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RESERVOIR BANK EROSION CAUSED BY ICE

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ABSTRACT

The purpose of this study was to evaluate the documented and potential importance of ice erosion along reservoir banks. The evaluation is based on a literature review and on inferences drawn from field observations and experience. Very little is known about the amount of reservoir bank erosion caused by ice action, although considerable information exists on ice erosion processes along the shorelines and beaches of oceans, rivers and lakes. The importance of ice-related erosion along a reservoir bank would depend primarily on water level, but ice conditions and bank sediment characteristics would also be important. If the reservoir water level is at bank level, ice could directly erode a bank face. If the water 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.

INTRODUCTION

Reservoirs are in a special category of inland water bodies, and they differ from natural lakes in two ways: their construction disturbs existing natural conditions by reforming shorelines and riverbeds, and their water level is usually controlled by man (Doe, 1980). Reservoirs typically have one or more of the following functions: water supply, irrigation, flood control, navigation, hydropower generation, recreation, and development and expansion of plant and animal habitats (Hagan and Roberts, 1972; Hodgins et al., 1977), although flood control is usually their primary purpose. Since water level controls the water-holding capacity of flood control reservoirs, the water level is changed according to annual flood control requirements, which are dictated by precipitation and runoff.

In the northern U.S., water levels on flood control reservoirs are usually lowered during the late fall and winter and kept at a minimum in preparation for high spring runoff. The levels rise in the spring because of frequent storms and snow melt and because the amount of water released from a reservoir at this time is low to reduce or eliminate downstream flooding. Water levels are maintained at their highest during the summer and early fall as water is stored or slowly released for other purposes. Superimposed on these large annual fluctuations are the small water level changes caused by daily operations and by those operations required to fulfill other reservoir functions.

Bank erosion occurs in many reservoirs and reduces their usefulness. The causes of, and factors contributing to, bank erosion and the complexity of their interrelationships have been described (Lawson, 1983, 1984; Pincus, 1962; Seibel, 1972; Simons et al., 1978, 1979; Sterrett, 1980), but the relative importance of the factors and processes has not been determined. This study focuses on bank erosion caused just by reservoir ice and was done as part of an on-going investigation to measure and determine some of the erosion processes and factors that are important in cold regions. It is based on a literature review and on field observations made by colleagues and myself.

Most of the literature dealt with ice erosion processes along ocean, river and lake shorelines and beaches. I did not find any references that addressed ice erosion along reservoir banks. However, since the processes that cause shoreline and beach erosion can also cause bank erosion, I reviewed references that dealt with all three environments and used field observations to infer how ice may erode a reservoir bank. However, I did not attempt an exhaustive literature search and review. It was primarily limited to papers in the open literature, those referenced in computer data bases, and those in the English language. Papers published in a foreign language were not translated and reviewed. I tried to review enough literature to cover adequately the variety of reported observations and discussions.

ICE AS BANK PROTECTION

Before discussing how ice can erode reservoir banks, it is important to mention that it can protect a shoreline, beach and bank by limiting wave action and the effects of storm surge and nearshore currents and by stopping the scraping, shoving and scouring caused by drift ice. This protective ice can occur in four forms: as shore ice which is lake ice attached to the shore (Brochu, 1961; Coakley and Rust, 1968; Cohn, 1975; Gatto, 1982; Hadley, 1976; John and Sugden, 1975; MacCarthy, 1953; McCann, 1972; McCann and Owens, 1970; Nordstrom and Sherman, 1982; Ouellet and Baird, 1978; Outhet, 1974; Owens, 1976; Owens and McCann, 1970; Varjo, 1960); as an ice foot (Fig. 1) which is partially on the beach and formed primarily by freezing of wind-blown wave spray (Dionne, 1974a; Dozier et al., 1976; Evenson and Cohn, 1979; Knight and Dalrymple, 1976; Marsh et al., 1973; O'Hara and Ayers, 1972; Zumberge and Wilson, 1954); as a rampart of alternating beach sediment and ice formed by wave swash on the upper part of a frozen beach before formation of an ice foot or lake ice (Rosen, 1978); and as a coating of ice on the bank face which could be frozen ground water seepage (Carey, 1973) or frozen sheet flow.

Fig. 1. Ice foot along Grand Traverse Bay, Michigan; note the sediment deposited within and on the ice surface (by J. Wuebben).

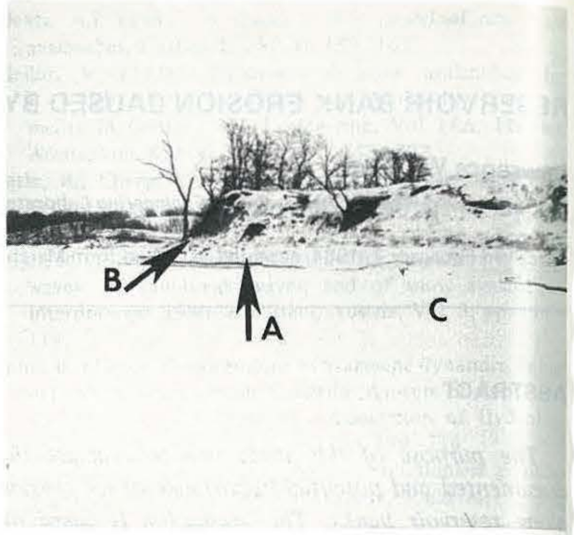

Fig. 2. Attached shore ice (A) below the bank toe (B) and separated from and higher than the ice cover (C), Orwell Reservoir, Minnesota (by L. Gatto).

I have observed shore ice along reservoirs (Fig. 2), but I have not observed or found documentation of a protective rampart or ice foot along reservoirs. It may be that the rampart usually does not form along reservoirs since the water level of most northern reservoirs is lowered in the winter. As the water level falls, waves would break at successively lower levels. The repeated wave swash at the same level necessary for rampart development would not occur.

Regarding an ice foot, it is possible that a small ice-foot could form along reservoirs but does not reach the size of those reported along large lakes. Judging from the time required for an ice foot to form (O'Hara and Ayers, 1972), I suspect that reservoirs where ice usually forms do not remain ice-free long enough into the winter for storms to cause the repeated wave spray necessary for large-scale ice foot formation. In addition, the winter storms would have to be severe enough to cause significant wind-wave spray during freeze up.

ICE EROSION PROCESSES

Direct erosion

Ice can erode reservoir banks when the reservoir water level is high enough for the ice to loosen and remove soil particles directly by pushing or grinding along the face or toe of a bank (Van Everdingen, 1967; Jahn, 1975). This erosion sometimes occurs along rivers, especially during spring breakup (Martinson, 1980), where it can cause local bank failures (Dionne, 1974a) and may be more severe than scour by water (Michel, 1970). Eardley (1938) reported, however, that the amount of bank erosion by ice along the Yukon River appears to be inconsequential. Alestalo and Haikio (1979) observed ice that was thrust into the bank along lakes in Finland which disrupted and broke away bank sediment. Ice pushing and grinding can also disrupt the bank soil structure sufficiently to reduce soil strength, so that the banks are more easily eroded by other processes.

Several papers (Bergdahl and Wernerson, 1978; Monfore, 1952; Montagne, 1963; Pessl, 1969; Ponter et al., 1983; Sommerville and Burns, 1968; Zumberge and Wilson, 1952, 1953) address the thrust forces exerted by an expanding ice cover on shores, dams and other structures and describe how air and ice temperatures, solar energy absorption, rate of temperature change in the ice, coefficient of thermal expansion, rheology of ice, ice thickness, amount of water-filled cracks, and shore restrictions affect the magnitude of these forces. I did not find any references to thrust forces exerted by wind-driven ice.

Rose (1946) predicted maximum probable ice thrust forces of 73–292 kN/m (5,000–20,000 lbf/ft) of shoreline in the continental United States and about 438 kN/m (30,000 lbf/ft) in colder areas caused by ice cover expansion. Michel (1970) summarized field measurements of the horizontal force exerted by a solid ice sheet on engineering structures. The measurements ranged from 51 kN/m (3,500 lbf/ft) on Hastings Dam on the Mississippi River to 292 kN/m (20,000 lbf/ft) on Eleven Mile Canyon Reservoir in Colorado. Most measured forces were between 44 kN/m (3,000 lbf/ft) and 146 kN/m (10,000 lbf/ft). Similar thrust forces could be

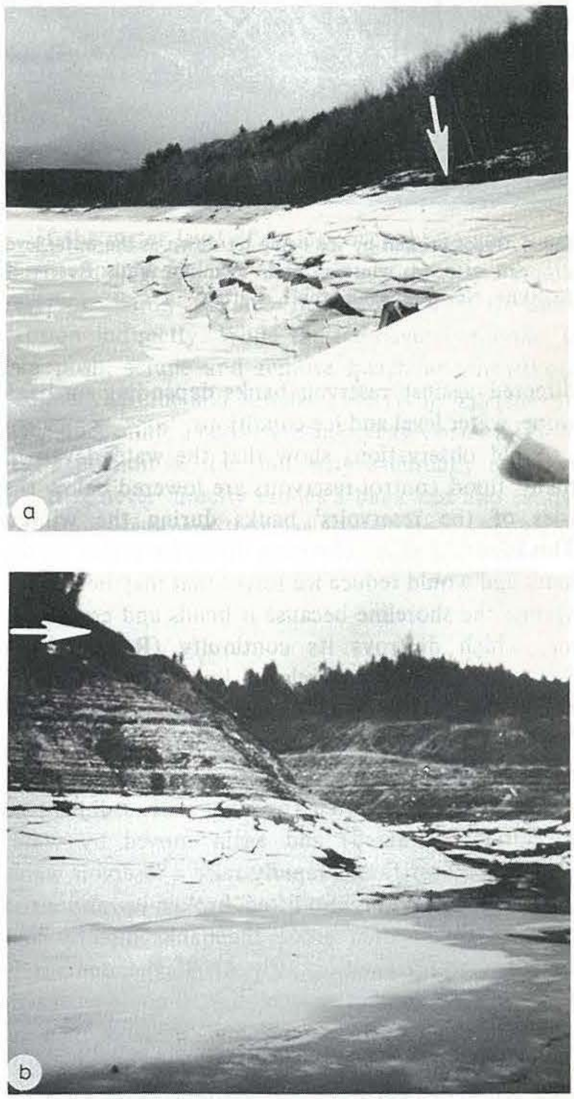

Fig. 3. Reservoir ice cover laid down onto the exposed reservoir bed below the banks (arrow); (a) Waterbury Reservoir, Vermont (by L. Gatto), (b) Lake Koocanusa, Montana (by B. Brockett).

Fig. 4. Trees broken by ice being let down as the water level dropped after a winter flood, Franklin Falls Reservoir, Franklin, New Hampshire (by L. Gatto).

directed against reservoir banks depending on bank slope, water level and ice conditions.

Field observations show that the water levels of many flood control reservoirs are lowered below the toes of the reservoirs' banks during the winter. This lowering would eliminate direct ice action on the bank and would reduce ice forces that may be applied against the shoreline because it bends and cracks the ice, which destroys its continuity (Rose, 1946). Some reservoir water levels are lowered to where ice is laid down onto the reservoir bottom (Fig. 3), and becomes immobile and ineffective in causing direct erosion. When the water level rises, if the ice has not melted, it can be lifted (possibly with sediment or vegetation entrained) and again moved by wind.

When winter floods rapidly raise a reservoir water level, the ice cover is also lifted, broken up, and made mobile. It can then erode the banks directly and damage bank vegetation (Fig. 4). If the damage is severe enough to kill the vegetation, it could eventually lead to increased bank instability because the root systems of the plants which tend to bind the sediment in the upper bank would decay, and the root reinforcement would be lost.

In reservoirs that are not substantially lowered during the winter and that have a complete or nearly complete ice cover, as spring progresses and temperatures rise, the ice initially melts along the shore, leaving a partial ice cover that may move with the wind. The mobile ice may gouge the reservoir bottom, plough the beach or shove and erode bank sediments, depending on the elevation of the water level. Ice could also be wind-driven up to and over a reservoir bank by strong winds. The distance that

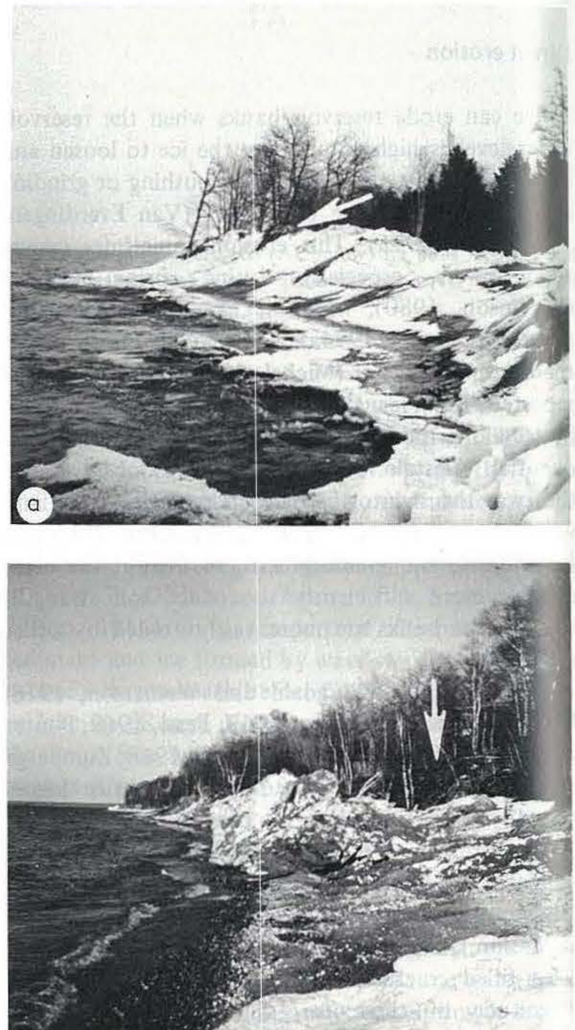

Fig. 5. Wind-driven ice, Whitefish Bay, Lake Superior, Michigan; (a) ice pushed up to and over the bank (top of bank at arrow), (b) note the sediment dislodged by the ice (top of bank at arrow) (by J. Wuebben).

ice will ride up depends on several factors: wind velocity and duration, amount of fetch, presence of a shore lead, water current drag, ice flexural strength and thickness, friction within the ice, between ice blocks and between ice and the overridden materials, freeboard, beach slope, amount of ice jamming and pile-up on the beach (Bruun and Johanneson, 1971; Bruun and Straumsnes, 1970; Croasdale et al., 1978; Kovacs, 1983; Kovacs and Sodhi, 1979; Tsang, 1975).

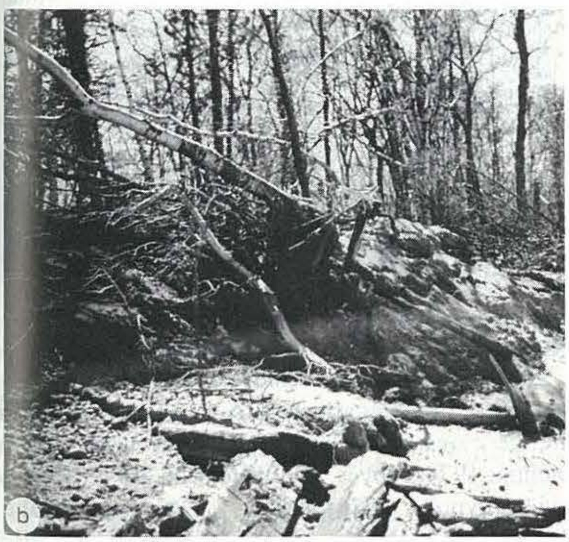

Fig. 6. Damage to trees (a) and bank (b) caused by ice ride-up, Whitefish Bay, Michigan (by J. Wuebben).

Observations made along Whitefish Bay in Lake Superior in Spring 1979 show that ice was driven by winds up to, and in some places over, banks (Fig. 5a) that are locally 5 m high. The erosion of and disruption to bank sediment and the damage to bank vegetation was extensive (Fig. 6). Ice has also been pushed over the banks and damaged backshore brush and trees along the Mackenzie River delta, Canada (Outhet, 1974), Knob Lake in Labrador, Canada (Jones, 1970) and many lakes in central Quebec and Labrador (Pyokari, 1981). If the water level of a reservoir were very low, however, it is unlikely that winds would be strong enough to drive an ice cover over the shore up to the banks.

Indirect erosion

If the water level of an ice-covered reservoir is not high enough for the ice to act directly on the reservoir bank, the ice may contribute to bank erosion indirectly. While the ice cover is mobile, it can push, scrape and remove beach and nearshore sediment (Hume and Schalk, 1976) (Fig. 7). This can help undermine a bank, which increases bank instability; a portion of the bank may eventually collapse. Ice that never directly erodes a bank can also scrape and shove sediment that has eroded from a bank and

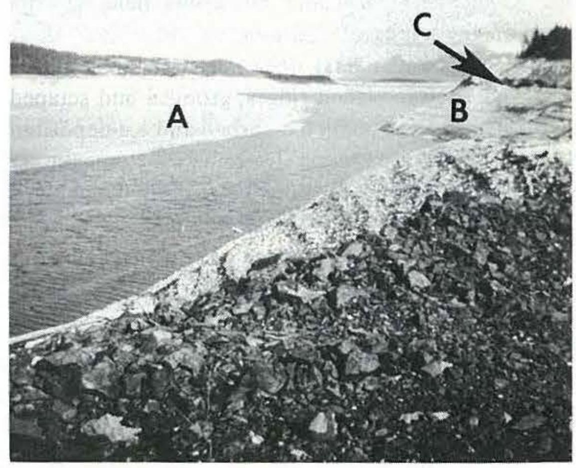

Fig. 7. Mobile ice (A) can grind and shove the reservoir bottom (B) as the water level rises to the base of the banks (C), Lake Koocanusa, Montana (by B. Brockett).

Fig. 8. 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, Orwell Reservoir, Minnesota (by L. Gatto).

accumulated along the bank toe. By removing this accumulation, water waves and currents can directly erode the bank toe after the ice has melted or moved away.

There are several reviews of how ice erodes and reshapes nearshore zones, shorelines and beaches (Alestalo and Haikio, 1979; Bryan and Marcus, 1972; Code, 1973; Mackay and Mackay, 1977; Reimnitz and Kempema, 1982) and numerous field descriptions of the types of features formed by ice along oceans, lakes and rivers: linear, arcuate, and cellular scars and basins: planed ridges; grooved and scraped surfaces; pit topography; ice-pushed and ice-deposited ridges (Fig. 8) or mounds (ice ramparts); ice-contact cusps; and ice-rafted sediments, including boulders, pebbles and ice-cemented blocks, boulder concentrations along the beach, boulder pavements and trails (Adams, 1977; Adams and Mathewson, 1976; Alestalo and Haikio, 1976, 1979; Barnes, 1982; Barnes et al., 1977; Brochwicz-Lewinski and Rudowski, 1976; Collinson, 1971; Davis et al., 1976; Dionne, 1969, 1974a,b, 1981; Dionne and Laverdiere, 1972; FENCO, 1975; Goebeler, 1972; Hult, 1971; Hume and Schalk, 1964; Kovacs and Sodhi, 1979; Lawson, 1972; Montagne, 1963; Nichols, 1953; Owens and McCann, 1970; Pessl, 1969; Rosen, 1978; Short and Wiseman, 1973; Taylor, 1978; Wagner, 1970; Ward, 1959; Weeks et al., 1983; Worsley, 1975; Zumberge and Wilson, 1952, 1953).

It is generally agreed that these ice-pushed features result from ice expansion or wind-driven ice (Montagne, 1963; Jones, 1970). Some investigators (Laskar and Strenzke, 1941; Jennings, 1958) feel that ice push due to ice expansion dominates along 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 (Hult, 1971; 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). Monfore (1952) described ice-push ridges along Eleven Mile Canyon Reservoir in central Colorado, and Panov (1956) described those along Tsimliansk Reservoir in the USSR. I found no other references describing ice-push features along reservoirs.

Many of the ice-scour features could form, especially in the Spring, along reservoir shores 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.

Field observations show that when an ice cover completely covers a reservoir, the compressive forces that form pressure ridges in the ice can also cause shore sediment to be thrusted where the pressure ridges intersect the shoreline (Fig. 9). It is clear that ice disrupts and erodes lake shorelines. When winds are strong enough or water levels 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 rafting can also remove beach or bank sediment that becomes attached to or incorporated into the ice cover or an ice foot (Barnes et al., 1982; Dionne, 1974a; Joyce, 1950; Hamelin, 1972; Knight and Dalrymple, 1976; Nielsen, 1979; Reimnitz and Bruder, 1972; Rosen, 1979). This could indirectly add to bank instability, but its importance in reservoirs is not documented. I found no references that

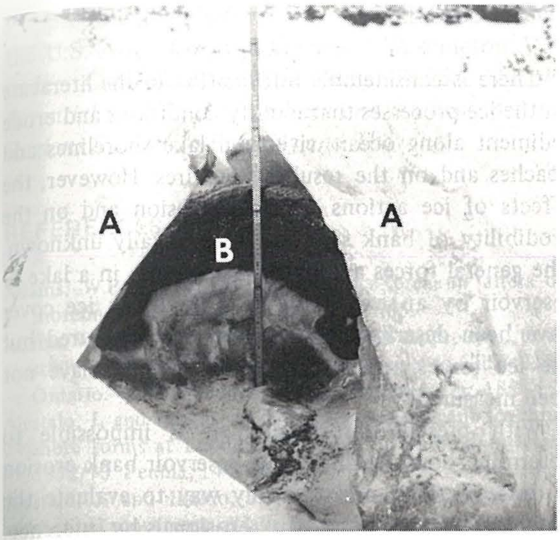

Fig. 9. Ice (A) and shore sediment (B) uplifted (about 60 cm) where an ice pressure ridge intersects the shoreline, Orwell Reservoir, Minnesota (by L. Gatto).

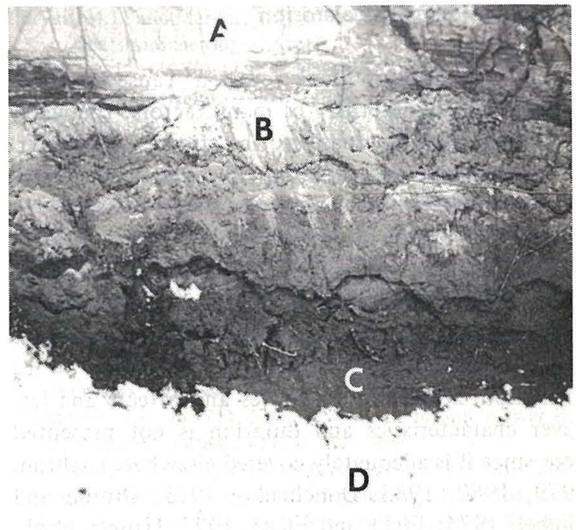

Fig. 10. Bank sediment (A) sliding (B) or flowing (C) onto snow-covered shorefast ice (D), Wilder Lake, Vermont (by L. Gatto).

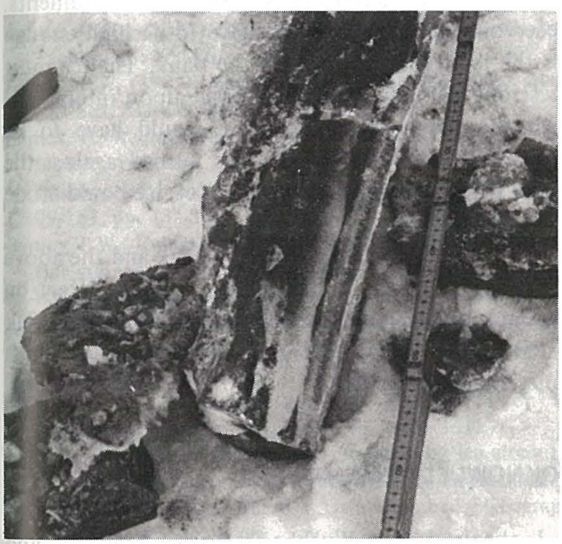

Fig. 11. Shorefast ice with beach sediment attached to and entrained, Orwell Reservoir, Minnesota (by D. Lawson).

Fig. 12. Sediment frozen to the bottom of ice laid down onto the reservoir bed, Lake Koocanusa, Montana (by B. Brockett).

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. 10), especially in the spring as the banks thaw. Also, when ice is attached to the shore (Fig. 11) or bank or laid down onto the reservoir bottom (Fig. 12), sediment can freeze to it. 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 became mobile.

Factors influencing ice erosion

The amount of bank erosion caused by ice depends on the interplay of many factors: the water levels and their fluctuations; the strength, characteristics, pressures and mobility of the ice; the degree of ice attachment to beach, nearshore or bank sediments; the extent to which bank, beach and nearshore sediments are frozen; and the shore configuration. The importance of water levels, ice pressures and mobility, and ice attachment to sediment have been discussed briefly. However, information on ice formation, structure, properties and effects and ice-cover characteristics and duration is not presented here since it is adequately covered elsewhere (Ashton, 1979, 1980, 1983; Donchenko, 1972; Drouin and Michel, 1974; Ficke and Ficke, 1977; Haugen et al., 1979; Korzhavin, 1962; Marshall, 1977; Michel, 1971, 1978; Timco and Frederking, 1982; Weeks and Assur, 1969). In addition, there are no published data relating these variables to bank erosion.

If the shoreline or bank sediment is frozen, ice effects can be minimal (Davis, 1973; Davis et al., 1976; Harper et al., 1978; McCann and Taylor, 1975; Owens and McCann, 1970) and normal beach and bank erosion processes are slowed or stopped. Along a straight reach of reservoir shoreline, ice erosion would likely be more evenly distributed, with no location being eroded more than another. Along an irregular reach, however, ice would be more likely to erode the banks on the promontories than along the bays, since ice in the bays tends to be more stable than that in the main part of a reservoir.

Along reservoir shores with gentle offshore slopes, it is more likely that ice could become attached to or gouge bottom sediment offshore or at the shoreline and never reach the banks. However, as previously mentioned, wind-blown ice can be driven over banks. As the water level drops in these areas, ice becomes grounded sooner than in areas with steep offshore slopes, so less ice pressure is directed to shorelines or banks. Also, along shorelines with steep offshore slopes, ice can advance to the shoreline or banks and erode them directly.

CONCLUSIONS

There is considerable information in the literature on the ice processes that modify conditions and erode sediment along ocean, river and lake shorelines and beaches and on the resulting features. However, the effects of ice actions on bank erosion and on the erodibility of bank sediment are virtually unknown. The general forces applied to a structure in a lake or reservoir by an expanding or wind-driven ice cover have been described and occasionally measured but the ice forces applied to reservoir banks have not been measured.

With present information, it is impossible to determine how much, if any, reservoir bank erosion is caused by ice and the only way to evaluate the potential for ice-caused bank erosion is by inference. As previously mentioned, the amount of bank erosion caused by ice would depend on the interplay of many factors: e.g. water level, ice characteristics and conditions, and characteristics of the bank sediments. Reservoir water level would have to be high enough for the ice to act directly on the bank. The ice must be strong enough to remain intact upon interaction with the bank. Bank sediment would have to be erodible at the time the ice was pushed against the bank. When these conditions are met, ice could erode bank sediment.

If the water level is below the bank and the above conditions are met, ice may have no direct effect on the bank but it could indirectly cause increased bank instability by disrupting the nearshore and beach zones along a reservoir.

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