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Ice Considerations in the Design of River Restoration Structures

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February 2008

COVER: Freezeup ice jam at Rio Blanco diversion weir on the White River in Colorado.

Flood and Coastal Storm
Damage Reduction Program

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Ice Considerations in the Design of River Restoration Structures

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Abstract: Modern river restoration and streambank stabilization projects constructed of natural materials are gaining favor over traditional materials such as riprap and concrete. These new structure types provide a more aesthetic and lower-cost means of controlling bed and bank erosion, while improving flow diversity and habitat. Little design guidance exists for these structures on ice-affected rivers, however. This report provides basic design guidelines for these in-stream structures in the ice environment. Critical design questions are whether the structure or project will cause ice jams where none occurred before and also how well the structures will survive ice processes. For the freezeup period, simple water velocity and ice arching theory may be adequate to predict whether an in-stream structure will retain or pass ice. Predicting the structures' effect on breakup ice jam formation is much more difficult and, because of this uncertainty, it is recommended that designers avoid locating these types of in-stream structures in sections of river known for destructive breakup ice jams and ice jam flooding.

Contents

Figures

Preface

This technical report was prepared by Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Group, RS/GIS and Water Resources Branch, US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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This report was prepared under the general supervision of Timothy Pangburn, PE, Chief, RS/GIS and Water Resources Branch; Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; Dr. Lance D. Hansen, Deputy Director, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this work was performed, Colonel Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To obtain
feet	0.3048	meters

1 Introduction

Modern river restoration (RR) and streambank stabilization (SS) efforts are increasingly turning to more natural methods compared to traditional alternatives constructed of stone and concrete. Examples include vanes and weirs constructed of rocks or logs to direct flow away from the banks toward the channel center. These in-stream structures are often complemented by plantings to reinforce streambank soils. Successful applications help control bed and bank erosion, improve flow diversity[1], re-connect floodplains, and improve habitat for fish and wildlife. To date, the design of these increasingly popular structures has been largely empirical and little is known about their performance on rivers with ice. In addition to the uncertainty of the structures' winter survival, little has been documented about their effect on the ice regime. A critical question is whether or not these in-stream structures will cause ice jams, and ice jam floods where none occurred before, and whether these changes are of consequence. Little or no design guidance exists for river restoration projects in cold climates. Current research at CRREL addresses this knowledge gap. This report draws on this research and offers preliminary design guidance for in-stream structures along rivers with ice.

[1] A section of river is said to have flow diversity if the velocity distribution, water depth, and channel width vary over relatively short distances. Flow diversity is a positive feature in terms of aquatic habitat.

2 Popular In-Stream Structures

Popular natural methods include rock and log vanes that extend out from one bank to direct flow toward the channel center, decrease bank erosion, and improve conveyance of water and sediment, particularly through bends. Vanes are typically angled upstream from the banks at angles ranging from 20 to 30 degrees. Vane structures usually tie into the bank at the top-of-bank height and slope downward to merge with the bed elevation about one-third of the way out into the channel. Figure 1 shows a series of rock vanes that protect the bank of the Winooski River near Bolton, Vermont. In-stream structures that extend across the entire channel include cross vanes, W-weirs, rock riffles, porous rock weirs, and U-drops. Cross vanes and W-weirs consist of connected systems of vanes that concentrate flow toward the channel center and erode pools downstream, while maintaining the pre-existing thalweg[1] elevation at their low points (Rosgen 2001). These structures have been used in conjunction with vanes to channel flow and sediment through bridge openings (Johnson et al. 2002).

While maintaining an upstream U-configuration, the crests of porous rock weirs are typically more level. Figure 2 shows a rock weir on the Trout River in northern Vermont. Rock riffles, consisting of more closely spaced rock weirs, typically extend straight across the channel. U-drops, constructed of grouted rocks and boulders, combine aspects of cross vanes and rock weirs with crest elevations that more or less contour the pre-existing cross-sectional geometry (Lacy et al. 1995). Because the inverts of rock riffles, rock weirs, and U-drops are higher than the existing river bed, they are more likely to raise upstream water levels than vanes or cross vanes that maintain the existing bed elevation at the channel center.

Purposes of rock weirs, rock riffles, and U-drops include flow diversity, grade control, flow diversion, fish passage, and recreation in the form of increasingly popular white-water parks. The above described in-stream structures are best suited to rivers of pool-riffle bed morphology with bed materials in the sand-to-cobble size range. Caution is needed when locating these structures on high bed load streams, as they may become buried

[1] The thalweg is the path of deepest flow in the river channel, often coinciding with the highest water velocities.

following large flood events[1]. At the same time, on lower gradient, fine-bedded rivers, undermining of the rock structures can be a problem[2].

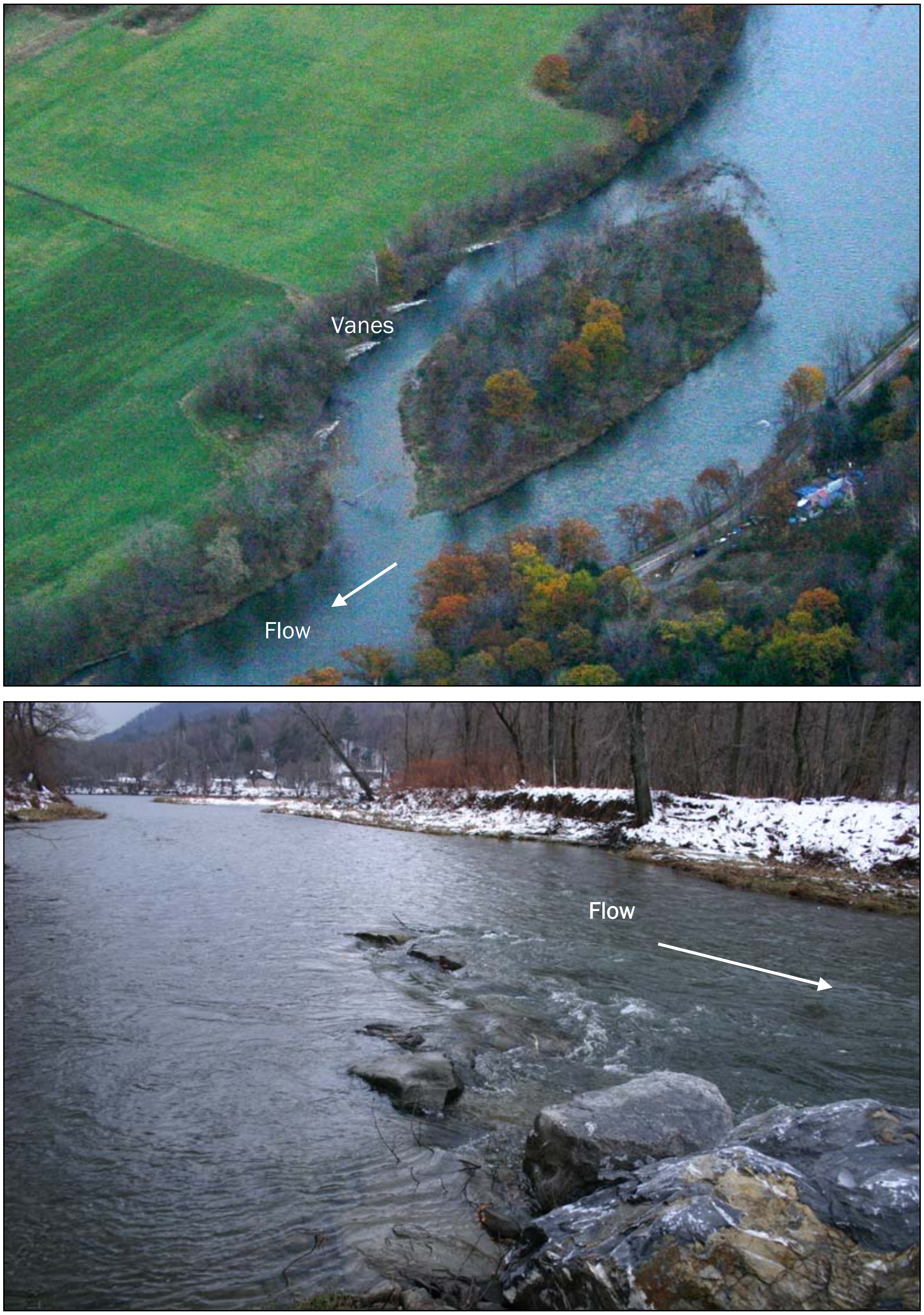

Figure 1. Rock vanes designed by NRCS to stabilize bank of the Winooski River at Bolton, Vermont.

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[1] Observation by Chris Brunelle, Vermont Agency of Natural Resources (VT ANR), Waterbury, Vermont

[2] Observation by Mike Klein, VT ANR, Waterbury, Vermont

Figure 2. Rock weir on the Trout River in Vermont.

3 Important Ice Issues Associated with RR and SS Structures

The central issue when placing in-stream structures in an ice-affected river is ice passage, which is somewhat difficult to predict with existing theory and models. Considerable ice control research has identified ice and hydraulic conditions needed to retain ice on rivers, and this guidance also can be used to predict conditions for which an in-stream structure will pass ice (USACE 2006). Important questions for a designer include the following:

a. What is the general ice regime on the river system and what type of ice conditions can be expected in the project area?

b. Will the proposed in-stream structure(s) affect the ice regime? Specifically, will the structure(s) retain or pass ice, and under what conditions?

c. If the project affects the local ice regime, will this be a problem in terms of ice jams, ice jam floods, or ice-related bed and bank erosion?

d. How well will the structures survive the ice environment?

e. If ice problems are anticipated, can the project be designed to avoid or mitigate them?

3.1 Characterize Existing Ice Conditions

Before locating in-stream structures on an ice-affected river, knowledge of the existing-conditions ice regime is essential. A relatively straightforward first step is to estimate the maximum probable ice thickness from historic air temperature data. White (2004) describes techniques for estimating the distribution of maximum annual ice thickness from accumulated freezing degree-day (AFDD) data.

A second step is to determine if and where the host river has experienced ice jams or ice-related flooding in the past. The CRREL Ice Jam Database

(White 1996), with more than 16,000 entries, is an excellent resource in this regard. Last, but not least, discussions with locals can be invaluable in terms of learning about a river's ice regime and history of ice problems.

The river ice regime can be viewed in three periods: ice formation, midwinter, and breakup. In terms of the design of RR and SS structures, the formation and breakup periods are the most important. The complex processes of river ice formation and breakup have been the subject of much engineering research (Ashton 1986, Beltaos 1996). The following discussion highlights a few key points that relate to common ice processes and the potential effects of placing structures in rivers.

3.1.1 Ice Formation Period

The predominant ice type on pool-riffle rivers is frazil ice, formed from the supercooling of turbulent open water. Thermally grown sheet ice also appears along the banks in the form of border ice, and across slower moving sections such as pools, where average velocity is less than about 1 ft/s (Perham 1983). In faster moving, more turbulent sections of river, frazil ice initiates as tiny crystals that bond together to form frazil slush and eventually pan-shaped floes, with floe size and surface ice concentration increasing as the ice drifts downstream. Provided the water temperature is close to the freezing point, frazil typically begins to appear at air temperatures of about 20°F, and heavy frazil production occurs when the air temperature falls below about 10°F. Figure 3 shows frazil ice pans drifting down the Kennebec River below Waterville, Maine.

Under open water conditions, rivers with high-elevation, steep-gradient headwater reaches can produce large volumes of frazil ice, particularly on cold, clear nights. The frazil ice may travel long distances until the surface ice concentration exceeds the conveyance capacity of the channel, or the moving ice floes encounter an obstruction such as an intact ice cover, sharp bend, island, channel constriction, or a man-made structure such as a weir or dam. At this point, the frazil floes may accumulate edge to edge and freeze together to form a "juxtaposed" cover. This type of ice accumulation typically occurs where average velocity is in the 1.2- to 2.3-ft/s range and the Froude Number is less than about 0.08[1]. Where water velocity is

[1] Froude number $F = \frac{v}{\sqrt{gy}}$ where v = average channel velocity, g = acceleration due to gravity, and y = average channel depth

greater than about 2.5 ft/s, under-ice water drag may be sufficient to tilt and "under-turn" the arriving floes into a multi-layer "shoved" ice accumulation[1]. In faster riffle and rapids sections, where water velocity exceeds about 5 ft/s, the river may remain open all winter.

Figure 3. Drifting frazil ice pans on the Kennebec River upstream of Augusta, Maine.

Once a bank-to-bank ice cover has formed, arriving ice will lengthen the cover in the upstream direction in a process known as "ice cover progression." Another possibility is for arriving frazil floes and slush to be drawn beneath the upstream edge of the ice cover to deposit in the form of a "hanging dam" or freezeup ice jam. Eventually most or all flow conduits beneath the jam may become ice-clogged, forcing flow onto the surface of the ice cover and/or out of bank to flood fields and other property. Freezeup ice jams can persist for weeks and even months, disrupting human activities and interfering with transportation and other economic activities. Figure 4 shows severe freezeup ice jam flooding of a cattle ranch on the White River below Meeker, Colorado.

[1] The HEC-RAS model (USACE 2002) contains an ice jam routine that calculates the thickness of a shoved accumulation of frazil or breakup ice floes.

Figure 4. Freezeup ice jam and flooding on the White River downstream of Meeker, Colorado.

As stated above, freezeup period water velocity is a useful indicator of ice-cover type and the potential for ice transport or retention and jamming. Methods for measuring or calculating water velocity range from direct observation and simple calculations to the use of hydraulic models such as HEC-RAS, where sufficient bathymetry data are available. Timing of floating drogues or ice pieces can provide estimates of surface velocity conditions in the project area. Lacking sufficient geometry data for a HEC-RAS model, constructing a simple river bed profile from USGS mapping gives a good idea of the overall channel gradient. This can be used to identify where sheet ice will grow thermally, or where frazil ice is likely to form, transport, or jam.

Figure 5 compares bed slope profiles of rivers of increasing overall steepness. The Grasse River in northern New York provides an example of a relatively low gradient stream with multiple sheet ice covers that form upstream of dams and natural control points. These sheet ice covers insulate the water beneath, limiting frazil production, and intercepting frazil ice that forms in upstream steeper sections. On medium slope streams such as the Cazenovia Creek near Buffalo in New York, and Blackfoot River near

Missoula, Montana, ice covers consisting of juxtaposed and shoved frazil floes predominate, except for thermal ice covers on backwater sections upstream of lakes and dams. At the steep end of the scale, the gradient of the White River in western Colorado is sufficiently high that, for certain flow conditions, frazil formed at higher elevations transports through the entire reach without forming an ice cover. In general, discharge is relatively low during the freezeup period, favoring thermal ice growth and frazil ice retention over long-distance ice transport. The combination of above-average discharge and below-average air temperature early in the winter can result in ice transport through sections where covers usually form, and thicker ice accumulations where covers do form downstream.

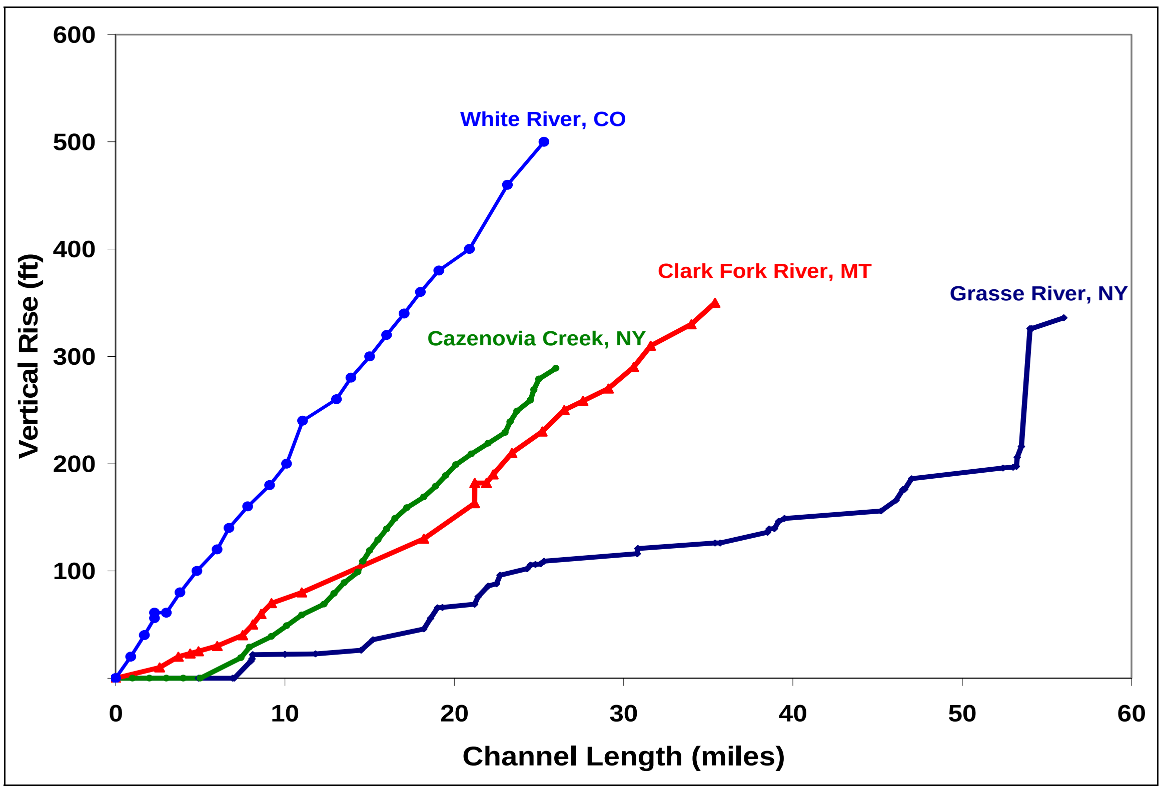

Figure 5. River bed profiles constructed from USGS 1:24,000 quadrangle maps.

This slope information, combined with estimates of channel width, depth, and discharge, allow calculation of average water velocity using the continuity equation for sections affected by backwater, or the Manning equation where uniform flow conditions are expected.

Designers must realize that an in-stream RR structure that raises water level or constricts the flow width can potentially initiate a freezeup ice cover or ice jam where none occurred before. Depending on the location, this may or may not be a problem. Indeed, in many instances, weirs and booms have been placed in rivers for the purpose of creating a freezeup ice cover at an upstream location to prevent ice problems at a downstream one (Tuthill 1995). Causes of freezeup ice covers and jams are discussed in Section 3.2 of this report, and are illustrated by the 2006 freezeup ice jam flood that occurred behind a porous rock weir constructed on the White River below Meeker, Colorado (Fig. 4, 5, and 6). This event is described in Tuthill (2008).

Figure 6. Freezeup ice jam at Rio Blanco diversion weir on the White River in Colorado.

3.1.2 Breakup Period Ice Processes

Determining the nature of ice breakup is a key factor in the design and location of an in-stream RR structure. River ice breakup can range from a gradual thermal meltout to a dynamic surge of ice floes and water known as a breakup ice run. Thermal meltout may extend over a period of weeks with minimal effect on channel bed and banks, riverside property, or in-stream structures. Dynamic ice breakups, on the other hand, may scour and erode the bed and banks and damage or destroy in-stream structures.

Breakup ice jams may result, causing sudden flooding, property damage and, in some cases, loss of life.

Because of their potentially destructive nature, breakup ice jams have been the subject of much research. In the simplest sense, a breakup ice jam occurs when the concentration of the moving ice floes exceeds the hydraulic conveyance capacity of the channel. Rapid thaw, often accompanied by rainfall, causing a sharp rise in river discharge and stage, typically triggers severe ice breakups and ice jams, and the most dynamic ones typically progress from upstream to downstream in a series of ice jams and releases. Common ice jam causes are a decrease in channel slope or physical obstructions to ice passage, such as intact ice covers, channel constrictions, bridge openings, bends, dams, or weirs. Since the physical processes governing ice and sediment transport are similar, ice jams tend to initiate in the same areas in which sediment deposits, such as the upstream ends of reservoirs. The moving ice may also stall as the flood wave conveying the ice attenuates, effectively decreasing the carrier discharge and increasing the ice concentration.

A few numerical models simulate breakup ice jam processes, but with limitations. HEC-RAS calculates the profile resulting from a breakup ice jam reasonably well. It requires the user to specify jam location and make a number of simplifying assumptions. In terms of analyzing ice effects on river restoration projects, a major limitation of HEC-RAS and similar models is their inability to simulate ice transport and ice jam initiation.

DynaRICE, a more complex, two-dimensional model, better calculates the interrelated processes of ice concentration, ice conveyance, and ice jam initiation (Shen and Liu 2000). The model has limited ability to simulate three-dimensional ice, water flow, and river bed interactions at the downstream end of the jam, however. Physical models, which are typically more costly than numerical ones, remain the best tool for analyzing how an instream structure will interact with ice. To serve as a design tool at a reasonable level of confidence, any type of model needs to be validated against field data and observations.

Lacking time and resources for model studies, basic background research can go far in terms of assessing the potential for dynamic breakup and ice jams in the project area. Interviews with local people familiar with the river can provide valuable information on the location, frequency, and severity of ice jams. The CRREL Ice Jam Database is another good information source. USGS gage records augment historical ice data, as ice jamming and release often coincide with abrupt and large changes in river stage and discharge. Air temperature and precipitation data also help define historic ice events, since rapid thaw and rainfall often trigger dynamic breakups. Vuyovich and White (2006) used this type of approach to assess the effectiveness of an ice control weir on the Israel River in northern New Hampshire.

The above-listed information may be incorporated into a hindcasting analysis to estimate the frequency of past ice jam events in the project area (Shen et al. in preparation). Last, but not least, a field inspection of the project reach may yield signs of past ice action, such as bed and bank scour and jam tree scars. Ideally, a series observations of should be made through several winter seasons to document ice formation and breakup processes and their variability.

3.2 Effect of In-Stream Structures on Ice Transport

An in-stream structure, or series of structures, may affect how drifting ice travels through a section of river. Possible effects include an increase or decrease in ice conveyance capacity through the project reach. Again, the greatest concern is that the hydraulic changes caused by the project may increase the likelihood of freezeup or breakup ice jamming. Possible negative consequences include upstream flooding, bed and bank scour, and property damage, in addition to disruption of human activities such as transportation and agriculture. On the other hand, the in-stream structure(s) may have no discernable effect on ice conveyance, or may actually improve ice passage through the reach. Because very little research on ice conveyance past in-stream structures has been carried out to date, the following discussion relies on field observation and simple open channel hydraulics as well as basic ice retention and ice jam theory. Possible effects of in-stream structures are discussed for the freezeup and breakup periods in the following two sections.

3.2.1 Possible Effects of In-Stream Structures During the Freezeup Period

3.2.1.1 Thermal Ice Cover Growth as a Barrier to Frazil Ice Transport

In terms of designing a restoration project that ensures ice passage during the freezeup period, it is important that the in-stream structures do not increase upstream water levels and reduce water velocity to the point where a thermal ice cover grows across the entire channel width to create a barrier to drifting frazil ice from upstream. As discussed in Section 3.1.1, average water velocity can be a good predictor of freezeup ice cover initiation, ice type, and progression. With some basic hydraulic calculations or HEC-RAS modeling, one can predict how the addition of in-stream structures will change the open water velocity magnitude and distribution, and how these changes might affect ice formation and transport through the project area.

For example, in a straight section of river with relatively uniform slope and width, and an average velocity of about 2 ft/s, one would not expect thermal ice growth, and, lacking physical obstructions to flow, frazil ice would probably drift through without stopping. Addition of in-stream structures such as rock weirs, U-drops, or cross vanes, while increasing flow diversity, might raise stage and reduce velocity to the point where thermal ice grows across the entire channel width. Rather than drifting through, frazil may be retained by or stored beneath these ice covers. Accumulation of additional frazil ice further increases flow resistance, deepening and lengthening the pool. Through the processes of juxtaposition, shoving, and under-ice deposition of frazil slush and floes, the ice accumulation may progress upstream in the form of a freezeup ice jam, with the negative effects described in Section 3.3.1.

Freezeup ice covers or ice jams may not be undesirable, but in places where they are, a conservative approach would be to design restoration measures such that the lowest with-project base-flow water velocities are well above the lower threshold for thermal ice growth, which is thought to be about 1 ft/s.

3.2.1.2 Ice Arching and Frazil Ice Transport

Decreasing channel width can initiate a thermal ice cover by structurally raising stage and reducing water velocity. It can also cause frazil ice floes to arch[1] across the gap and initiate an upstream ice cover. Common river restoration structures that intermittently decrease the flow width include porous rock weirs, U drops, spur dikes, and cross vanes.

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[1] An ice arch across a river channel is a horizontal analogy to a stone archway. An ice arch generally takes the form of an upstream U-shape.

Through flume experiments with plastic ice pieces, Calkins and Ashton (1975) found that arching occurs when the surface ice concentration equals or exceeds about 30% and the maximum floe diameter is at least one quarter of the channel or gap width. During periods of extreme cold, concentrations of frazil ice often exceed 30%, and, depending on river size, gradient, and distance traveled, floe diameter can easily exceed one-quarter of the channel width, even on wide rivers.

At the same time, one needs to ensure that, under the expected freezeup discharge range, the approach velocity upstream of the structure is well above the upper threshold for thermal ice growth of ~1 ft/s, (say 1.5 ft/s to be safe). These two criteria (approach water velocity ≥ 1.5 ft/s and gap width ≥ 4 × largest floe diameter) are based on observation and experiments, and, under certain conditions, may not be conservative.

One reason is that the two criteria tend to work against each other: In-stream structures such as vanes, cross vanes and U-drops intermittently decrease the channel width, and increases the flow velocity near the channel center and decreases it near the banks. As a result, thermal ice tends to grow out from the banks, forming an hourglass configuration, with faster-moving open water in the channel center (Fig. 7). Although the faster flow at the channel center may increase unit stream power[1] and ice conveyance, the tapering approach channel increases surface ice concentration and the likelihood of arch formation.

A second factor not addressed by the velocity or arching criteria for ice formation is the role played by ice cohesion, and the fact that the open water channel upstream of a structural gap may progressively narrow by the adhesion of frazil ice slush or floes to shorefast border ice (Fig. 8).

Finally, in the case of porous rock weirs, where a significant portion of the freezeup discharge passes through the structure rather than over a spillway section, progressive frazil ice clogging of the pore spaces may lead to upstream ice jam formation. This ice straining process likely contributed to the December 2005 ice jam and subsequent upstream flooding caused by the Rio Blanco diversion weir on the White River in Colorado (Fig. 6 and 4). Based on the above considerations and the White River experience,

[1] Unit stream power $\omega = \gamma v d S$ where γ = unit weight of water, v = average channel velocity, d = average channel depth, and S = water surface slope. Unit stream power can be used as a simple indicator of a river's capacity for transporting sediment (Dunne and Leopold 1978).

on rivers with concentrated frazil ice, a single well-defined spillway section is preferable to multiple gaps, which are more prone to ice arching or frazil ice clogging.

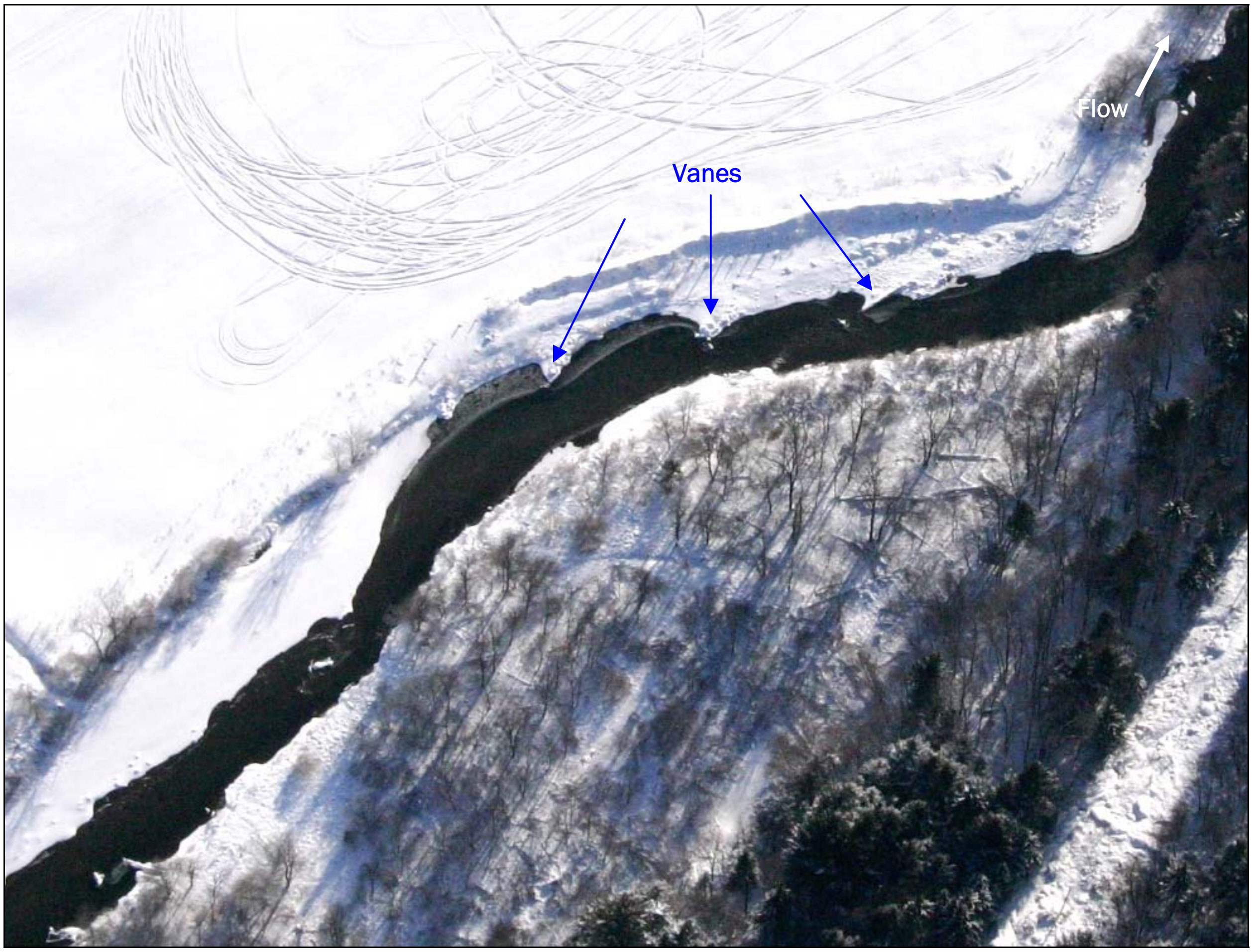


Figure 7. Border ice growth along rock vanes on the White River, Vermont.

Figure 8. Border ice formed by frazil adhesion, reducing flow width and promoting arching on the White River in Vermont.

3.2.2 Possible Effects of In-Stream Structures on the Ice Regime During River Ice Breakup

It is during the ice breakup period that the uncertainty and potential consequences of a river restoration project's effect on the ice regime may be greatest. An in-stream structure, or series of them, may affect how breakup ice travels through a section of river in a number of ways. First, it is important to consider the relationship of freezeup and breakup ice jams, as the first may lead to the second. As discussed in 3.2.1, an RR project may create a freezeup ice cover or ice jam, where none existed previously. The ice accumulation may in turn slow or block the breakup ice run, creating a second, more serious, ice jam. Even without a freezeup ice accumulation in place, local changes in hydraulics and bed geometry may increase the ice jam potential relative to pre-project conditions. For example, the slope reduction created by in-stream structures or series of them may stall the breakup ice run. The intermittent decreases in channel width and resultant increases in ice concentration could decrease conveyance through the project reach. Also, the increased resistance to ice movement imposed by the structures, which occupy a large portion of the channel cross section, could initiate jamming.

Using existing design methods and tools, the effect of in-stream structures on breakup ice conveyance is difficult to quantify. A laboratory study at CRREL (Vuyovich et al. in preparation) examined the effect of a series of cross vanes on the conveyance of plastic ice in a flume and compared results to DynaRICE simulations. In the 1:50-scale lab experiments, the model cross vanes slowed ice passage, but fell short of initiating an ice jam (Fig. 9).

Figure 9. Physical model tests of ice passage over cross vanes in the CRREL flume.

Though no river restoration projects have been constructed at known ice jam flood sites, several have been proposed. A series of full-scale rock vanes were seriously considered as a means of improving sediment and possibly ice conveyance through an ice-jam-prone reach of the Winooski River at Montpelier, Vermont (Dubois and King 2005) (Fig. 10). Recreational Management, Inc., developed preliminary plans for a whitewater park consisting of a series of U-drops and spur dikes at Oil City, Pennsylvania (Fig. 11). The project would be located near the mouth of Oil Creek where the ice historically jams against thick frazil ice deposits in the Allegheny River (Tuthill 2006). After serious consideration and debate, both projects were shelved because of uncertainty about the possibility of increased breakup ice jams and related flooding as a result of the structures. This uncertainty stems in large part from the lack of research, design tools, and design guidance on river restoration structures on ice-affected rivers.

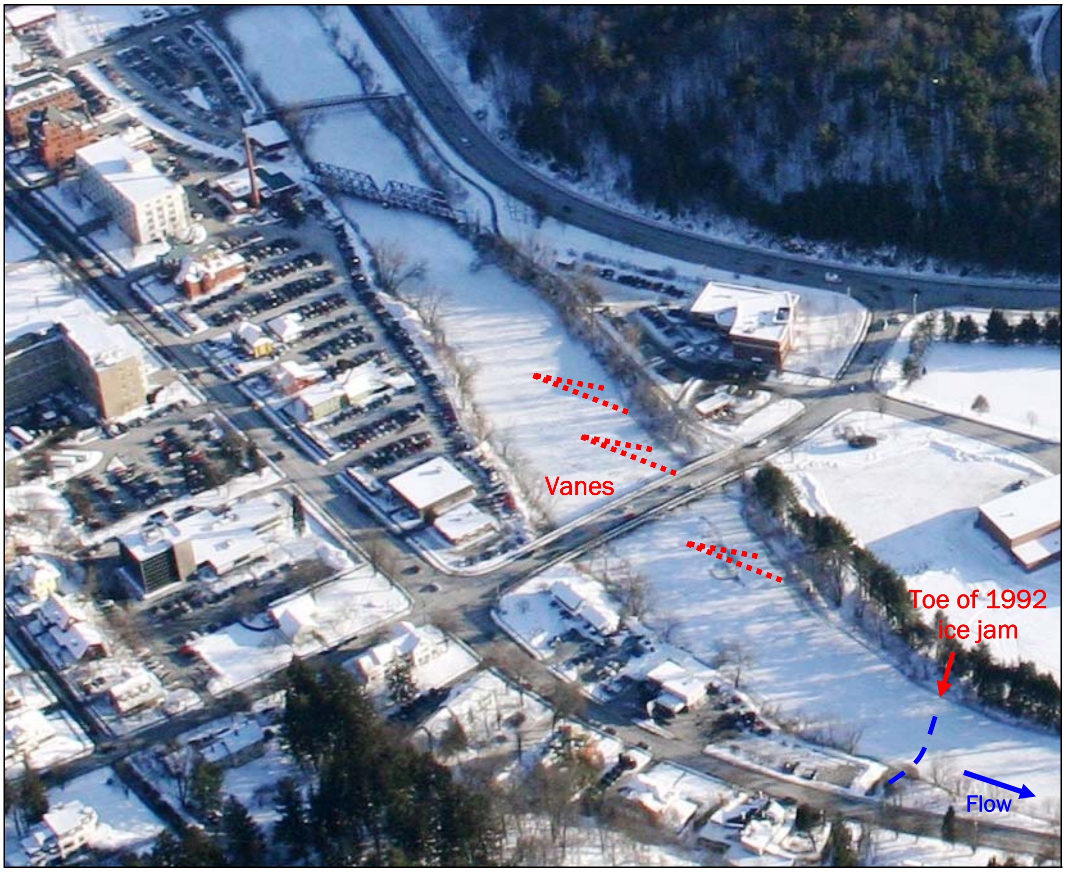
Because of this uncertainty, the conservative approach would be to avoid locating river restoration projects in sections of river with a known history of breakup ice jams and ice jam flooding. It is important to consider that, once built, even if its effect is neutral, an in-stream structure may be perceived as the cause if a severe ice jam does occur at the site. Also, because these projects are costly, locating them at known ice jam sites may make poor economic sense, since periodic repair or replacement may be needed following ice events.

3.3 Survivability of In-Stream River Restoration Structures on Ice-Affected Rivers

The potential for ice damage to in-stream structures ranges from minimal during the freezeup period to considerable during breakup. Because these structures represent a significant investment to build and maintain, it is important to consider their chances of long-term survival in the ice environment.

3.3.1 Freezeup Period

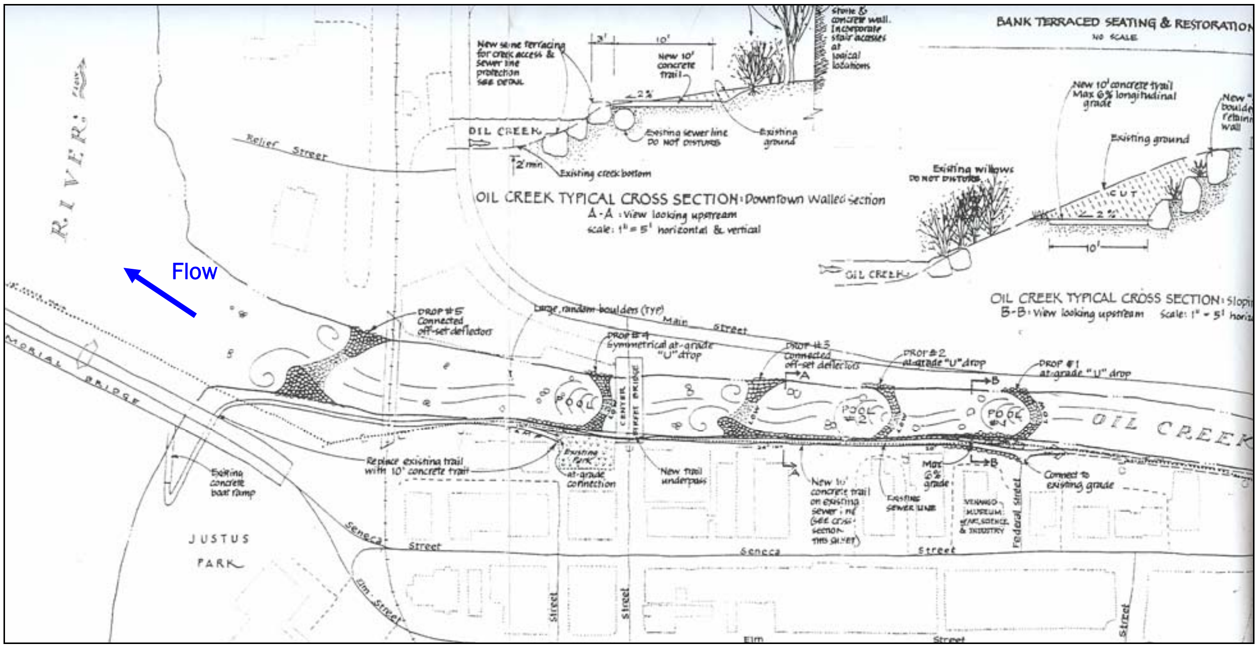
During freezeup, discharge is typically low, allowing ice to form gradually around the structures' sides and along the banks in between, as illustrated in Figure 7. This shorefast border ice may actually protect the structures and banks from damage caused by ice impact. Because the structures are typically constructed of loose rock with some flexibility, static ice pressure due to thermal expansion of a sheet ice cover is not an important factor.



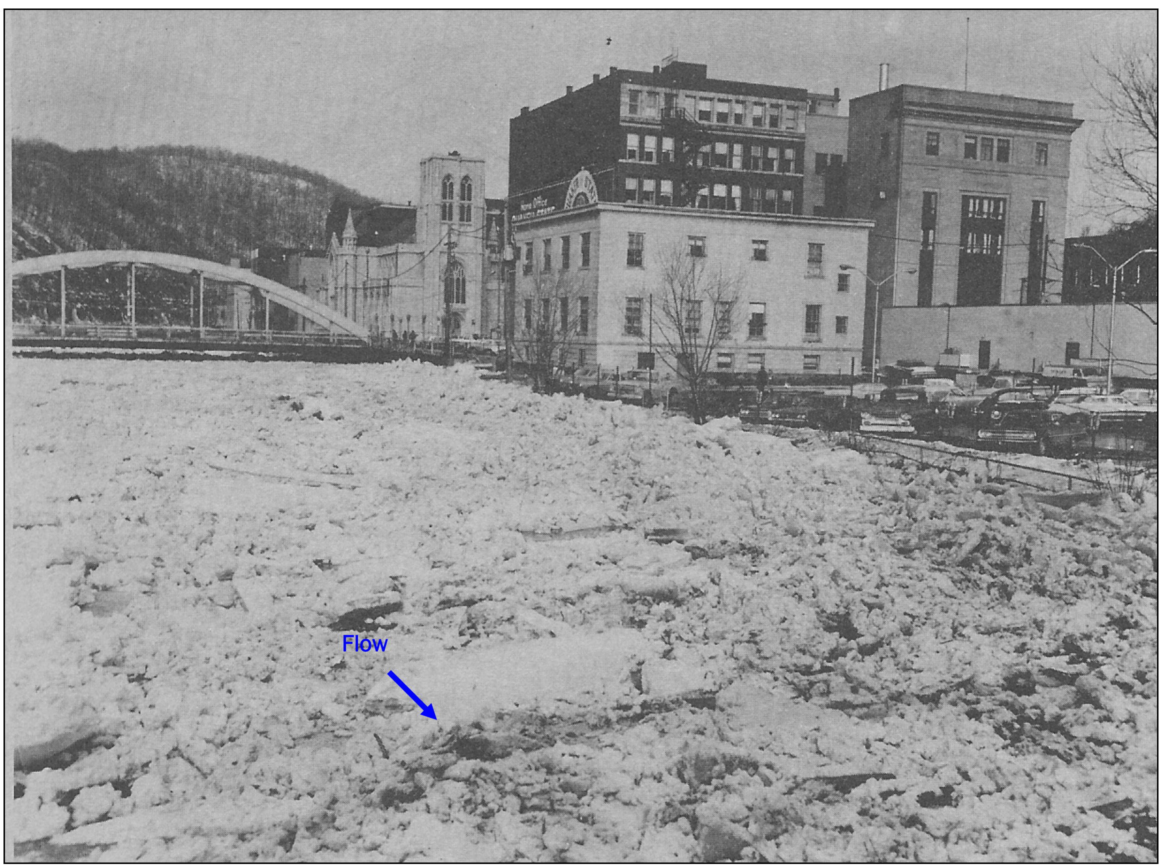
a. Proposed rock vanes to improve flow conveyance
through ice-jam-prone section near the Bailey Avenue Bridge.

b. Ice jam (same area as top photo) that flooded the city on 12 March 1992. (Photo by George W. Wood.)

Figure 10. Winooski River at Montpelier, Vermont.



a. Conceptual plan for whitewater on Oil Creek.
(Plan by Recreational Engineering and Planning, Boulder, Colorado.)



b. Severe breakup ice jam in early 1980s.

Figure 11. Oil Creek in Oil City, Pennsylvania.

3.3.2 Breakup Period

During river breakup, ice forces on in-stream structures can be extreme. Because high stages often accompany the breakup surge, the ice forces can act over a wide range of depths from the river bed to above bank top.

The designer needs to consider the site of the RR project with respect to the breakup regime on the river, since potential ice damage varies greatly with location. Section 3.2.1 describes breakup ice processes and the common causes and locations of breakup ice jams, and Section 3.2.2 discusses how in-stream structures might affect breakup processes. In terms of location and expected ice impacts during breakup, potential project locations fall into three general categories: 1) breakup ice effects in the project area are expected to be minimal; 2) the breakup ice run is expected to transport ice past the project area without stopping; and 3) the project site is a known or likely ice jam location.

Under the first category, minimal breakup ice damage to in-stream rock structures would be expected. An example would be an in-stream structure that is located a short distance downstream of a natural feature or structure that reliably retains ice from upstream; as a result, little or no breakup ice would pass the site. Under the second category, large ice floes would be expected to displace some of the structure rocks in instances where median rock size is less than twice the ice thickness (Sodhi and Donnelly 1999). Methods of minimizing rock displacement are discussed in the next section. The third category probably represents the greatest potential for damage of in-stream rock structures, both from direct contact of large moving ice floes and also from under-ice hydraulic scour should the ice jam at the structure. Though different from the above-described in-stream structures, hydraulic scour beneath an ice jam was identified as the cause of damage to a pilot cap placed over contaminated sediments in the Grasse River in 2003 (Alcoa 2004). The possibility of an RR project increasing breakup ice jam potential plus the probability of ice damage to the structures are reasons for caution when designing RR measures in sections of river that are prone to ice jams.

3.4 RR Structure Design to Minimize Ice Damage

The potential for ice damage to RR structures can be minimized by 1) choice of project location with respect to ice processes; 2) stone size design and placement; and 3) use of ice-resistant design features. The previous section discusses project location with respect to the ice regime. Although avoiding sites where severe ice impacts are expected is advisable, doing so may not always be possible. Also, sizing rock such that the median stone diameter is two to three times the maximum ice thickness, as recommended by Sodhi and Donnelley (1999), may not be practical on northern rivers where the maximum ice thickness typically reaches 1.5 ft and can exceed 2.0 ft. Remaining options, in addition to accepting some degree of ice damage during extreme events, include careful stone placement and incorporation of ice-resistant design features.

Through experience, the Natural Resources Conservation Service (NRCS) in Vermont has developed a rock vane design that is highly resistant to ice action. The purpose of these vanes is to stabilize the banks of the Winooski River, which, at some locations, can experience dynamic breakup ice runs. The vanes, constructed of large quarried stone 3–4 ft in diameter, resemble tilted ramps that extend out into the river, a useful feature in terms of providing equipment access during construction. The stones are placed one at a time by a large excavator with a thumb on the bucket. To minimize ice impacts, the upstream sides of the vanes are inclined at a low angle (about 15°) while the downstream side of the vanes is quite steep (Fig. 12). This allows the ice to ride over the top of the structure and minimizes displacement of the rocks. Modified log trucks with cherry picker arms are used to transport and unload the rocks to the site. In addition to aesthetics, the NRCS rock vanes have the advantage over a traditional riprap revetment in that only narrow access points are needed to construct them, resulting in less disturbance of the river bank and riparian vegetation[1].

[1] This paragraph is based on discussions and a site visit with Danny Peet of the Williston, Vermont, office of the NRCS.

Figure 12. NRCS ice-resistant bank stabilization vane in Winooski River near Richmond, Vermont.

4 Summary and Conclusions

This report provides ice-related design guidance for river restoration structures such as rock vanes, cross vanes, and rock weirs. The report discusses how these projects may affect the local ice regime during ice formation and ice breakup periods as well as survivability of the structures in the river ice environment. For the freezeup period, a major concern would be frazil retention at the structure(s) causing freezeup ice jams and flooding where none occurred before. For breakup, concerns are possible ice jam initiation and flooding, and also ice damage to the structure.

Based on observation of existing RR structures, water velocity criteria, and ice arching theory, the report provides guidelines to predict the effect of in-stream structures on freezeup ice processes. This study recommends that, to avoid thermal ice cover formation and arching of frazil ice pans, approach velocities upstream of an in-stream structure should be at least 1.5 ft/s, and the narrowest gap formed by the structure should be at least four times the expected diameter of the largest frazil ice floes. Simple design methods and models are described, as well as techniques for collecting bed slope and water velocity data necessary for predicting frazil ice transport, ice cover formation, and ice type, with and without project.

How an RR project may affect ice breakup, transport, and ice jamming is more difficult to predict. The report offers preliminary guidance discussing project location with respect to breakup processes and what effect the structures might have, and also the expected degree of ice damage. Because of the uncertainties regarding the effect of in-stream structures on the breakup process and the current lack of design tools, this report recommends against locating RR projects at sites of known ice jams and floods. Also, should a jam occur after construction, even if it had no effect, the project could be perceived as the cause.

Finally, ice-resistant design methods are described for rock RR structures. These methods, developed by the Vermont NRDC and Vermont Agency of Natural Resources, include careful placement of structural components and also inclining the structures' upstream face toward the flow at a low angle so the ice floes will ride over the top without displacing the rocks.

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14. ABSTRACT

Modern river restoration and streambank stabilization projects constructed of natural materials are gaining favor over traditional materials such as riprap and concrete. These new structure types provide a more aesthetic and lower-cost means of controlling bed and bank erosion, while improving flow diversity and habitat. Little design guidance exists for these structures on ice-affected rivers, however. This report provides basic design guidelines for these in-stream structures in the ice environment. Critical design questions are whether the structure or project will cause ice jams where none occurred before and also how well the structures will survive ice processes. For the freezeup period, simple water velocity and ice arching theory may be adequate to predict whether an in-stream structure will retain or pass ice. Predicting the structures' affect on breakup ice jam formation is much more difficult and, because of this uncertainty, it is recommended that designers avoid locating these types of in-stream structures in sections of river known for destructive breakup ice jams and ice jam flooding.

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