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Ice in Regulated Rivers and Reservoirs

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Abstract: Northern reservoirs, lakes, and rivers are often regulated for hydropower production, flood control, navigation, recreation, water supply, or a combination of these purposes. Regulation can be inter-annual, seasonal, short-term, or a combination of these depending upon the need to store or utilize water. Using dams, spillways, and other water control structures to regulate the flow and water level of rivers and reservoirs has several hydrological, economic, and ecological effects. Regulation alters river ice regimes by modifying the temporal and spatial characteristics of flow, water level, and thermal regimes in a watercourse. Higher discharge from reservoirs, which may include warmer water, during the winter season causes enlarged open water areas, increased production of frazil ice, and more frequent formation of anchor ice and hanging dams in downstream river reaches. Open water and weak ice cover areas in lakes and reservoirs may be expanded by regulation. Reservoir backwater or flow releases may create ice jams and associated flooding at sites where there were no such problems prior to regulation. Restoration of the river or stream by the removal of a water control structure and reservoir can eliminate some problems, but create new problems in areas where environmental or development conditions have changed. The effects of regulation on ice conditions have been studied in many countries. Reviewed in this paper are regulation-induced changes in river ice conditions, various impacts of ice formation on the generation of hydro-electric energy, and some ice-related considerations associated with dam removal and de-regulation

1. Introduction

River regulation is the act of controlling water levels or flow variability to meet human demands. Seventy-seven percent of the 139 largest river systems in the United States, Canada, Europe, and the countries of the former Soviet Union are strongly or moderately affected by regulation (Dynesius and Nilson, 1994). River regulation is also extensive in China (Miao et al., 2015). Many northern rivers and lakes subject to seasonal ice formation are regulated for hydropower production, flood control, navigation, recreation, water supply, or a combination of several purposes. Regulation occurs along both large and small northern rivers and lakes.

Flows and water levels can be altered by

- dams, hydropower projects, and other flow control structures,
- pumping, flow diversion, and other means of water extraction,
- changes to the channel and flood plain of a river or stream, and by
- construction of barriers to water flow onto a flood plain.

Regulation constructions differ in their layout, materials, structural design, and operation. Therefore, different constructions can have very different influences on upstream and downstream water levels and flow, particularly the magnitude, intensity, and duration of flows in the channel downstream. Dams and associated water control structures can attenuate the magnitude and timing of peak flow downstream, and create a physical barrier to ice movement. Reservoirs and regulated lakes provide a pond for sheet ice formation and an area for water storage and the deposition of sediment and ice.

Anthropogenic flow and water-level regulation of rivers and reservoirs have several hydrological, economic, and ecological effects. One of the most visible effects of flow regulation in northern countries is the change of ice conditions in rivers and reservoirs. Higher discharge in rivers during the winter season causes enlarged open water areas and increased production of frazil ice while the formation of anchor ice and hanging dams becomes more frequent (Figures 1 and 2). The thermal regime of a river is changed by released heat storage from reservoirs. The release of warm water from a reservoir together with the increased flow keeps the downstream channel open. In the upstream channel, the backwater caused by a reservoir may create freeze-up jams at sites where there were no such events prior to regulation. Moreover, open water and weak ice cover areas in lakes and reservoirs may be expanded by regulation.

The effects of regulation on ice conditions have been studied in many countries, especially in Canada, the United States, Russia, China, and the Northern European countries. The purpose of this paper is two-fold: to recognize the importance of the topic in northern countries, and to present some key points about ice in regulated river systems. In cold regions, regulation affects, and is affected by, ice formation, growth and breakup in multiple ways. This is discussed in this paper under three headings: ice at dams and water control structures, ice in reservoirs, and ice in regulated rivers. This is followed by a section on dam removal, which is a topic of increasing significance as many dams are no longer required and (or) have reached the end of their design life. The two sections before the concluding remarks highlight some of the effects of ice in regulated rivers on hydropower generation and ecology.

Figure 1. Frazil formation downstream of a generating station. (Photo: Manitoba Hydro)

Figure 2. Anchor ice formation caused by increased flow in a small, regulated river.
In small rivers increased amount of anchor ice and hanging dams are the typical effects of increased flow. (Photo: Pohjolan Voima Ltd.)

2. Ice at Dams and Water Control Structures

2.1 General

Some of the ice effects on dams and component / associated structures are listed in Table 1.

Table 1. Effects of Ice on Dam and Associated Components

Component	Ice Effect
Dams	Ice loads on dams and dam faces, staging/overtopping
Spillways	Frozen gates, ice loads on spillway gates, ice formation in spillway tunnels, ice buildup from spray, ice impact forces on gates
Trash Racks	Clogging by frazil or blockage by drifting ice
Intakes	Ice loads on gates, frozen gates

The ability to operate a spillway gate during the winter is critical for the safety of a dam or control structure. For some structures, winter operation of a spillway may not be typical, but maintaining the ability to operate the spillway may still be required in the case of an emergency or to pass a mid-winter flood.

Operation of a spillway in the winter has many challenges. Gates that are exposed to the atmosphere will typically freeze to the gate guides. Often the force to free a frozen gate exceeds the capacity of the gate hoisting equipment (Gebre at al., 2013). To allow for winter operation, the gates will need to be equipped with gate/guide heaters or be steamed free prior to operation. During a winter spill event, mist or spray may freeze to surrounding structural, mechanical and electrical infrastructure causing structural and operational concerns. (Figures 3 and 4).

Consideration of ice impact forces on spillway gates is important during winter/spring operation of a spillway. Large ice pieces from a reservoir or forebay impacting a partially open gate or ice buffeting from return currents and eddies on the downstream gate face may cause significant damage. Static loads on spillway gates also need to be considered. Figure 5 shows crews cutting slots in the ice cover immediately upstream of a spillway to minimize static loads on the gates.

Frazil ice control methods commonly used at hydroelectric power plants on small, steep rivers in Hokkido, Japan, include (a) hydraulic control such as ice booms, ice fences, weirs, air bubblers, and submerged mixers, (b) supply of warm water, (c) mechanical removal, and (d) chemical coatings (Mineta et al., 2006). When using these control methods, it is necessary to determine the installation locations and sizes of control works, taking into consideration the severity of the frazil ice problem.

Figure 3. Buildup of several metres of ice on a deck from the spray of a spillway operated during the winter. (Photo: Manitoba Hydro)

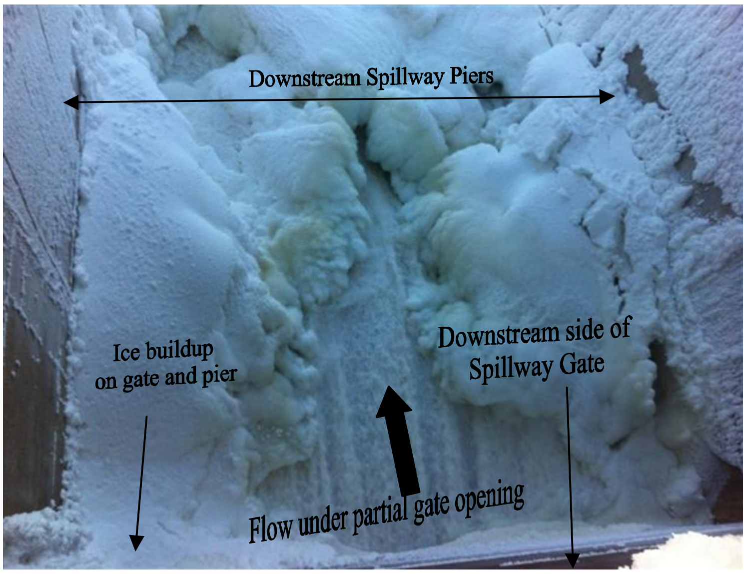

Figure 4. Looking down at ice buildup on downstream spillway piers and gate, temporarily rendering the spillway gate inoperable. (Photo: Manitoba Hydro)

Figure 5. Cutting slots in the ice upstream of a spillway to minimize static ice loads on spillway gates. (Photo: Manitoba Hydro)

2.2 Ice Loads

Dams in cold regions are designed taking into account static/thermal and dynamic ice loads. These loads are traditionally computed using empirical formulae as a function of the maximum ice thickness in the reservoir (Gebre et al., 2014). Ice loading on structures has been the subject of many publications. Riska (2014) states that ice action against structures can be considered in terms of ice load and strength calculations based on ice contact with a structure, and in terms of the process of ice failures against structures. Ice loading can be due to the static loads from ice sheets in contact with structures or due to dynamic loads caused by moving ice sheets. Static forces result from thermal expansion or contraction of an intact ice sheet or an applied steady force. Dynamic forces result from the drag forces on floating ice caused by wind, current, and streamflow. Dynamic forces are controlled by mechanical properties of ice with respect to possible crushing, splitting, shearing, and bending caused by ice-structure interaction. Physical properties of ice such as grain structure, density, and temperature and mechanical properties of ice such as ice strength, modulus of elasticity, friction, and adhesion are described in a wide body of literature (Frederking et al., 2014).

The size and shape of the structure, the ice conditions, and environmental driving forces interact to create differing scenarios defining ice forces (Frederking et al., 2014). For vertical or steep upstream faces of dams, failure usually occurs by crushing at the contact surfaces (USACE, 1999).

Most dam reservoirs in Canada are covered with ice sheets for significant periods each year. Ice loads generated by the ice sheet or moving ice should be considered during analyses of dam stability, and the design of dam appurtenances such as gates and spillways. Although dams have been built and operated for many years in northern climates, the ice loads exerted on them are still not fully understood (Comfort et al., 2003).

Considering the force that ice can exert on a structure is a function of structure width, ice thickness, and ice pressure, the global ice force, F_g, can be determined as follows:

$$F_g = p\,h\,w \qquad [1]$$

where p = the global ice pressure = f (ice strength, ice thickness, structure width),
h = ice thickness, and
w = structure width.

Attempts to evaluate global ice pressure based on measurements, physical model tests, numerical modelling, and judgment have resulted in empirical equations found in national and international standards for hydraulic structures (Frederking et al., 2014). Several of these equations involve parameters of ice strength and aspect ratio (i.e. ice thickness to structure width ratio).

A safe, realistic, and practical design value for ice thrust against linear structures is required. The Canadian Dam Association has recommended a value of 150 kN/m, but in practice lower design values of ice thrust forces (~ 100 kN/m) have been chosen for smaller dams (Morse et al., 2009). No known dam has failed due to static ice forces on the dam face (Morse et al., 2009).

The crystallographic structure of ice results in spatial configurations of the ice molecule atoms according to preferential axes and planes that cause highly anisotropic behaviour, ranging from ductile to brittle within a variable transition zone, depending on the strain rate and on whether the specimen is under compression or tension (Bouaanani et al., 2004).

The mechanical properties of a reservoir ice cover are variable and complex, and difficult to assess at its dynamic interface with the dam and reservoir boundaries (Bouaanani et al., 2004). To consider the seismic response of concrete gravity dams during winter months to seismic loads, Bouaanani et al. (2004) developed a two-dimensional analytical approach, which takes into account the effects of an ice cover, the influence of water compressibility, and reservoir bottom absorption. They propose a new boundary condition along the ice cover–reservoir interface and assume both concrete and ice have linear, isotropic, and elastic behaviour.

Comfort et al. (2003) describes a nine-year investigation of the magnitude and distribution of ice loads along the face of a dam. The highest ice loads were produced by a combination of ice temperature and water level changes, with water level changes being an important ice load generating mechanism depending upon how the dam is operated (Comfort et al., 2003). The main factors controlling loads induced by water level changes include the amplitude and duration of the water level change, with variations of water level about a mean level producing higher loads than a mean water level increase or reduction or a one-time early-winter drop in water level. Ice processes in a reservoir near a dam face subject to water fluctuations are complex resulting in spatial and temporal distributions of ice forces against the dam as the ice-structure connectivity changes (Morse et al., 2009). The main factors controlling thermal loading were overall ice thickness, ice temperature changes over the full ice thickness, the thermal insulating effects of snow cover, and load duration. Equations developed for predicting ice loads work well for thermal loads, but are less accurate for loads produced by a combination of water level and ice temperature changes.

2.3 Dam Failure

Dams and water control structure failures are more likely to occur during peak flow conditions that often occur after the ice season. If dam failure occurs when an ice cover exists downstream, the ice cover is likely to break up with the passage of the surge and add to the destructive force of the ice-water mix downstream.

Tchamen et al. (2007) state the presence of ice has an important impact on river flow characteristics and modify the behaviour of the propagation of a surge wave (as well as other important hydraulic parameters) following a dam break. A dam break may create a surge of water that lifts and detaches the ice sheet, which breaks into large sheets that move downstream breaking as it interacts with the river banks and instream impediments to their movement. As the ice cover fragments and moves downstream with the flood wave, much of the ice may become stranded on low-lying flood plains and terraces along a river with the ice remaining in the channel creating a potential for sequential ice jamming along the downstream river reach. The interaction of ice with fast moving dam-break waves is complex and still involves considerable uncertainties with respect to dam-break analyses.

Basic dam-break analysis requires simulation of reservoir drawdown after dam failure, estimation of dam failure characteristics and evolution, and modelling of the flood wave through the valley downstream. Of particular importance with respect to risk assessment is the effects on water levels downstream of the dam. The presence of ice in northern rivers during the winter season should be included in the analysis but the presence of ice is often ignored in dam-break analyses (Tchamen et al., 2007). In dam-break analyses, river conditions (flows, ice cover) during the winter months may be used as initial conditions and mechanical ice breakup assumed as the flood wave propagates downstream (Tchamen et al., 2007).

Existing models for dam break, hydrodynamic, and ice jam hydraulics could be used sequentially and perhaps in an iterative process that leads to a reasonable estimation of the risk of flooding and ice damage to downstream structures. Reiter and Huokuna (1986) developed ICEDAMBRK for dam-break analysis on a river with an ice cover, by using the modified DAMBRK model (NWS unsteady hydrodynamics model). The location and thickness of ice jams were input manually to the model (Tchamen et al., 2007; Reiter and Huokuna, 1986). Nzokou et al. (2011) coupled a river-ice and a hydrodynamic numerical model to develop the model HYDROBEAM, which can be used to find a simultaneous solution to both flow and ice cover models at each time step using the Galerkin finite element method (FEM) and an iterative computation process. HYDROBEAM's performance was found to be adequate for the simulation of rivers with open-channel flow, passive (flexible) ice covers, and for stiff ice covers that respond as a beam on an elastic foundation (Nzokou et al., 2011).

3. Ice in Reservoirs

3.1 Ice cover conditions in reservoirs

River flow regulation all over the world has given rise to many reservoirs, which change the regime of a river and influence its ecosystem (Dolgopolova and Speranskaya, 2006). In larger hydropower developments, there are usually several reservoirs. These are often based on natural lakes, but they may also be artificial lakes formed by damming of rivers. Reservoir outflow is controlled by technical structures. The height of regulation of a reservoir may vary considerably. In some cases, the water level variation in a reservoir does not differ much from the natural variation and it is then possible to use the term “regulated lake” instead of reservoir. In this context, the word reservoir may also mean regulated lake.

The freeze-up of a reservoir will be delayed compared to that of an unregulated lake, due to increased depth and surface area. Where changes in depth and area are large, the delay may be considerable. Ice sheets form quicker on reservoirs than rivers due to the low surface flow velocity, unless formation of a stable ice sheet is hampered by wind-induced wave action (Rossinsky and Lubomirova, 1975). Once the reservoir is frozen over, the development of the ice cover on the deeper parts will be less affected by regulation throughout the winter. As the water level of a reservoir decreases, the ice cover will ground along the shore and on shallow areas (Figure 6), resulting in the formation of cracks, especially where the terrain is steep or uneven. The cracks may be covered by snow bridges, and thus represent a hazard to people and animals. Due to fracturing along the temporary shoreline, there will be more water on the ice than before regulation. If the reservoir water level is increasing during the ice-covered period, an open lead may form along the shoreline. Such leads tend to form thin thermally grown ice covers that are often covered with snow and hazardous to cross. Access to the main reservoir ice cover can be difficult, gentle and smooth areas where the ice is less affected by the regulation usually exist. Short-term regulation, which leads to rapid changes of the water level, aggravates ice conditions and the ice cover may be inaccessible for long periods of time.

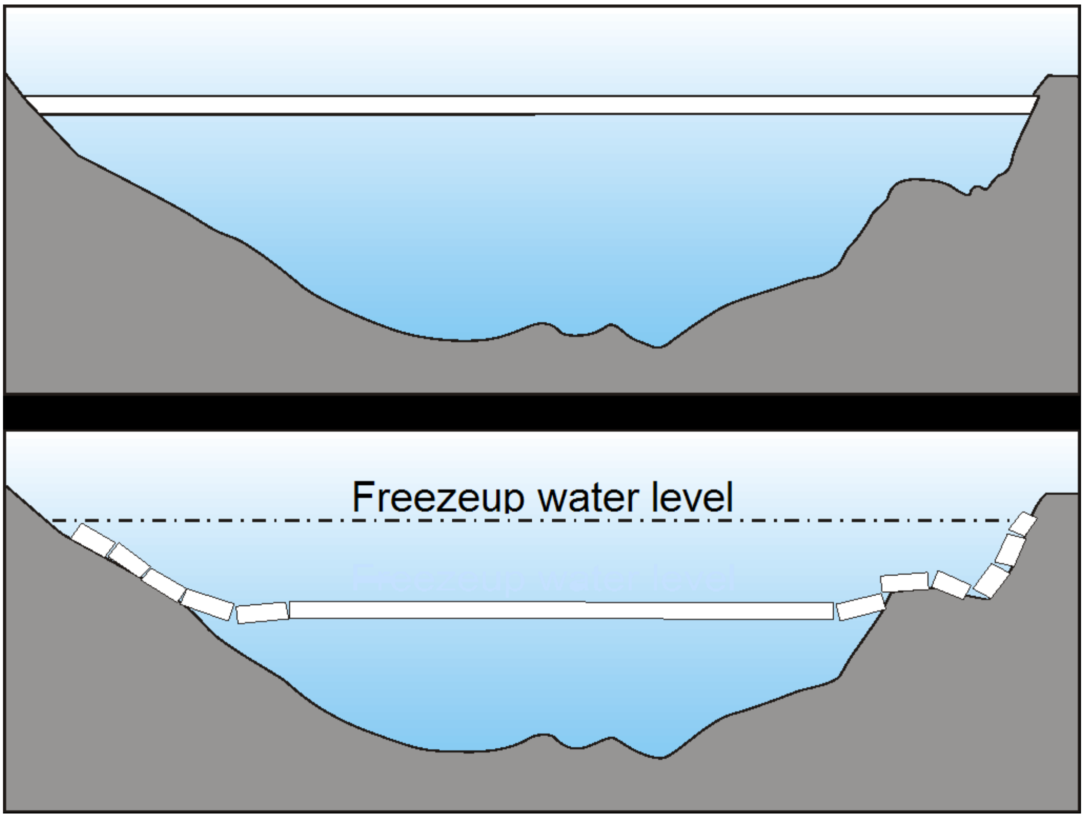

Figure 6. The ice cover in a reservoir will ground along the shore and on shallow areas when the water level decreases. There may be cracks in the ice cover. From Asvall (2010).

Reservoir water temperature increases with depth in winter, as it does in unregulated lakes. However, in reservoirs there may be local temperature variations at the sites of inflow and outflow. Generally, the water temperature will be very close to 0 ºC at the interface between the ice and water, and increase to between 1 and 4 º C in deeper waters. This range varies with weather conditions, from place to place and from year to year, but there are normally small variations during the same winter at the same place. Weather conditions, especially wind speed, and air temperature before freeze-up, influence water temperature variations from year to year.

Water parcels from surface and deeper layers mix when passing through relatively narrow areas where the water velocity and turbulence increases, in the same way as in natural lakes. This effect is magnified in regulated reservoirs owing to larger through-flow and thus higher water velocity. As the water level in the reservoir decreases, it may create significant currents in new locations. These effects weaken the ice locally and result in new open leads (Figure 7).

Tuo et al. (2014) report on 2013-2014 temperature and ice conditions in Fengman Reservoir, upstream of the 91.7 m high Fengman hydropower station on the Second Songhua River, China. The observed data showed that heat distribution in the river caused temporal and spatial variations in ice cover formation, growth, and decay. The observations revealed longitudinal differences in water temperature that resulted in a variation of freeze-up dates along the 153-km long reservoir. Inversion of the water temperature distribution under the ice cover, formation and breakup of ice from upstream to downstream, spatial variations of ice thickness in the reservoir with the thinner ice in the middle of the reservoir, and a relatively constant outflow temperature were also observed (Tuo et al., 2014).

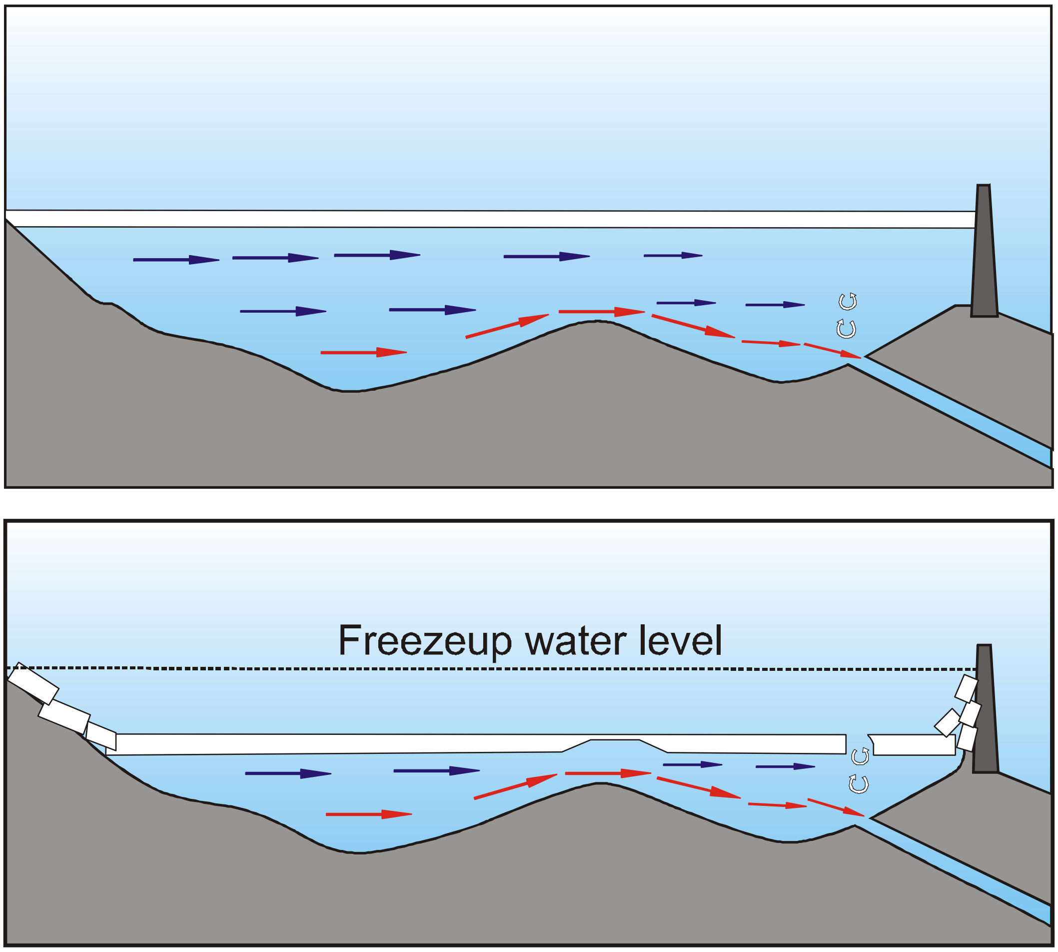

Figure 7. In reservoirs there are often open areas or weak ice at inlets, outlets, and straits. Red and blue arrows indicate warmer and colder water respectively. From Asvall (2010)

The temperature of the water being released from a reservoir increases with increasing depth of the intake, and may decline somewhat as the water level decreases throughout the winter and the depth of the intake is reduced. The weather conditions at the time of freeze-up may also play an important role. If the days after the initial turnover are cold and windy, water is cooled down deeper due to more effective mixing of the water masses.

The ice cover may weaken at the locations of intakes and outlets of tunnels and power stations, relative to its pre-regulation strength. The size of open water areas depend on discharge, depth of outlets and intakes, local conditions and weather conditions. It is important to be aware that intakes of tunnels can be located anywhere in the reservoir, and rarely at natural river mouths where the ice cover is normally weakened on unregulated lakes. Sometimes intakes and outlets are located at greater depths, away from the shore. Eddying currents that form near intakes and tunnel outlets may swirl warmer water from deeper layers to the surface and weaken the ice or even create open leads a good distance from shore, where one would not normally expect them (Figure 7).

Ice conditions on reservoirs depend on the discharge and temperature of the winter inflow as well as on water temperature and depth conditions in the reservoir. In most cases the winter flow through reservoirs will increase with regulation, but in some cases it may be reduced. The temperature of the inflow water is a key factor in ice cover conditions. If the inflow comes from a river, the winter temperature will normally be close to 0°C. Higher temperatures will be encountered in outflow from a deep intake from an upstream reservoir or an upstream power plant.

Shen and Cheng (1984) present a heat balance equation for the bottom of an ice cover.

$$q_{wi} = k_i \frac{\partial T_i}{\partial z} - \rho_i L_i \frac{\partial h}{\partial t} \qquad [2]$$

where q_{wi} = the heat influx from water to ice,
k_i, p_i and T_i = conductivity, density, and temperature of the ice, respectively,
Li = the latent heat of ice melting, and
($\delta h/\delta t$) = the rate of ice thickness variation.

The heat flux of water to ice can be determined by considering the conductivity, density, temperature, flow velocity, specific heat of water, and the heat transfer coefficient between water and ice. Based on one year of observations along Fengman reservoir, Tuo et al. (2014) determined the heat flux from the water to the undersurface of the ice to be 8.5 W/m^2.

3.2 Effects of "cold" and “warm” water inflows

Asvall (1974) describes the effect of cold and warm water inflow on reservoir ice conditions. She defines the temperature of cold water to be 0°C – 0.2°C and warm water to be greater than 0.2°C. If the intake is located in deep water, the cold inflow water will mix with the warmer water of the deeper layers. Because of that, an ice-free zone may form at the intake area. If the intake area is shallow and more like an extension of the river, there is no available warmer water to stir up and the area will soon be ice-covered. In both deep and shallow reservoirs, the cold layer will increase in thickness as the winter progresses. A cold surface layer of moderate thickness can lead to earlier freeze-up, especially in cold weather with little or no wind. A thin cold layer will soon be mixed with underlying warmer water and prevent ice formation.

Inflow of "warm” water occurs when water flows directly from another reservoir, through tunnels and power stations. The influence on the ice cover is governed by the density difference between cold (lighter) and warm (heavier) water. The influence differs between deep and shallow reservoirs.

In deep reservoirs, warm inflow with considerable velocity mixes with somewhat colder reservoir water in the inlet area. The energy is transferred to a larger volume of water and flows through the rest of the reservoir in a restricted layer of low speed and fairly uniform temperature, under a thin and cold surface layer that is practically at rest beneath the ice. This was concluded from temperature measurements and observations of ice conditions presented by Devik (1964). The slow moving water retains its temperature, almost unchanged until the end of the reservoir, without noticeable influence on the ice. In narrow straits and shallow areas, however, "warm" water will be forced to the surface because the flow velocity increases. In the moving layer, the temperature increases gradually with depth. Large water volumes of relatively high temperature can therefore flow through the reservoir without significantly affecting ice conditions. Studies show that this occurs in several Norwegian reservoirs, including Norefjord (Figure 8).

Generally, the inlet area is more turbulent than the outlet area. Therefore, the ice conditions are often more influenced by the flow at the inlet than at the outlet. Nevertheless, the ice-free area near the outlet area will also increase with significant quantities of “warm” water flowing through the reservoir.

In shallow and medium-depth reservoirs with a substantial inflow of "warm" water, large quantities of water will be replaced during the winter. Flow of "warm" water in shallow reservoirs has a significant influence on ice conditions, delaying or entirely preventing ice formation on all or part of the reservoir.

Practically all energy from solar radiation in the spring is spent initially to melt the snow on the ice cover of a reservoir (Dolgopolova and Speranskaya, 2006). Once the snow has melted, the solar radiation penetrates through the ice, and warms the upper layer of water, thereby creating a source of heat at the undersurface of the ice cover. Generally, ice breakage on the water reservoirs occurs later than that on the river, with thermal processes and inundation factors in the disappearance of the ice cover (Rossinsky and Lubomirova, 1975).

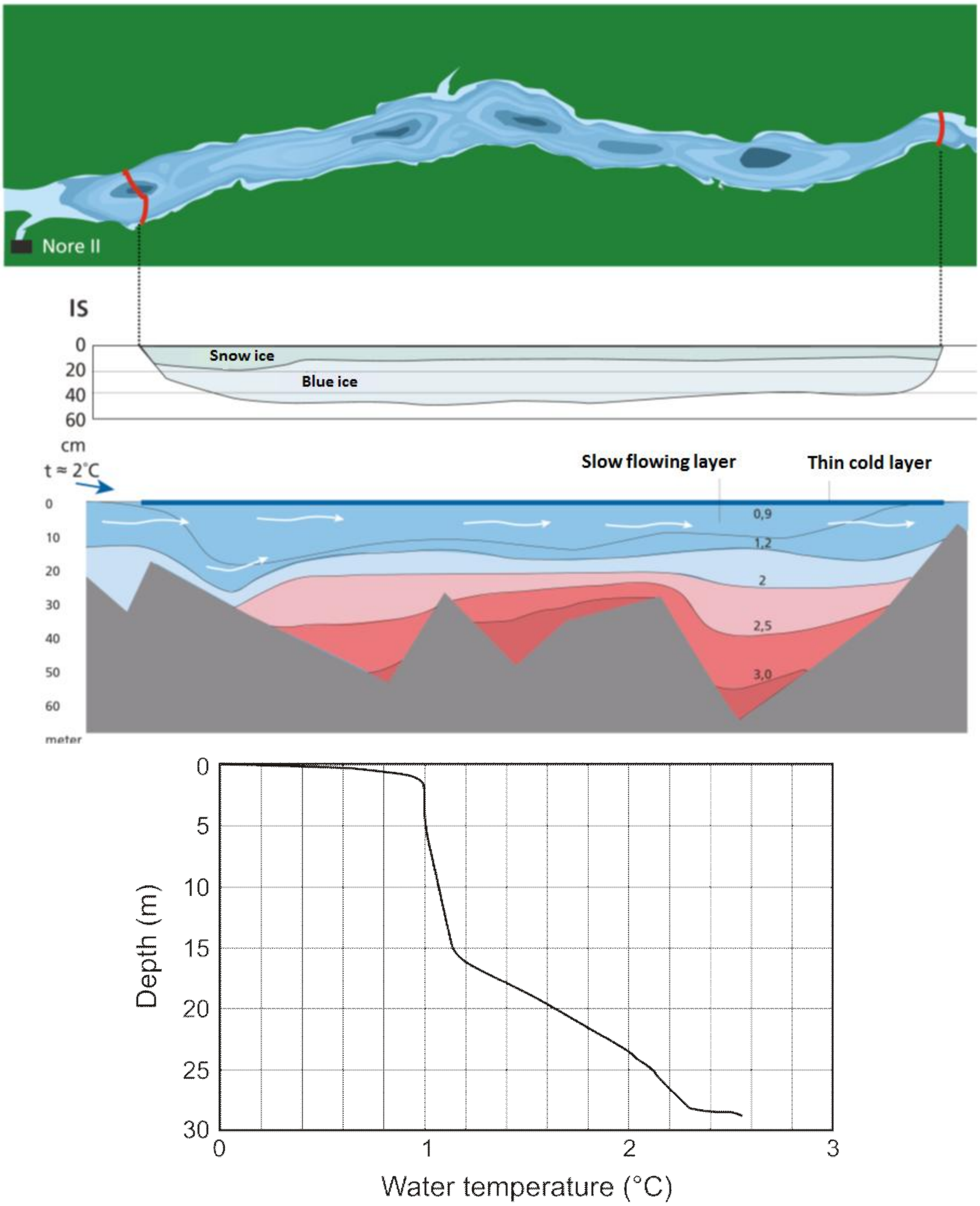

Figure 8. Water temperature conditions of increased flow of "warm" water in Norefjord River (Devik, 1964; Asvall and Roen, 1974; Asvall, 2010). Water depth, ice thickness and water temperature conditions at the flow of 60 m^3/s water at a temperature of 2 °C. The "warm" inflow mixes with colder lake water at the inlet and flows slowly through the lake (marked with the blue) under a thin layer of colder water (shown in dark blue). To the left is an average temperature in Norefjord, March 1956.

4. Ice in Regulated Rivers

4.1 General

Regulation-induced changes in river ice conditions are reviewed in this section. They generally derive from modifications to the discharge hydrograph and the water temperature regime. However, far downstream from a reservoir where water attains normal winter temperatures, changes in ice conditions are solely caused by the modified discharge hydrograph.

4.2 Effects of the modified discharge hydrograph

Regulation alters river ice regimes (Starosolszky, 1990; Wigle et al., 1990; Majewski, 1996; Xiaoqing et al., 1996; Difang et al., 1996; Sujuan and Zhanting, 1996; Sujuan et al., 2002; Donchenko 1972; Rossinsky, 1975) by influencing both flow distribution and water level and can be categorized as inter-annual, seasonal, short-term or a combination of these. Inter-annual regulation stores surplus water during wetter years and releases it during drier years. This type of regulation requires a relatively large reservoir compared to the sub-basin area. Seasonal regulation, especially for hydropower production in northern regions, stores water during the high inflow season, to be used for electricity generation during the winter, when the inflow is low but the energy demand high. Both inter-annual and seasonal regulation reduces flow extremes, creating less variable annual flow regimes.

Winter discharge and flow velocity in a river may be strongly modified by regulation. This change affects the freeze-up process, which is known to depend on the magnitude of the prevailing velocities.

Most instances of river regulation are for the purpose of hydropower production. As noted earlier, the demand for energy is normally high during freeze-up and the regulated discharge is often much higher than the corresponding natural discharge. This may result in: (a) enhanced open water areas and frazil ice generation; (b) formation of thick ice covers instead of sheet ice covers that form thermally or by juxtaposition; and (c) more frequent occurrences of anchor ice and hanging dams. The higher discharge during freeze-up will delay the ice formation, and may cause ice runs requiring the ice formation to start over.

Less frequently, the river winter flow may be reduced by regulation. This happens especially at locations where the main flow is diverted to the power plant via a canal or a tunnel. Normally, the reduced flow does not cause any special ice problems. However, at locations where the river is wide and shallow, a significant reduction in flow may cause formation of aufeis.

An example of how regulation alters the seasonal distribution of flow is presented in Figure 9. The figure shows the pre-regulated (historical), regulated and naturalized daily discharge values for Peace River just downstream of the Williston Reservoir (Peters and Prowse, 2001). The Peace is a Canadian river that originates in British Columbia but for the greater portion of its length flows through Alberta. The reservoir is large compared to the basin area and the outflow from the reservoir is almost constant during the whole year. Further downstream from the reservoir, the effect of regulation on the flow distribution is less pronounced, mainly due to flows from unregulated tributaries (Figure 10).

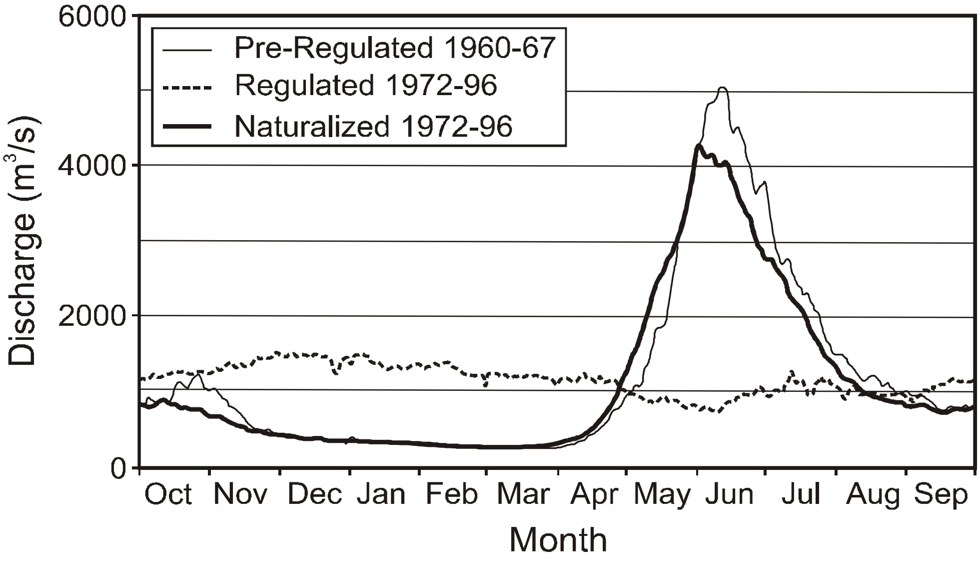

Figure 9. The pre-regulated, regulated, and naturalized daily discharge values for the Peace River at Hudson Hope just downstream of the Williston Reservoir (Peters and Prowse, 2001).

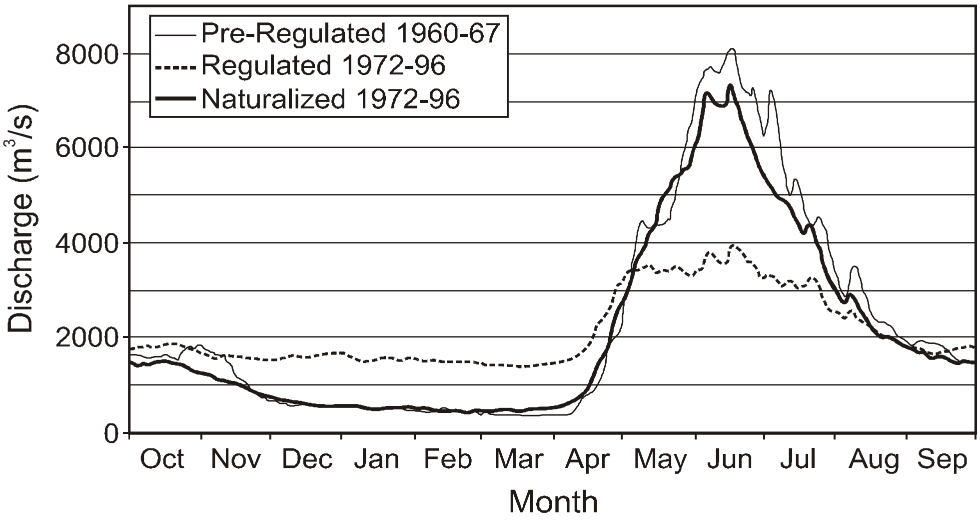

Figure 10. Pre-regulated, regulated, and naturalized daily discharge values for the Peace River at Peace Point located about 1150 km downstream from the Williston Reservoir (Peters and Prowse, 2001).

The regulation of discharge on the Peace River has altered the freeze-up regime downstream of the Williston Reservoir. The changes essentially result from the near three-fold increase in freeze-up flows, an increase in water temperature from the reservoir, and an increase in daily discharge fluctuations.

Prior to regulation, ice cover formation was initiated at several locations along the river (Acres, 1980). At the Town of Peace River, which is located some 410 km downstream from the Williston Reservoir, a juxtaposed ice cover was generally formed in late November or early December and resulted in approximately 1 m of staging. After regulation, a much thicker cover generally initiates at a single location and progresses upstream, delaying the formation of the ice cover at the Town of Peace by at a period ranging from 1 week to 2 months (Andres and Van der Vinne, 1994). As this cover progresses through the Town of Peace River, water levels can stage up to 3 m.

Carr et al. (2014) discuss the effects of winter flow release on the potential for ice formation, ice jamming, and snow-slush blockage in the channel of Willow Creek and flood diversion channel downstream of Ririe dam and reservoir, Idaho, USA. The initial flow release wave that lifts and transports from the stream bed resulting in ice formation in the channel, and ice formation in the floodway channel (which starts approx. 23 km downstream of the dam) were found to be critical periods for increased flood risk (Carr et al., 2014). The temperature of the release water determines if it melts the snow or aids in ice formation. The locations and rates of ice formation in the floodway (flood diversion channel) depend upon the release of water from Ririe Dam, the meteorological conditions, and the flow release rate (Carr et al., 2014).

4.3 Effects of reservoir heat storage on thermal regimes of rivers

The effect of a reservoir on the thermal regime of a river is also an important consequence of regulation. Warm outflow from a reservoir together with increased discharge keeps the river open for a considerable distance downstream (Figure 11). Parts of a river, which prior to regulation, were ice covered may stay open for the whole winter. The length of the open area depends on the discharge and temperature of the outflow and on local conditions.

The temperature of the water being released from a reservoir depends on the depth and size of the reservoir, the discharge, and temperature of the inflow, and the design of the withdrawal structure. In winter, the temperature of the outflowing water will be lower if it is drawn from a higher elevation. In some cases, a power station may be equipped with several intakes which are located at different heights. This makes it possible to use a higher intake, at least during part of the winter, to reduce the temperature of the outflow relative to that from a deeper intake (Asvall, 2007).

Figure 11. Warm water flowing from a reservoir keeps the downstream river open through the whole winter. View looking downstream. The canal downstream from the power station is located on the left. (Photo: Kemijoki Ltd.)

Maheu et al. (2014) found that storage dams and run-of-the-river dams had, respectively, significant and insignificant effects on the thermal regime of small rivers in eastern Canada. The storage dams modified the magnitude and diel variability of water temperatures (Maheu et al., 2014).

Ashton (1986, 2013) presents an equation for the estimation of the temperature response of a river as presented below:

$$\frac{T_w - T_a}{T_{w,0} - T_a} = e^{\frac{-h_{wa} L}{\rho C_p U D}} \qquad [3]$$

Where $T_{w,0}$ = temperature of release water (^{o}C),
T_w = temperature of water at distance L downstream from a reservoir (^{o}C),
T_a = air temperature (^{o}C),
h_{wa} = heat transfer coefficient between water surface and air (W/m^{2}°C),
ρ = fluid density (1000 kg/m^{3}),
Cp = specifc heat of water (4186 J/ kg-^{o}C),
D = flow depth (m),
U = mean flow velocity (m/s), and
L = distance along river, measured from the downstream end of a reservoir (m).

The downstream length of the 0 °C isotherm, L_0 (m), can be determined as follows (Ashton, 1986, 2013):

$$L_0 = \frac{-\rho\, C_p\, U\, D}{h_{wa}} \left[\ln \left(\frac{-T_a}{T_{w,0} - T_a} \right) \right] \qquad [4]$$

Underlying assumptions are complete vertical mixing of temperature in the river and heat transfer from the open water surface to the air is related directly to the difference in air and water temperatures. The possible formation of moving skim ice on the water surface will decrease the cooling of water and it is not taken into account. T_a is also assumed to be constant in time and space but in reality will change.

The heat transfer coefficient, h_{wa}, depends strongly on the wind speed and this has to be taken into account when Equations 3 and 4 are used. According to Ashton (2013) h_{wa} for a typical wind speed (4.4 to 6 m/s at the 30 m level) is about 20 W/m^2°C. By using this value for h_{wa} and assuming $T_{w,0}$ = 2 °C, U = 1 m/s, D = 2 m and T_a = -20 °C, from equation 4, we obtain the location of the 0 °C isotherm to be about 42 km downstream from the reservoir.

These equations can only be used for quick estimates of the downstream water temperature or the distance to the 0°C isotherm. For more accurate predictions, one would need to use a numerical model.

4.4 Ice Jamming in Regulated Rivers

4.4.1. River ice jams: impacts and mitigation

Ice jams are blockages to flow that cause an increase in water levels and can result in flooding and associated damages. Flood damages may include: (a) direct damage to infrastructure or property; (b) indirect damages such as the costs of emergency measures, transportation delays, and loss of workforce hours; and (c) intangibles such as stress, dislocation, and loss-of-life. Ice-related flooding is therefore a public safety issue. Ice jams can cause damage to or loss of bridges by undermining of bridge piers or by uplifting or pushing a bridge's superstructure (deck) off its supports. In addition, ice jams can gouge river banks, scour river beds, and affect aquatic ecosystems and species populations. Upon release of an ice jam, water and ice may move downstream at very high velocity, potentially impacting downstream structures and endangering nearby residents who have very little warning of the advancing wave. The effects of ice jams are discussed in several publications, including Ashton (1986) and Gerard and Davar (1995).

Ice jams can form during freeze-up and breakup; the latter kind typically occurs in the spring but can also occur in mid-winter as a result of a winter thaw (Beltaos et al., 2003). Other factors being equal, the higher the discharge, the higher will be the water levels caused by an ice jam (provided of course that the discharge is so high as to cause the jam to release). In unregulated rivers, flow is higher at breakup than at freeze-up; therefore, breakup jamming is normally the most severe.

Burrell (1995) divides ice-jam mitigation into three categories:

i. ice-jam prevention - preventive measures undertaken to eliminate or reduce the likelihood of a damaging ice-jam event from occurring,
ii. flood-damage-reduction - precautionary measures undertaken to reduce the potential for flood damages, and
iii. ice jam breaking and removal - remedial measures undertaken to alleviate flooding or other problems once an ice jam has formed.

Burrell (1995) thus relates the prevention of the damages associated with ice jams to the broad field of flood-damage-reduction, therefore, highlighting that the reduction of ice-related flood damages may not only involve measures to control ice but also measures to control floodwaters associated with ice-related events.

4.4.2. Upstream and downstream effects of regulation on freeze-up ice jams

Changes in winter discharge, flow velocity, and water temperature affect the freeze-up process, which is known to depend on the magnitude of the prevailing velocities and water temperature. Higher flow velocities mean thicker freeze-up jams and higher water elevations. Regulation-induced increases in freeze-up flows may delay formation of an ice cover downstream of a dam, resulting in increased generation of frazil ice under certain weather conditions. This ice can form severe hanging dams if it encounters a deep and flat river section as it is being transported by the flow. A related case study of flooding on the Kaministiquia River near Thunder Bay has been described by Beltaos et al. (2007). More recently, a four-fold increase has been reported (Chang et al., 2016) in the frequency of freeze-up -jam flooding downstream of two dams, built in 1968 and 1986 in the Ning-Meng reach of the Yellow River (China).

During freeze-up, ice problems can occur at the upstream end of reservoirs (reservoir entrances). Hanging dams of frazil ice deposits can occur where the steepness of the hydraulic grade line changes abruptly, such as the upstream end of reservoirs (Beltaos, 1995). Freeze-up ice jams often form at locations where the river slope changes from relatively steep to mild. This situation may occur naturally, but is characteristic of the vicinity of reservoir entrances. Flow velocity decreases abruptly at the upstream ends of reservoirs and the ice cover is initiated either by static growth or by bridging of ice floes. Mouths of rivers flowing into reservoirs and regulated lakes are natural locations for ice jams. In some cases, wind blowing along a lake may also stop the ice movement (Beltaos, 1995).

The type of ice jam depends on flow conditions upstream of the reservoir entrance. Low and moderate velocities lead to single-layer ice covers, but higher velocities may cause formation of thick ice jams and hanging dams. Hanging dams can attain extreme thicknesses (e.g. tens of metres) via accumulation of frazil ice produced in steep upstream reaches that remain open for protracted periods or even for the entire winter. The water level of the reservoir may affect the location and the thickness of any accumulations that may form.

Radoane et al. (2010) describe freeze-up ice jamming upstream of the Izvory Muntelui Reservoir at the Bistrita River, which is located in a mountainous area of North-East Romania. The conditions along the river are favorable for formation of frazil ice and frazil-pans. After the reservoir became operational (1960) there have been several freeze-up ice jams along the Bistrita

River upstream of the reservoir. In the winter of 2002-2003 ice jams had disastrous effects for the inhabitants of the villages on Valea Muntelui, including loss of human lives. Radoane et al. (2010) indicated that at low reservoir levels, frazil ice moves downstream without jamming. If the reservoir level is higher, an ice jam forms and propagates upstream, causing flooding. An extensive hanging dam has also been observed in the reservoir downstream of its entrance. According to Radoane el al. (2010), no ice jams were reported in the area before the start of the operation of the Izvory Muntelui Reservoir. Related measurements and data were also reported by Gaman (2014).

4.5.2. Upstream effects of regulation on breakup ice jams

Since incoming flows to reservoirs are not affected by regulation, one impact is to eliminate any jams that would have naturally formed within the length of the reservoir. At the same time, the reduction in water surface slope at the reservoir entrance can cause jamming when breakup ice runs from upstream reaches of the river arriving at the edge of the still-intact reservoir ice cover. For example, extreme breakup jams can form near Perth-Andover (New Brunswick, Canada), a community located on both banks of the Saint John River, between ~21 and 27 km upstream of Beechwood Dam. All but two of the 13 ice-jam related floods since 1887 occurred after construction of this dam (1955). This is consistent with a recent quantitative assessment of the potential for jamming near Perth-Andover: Beltaos and Burrell (2015) found that jamming potential is considerably higher in the Beechwood headpond section (0 to ~30 km from the Dam) than farther upstream. This result stems from the low water surface slope and large channel width and depth, all typical features of reservoirs. A smaller control structure, located farther upstream on the Saint John River at Grand Falls, also creates a headpond. Major, though less destructive, jams are also known to form near the upstream end of this headpond (Beltaos et al 1994, 1996).

4.5.3. Downstream effects of regulation on breakup ice jams

Regulation for hydropower generation alters the downstream flow hydrograph: in cold regions, the modified hydrograph comprises increased flows in the high-demand winter season and reduced flows in the summer (Figures 9 and 10). The high flows and relatively warm reservoir water combine to ensure that a reach of the river below the dam will remain open throughout the winter. The length of this reach will depend on local hydro-thermal and climatic conditions; any jams that might have naturally formed in this reach before regulation will no longer occur.

Farther downstream, the higher winter flows result in higher freeze-up water levels. The initial ice cover may now comprise a surface or thickened accumulation of slush and ice floes, which is stabilized by downward freezing of interstitial water near the water surface. Depending on flow and weather conditions, this accumulation may collapse and re-form with higher thickness and cause much higher water levels that may pose serious flood risks to nearby communities (Neill and Andres, 1984; Andres et al., 2003). Though such collapses occur during the winter, they result in limited breakup of the ice cover and the ensuing jams are of the breakup type.

Other factors being equal, higher freeze-up levels increase the resistance of the winter ice cover to mobilization during the spring freshet. In turn, this may result in less frequent ice-jam floods and more frequent “thermal” breakup events, which are characterized by extensive in-place deterioration and melt of the ice cover with minimal, if any, jamming (Beltaos et al., 2006). This effect may be respectively moderated or enhanced by increased or decreased spring breakup flows. Warming spring weather and increased daylight duration reduce energy demand, and thence the need for large reservoir water releases, though not to the same degree as in the summer. Whether regulation has a positive or negative impact on spring flows may depend on regional factors and year-to-year weather conditions. A good example is provided by Figure 10, which applies to the Peace Point hydrometric station, where the regulated Peace River typically breaks up in the first half of May. Naturalized flows (averaged over the period 1972-1996) are slightly lower than corresponding regulated flows at the end of April, but the opposite applies to the middle of May. It is difficult to discern in Figure 10 whether regulation has had an effect on breakup flows, on "average". In any event, such an effect appears too small to make any difference in ice-jam flood frequency, which therefore would be dominated by the strong effect on freeze-up levels.

It is not known whether this inference, which derives from the regulated Peace River, applies generally to rivers in cold regions but is corroborated by experience in the regulated Ning-Meng reach of the Yellow River (China). Chang et al. (2016) determined that construction of two dams, in 1968 and 1986, has reduced the frequency of downstream floods due to breakup jams by about 36% after eliminating the impact of climatic conditions.

Reduced ice-jam flood frequency is beneficial from the viewpoint of flood damages and direct impacts on aquatic life. On the other hand, the ecosystems of the large freshwater deltas of northern Canada depend on regular ice-jam flooding for replenishment with water, sediment, and nutrients. In the case of the Peace-Athabasca Delta (PAD), it is jamming within the lower 100 km of Peace River that can raise water levels sufficiently for replenishing the higher-elevation, or perched, basins (Prowse and Conly, 1998).

Figure 12 suggests that the frequency of ice-jam flooding of the Peace-Athabasca Delta (PAD), has decreased conspicuously after completion (1968) of the W.A.C. Bennett Dam, which created the Williston Reservoir. In this figure, frequency is by definition equal to the derivative, or slope, of the graph. The indicated post-regulation halving of ice-jam frequency is consistent with earlier estimates by Beltaos (2014). The gap between 1967 and 1972 is due to the fact that the reservoir was filling up during the period 1968 to 1971, which therefore is not representative of either regulated or natural flow conditions. The concave shape of the pre-regulation line suggests a consistent frequency increase during the 20th century. This may reflect the influence of changing hydro-climatic conditions but could also be due, at least in part, to fading local "memory" over time.

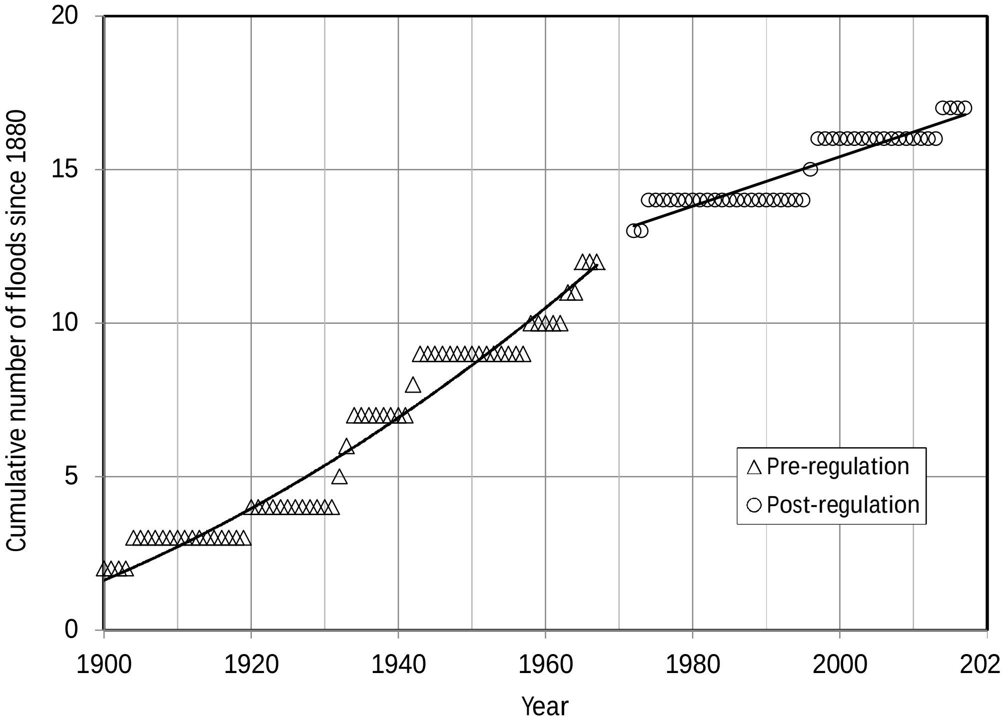

Figure 12. History of large ice-jam floods of the PAD according to the comprehensive compilation by Timoney (2009); the 2014 event is included. Frequency during 1950-1967 ~ 0.2; during 1972-2017: ~ 0.1.

5. Ice Effects on Hydropower Generation

Ice formation and related processes in rivers and lakes/reservoirs influence the operation of hydropower plants in cold regions. Frazil ice, anchor ice, ice runs, and ice jams can cause operational constraints that lead to reductions in power production (Gebre at al., 2013). Meeting ice-related challenges is an important and costly aspect of hydropower generation in cold regions. For example, Raban (1995) indicated that a single utility (Manitoba Hydro, Canada) loses tens of millions of revenue dollars per annum as a result of river ice processes.

Wigle et al. (1990) provide a detailed discussion of ice-related problems and practical solutions for Canadian rivers, including many site-specific examples. More recently, Hou and Wang (2008) discussed ice damage to water transfer projects in diversion-type hydropower stations of the Xinjiang Uyghur Autonomous Region of China.

The major ice effects/problems on hydropower systems include:

- Intake blockage with frazil ice and anchor ice causing head losses and even complete generating plant shutdown;
- Flow reductions to the intakes in the case of run-of-river intakes causing reduced output and even complete shutdowns;
- Icing of structures especially gates (intake gates and spillway gates) that causes operational and safety concerns in the case of spillway gates;

- Extensive frazil ice formation and jamming in open water reaches downstream of power plant; and
- Operational restrictions on hydro-electric operators to avoid ice problems such as ice jamming and flooding (Gebre et al., 2014; Gebre et al., 2013).

The clogging of intake trash racks by accumulation of frazil ice and energy losses caused by rising tailwater levels because of increased hydraulic resistance generated by anchor ice accumulations are common ice problems affecting hydropower generation. Figure 13 shows an increase of over 5m in differential pressure across a trash rack of the Kettle Generating Station in northern Manitoba, caused by frazil ice accumulation during freeze up, before the generating unit was forced out of service for several days to remove the blockage. Most of these problems with frazil and anchor ice are minimized once a stable ice cover is in place. As a general rule, the sooner an ice cover forms the better, because the cover reduces heat loss and greatly inhibits further ice production. Depending on weather conditions, open water will generate 4-10 times the volume of ice that it would under an ice cover during the winter (Wigle et al., 1990). Rapid ice cover formation can be promoted with judicious flow regulation (Wigle et al., 1990; Sujuan and Zhanting, 1996; Laifei, 1996; Tuthill, 1999). When the flow velocity is low enough, less than 0.6 - 0.7 m/s, a single-layer cover forms by surface juxtaposition of ice floes. The magnitude of heat flux from the water to the atmosphere dictates how quickly the newly formed cover will stabilize by the freezing of interstitial water. Flow cutback alone may suffice to enable ice cover formation, or it may be combined with other measures like ice-booms, dams, weirs, channel modifications or special ice control structures (Jain et al., 2003). Flow reduction at freeze-up may also be used to avoid flooding caused by freeze-up ice jamming (Tuthill, 1999; Huokuna, 2007).

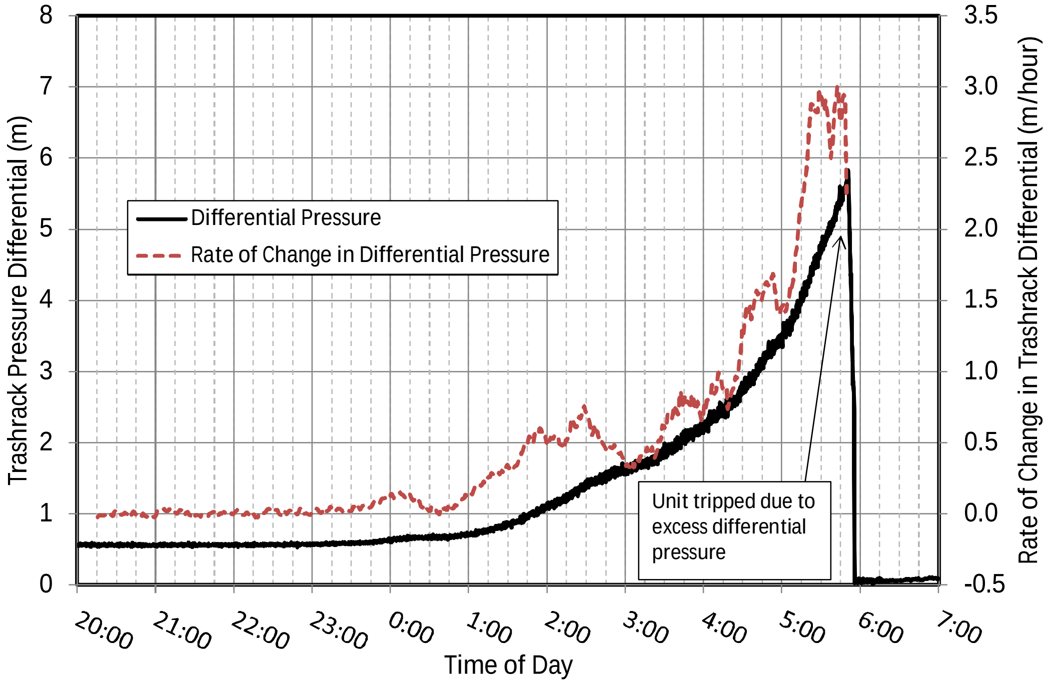

Figure 13. Trash rack differential pressure during a frazil ice event at the Kettle Generating Station in northern Manitoba.

Flow reduction at hydropower stations for freeze-up control also means reduced power production at the time when consumption demand is high. For that reason, the duration of flow cutback should be as short as possible. In the case of flood control, the lack of available reservoir capacity may also constrain flow reduction (Huokuna, 2007). Water level and temperature observations, flow and weather forecasts, and practical knowledge of the river are needed to determine the correct timing and duration of flow reduction.

The flow rate has to be increased very carefully after the formation of the ice cover. Otherwise, the newly formed ice cover may break up when the discharge is increased. To avoid potential ice problems downstream of a power plant, hydro-power companies avoid intense short-term regulation during the freeze-up period. Flow that is more constant is used to enable smooth ice cover formation (see also Wigle et al., 1990). The increase of the strength of the ice cover with time by freezing is an important factor in the stability of the cover (Andres, 1999).

Water may spill onto the ice cover, leading to formation of a layered snow-ice cover if the discharge fluctuation is large. Inundation of the ice cover is especially probable if a rapid flow increase is preceded by a few days of low discharge, for example during weekends when power consumption is low.

Short-term regulation causing large variations in daily discharge is done to optimize power production in response to actual or projected weekly and daily variations in power price and consumption demand. A thin ice cover formed downstream of the power plant during low-discharge periods may break up as a result of short-term regulation involving large flow fluctuations (hydropeaking). This broken ice may contribute to the thickening of the downstream ice cover and the formation of ice jams. In addition, uncontrolled short-term regulation may increase the possibility for ice runs. Peaking operations also influence the ice strength on regulated reservoirs. Thinner reservoir ice covers could lead to more frequent ice breakups and contribute to a higher dynamic load on structures (Gebre et al., 2014). Given that, fluctuating water levels can destabilize a fragile developing ice cover resulting in a severe freeze-up ice jam and associated flooding, early winter is typically a time of severely constrained flow-peaking operations for hydropower facilities (She et al., 2012).

The effects of a hydropower plant on flow and ice regimes depend upon the type of facility and its size. Dams with large storage reservoirs can alter the flow and temperature regimes, and thus ice processes differently than run-of-the-river facilities. When water for hydropower generation is diverted rather than stored, the effects of ice in the diversion and by-passed channels have to be considered. For example, lower water depths in the by-passed channel may lead to freezing to the channel bed as more of the channel is exposed to freezing temperatures (FERC, 1992).

NRCC (1988) describes Canadian experiences in solving problems that occurred (to 1988) in operating hydropower plants in winter to obtain optimum outputs. Wigle et al. (1990) indicate that a key constraint to hydropower generation in Canada is the need to avoid the breakup of a newly formed ice cover downstream of a reservoir and subsequent formation of ice jams. Operational restrictions on hydro-electric operators often exist to avoid ice problems, including extensive frazil ice and breakup jamming in downstream stretches of the river and upstream flooding caused by breakup ice jams at the upstream end of reservoirs, and associated flooding.

Climatic change is expected to change the ice regime thereby affecting hydropower production in northern rivers. Gerbe et al. (2014) evaluated possible effects of ice to hydropower facilities and operations under projected future climates, and found that changes in river and reservoir ice regimes may have both positive and negative consequences. Although shortening of the ice season would reduce the period required for operational constraints and ice mitigation, instability in winter conditions could create new challenges with respect to hydropower generation (Gebre et al., 2014).

6. Ice Effects on Ecology

The changes in ice regime caused by regulation may have several effects on ecology, especially on fish. Both winter discharge and water temperature downstream of a dam are modified by regulation and these altered conditions affect fish habitat. Higher discharge during winter increase open water areas and formation of frazil ice, anchor ice, and hanging dams. According to Jakober et al. (1998), the harshest winter conditions for fish may occur where incomplete surface ice cover results in extensive frazil and anchor ice formation. Laboratory studies have shown that frazil ice can stress rainbow trout and reduce their swimming capacity (Bergeron and Enders 2013). Strongly fluctuating flows caused by hydropeaking operations may be especially harmful for fish. They may lead to frequent ice cover break up events maintaining the river without solid ice cover and enabling frazil formation. Strongly fluctuating discharges and water levels may also increase the probability of fish stranding in dewatered channel margins (Bergeron and Enders, 2013).

The increase of water temperature in a river may also have positive consequences. A hydropower project with storage of sufficient depth could increase water temperature, thereby benefiting stream biota in both the reservoir and downstream reaches (FERC, 1992). Less anchor ice generally means reduced disruption of bottom substrate and less extreme fluctuations in stage, discharge, and velocity to the benefit of fish, fish eggs, and insects for which the substrate provides cover (FERC, 1992).

In some regions, a return to original reindeer migration routes would be almost impossible because of poor ice conditions resulting from flow regulation (Tockner et al., 2009). Reduced frequency of breakup ice-jam floods has been linked to the higher freeze-up levels of regulated rivers, limiting an important habitat replenishment mechanism for floodplain lakes and wetlands (Beltaos et al., 2006). Predicting the effects of hydropower projects on aquatic biota requires comparison of observations of the physical and biological effects of stream ice in natural settings with projections of how the facility will modify stream conditions (FERC, 1992).

7. Dam Removal and River Restoration

Dams have a profound influence on fluvial processes and morphology (Pizzuto, 2002), and the response of a river channel to dam removal is complex (Grant, 2001).

The dynamic equilibrium established by a river since dam construction as a result of the effects of flow regulation, natural events, and human activities in the watershed (such as flow diversion, deforestation and urbanization) could be very different from the regime that existed prior to dam construction (Vuyovich and White, 2007). Regime changes are especially evident for older dams and for dams on tidal rivers (e.g. the Petitcodiac River in New Brunswick). Dam decommissioning and removal will disrupt the established flow regime and could lead to consequences that would not have occurred should the river have remained in a natural state (Vuyovich and White, 2007). Dam decommissioning is therefore a complex non-trivial issue that requires scientific environmental, engineering, and socio-economic analyses. Conynham et al. (2006) provides an overview of engineering and ecological aspects of dam removal, presents a list of the benefits and costs of dam removal, and identifies the data compilation and evaluation that may be necessary to evaluate the consequences of dam removal and river restoration alternatives.

Dam removal can modify the ice regime of a river by eliminating a barrier to ice passage thereby allowing ice movement to downstream reaches (Carr et al., 2011; Tuthill et al., 2007; Vuyovich and White, 2008). Removal of a dam on a steep river may result in a steep, turbulent reach that produces frazil instead of the slower-moving impoundment that captured it. Frazil ice formed in exposed rapids could flow downstream thickening downstream thermally grown ice covers, posing a possibility of hanging dams. Broken ice previously held in place during breakup by the dam and its headpond would be available to contribute to ice jamming downstream. Dam removal thus can cause increased freeze-up and breakup ice jams downstream, change the locations where ice jams form, and change the severity of ice-jam events (Vuyovich and White, 2008).

During the period that a dam was in place, the river regime and land use may have changed. For example, Stantec (2015) found that since the construction of the Mactaquac dam on the Saint John River, New Brunswick, there has been an increase in ice-jam flooding in the upstream half of the headpond, and a decrease in the observed number of ice jams in the downstream half of the headpond, and in the river downstream of the dam (Stantec, 2015). For dams that provided major attenuation of downstream peak flows, the size and morphology of the downstream flood plain may have reduced. Removal of these dams and re-establishment of greater peak flows to the downstream channel could result in altered channel form and widening, bank erosion and instability, increased flooding, and alteration and destruction of fish habitat (OMNR, 2011). The quality, quantity, and transport of reservoir sediments after dam removal may also affect downstream channel conditions and fish habitat.

Stream characteristics and aquatic habitat, and the population and development along the river adjust to the conditions existing during decades the dam and reservoir are in place. The possible effects of dam decommissioning and removal on upstream and downstream infrastructure need to be considered. Removing a dam can result in changes in the ice and flow regimes that may result in possible increases in ice jams, flooding or sedimentation in downstream areas.

Development and infrastructure, such as bridges, that were not considered susceptible to damages caused by ice jams, ice runs and javes when the dam was in place may become susceptible once the dam is removed. Lower upstream water levels and water table elevations may also require the extension or relocation of water intake structures, sewage outfalls, and boat docks and ramps, and the evaluation of the ice on these structures.

The removal or lowering of dam structures from a river channel has the potential to restore and/or enhance fish habitat, but a net increase in fish habitat may not necessarily occur due to changes to the channel form, reduced upstream water levels and increased downstream channel flows resulting from the loss of the storage reservoir. Furthermore, reservoirs created behind dams may have created new habitat preferable for different fish species than in lotic systems. The overall outcomes of fish and riparian habitat impact assessments depends on the quality and quantity of habitat existing when the dam and reservoir are in place versus the quality and quantity of habitat which can be created both naturally and artificially following the dam decommissioning (OMNR, 2011).

The potential effects of dam removal on ice conditions can be evaluated following the compilation and review of historical records, channel geometry, hydrologic data, and climate data. Historical accounts (newspaper accounts, photographs, and reports on past events) can provide information on the location of ice jams and on their time and frequency of occurrence, the length of the stretch of river contributing ice, and the resultant ice-jam stages and damages (Vuyovich and White, 2008). However, minor ice jams can go unreported if their water levels fall below perception stage (i.e., water levels are below flood levels the public considers noteworthy), thereby giving an under-estimation of the frequency of ice jamming. The locations of these minor ice jams may indicate locations of significant future jamming once the supply of ice from upstream is restored following dam removal. Channel geometry also provides information on possible jam formation as ice jams tend to form where channel cross-sectional shape, river slope, or channel planform changes to affect the conveyance of ice. Estimates of the range of ice thickness and discharges at which ice jams occur can be derived using meteorological hydrologic data (Vuyovich and White, 2008). Climate data can be used to estimate ice thickness based on the number of accumulated freezing degree-days, to estimate the amount of thermal decay of the ice cover, and to estimate the seasonal occurrence of freeze-up and breakup. Discharge records can be used to identify breakup flows, the flows required for ice transport, and the effects of flow rates and changes in flow rate on ice processes. For example, a slow rate of rise might be associated with snowmelt due to high temperatures that would also cause deterioration of a sheet ice cover.

Once historic information, hydro-climatic data, and channel geometry has been evaluated, the impact of a dam on the ice regime and the potential effects of its removal can be evaluated by:

- Hindcasting – a comparative review of the conditions that existed along the river before the dam with the conditions that exist since dam construction.
- Threshold Evaluation – establishment of criteria with respect to ice conditions (e.g., ice thickness), climate (e.g. antecedent changes in precipitation and temperature), and hydrology (e.g., estimated discharge) that distinguish events with high flood stages from other events.

- Numerical Modelling – application of hydrodynamic (unsteady state) models to estimate changes in ice processes and (or) hydraulic (steady-state) models to quantify estimated stage resulting from ice jams.

Vuyovich and White (2007) found removal of the Merrimack Village Dam on the Souhegan River would allow ice that currently stops in the impoundment to travel downstream to the backwater area of the Merrimack River. A georeferenced HEC-RAS hydraulic model of the Souhegan River was used to estimate ice-jam thickness and resulting water surface profiles for ice jams for both pre- and post-dam conditions. The likely locations of ice jam formation were determined from evaluation of historical information and channel morphology, and the ice thickness, ice supply volumes, and discharges were estimated from historical meteorological and hydrologic data (Vuyovich and White, 2007).

Chateauvert et al. (2015) discuss several aspects of large dam removal, including the effects on the ice regime and possible mitigation measures. The natural ice regime has major effects on winter flows, inundation of backwaters or riparian areas, dissolved oxygen concentrations, sediment transport/deposition, and river geomorphology, but a dam changes the natural processes in the river. They state that the ecological aspects of changes in river-ice processes and characteristics have received little attention but the seasonal evolution of river ice, particularly breakup and ice jamming, represent disturbance to aquatic and riparian habitat and the organisms that use them.

Ice-related adverse impacts associated with dam removal can be mitigated through ice control measures (White and Moore, 2002). Burrell (1995) highlighted that both structural measures (the design of engineering structures) and non-structural measures, can be used to alleviate future ice-related damages. He presents an overview of structural and non-structural ice-jam mitigation measures under the three categories previously mentioned.

8. Concluding Remarks

A large part of northern rivers and lakes are strongly or moderately affected by regulation. Dams and other forms of river regulation create unnatural river stretches into naturally free-flowing rivers and streams, causing changes in river water levels, flow, sediment movement and deposition, ecology and ice transport. Regulation alters river ice regimes by modifying the temporal and spatial characteristics of flow, water level, and thermal regimes in a watercourse. Higher discharge of warm water from reservoirs during the winter season causes enlarged open water areas, increased production of frazil ice, and more frequent formation of anchor ice and hanging dams in downstream river reaches. Open-water and weak ice-cover areas in lakes and reservoirs may be expanded by regulation. Reservoir backwater or flow releases may create ice jams and associated flooding at sites where there were no such problems prior to regulation.

Hydropower production is the main reason for river regulation and, by altering the natural discharge, water level and water temperatures in the river, can cause significant changes to the ice conditions. Hydropower production is also affected strongly by ice. Frazil ice, anchor ice, ice runs, and ice jams can cause operational constraints that lead to reductions in power production and significant economic losses.

It is reasonable to assume that the removal of a dam will alter hydraulic, thermal and ice conditions in a river from those that existed during the time the dam was in place. Removal of a water control structure can eliminate some ice problems, but create new problems in areas where environmental or development conditions have changed.

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