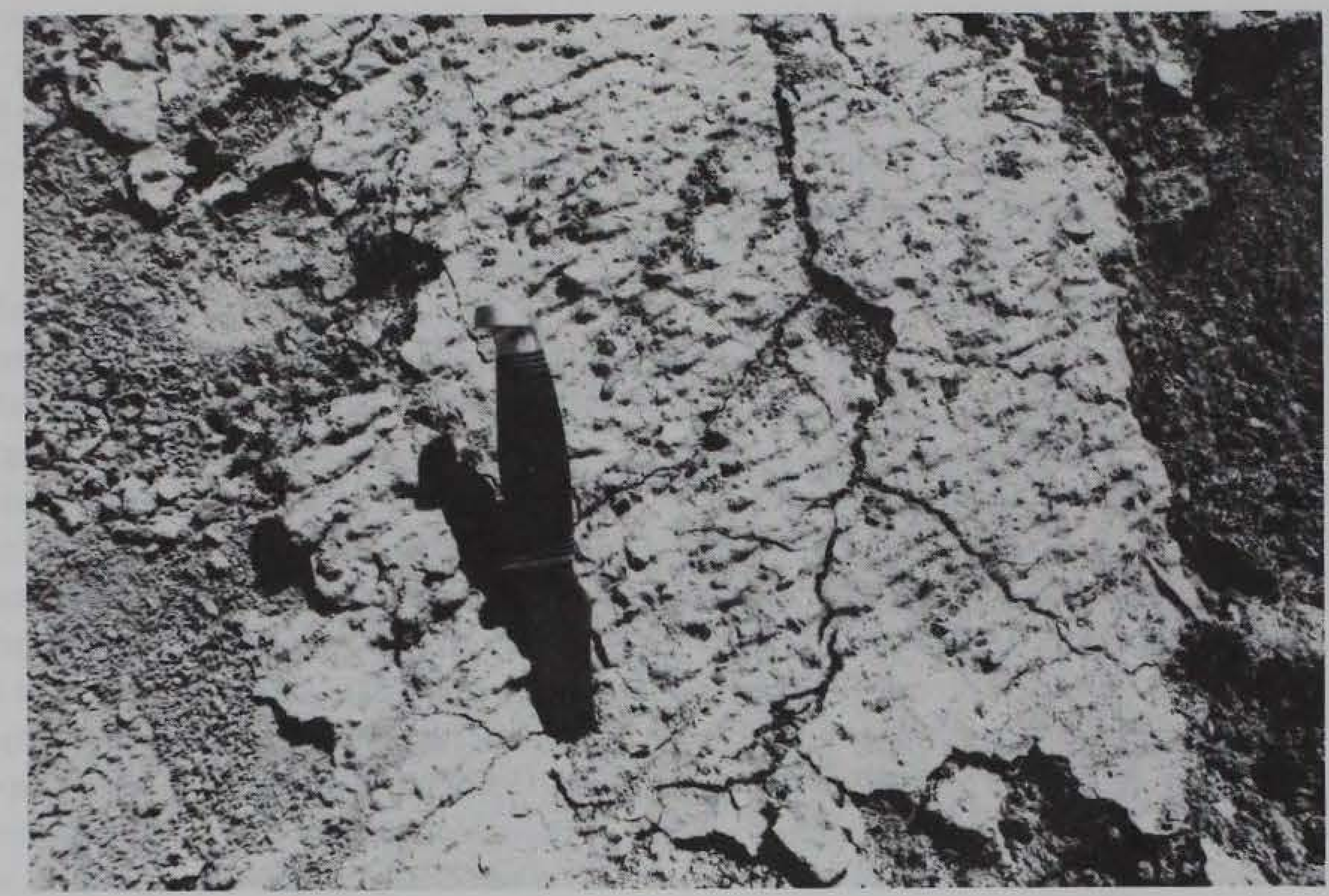


Figure 51. Stripewash caused by wind-directed rainsplash and overland flow at east end of Orwell Lake, June 1980.

Table 12. Summary of dominant erosion for each season at shoreline sections with common orientations (Mg/m of shoreline), 1981–1982.

Shoreline sections	Orientation	Average summer overland erosion (Mg/m)	Average fall wave erosion (Mg/m)	Average spring thaw failure (Mg/m)
4,9,11	N	0.04 (11.2%)	1.23 (13.9%)	0.50 (21.0%)
1,3,6,7,8	NE	0.07 (19.1%)	>0.75 (8.4%)	0.68 (28.9%)
15	SE	0.02 (5.5%)	1.22 (13.7%)	0.15 (6.4%)
16	S	0.05 (12.7%)	1.22 (13.7%)	0.15 (6.4%)
14	SW	0.06 (14.9%)	1.54 (17.3%)	0.15 (6.4%)
12,13	W	0.08 (21.9%)	1.25 (14.0%)	0.15 (6.4%)
2,5,10	NW	0.06 (14.8%)	1.70 (19.0%)	0.59 (24.8%)
	Average	0.05 (3.2%)	1.27 (76.5%)	0.34 (20.3%)

during rain events. Figure 52 and Table 12 include the summer overland erosion data for 1981; the summer 1982 data are shown in Figure 53 and Table 13. (All percentages are averages per unit meter of shoreline having that specific exposure direction.) There are no erosion data for east-facing banks because winds rarely blow from the east and no east-facing banks have formed.

The greatest overland erosion during the 1981-82 study year (summer 1981) was on northeast- and west-facing banks (Fig. 52), composing about 41% of overland erosion that year. The following year (Fig. 53), only about 34% of the overland erosion was on those same banks; over 72% however, was on banks facing north between those two extremes. Of more significance is the fact that there were about 102 Mg eroded (0.05 Mg/m of shoreline) in 1981 but 208 Mg (0.13 Mg/m) eroded the next summer, a three-fold increase in overland erosion (Tables 12-13). This increase occurred even though the total precipitation for the two summers was almost the same (414 vs 408 mm). A prime factor in the increase in erosion was the increase in the bank angle, resulting from the wave erosion in the fall of 1981.

Slope angle

Another factor influencing the rate of erosion is the slope angle. Generally speaking, the steeper the angle the more effective the rainsplash (Ellison 1944). For a given rainsplash ejection diameter, the steeper

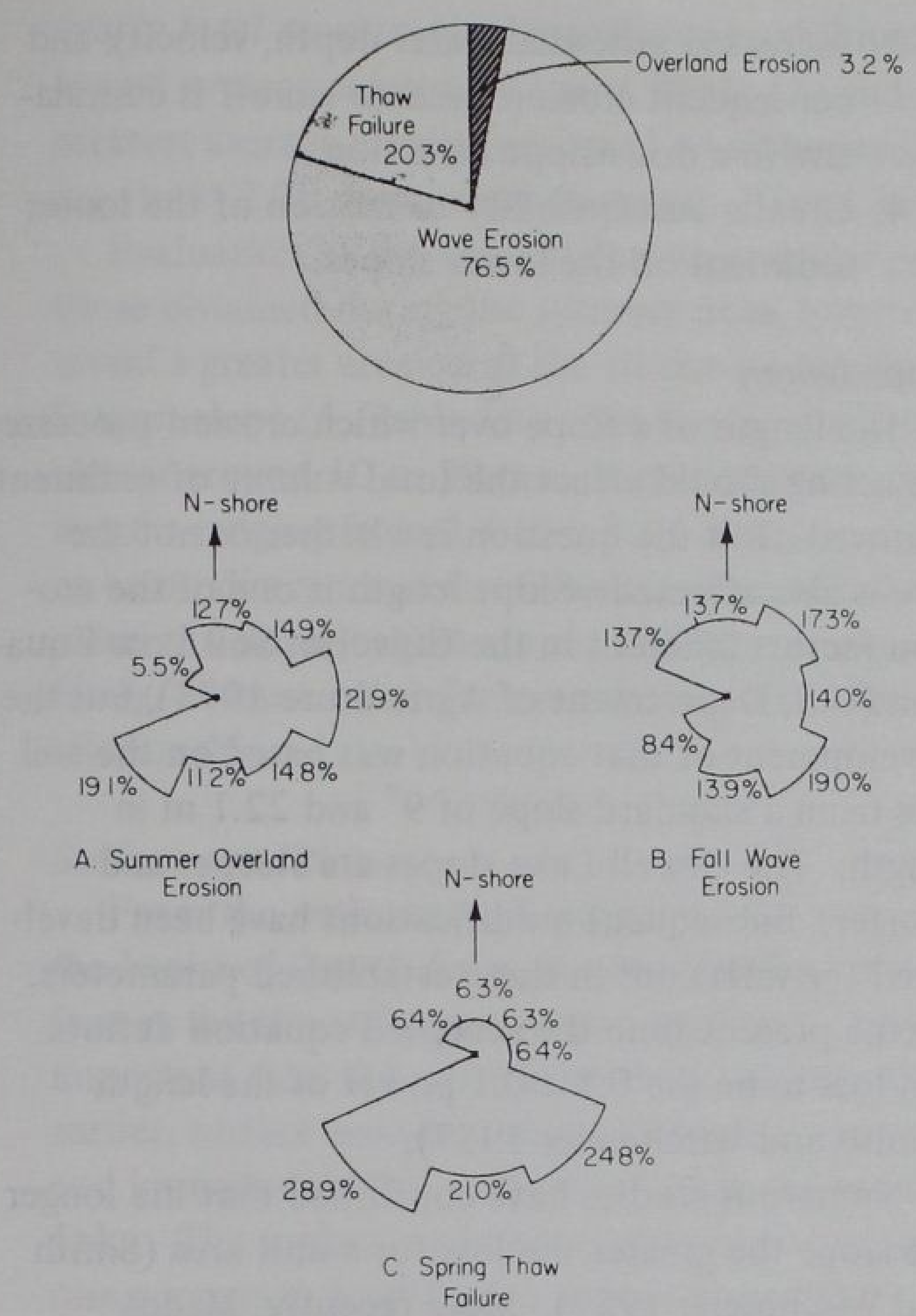


Figure 52. Effect of bank orientation on erosion processes, 1981–1982 (average of all eroded shore sections).

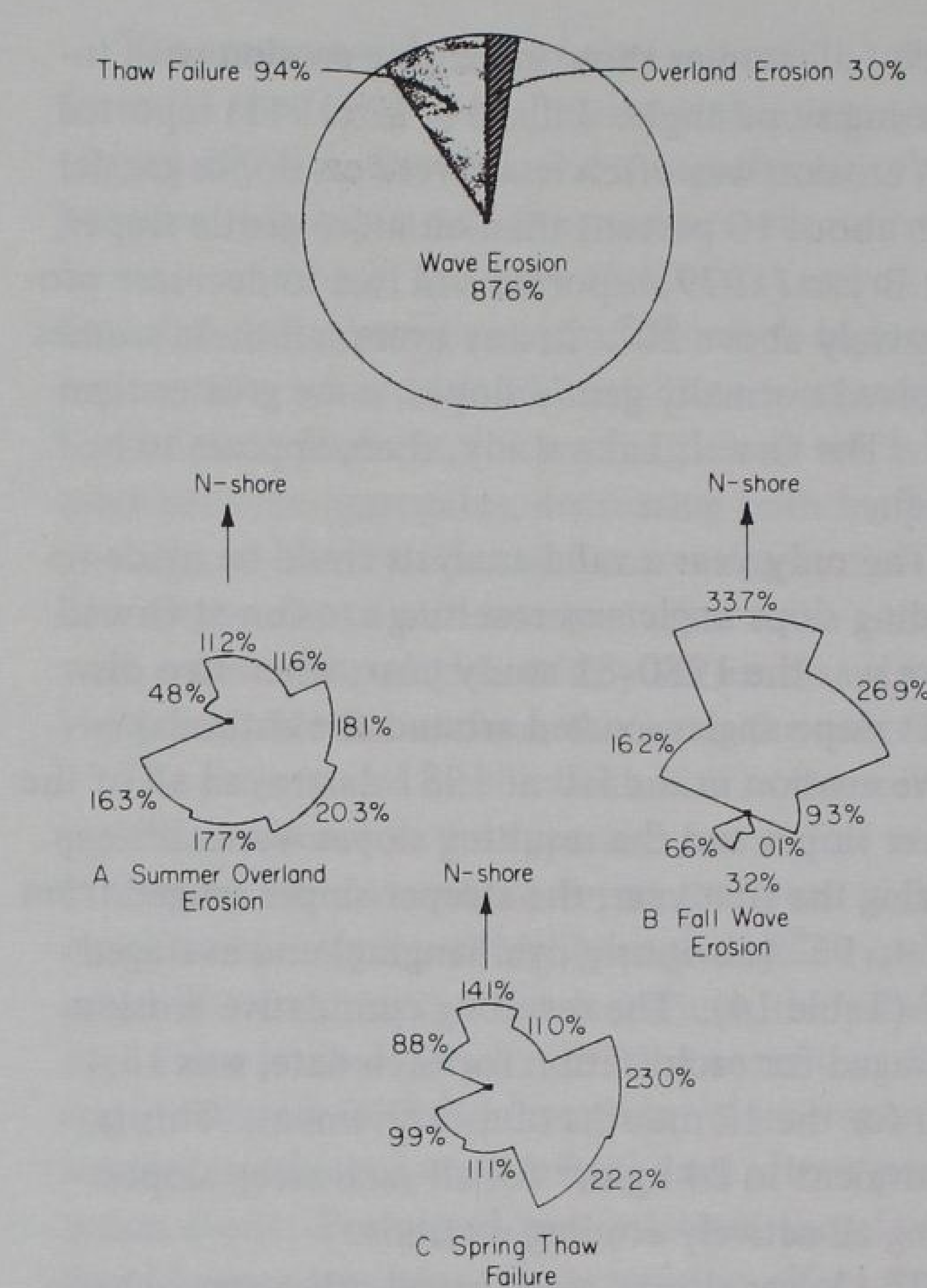


Figure 53. Effect of bank orientation on erosion processes, 1982–1983 (average of all eroded shore sections).

Table 13. Summary of dominant erosion for each season at shoreline sections with common orientations (Mg/m of shoreline), 1982–1983.

Shoreline sections	*Orientation*	*Average summer overland erosion (Mg/m)*	*Average fall wave erosion (Mg/m)*	*Average spring thaw failure (Mg/m)*
4,9,11	N	0.16 (17.7%)	0.85 (3.2%)	0.31 (11.1%)
1,3,6,7,8	NE	0.14 (16.3%)	1.73 (6.6%)	0.28 (19.9%)
15	SE	0.04 (4.8%)	4.27 (16.2%)	0.25 (8.8%)
16	S	0.10 (11.2%)	9.96 (33.7%)	0.40 (14.1%)
14	SW	0.10 (11.6%)	7.12 (26.9%)	0.31 (11.0%)
12,13	W	0.16 (18.1%)	2.46 (9.3%)	0.65 (23.0%)
2,5,10	NW	0.18 (20.3%)	0.04 (0.1%)	0.63 (22.2%)
	Average	0.13 (3.0%)	3.77 (87.6%)	0.40 (9.4%)

the slope the farther downslope a grain ought to be ejected before coming to rest. Moeyerson and DePloy (1976) and Savat (1981) found such splash erosion to increase with increasing slope angle, but their studies involved slopes only up to 20°. Bryan (1979) was able to delineate rainsplash from sheetwash in his experiments on slopes up to 30°. He determined that splash loss increases with slope angle only if the surface water layer is thinner than the maximum raindrop diameter. A thicker water layer will absorb much of the impact of the raindrops and will thereby cause a reduction in splash loss. Palmer (1963) concluded that the maximum dispersion of surface grains occurs when the water depth is approximately equal to the raindrop diameter.

Not all studies show increasing erosion with increasing slope angle. Lillard et al. (1941) reported that erosion was often less severe on slopes greater than about 10 percent than on more gentle slopes, and Bryan (1979) reported soil loss to decrease progressively above 20°. In any event, all these studies involved normally gentle slopes, none greater than 30°. The Orwell Lake study, then, appears to be unique.

The only year a valid analysis could be made regarding slope angle and resulting erosion at Orwell Lake was the 1980-81 study year, when two distinct slope angles existed around the entire lake. Wave erosion in the fall of 1981 destroyed all of the lower slopes and the resulting slopes were all steep. During the first year, the steeper slopes ranged from 66° to 95° (obviously overhanging) and averaged 77° (Table 14). The resulting cumulative erosion, averaged for each station for each date, was 15.4 mm for the 12 months of measurement. This is equivalent to 24 kg/m^2 for all such steep slopes along all actively eroding sections.

The lower slopes, steep by all other researcher's studies, are here termed "gentle." These ranged from 17° to 42° and averaged 34°. The resulting erosion that same period amounted to 27.2 mm, or 42 kg/m^2, almost twice that of the steeper slopes.

The greater erosion on the lower slopes is due to at least four factors:

1. More instances of direct raindrop impact than on the higher, more protected slopes (i.e. the lower slopes extended beyond the occasional rainshadow zone).
2. Higher raindrop impact density with a lower slope angle than a steeper slope under the same rainfall intensity.
3. Increased potential water depth, velocity and consequent erosion because runoff is cumulative in a downslope direction.
4. Greater susceptibility to erosion of the looser sediment on the lower slopes.

Slope length

The length of a slope over which erosion processes are acting should affect the total *volume* of sediment removed. But the question is whether or not the *rate* is also affected. Slope length is one of the erosion factors inherent in the Universal Soil Loss Equation (U.S. Department of Agriculture 1978), but the development of that equation was based on the soil loss from a standard slope of 9° and 22.1 m in length. The Orwell Lake slopes are steeper and shorter. Subsequent modifications have been developed for variations in these established parameters. At the present time the accepted equation defines soil loss to be the 0.5 ± 0.1 power of the length (Smith and Wischmeier 1957).

Numerous studies have confirmed that the longer the slope the greater the loss for a unit area (Smith and Wischmeier 1957). More recently, Maddy (1974) has observed that a doubling of the slope length increases the soil erosion by about 1.5 times. The interpretation is that any runoff will be cumulative in a downslope direction, thereby increasing the effective water depth and therefore the basal shear. However, the erosion rate may not increase downslope, if the increase in surface roughness overcompensates for the increase in water depth in the downslope direction.

In the case of the Orwell Lake erosion data, evaluation shows the complexity of operational processes acting on the exposed slope. Using the

Table 14. Slope angles/lengths and resulting total erosion, 1980-1981, Orwell Lake (data in parentheses are minimum values only).

	Steep slope				*Gentle slope*			
		Slope				*Slope*		
Erosion	*Average*	*length*	*Erosion*		*Average*	*length*	*Erosion*	
station	*angle*	*(m)*	*(mm)*	*(Mg/m^2)*	*angle*	*(m)*	*(mm)*	*(Mg/m^2)*
2	82°	0.93	50.7	0.078	40°	2.75	60.6	0.093
3	95°	2.67	24.4	0.038	28°	1.38	18.5	0.029
4	66°	2.75	35.3	0.054	32°	1.42	19.8	0.031
5	79°	2.05	22.5	0.035	33°	2.82	14.4	0.022
6	74°	6.06	1.7	0.003	33°	1.41	33.2	0.051
7	81°	3.37	10.2	0.016	42°	2.72	29.4	0.045
8	81°	3.62	12.3	0.019	40°	2.83	31.8	0.049
9	80°	3.54	0.3	0.001	40°	1.98	27.8	0.043
10	94°	3.58	5.6	(0.009	41°	2.05	30.4	0.047
11	73°	2.20	(6.8)	(0.011)	27°	0.80	(21.5)	(0.033)
12	69°	3.34	0	0	17°	0.69	(12.0)	(0.019)
Average	77°	3.10	15.4	0.024	34°	1.90	27.2	0.042

yearly total erosion, the longest slope exhibited the lowest average erosion (<2 mm, Table 14) and the greatest average erosion occurred on slopes averaging about 2.75 m in length (between 20 and 35 mm).

Evaluation of the erosion data to consider only those obtained during the summer does, however, reveal a greater erosion at the station having the longest slope (6, Table 14). The rest of the data cluster around 10 to 20 mm of erosion, with slope lengths ranging from 2.4 to 6.3 m. There appears to be no direct trend for those stations, either because the slope lengths are too similar, or, more likely, because other factors interfere with this relationship.

Surface condition

From the evaluation of rainfall on the erosion of the banks of Orwell Lake, the condition of the surface at the time of precipitation appears to be more important than the rainfall intensity. As discussed earlier, surface moisture was determined prior to and immediately following rain events at Orwell Lake. The surface moisture ranged from less than one percent to 5.66% prior to rainstorms and between 13 and 18% after those storms. Attempts to correlate between the amount of erosion and the wetness of the surface, however, were frustrated by the fact that collection of data immediately following storm events was not always possible. Often, several storms passed through the area in a single night. Which storm caused the erosion was impossible to determine.

Numerous other studies evaluating the various factors of surface conditions have been reported. These generally are concerned with either surface crusting or aggregate formation. According to the numerous laboratory analyses of Bryan (1971, 1974a,b, 1976) the most significant parameter of the soil properties that affect soil erosion is the percentage of water-stable aggregates (WSA) greater than 0.5 mm diameter. The percentage of WSA is determined by a technique first described by Yoder (1936) in which an initially dry soil sample is agitated under water on a 0.5-mm sieve for 20 minutes. If aggregates are water-stable (i.e. they maintain their size and shape upon wetting) they will greatly influence the degree of erosion.

As noted earlier, aggregate accumulation at the base of steep slopes is characteristic of Orwell Lake in late winter, as sublimation of interstitial ice occurs, but these may or may not be related to WSA. The presence of WSA during the rain season is important because increased aggregate stability should result in reduced rainsplash entrainment and erosion.

The amount and type of clay mineral is a strong factor in the formation of water-stable aggregates (Bryan 1974b). Bryan found a negative correlation between splash loss and the presence of montmorillonite, common in the soils of Alberta (and at Orwell Lake), despite montmorillonite's high swelling capacity which should contribute to aggregate breakdown. Perhaps this swelling closes the boundaries between aggregates, decreasing both surface porosity and infiltration and increasing surface runoff. Bryan found this interpretation to be consistent with a direct correlation with wash erosion, i.e. the less permeable the surface, the more the runoff.

The presence of montmorillonite in the soil is a significant factor in the type and amount of erosion. It must be understood, however, that even if the montmorillonite is the most highly expandable type, in which the dominant cation is sodium, the process of expansion is slow. Bryan (1974b) notes that the approximately 2000% increase in volume upon wetting is achieved only several days after a precipitation event. Prolonged precipitation, therefore, should cause a greater clay expansion effect than an intense and short-duration event. The high percentage of sodium montomorillonite in the Barnesville till tends to support the interpretation of the measured net "accumulation" following rain events at Orwell Lake. The interpreted expansion amounts, although minimum values, are included in Figure 19 and Table 5.

The second factor affecting surface conditions is the presence and character of a surface seal. Such seals consist of a crust formed over an exposed surface. Crusts were observed on many occasions at Orwell Lake, especially during installation or resetting of erosion pins and during the attempts to take penetrometer measurements.

Surface sealing has been interpreted to be caused primarily by rainsplash impact (Ellison 1945). The mechanics involve disaggregation of soil aggregates which are then either forced by raindrop impact into available pore spaces, or are carried by illuviation into the soil (Luk 1979), initiating the surface sealing. The degree of compactness resulting from this process is reported to increase rapidly at first (about six minutes) and then more slowly (Epstein and Grant 1967). McIntyre (1958), on the other hand, determined that surface seals are composed of two layers, an upper 0.1-mm-thick layer, and a washed-in lower layer 1.5-mm-thick. The upper layer was determined to be 10 times more effective in reducing infiltration than the lower layers. Bryan (1976) supported this observation. Furthermore, he concluded that the upper layer was produced by evaporation, not raindrop impact.

On several occasions close observations were made to see if a surface seal existed at erosion stations during an intense rainstorm. In each of these instances the only sediment moved was by rainsplash even after heavy rain had been falling for 15 minutes. The condition of the surface is concluded to be a prime factor in whether erosion occurs in conjunction with a storm at Orwell Lake.

In addition, the compactness of the sediment obviously affects the erosion rate. As reported in the section on the geotechnical properties the Barnesville till, the dominant sediment of the banks at Orwell Lake, is well-consolidated, allowing it to be characterized by nearly vertical banks for extended periods.

Wave erosion

General

Numerous studies have cited the importance of wind- and boat-induced waves on the stability of river banks (Gatto 1982, Simons et al. 1979, Ouellet and Baird 1978). In each study wave action was concluded to be of major importance to such bank stability.

Recent studies on large lakes, e.g. Lake Michigan (Sterrett 1980, Sterrett and Mickelson 1979, Mickelson et al. 1977, and Hadley 1976) as well as on large reservoirs, e.g. in the U.S.S.R. (Shur et al. 1978, Savkin 1975), have also supported the conclusion that wave erosion is the dominant erosion process on the margins of large bodies of water. Even on small lakes, property owners will confirm the damage that can occur as a result of windstorms (Black 1981). Quantification studies are, however, rare; although most studies support the importance of wave action on bank erosion "actual field and theoretical work linking the erosive energy of waves with (bank) toe erosion is rather limited" (Sterrett 1980, p. 27).

Orwell Lake

Because no motorboats operate at Orwell Lake to cause wave erosion, over 76% of all bank erosion there is by wind-driven wave action accompanying high pool levels (Table 12 and 13, Fig. 52 and 53). The strength of the waves is a function of the wind velocity, duration, fetch, and the water depth. Whether or not erosion occurs is also a function of the resistance of the sediment. The obvious fact that most of the erosion by waves is limited to the eastern half of the lake is not surprising when it is understood that the dominant wind direction is from the west and the greatest fetch is east-west.

The conclusion has already been drawn that the dominant effect of waves is to remove the colluvium brought to the lower slopes by mass wasting resulting both from thaw failure and the processes accompanying rain. The importance of wave erosion was not clear until the fall of 1981 when extensive erosion occurred. The high pool level in the fall of 1979 was only 323.7 m m.s.l., while that of the following year was higher, but still only 325.5 m. The only site that fall that experienced wave erosion was at station 6. A significantly higher pool level of 326.3 m in early September of 1981 and a level of 326.5 m in 1983 were accompanied by several windstorms.

Erosion during the 1981 event removed 35% of all the erosion pins. But these were in the more gentle, lower slopes of the banks, all in colluvium accumulated over the previous two years. The only site with evidence of erosion of the much more resistant till was at station 5 where till cobbles were found on the beach after the water began receding.

With the colluvium all but completely removed from the banks, the center of gravity was raised and the steeper slopes promoted increased thaw failure the following spring (1982). But, even by late summer 1982 comparatively little colluvium had accumulated to approximate the gentle slopes that existed when the project began.

The exceedingly high pool level of 326.5 m in September and October 1982 again removed all the colluvium that had accumulated. But because there was less colluvium than the previous year, wave energy was directed at the till more effectively. A considerable volume of original bank sediment was eroded (Fig. 28). Forty-five percent of the erosion pins were destroyed. The resulting banks were again nearly vertical and ready for massive thaw failure in the spring of 1983.

It is apparent from Figures 52-53 that wave erosion is by far the most significant process of erosion at Orwell Lake, constituting between 76 and 88% of the total erosion. The bank sediment eroded by thaw failure and overland erosion tends to accumulate as colluvium at the base of the steep banks. It is this sediment that is removed during active wave erosion. The primary sediment is a cohesive, compact till which is quite resistant to wave impact even during intense storms occurring at high pool levels. The amount of original till eroded by waves could not be measured because the pre-colluvium profiles could not be determined. Evidence of erosion of the till existed as till cobbles and undercut banks (Fig. 28). Regardless of how much original sediment was eroded, the mass removed by waves was included in the total because it is a measure of the effectiveness of that process and because the removal of sediment at the base of banks controls the degree of subsequent thaw failure and, to a lesser extent, overland flow. All three processes are interrelated at Orwell Lake.

Wave erosion during the 1981-82 year composed over 75% of the total erosion. This represented in excess of 2088 Mg over the 1.62 km of active shoreline (Fig. 52). Except for the east- and northeast-facing banks, the erosion that year was fairly evenly distributed over the various shoreline orientations, but the northwest- and southwest-facing banks composed about 37% of the wave erosion. It must be remembered that these percentages are for sections having the same orientation. Tables 8-9 show the total mass eroded for each section of shoreline; Tables 12-13 summarize the erosion values for each process and each orientation. Of the 1.62 km or eroding shoreline, almost 1.1 is along the southern shore (facing north). The total mass eroded with respect to orientation is quite different. For the purposes of comparing rates of erosion, therefore, the mass per meter of shoreline was used. That the greatest rates should be on those shoreline segments facing northwest and southwest is not surprising. As previously stated, the greatest fetch is from the west. Most storms accompany well-developed weather fronts which bring strong winds from the south (in advance of the front) and from the northwest (behind the front), the result being wave action along the northwest- and southwest-facing banks.

During the fall of 1982 (Table 13) wave erosion was more than double what it had been the previous fall (Table 12). The preferred orientation of erosion was much stronger (Fig. 53). Over 80% of all wave erosion was along the south-facing banks because of the existence of several days of south winds during the high pool level. Not only was the colluvium eroded from these banks, but the till was severely undercut, too. Again, because there was no adequate way to determine the sub-colluvium profile, the actual mass of till eroded can only be estimated. But, because so little colluvium had accumulated since the previous fall, most of the erosion during the 1982 event was the compact, cohesive till of the banks.

Thaw failure

General

The process of sediment freezing is a complex thermodynamic process. Moisture in a system migrates toward the freezing plane, especially in fine-grained sediments (Taber 1930, Nixon 1973), and mineral grains are expelled from the developing ice, resulting in segregated ice (Washburn 1973, 1979, Takagi 1978). How this all occurs is still not firmly established (Chamberlain 1981). The availability of moisture, of course, is fundamental to frost heave (Saetersdahl 1981). The rate of freezing is also critical (Nixon and McRoberts 1973); if freezing is rapid, moisture is frozen in place with movement of the moisture toward the freezing plane will result in segregation of ice into bands and lenses (Palmer 1967, Scott 1969, Nixon 1973).

Frost heave is due more to preferential growth of ice crystals (especially needle ice) than to volume increase upon freezing (Tabar 1930, Penner 1963). Such preferential growth is often controlled by the particle size distribution of the sediment. Soils in adjacent Manitoba have been termed frost-susceptible if they are composed of less than 20% clay-size particles and greater than 60% silt and sand-size particles (Champerlain 1981). This definition is but one of many attempts to define frost susceptibility for the purposes of construction requirements. Regardless of whether or not this definition is acceptable, most definitions would label the bank sediments at Orwell Lake as frost-susceptible. The banks, for the most part, are pebbly silt loams, averaging 25% clay, 55% silt, and 20% sand. Journeaux and Coutard (1972) reported from laboratory studies that expansion of similar clayey silt upon freezing amounted to 27%, but with no expansion of sand and gravel.

The mineral composition also controls frost expansion. Of all the common minerals, clays are most susceptible to expansion during freezing (or wetting). The clays in the Orwell Lake sediments are a mixture of Na- and Ca-rich montmorillonites (between 65% and 79% of the clay-size particles). Of further significance is the fact that frost action significantly increases permeability (Williams 1959). This assumes importance later during thawing. The frozen sediment, of course, is stronger than the unfrozen sediment. Once thaw begins, failure of the material also begins.

Most studies of the effects of thawing of frozen sediments on bank erosion have been in arctic areas. The failure of banks with ice lenses and wedges exposed by river erosion is perhaps the most widely studied aspect (Shur et al. 1978, Walker and Arnborg 1966). Studies of the effects of frost action on bank stability in temperate areas are fewer and usually more generalized. Wolman (1959) reported that frost action on a stream bank in Maryland was responsible for erosion of 0.07 ft/yr, all of which was subsequently removed by stream action. Sterrett (1980, 1981) observed that 87% of the Lake Michigan bluffs failed through what he called solifluction, slab slides, and mudflows accompanying thaw. In a particularly relevant study by Hill (1973) in northern Ireland, frost action (needle ice heaving, melting, and subsequent erosion) was responsible for removal of 23,000 g/m^2 at one site. It is appropriate to conclude, however, that "suprisingly few systematic studies of bank erosion have been made in which a comprehensive set of factors likely to control erosion have been analyzed" (Hooke 1979). This is especially true for studies of thaw failure in the conterminous United States.

Orwell Lake

Thaw failure of the banks of Orwell Lake has been found to be a highly significant process. The question is the cause of such massive failure, comprising between 10 and 20% of all erosion of the banks at Orwell Lake (Fig. 52 and 53).

The most likely factors in such thaw failure are 1) moisture content, 2) number of freeze-thaw cycles, 3) slope angle and 4) sediment texture and structure.

Although the surface and near-surface moisture content at the test stations at Orwell Lake varied with the season, the moisture immediately prior to fall freeze averaged about 15% by weight. With an average porosity of about 40% the freezing moisture would have expanded first into the voids before effectively displacing mineral particles (Sayward 1979). So, unless there was significant migration of water to the freezing plane, or addition of water from above (from melting snow), heaving of the surface would be expected to be minor. The recorded vertical heave of only 4 mm is, therefore, not surprising. Horizontal thrust on exposed banks ought to be greater, the force of gravity adding to the direction of displacement. Attempts to install frost tubes into such steep banks failed; holes could be drilled and tubes inserted, but packing could not properly be done.

Myriad nearly vertical cracks observed in midwinter parallel to the bank surfaces are concluded to be the result of sublimation of segregated ice. The fact that there are so many cracks attests to the efficacy of ice segregation, albeit at a small scale. Such cracks would then serve as channels for any snowmelt, thus adding to the instability of the bank sediment in the spring. One might conclude, then, that snowmelt is a significant contributor to thaw failure at Orwell Lake, especially as the pre-freeze moisture content was only about 15%. Although snowmelt certainly does contribute to thaw failure, normally very little snowmelt reaches the steep banks, except for the lower snow-covered slopes. Most surfaces above the banks at Orwell Lake are fairly level or slope away from the lake. Erosion stations 9 and 11 are exceptions. Most snowmelt would tend to flow away from the steep adjacent banks.

One factor that affects moisture content and the number of freeze-thaw cycles is the bank orientation. Tables 12 and 13 and Figures 52-53 show the relationship between thaw failure and bank orientation. It is especially striking that for the 1982 spring (Fig. 52c) the only appreciable thaw failure was along northerly facing banks, which accounted for more than 74% of all thaw failure at Orwell Lake. This striking contrast with south-facing banks occurs despite the essentially identical pre-freeze moisture content and the very similar snow depth during the winter. Why, then, the difference? The explanation lies in a consideration of the effects of exposure direction. South-facing banks are exposed to considerably higher energy levels. In the winter this results in greater sublimation of interstitial ice. By the end of the winter the moisture content of south-facing banks is reduced considerably over what it was at the time of freeze. Then, if subsequent snowmelt were the major contributor to thaw failure at Orwell Lake there would not be such a great difference in the thaw activity between northerly facing and southerly facing banks, each with similar snow depths. The difference is, therefore, concluded to be the result of a higher remnant soil moisture in the sediments of the more northerly facing banks, not primarily to snowmelt differences. Whereas about 74% of the thaw failure occurred along northerly facing banks in the spring of 1982 (Fig. 52), only 43% was along these orientations the following spring (Fig. 53). Another 23%, however, was along west-facing banks in contrast to only 6% the previous year. The expected sites of increased thaw failure in 1983 were the northern and northeastern shores where extensive wave erosion had occurred (Fig. 53b). The data in Table 13 support this expectation; the subsequent thaw failure increased from 0.15 Mg/m to 0.35 Mg/m for those orientations. The orientations exhibiting the greatest thaw failure were northwest- and west-facing banks, again presumably the result of better moisture retention over the winter, compared with the sites of most active wave erosion where winter sublimation is more effective.

The concurrent drastic decrease in thaw failure along the banks facing north and northeast (from 0.59 Mg/m to 0.30 Mg/m) more than offset the increase along the more active sites, resulting in a lower total percentage of thaw failure compared to the overland and wave erosion during the 1982-83 budget year.

The number of fluctuations above and below the freezing point affects the strength of a sediment (Johnson et al. 1978). With repeated freezing and partial melting, there is a greater opportunity for segregation of interstitial ice. With this in mind, the winter of 1980-81, with 122 major fluctuations above and below the freezing point should have been expected to be characterized by greater thaw failure in the spring than the following winter, which had only 75 such major fluctuations but less than the 1983 spring which followed a winter having 103 days of fluctuations (Table 10). Plastic sheets were emplaced to measure such failure only during the second and third winters. From direct observation as well as comparison of photos, it appears that the second year, with fewer freeze-thaw cycles, experienced greater thaw failure than the first. The reason for this, if true, is most likely due to the steeper slopes the second year. This increase in slope angle was caused by erosion of the more gentle slope by waves in the fall of 1981. A steeper slope angle contributes to greater masses of sediment being transported to the base of the slopes. The problem with this conclusion is that the 1983 spring thaw failure should have been the most severe, with extensive wave erosion of the banks having occurred prior to freezing. The 1982 thaw failure of about 824 Mg was in fact, slightly greater than the 1983 thaw failure (746 Mg).

The texture and structure of the sediment at Orwell Lake also contribute to the high percentage of thaw failure there. The fairly equal percentages of sand, silt and clay, the high content of sodium-rich montmorillonite, and the highly jointed character of the Barnesville till all combine to reduce the strength of the sediment of the banks.

Universal soil loss equation

Although the Universal Soil Loss Equation (USLE) was developed to predict soil erosion (tons/acre) for crop fields of extensive length and having slopes of less than 20°, many correction factors have been added since to permit estimations for shorter and steeper slopes. Table 15 is a summary of measured erosion at each of the 12 stations at Orwell Lake and the calculated erosion using the modified USLE. The results show five stations for which the calculated erosion is greater that the actual erosion, and seven stations for which the measured erosion is greater than the calculated values. The differences are so great that it must be concluded that even the modified USLE is inadequate for such steep, short slopes as exist at Orwell Lake.

Table 15. Comparison of measured bank erosion (1981-82 budget years) and calculated erosion from universal soil loss equation (see Table 14 for slope length and angle data).

	Measured erosion 1981-1982		*USLE erosion*		
Erosion station	*(mm)*	*(equivalent) (tons/acre)*	*LS* factor*	*A† (tons/acre)*	*Difference*
1	21.3	1088	13.941	379.89	-65%
2	17.3	884	13.744	374.5	-58%
3	10.6	541	24.123	657.3	+18%
4	20.5	1047	20.704	564.2	-46%
5	16.9	863	20.541	559.7	-35%
6	31.6	1614	33.937	924.8	-43%
7	13.0	664	26.668	726.7	+9%
8	14.0	715	27.626	752.8	+5%
9	17.4	889	27.196	741.1	-17%
10	6.8	347	28.019	763.5	+55%
11	18.6	950	20.236	551.4	-42%
12	11.3	577	23.829	649.3	+11%

*$LS = (\ell/72.6)^{0.5}\,(65.41 \sin^2\alpha + 4.56 \sin\alpha + 0.065)$

†$A = RKLSCP$, where $R = R_s$; ($R_s = 0.0591 \times$ Dec to Mar precipitation at Orwell Lake)

$K = 0.026$ (Barnesville till)

$C = 1$

$P = 1$

R_s = snowfall factor

ℓ = slope length

α = slope angle

A = computed soil loss in tons (dry weight) per acre from a given storm period

R = rainfall erosion index for the given storm period

K = soil erodibility factor

$\left.\begin{array}{l} L = \text{slope length factor} \\ S = \text{steepness factor} \end{array}\right\}$ topographic factor

C = cropping management factor

P = erosion control practice factor

CHAPTER 5. SUMMARY AND CONCLUSIONS

Techniques

Although the results of the erosion pin measurements have provided an excellent approximation of erosion processes and magnitudes at Orwell Lake, a more accurate assessment is from a combination of techniques, specifically, the erosion pins for rain erosion processes (rainsplash, overland flow), bank profile surveys (together with stakes emplaced at the base of banks) for determining the magnitude of wave erosion, and plastic sheets also placed at the base of banks for measuring thaw failure accumulation.

For the erosion pin data to be significant, they should be measured frequently, ideally immediately after rain events. The bank profiles need to be determined sometime before high pool levels begin to encroach upon the base of the banks, and again upon lowering of the water. These profiles preferably should be measured according to the technique described by Hudson (1971). Wave erosion stakes also need to be installed before the water reaches the high pool level. The plastic sheets or strips should be positioned and secured at the base of the representative banks before the first snowfall and excavated after all signs of thaw are completed. Finally, bank recession pins can be installed anytime, but preferably just before causal processes become active.

Erosion processes at Orwell Lake

Waves

The three years of data collection at Orwell Lake have provided a clear insight into the magnitude of erosion according to process. The dominant process is that of wave erosion composing over 76% of total erosion during the 1981-82 study year and 88% during the 1982-83 study year (Fig. 52-53). During years when the pool level does not exceed 325.5 m, colluvium accumulates along the base of the banks, forming a relatively gentle apron averaging 34°. Any year the pool is allowed to approximate its maximum level, waves accompanying weather fronts remove the colluvium and transfer the sediment into deeper parts of the lake. If there are two successive years of high pool levels the colluvium veneer will be thin and the waves will quickly remove it; the remaining wave energy will be directed toward the erosion of the more resistant, in-situ till. Vertical banks result (Fig. 27-28). The actual magnitude of wave erosion is dependent on many factors, most of all the wind direction, velocity and duration. For this reason, almost 75% of the wave erosion at Orwell Lake is along northeast-, southwest-, and south-facing banks. Wave erosion in the fall of 1981 averaged 1.3 Mg/m of eroding shoreline (Table 12). Wave erosion in the fall of 1982 averaged 3.8 Mg/m of active shoreline (Table 13), a significant increase due solely to the fact that the pool level was higher than in 1981 and strong southerly winds persisted over several days during the high level.

Thawing

The second most effective erosion process at Orwell Lake is that of thaw failure, which composed over 20% of total erosion in the spring of 1982 (Fig. 52) and about 10% the following spring (Fig. 53). The mechanics of failure first involve slab slips along frost-enhanced joint surfaces and, later, mud and earthflows. Erosion accompanying thaw is relatively minor along south-facing banks because winter sublimation is more intense there, reducing the moisture content significantly. In the spring of 1982 more than 74% of total thaw failure occurred along north-facing exposures (Fig. 52). The magnitude of such erosion ranged from 0.25 to 0.65 and averaged 0.40 Mg/m of eroding shoreline that spring (Table 13). The thaw failure in the spring of 1983 followed severe wave erosion of the banks. Despite this, the amount of thaw failure was slightly smaller than the previous year (746 vs 824 Mg). The reason for this may lie with the significantly warmer winter of 1982-83 during which time more moisture was lost by evaporation and sublimation.

Rain

The erosion process active the longest part of the year, erosion by rainsplash and overland flow (rill and interrill wash), is the least significant of the three dominant erosion processes at Orwell Lake, composing about three percent of the total erosion (Fig. 52-53). The percentage of erosion by rain was surprisingly evenly distributed around the lake in the summer of 1981, but concentrated on north-facing banks the following summer (Fig. 53). The variation in erosion is high from event to event, depending mostly on the condition of the sediment at the time the rain falls.

The magnitude of erosion by rain ranged from 0.02 to 0.08 and averaged 0.05 Mg/m of eroding shoreline during the summer of 1981 (Table 12). The erosion that summer was significantly higher than the previous year. Erosion by rain the summer of 1982 was significantly greater, largely as a result of increased rainfall, especially in the form of brief storms. The range was from 0.04 to 0.18 Mg/m of active shorelines, averaging 0.13 Mg/m (Table 13).

Rainsplash is concluded to be the dominant entrainment mechanism; it occurs during each rain event. More erosion occurs as a result of wash during the intense storm events, but rainsplash is still the mechanism by which particle movement is initiated. On such steep slopes as exist at Orwell Lake it would be difficult to separate the volumes removed by each mechanism. Rainsplash is certainly a highly important process in the erosion of these slopes during the summer season.

Other processes

Erosion by the mass wasting of soil aggregates that have been separated by sublimation of interstitial ice during the cold, dry winter is a recognized process at Orwell Lake. The result is an accumulation of soil aggregates at the base of steep banks, often burying snowbanks in the process. The volume, however, is small, only a fraction of one percent of the total erosion occurring in any year.

Larger mass wasting events are known to have occurred at Orwell Lake, the most recent one in the spring of 1977. The mode of failure is rotational slumping. It is concluded that even though no such events occurred in the three years of this study, the most likely passive cause is desiccation during occasional summer and fall droughts of the surface of a clay-rich lacustrine unit between tills. The activating cause probably is spring snowmelt or rains which are directed into the cracks to the relatively impermeable lacustrine unit along which failure takes place. Future massive slumping can be expected to occur following drought periods, especially at the east end of the lake where the lacustrine unit is stratigraphically and topographically favorable for such slope failure.

Deflation was found to be ineffective as an agent of erosion of the banks of Orwell Lake. Some sand grains have been felt in the air during high winds, but because the primary sediment is so compact and because the secondary sediment is so fine, erosion by this process can be ignored.

In summary, the dominant processes are wave action, thaw failure, and rain erosion. Taking four representative stations (Fig. 54) the magnitude and variability of each process at Orwell Lake can be seen. Any attempt to interpret the processes acting to modify a slope must consider the fact that variation from place to place and from year to year is apt to be great. Long-term studies are required to understand these processes more fully.

Bank recession

Rates

The ultimate result of the erosion of banks of Orwell Lake is their recession. Measurements

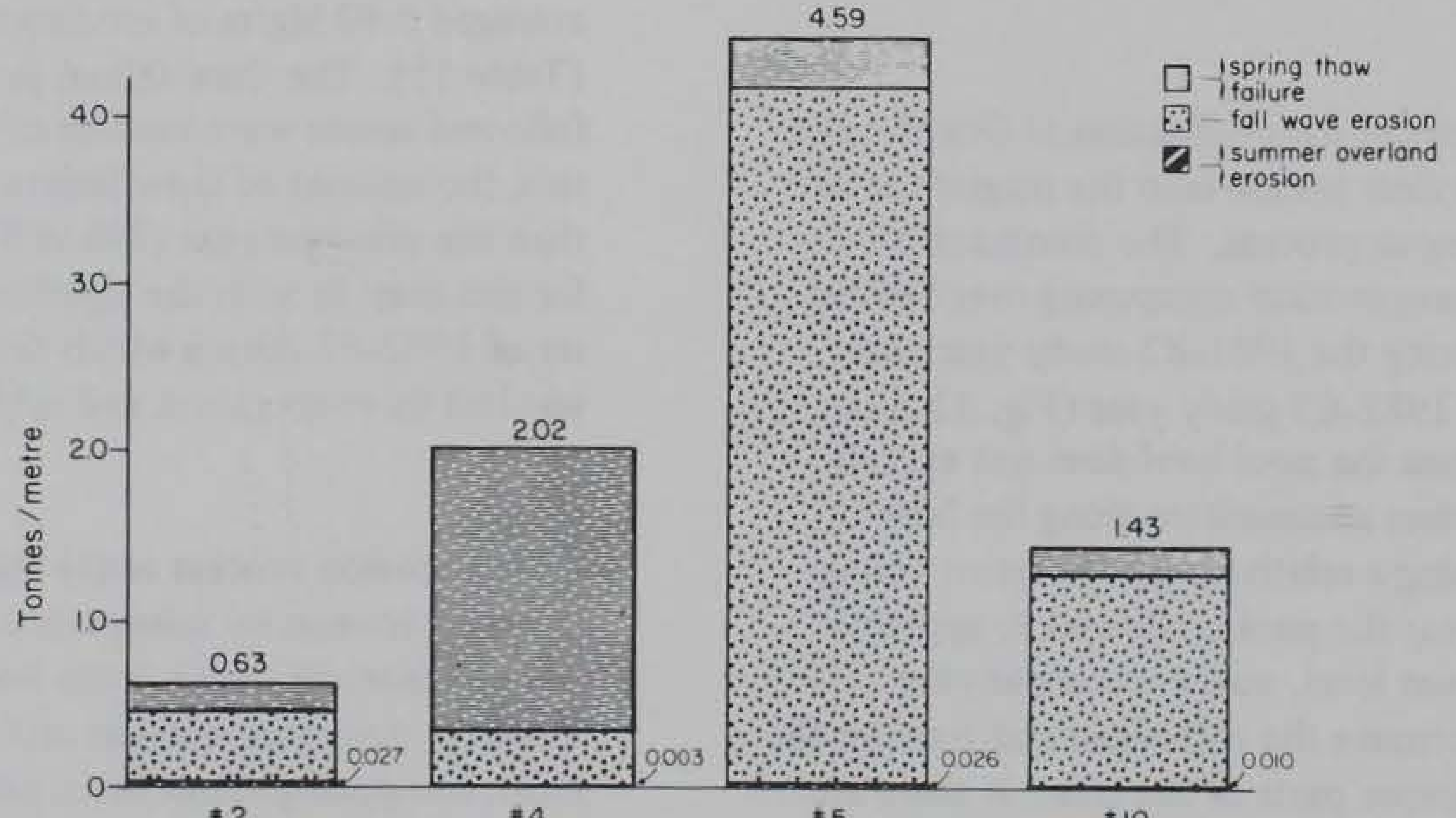


Figure 54. Total bank erosion at four erosion stations, 1981-82.

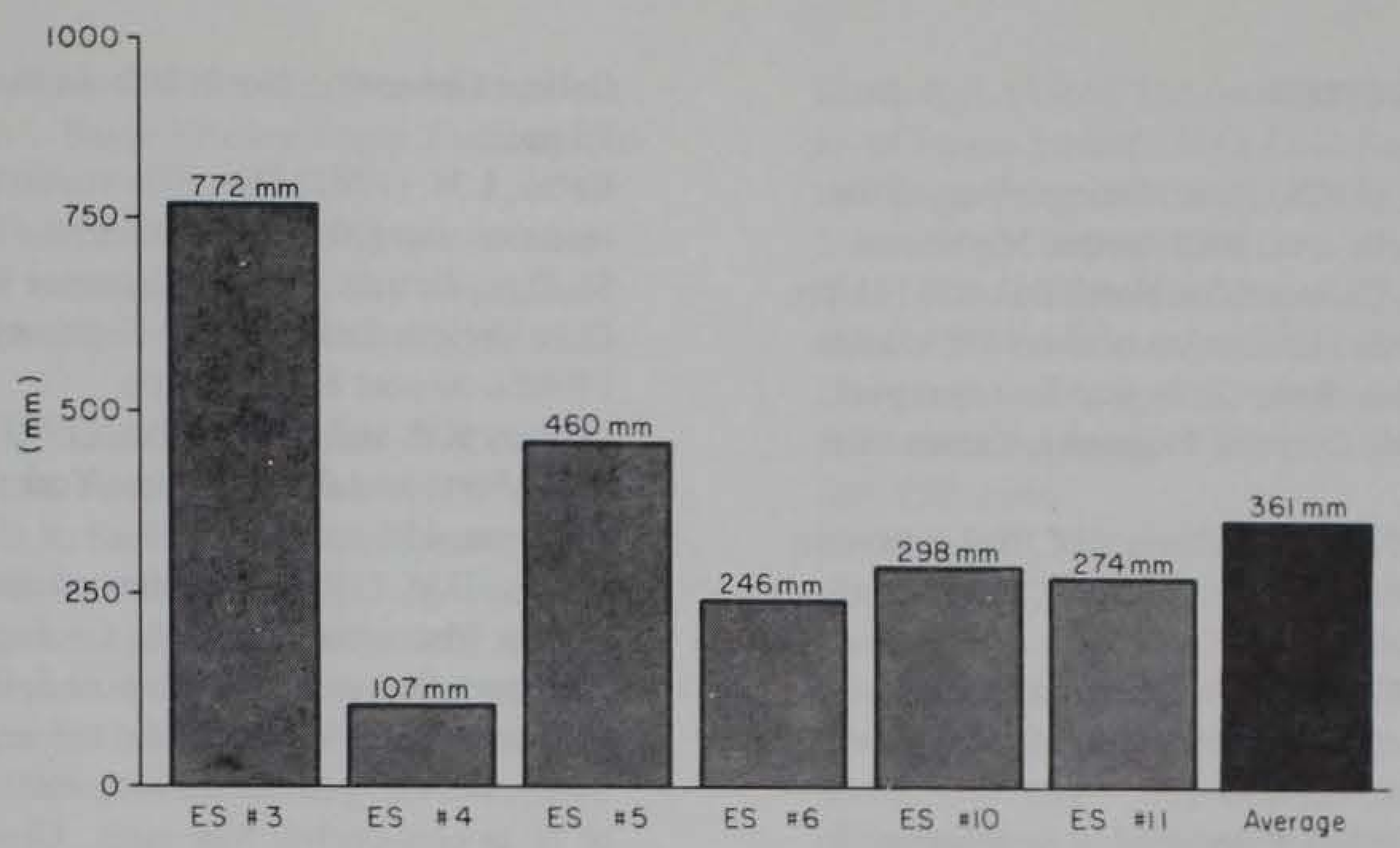


Figure 55. Average yearly bank recession, 1982–83.

of bank recession, by the installation of pins and other markers beyond the top edge of the banks around the lake, indicate an average yearly retreat of the bank top of 0.8 m at erosion station 3 (Fig. 55) and 0.36 m for the stations as a whole. These recession rates are probably good approximations of future rates, provided that pool level fluctuations are maintained as in the past.

Mitigation possibilities

Proposing methods for bank stabilization is not an objective of this report. However, based on the results of this study, it is possible to suggest some ways to mitigate the bank erosion.

Because wave action during high pool levels removes the colluvium that has accumulated by the other processes and thereby makes room for continued transfer of sediment from the steeper banks, it is concluded that limiting the practice of permitting the pool level to exceed 325.5 m (1067.9 ft) m.s.l. would quickly reduce the rate of erosion of the banks at Orwell Lake. If this were to be adopted, a lower slope, averaging perhaps 30–35°, would begin to develop at the expense of the higher, steeper bank. Furthermore, if this more gentle slope were to become completely stabilized (i.e. not experience secondary erosion) the upper bank would retreat until the lower slope extended to the top; the retreat of the upper slope would continue, especially by thaw failure, only as long as a steep slope still existed. Once the more gentle slope had completely replaced the steeper slope it would probably become fixed by vegetation within a couple of years. The problem with this scenario is that:

1. To limit the pool levels to less than 325.5 m (1067.9 ft) would eliminate a great percentage of the storage capacity of the reservoir, thus limiting its function.
2. Erosion of the lower slope would continue, and in fact, increase as the length of the surface increased; it cannot remain unchanged.

An alternative approach is the method widely employed by the Corps of Engineers, to stabilize such banks by armoring them with riprap. Lake Ashtabula, North Dakota, is a recent example (U.S. Army Corps of Engineers 1980). This technique, although costly, would tend to stabilize the slopes. Besides the cost involved, though, another disadvantage of this method is that it interferes with the normal shoreline ecology* and is esthetically unattractive.

Instead of protecting the base of the banks with riprap, establishing vegetation on the slopes should be considered.* Cottonwood trees and willows are common along many parts of the lake. These native trees grow rapidly and are effective in protecting the banks from wave action. The problem would be to protect the seedlings from wave action. This would be possible only if the pool level were kept low enough for a couple of years after seedlings had been planted. The trees would serve the same role as the riprap, effectively absorbing the force of the waves, but also providing shore and ground cover for fauna. Other types of vegetation should also be considered. The advantages of establishing vegetation on the banks would be the lower costs and new habitat for wildlife, and it would be attractive.

*Research at the Corps of Engineers Waterways Experiment Station has addressed these two topics: Thomas Wright investigated the effects of riprap on shoreline ecology; Hollis Allen studied the use of vegetation for bank stabilization.

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APPENDIX A1: AVERAGE CUMULATIVE CHANGE OF SURFACE AT EROSION STATIONS #2-12 (#1, 11 EXCLUDED) 1980-81

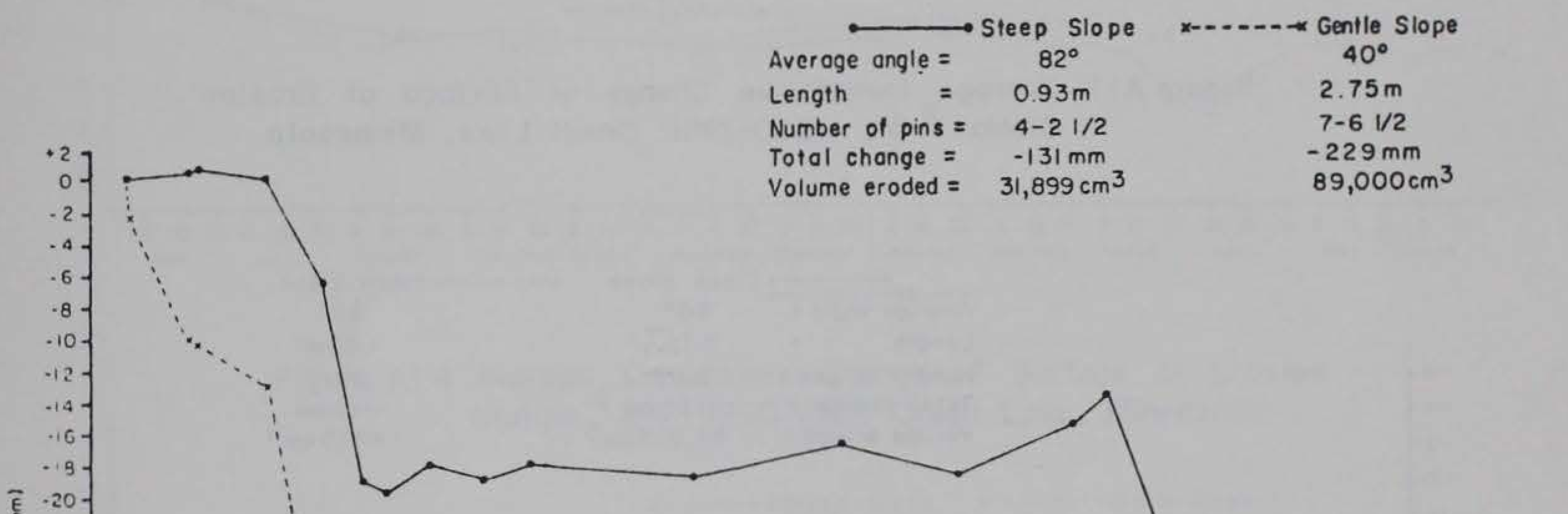

Figure AI.1 Average Cumulative Change of Surface at Erosion Station #2, 1980-1981. Orwell Lake, Minnesota

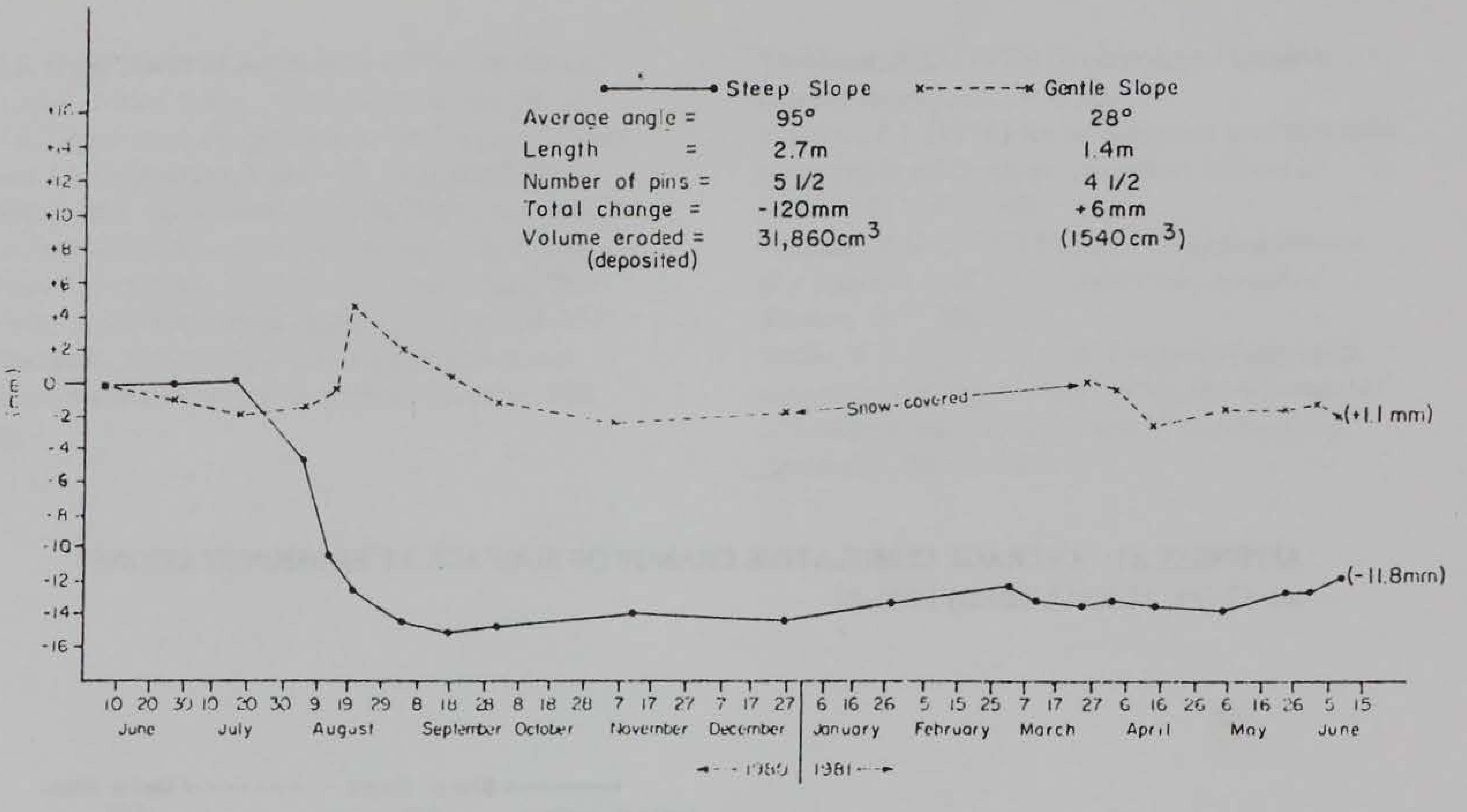

Figure A1.2 Average Cumulative Change of Surface at Erosion Station # 3, 1980-1981. Orwell Lake, Minnesota

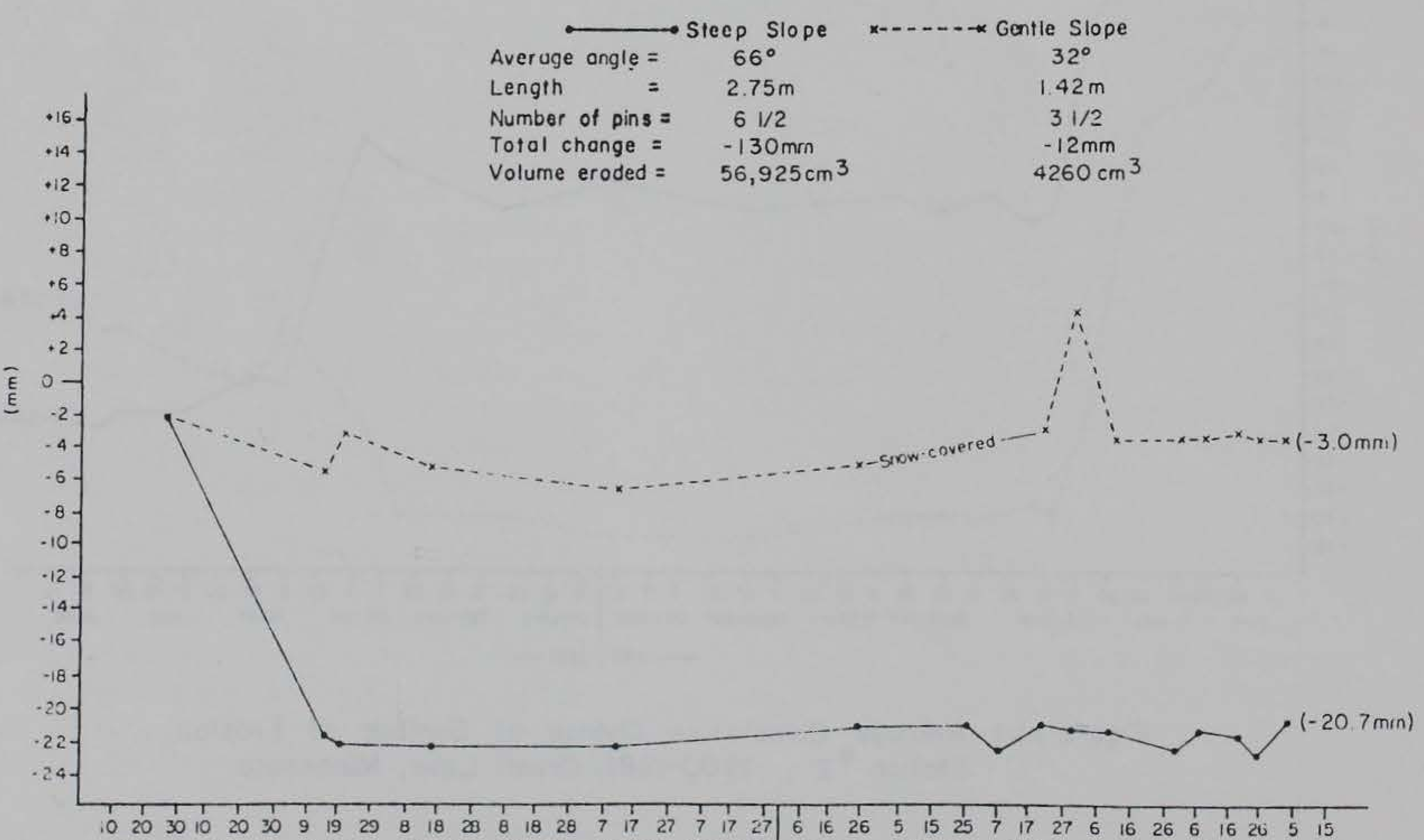

Figure A1.3 Average Cumulative Change of Surface at Erosion Station #4, 1980-1981. Orwell Lake, Minnesota

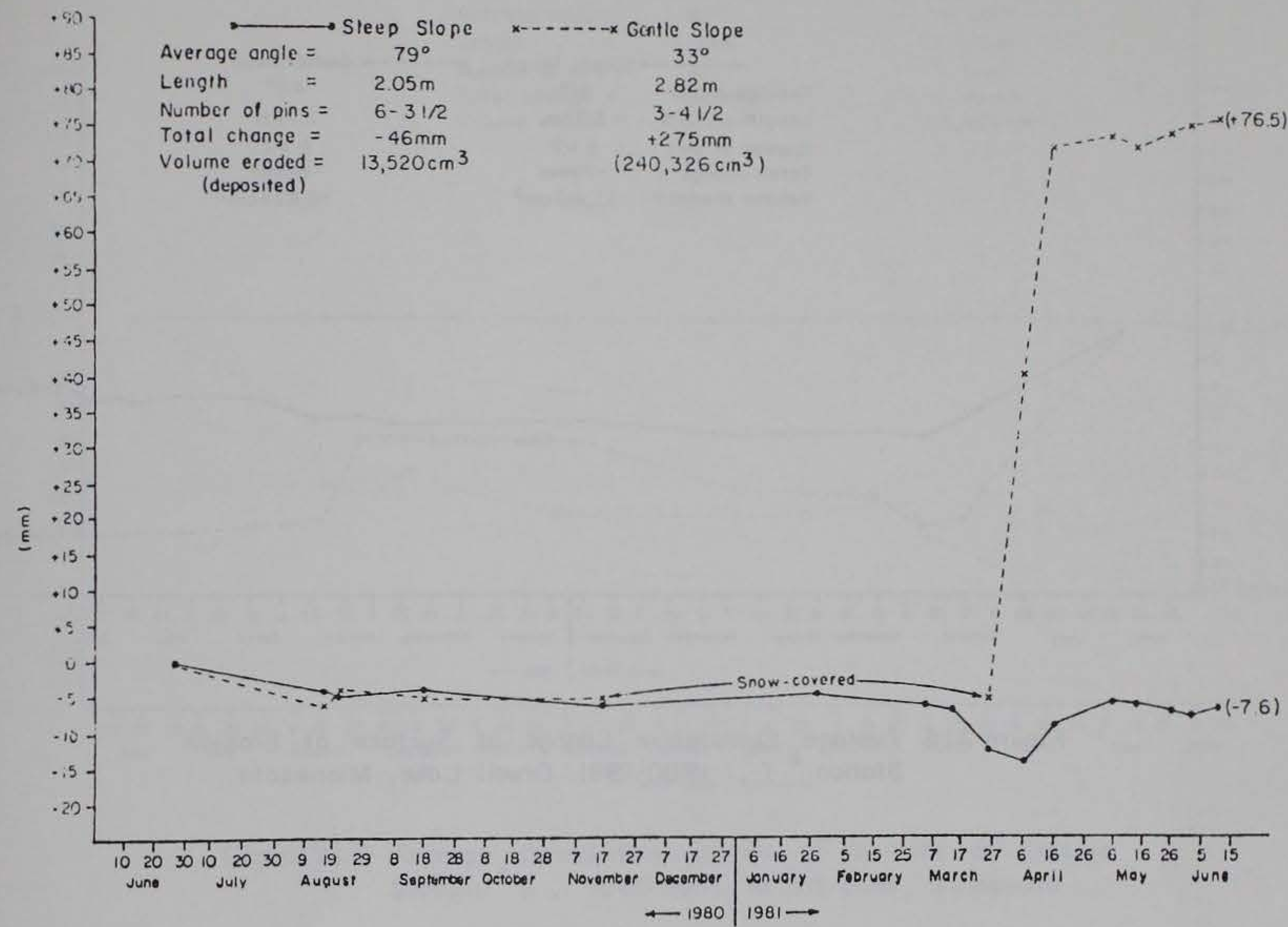

Figure A1.4 Average Cumulative Change of Surface at Erosion Station # 5, 1980-1981. Orwell Lake, Minnesota

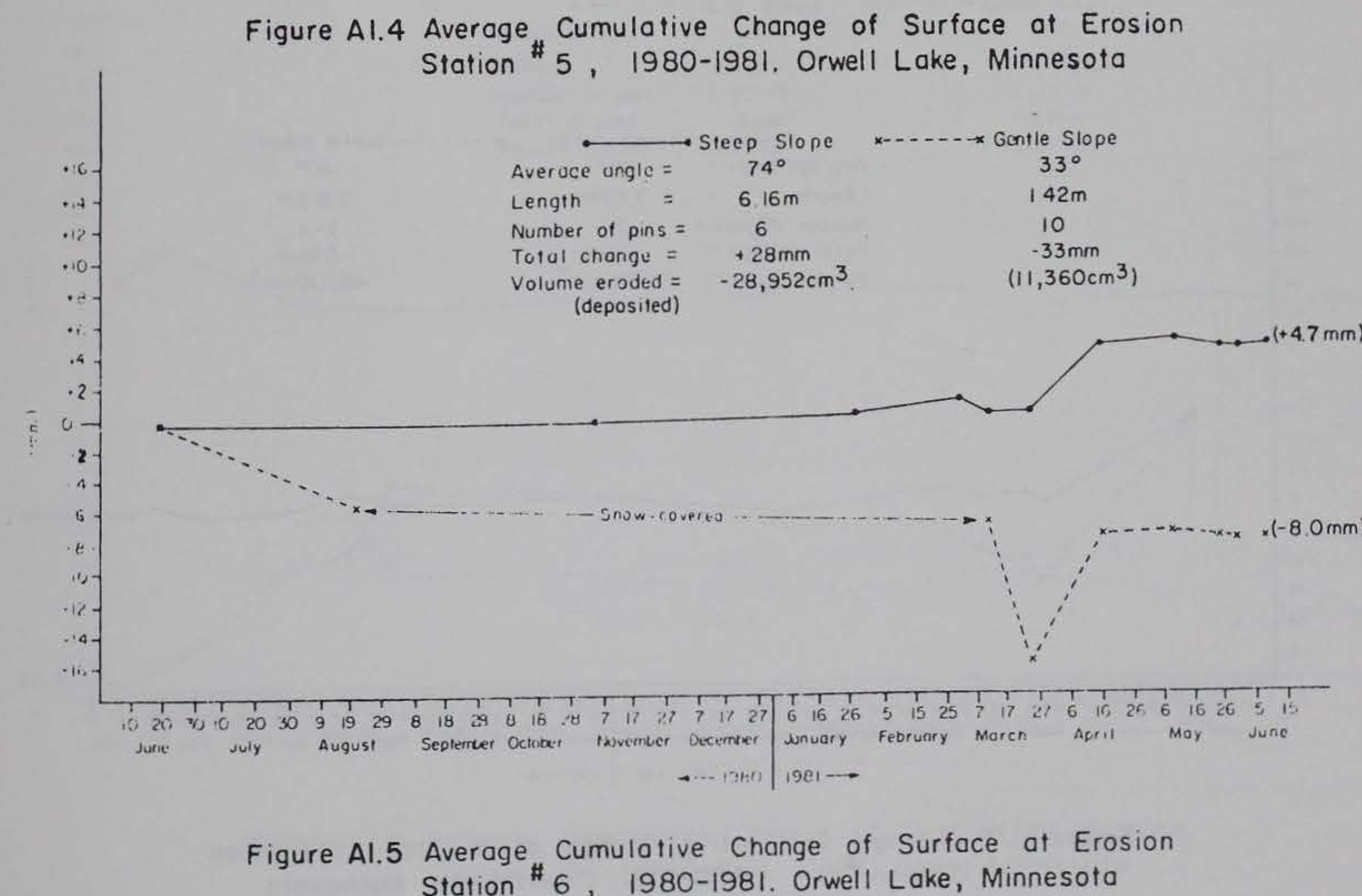

Figure A1.5 Average Cumulative Change of Surface at Erosion Station # 6, 1980-1981. Orwell Lake, Minnesota

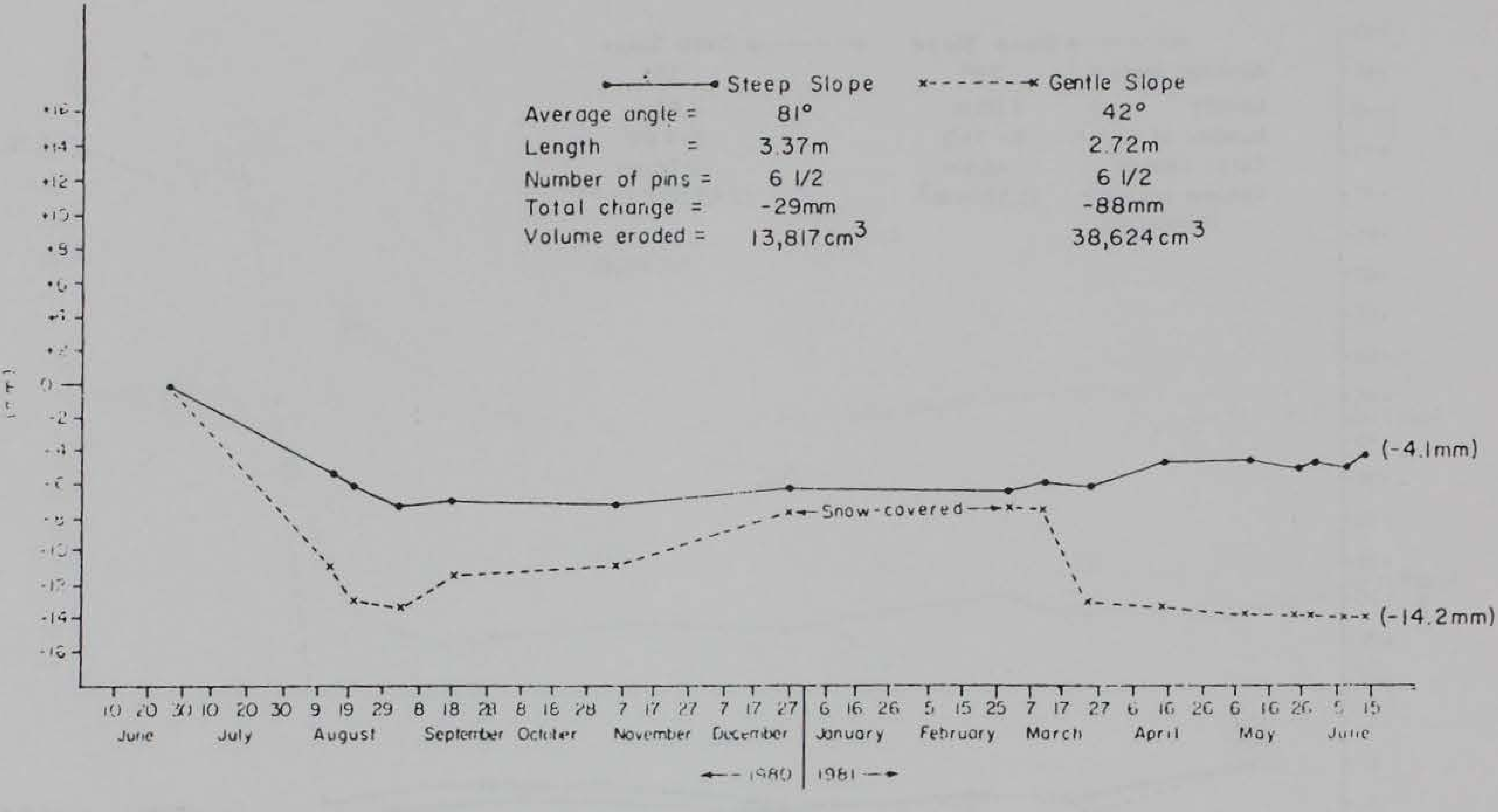

Figure AI.6 Average Cumulative Change of Surface at Erosion Station # 7, 1980-1981. Orwell Lake, Minnesota

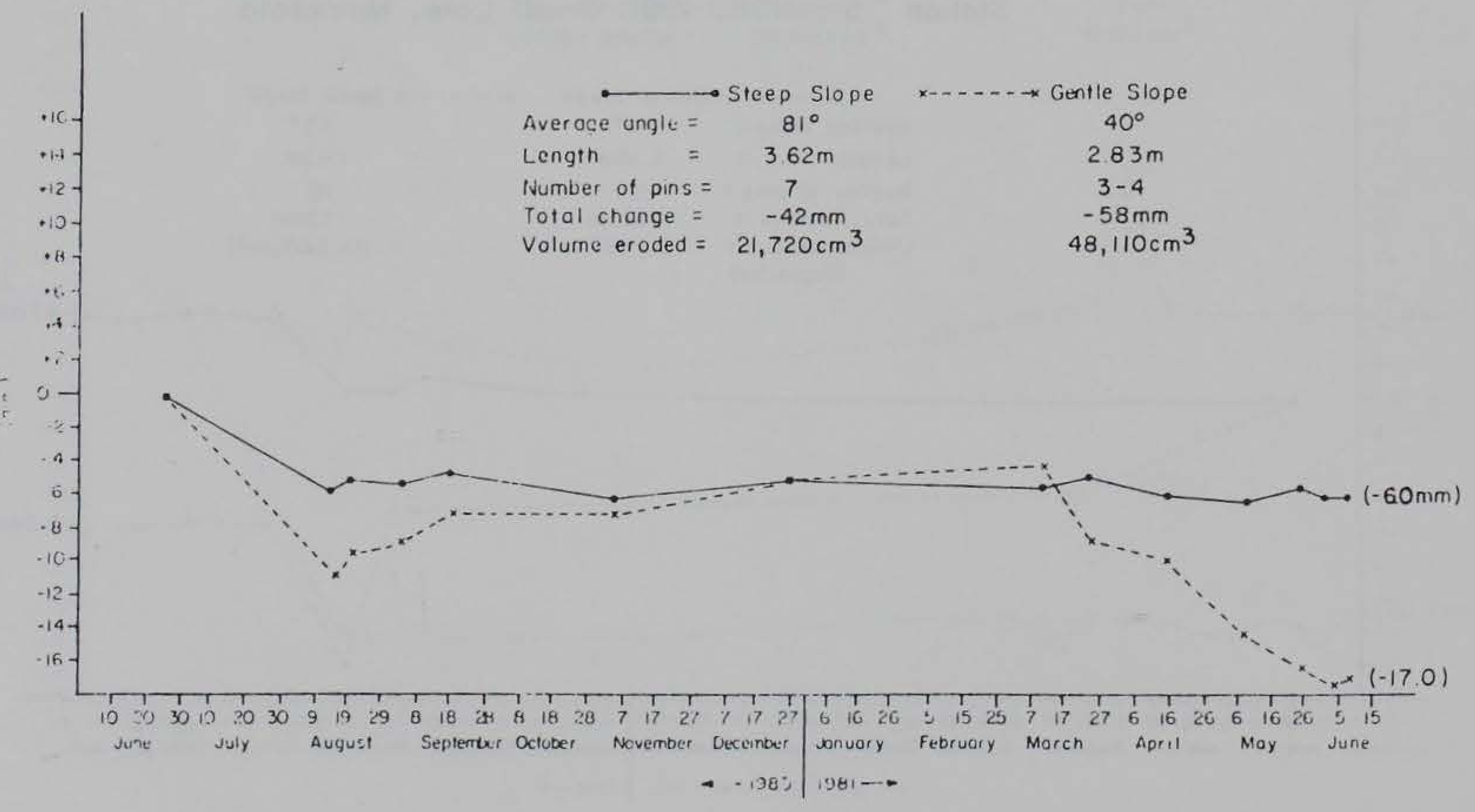

Figure AI.7 Average Cumulative Change of Surface at Erosion Station # 8, 1980-1981. Orwell Lake, Minnesota

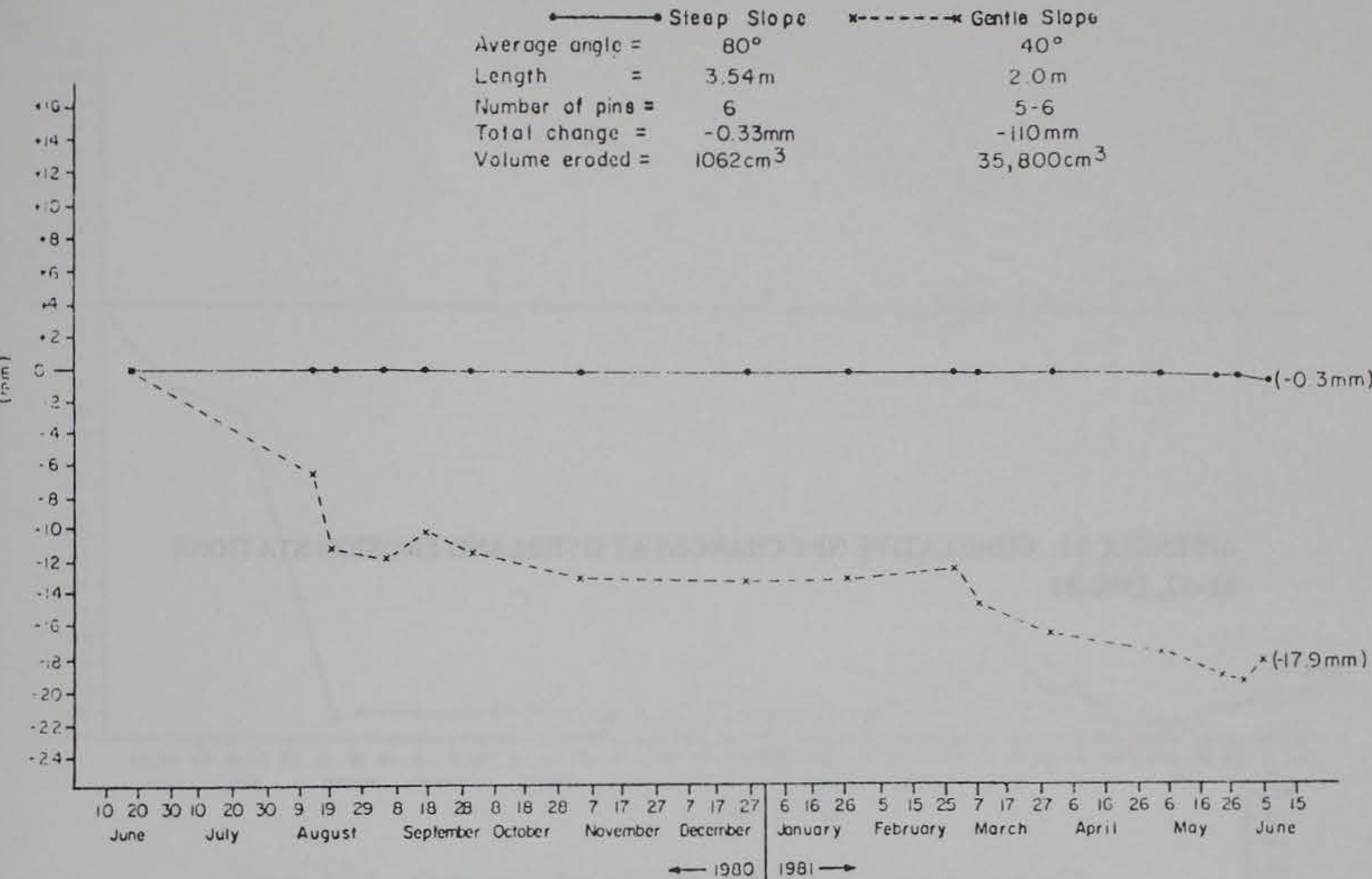

Figure AI.8 Average Cumulative Change of Surface at Erosion Station # 9, 1980-1981. Orwell Lake, Minnesota

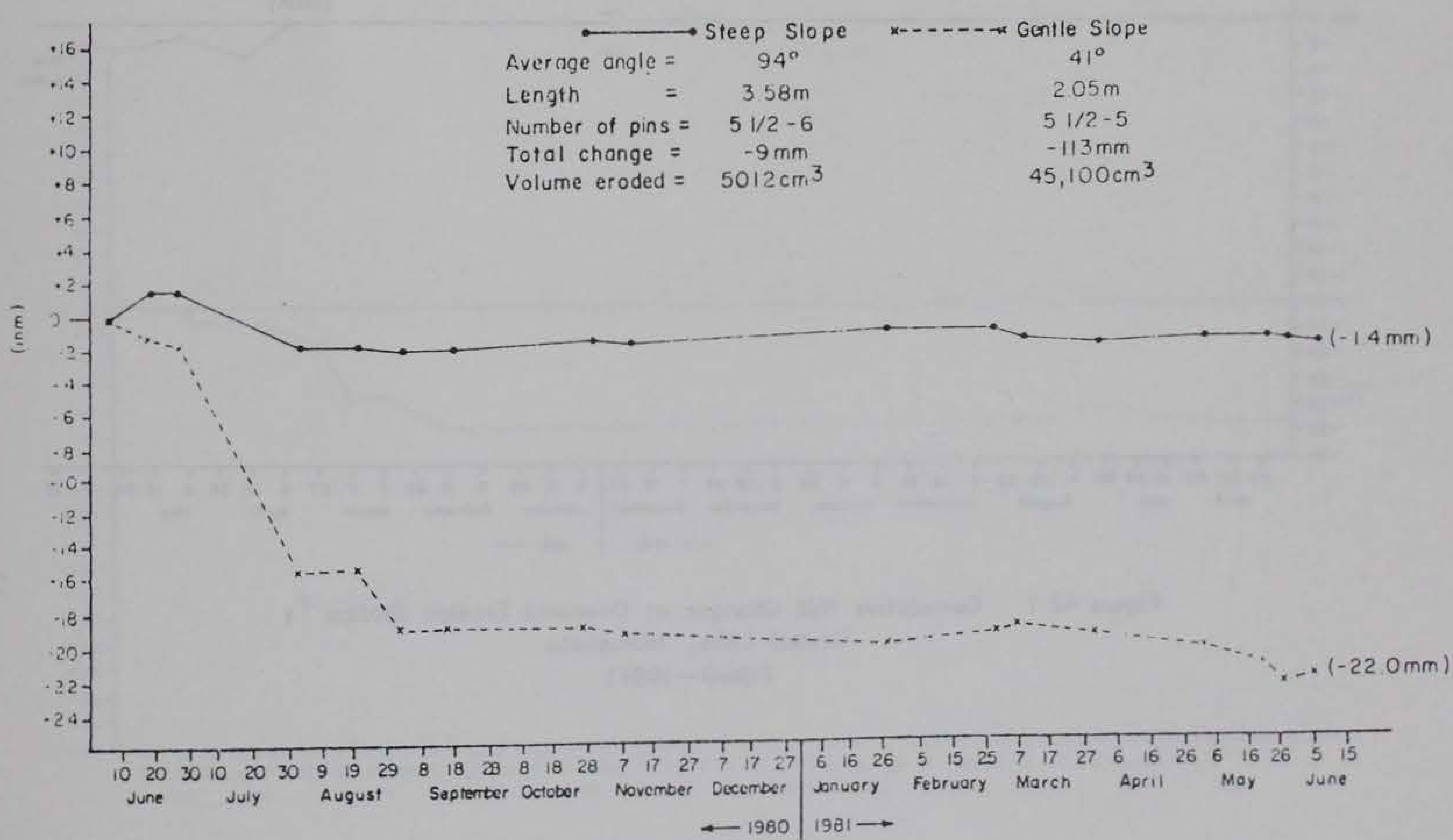

Figure AI.9 Average Cumulative Change of Surface at Erosion Station #10, 1980-1981. Orwell Lake, Minnesota

APPENDIX A2: CUMULATIVE NET CHANGES AT OVERLAND EROSION STATIONS #1-12, 1980-81

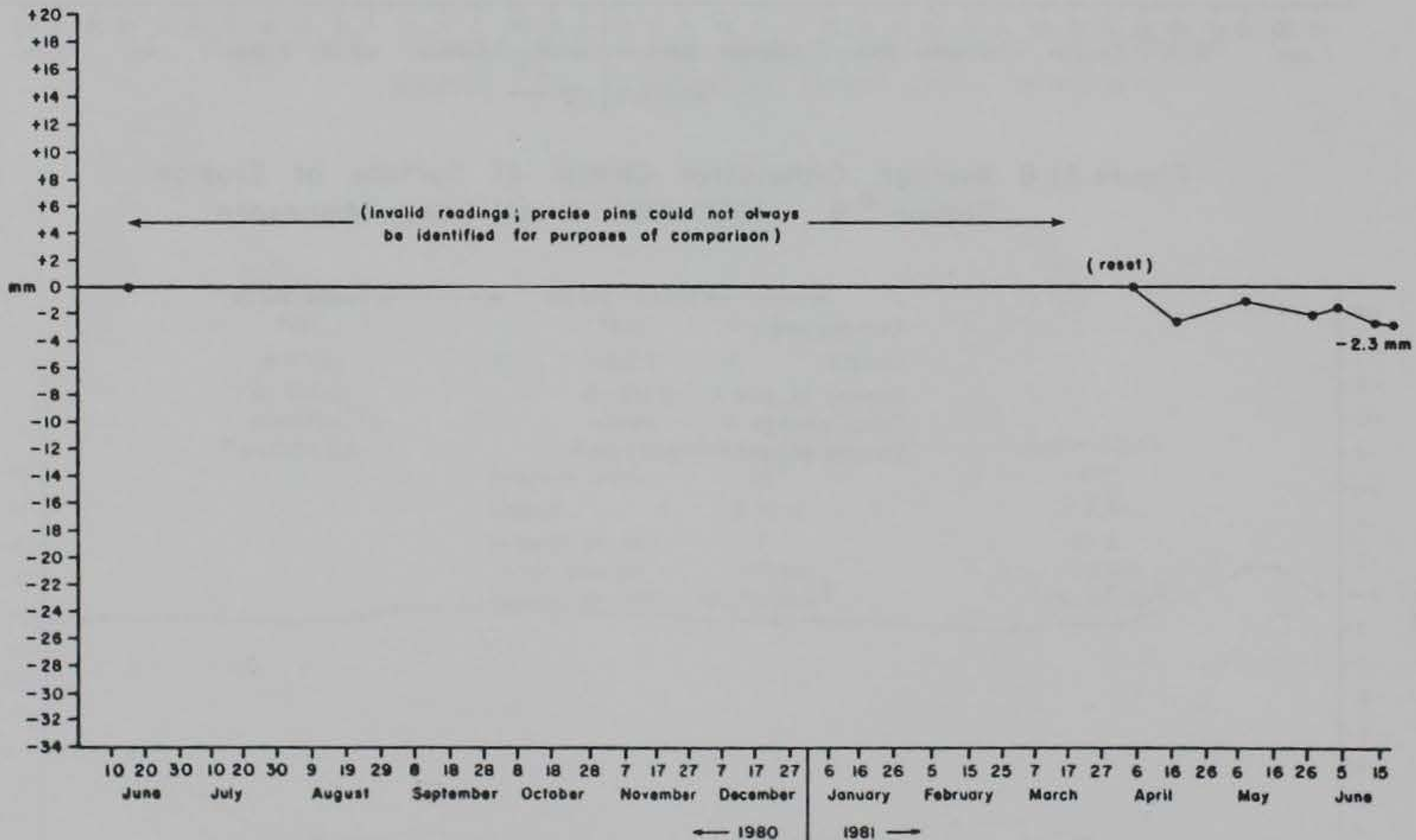

Figure A2.1 Cumulative Net Changes at Overland Erosion Station # 1
Orwell Lake, Minnesota
(1980 – 1981)

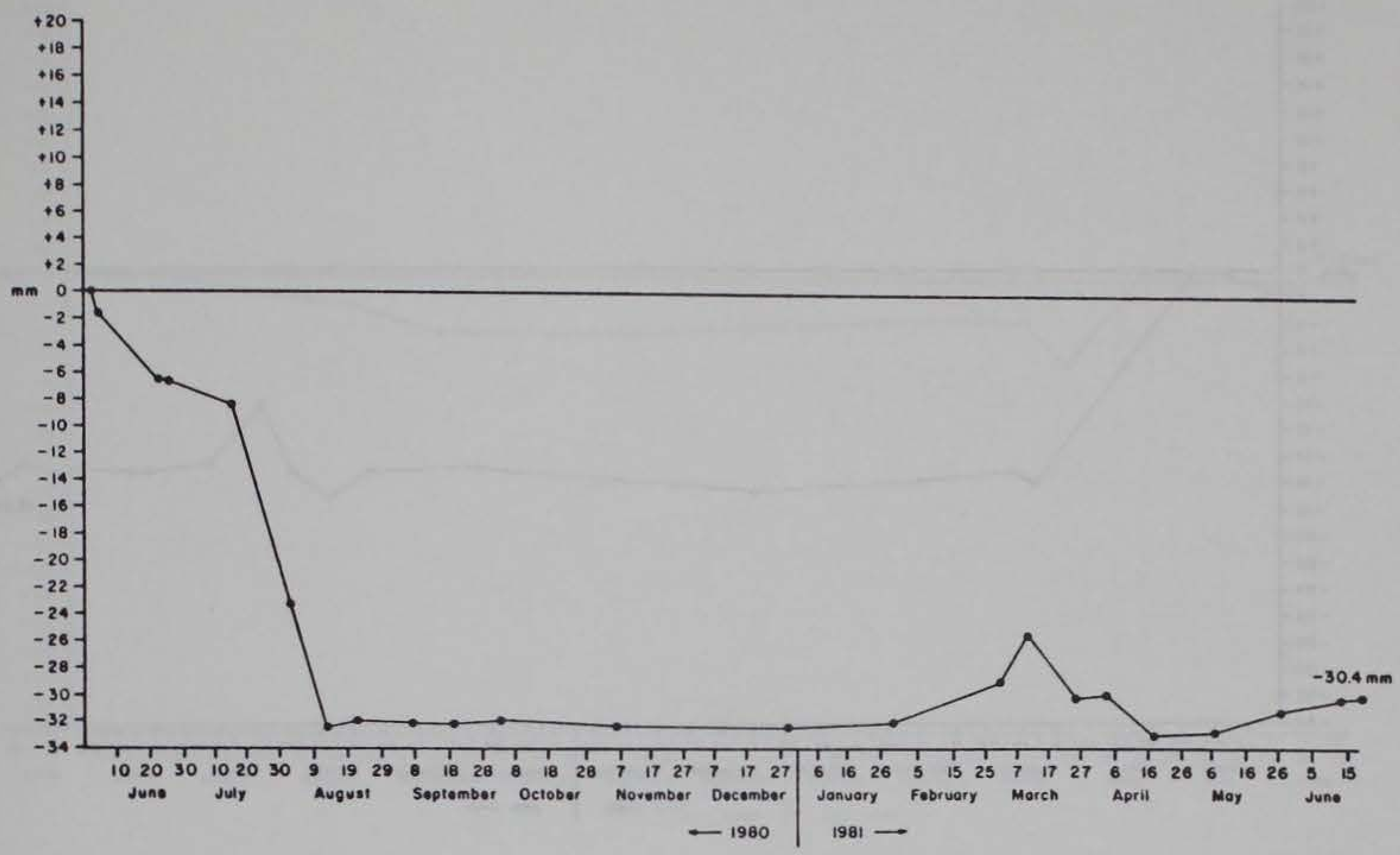

Figure A2.2 Cumulative Net Changes at Overland Erosion Station #2
Orwell Lake, Minnesota
(1980 – 1981)

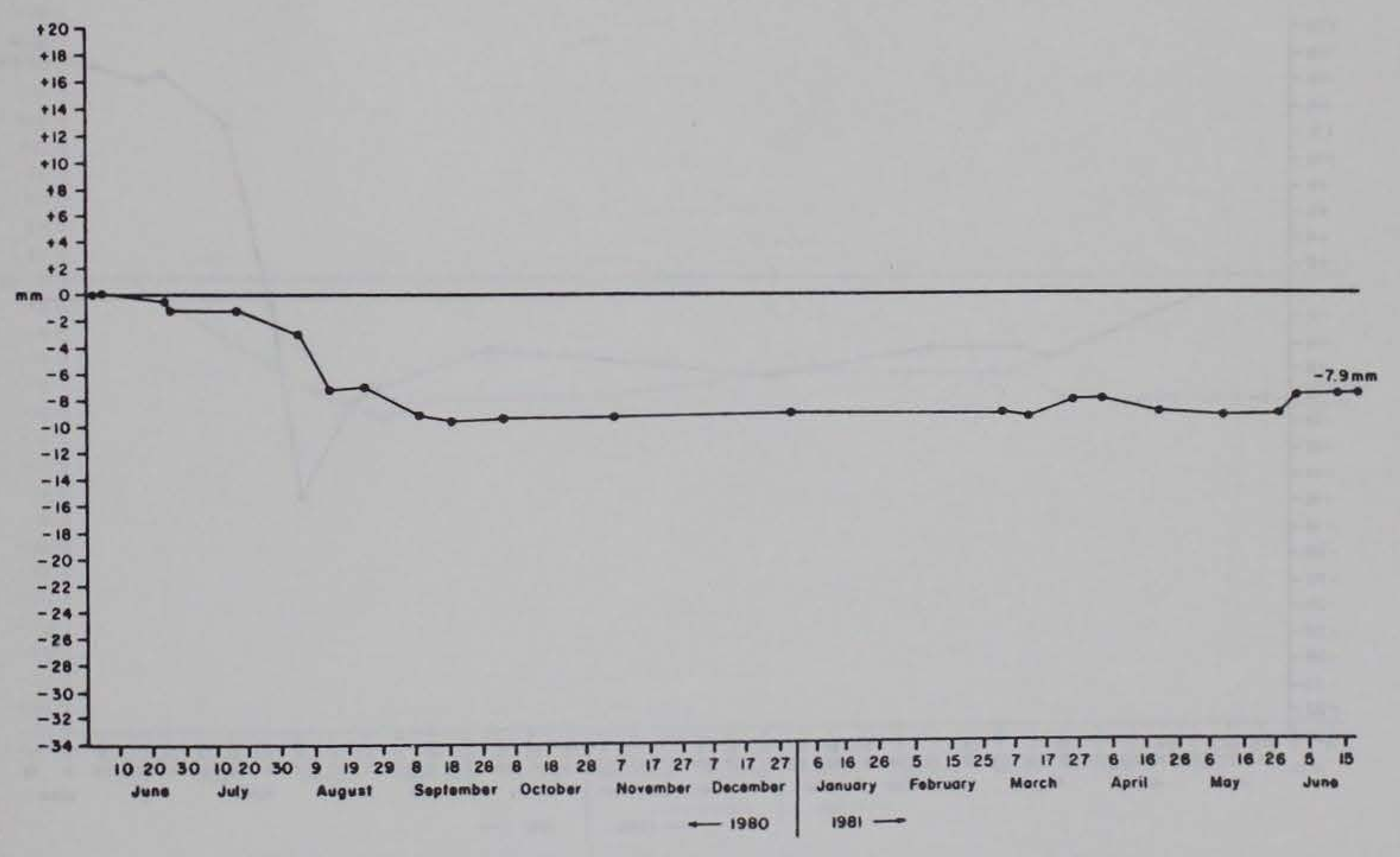

Figure A2.3 Cumulative Net Changes at Overland Erosion Station #3
Orwell Lake, Minnesota
(1980 – 1981)

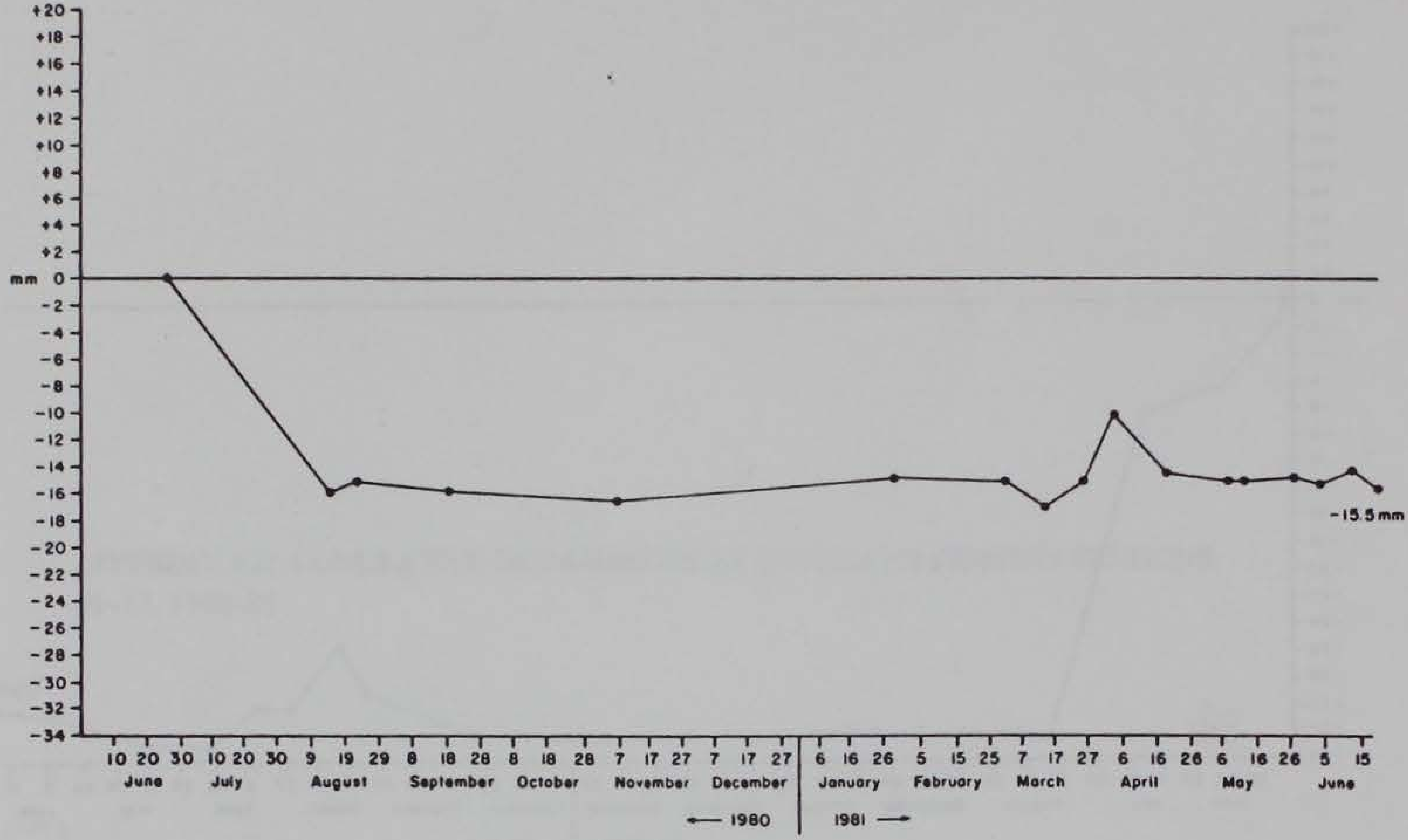

Figure A2.4 Cumulative Net Changes at Overland Erosion Station #4
Orwell Lake, Minnesota
(1980 – 1981)

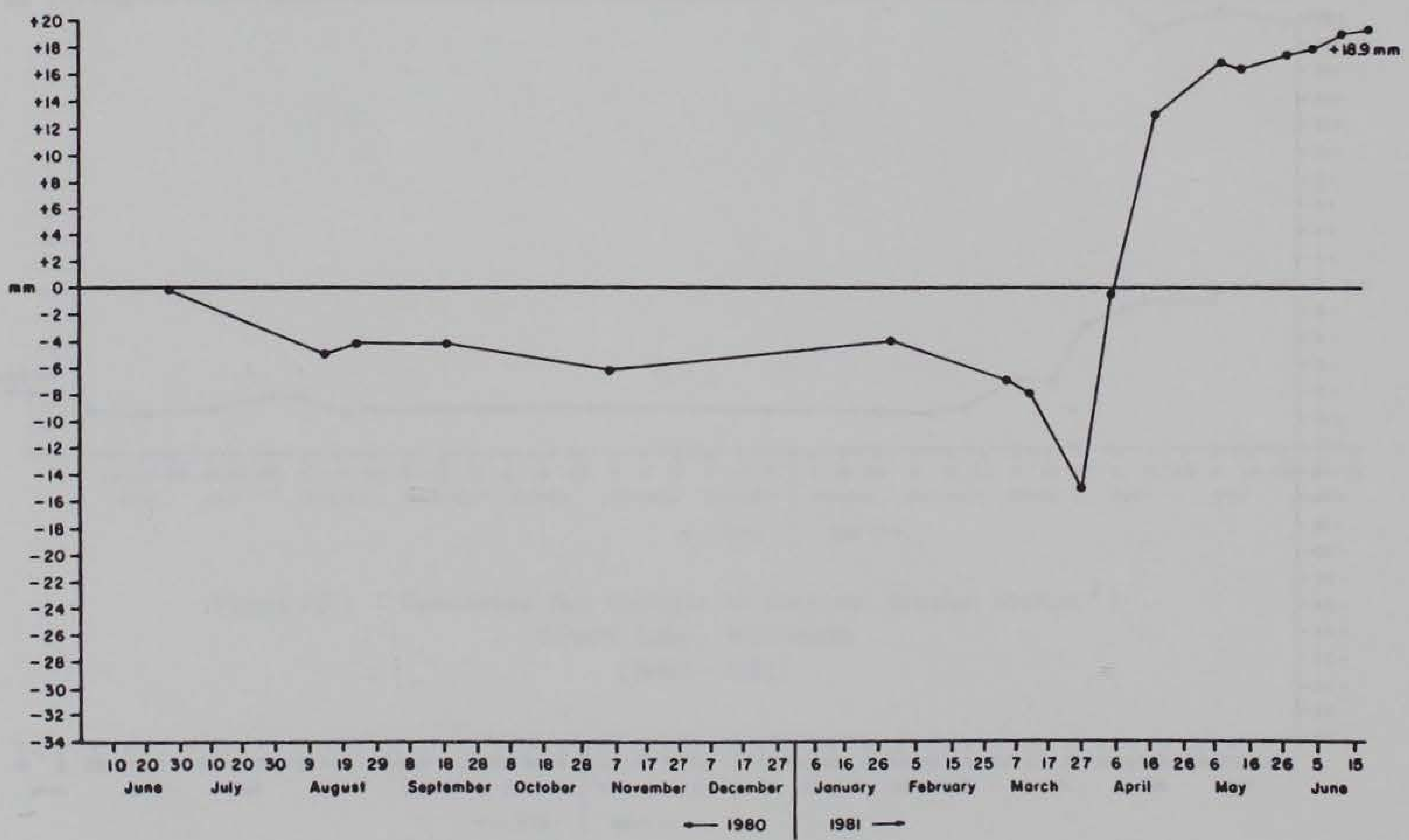

Figure A2.5 Cumulative Net Changes at Overland Erosion Station #5
Orwell Lake, Minnesota
(1980 – 1981)

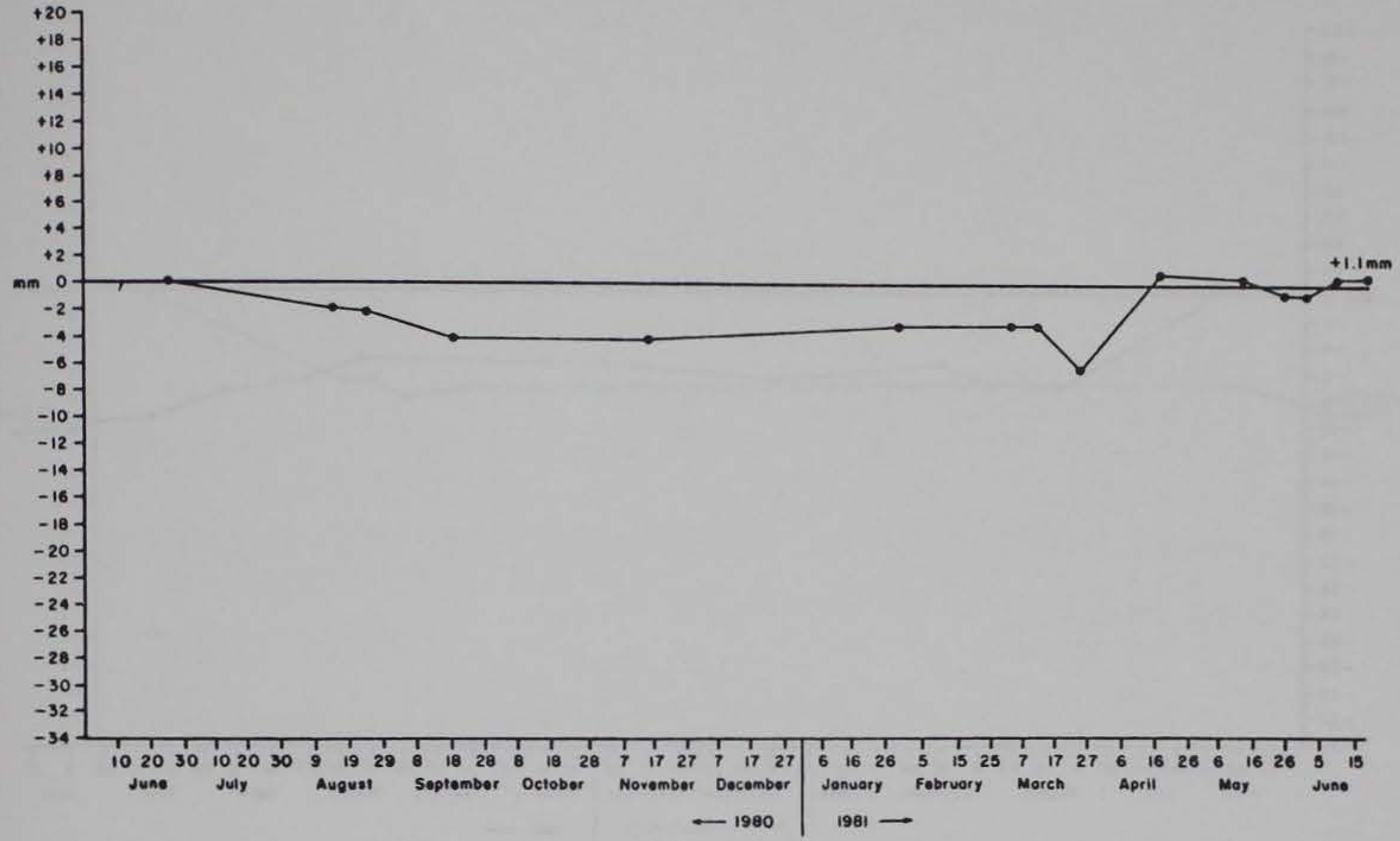

Figure A2.6 Cumulative Net Changes at Overland Erosion Station #6
Orwell Lake, Minnesota
(1980 – 1981)

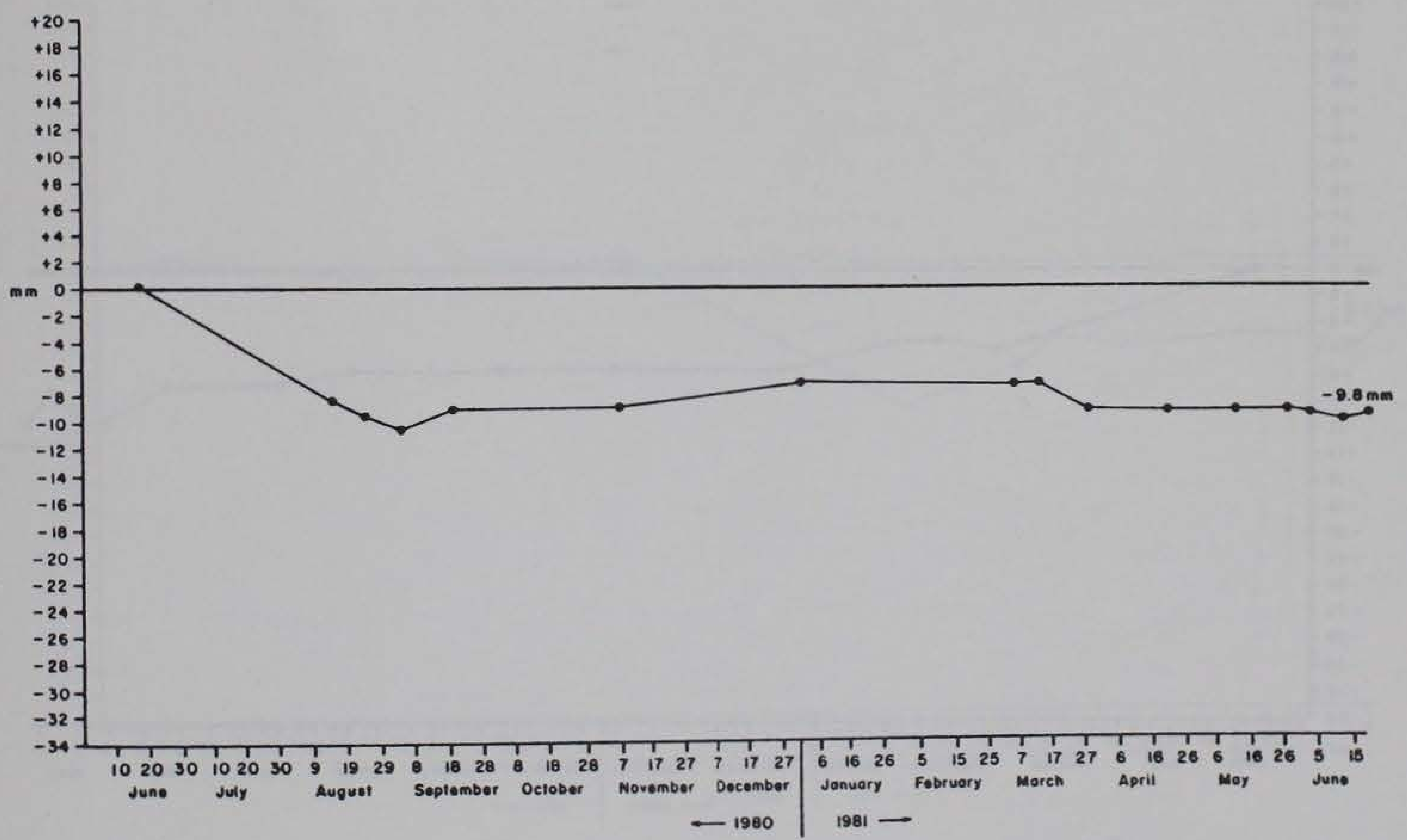

Figure A2.7 Cumulative Net Changes at Overland Erosion Station # 7
Orwell Lake, Minnesota
(1980 – 1981)

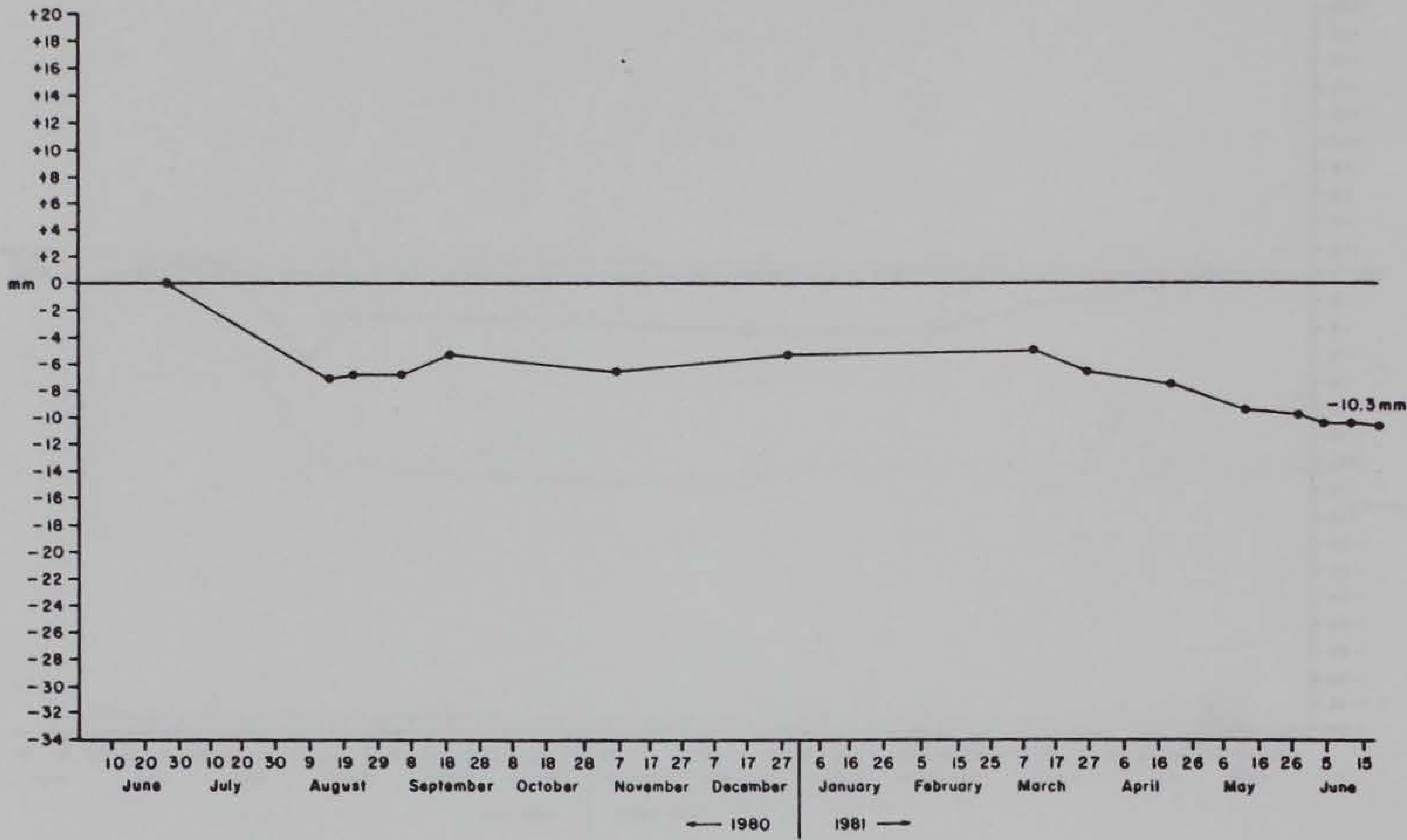

Figure A2.8 Cumulative Net Changes at Overland Erosion Station #8
Orwell Lake, Minnesota
(1980 – 1981)

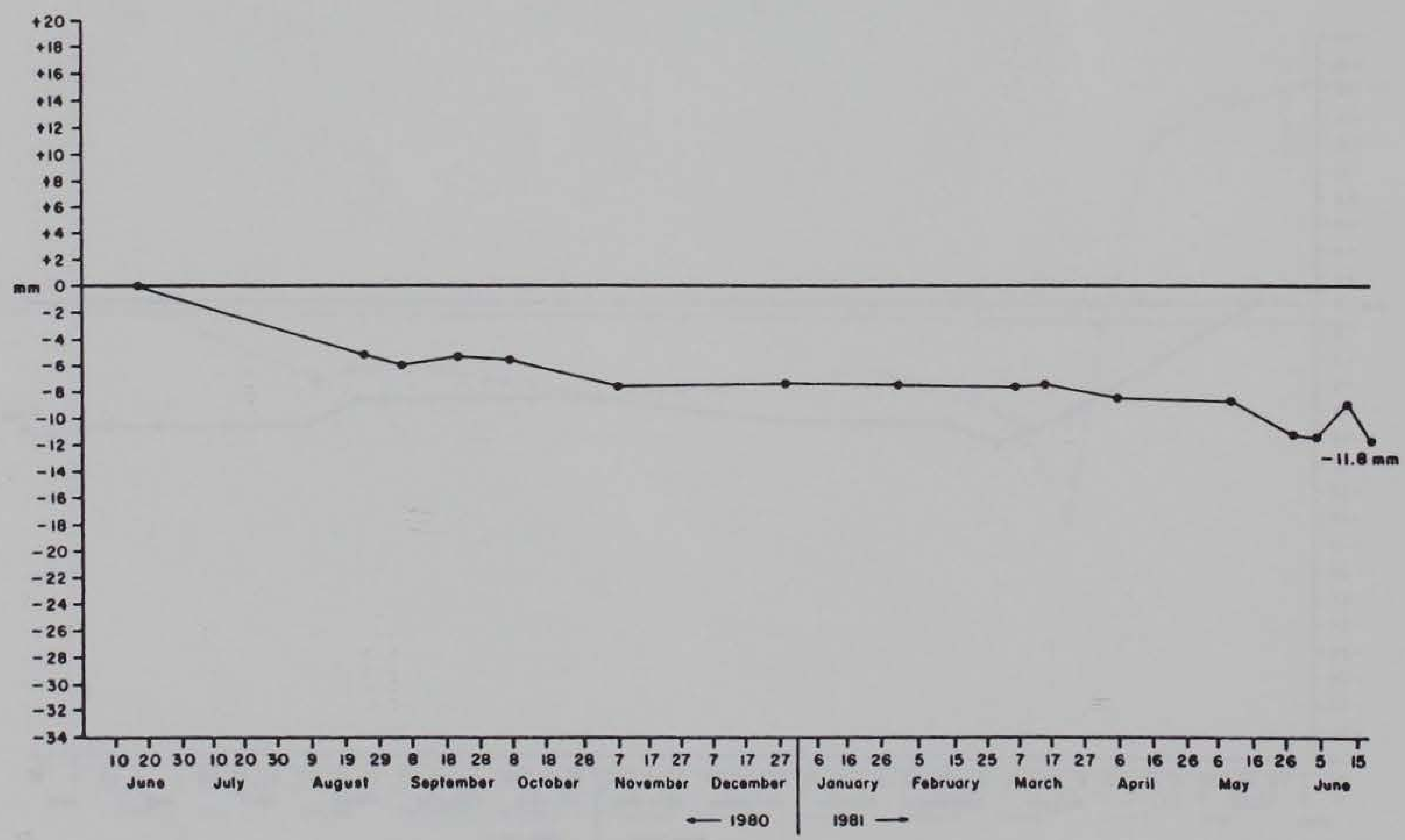

Figure A2.9 Cumulative Net Changes at Overland Erosion Station #9
Orwell Lake, Minnesota
(1980 – 1981)

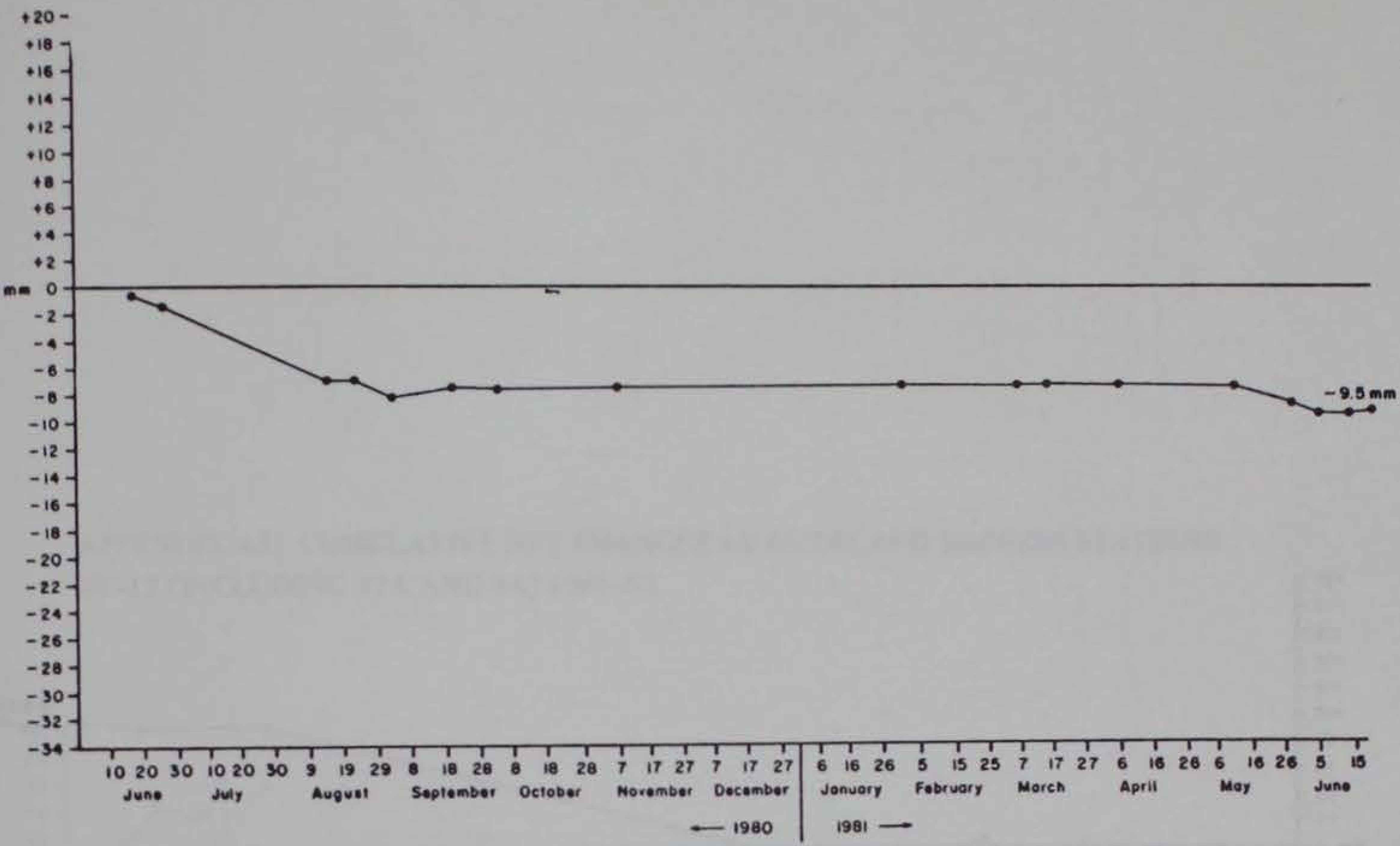

Figure A2.10 Cumulative Net Changes at Overland Erosion Station #10
Orwell Lake, Minnesota
(1980–1981)

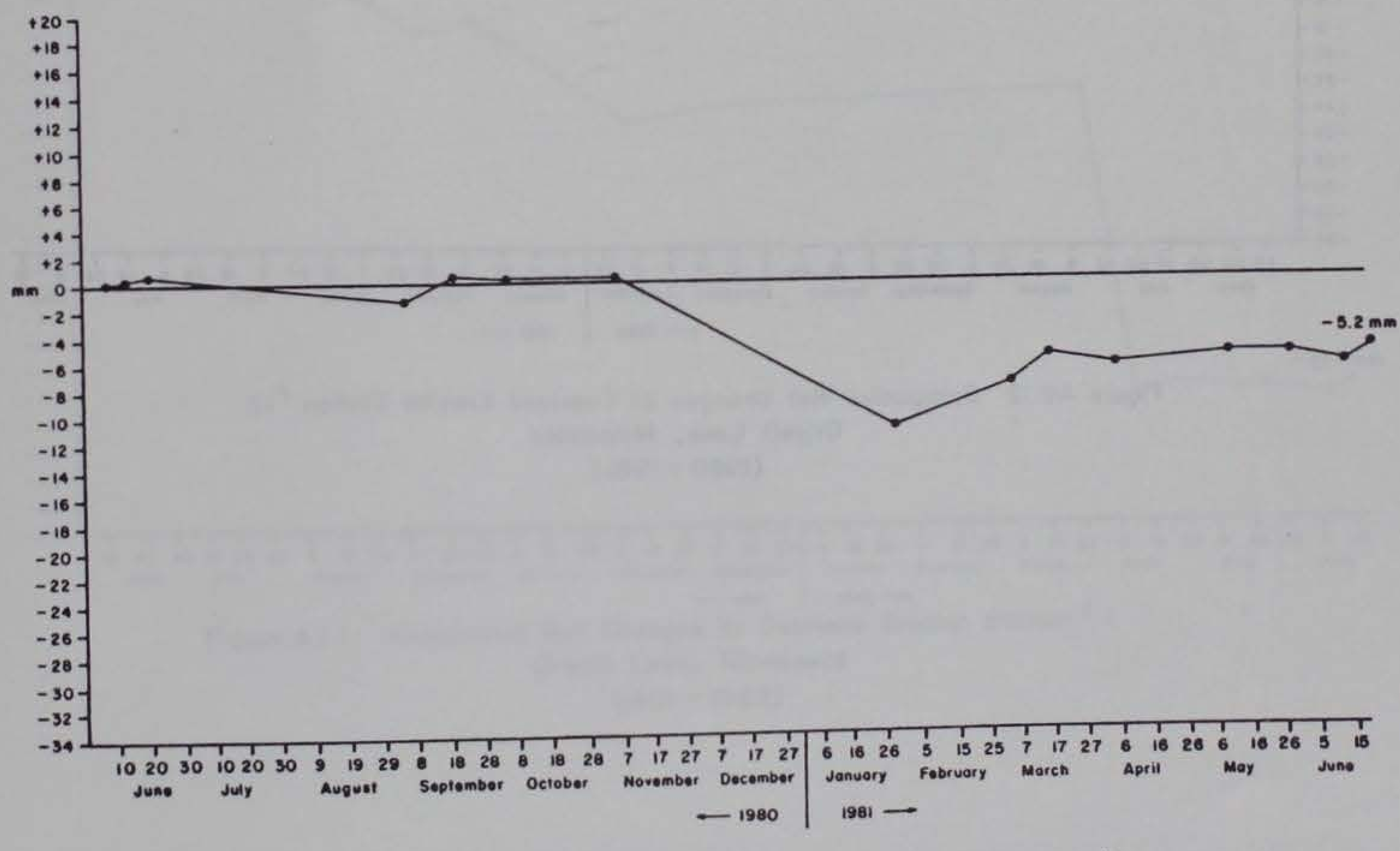

Figure A2.11 Cumulative Net Changes at Overland Erosion Station #11
Orwell Lake, Minnesota
(1980–1981)

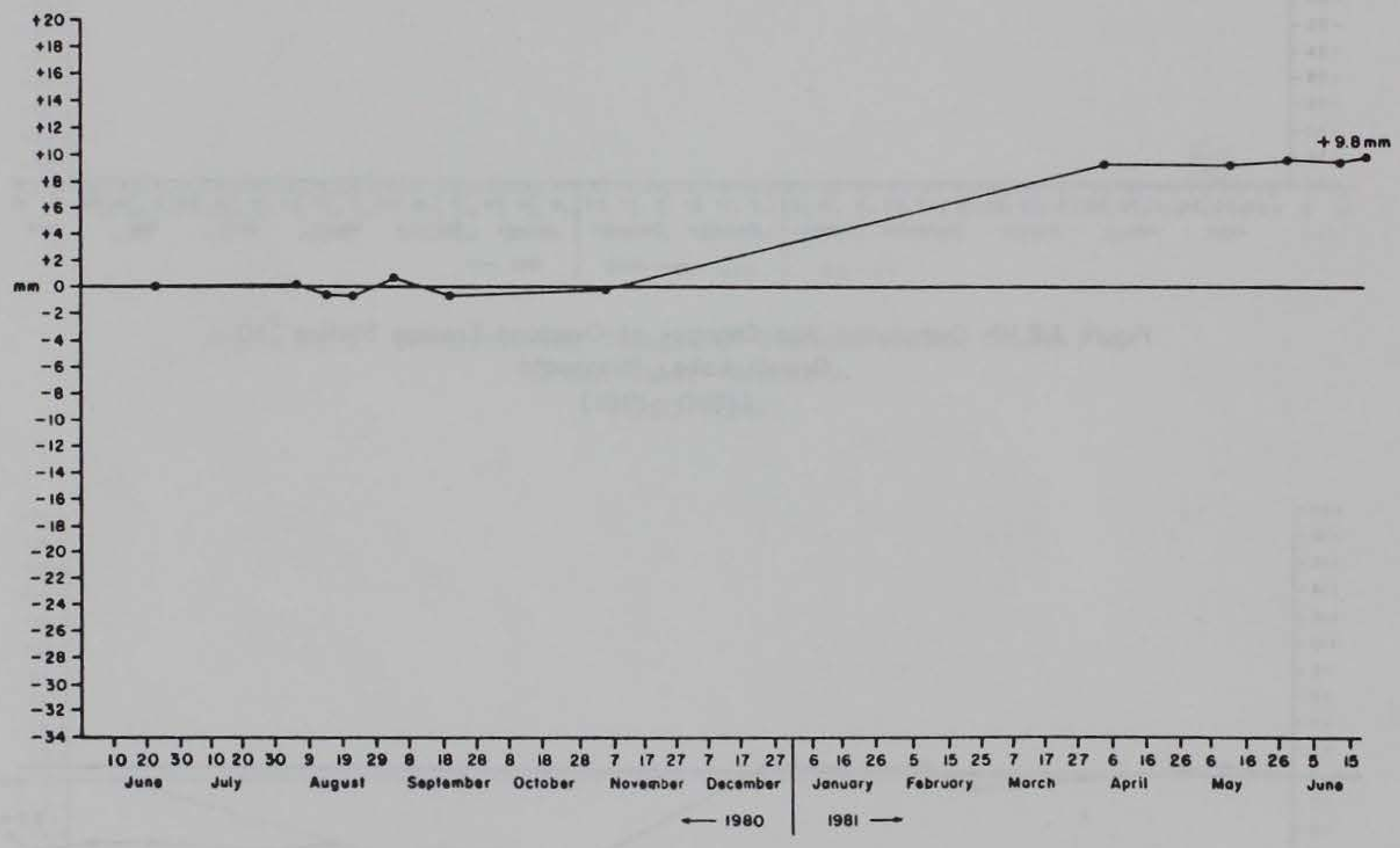

Figure A2.12 Cumulative Net Changes at Overland Erosion Station #12
Orwell Lake, Minnesota
(1980 – 1981)

APPENDIX A3: CUMULATIVE NET CHANGES AT OVERLAND EROSION STATIONS #1-12 (INCLUDING #7A AND 8A) 1981-82

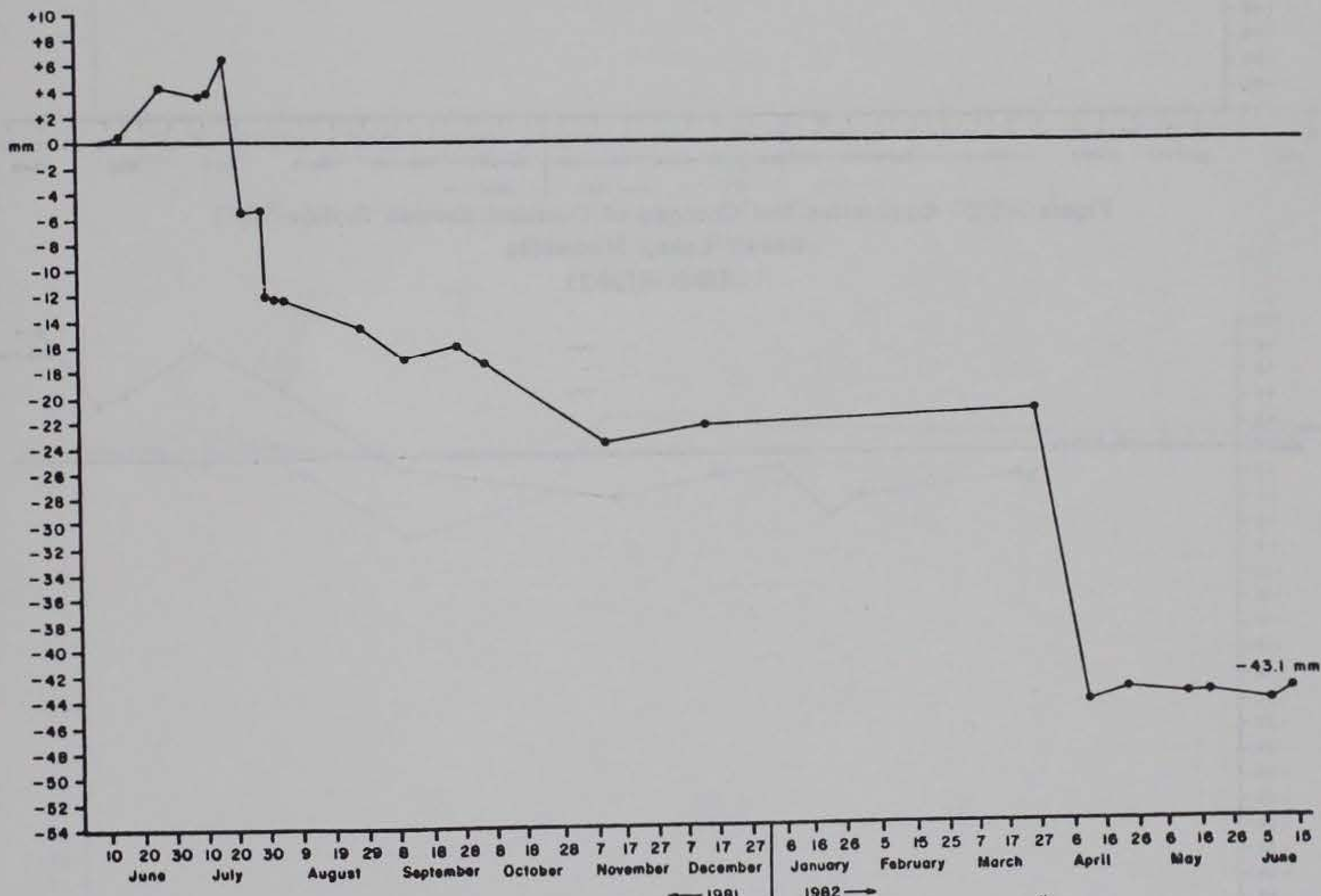

Figure A3.1 Cumulative Net Changes at Overland Erosion Station # 1
Orwell Lake, Minnesota
(1981 – 1982)

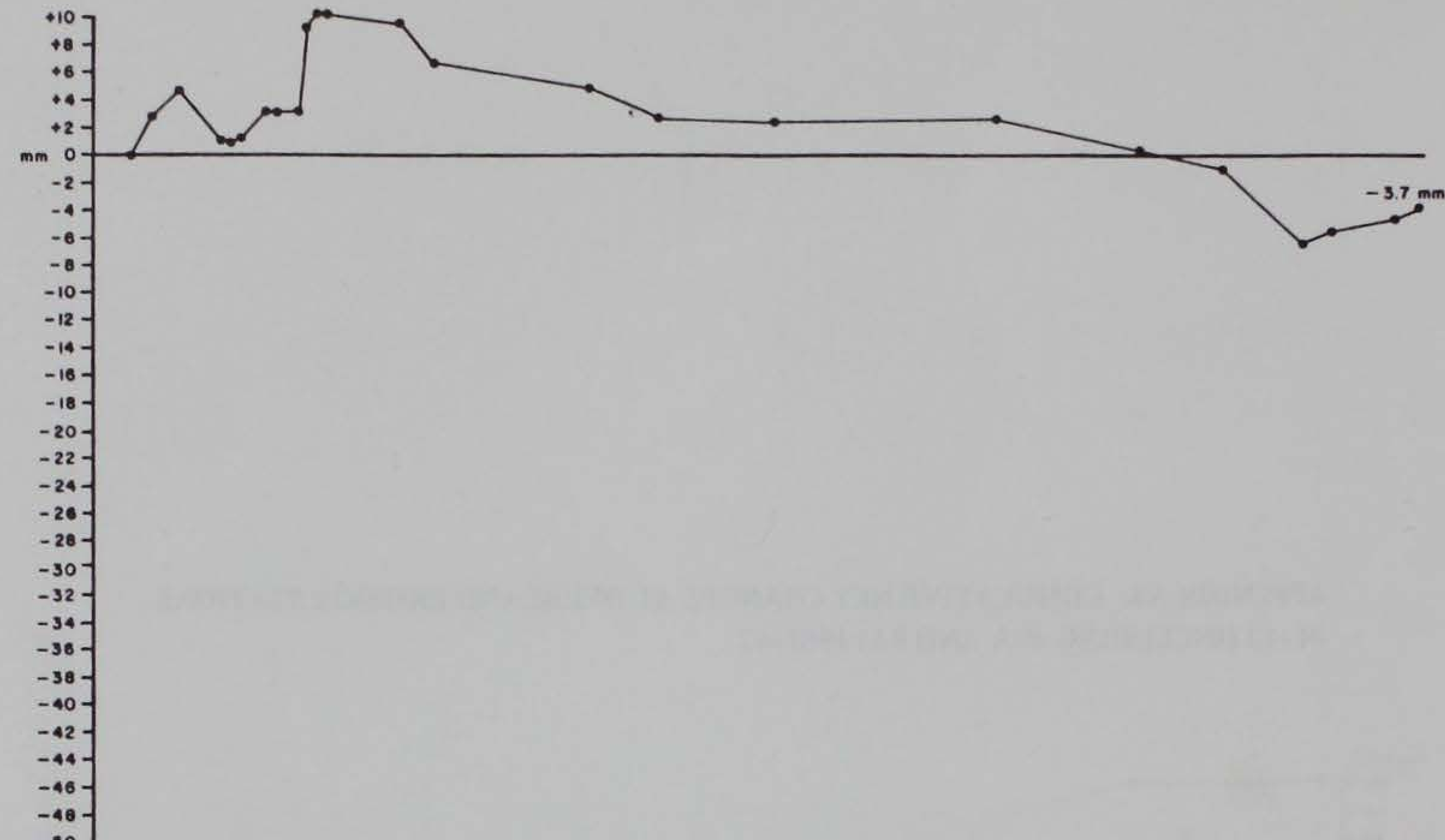

Figure A3.2 Cumulative Net Changes at Overland Erosion Station # 2
Orwell Lake, Minnesota
(1981 – 1982)

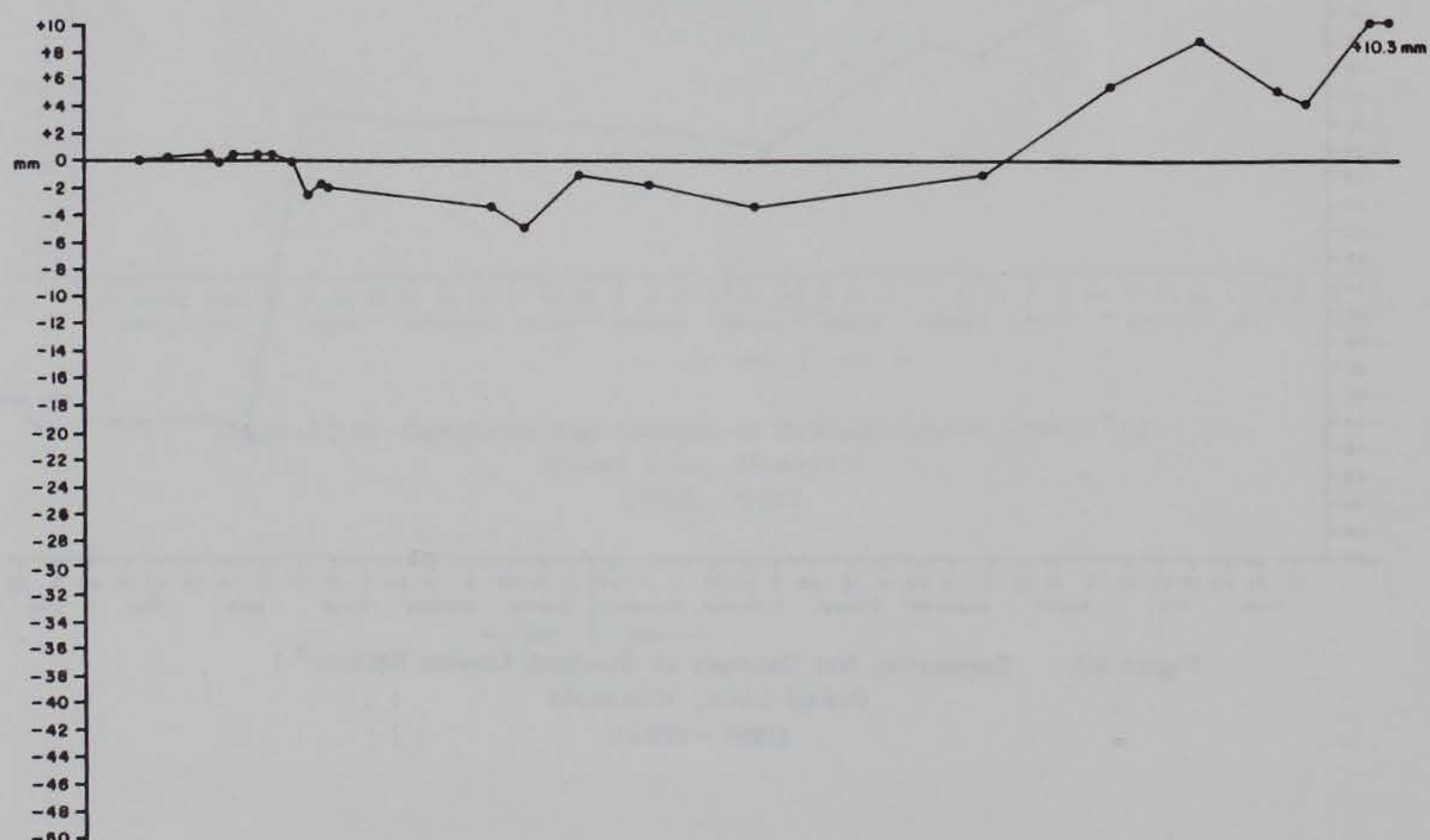

Figure A3.3 Cumulative Net Changes at Overland Erosion Station # 3
Orwell Lake, Minnesota
(1981 – 1982)

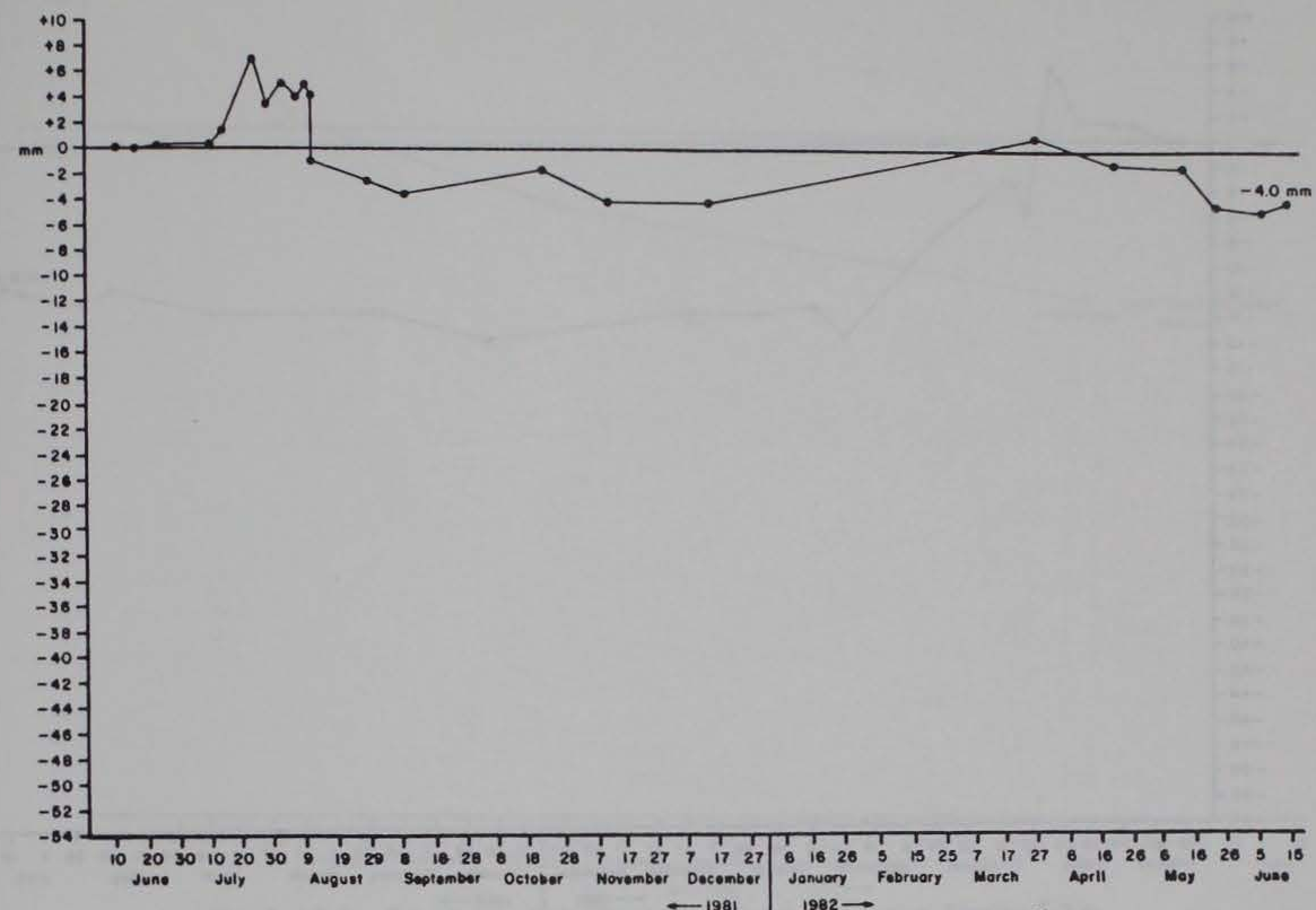

Figure A3.4 Cumulative Net Changes at Overland Erosion Station # 4
Orwell Lake, Minnesota
(1981 – 1982)

Figure A3.5 Cumulative Net Changes at Overland Erosion Station # 5
Orwell Lake, Minnesota
(1981 – 1982)

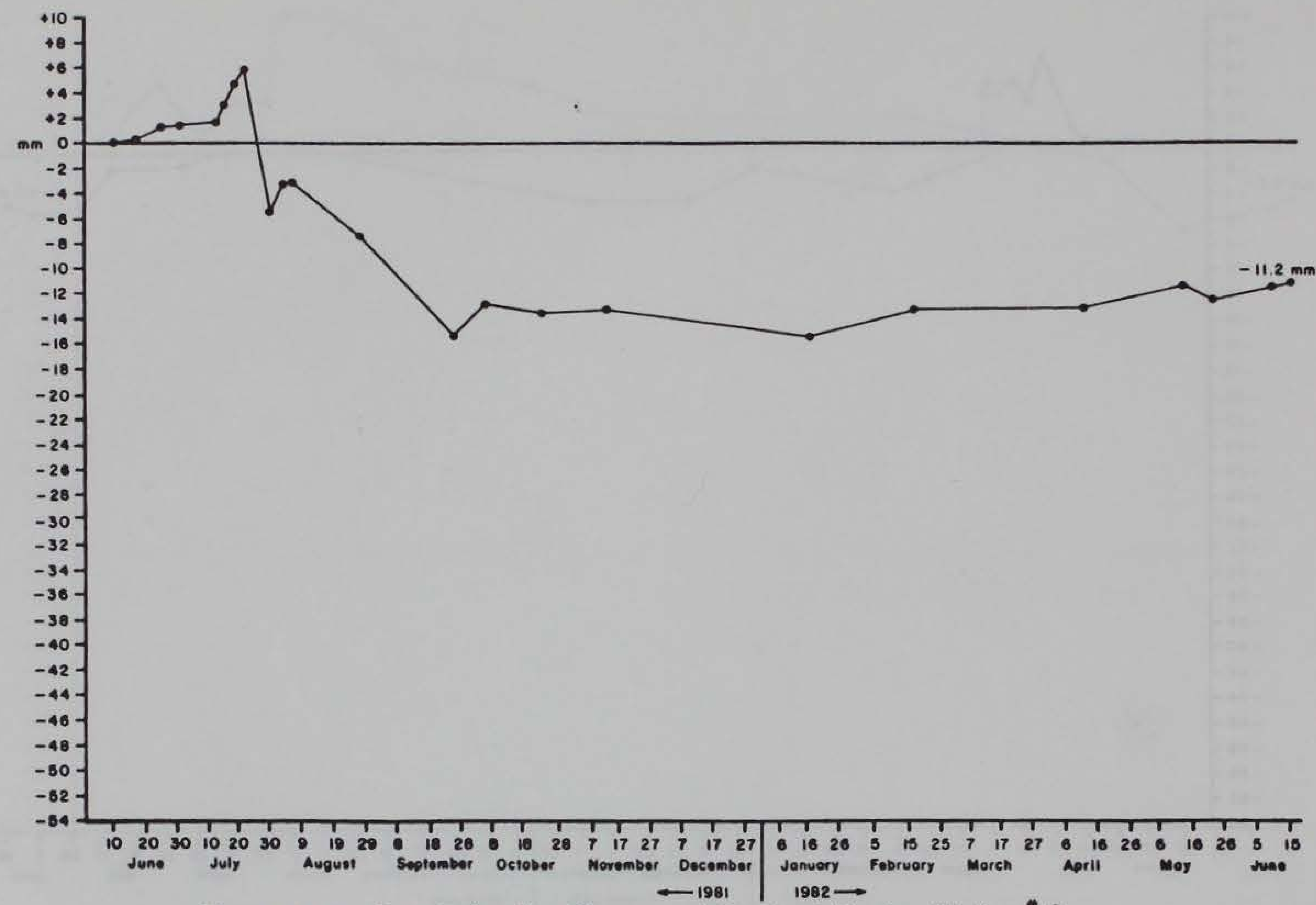

Figure A3.6 Cumulative Net Changes at Overland Erosion Station # 6
Orwell Lake, Minnesota
(1981 – 1982)

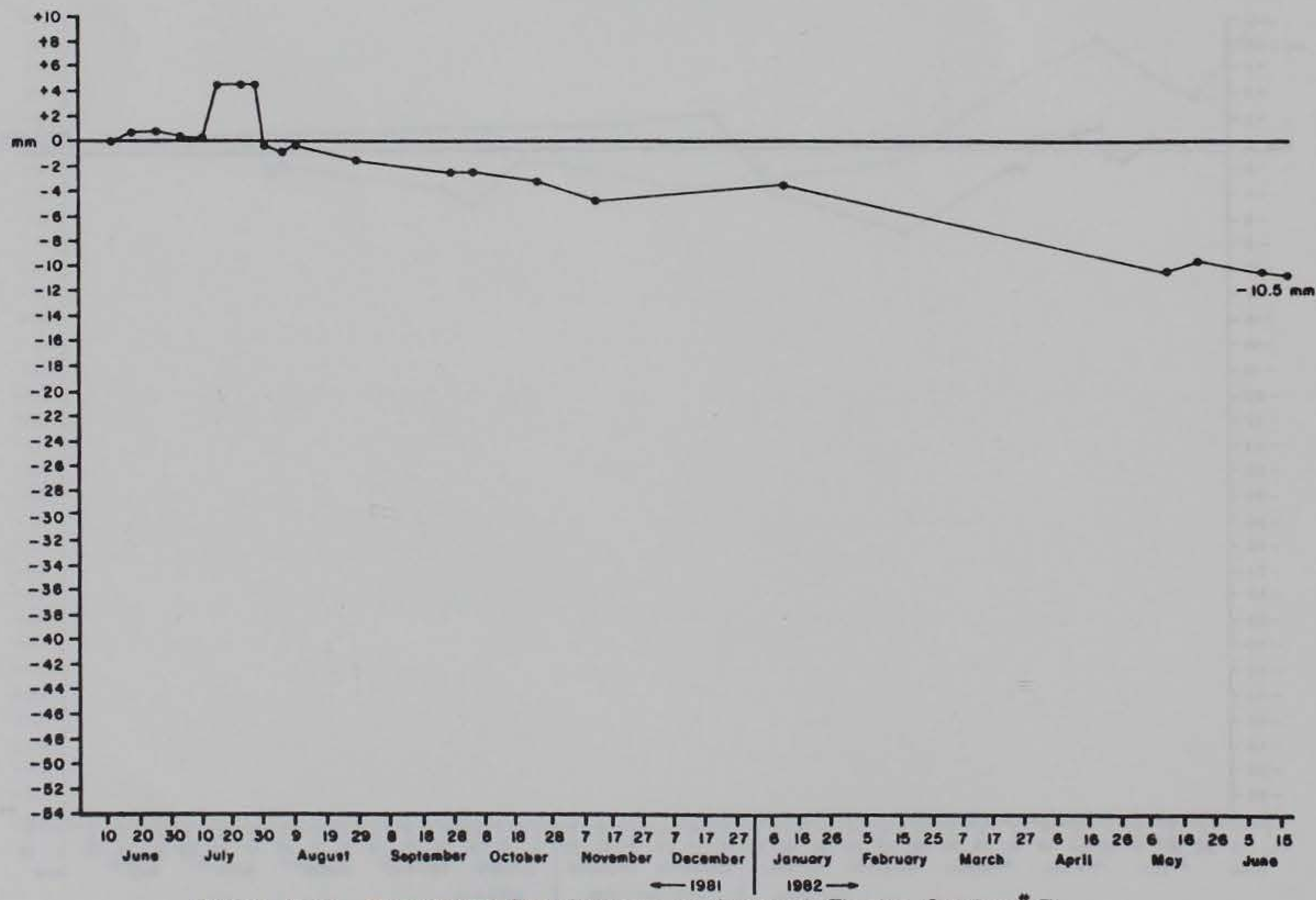

Figure A3.7 Cumulative Net Changes at Overland Erosion Station # 7
Orwell Lake, Minnesota
(1981 – 1982)

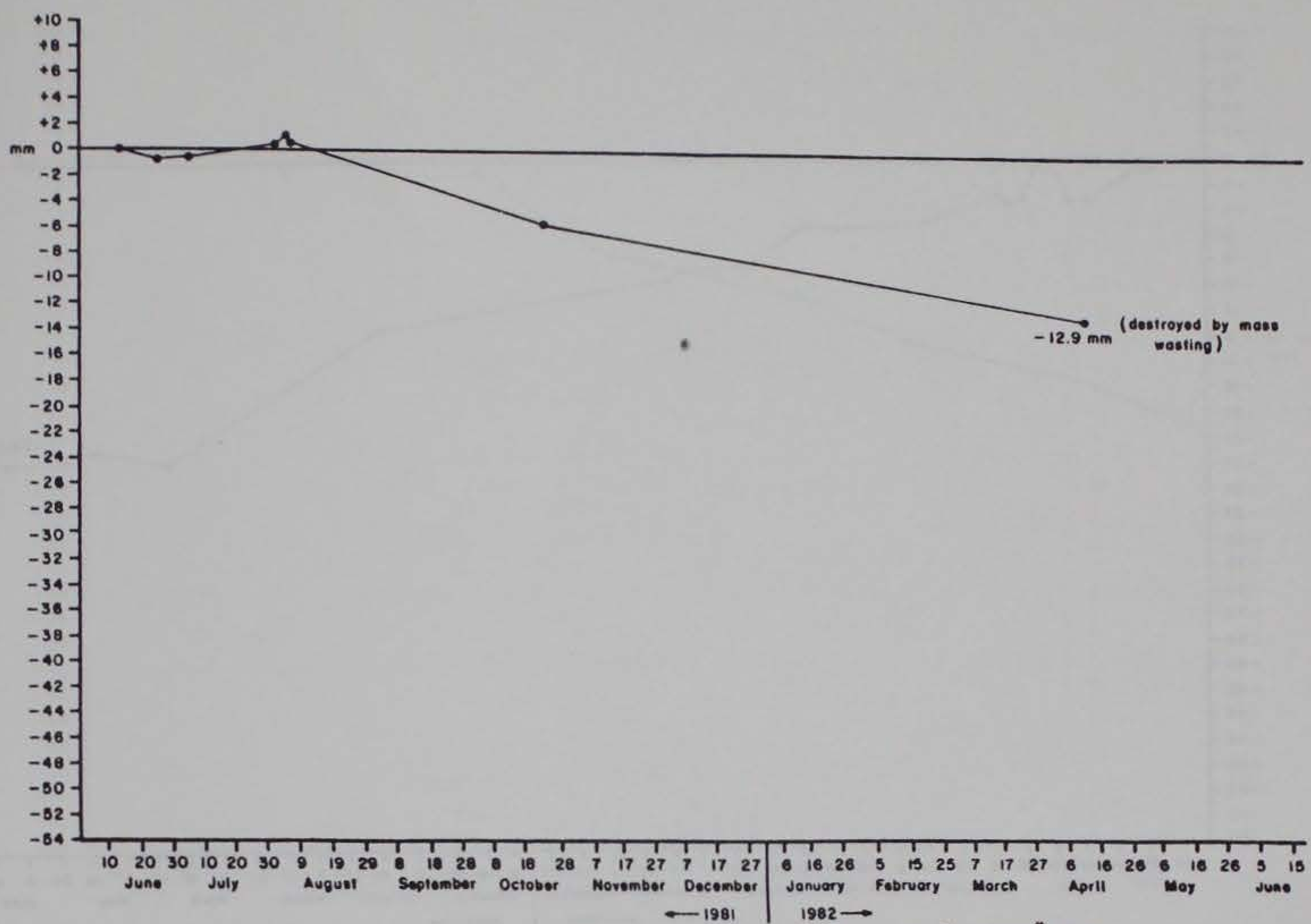

Figure A3.8 Cumulative Net Changes at Overland Erosion Station # 7A
Orwell Lake, Minnesota
(1981 – 1982)

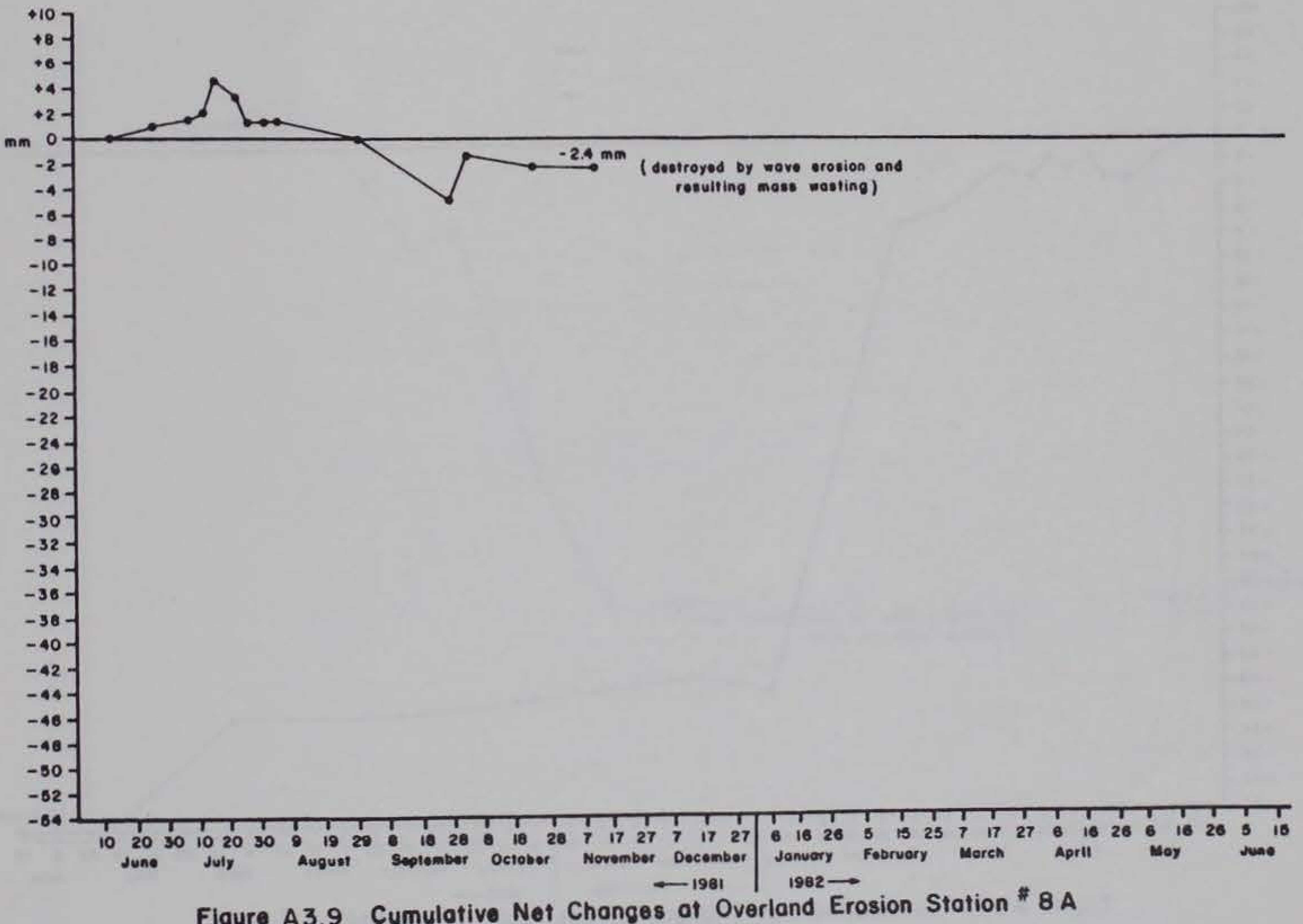

Figure A3.9 Cumulative Net Changes at Overland Erosion Station # 8A
Orwell Lake, Minnesota
(1981 – 1982)

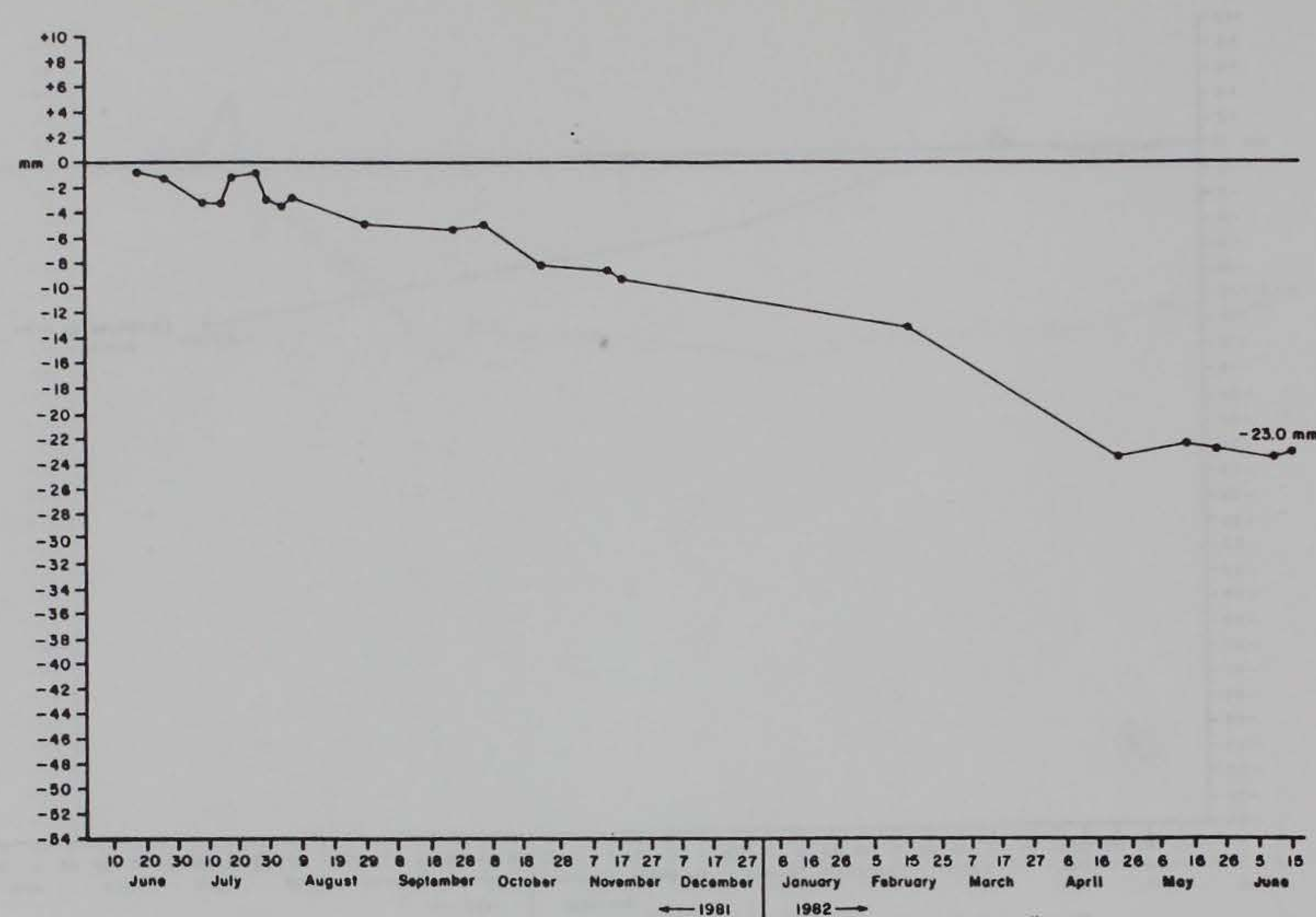

Figure A3.10 Cumulative Net Changes at Overland Erosion Station # 8
Orwell Lake, Minnesota
(1981 – 1982)

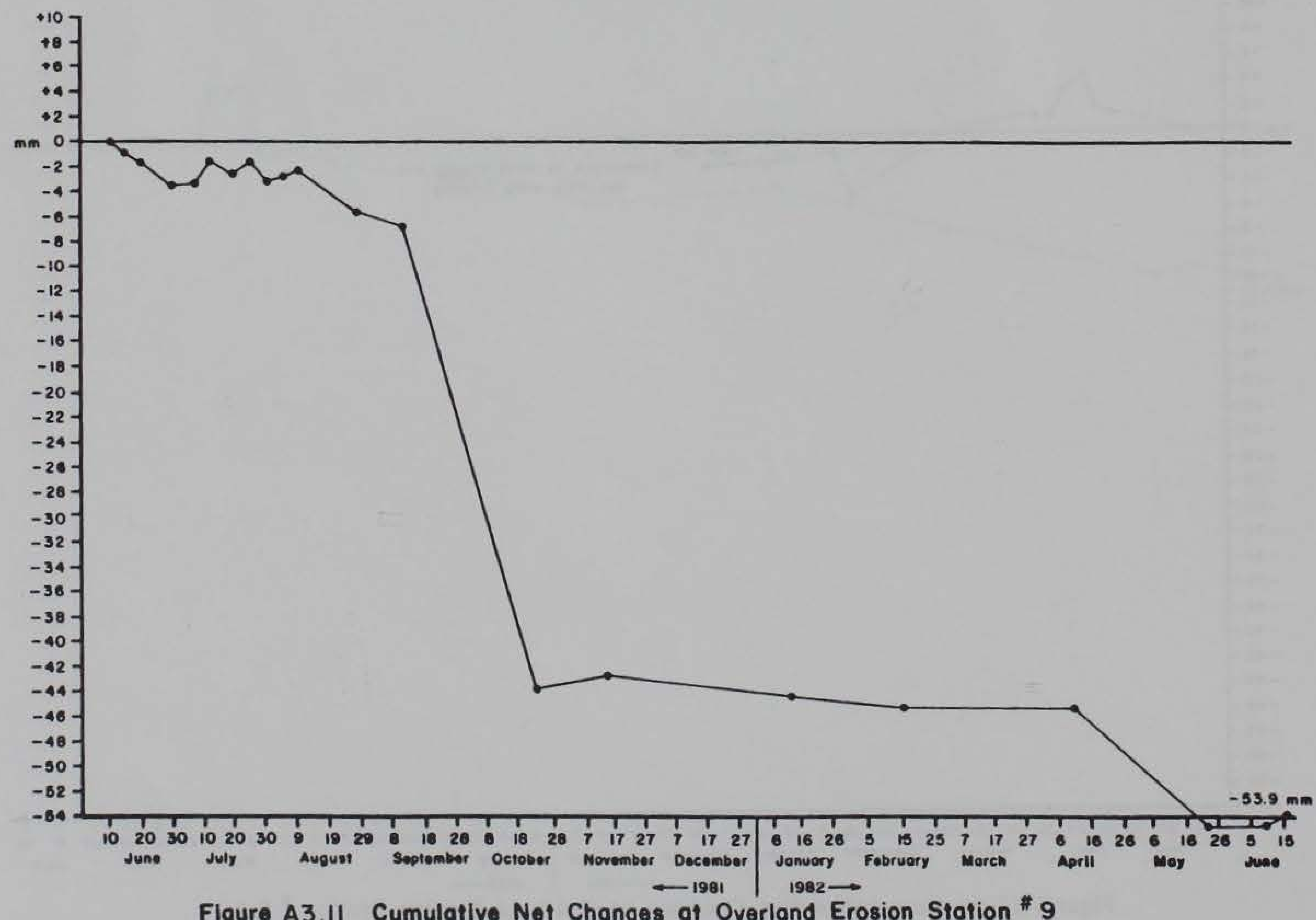

Figure A3.11 Cumulative Net Changes at Overland Erosion Station # 9
Orwell Lake, Minnesota
(1981 – 1982)

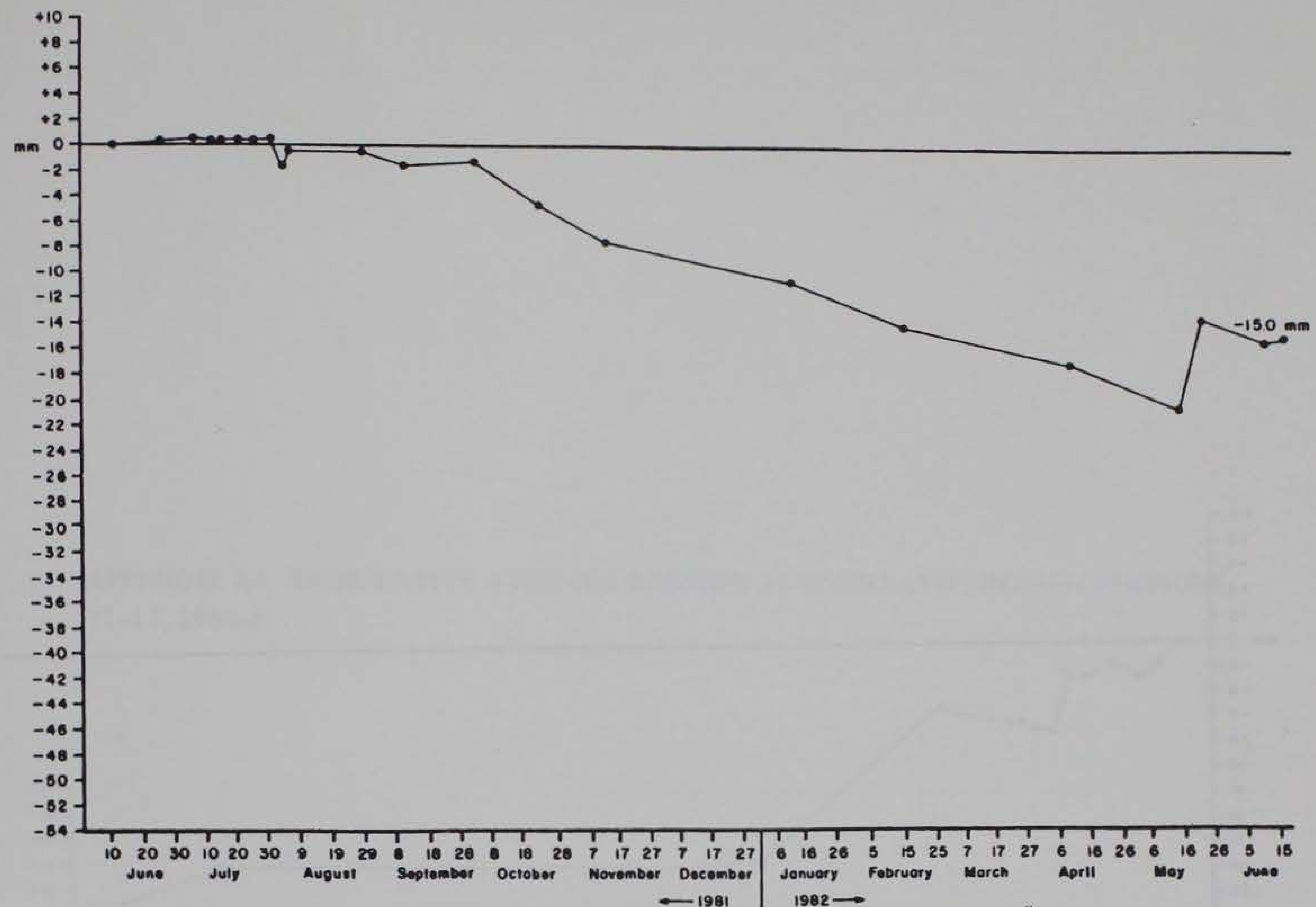

Figure A3.12 Cumulative Net Changes at Overland Erosion Station # 10
Orwell Lake, Minnesota
(1981 – 1982)

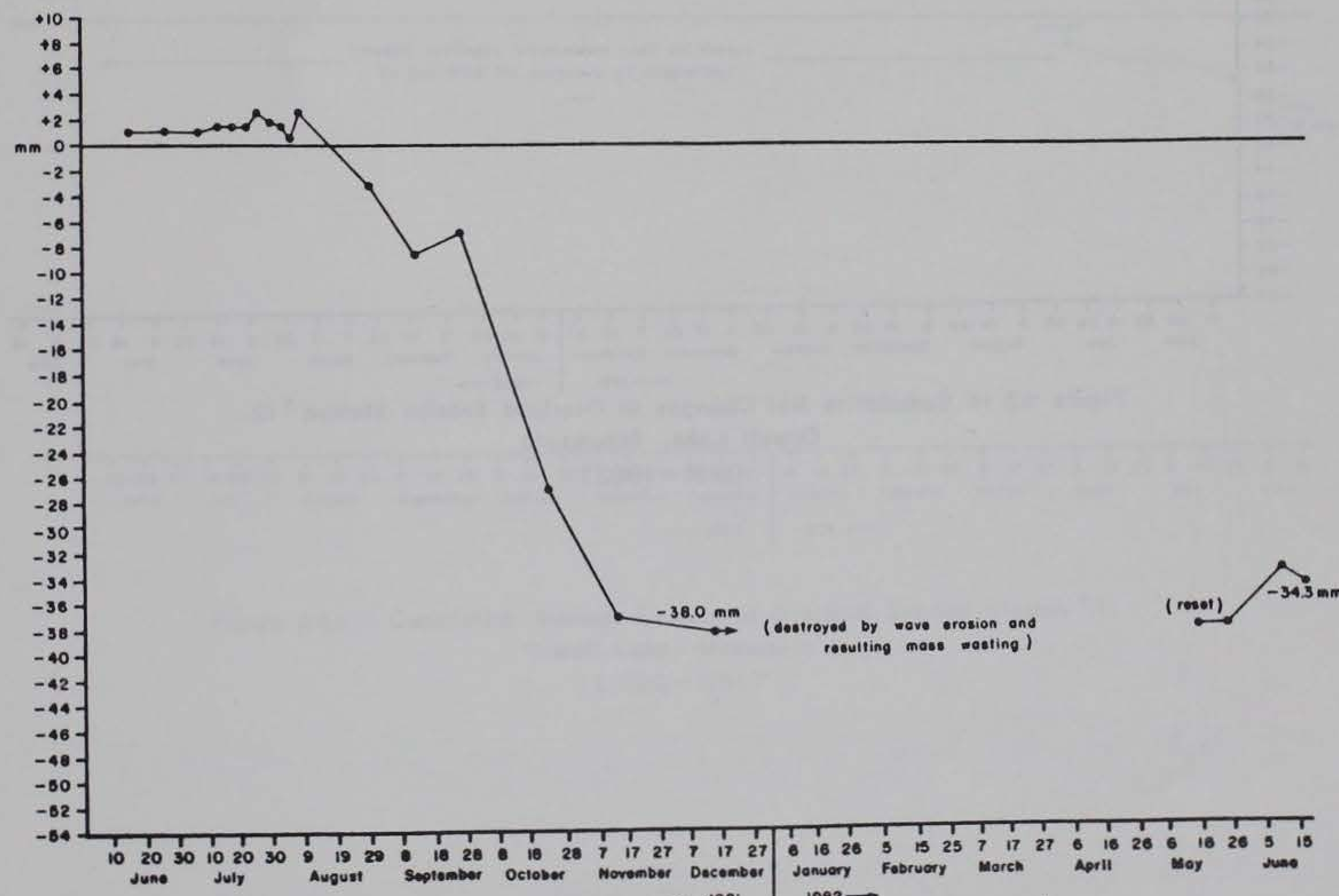

Figure A3.13 Cumulative Net Changes at Overland Erosion Station # 11
Orwell Lake, Minnesota
(1981 – 1982)

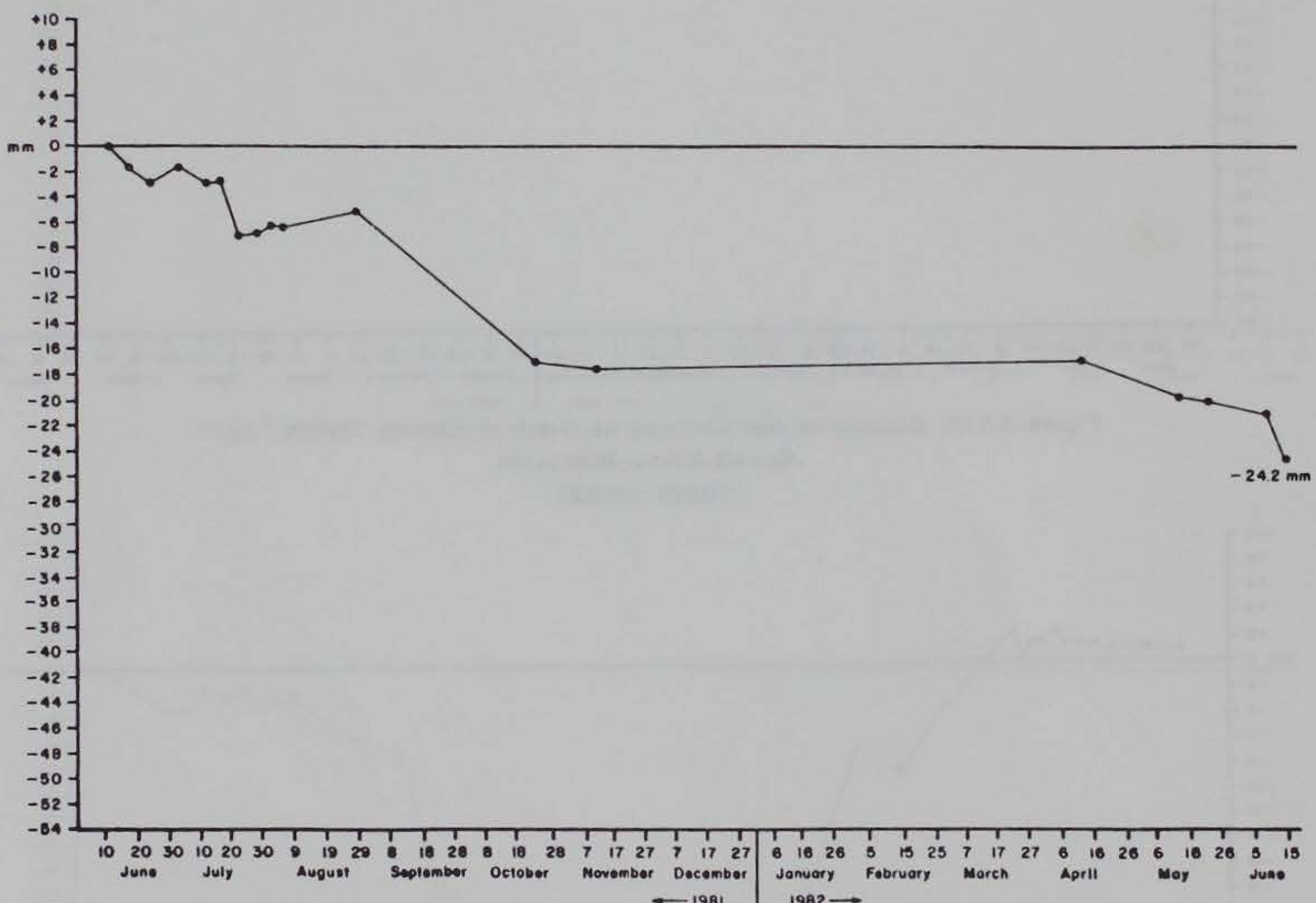

Figure A3.14 Cumulative Net Changes at Overland Erosion Station # 12
Orwell Lake, Minnesota
(1981 – 1982)

APPENDIX A4: CUMULATIVE AVERAGE EROSION AT OVERLAND EROSION STATIONS #1-12, 1980-81

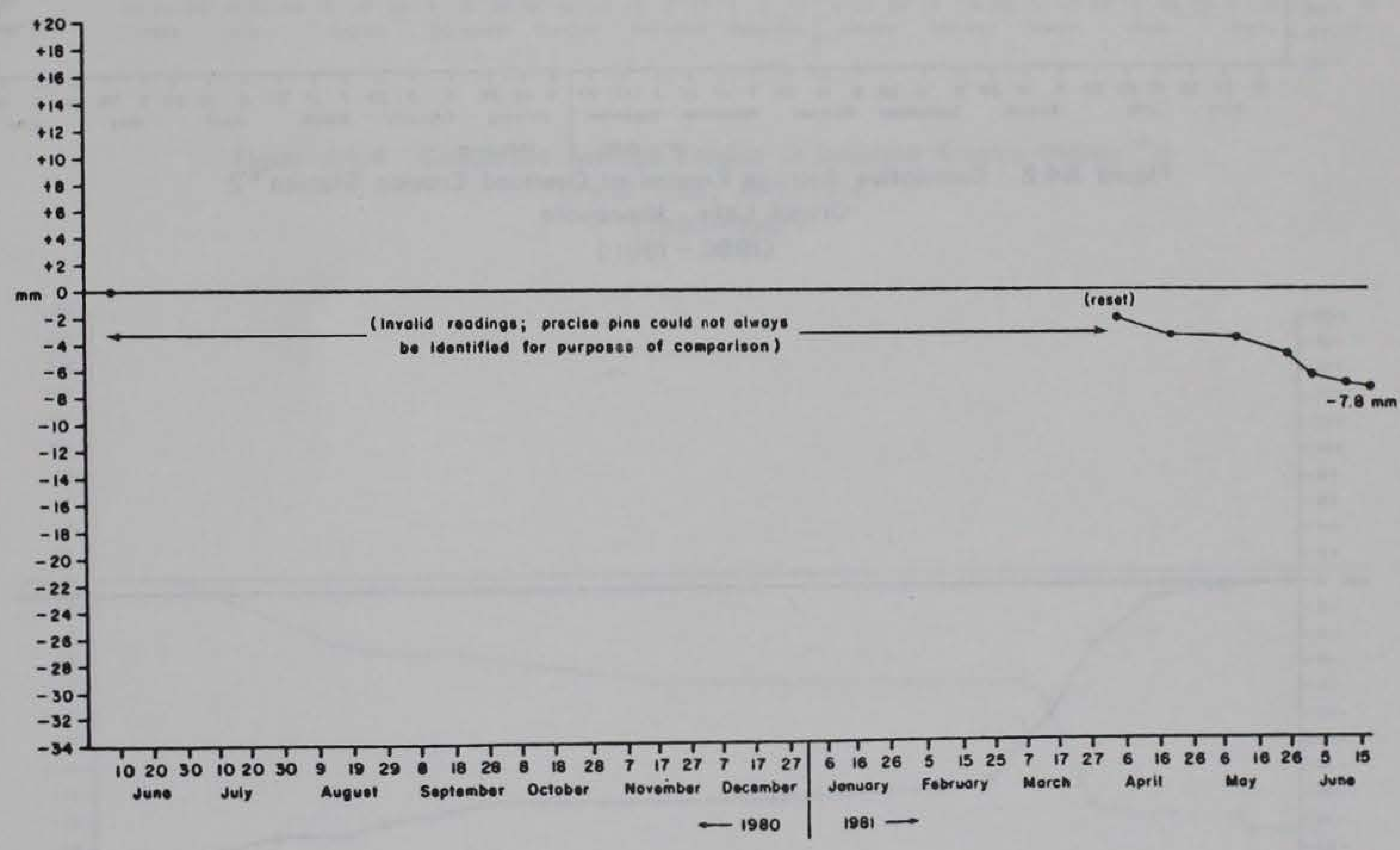

Figure A4.1 Cumulative Average Erosion at Overland Erosion Station #1
Orwell Lake, Minnesota
(1980–1981)

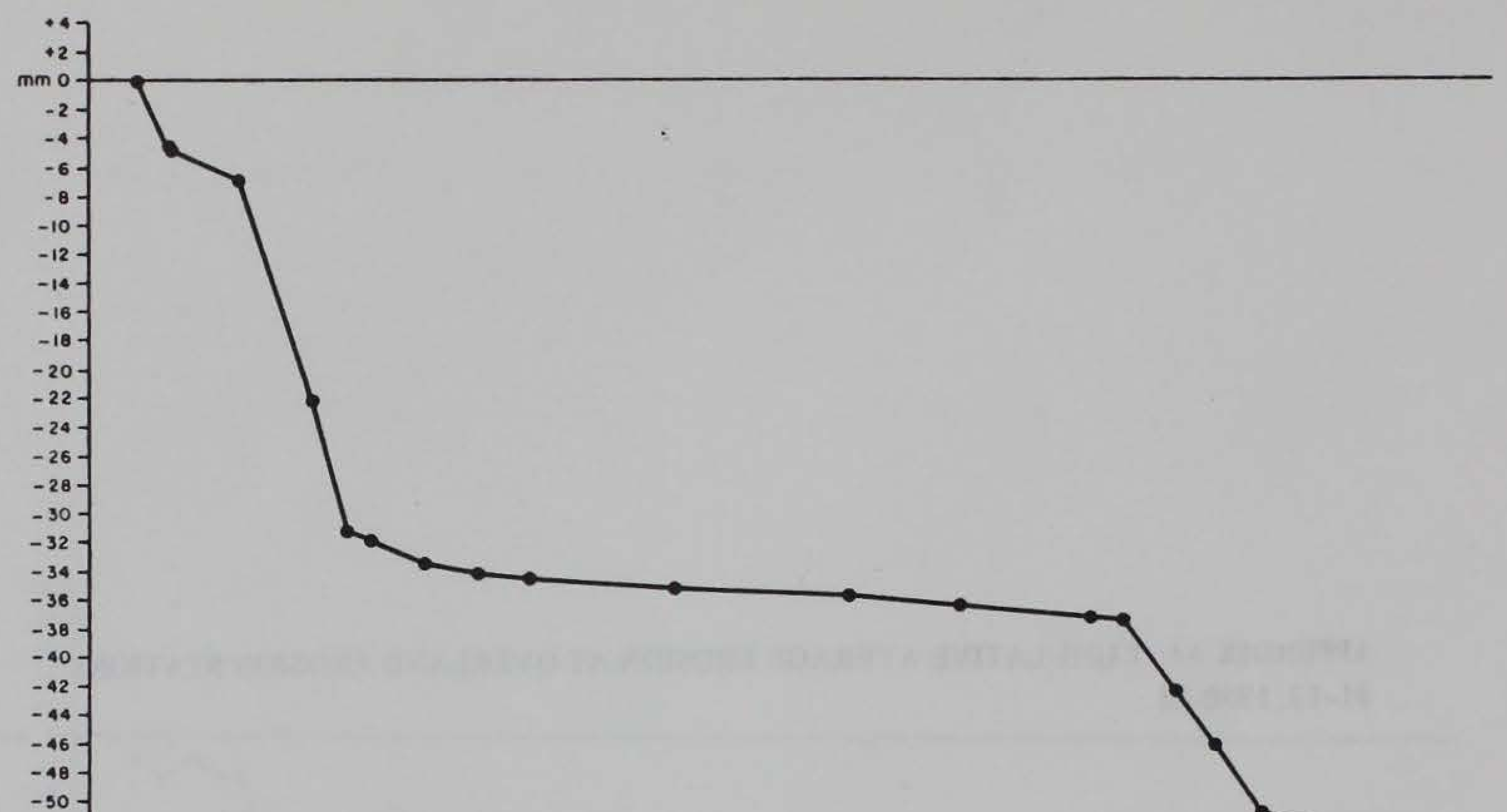

Figure A4.2 Cumulative Average Erosion at Overland Erosion Station #2
Orwell Lake, Minnesota
(1980 – 1981)

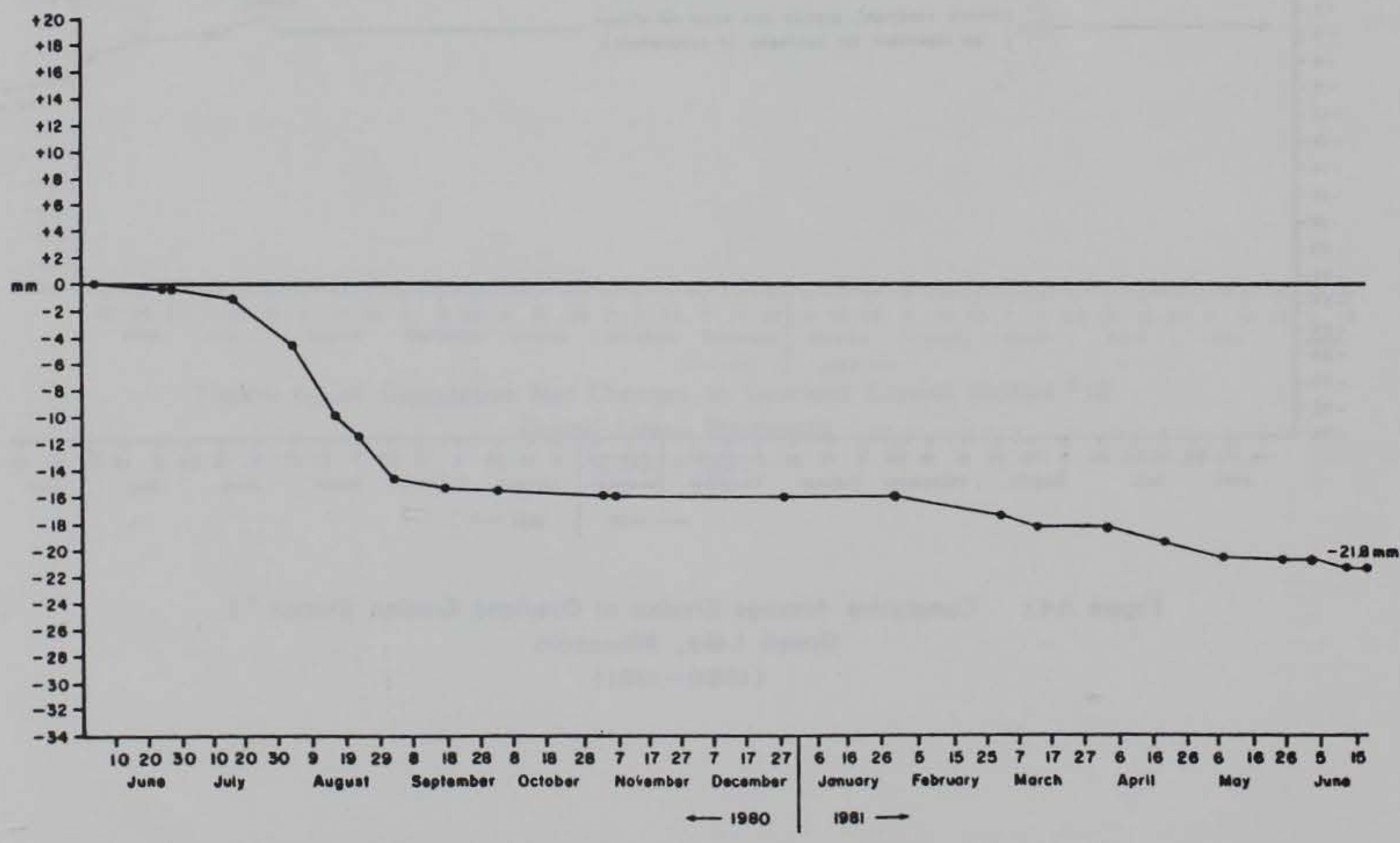

Figure A4.3 Cumulative Average Erosion at Overland Erosion Station # 3
Orwell Lake, Minnesota
(1980–1981)

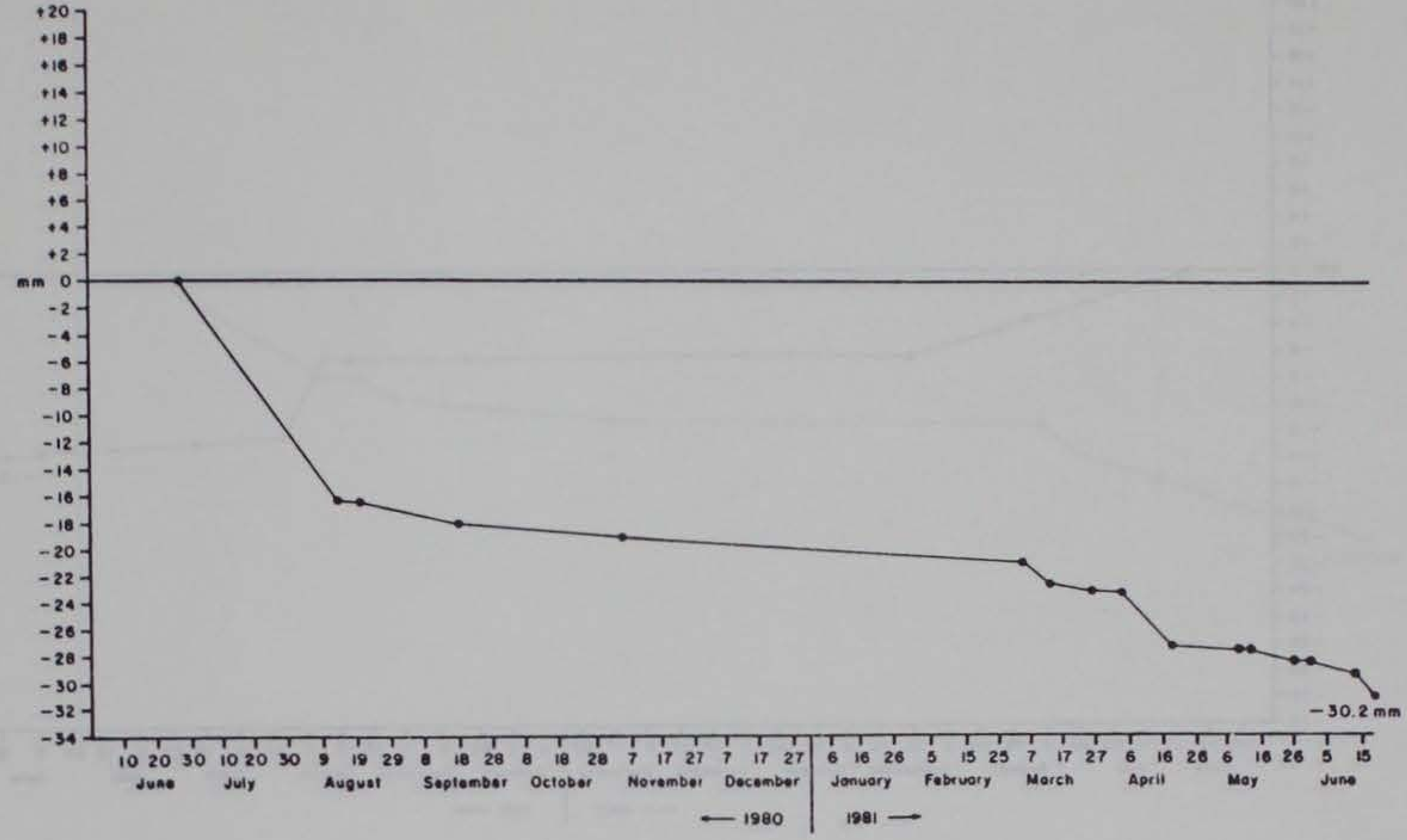

Figure A4.4 Cumulative Average Erosion at Overland Erosion Station # 4
Orwell Lake, Minnesota
(1980 – 1981)

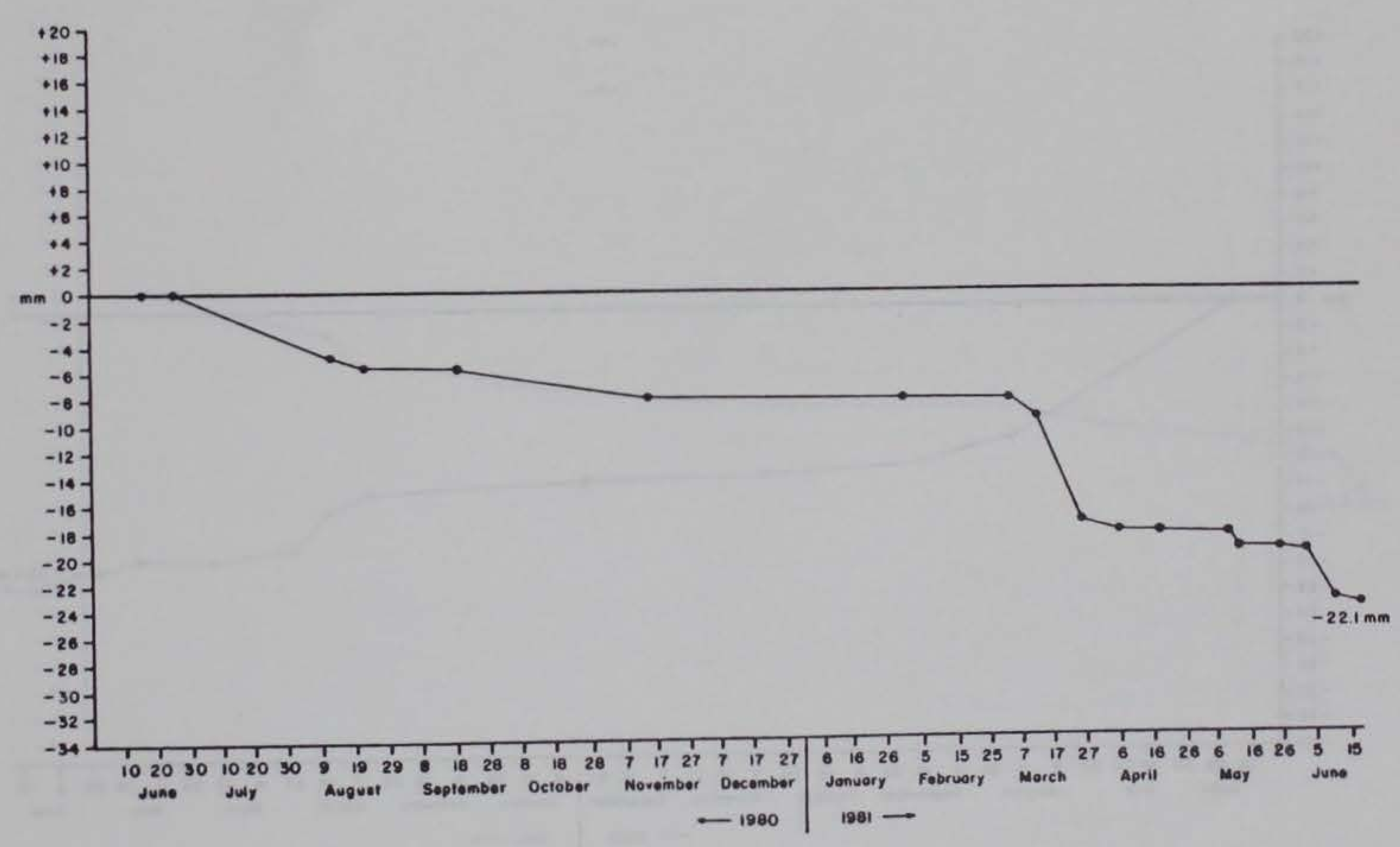

Figure A4.5 Cumulative Average Erosion at Overland Erosion Station # 5
Orwell Lake, Minnesota
(1980 – 1981)

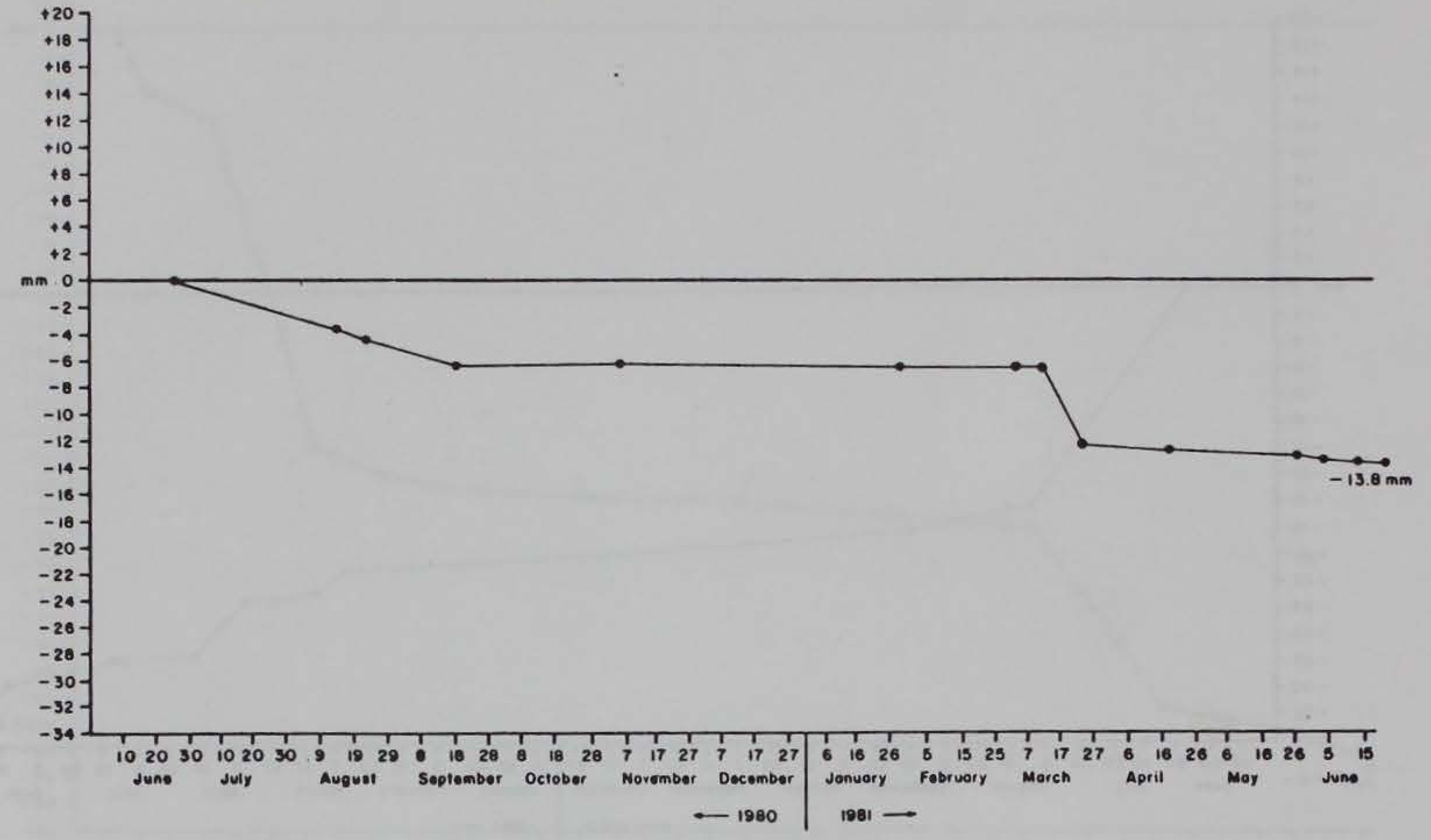

Figure A4.6 Cumulative Average Erosion at Overland Erosion Station # 6
Orwell Lake, Minnesota
(1980-1981)

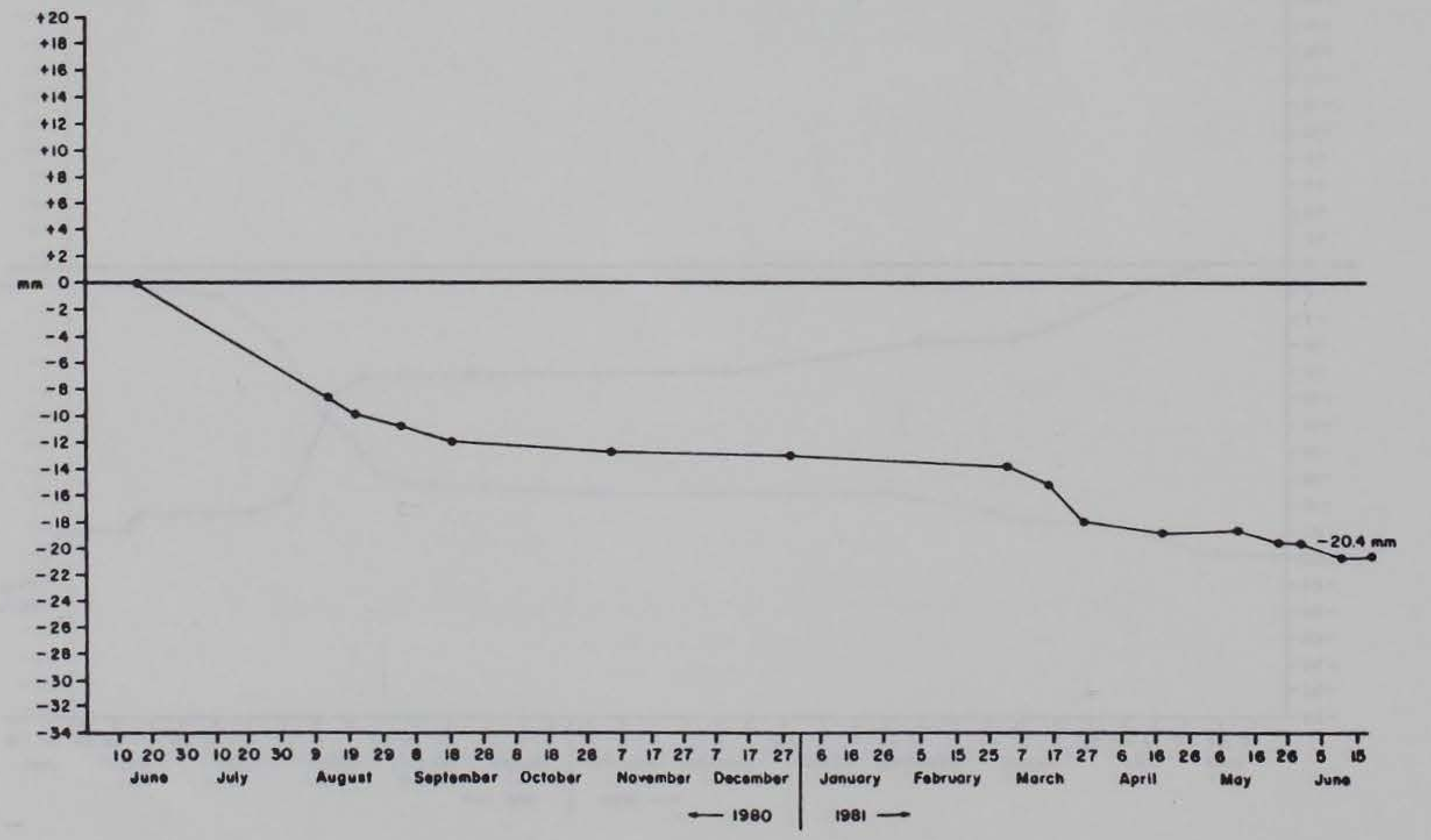

Figure A4.7 Cumulative Average Erosion at Overland Erosion Station # 7
Orwell Lake, Minnesota
(1980-1981)

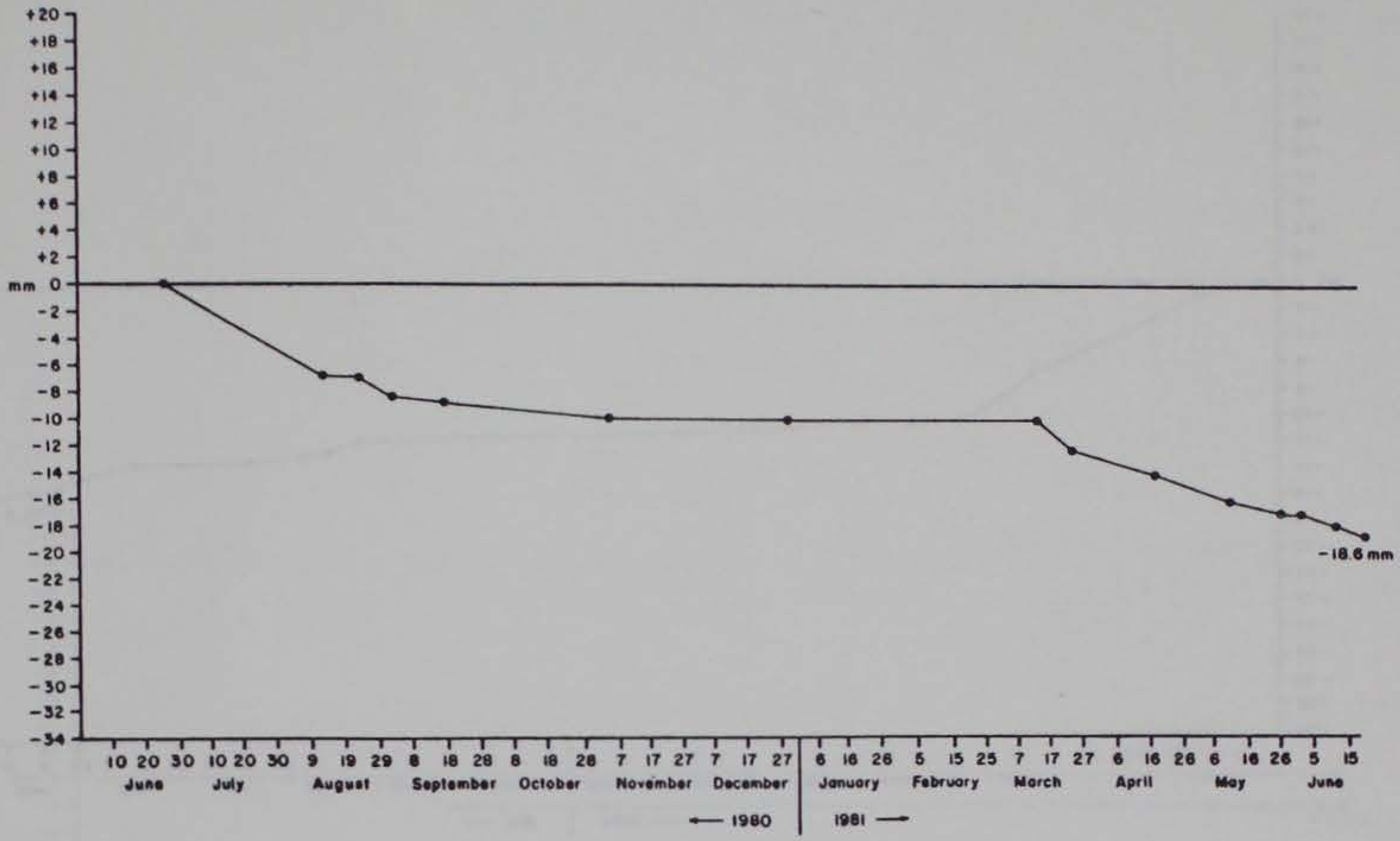

Figure A4.8 Cumulative Average Erosion at Overland Erosion Station # 8
Orwell Lake, Minnesota
(1980–1981)

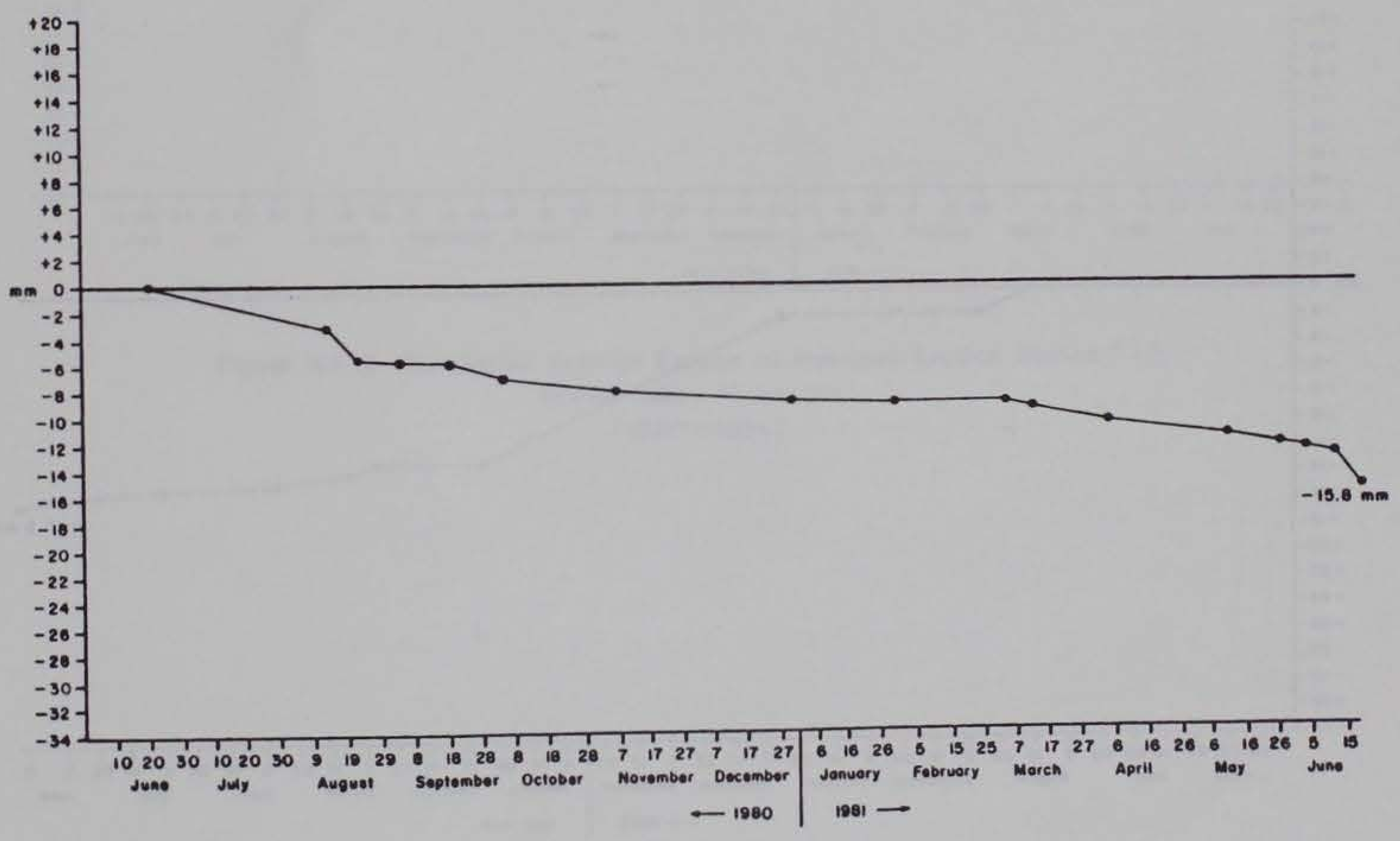

Figure A4.9 Cumulative Average Erosion at Overland Erosion Station # 9
Orwell Lake, Minnesota
(1980–1981)

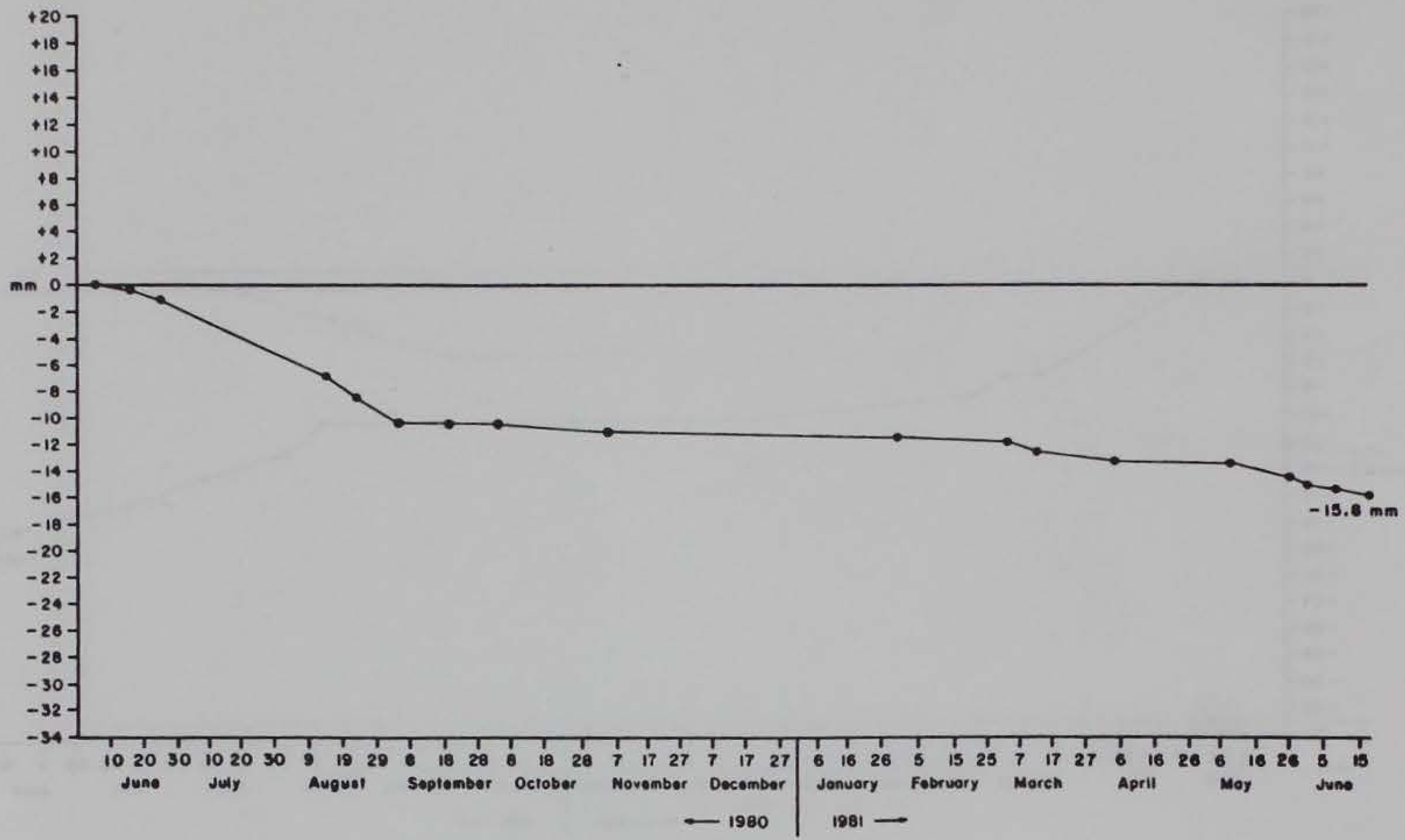

Figure A4.10 Cumulative Average Erosion at Overland Erosion Station # 10
Orwell Lake, Minnesota
(1980–1981)

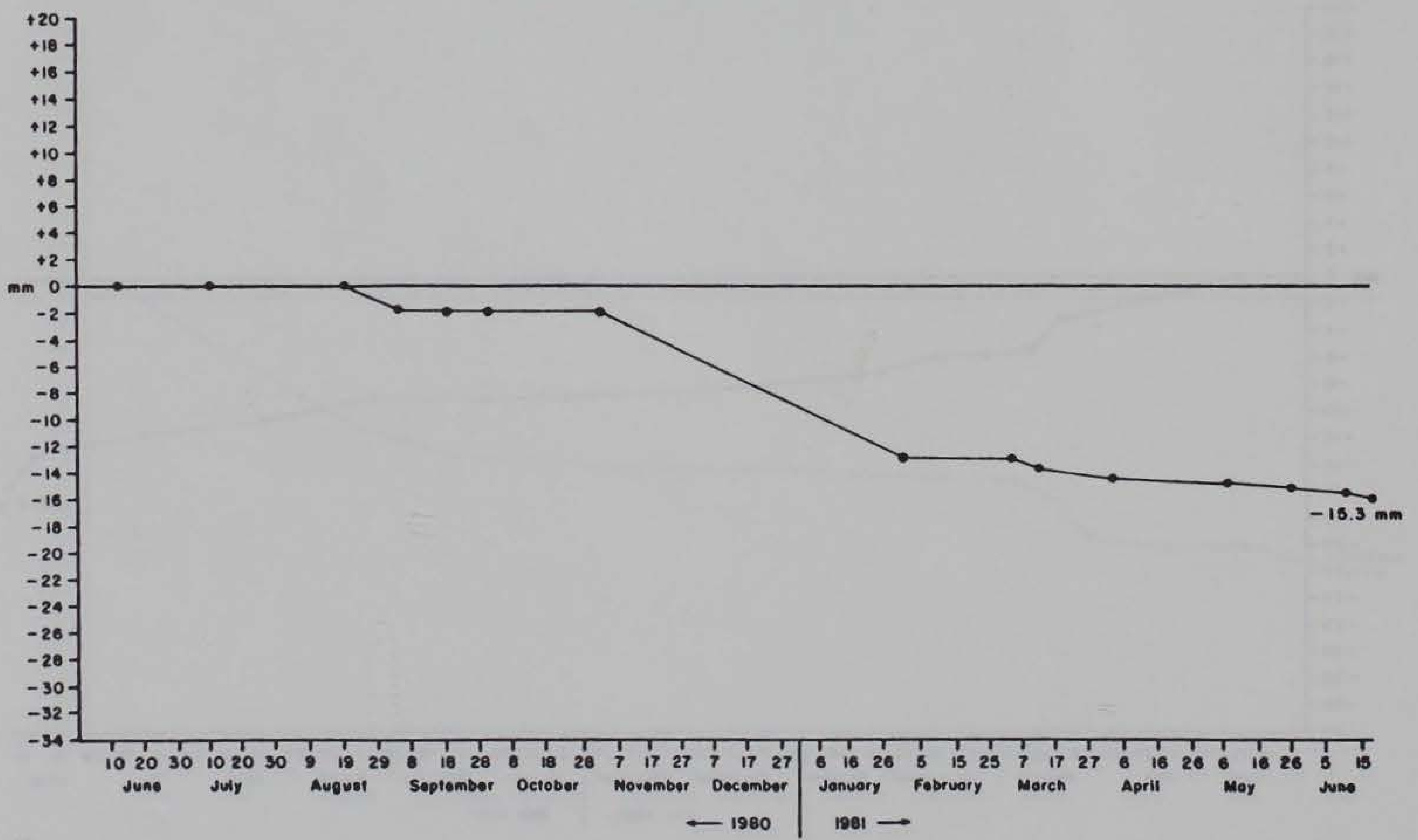

Figure A4.11 Cumulative Average Erosion at Overland Erosion Station # 11
Orwell Lake, Minnesota
(1980–1981)

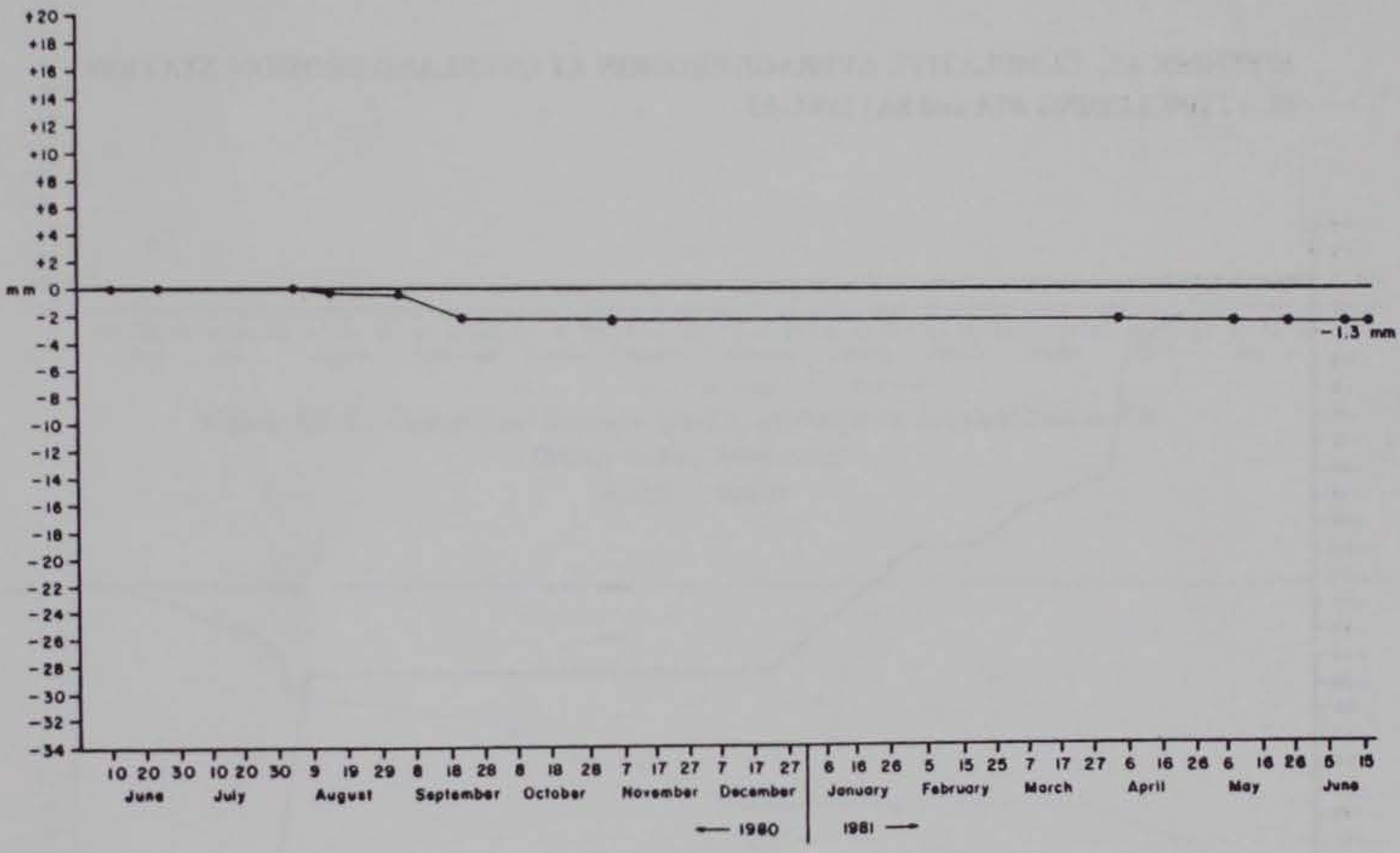

Figure A4.12 Cumulative Average Erosion at Overland Erosion Station # 12
Orwell Lake, Minnesota
(1980–1981)

APPENDIX A5: CUMULATIVE AVERAGE EROSION AT OVERLAND EROSION STATIONS #1-12 (INCLUDING #7A and 8A) 1981-82

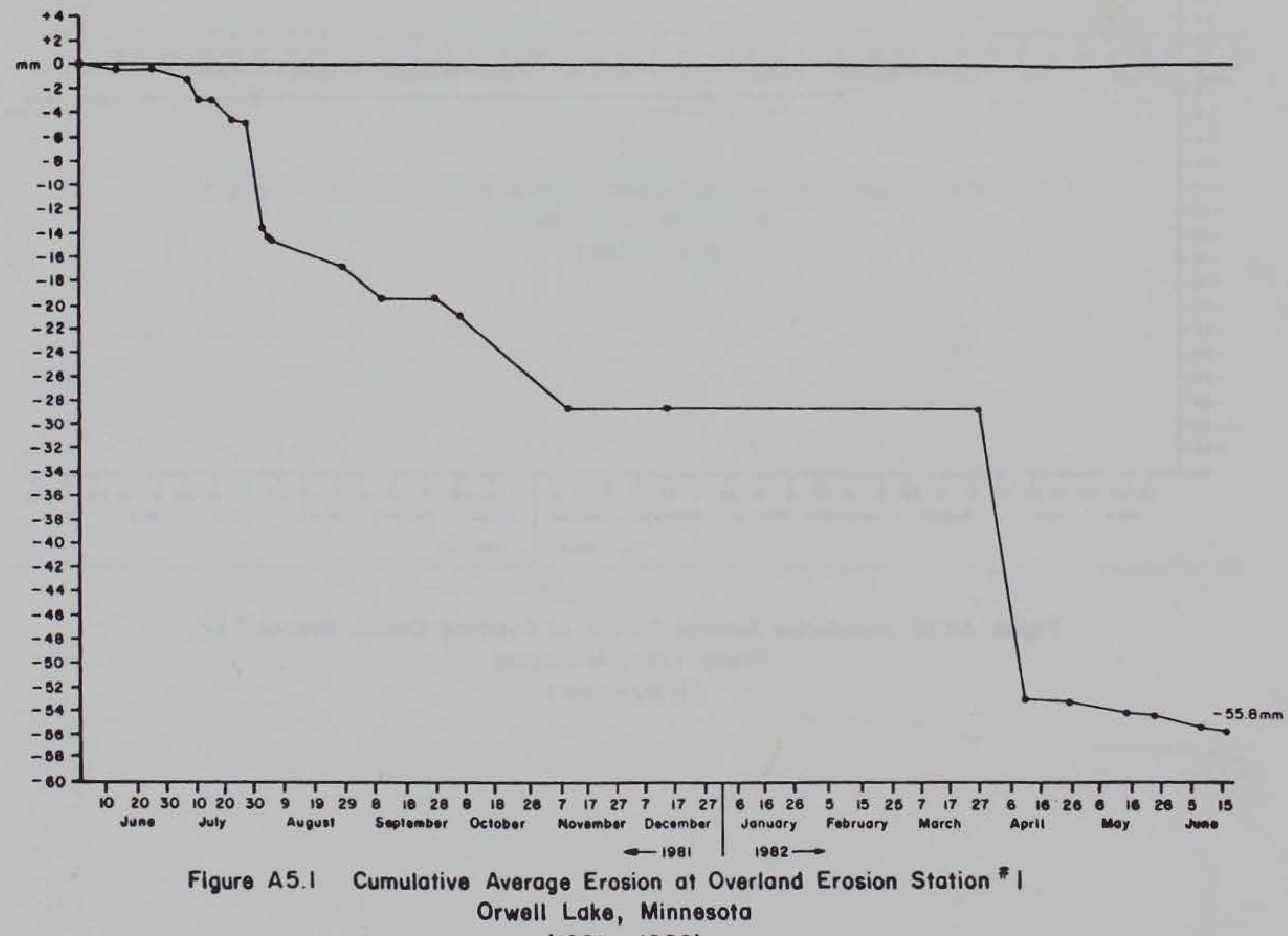

Figure A5.1 Cumulative Average Erosion at Overland Erosion Station # 1
Orwell Lake, Minnesota
(1981 - 1982)

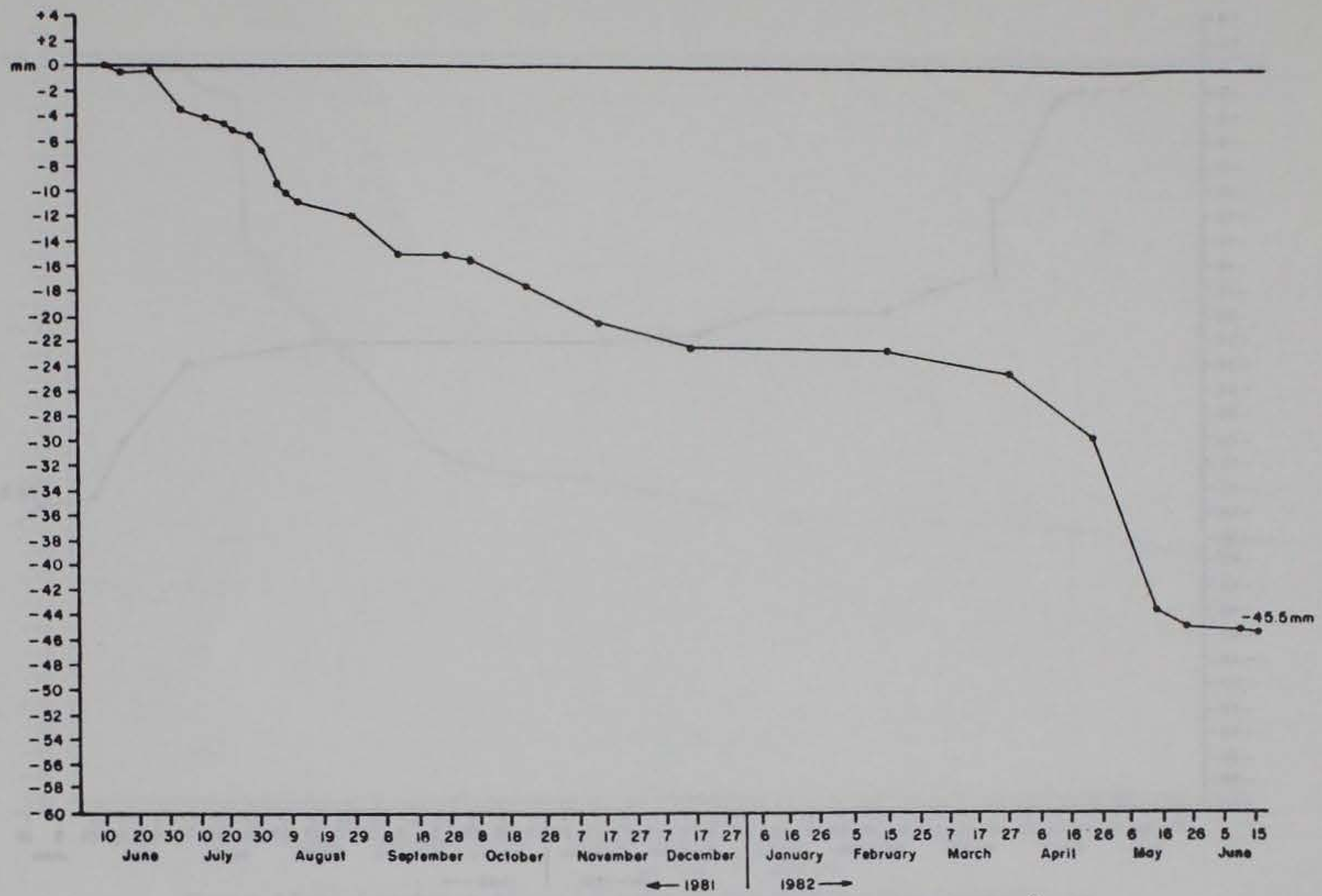

Figure A5.2 Cumulative Average Erosion at Overland Erosion Station # 2
Orwell Lake, Minnesota
(1981 - 1982)

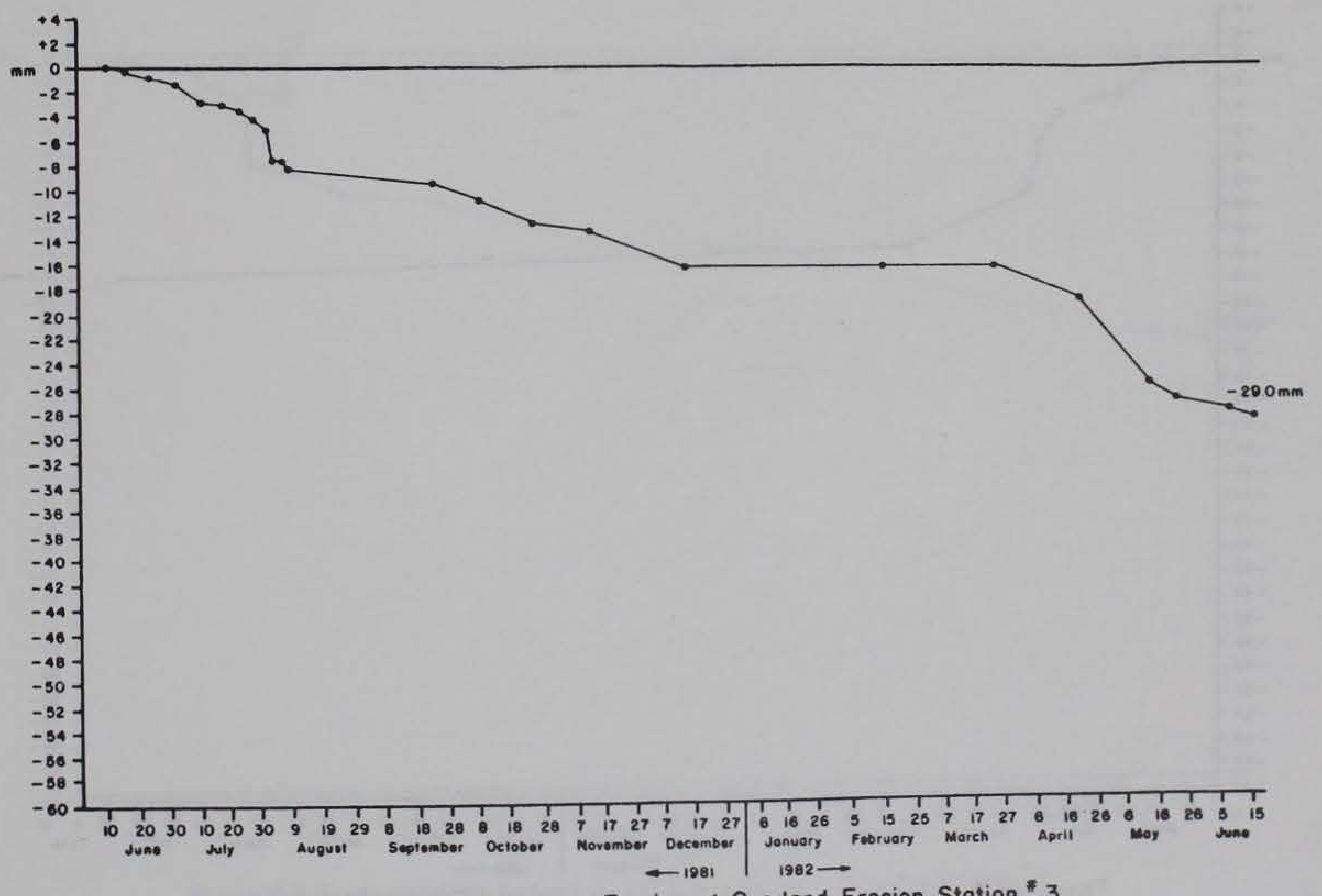

Figure A5.3 Cumulative Average Erosion at Overland Erosion Station # 3
Orwell Lake, Minnesota
(1981 - 1982)

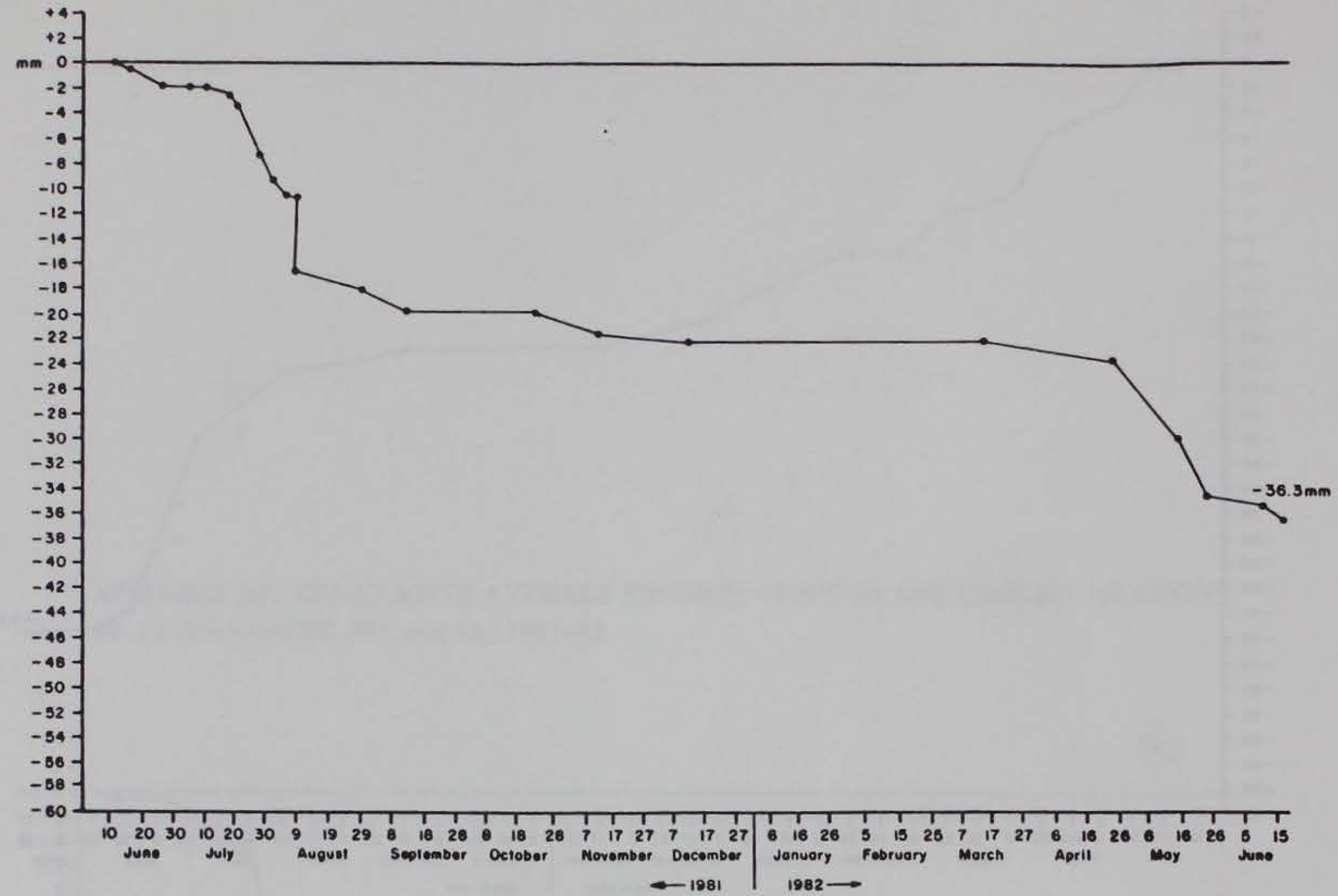

Figure A5.4 Cumulative Average Erosion at Overland Erosion Station #4
Orwell Lake, Minnesota
(1981 – 1982)

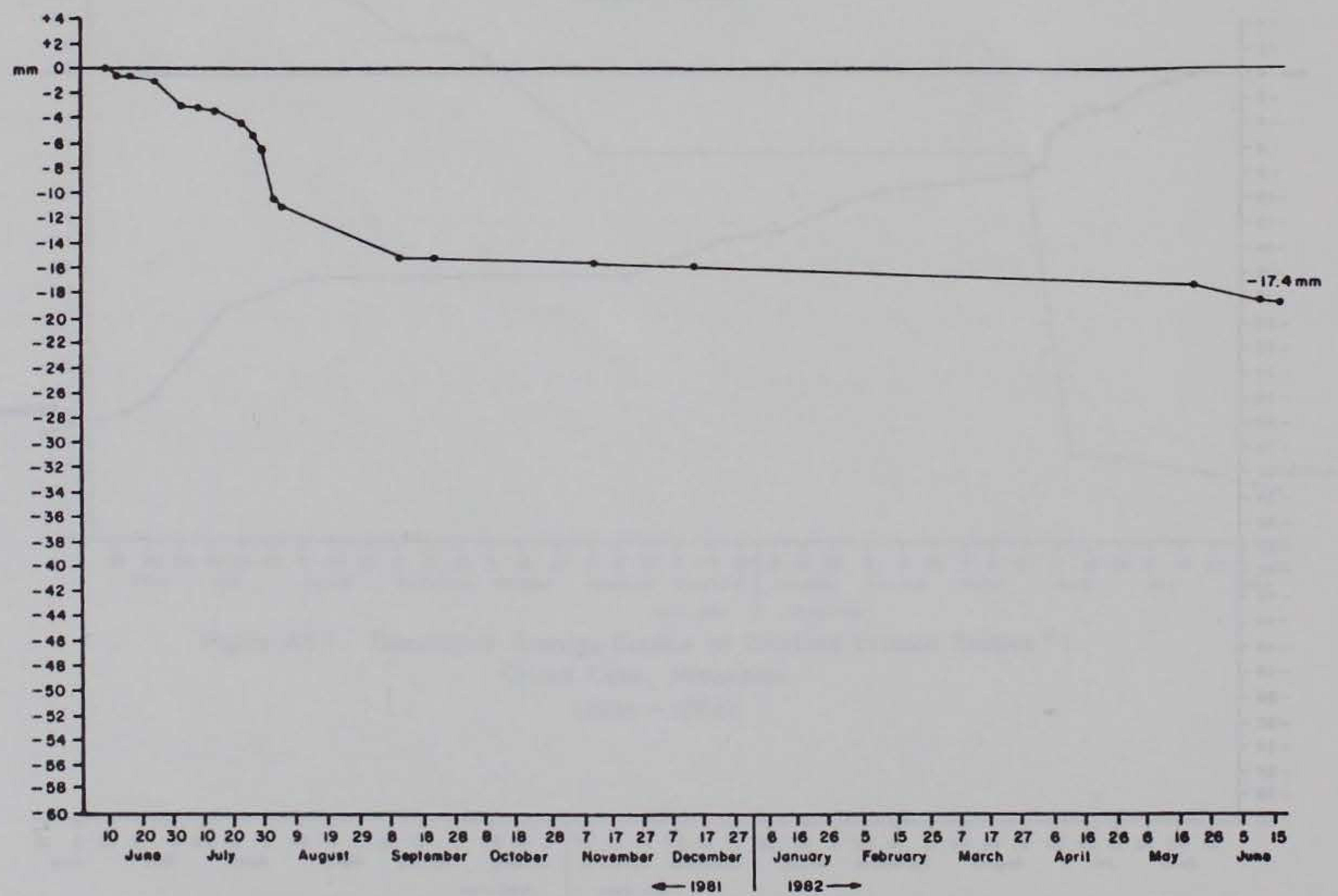

Figure A5.5 Cumulative Average Erosion at Overland Erosion Station #5
Orwell Lake, Minnesota
(1981 – 1982)

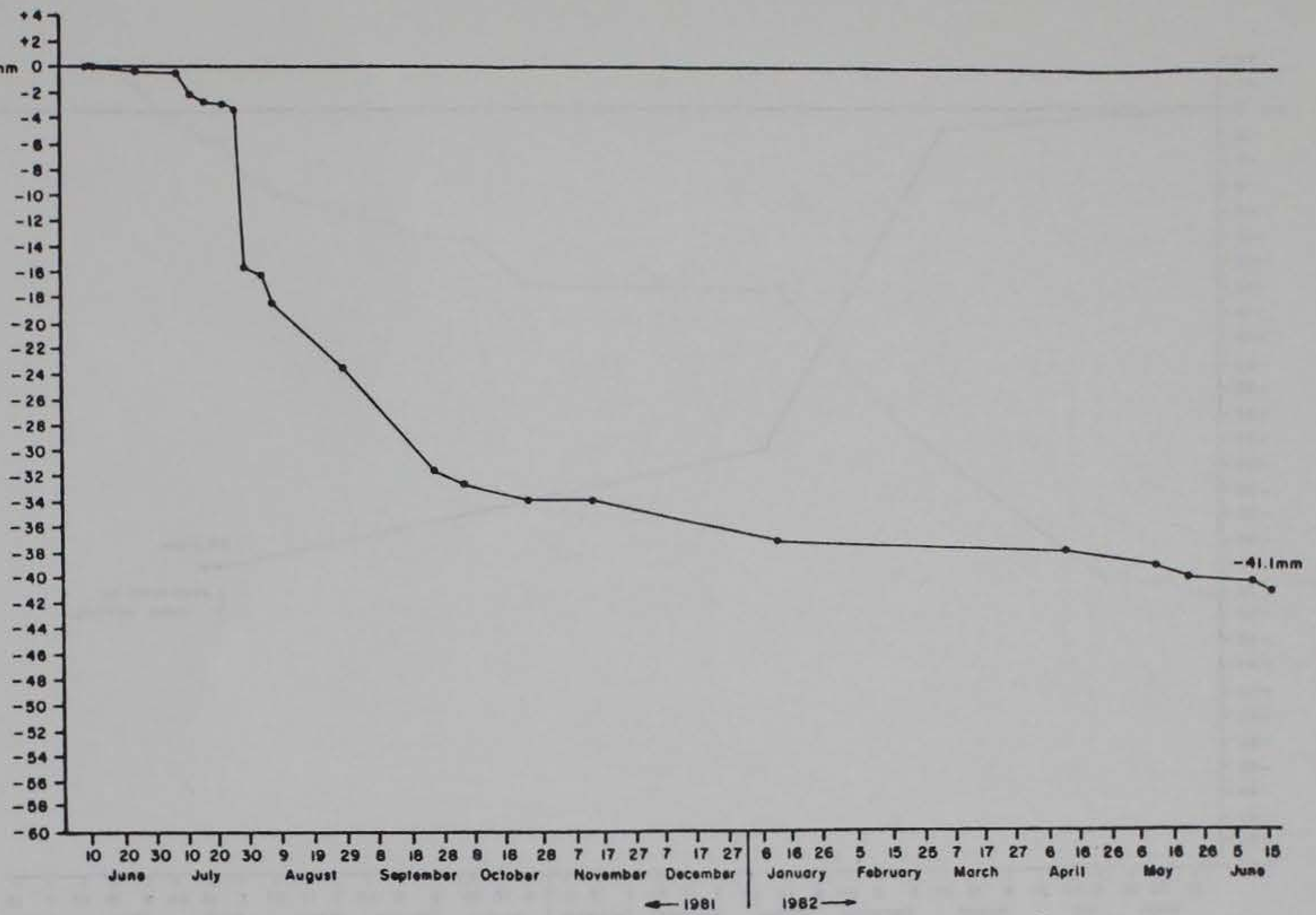

Figure A5.6 Cumulative Average Erosion at Overland Erosion Station #6
Orwell Lake, Minnesota
(1981 - 1982)

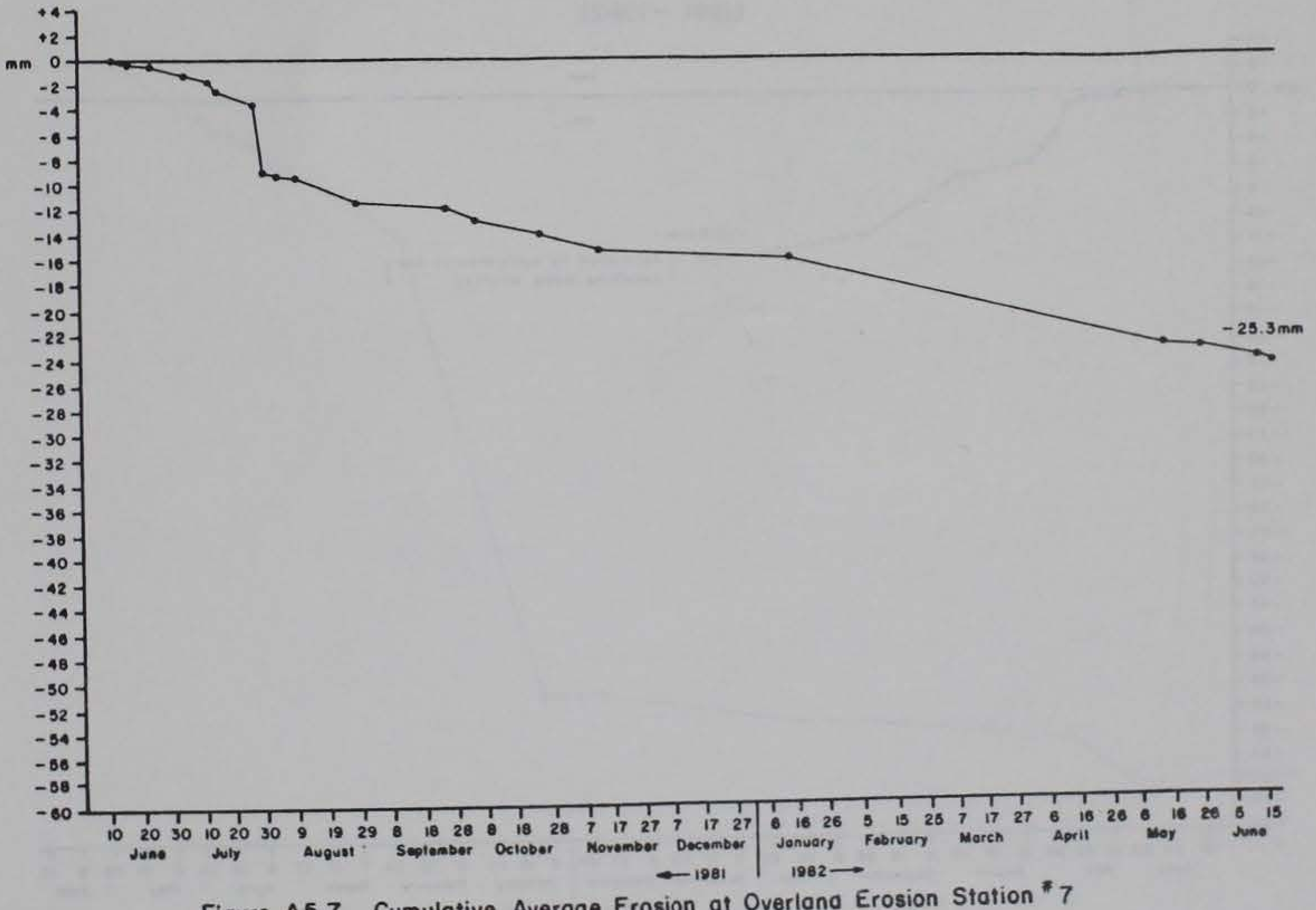

Figure A5.7 Cumulative Average Erosion at Overland Erosion Station #7
Orwell Lake, Minnesota
(1981 - 1982)

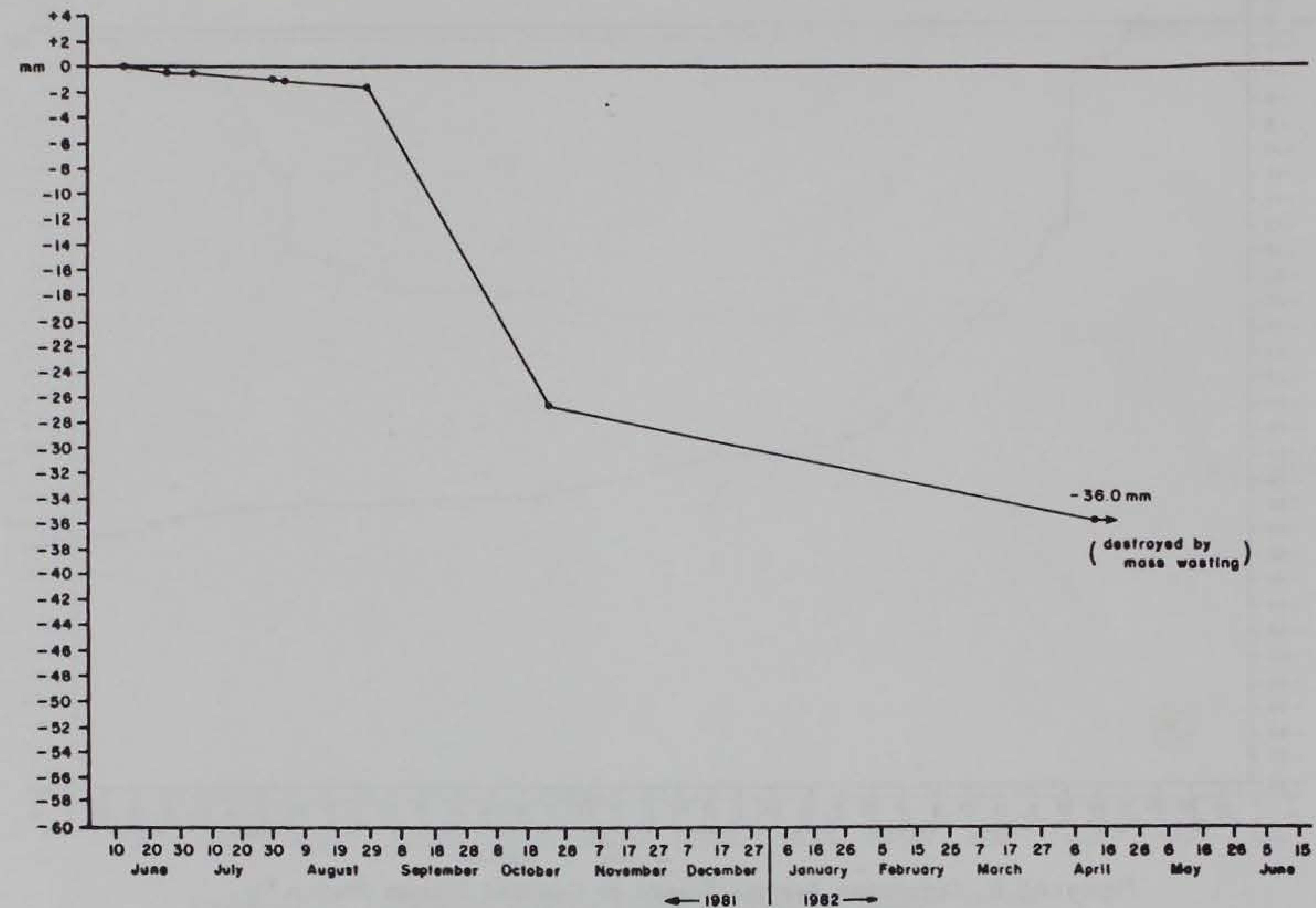

Figure A5.8 Cumulative Average Erosion at Overland Erosion Station #7A
Orwell Lake, Minnesota
(1981 – 1982)

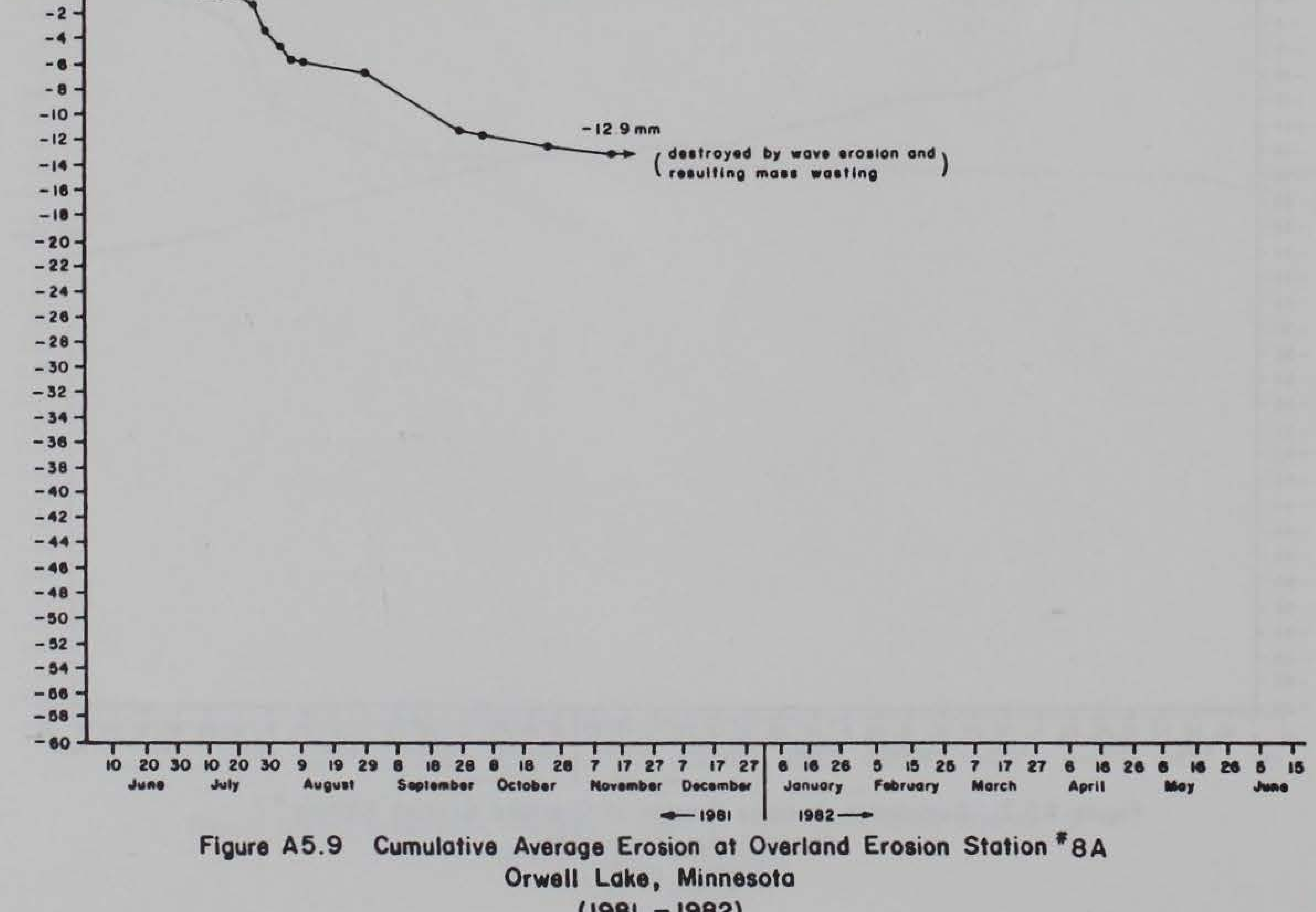

Figure A5.9 Cumulative Average Erosion at Overland Erosion Station #8A
Orwell Lake, Minnesota
(1981 – 1982)

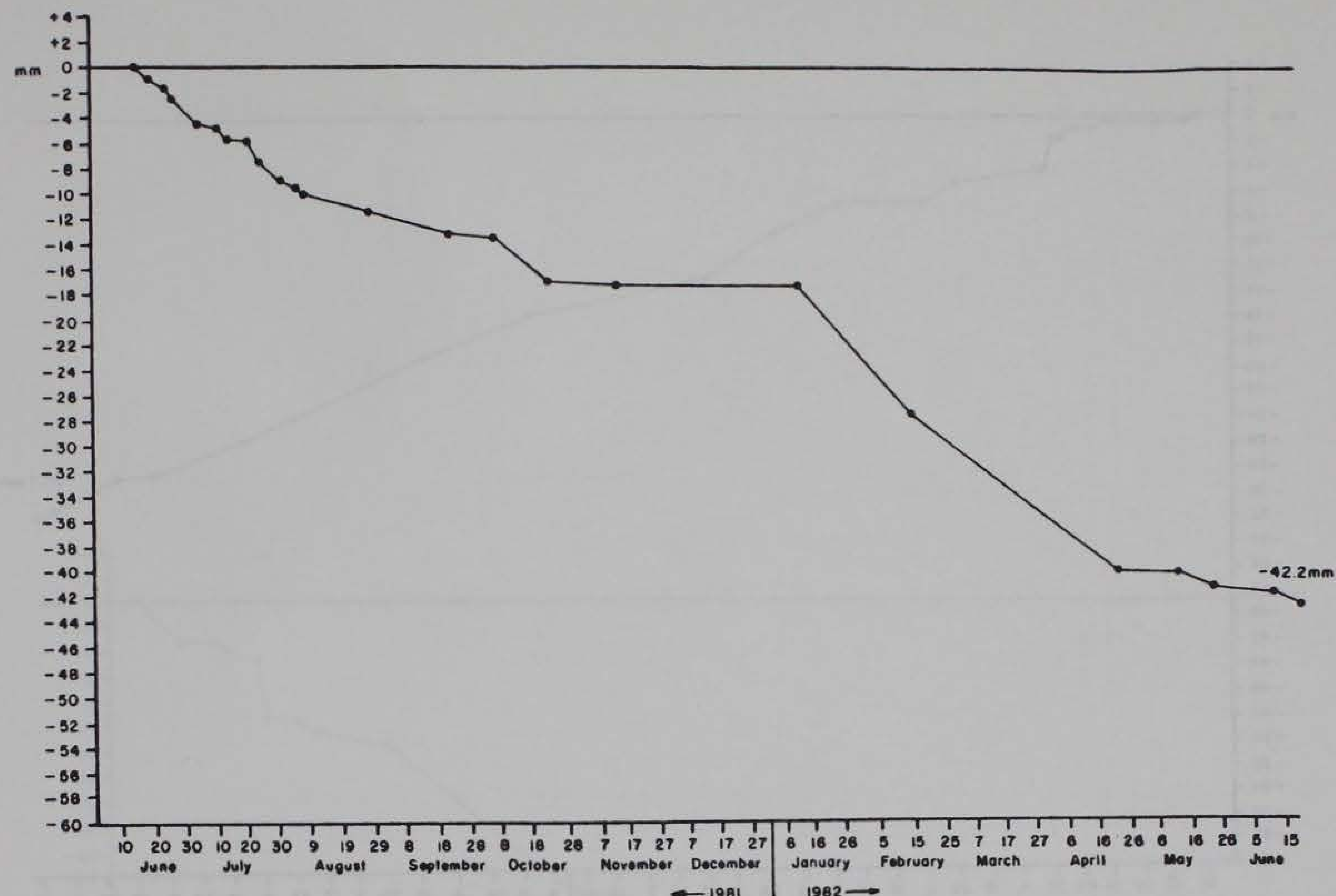

Figure A5.10 Cumulative Average Erosion at Overland Erosion Station #8
Orwell Lake, Minnesota
(1981 – 1982)

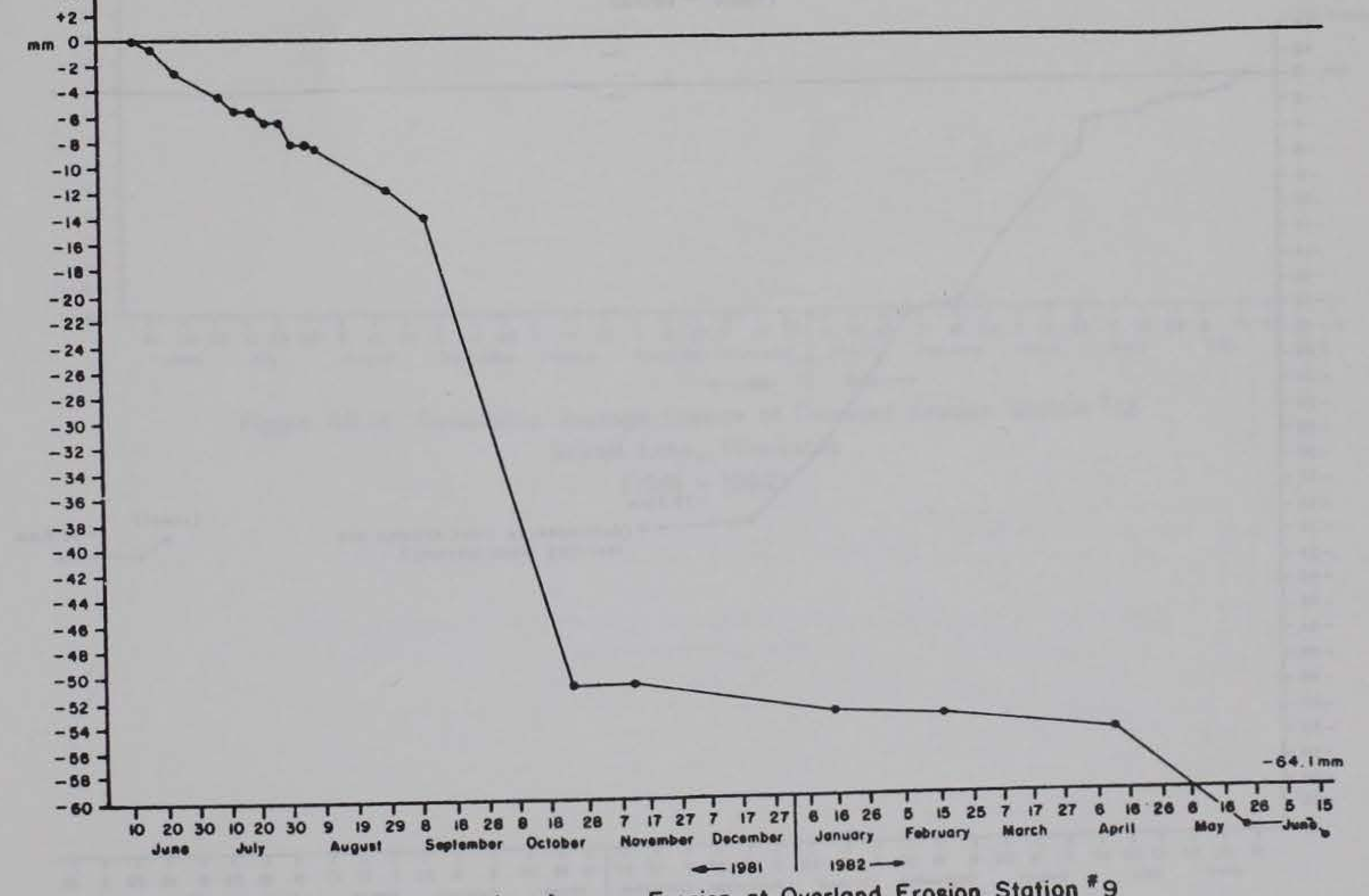

Figure A5.11 Cumulative Average Erosion at Overland Erosion Station #9
Orwell Lake, Minnesota
(1981 – 1982)

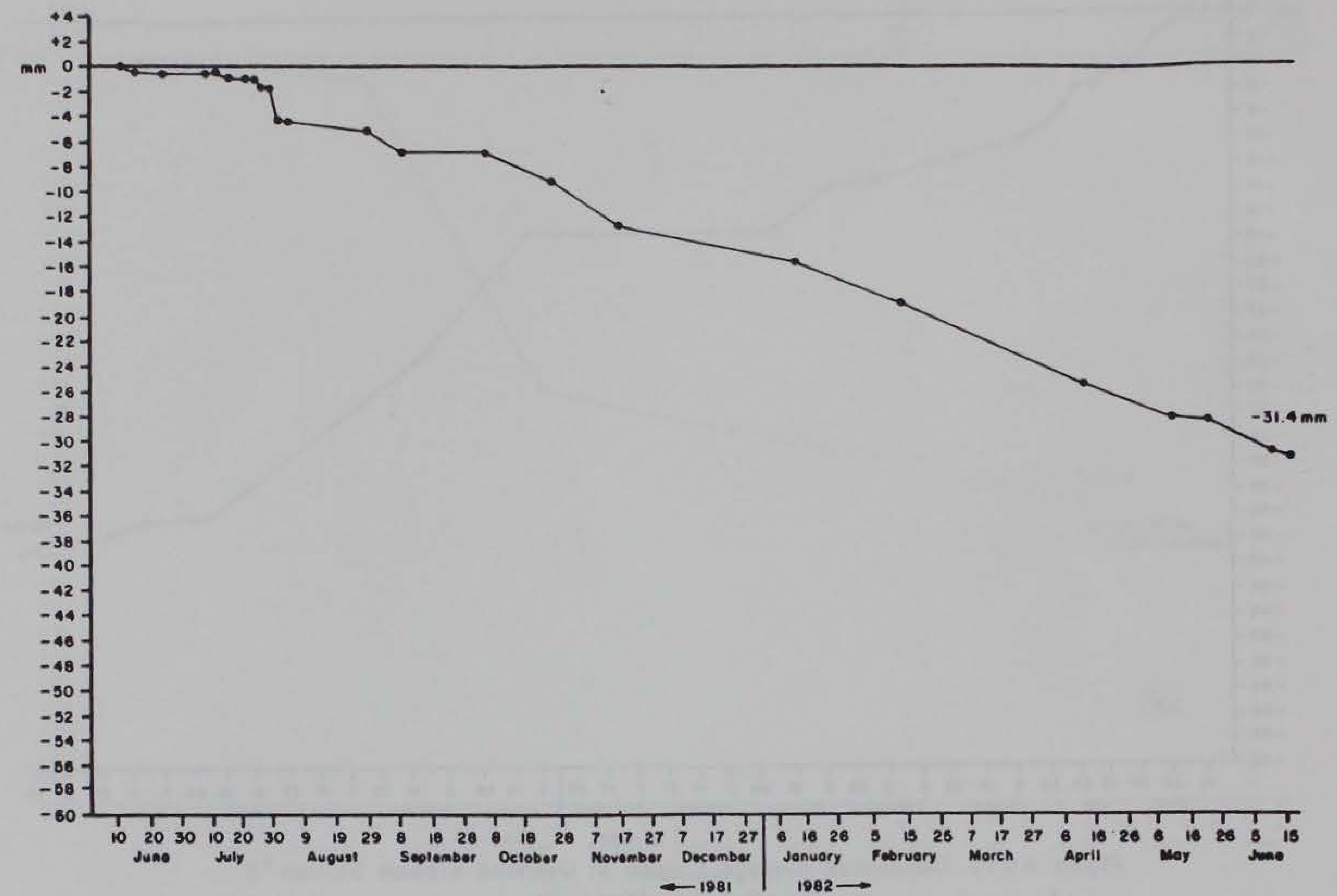

Figure A5.12 Cumulative Average Erosion at Overland Erosion Station # 10
Orwell Lake, Minnesota
(1981 – 1982)

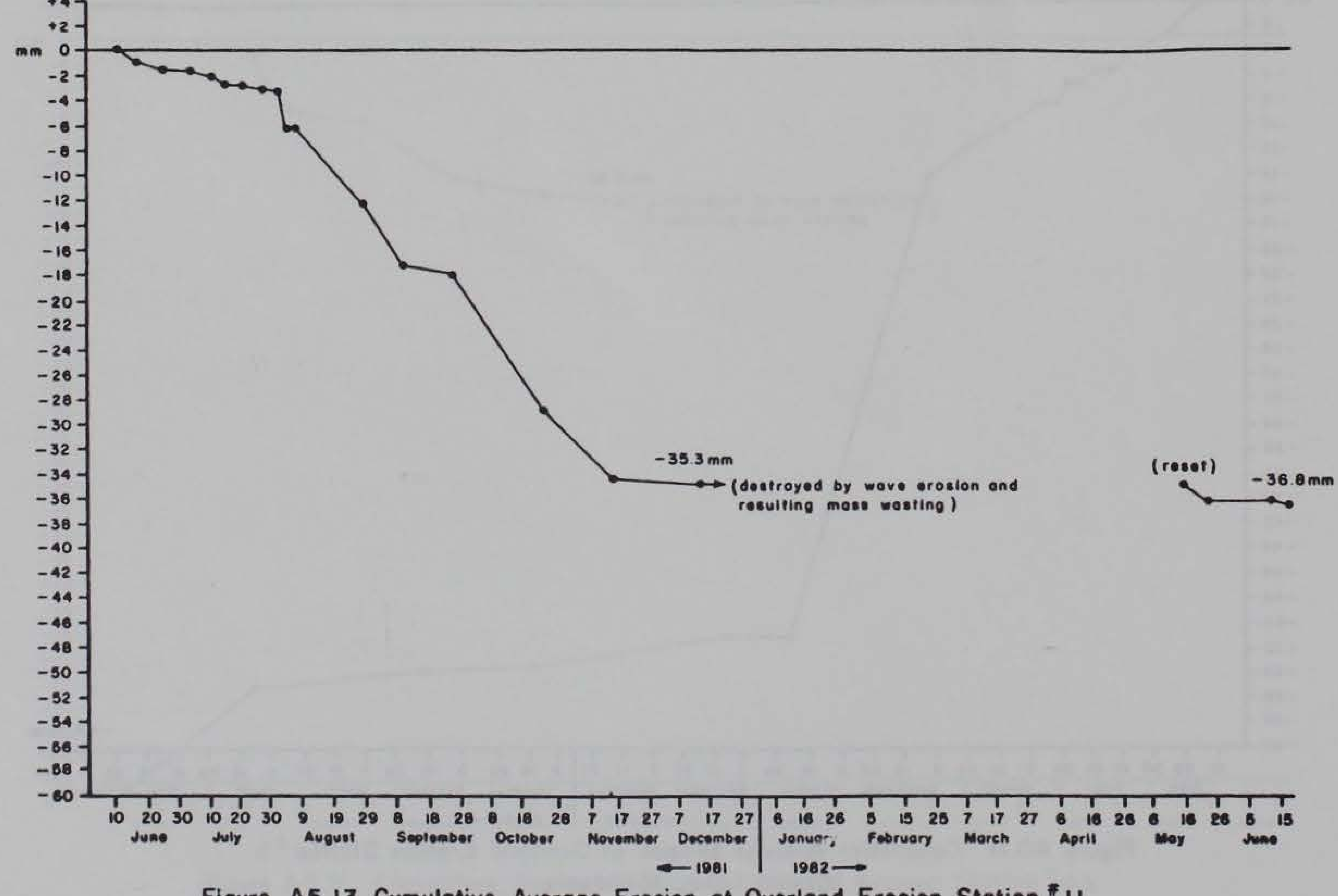

Figure A5.13 Cumulative Average Erosion at Overland Erosion Station # 11
Orwell Lake, Minnesota
(1981 – 1982)

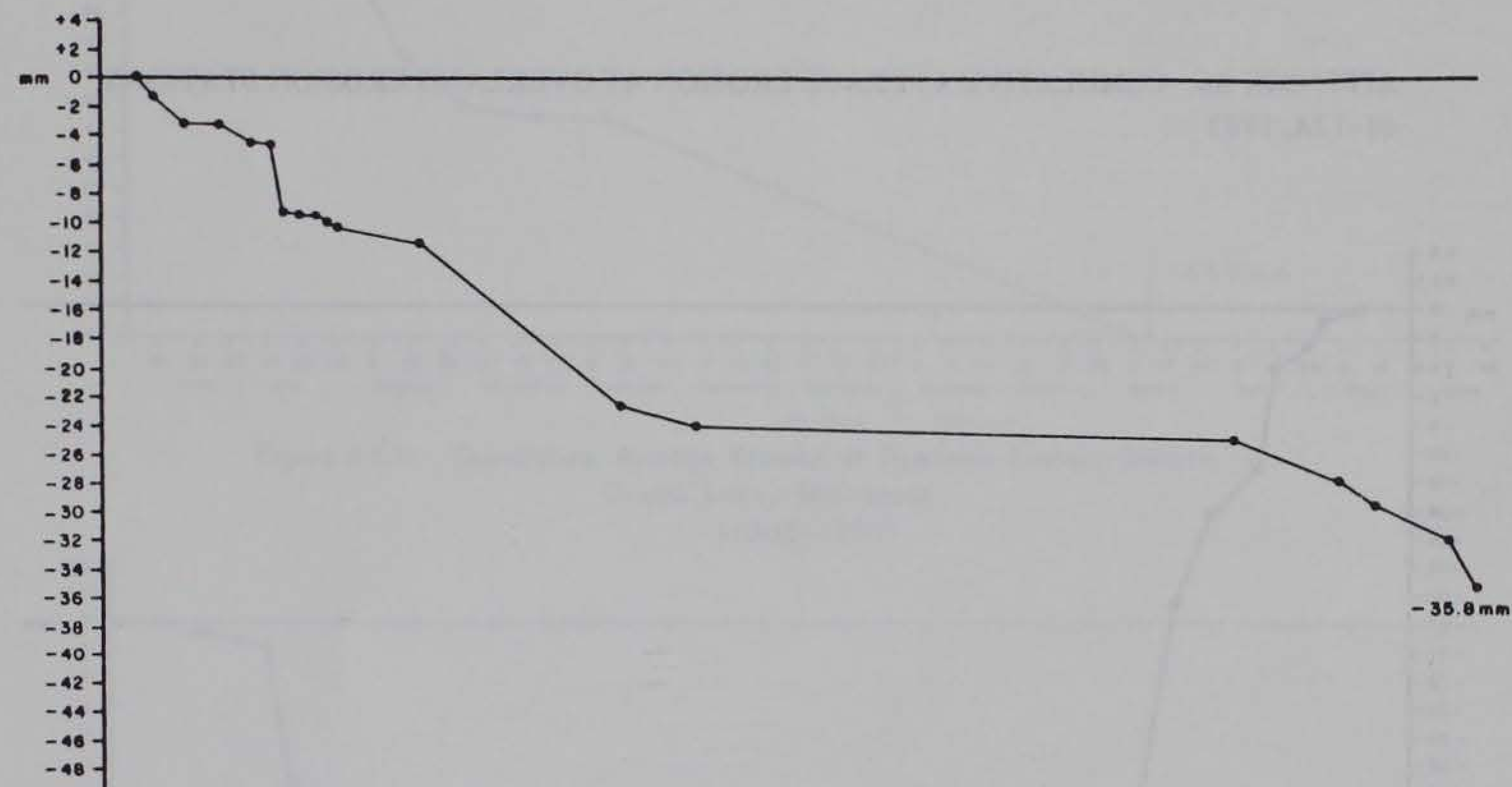

Figure A5.14 Cumulative Average Erosion at Overland Erosion Station #12
Orwell Lake, Minnesota
(1981 – 1982)

Camera
Focusing
Aid

APPENDIX A6: CUMULATIVE AVERAGE EROSION AT OVERLAND EROSION STATIONS #1-12A, 1982

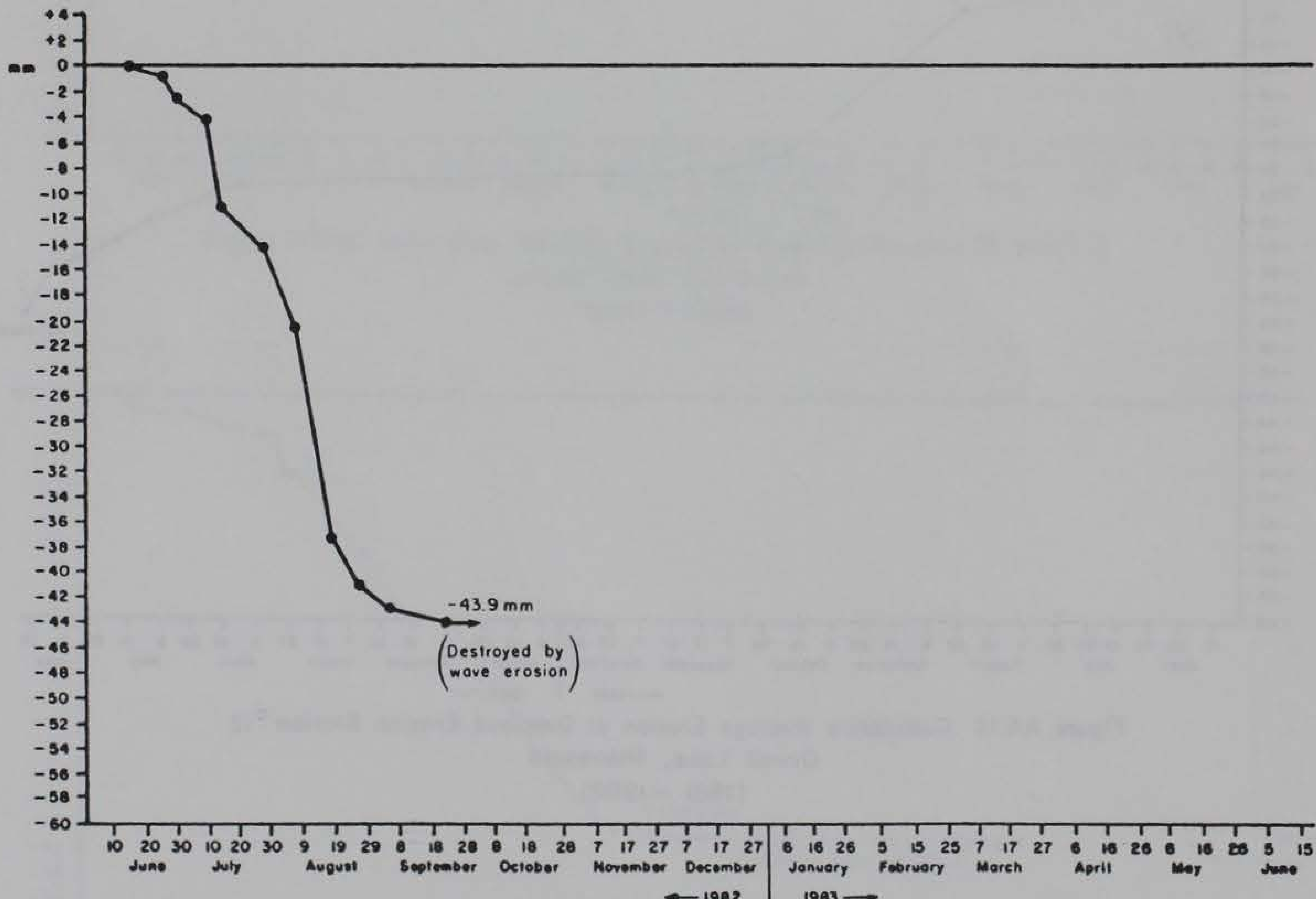

Figure A6.1 Cumulative Average Erosion at Overland Erosion Station # 1
Orwell Lake, Minnesota
(1982)

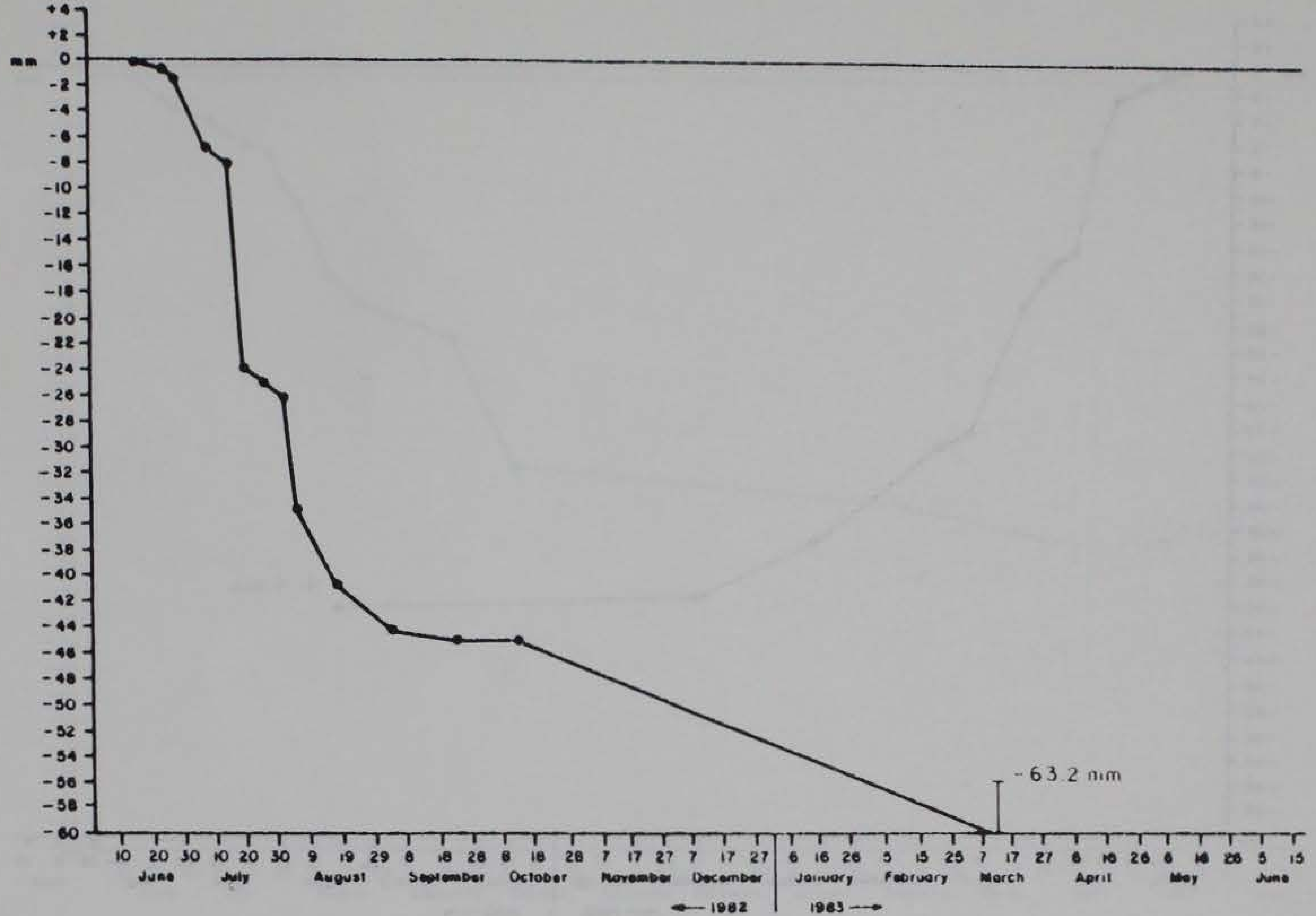

Figure A6.2 Cumulative Average Erosion at Overland Erosion Station # 2
Orwell Lake, Minnesota
(1982 - 1983)

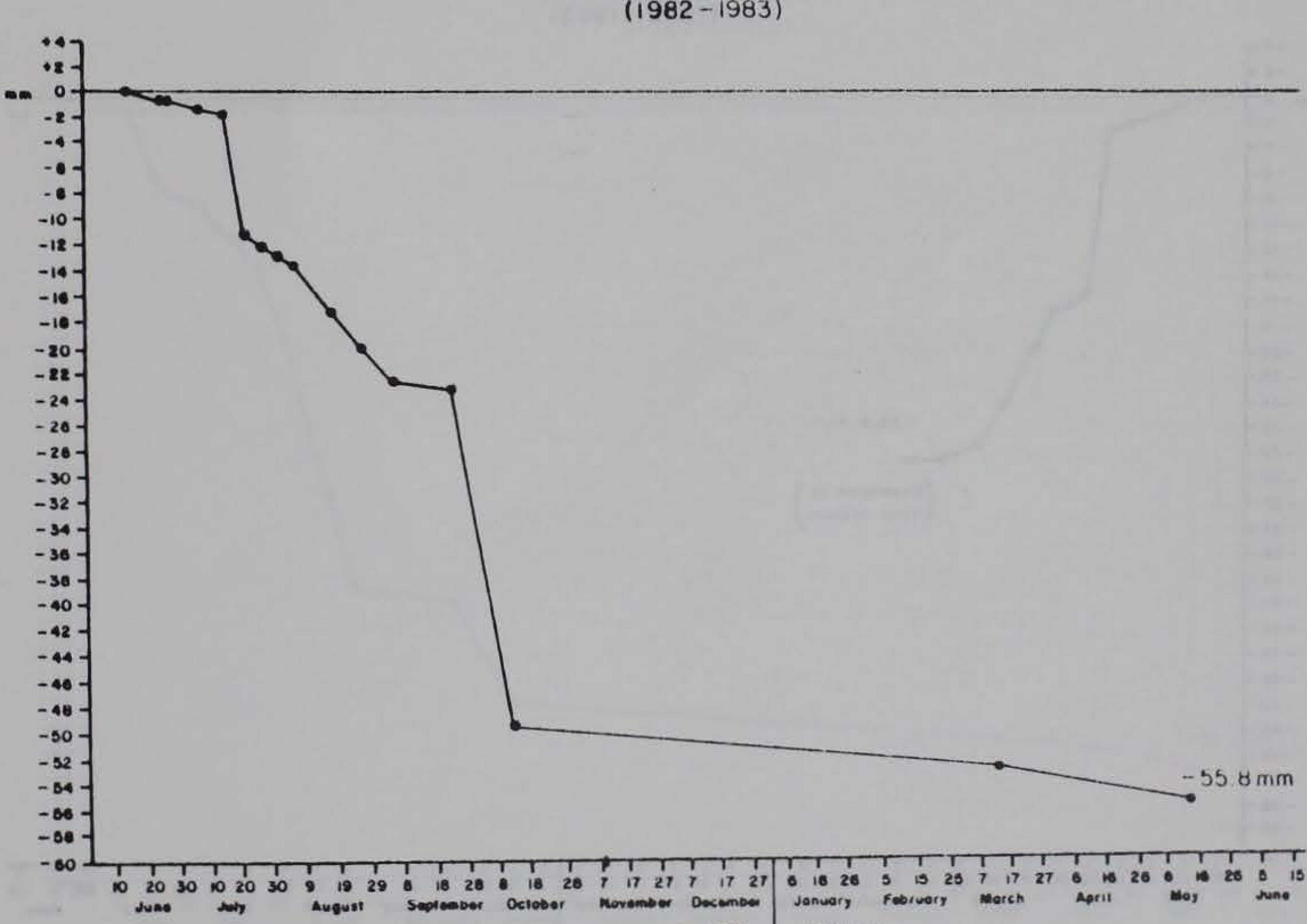

Figure A6.3 Cumulative Average Erosion at Overland Erosion Station # 3
Orwell Lake, Minnesota
(1982 - 1983)

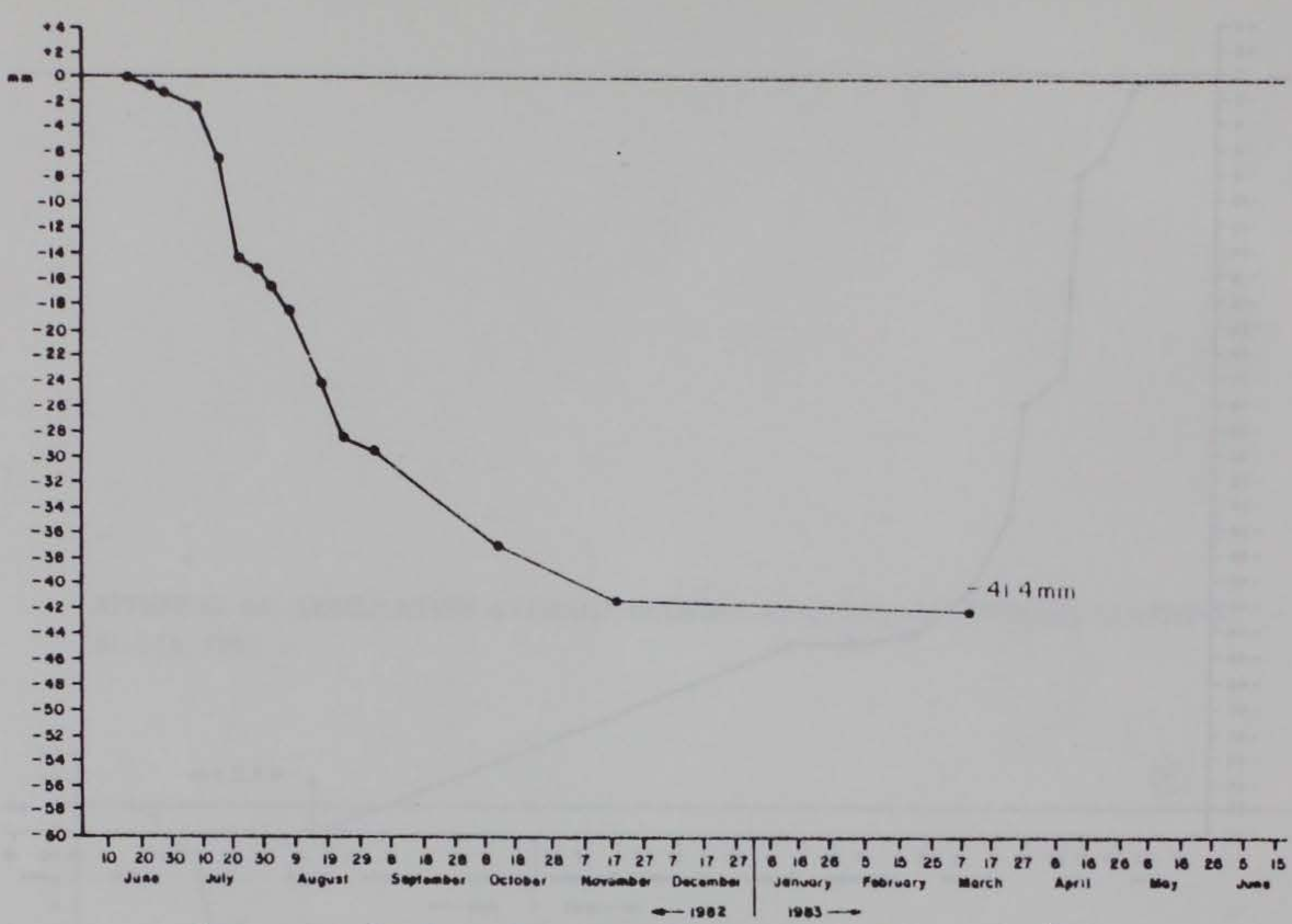

Figure A6.4 Cumulative Average Erosion at Overland Erosion Station # 4
Orwell Lake, Minnesota
(1982 – 1983)

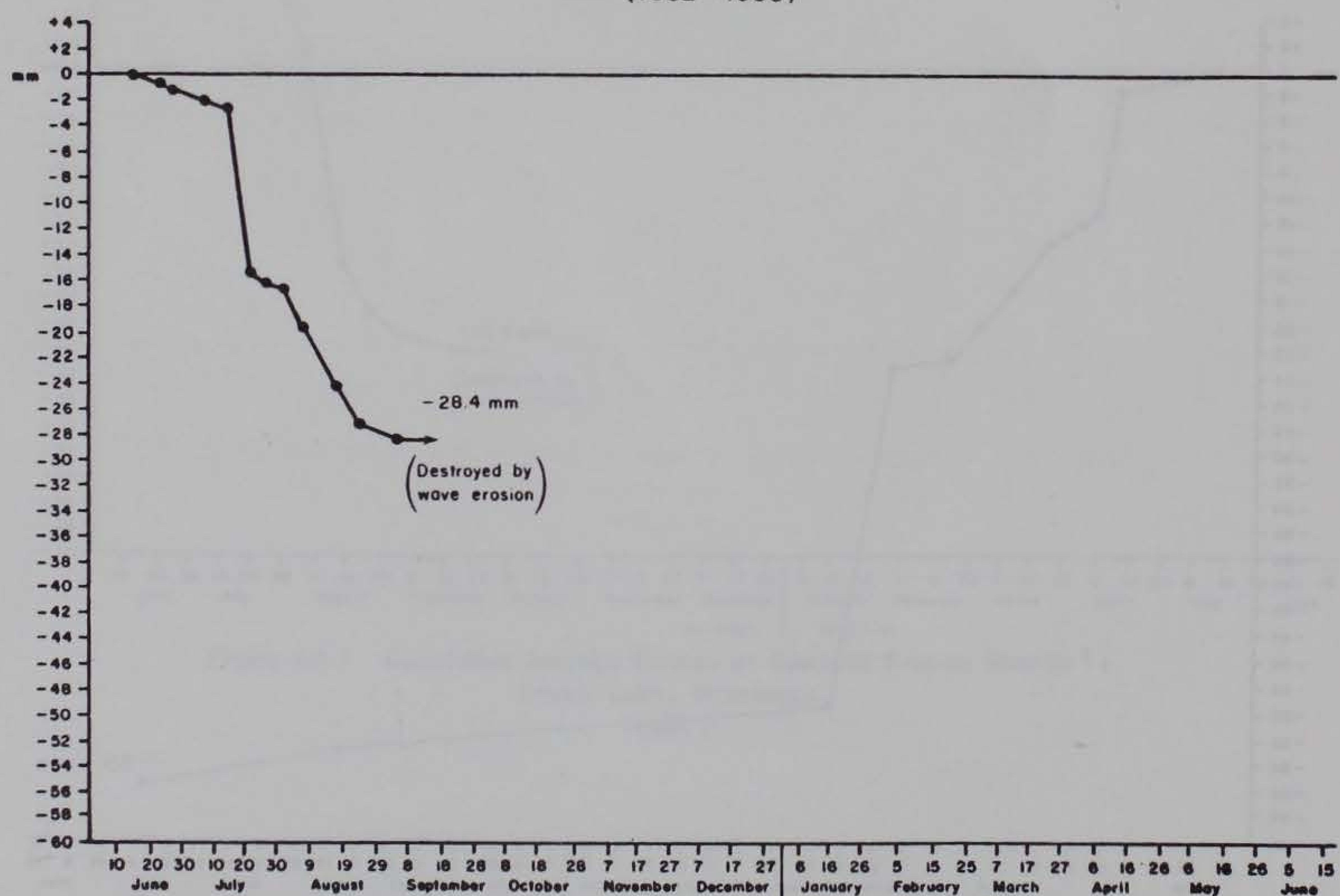

Figure A6.5 Cumulative Average Erosion at Overland Erosion Station # 5
Orwell Lake, Minnesota
(1982)

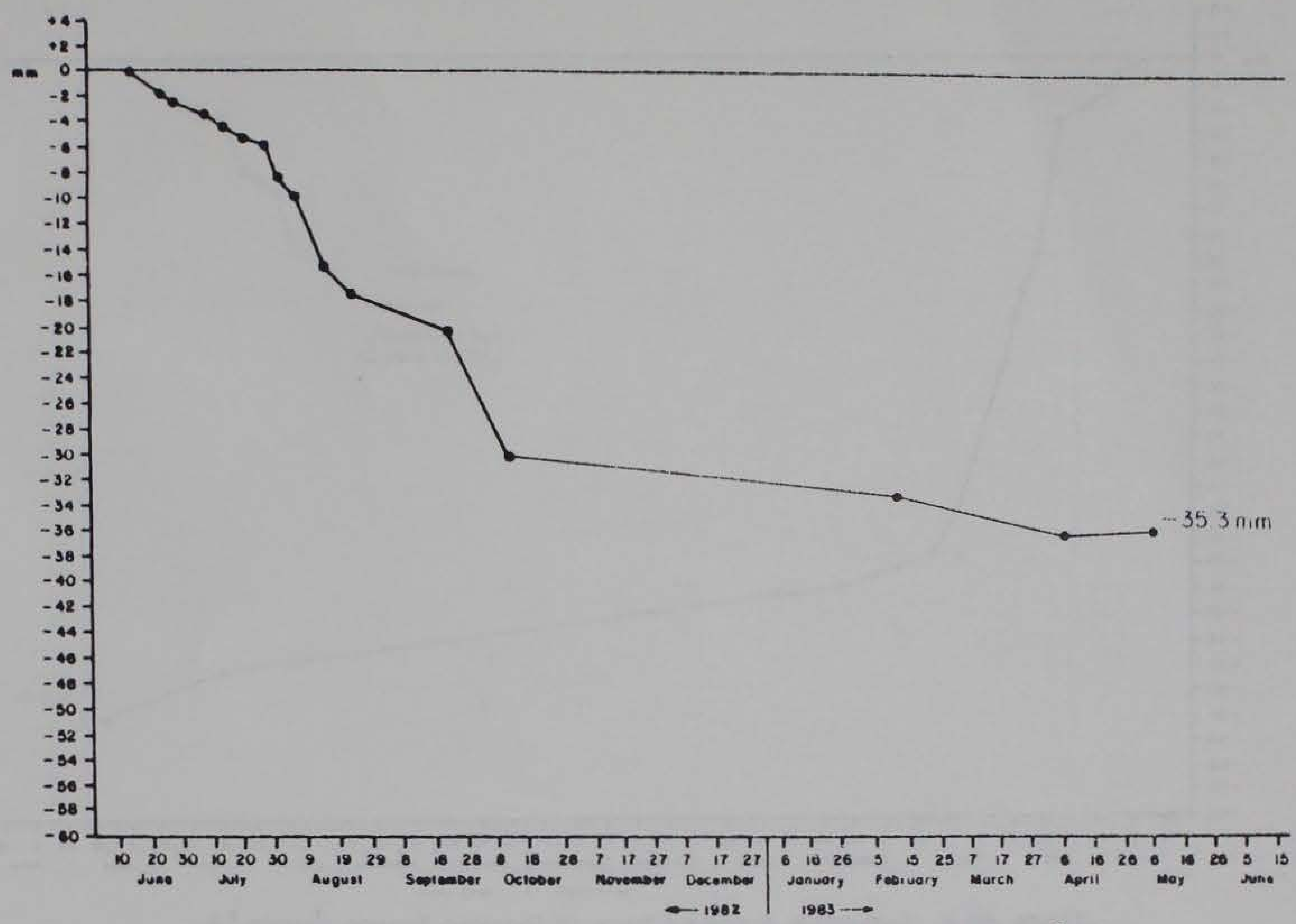

Figure A6.6 Cumulative Average Erosion at Overland Erosion Station #6
Orwell Lake, Minnesota
(1982 – 1983)

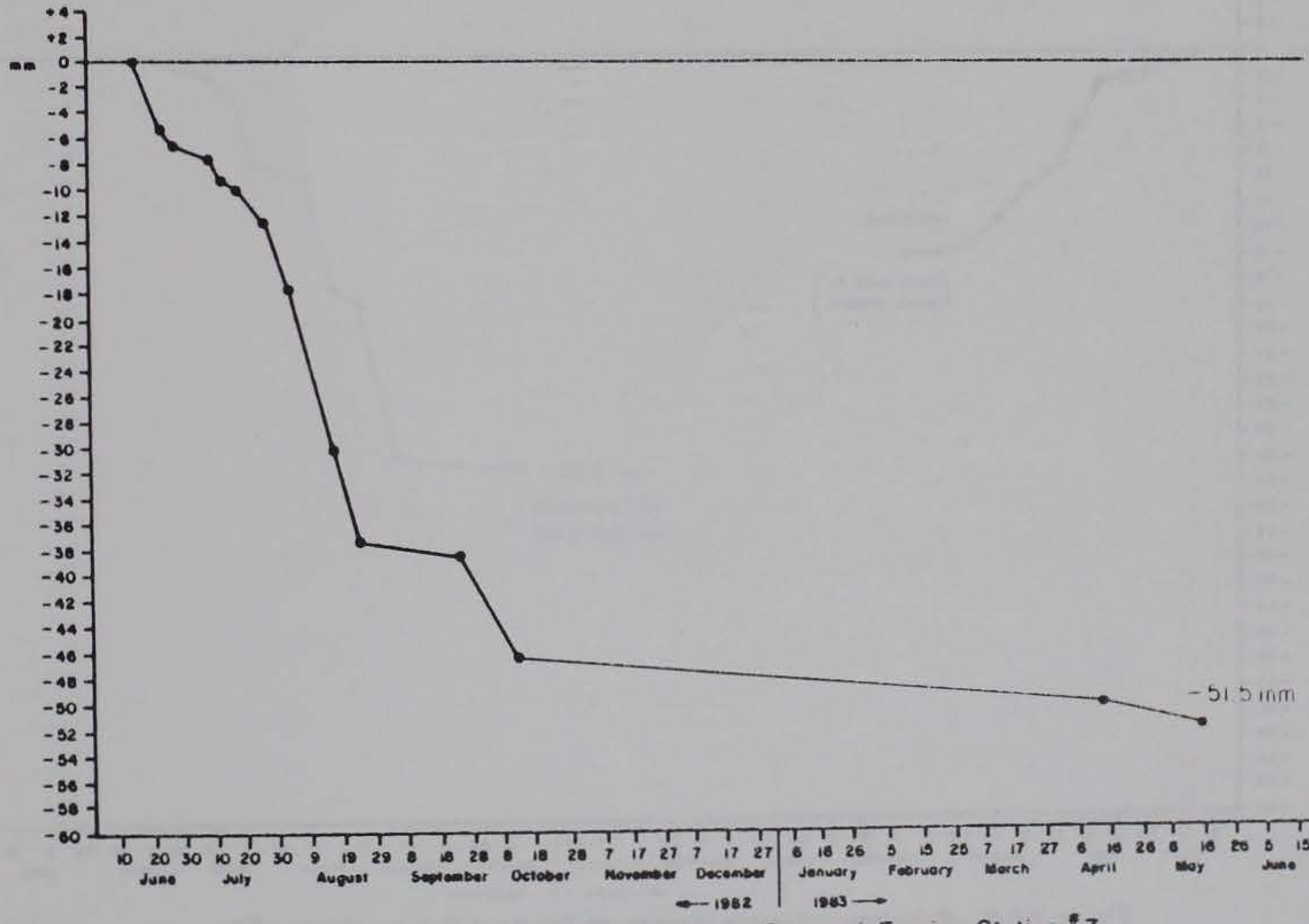

Figure A6.7 Cumulative Average Erosion at Overland Erosion Station #7
Orwell Lake, Minnesota
(1982 – 1983)

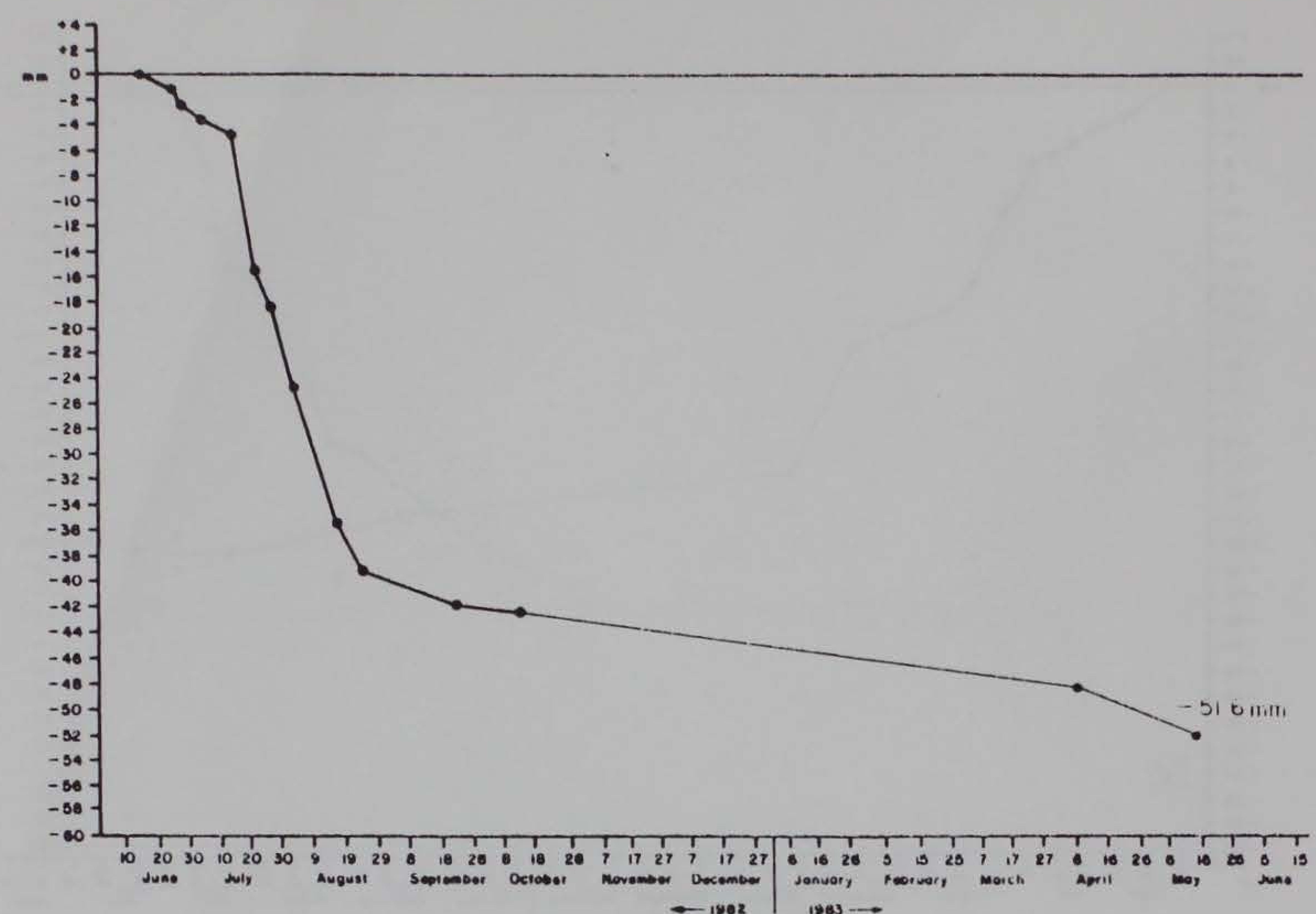

Figure A6.8 Cumulative Average Erosion at Overland Erosion Station #8
Orwell Lake, Minnesota
(1982 – 1983)

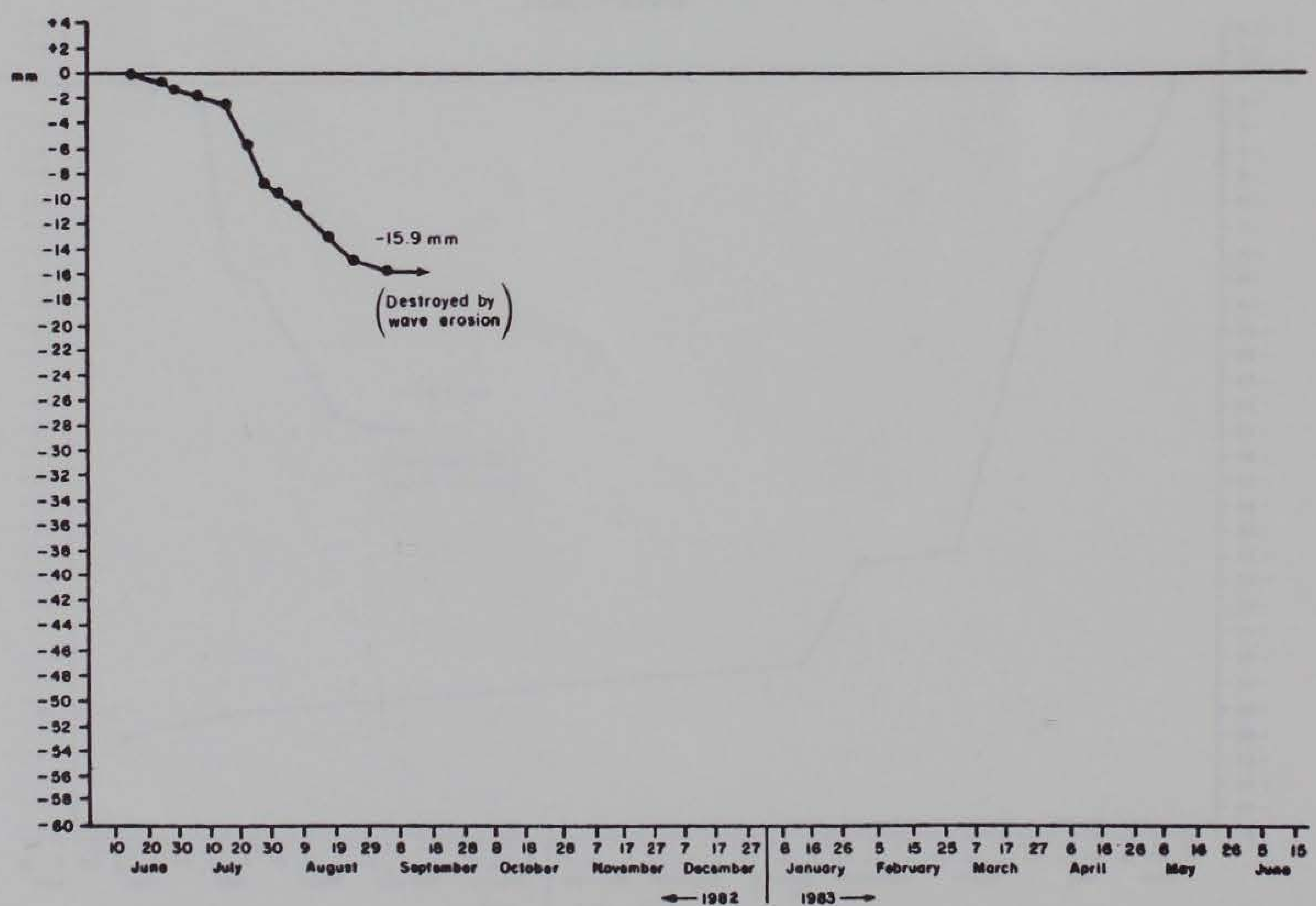

Figure A6.9 Cumulative Average Erosion at Overland Erosion Station #9
Orwell Lake, Minnesota
(1982)

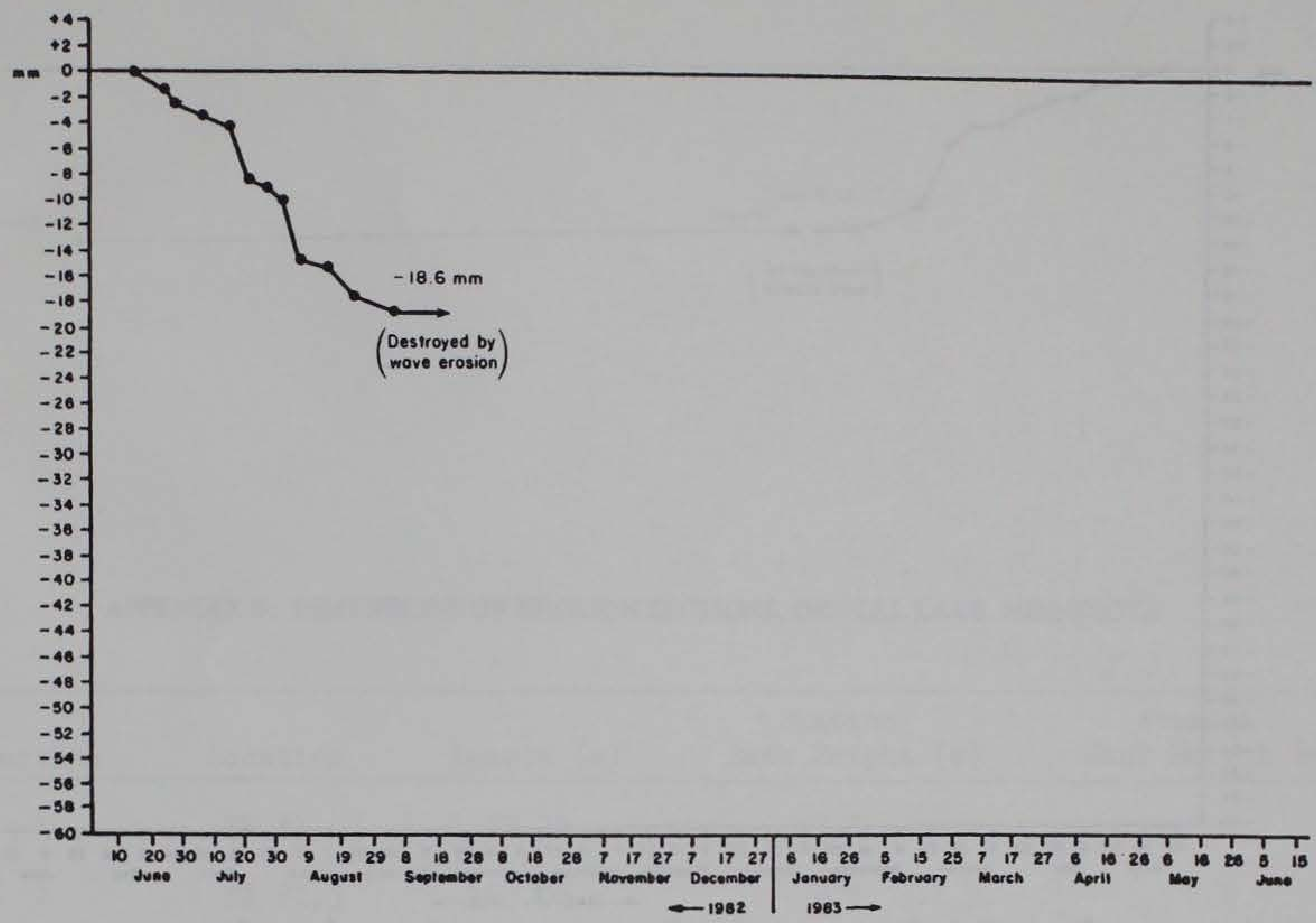

Figure A6.10 Cumulative Average Erosion at Overland Erosion Station #10 Orwell Lake, Minnesota (1982)

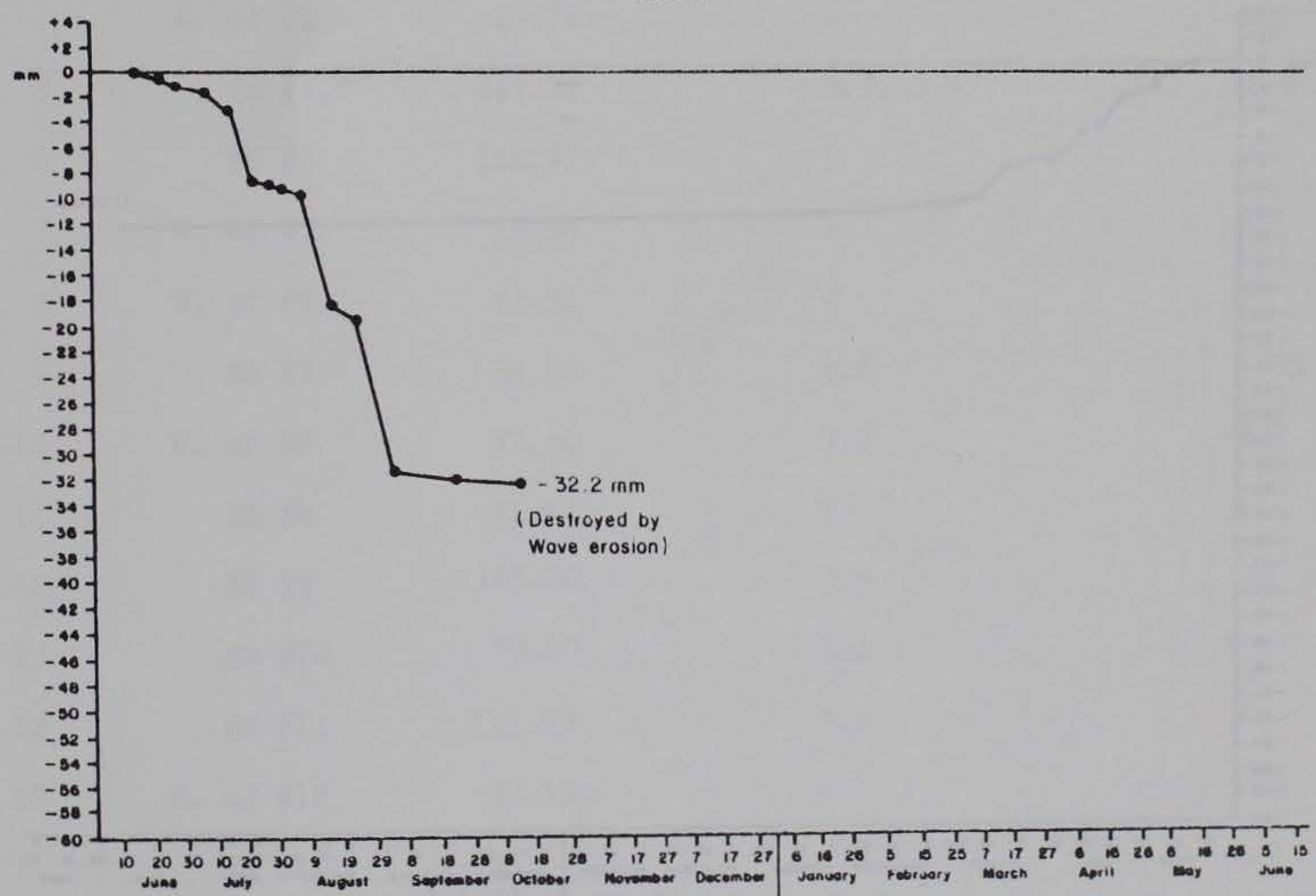

Figure A6.11 Cumulative Average Erosion at Overland Erosion Station #11 Orwell Lake, Minnesota (1982)

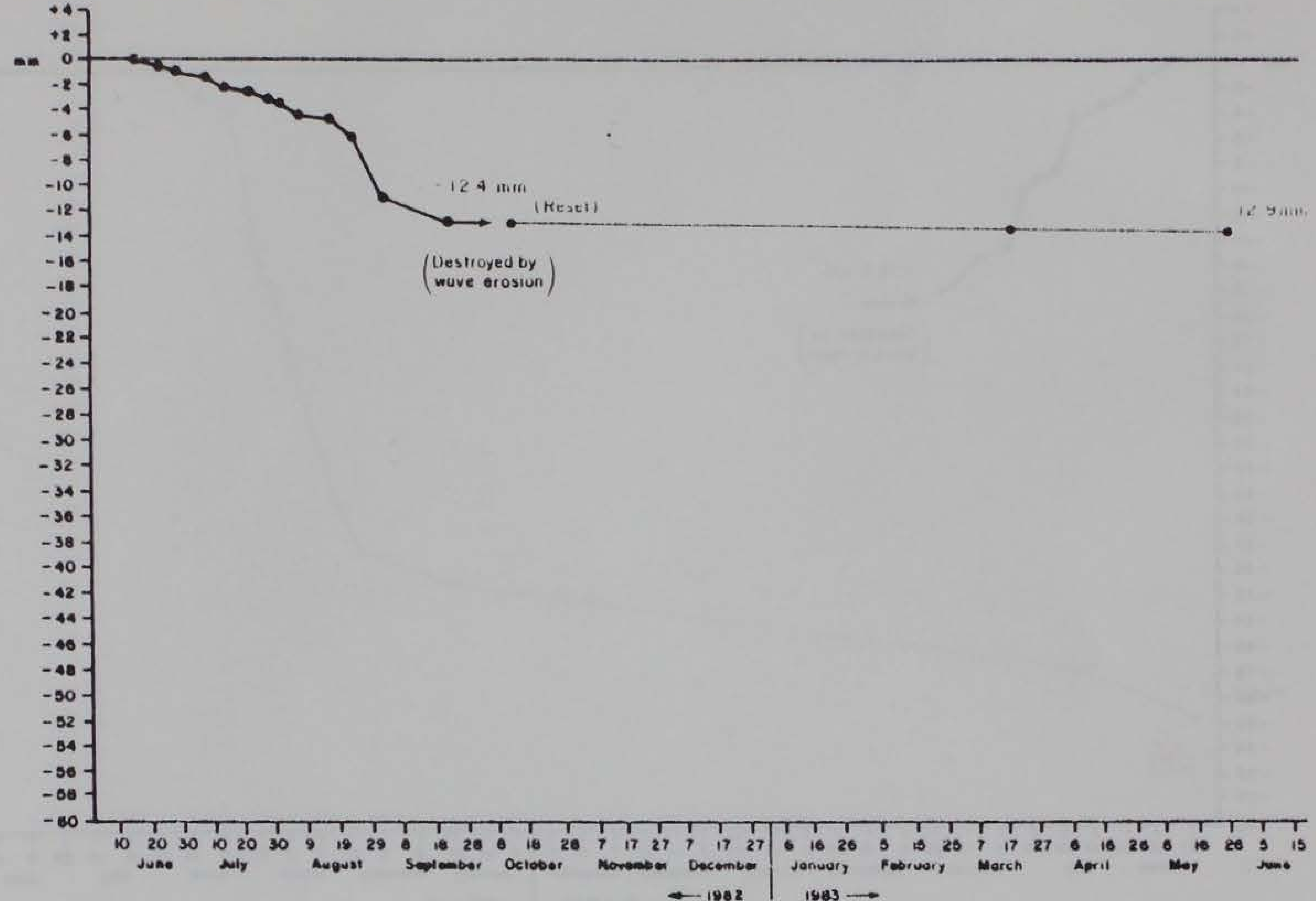

Figure A6.12 Cumulative Average Erosion at Overland Erosion Station # 12
Orwell Lake, Minnesota
(1982 – 1983)

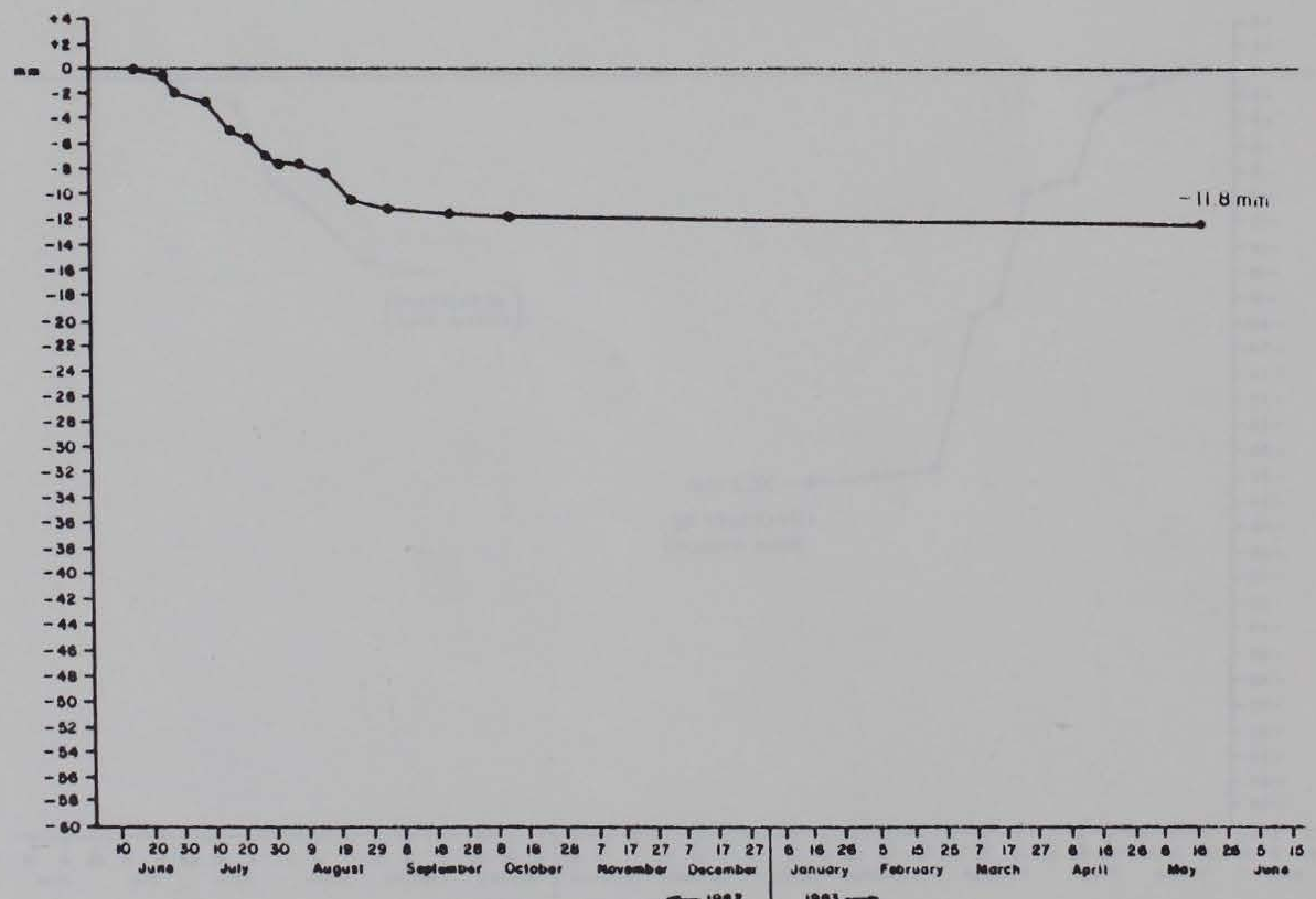

Figure A6.13 Cumulative Average Erosion at Overland Erosion Station # 12 A
Orwell Lake, Minnesota
(1982 – 1983)

APPENDIX B: DIMENSIONS OF EROSION SECTIONS, ORWELL LAKE, MINNESOTA

Section	Location	Length (m)	Station Bank Height (m)	Average Bank Height (m)
1	ES #1	82.30	3.2	2
2	ES #2,3	163.06	2.5, 3.4	2
3	E. of #3	70.10	-	1
4	W. of #4	45.72	-	1.5
5	ES #4,5	247.32	3.5, 3.5	2.9
6	ES #6	156.97	6	3
7	W. of #7	28.96	-	3.5
8	W. of #7	53.34	-	3
9	ES #7	38.10	3.6	1.75
10	W. of #8	97.54	3.2	3.2
11	ES #8	51.82	4	4
12	ES #9	105.00	3.3	5
13	ES #10	79.80	3.4	3
14	ES #11	141.73	3.1	2
15	E. of #12	33.53	-	1.2
16	ES #12	195.07 T=1590.36	3.5	2.8

APPENDIX C: PIEZOMETER INSTALLATION DATA, ORWELL LAKE, MINNESOTA

Piezometer Number*	Date Installed	Screen Interval	Surface Elevation	Location	Stratigraphic Location	Comments
1	7/07/80	-3.05 to -4.42m (-10 to -14½')	328.52 m (1077.81')	≅3.8m (12½') above lake level; W of old slump on NE shore of lake	Dunvilla Formation; water-lain unit	Bottom of hole at -4.4m (14½')
2	7/09/80	-6.24 to -7.77m (-20½ to -25½')	334.73m (1098.21')	≅64m W of Piezometer #3	Dunvilla Formation till; may reach into fine sand unit	Hole bottomed at -14.3 (-47')
3	7/08/80	-4.88 to -6.10m (-16 to -20')	335.34m (1100.21')	≅20m W of #4; above 1977 slump zone	Dunvilla Formation; water-lain sediments	Bottom of hole at -8.2m (-27')
4	7/08/80	-12.36 to -13.88m (-40½ to -45')	335.54m (1100.85')	≅13.1m (43') above lake level; top of 1977 slump; NE shore of Orwell Lake	Dunvilla Formation; water-lain silts at -12.2m (40'); fine sand between -5.2m (-17') to -8.2m (-27')	Bottom of hole at -15.8m (-52')
5	7/12/80	-8.08 to -9.30m (-26½ to -30½')	330.42m (1084.04')	Level area east of Orwell Dam station	Dunvilla Formation; in coarse sand and gravel beds within till unit	Hole bottomed at -10.5m (-34½')
6	7/30/81	-6.71 to -8.08m (-22 to -26½')	330.43m (1084.10')	Upslope from Piezometer #5	Dunvilla Formation; sand and gravel unit	
7	7/29/81	-3.2 to -4.58m (-10½ to -15')	329.54m (1081.33')	Above discharge zone; E end of lake (N of ES #10)	Dunvilla Formation	Spring discharge along beach

*See Figure 12 for locations

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