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Ice Engineering

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

Considerations for Dam Removal in Ice-Affected Rivers

During the past several hundred years, many dams have been built in the United States to meet the power, water supply, flood control, and recreational needs of a variety of users. The National Research Council estimates that there are about 2.5 million dams in the United States, ranging from small farm pond dams to large hydropower dams (NRC 1992).

Recently, increased awareness of the ecological, recreational, economic, and safety issues associated with dams has led to a reevaluation of the continuing existence of a number of dams. American Rivers et al. (1999) identified 467 dam removals in 43 states since 1912, with most removals in the latter part of that century (92 in the 1980s and 177 in the 1990s). Remediation or mitigation of ecological impacts are cited as the primary cause for many recent dam removals. Dam safety concerns and the costs associated with rehabilitation to meet dam safety criteria or environmental requirements also lead to dam removal (ASCE 1997).

Ecologically based dam removal often seeks to reestablish the pre-dam hydraulic regime of the river, which in turn can significantly affect the timing and peak values of flood hydrographs. As a result, typical dam removal studies (e.g., ASCE 1997) address open-water impacts of dam removals.

Another critical aspect of dam removal is the potential for adverse affects that can result from uncontrolled releases of sediment if dam removal is undertaken without an adequate sediment management plan. This is particularly important in impoundments known to contain contaminated sediments or fluvial tailings. ASCE (1997) provides a process for formulating sediment management plans associated with dam removal. USACE (1983) also addresses sediment management following dam removal under open-water conditions.

In northern rivers, dam removal and ensuing changes in hydraulic regime cause changes to the ice regime that may have significant local impacts on ice formation, ice cover growth and progression, ice cover breakup, and the movement and jamming of ice. In several cases, dam removal has resulted in increased frequency and severity of downstream jams (Fig. 1). Furthermore, lowering of water levels in impoundments containing sediment deposits may result in more frequent or longer duration ice-induced scour and erosion of bed and bank material. This is particularly important in impoundments where contaminated sediments have been deposited during the lifetime of the dam.

Ice-related adverse effects associated with dam removal can be miti-

Figure 1. March 1968 ice jam on the Israel River at Lancaster, New Hampshire. Ice jams increased in frequency and duration here following the failure or removal of four dams on the river between 1936 and 1950.

Figure 2. The ice regime following dam removal can cause jams to form in places where they had not been previously observed. Shown here is a freezeup ice jam that formed on the Kennebec River, Augusta, Maine, in February 2000, following the removal of the Edwards Dam. Historical records indicate that jams occurred near here between 1794 and 1835, when the dam was constructed.

gated through ice control measures. An understanding of the ice regime and sediment geochemistry and morphology at an existing dam site is required prior to removal so that ice control and sediment stability measures can be included as part of a removal project where necessary. Thus, the removal of dams in northern rivers should not be undertaken without first studying potential impacts on the ice regime and ice-affected mobilization of sediments impounded behind dams (Fig. 2). This *Ice Engineering Information Exchange Bulletin* discusses the potential effects of dam removal on river ice regime and provides guidelines for use when considering dam removal in ice-affected rivers.

Background

The impoundment formed by a dam is generally characterized by relatively deeper, slower-moving water compared to conditions upstream from the impoundment or downstream from the dam. Ice covers tend to form more quickly in these slower-moving areas than in the more turbulent downstream and upstream reaches. The ice cover may form from thermal processes or from mechanical processes such as juxtaposition, which forms a single layer accumulation. Where velocities are higher, shoving may result in multiple-layer ice accumulations.

Once an ice cover forms, it can thicken because of thermal processes or by deposition of frazil or ice pieces beneath the ice cover. Frazil deposits under ice (sometimes called hanging dams) can become quite thick, decreasing flow area and increasing velocities beneath the ice. Frazil deposits are often located at the upstream end of an impoundment where the energy slope changes from steep to mild. These deposits may provide a natural impediment to the downstream movement of broken ice or ice runs later in the season, and can result in local scour.

Ice cover breakup can be caused by thermal processes (i.e., the cover melts and thins as a result of warming air and water temperatures) or mechanical processes. Thermal breakup is largely benign, although it can result in the movement of ice pieces that later jam. Mechanical breakup occurs when the mechanical forces on the ice cover become larger than the resisting forces. This usually results from increases in flow that are caused by a rapid snowmelt or precipitation combined with snowmelt. During mechanical breakup, the ice cover rapidly breaks into smaller pieces that are transported downstream until the transport capacity of the river is exceeded. This may occur because the moving ice rubble has reached an intact ice cover or other obstacle that resists movement, or can occur under favorable hydraulic or morphological conditions (e.g., decrease in energy slope, increase in channel depth or width).

Once a jam is initiated, incoming ice and flow build up to cause increased forces that can result in jam failure. Jam failure can be quite sudden, with observed sustained ice floe and water velocities of 5 m/s (16 ft/s) or more (Andres and Doyle 1984, Jasek 1997). These surges can cause significant erosion to bed and banks, resulting in high concentrations of suspended sediment. Or, the jam may remain in place as discharge drops, eventually freezing in place if temperatures are cold, or melting out if air and water temperatures remain warm. Because of their additional thickness and increased roughness, jams that freeze in place during midwinter can cause significant erosion to bed and banks compared to a normal ice cover.

Potential effects of dam removal in ice-covered rivers

Dam removal can affect the ice regime both upstream and downstream from the dam site. If the dam is located on a steep river, its removal may result in a steep, turbulent reach that produces frazil instead of the slower-moving impoundment that captured it. Thus, ice covers downstream are likely to be thicker as a result of incorporating the additional ice volume, either through juxtaposition, shoving, or deposition of frazil ice. Locations with thicker ice covers can become impediments to ice movement during breakup. Increasing the overall volume of ice also may result in thicker downstream jams, or in the formation of jams in areas that did not experience jams while the dam was in place (Fig. 2). Jams that might formerly have occurred at the upstream end of the impoundment because of loss of energy gradient could form instead at another location downstream.

Increased riverbed scour and erosion that will occur within the former impoundment under open water conditions because of increased near-bed velocity will be exacerbated by the presence of the ice cover. Moving or jammed ice will significantly increase scour within the former impoundment and at downstream locations where jams now form. Ice jam events can mobilize large amounts of sediment (Fig. 3).

It is possible for ice jam flooding to lower contaminant levels by depositing large amounts of cleaner sediments from scoured banks on the contaminated material, as long as clean sediments exist. However, ice jam flooding can also increase contamination when contaminated bed or bank soils are eroded and deposited elsewhere. If dams are removed and ice events increase in severity, ice jam events will "short circuit" the normal sediment-trapping capability of reservoirs and increase the release of contaminated sediments downstream. The only remedy for this is to completely remove sediment before dam removal or protect sediment from ice erosion under the new hydraulic regimes established after dam removal.

Some effects of dam removal on riverine ice regime can be mitigated using standard ice mitigation techniques, such as those suggested by Tuthill (1995) and Haehnel (1998). Monitoring of ice conditions while the dam is still in place is vital to determining its role in the ice regime and predicting potential impacts associated with dam removal. Historical records should be examined to obtain information on pre-dam conditions as well as current conditions. Where structural ice control methods are necessary, design and construction should be included as part of the dam removal plan. White and Moore (in prep) discuss potential impacts of dam removal on river ice regime and provide two case studies in which dam removal has required the later construction of ice control structures. Two other cases in which ice regime is important are also presented, one of which involves the movement of fluvial tailings during ice events.

Recommended studies for ice-affected rivers

ASCE (1997) provides guidelines for studies to be undertaken when considering removal of a dam. Their six-phase process includes an evaluation of flood hazards and the development of a sediment management plan. Data collection required to support this process is also presented. However, the guidelines do not address the potential impacts of dam removal on ice regime. In order to identify the likelihood of adverse effects occurring in ice-affected rivers because of dam removal, the following additional steps are recommended for ice-affected rivers:

1. Characterize the existing ice regime, including formation, growth, breakup, transport, and jamming in the reaches upstream and down-

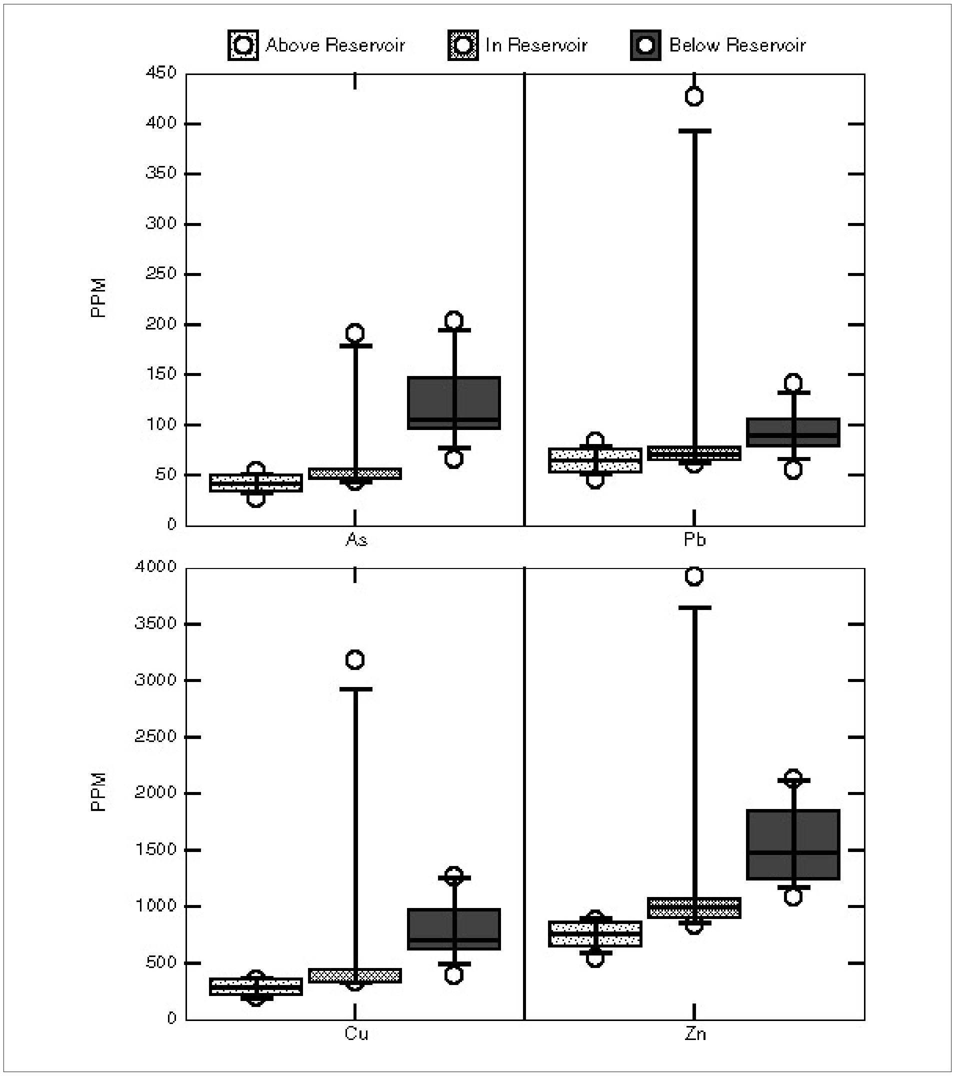

Figure 3. The erosion and scour of fluvial tailings can be dramatic during ice events. Here, metals concentrations measured in the Clark Fork River upstream and downstream from the Milltown Dam reservoir are shown following the ice jam event of February 1996. (After Moore and Landrigan 1999.)

stream from the dam. Information on local ice processes may be found in the CRREL Ice Jam Database (http://www.crrel.usace.army.mil/ierd/icejam/icejam.htm) or USGS records. At least one winter of ice monitoring should be performed.

2. Characterize the ice regime that existed prior to dam construction. This will involve a search of historic records. Again, USGS records and the CRREL Ice Jam Database may contain information useful in characterizing the historic ice regime.

3. Hydraulic modeling of the ice conditions should be performed if jams are known to occur near the dam, both with and without the dam in place, to determine whether dam removal will affect the hydraulic conditions leading to jam formation. If the modeling indicates that the jam location will change, or severity will increase, ice mitigation measures should be considered. Summaries of applicable techniques may be found in Tuthill (1995) and Haehnel (1998).

4. Sediment management alternatives that include riverbed or bank erosion or sediment stabilization should include hydraulic modeling of ice conditions to identify areas of ice-induced scour and erosion.

Conclusions

The decommissioning and removal of dams in order to improve aquatic habitat is becoming more frequent in the United States. However, two potential problem areas are largely being ignored: the potential for increased frequency and severity of ice jams downstream from these former dam sites because of changed hydraulic conditions, and, for northern rivers, the potential for increased movement of contaminated sediments from the former dam impoundments during the ice-covered period. The time to design ice control measures is before dam removal, so that mitigation costs can be included in the removal project cost-benefit analysis. Inclusion of the steps recommended above during the evaluation of dam removal in ice-affected rivers may decrease the likelihood of adverse impacts.

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This issue of Ice Engineering *was written by Kathleen D. White, Research Hydraulic Engineer, Ice Engineering Group, RS/GIS/Water Resources Branch, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Engineer Research and Development Center (ERDC).*

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Communications are welcomed. Write to CRREL, ATTN: Tim Pangburn (RS/GIS/WRB), 72 Lyme Road, Hanover, NH 03755-1290, or call 603-646-4296.