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Reservoir bank erosion caused and influenced by ice cover

Lawrence W. Gatto

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The purpose of this study was to evaluate the importance of reservoir bank erosion caused by an ice cover. The evaluation is based on a literature review and on inferences made from field observations and experience. Very little is known about the amount of reservoir bank erosion caused by the actions of an ice cover, although considerable information is available on the processes of ice-related erosion along the shorelines or beaches of oceans, rivers or lakes. The importance of ice-related erosion along a reservoir bank seems to be determined primarily by water level. If the reservoir water level is high enough

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for ice to act directly on the bank face, the amount of erosion caused by ice could be substantial. If the water level is below the bank, ice would have no direct effect on it. However, ice could indirectly increase bank instability by disrupting and eroding nearshore and beach zones, which could lead to bank erosion.

PREFACE

This report was prepared by Lawrence W. Gatto, Geologist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded by the Office of the Chief of Engineers under Civil Works Work Unit 31568, Erosion Potential of Inland Shorelines and Embankments in Regions Subjected to Freezing and Thawing.

The author thanks James Wuebben, Ice Engineering Research Branch, CRREL, and Bruce Brockett and Dr. Daniel Lawson, Earth Sciences Branch, CRREL, for sharing their field observations. Most of the photographs in this report are from their collections. Mr. Wuebben, Dr. Lawson, Dr. John Reid of the University of North Dakota, and Dr. Tsong Wei of the U.S. Army Corps of Engineers, Missouri River Division, technically reviewed the manuscript.

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RESERVOIR BANK EROSION CAUSED AND INFLUENCED BY ICE COVERS

by

Lawrence W. Gatto

INTRODUCTION

This report was prepared as part of an investigation of reservoir bank erosion processes and impacts in cold regions. The specific objectives of the investigation are 1) to measure and analyze the causes of and factors contributing to bank erosion, 2) to determine the relative magnitudes of the causes and factors, and 3) to assess the environmental impacts resulting from the erosion. This report was done as part of the first two objectives. The data acquired and the process-response relationships analyzed during this investigation will aid in developing improved methods for predicting the erosion potential of a slope, the rate and areal extent of that erosion, and the time required for a slope to reach a noneroding dynamic equilibrium.

Simons et al. (1978, 1979) and Pincus (1962) described some of the causes of and factors contributing to bank erosion and recession, and Seibel (1972) and Sterrett (1980) describe the complexity of their interrelationships. This report, however, focuses on bank erosion caused just by reservoir ice. It is based on a literature review and on field observations made by colleagues or myself.

The literature review showed that the causes and impacts of erosion have been identified; however, the magnitude of erosion caused by a given process is only superficially known if at all. In fact, Ouellet and Baird (1978) feel that it may be impossible to quantify the amount of erosion that any one process contributes to total bank erosion since there are many contributing processes, all of which are interdependent.

I did not find any references that reported measurements of ice-caused bank erosion. Most of the literature on ice-related erosion dealt with ice erosion processes along oceans or rivers and did not address ice erosion of reservoir banks. Since the processes that cause ice erosion along oceans, rivers or lakes can be similar, I reviewed references that dealt with all three environments and used field observations to infer how ice-erosion processes may act along a reservoir bank.

By necessity the review was limited to papers in the open literature. Theses, dissertations and consultant reports not referenced in data bases or in the open literature could not be obtained and reviewed. In addition, foreign language papers were not reviewed.

ICE AS BANK PROTECTION

Before describing some of the ways an ice cover can erode reservoir banks, it is important to mention that ice can also protect the bank from erosion by waves and nearshore currents. Erosion caused by ice action is frequently reduced by a nearshore ice barrier (Outhet 1974). Avakyn (1975) reported that reservoir shore changes usually occur when the reservoir is ice-free. When ice covers a river, lake or reservoir from shore to shore, it dampens waves and protects the banks from normal wave erosion processes (MacCarthy 1953, Varjo 1960, Brochu 1961, Coakley and Rust 1968, McCann 1972, Cohn 1975, John and Sugden 1975, Hadley 1976, Ouellet and Baird 1978). Erosion restarts at breakup when the ice becomes mobile; the ice scrapes, shoves and scours the shore or bank, and transports sediment away.

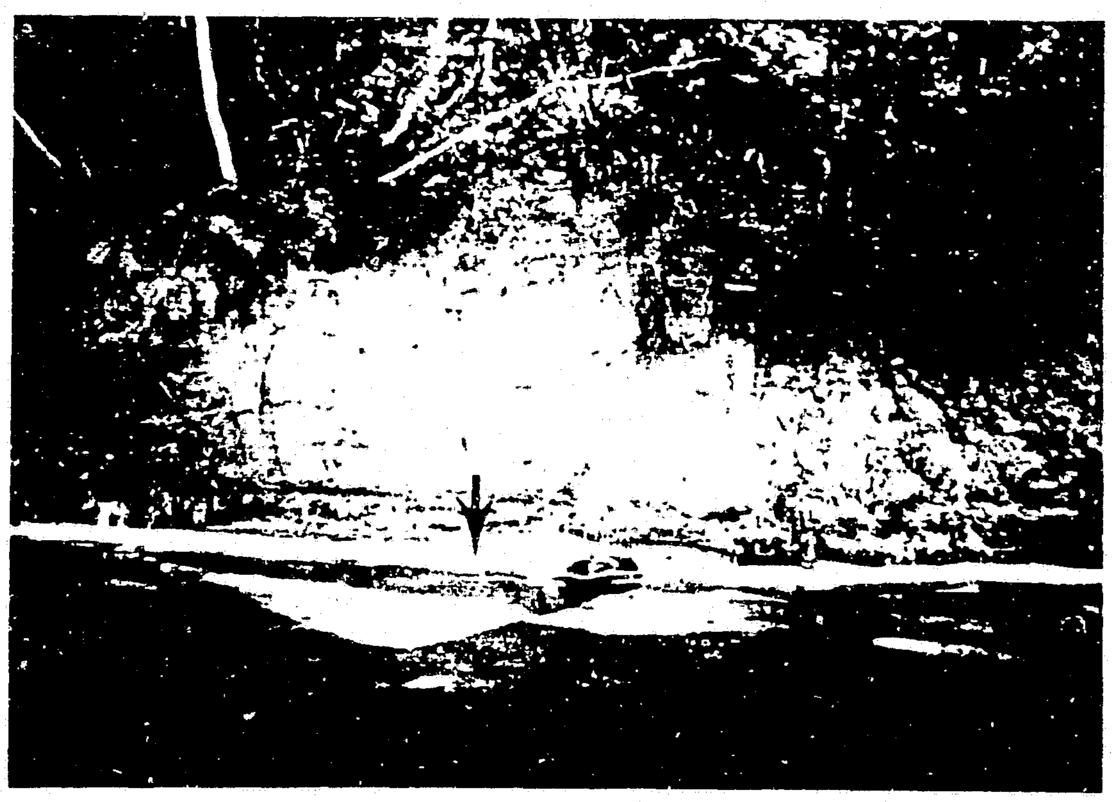
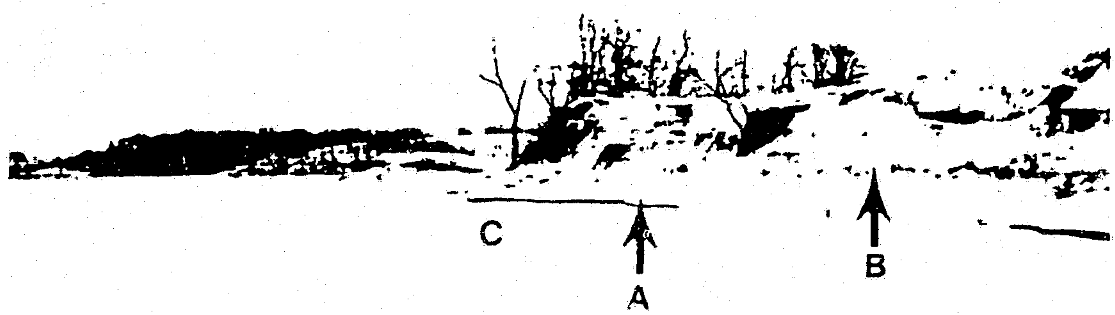
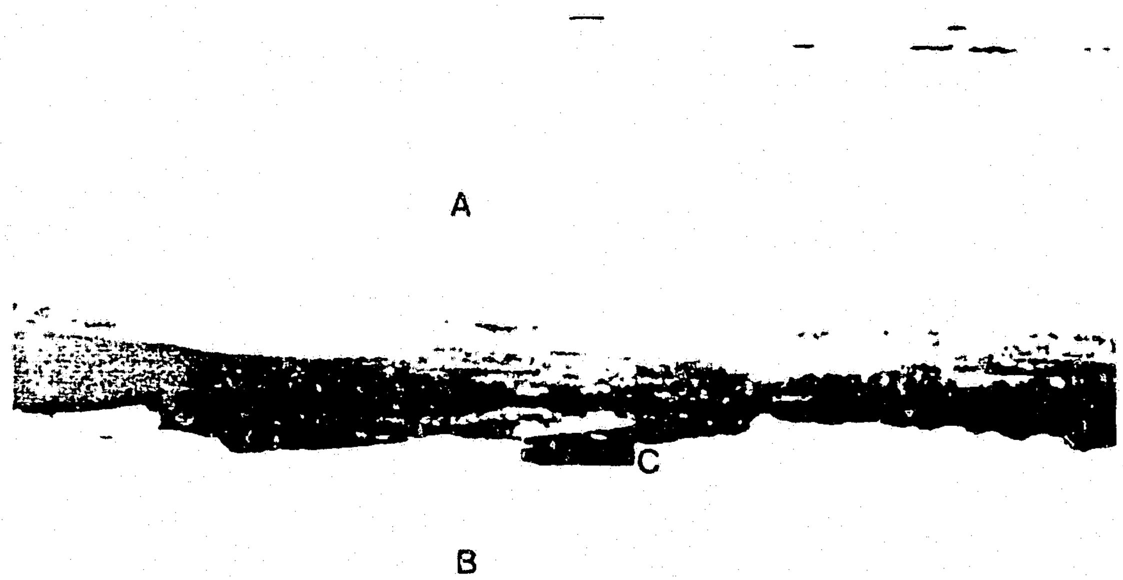


Figure 1. Narrow zone of shorefast ice (5 December 1980, Wilder Lake, south of Hanover, New Hampshire).

The ice cover usually begins to form along the shoreline of a reservoir. It can be attached to the sediment at the shoreline and continue to grow offshore (Fig. 1). After the ice completely covers the reservoir and the water level drops during the winter, a shelf of ice can remain attached to the shore as the ice farther offshore cracks and collapses (Fig. 2).



a. The shelf (A) is below the bank toe (B) and is separated from and higher than the ice cover (C), which is being lowered as the water level drops.



b. A crack has formed between the ice shelf (A) and the lowered ice cover (B); the glove (C) is for scale.

Figure 2. Attached ice shelf (30 January 1980, Orwell Reservoir, Minnesota).

Figure 3. Protective shorefast ice along Wilder Lake, Norwich, Vermont, 4 March 1981.

Figure 4. Ice foot along Grand Traverse Bay, Michigan, spring 1975. Note the sediment deposited within the ice and on the ice-foot surface by waves overtopping the ice foot.

This shelf can remain intact through the winter and protect the shoreline from direct erosion by mobile ice farther out in the reservoir (Fig. 3).

The ice foot (Fig. 4) that often forms along portions of the Great Lakes also stops shore erosion in the winter (O'Hara and Ayers 1972). Descriptions of an ice foot as a protective structure along lakes are common in the literature (Zumberge and Wilson 1954, Dionne 1974b, Dozier et al. 1976, Evenson and Cohn 1979). An ice foot can also erode a shoreline by freezing to the shoreline material during the winter (Nielsen 1979). In the spring the ice foot can fall from the shore, removing attached sediment and bedrock (Hamelin 1972). The ice and attached material then float away and the sediment is deposited in the lake as the ice melts.

I have not observed nor found documentation of an ice foot forming along reservoirs. It may be that small ice-foot features form but do not reach the size of those reported along the Great Lakes. Judging from the time required for an ice foot to form as described by O'Hara and Ayers (1972), I suspect that most reservoirs do not remain ice-free long enough into the winter for winter storms to cause the repeated wave spray necessary for large-scale ice-foot formation. Lawson[1] suggested that an ice foot may form in the large reservoirs of the western U.S.

ICE-COVER EROSION PROCESSES

Direct erosion

Ice can erode reservoir banks when the reservoir water level is high enough for the ice to directly loosen and remove soil particles by pushing or grinding along the face or toe of a bank (Van Everdingen 1967, Jahn 1975). This sometimes happens along rivers, especially during spring breakup (Fig. 5). Typically during a river ice run, mobile ice will slide along shorefast ice at a shear wall (Outhet 1974). Occasionally ice will slide directly against the bank and erode the soil (Martinson 1980). This erosion can be significant enough to cause local bank failures (Dionne 1974b), although Eardley (1938) reported that the amount of bank erosion by ice along the Yukon River appears to be inconsequential. These ice actions can also disrupt the bank soil structure sufficiently to reduce soil strength, so that the banks are more easily eroded by other processes.

[1]Personal communication, CRREL, 1982.

Figure 5. Erosion during spring breakup. The water level is high enough for mobile ice to grind and shove against the beach (A) and the bank (B) directly (spring 1979, southwest of Mirre Point, St. Marys River, Michigan).

Rose (1946) described a predictive analysis of ice pressures based on temperature and ice thickness. He reported maximum probable ice thrusts of 75,000-300,000 N/m of shoreline in the continental United States and about 440,000 N/m in colder areas. He also pointed out that lowering a water level reduces the ice pressure against the shoreline because the lowering would likely cause the ice to bend and crack, rupturing the continuity of the ice sheet. This reduces the ice thrust at the waterline, except when water fills the cracks in the ice, freezes and expands the ice cover; if the ice cover was complete, this expansion would then increase the thrust at the edge of the ice cover.

Field observations show that water levels in many reservoirs are lowered below the toes of the reservoirs' banks during the winter, and the ice is laid down onto the reservoir bottom. The ice is then ineffective in causing erosion (Fig. 6). The water level normally rises in the spring, and if the ice persists, it can be lifted and again moved by winds. The ice may erode bottom or beach sediment during this time. If the level is raised high enough, the mobile ice may strike the bank directly.

Reservoirs with complete covers of ice during winter are modified by

Figure 6. Reservoir ice cover (A) laid down onto the exposed reservoir bottom below the banks (B).

ice mainly during spring breakup. Typically, as spring progresses and temperatures rise, the ice initially melts along the shore, leaving a partial ice cover that moves with the wind. Also, the water levels of reservoirs, especially flood-control reservoirs, usually rise in the spring. The more mobile ice can then grind and shove along the banks. These ice actions may not be as strong along reservoirs as along rivers, however, since river currents are usually more rapid than wind- or thermally induced currents along reservoirs.

Wuebben[2] pointed out, however, that river currents are not always faster than reservoir ice moved by wind shear. Also, wind-driven ice can be pushed perpendicularly into a reservoir shore or bank; this more normal force may cause more erosion than the river ice, which usually moves more nearly parallel to the shoreline.

Indirect erosion

If the water level of an ice-covered reservoir is not high enough for the ice to act directly on a bank, the ice may contribute to bank erosion indirectly. While the ice cover is mobile, it can push, shove and remove beach and nearshore sediment (Fig. 7). This can contribute to undermining of the bank, which increases bank instability; the bank may eventually

[2]Personal communication, CRREL, 1982.

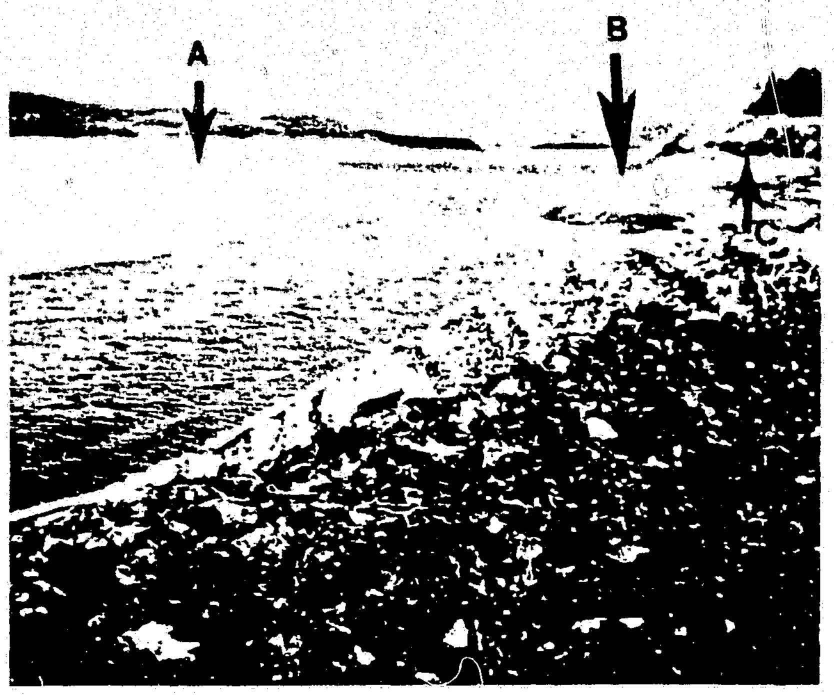


Figure 7. Mobile ice (A) can grind and shove the reservoir bottom (B) as the water level rises to a higher level at the base of the reservoir banks (C) (February 1974, Lake Koocanusa, Montana).

collapse and the bankline recede. Ice can also remove sediment that has eroded from a bank and accumulated along the bank toe. By removing this accumulation, water waves and currents can erode the bank toe directly.

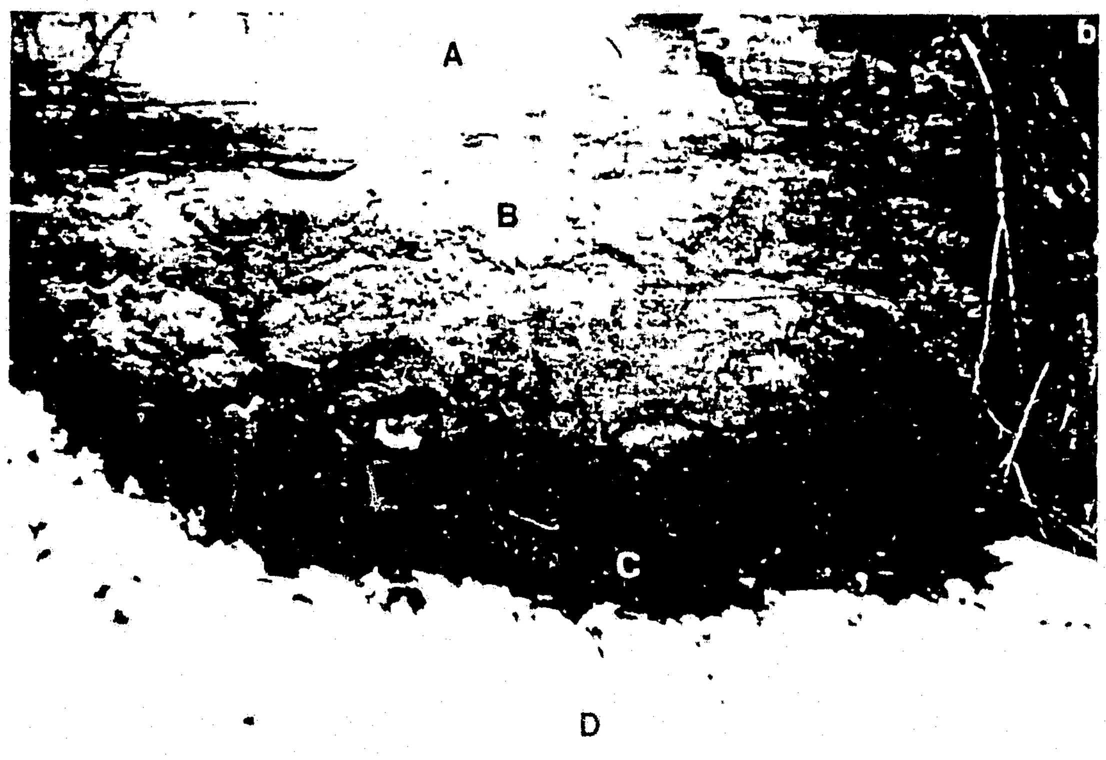
Ice rafting

Ice rafting can also remove bank or beach sediment that becomes attached to or incorporated into the ice cover. Dionne (1974b) observed clay- to boulder-size sediment at the base, on the surface and within the ice cover on the St. Lawrence River. At spring breakup the sediment is transported and redeposited. Intertidal sediments are also frequently rafted in Labrador fjords (Rosen 1979).

Reimnitz and Bruder (1972) reported that only an insignificant amount of sediment is rafted away from arctic Alaska's deltas during sea ice breakup. Much of the shorefast ice melts in place, and most of the incorporated sediment is dropped before final breakup. Rafting of large quantities of beach material attached to the bottom of an ice foot occurs, however, in the Antarctic (Joyce 1950).

The importance of ice rafting in lakes or reservoirs is poorly documented. I found no references that described the processes of ice rafting or that reported measurements of the quantities of sediment that are ice-rafted in lakes or reservoirs. Field observations show, however, that sediment fallen from reservoir banks is frequently deposited on the surface of shorefast ice (Fig. 8), especially in the spring as the banks thaw.

a. Bank sediment (A) sloughing (B) onto nearshore ice (C) (15 December 1981).



b. Bank sediment (A) sliding (B) or flowing (C) onto snow-covered nearshore ice (D) (4 March 1981).

Figure 8. Bank sediment deposited on shorefast ice, Wilder Lake, Norwich, Vermont.

Figure 9. Sediment frozen to the bottom of ice laid down onto the reservoir bed (February 1974, Lake Koocanusa, Montana).

Figure 10. Dirty ice (A) after shoving and grinding along the shore (20 February 1981, Connecticut River, Haverhill, New Hampshire).

When ice is attached to the shore or bank or laid down onto the reservoir bottom, sediment can also freeze to the ice (Fig. 9). On many lakes, though, the shorefast ice melts in place and drops its sediment without transport. It seems reasonable to assume that some sediment would be removed if the shorefast ice becomes mobile.

When ice grinds and shoves along the shoreline and banks of rivers, it can accumulate sediment on its surface. The sediment becomes frozen in and on the ice (Fig. 10) and can be transported away. Bank or beach sediment can be removed from along a reservoir in a similar fashion, but the water level would have to be high enough for the ice to act directly on the beaches or banks.

Factors influencing ice erosion

The amount of bank erosion caused by ice processes depends on the interplay of many factors: water levels and their fluctuations; ice strength and characteristics; mobility of the ice cover; degree of ice attachment to the beach, nearshore or bank sediments; the extent to which the bank, beach and nearshore sediments are frozen; and shore configuration. The importance of water levels, ice attachment to sediment, and mobility of the ice has been discussed briefly. Additional information on the strength, properties, mobility and duration of and pressures exerted by an ice cover is available in the proceedings of the following conferences: Conference on Ice Pressures Against Structures, Laval University, Quebec, Canada, 1966; The Role of Snow and Ice in Hydrology, Banff, British Columbia, Canada, 1972; International Conferences on Port and Ocean Engineering under Arctic Conditions; Symposium on Applied Glaciology, Cambridge, England, 1976; International Association of Hydrologic Research International Symposia on Ice Problems; and Third National Hydrotechnical Conference, Canadian Society for Civil Engineering, Quebec, Canada, 1977.

The following individual reports also address ice formation, ice structure, ice properties, ice-cover characteristics and duration, and ice effects: Korzhavin 1962, Weeks and Assur 1969, Michel 1971, 1978, Donchenko 1972, Marshall 1977, Ashton 1979 and Haugen et al. 1979. Ficke and Ficke (1977) summarized the literature on ice formation, characteristics and effects on navigation, currents, shoreline structures and water quality. Drouin and Michel (1974) reviewed the literature from 1922 to 1968 and described the thermal properties of ice and ice-cover expansion or contraction.

Several papers address the pressures exerted by an ice cover on shores, dams and other structures and discuss the factors that affect the magnitude of the pressures (Rose 1946, Monfore 1952, Zumberge and Wilson 1952, 1953, Montagne 1963, Sommerville and Burns 1968, Pessl 1969, Bergdahl and Wernerson 1978). Some of these factors are air temperature, solar energy absorption, ice temperature, rate of temperature change in the ice, coefficient of thermal expansion, rheology of ice, ice thickness, amount of water-filled cracks, and shore restrictions.

If the shoreline or bank sediment is frozen, ice effects can be minimal (Harper et al. 1978). Freezing along Monomoy Island, Massachusetts, creates a stabilized beach of rocklike coarse sand, which slows or stops normal beach processes (Davis 1973, Davis et al. 1976). Along the Great Lakes shores, after the beach sands freeze and an ice foot forms, the beach typically remains static for about 10 weeks. There are some ice-push features that form, but for the most part, normal shore processes slow or stop (Davis et al. 1976).

Owens and McCann (1970) concluded that offshore, nearshore and beach ice limit wave action on the beach and bank, but do form ice-push and ice-melt features along the shore. However, when the beach and nearshore zone are frozen, the sediment there is stable and unaffected by either ice push or storm waves.

The configuration of the shoreline also influences the amount of bank erosion that could result from actions of a mobile ice cover. Along a reach of reservoir with a straight shoreline, ice erosion of the shoreline or bank could be more evenly distributed, with no one location being eroded more than any other. Along a reach with an irregular shoreline, however, ice would be more likely to erode the banks on the promontories than along the bays.

Along reservoir shorelines with gentle offshore slopes it is more likely that ice could become attached to or gouge offshore bottom sediment and never reach or erode the shorelines or banks. As the water level drops in these areas, ice becomes grounded sooner than in areas with steep offshore slopes and less ice pressure is directed to shorelines or banks. Along shorelines with steep offshore slopes, ice can advance to the shoreline or banks and erode them directly.

EROSION FEATURES CAUSED BY ICE COVERS

There are several reviews of how ice erodes and reshapes nearshore zones and shorelines (Bryan and Marcus 1972, Code 1973, Mackay and Mackay 1977). The ice creates a variety of erosion features: linear and cellular scars, basins, ice-pushed and ice-deposited ridges or mounds (ice ramparts), ice-contact cusps, and ice-rafted sediments including boulders, pebbles and ice-cemented blocks (Dionne and Laverdiere 1972, Lawson 1972, Short and Wiseman 1973, Dionne 1974b, 1981, Brochwicz-Lewinski and Rudowski 1976, Kovacs and Sodhi 1979). However, I did not find any references that describe features left by ice erosion on reservoir banks.

It may be that the water level of most reservoirs is low enough when there is ice that the ice seldom erodes the bank directly. This is probably true for most flood-control reservoirs. Ice could be driven up a reservoir bank, but this would require a large fetch and sustained winds. Also, if the water level was low, it is unlikely that winds would be strong enough to drive the ice cover over the shore up to the banks. Some of the factors that limit the amount of shoreline rideup are water current drag, friction, jamming, ice pileup on the beach slope, steep beach slopes, ice flexural strength and thickness, and high freeboard (Croasdale et al. 1978). Tsang (1975) reported that a shore lead and gently sloping shores allow more ice rideup.

Field observations along Whitefish Bay in Lake Superior show that ice can be driven by winds up to and over banks that are as high as 25-30 ft (Fig. 11). Ice driven by currents can also ride up and directly erode a riverbank (Fig. 12). The erosion of the banks and the damage to bank vegetation can be extensive (Fig. 13). Outhet (1974) also described how ice can be pushed onto and over low banks and small willow trees along the Mackenzie River delta, Canada.

Reservoir bank erosion can occur when winter floods rapidly raise the water level of flood-control reservoirs. The ice cover on the reservoir is lifted, broken up, and made mobile. It can then erode the banks directly and damage bank vegetation (Fig. 14). This type of vegetation damage could eventually lead to increased bank instability if the damage is severe enough to kill the vegetation. The root systems which tend to bind the upper sediment would decay, and the added stability would be lost.

As previously stated the disruption of the beach and nearshore zone by ice can also lead to increased bank instability. The following sections

a. Ice over the bank (March 1979).

b. Ice remained into May 1979. Note the sediment dislodged by the ice.

Figure 11. Wind-driven ice (Whitefish Bay, Lake Superior, Michigan).

Figure 12. Ice pile-up on Belle Isle, Detroit River, Michigan, during an ice run (March 1978).

a. Tree damage.

b. Upper bank damage.

Figure 13. Bank damage due to ice ride-up (Whitefish Bay, Michigan, May 1979.

Figure 14. Trees broken by ice being let down as the reservoir water level dropped after a winter flood (December 1973, Franklin Falls Reservoir, Franklin, New Hampshire).

address some of the erosion processes and features left by ice erosion along the beach and nearshore. The most frequently reported features along lakes are ice-push features.

Ice-push features

Dionne (1974a) summarized the literature on ice-push features, which include ice ramparts, ice-push ridges (Fig. 15) and ice-thrust ridges. Field observations of ice-push features cited in the literature are numerous; there is a debate on whether they result from ice expansion or from wind-driven ice (Jones 1970, Montagne 1963). Since I am more concerned with the extent rather than the causes of the shore disruption, I will only summarize the debate.

Some investigators (Laskar and Strenzke 1941, Jennings 1958) feel that ice push due to ice expansion dominates on lakes with diameters less than 3-4 km (Worsley 1975), small lakes about 5 km^2 in area (Dionne 1979), and narrow, shallow bays on large lakes (Pessl 1969). Wind-generated ice push occurs more often on wide lakes (Dionne 1979, Varjo 1960) or large lakes with fetches greater than 4 km (Worsley 1975). When winds are the cause of the ice movement, moderate prevailing winds can push ice sufficiently to

Figure 15. Ice-push ridge (about 90 cm high) formed at the end of November 1979 during a storm with 45-mph northwesterly winds; the ice was 10-12 cm thick (30 January 1980, Orwell Reservoir, Minnesota).

form a shoreline ridge (Bruun and Johanneson 1971, Bruun and Straumsnes 1970); strong winds are not necessary.

Taylor (1978) observed ice-push ridges and pit topography 185 m inland across the beach of Somerset Island, Northwest Territories, Canada. Ice-push ridges were observed along the South Arm of Yellowstone Park in Wyoming (Montagne 1963), Wamplers Lake in southeastern Michigan (Zumberge and Wilson 1952, 1953), Eleven Mile Canon Reservoir in central Colorado (Monfore 1952), and Generator Lake on Baffin Island (Ward 1959). Along a lake near Resolute Bay on Cornwallis Island, Northwest Territories, Canada, the ridges were several feet high and usually had an asymmetrical cross section (Nichols 1953). Backshore brush and trees have been damaged or broken along Knob Lake in Labrador, Canada (Jones 1970) and along many lakes in central Quebec and Labrador (Pyokari 1981).

Wagner (1970) observed that small ramparts formed along shores of embayments with fine sediment and gentle slopes and that larger ramparts formed along straight shores with intermediate-size sediment and moderate slopes along Shelburne Bay, Lake Champlain, Vermont. He concluded that ice-rampart formation was limited by a continuous snow cover, the development of pressure ridges in ice, short periods of partially open water, and

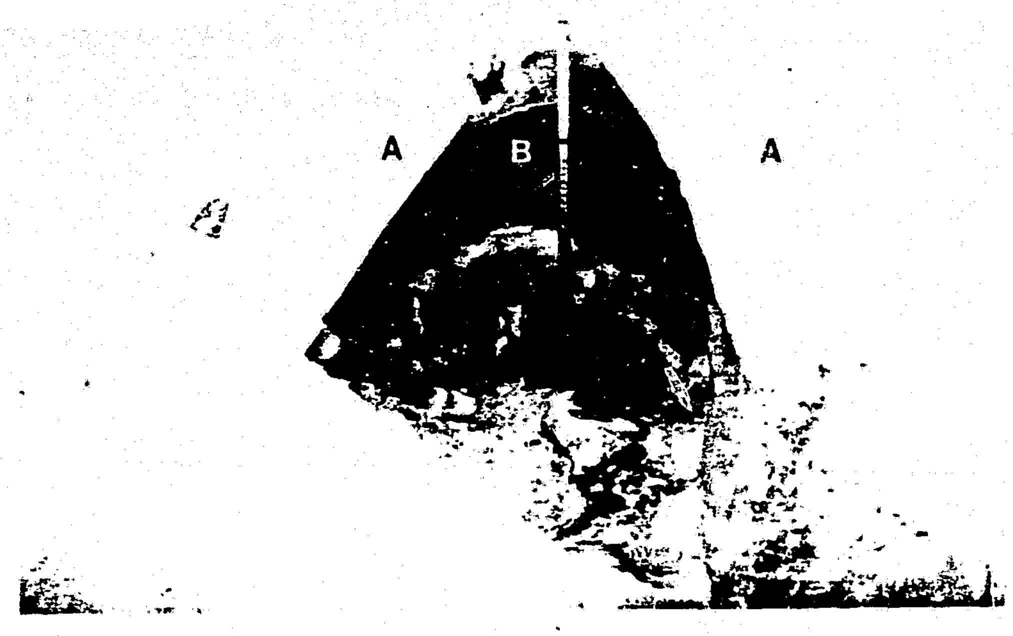


Figure 16. Ice (A) and shore sediment (B) uplifted (about 60 cm) where an ice pressure ridge intersects the shoreline (30 January 1980, Orwell Reservoir, Minnesota).

ice weakened by breakup. The continuous snow cover insulates the ice from air temperature fluctuations; consequently the ice temperature fluctuations and resulting expansion and contraction are less. Field observations show that when an ice cover is complete, the compressive forces that form pressure ridges in an ice cover can also cause shore sediment to be thrusted where the pressure ridges intersect the shoreline (Fig. 16).

Worsley (1975) described the following ice-push features around Grasvatn, Scandinavia, where ice thicknesses are normally 1.25 m: boulder concentrations along the beach, boulder pavements, boulders and trails, ramparts, planed subaqueous moraine ridges, and grooved or scraped surfaces due to floe grounding. The average net shoreward movement of the ice cover on Gardner Lake, Connecticut, was approximately 1 m in 30 days and produced an ice-push beach ridge 1 m high (Pessl 1969). Ice-push ridges 0.6 m high caused by ice expansion were reported along many German lakes (Goebeler 1972). Adams (1977) observed ice-push features and ice action along Astray Lake, Labrador, Canada. He reported that the features are due to ice expansion and wind; he found ice 6 m above the June water level and 18 m inland.

It is clear that ice disrupts and erodes lake shorelines. When winds are strong enough or water levels are high enough, ice can erode lake or reservoir banks and damage vegetation. How frequently this occurs and how much bank erosion results are unanswered questions.

Ice-scour features

Ice-scour features are documented along marine and estuary coasts and rivers, but I found no references for lakes or reservoirs. Ice along the Beaufort Sea coast typically striates, planes and gouges the bottom and beaches, leaving mounds and ridges (Hume and Schalk 1964, Barnes et al. 1977, FENCO 1975). Dionne (1969, 1974b) determined that most of the erosion along the tidal flats in the St. Lawrence River estuary occurs in the spring by ice gouging and ploughing. These processes form linear and arcuate scars and basins; they scratch and polish soft rock, dislodge previously broken rock fragments, and level weathered rock platforms. The bed of the Tana River in Norway has also been gouged and flattened by ice (Collinson 1971).

Many of these features could form along lake and reservoir shores in the spring, especially where bottom slopes are gentle and the water is shallow. As the water level rises, the ice breaks and floats. It can then be pushed over shallow areas and modify the bottom configuration. If this occurs near the toe of the bank, it may add to bank instability; if it occurs far from the bank toe, the bank would probably be unaffected.

SUMMARY AND CONCLUSIONS

There is considerable information in the literature on the ice processes that erode and deposit sediment along lake shores as well as on the features created by these processes. The general forces applied to a lake or reservoir shoreline by an expanding or wind-driven ice cover have been described and occasionally measured. The shoreline features formed and the changes resulting from ice actions along the waterline are documented. However, the direct effects of an ice cover on bank erosion, the importance of ice rafting, and the effects of an ice cover on the erodibility of bank sediment by other processes have not been documented.

The importance of ice-related erosion along a reservoir bank is determined by water level. If the reservoir water level is high enough for ice to act directly on the bank face, the amount of ice erosion can be substantial. If the water level is below the bank, ice may have no direct effect on the bank but could indirectly cause increased bank instability by disrupting the nearshore and beach zones.

The relative importance of the factors and processes that contribute to bank erosion has not been determined. Simons et al. (1979) developed a qualitative assessment using available data, a review of current theory, personal experience, and sound professional judgment. Field studies currently underway will provide measurements that can be used to evaluate the relative importance of ice and other processes contributing to reservoir bank erosion.

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