Salmon River Experimental Ice Boom: 1989-90 and 1990-91 Winter Seasons

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US Army Corps of Engineers

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Abstract

The city of Salmon, Idaho, is affected by flooding resulting from a frazil ice jam, known as the Deadwater jam, which forms annually on the Salmon River. Because the river has considerable environmental, economic, aesthetic, and recreational value, an innovative approach to frazil ice control is needed. The steep slope and turbulence of the river also add to ice control design constraints. Past investigations have examined a number of different methods to control the ice. This report documents two years of testing of an experimental ice formation boom located upstream from the city of Salmon. The observations show that boom configuration is an important factor in ice capture efficiency, and that conventional boom siting criteria may be modified under certain conditions.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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Cold Regions Research & Engineering Laboratory

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Kathleen D. White, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this work was provided in part by the Walla Walla District, Corps of Engineers, and by CWIS 32693, *Monitoring Ice Accumulation Characteristics.*

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KATHLEEN D. WHITE

INTRODUCTION

The city of Salmon, Idaho, has frequently experienced flooding along the Salmon and Lemhi rivers caused by frazil ice jams on the Salmon River. The ice jams generally originate in a slow-moving reach of the river known as Deadwater, about 42 km downstream from the city, and progress rapidly upstream. Ice jam flooding occurs at Salmon about one year out of three. Recent flood damages include $1.0 million in 1981–82 and $1.8 million in 1983–84 (U.S. Army Corps of Engineers 1986).

CRREL, in association with the U.S. Army Engineer District, Walla Walla, has been involved in researching the ice jam flooding problem at Salmon since 1982. This effort has included 1) identification of frazil ice jam initiation areas both upstream and downstream from Salmon, 2) location and characterization of frazil ice production areas, 3) collection of Deadwater ice jam data such as ice thickness, stage, and progression rates; and 4) development of numerical models of ice jam progression and its effects on stage (Cunningham and Calkins 1984, Earickson and Gooch 1986, Zufelt 1987, Axelson et al. 1990, Axelson and Zufelt 1990, Zufelt and Bilello in prep).

As part of this research, several experimental frazil ice control systems or parts of systems have been tested at Salmon and in CRREL's refrigerated flume facility (Perham 1983, Zufelt 1987, Axelson 1990, Foltyn 1990). These research efforts have been directed at controlling the transport and, to a lesser extent, production of frazil ice in the Salmon River through the use of an ice control structure located upstream from Salmon. An experimental ice boom was designed to test this concept (Axelson et al. 1990).

This report describes the operation of the experimental ice boom during the 1989–90 and 1990–91 winter seasons. Conventional ice boom design is reviewed and observations of the performance of the first, conventionally designed ice boom during 1989–90 are presented. These observations indicate that the capture efficiency of a formation ice boom is related to its configuration, the hydraulic and climatic conditions at the site, and the internal strength of the frazil ice transported to the boom. Before the 1990–91 test season, modifications were made to the boom configuration to take these factors into account and improve the boom's performance. The results of this second season of testing confirm that boom configuration is an important factor in boom capture efficiency, and suggest that conventional siting criteria based purely on hydraulic considerations may be modified in certain cases.

ICE BOOM DESIGN

Ice booms, among the simplest and most economical ice control structures, have the added benefit of being temporary structures that can be placed seasonally in the water. Booms are generally designed for either of two purposes: to collect or direct the path of floating pieces of broken ice (brash ice), or to aid in the formation of an ice cover. In the past, ice boom design was based on the expected boom loading. This is acceptable in the case of booms primarily used to control brash ice. Ice booms used to direct floating ice blocks away from navigation channels or to collect broken river ice have operated successfully on many large rivers and canals. Perham (1983, 1988) uses the terms *diversion* (or *shear*) *booms* and *retention booms* to describe these two different functions. Because their purpose is to control the direction or location of ice pieces, we suggest that these types of booms also be termed *control booms*. Control ice booms can

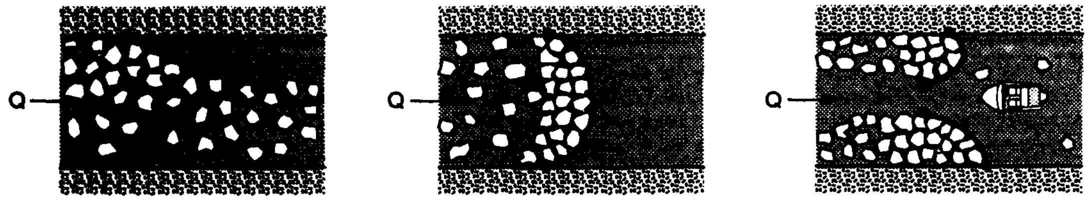


Figure 1. Examples of ice control booms.

extend the whole width of a river or can be designed with an opening to allow navigation (Fig. 1).

Ice booms have sometimes been used to control frazil ice, which is the major cause of ice jam flooding, disruption to navigation, and intake blockage in northern rivers. Since frazil ice is produced in highly turbulent, supercooled water, one way to prevent its formation is to minimize supercooling. This can be accomplished by encouraging a stable ice cover to form on the river where it would not occur naturally, or by accelerating the growth of the natural ice cover. The ice cover insulates the water beneath, thus preventing supercooling of that particular reach. In order to effectively suppress frazil ice production, rapid initiation and growth of the ice cover is desirable. In some cases, the rapid formation of an ice cover can be achieved through the use of an ice boom. But since the highly turbulent flow conditions conducive to the formation of frazil ice are usually associated with relatively high velocities and water slopes, hydraulic control of the river must often be provided to decrease the velocity enough to allow a stable ice cover to form. Hydraulic control can be achieved by constructing a weir in the river, which raises the water surface elevation and decreases velocity. An upstream boom in combination with a weir is then used to collect frazil ice and initiate an ice cover that can progress upstream. In some cases, an upstream dam may be used to provide hydraulic control in the form of temporary flow reduction during the initial freeze-up to allow initiation of an ice cover at a boom (Deck and Gooch 1984). Once the ice cover is established, the normal flow conditions may be resumed.

Ice cover formation booms may be grouped as a subset of control booms; their primary purpose is to provide the necessary conditions for the rapid formation of a stable ice cover, rather than to simply collect ice. The design considerations important in each type of boom are sufficiently different that they should be categorized separately. Therefore, we choose to define formation booms as those booms that are designed to aid in the rapid formation of an ice cover. As noted previously, formation booms can be designed to operate either independently or in conjunction with some form of hydraulic control.

Conventional boom design criteria

Ice boom design currently follows the same general principles as debris boom design (Kennedy and Lazier 1965). The hydraulic conditions of the river and the magnitude of the expected boom loads are used to determine boom location. The boom configuration is a result of the load distribution on the boom, which is a function of the river geometry and hydraulics. Conventional boom design does not differentiate between control booms and formation booms.

One of the primary functions of conventionally designed ice booms is to maximize the stability of the unconsolidated floating ice collected by the boom so that it will eventually become consolidated by freezing of the surface layer and/or compaction. Perham (1983) points out that an understanding of the natural formation of an ice cover is useful in designing an ice boom because the processes are essentially the same.

In natural ice cover formation, ice pieces in transport initially stop, usually due to an obstruction of some type, a sudden change in slope from steep to mild, or in a river bend. Once an ice cover initiates, some of the additional ice transported to the initiation point will collect, and the remainder will underturn and continue transporting downstream. The progression rate of the upstream edge of the ice cover is a function of the amount of ice in transport, the thickening and shoving of the ice cover, and the capture efficiency of the ice cover. The ice discharge is controlled by temperature, frazil ice production, and upstream accumulation. Thickening and shoving are related to the river geometry and hydraulics, and the strength characteristics of the ice cover. The capture efficiency is the ratio of the amount of ice that collects in the ice cover vs. the total ice transported to the ice cover. Since the rapid ice cover formation associated with a high capture efficiency is generally desirable, booms are usually located in areas where underturning will be minimized.

Underturning of ice blocks has been studied by a number of researchers. Stable ice blocks will tend to collect, while unstable blocks will underturn and continue transporting. Uzuner's (1977) discussion of floating ice block stability summarizes the research to date. In this discussion, he reports various criteria suggested by researchers including velocity, Froude number, and several modifications of Froude number (see, for example, Ashton 1974, Pariset and Hausser 1961). He reports such limiting values of critical velocity as 0.69 m/s (MacLachlan 1926), and 0.61 m/s (Kivisild 1959). Cartier (1960) found the upper limit for block stability to be 0.7 m/s. Cousineau (1960) reports the maximum velocity that will allow ice cover progression to be 0.69 m/s. Values listed by Uzuner and others for the limiting Froude number for stability are given in Table 1. Here, Froude number is defined as

$$F = \frac{v}{\sqrt{gd}}$$

where v is the velocity upstream of the ice cover (surface or mean), g is the acceleration due to gravity; and d is a length scale, generally the upstream water depth (h) or the ice floe thickness (t). Modified Froude number criteria include several listed by Uzuner (1977) and later modifications presented by Ashton (1974), Gogus and Tatinclaux (1981) and Daly and Axelson (1990).

Ice block stability criteria are used in siting both control and formation ice booms without discriminating between the different forms of ice (blocks vs. frazil) to be controlled. The U.S. Army Corps of Engineers (1982), in its discussion of site considerations for ice booms, states that booms should be located where the Froude number is less than 0.08 and the surface velocity less than 0.69 m/s. The forces exerted by the ice cover on the boom are also considered when siting an ice boom. A distance of five to seven times the river width upstream from the boom is estimated to be necessary before the ice forces are transmitted completely to the river bank. Any additional ice accumulation upstream from this point is considered to have a negligible effect on boom loading (Perham 1974). Ideally, the boom will be located so that the length of ice cover affecting the boom is within a gradually sloping reach. This rule of thumb is intended to minimize the forces on the boom because the thickness of an ice accumulation will be less in a pool than in a riffle section, thus decreasing the possible ice load.

Table 1. Critical Froude number for the block stability based on upstream water depth.

Froude no.	*Researcher*
0.08	Kivisild (1959)
0.13	Cartier (1960)
0.11	Mathieu and Michel (1967)
0.087	Newbury (1968)
0.06–0.09	Oudshoorn (1970)
0.12	Michel (*1971)
0.08–0.09	Tatinclaux et al. (1976)

*Block thickness to length ratio 0.25.

In conventionally designed booms, configuration is driven by the distribution of the expected load on the boom, which itself is a function of river geometry and hydraulics. Generally, they are anchored on either side of a river, with the boom assuming a sag downstream. The location of the anchors is usually chosen to equally distribute the expected forces, so that the axis of the boom anchors is often perpendicular to the direction of flow. For a single sag boom, each anchor would carry half the expected static load (Perham 1974). In the case of wide rivers, the forces typically exerted on booms are too great to allow a single sag boom. In this situation, multiple anchoring points are used, resulting in a scalloped edge boom configuration (Fig. 2). Perham (1974, 1983) presents several design calculations for conventionally designed booms.

Alternative boom design

Because formation booms are often required for steep, turbulent rivers, the optimum location for ice control purposes may be a site deemed marginal or unacceptable by the conventional boom design guidelines summarized above. For example, a site characterized by a Froude number exceeding 0.12 would be considered hydraulically marginal. River bed geometry might limit boom sites to short, pools between riffles. These situations require alternatives to conventional boom design.

In one such case, Burgi (1971) conducted laboratory experiments to determine the optimum boom configuration for a hydraulically marginal location. He used a model boom structure to capture model ice (0.32 cm, hemispherical, cohesionless, low-density polyethylene beads). He observed a funneling effect in a conventional sag type boom that caused the beads to move towards the center,

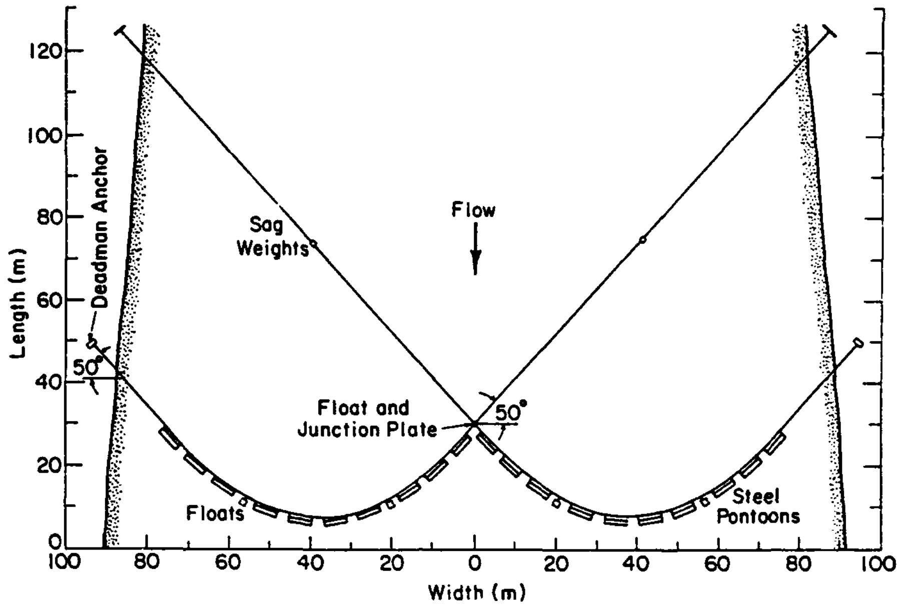


Figure 2. Example of scalloped-edge boom design for wide river (Allegheny River ice boom, Oil City, Pennsylvania).

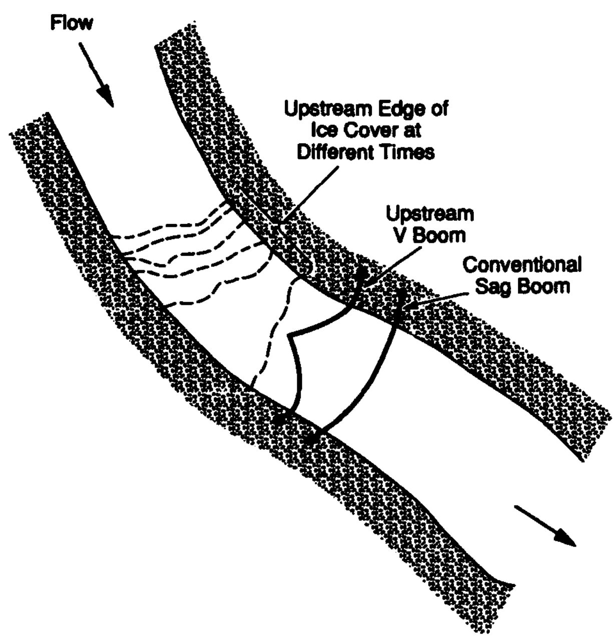


Figure 3. Results of run no. 10 by Burgi (1971) using hemispherical low-density polyethylene beads to model ice collection using combination of "upstream V" boom and conventional sag boom. In this case, the Froude number was 0.2.

high velocity, portion of the boom, where they became unstable more easily than in lower velocity areas. He also found that a boom with less cable sag retained more model ice than a boom with a large cable sag because the funneling effect was minimized. In addition, Burgi experimented with the use of multiple sag booms to stabilize an ice cover, and with an "upstream V"-shaped boom (Fig. 3). Multiple boom combinations of upstream V and conventional sag booms were also tested. He concluded that single booms or multiple booms with the upstream V configuration produced more stable ice covers than the conventional sag boom, in part because of the increased stability of ice wedged between the banks and the boom. He also found that closely spaced, multiple booms produced a more stable ice cover than booms spaced farther apart. No prototype test results are reported.

SALMON RIVER ICE CONTROL BOOM

The effects of boom configuration (dictated by hydraulics) on the performance of a formation boom are illustrated in a case study of an experi-

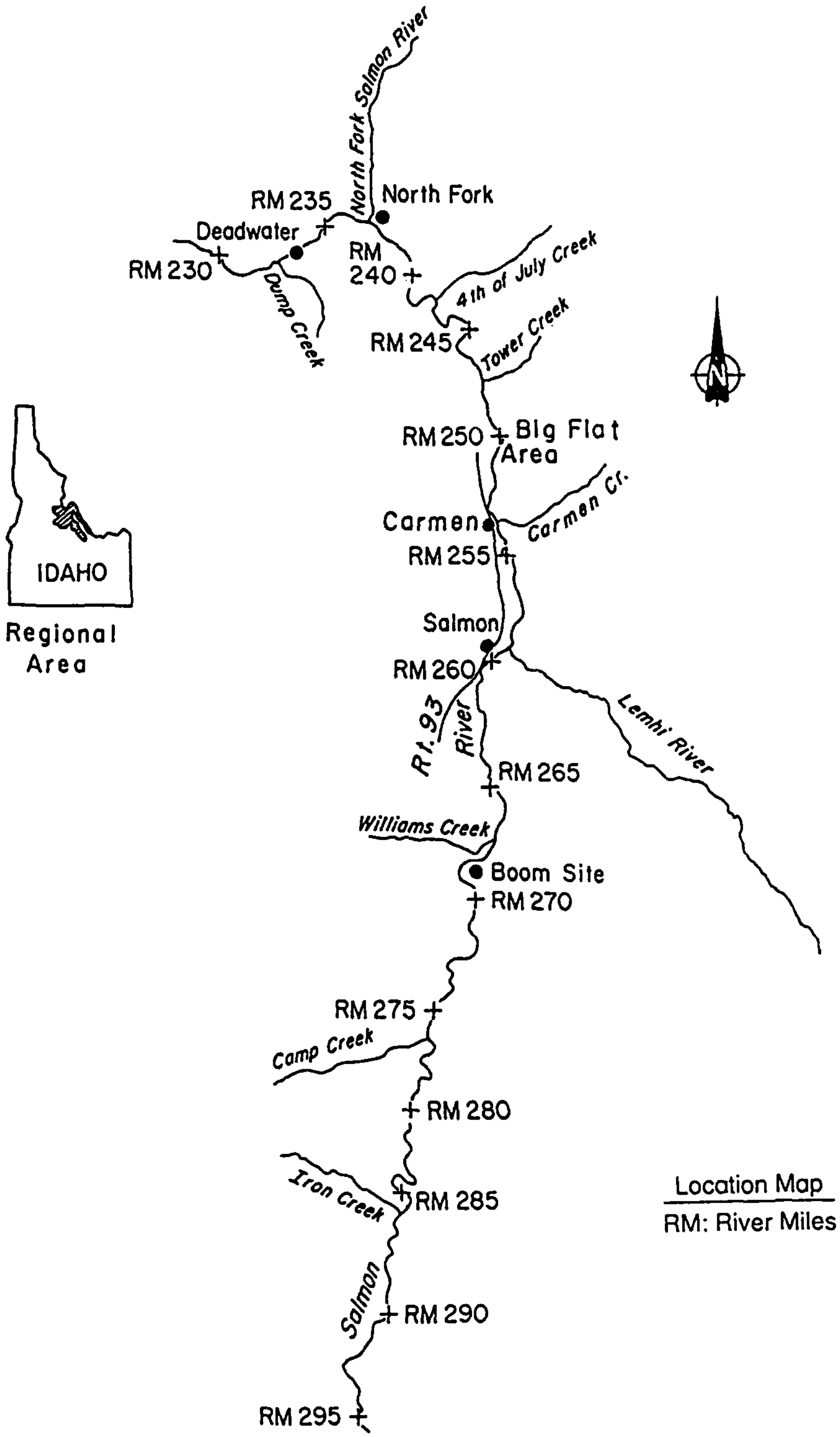


Figure 4. Salmon River study area. Distances along river are miles from mouth.

mental ice boom at Salmon, Idaho. A location map of the Salmon River is shown in Figure 4. The tremendous frazil ice production capacity of the Salmon River is a result of its steep slope, shallow depth, and high turbulence level, combined with the extended periods of cold weather common in this area during the winter. This frazil ice forms an ice jam known as the Deadwater jam, which causes flood related damages at Salmon. The jam generally originates in the vicinity of the upper end of the slow moving Deadwater reach at river kilometer (RK) 375 or river mile (RM) 233, where the slope changes suddenly from steep to mild. Ice jams also form at other sites, such as the confluence of the Salmon River and Fourth of July Creek at approximately KM 390 (RM 242.3). Frazil ice that collects at these initiation points eventually freezes in place and creates a barrier against which additional frazil ice accumulates. The resulting ice jam(s) progress upstream toward the city of Salmon.

Below Carmen Bridge (KM 409.7 or RM 254.6), the Salmon River is characterized by sparse residential development. Grazing is the predominant use of the overbanks, and the Deadwater ice jam results in only small amounts of local flooding with little damage. Residential and commercial development is concentrated along the Salmon and Lemhi rivers near the confluence. If the ice jam progresses near or beyond the confluence of the Lemhi River (KM 415.7 or RM 258.3), backwater effects can result in more extensive flooding along the Lemhi River. If there is sufficient frazil production and transport in the Lemhi River when the Deadwater jam reaches the confluence, a frazil ice jam can also form in the Lemhi River, causing additional flooding. When the Deadwater ice jam progresses into or past Salmon (KM 417 or RM 259), it results in more extensive flooding within the city because of higher water levels along the Salmon River.

Design considerations

Previous studies (e.g., Earickson and Zufelt 1986) have indicated that an ice control structure designed to create an ice cover upstream from Salmon might be successful in minimizing ice jam flooding at Salmon. The ice cover would serve a dual purpose: to collect a portion of frazil ice that would otherwise be transported to the downstream ice jams, and to suppress the production of frazil ice that would otherwise be produced in the ice-covered reach. The purpose of such an ice control structure would be to minimize ice jam flooding in Salmon. Therefore, the ice control structure would need only to control enough ice to keep the Deadwater jam from extending too far upstream past the bridge at Carmen. In other words, the Deadwater jam would be allowed to progress about 35.4 km (22 miles) to the vicinity of Carmen bridge, so that the ice control structure would need to control a maximum of approximately 16 km (10 river miles) of ice.

The ice control structure would not be expected to capture all of the available upstream ice: the capture efficiency of a progressing ice cover varies with the hydraulic characteristics of the river and with the quantity and characteristics of the ice supply. In most cases, very little frazil ice will be transported beyond a rapidly progressing ice jam. At other times, some frazil ice will continue to be transported beneath an ice cover.

The location of an ice control structure in this case must take into account the amount of frazil ice produced between the ice control structure and the Deadwater ice jam, the capture efficiency of the structure, the properties of the ice cover generated upstream from the structure, and the expected decrease in frazil ice production due to the presence of an ice cover. The river geometry and hydraulic characteristics of the river will further constrain the location of an ice control structure, as will the effect of an ice control structure on open-water flood events. Since the purpose of the ice control structure is to promote a stable ice cover, it must be sited so that the necessary hydraulic control is achieved over the range of expected flows. Due to environmental constraints, the most favorable ice control design on the Salmon River is considered to be one with minimal impact on the hydraulic conditions in the river, which preferably could be placed in the river on a seasonal basis. A formation boom would seem to be an ideal solution. However, because the river is characterized by a riffle-pool morphology in the study reach (KM 375-518 or RM 233-322), and has an average slope of about 0.003, boom sites that meet the conventional hydraulic criteria are quite limited, if they exist at all.

The most likely site for a formation boom appeared to be a pool located about 14.5 km (9 miles) upstream from the City of Salmon (KM 432.1 or RM 268.5). At this point, the river is about 85 m wide and 1.5 m deep. The pool is about 500 m long or about six river widths. However, the bed geometry at the downstream end of the pool limits the effective pool length to less than six river widths. Water slope averages 0.0011 in the pool and 0.0029 in the reach just upstream. With surface water velocities in the range of 0.6 to 0.9 m/s (2–3 ft/s) at the expected winter flows of 25–37 m^3/s (900–1300 cfs), Froude numbers ranged from 0.16 to 0.23 based on an average upstream water depth of 1.5 m and the surface velocity. This site is considered unacceptable, or hydraulically marginal at best, for the formation of an ice cover using a boom alone, according to the conventional velocity and Froude number criteria. However, downstream ice jams had progressed through or originated in this reach of the river in the past (most recently in 1988–89), and there was some promise that an ice cover could be formed in this location under the right conditions.

In order to obtain data on the test site, an experimental boom was installed during the winters of 1989–90 and 1990–91. The purpose of the experimental ice boom was to provide an opportunity to gather information on the hydraulic and meteorological characteristics of the site as well as needed data on frazil ice production and transport in the Salmon River. It was hoped that the boom would accumulate enough frazil ice to test the concept of an upstream ice control structure at Salmon.

The experimental ice formation boom consisted of twelve boom units, attached by chain to a wire boom cable. Each boom unit was made up of three 0.3- × 0.3- × 6.1-m-long Douglas fir timbers connected as shown in Figure 5. The 3.8-cm-diam. galvanized 6 × 19 independent wire rope center (IWRC) cable is attached to deadman anchors buried on each bank of the river. A 3.5-cm-diam. cable acts as a mechanical fuse at the right end of the cable so that, if extremely high loads were to occur, the structure would fail at the fuse and minimize damage to the boom itself. The estimated rated cable

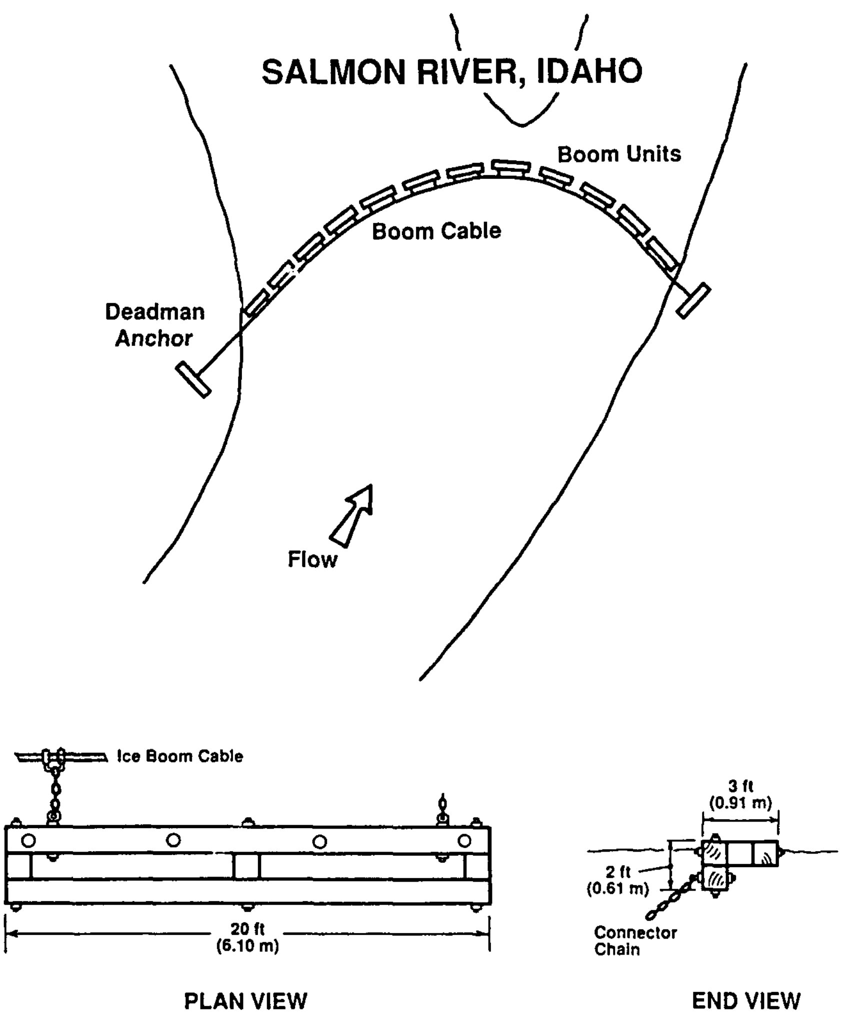


Figure 5. Salmon River experimental ice boom details.

strength of 772 kN and fuse strength of 625 kN are approximately double the static design tension load of 391 kN.

The boom was located close to the downstream end of the pool to obtain a distance as close to five to seven river widths as possible between the boom and the upstream riffle. The boom could not be located at the downstream limit of the pool because an island in the center of the channel at the pool's downstream end and the shallowness of the left portion of the channel cause velocities to increase there. Therefore, the actual distance from the boom to the upstream pool limit was about four to five river widths.

The boom was designed using the conventional force-based design for a single segment sag boom, with each anchor carrying approximately half the expected load. It was sited on a river bend, with the majority of flow and highest surface velocities found on the outside of the bend. The right anchor point was located downstream from the left anchor point to equally distribute the loads between the anchors, with the result that the maximum sag point of the boom was very close to the estimated point of maximum velocity. Due to the channel geometry, the boom was partially grounded near the left bank during low and normal flows. The head loss caused by the boom alone varied with flow and the amount of ice collected at the boom, but was generally in the range of 5 to 20 cm.

The ice boom was instrumented to measure tension load levels in the boom cable. Water levels just upstream and downstream from the boom were measured with pressure transducers. Other data collected at the test site included air and water temperature, dew point, wind direction and speed, and solar radiation. Velocity profiles were measured in open water conditions.

The relatively high surface velocities, which were estimated at 0.75 to 0.9 m/s (2.5 to 3 ft/s) just upstream from the boom, were expected to have a major effect on the boom's performance. The Froude numbers at these velocities (0.14 to 0.22) greatly exceeded those shown in Table 1. Consequently, capture efficiency of the boom was projected to be low. It was postulated, however, that once ice began to accumulate at the boom, the thickening of the ice cover would increase stage enough to decrease the Froude number and allow progression of the ice cover.

Winter 1989—90 test results

During the winter of 1989–90, the Deadwater jam formed and released several times. The jam never progressed more than 9.6 km (6 miles) above the Deadwater pool. Small amounts of ice did collect at the boom, but no appreciable ice cover formed. The poor capture efficiency of the boom was partially caused by the extremely warm winter conditions, which limited frazil ice production and thus decreased surface ice discharge. The combination of relatively high air temperatures and water temperatures (> 0°C) not only discouraged an ice cover from freezing in place, but melted ice that did accumulate. The average daily discharge measured at the USGS gage in Salmon was 28 m^3/s (1000 cfs) for the period November through February, which is in the low normal range of flows at Salmon during this time.

Some frazil ice did accumulate in lower velocity areas along the shores. As shore ice developed along both shores upstream from the boom, the effective river width was decreased. Shore ice growth at the upstream end of the pool narrowed the open water width to under 15.2 m (50 ft). This constriction compressed the frazil ice floes, increasing their density and hence their internal strength to some degree. The decreased flow area and added roughness of the shore ice caused a slight increase in stage for a given discharge. This slight increase in stage, combined with a smaller effective river width, was anticipated to encourage ice arching at the boom. However, no stable ice cover formed upstream from the boom.

Field observations and analysis of time-lapse video footage indicated that the frazil ice pans exhibited little internal strength and generally easily submerged under the boom. The floes were also observed to break up and pass between the timber boom units which, although normally spaced, had gaps that caused areas of localized high velocity. In addition to high surface velocities, the shape of the boom appeared to have significantly affected its capture efficiency by funneling ice to the point of maximum velocity. Instead of encouraging ice arching, the shore ice in the vicinity of the boom amplified the funneling effect caused by the boom configuration. No ice arching occurred within the funnel.

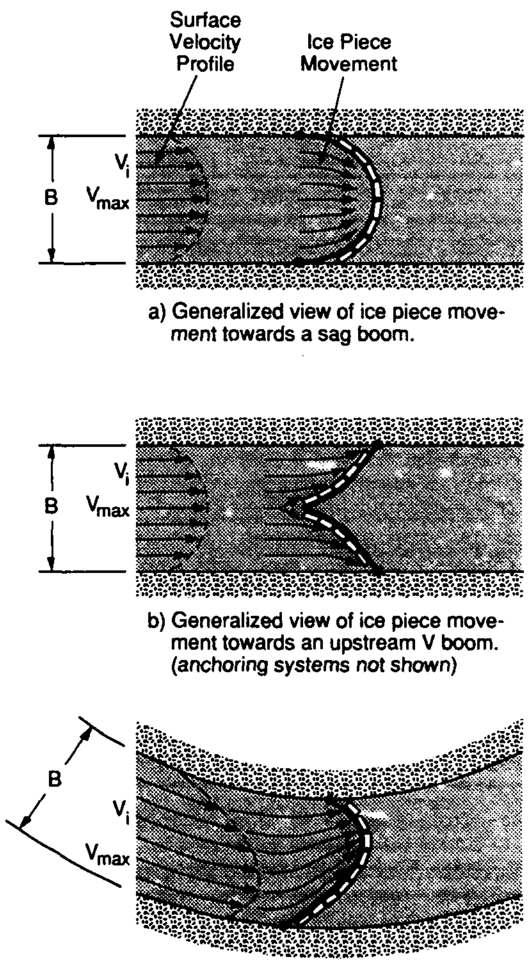
The winter season 1989–90 testing of the experimental ice boom did not provide an answer to our fundamental question: Will an upstream ice control structure capture enough frazil ice, and sufficiently suppress frazil ice production, to prevent the Deadwater ice jam from flooding Salmon? Based on this season's test results, one could conclude that a boom alone without hydraulic control of some type would not work at this site, and that hydraulic control would be necessary to achieve favorable conditions. However, the fact that the capture efficiency of the Deadwater jam was also much lower than normal during 1989–90 indicated that the low capture efficiency of the boom was not due only to the hydraulics. With this in mind, we decided to look for ways to improve the capture efficiency rather than simply conclude that the boom's low capture efficiency meant that an ice cover could not form upstream from the boom under any conditions.

We began by comparing the boom's performance to the natural ice jam that progressed through the site in the winter of 1988–89. Two major differences were noted. First, the increase in stage due to the jam was on the order of 0.6 to 1 m, significantly decreasing the velocities and Froude numbers in the pool. Use of a boom alone at this site could not increase stage to the same degree as the ice jam. The second major difference between the two years was air temperature. In 1988–89, the air temperatures were extremely low during rapid jam progression, with an average daily temperature of –25°C. These sustained low temperatures produced a large amount of frazil ice, characterized by a high surface concentration, which exhibited some internal strength. These stronger floes were less likely to submerge, and more likely to accumulate, than weaker floes, and they accumulated more easily with the combination of higher stage and low temperatures. As noted earlier, the winter air temperatures during 1989–90 were higher than normal, leading to smaller frazil ice production than in colder winters. Surface concentrations of frazil ice were therefore decreased, and the floes themselves appeared to be less buoyant and looser than those observed during colder conditions (notably, the previous winter). We theorized that if the ice floes transported to the boom had greater internal strength, they would be less easily broken up and submerged, and the capture efficiency would improve.

Given that weather and frazil ice characteristics could not be controlled, we turned to the boom design. Since some ice did collect at the boom, it seemed that the site hydraulics, although less than ideal, would not completely prohibit the formation of an ice cover. From the video observations, it appeared that the greatest obstacle to ice cover formation was the funneling of ice towards the high velocity, maximum sag point. Directing ice away from this point might allow an ice cover to form.

MODIFICATION OF SALMON RIVER ICE BOOM

The general relationship between surface velocity profiles and ice piece movement for both a sag-type boom and an upstream V-type boom is shown graphically in Figure 6. The sag-type boom will tend to channel ice pieces (or frazil ice floes) toward the center of the boom, coincident with the usual point of maximum velocity, as was observed with the first Salmon River ice boom and Burgi's tests of model sag booms. The upstream V-shaped boom, on the other hand, tends to direct the incoming floes toward the sides of the river, where the probability of deposition is higher. Although Burgi's upstream V-shaped boom held some promise as a solution at this site, it would have required the



a) Generalized view of ice piece movement towards a sag boom.

b) Generalized view of ice piece movement towards an upstream V boom. (anchoring systems not shown)

c) Generalized view of ice piece movement towards a shear boom in bend.

Figure 6. Idealized surface velocity profiles and resulting movement of ice pieces.

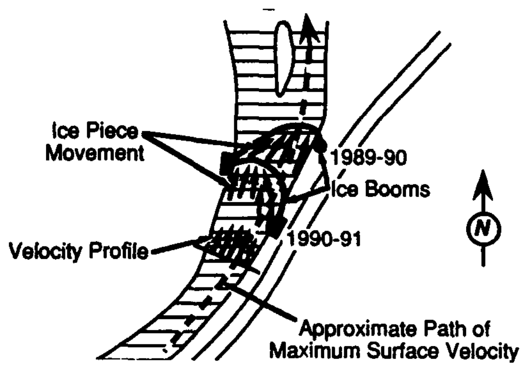


Figure 7. General view of ice piece movement due to difference in boom configuration.

construction and installation of several new anchors as well as reconstruction of the boom. Since the maximum velocity at this location is close to the right bank, a shear or deflection type boom such as the one illustrated in Figure 6c would essentially behave the same as half of an upstream V-shaped boom. The frazil ice floes would be directed away from the maximum velocities to the lower velocity areas with the hope of encouraging accumulation.

Consequently, the right anchor was moved approximately 73 m (240 ft) upstream in early fall 1990. In this configuration, the boom was located in deeper water with lower surface velocities, and the point of maximum sag was about 21.3 m (70 ft) to the west of the region of maximum surface velocity (Fig. 7).

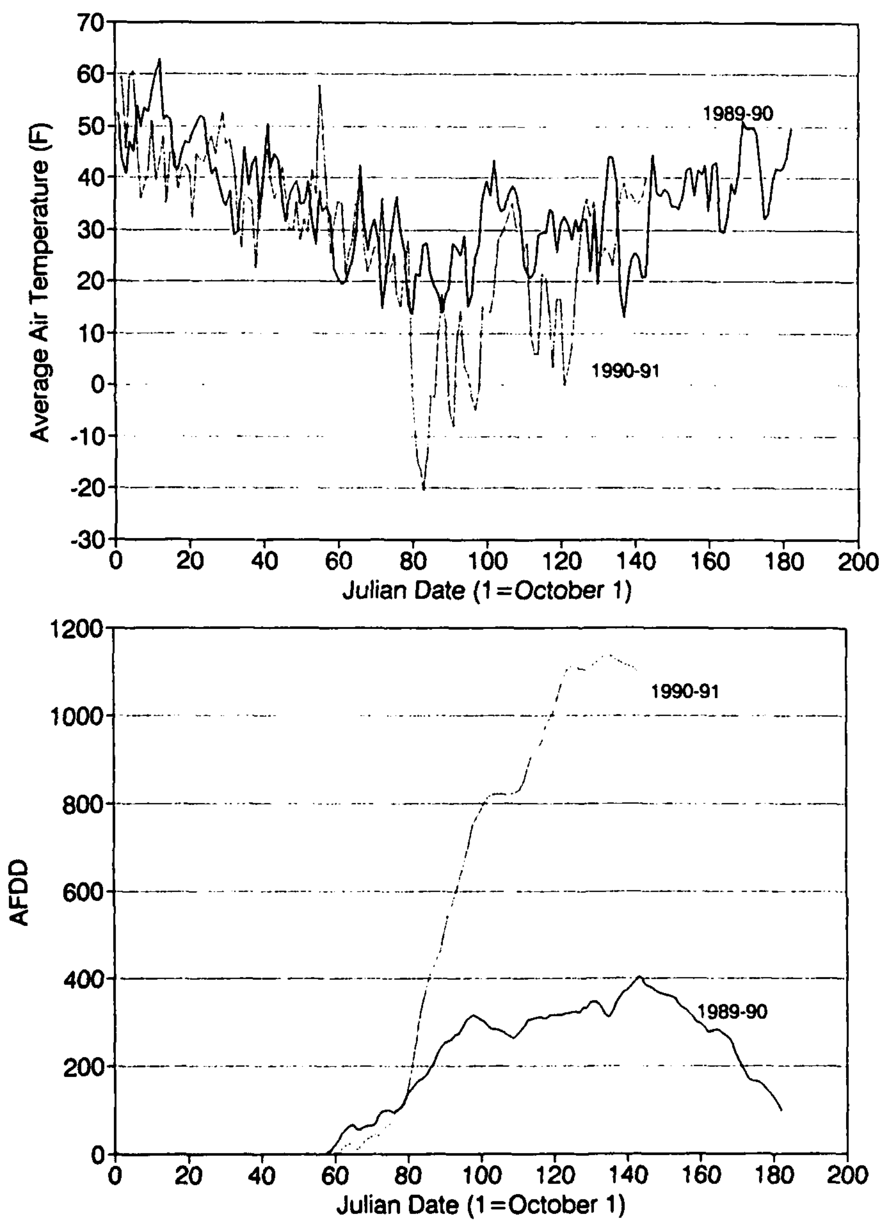


Figure 8. Air temperature data for ice boom test seasons (AFDD is accumulated freezing degree days).

Moving the boom anchor upstream also diminished the effects of the channel geometry at the downstream end of the pool so that surface velocities immediately upstream of the boom were smaller. In addition, the boom unit connections were relocated to decrease the distance between individual boom units so that the units on the right side of the river (the high velocity region) formed a virtually continuous surface barrier. This was intended to provide some directional control and to reduce the number of localized high velocity areas that allow frazil ice floes to easily push between boom units.

Winter 1990–91 test results

The 1990–91 winter was characterized by several periods of severe low temperatures (Fig. 8), leading to much greater frazil ice production than the previous test season, and the frazil exhibited higher internal strength than in 1989–90. The average daily discharge was similar to that of the previous season, about 27.7 m^3/s (980 cfs) for the period November through February. Both the boom and the Deadwater jam had higher capture efficiencies in 1990–1991.

Ice floes impinging on the virtually continuous right side of the boom were observed to travel along the barrier toward the point of maximum sag. The floes were moving transversely to the direction of maximum flow and experienced less force than if they had been moving parallel to the direction of the flow. Thus, stronger forces would be necessary to submerge the floes. The floes were also affected by shear forces caused by movement along the boom. The shearing of each floe against the boom (or against the ice cover accumulated at the boom) not only slows the movement of the floe but also tends to compress and thicken the floe, increasing its resistance to submergence and breakup. Frazil ice accumulation on the right side of the boom was primarily the result of frazil deposition in the form of shear walls (Fig. 9). On the left side of the river, ice accumulated via border ice growth on the boom and outwards from the shore, along with some frazil floe stoppage. This ice, which accumulated rather gradually, froze in place, allowing it to withstand greater forces than unfrozen ice. Figures 10a and b show the differences in funneling action due to the different boom configurations.

Figure 9. Typical frazil ice accumulation along right side of boom (13 December 1990).

a. Original boom configuration 19 February 1990; shore ice funnels frazil floes toward high velocity area. Note constriction at upstream end of pool.

b. Modified boom configuration 13 December 1990; combinations of shore ice along left bank and frazil ice accumulation on right side of boom funnel ice toward lower velocity area. Old right anchor marked "A," new right anchor marked "B."

Figure 10. Effects of boom configuration on shore ice growth, ice piece movement, and frazil accumulation.

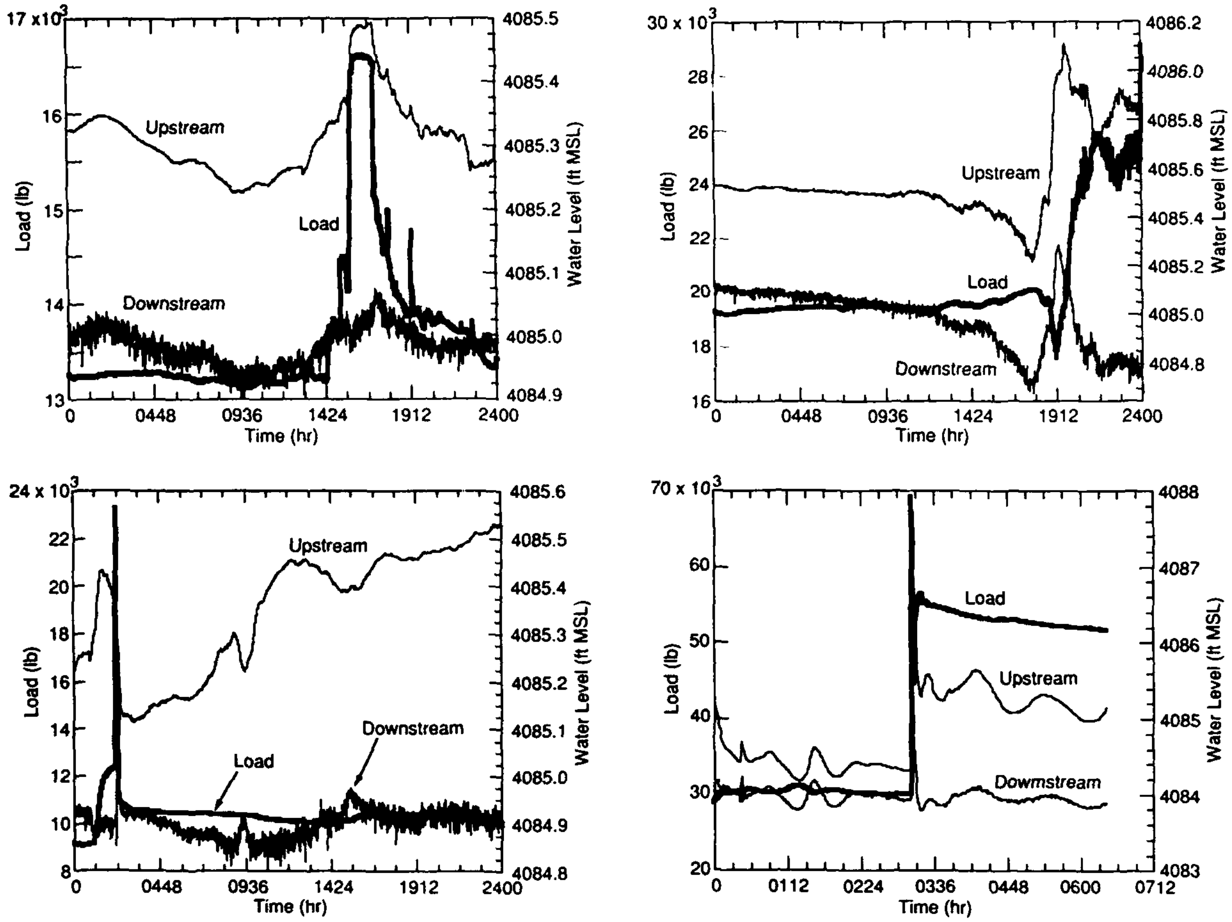


Figure 11. Portions of computer data record (load in pounds, water level elevation in feet MSL). Records show ice accumulation events.

Portions of the computer data record are shown in Figure 11 for several periods when the ice boom began collecting significant amounts of ice. The boom tension is the load measured by strain gauges in the load link between the boom cable and the right anchor cable. The upstream water level is measured by a 0 to 28.7 Pa (0 to 6 psig) pressure transducer just upstream from the right anchor, and the downstream water level is measured by another pressure transducer at the right bank just downstream from the boom's point of maximum sag.

In virtually every ice collection event recorded during the 1990–91 winter season, the process is a dynamic one involving rapidly increasing loads over a short time period. For example, on 20 December, the boom tension increased 178 kN (40,000 lbf) in under a minute, followed by a rapid decrease of about 111 kN (25,000 lbf). Similar dynamic load records are contained in Perham (1974) and Perham and Racicot (1975). The rapidity of the accumulation process implies both that surface ice concentration was high, and that the floes had enough internal strength to withstand rapid accumulation without the benefit of being frozen in place. Once frozen, the ice accumulation can withstand large loads without failure.

The time-lapse video record clearly showed the increased effectiveness of the reconfigured boom in capturing and stabilizing frazil floes. Several events were recorded in which ice accumulated at the boom and progressed upstream only to fail as temperatures warmed. These events coincided with periods of high boom load as recorded by the data acquisition system. Eventually a jam formed upstream from the boom during the night of 19 December. A decrease in discharge recorded at the USGS gage during this time appears to have been the result of water going into storage because of this ice jam and another cover that formed simultaneously at about KM 435.3 (RM 270.5). The boom ice jam progressed to just below KM 435.3 (RM 270.5) by the morning of 22 December, and incorporated the upstream ice jam later that day. The combined jam progressed to about 11.3 km (7 miles) upstream from the boom by 26 December. (A shoving event later reduced the length of this ice cover to about 8 km.)

At the same time, the Deadwater/Fourth of July Creek jam progressed as far as KM 407 (RM 253) on 23 December, but no farther, despite continued very low temperatures. Figure 12 shows the progression of the two ice jams for the period 19 December through 30 December. Although the Deadwater jam has a higher progression rate in the period 19 to 22 December, the growth rate slows on 24 December while the upstream jam continues

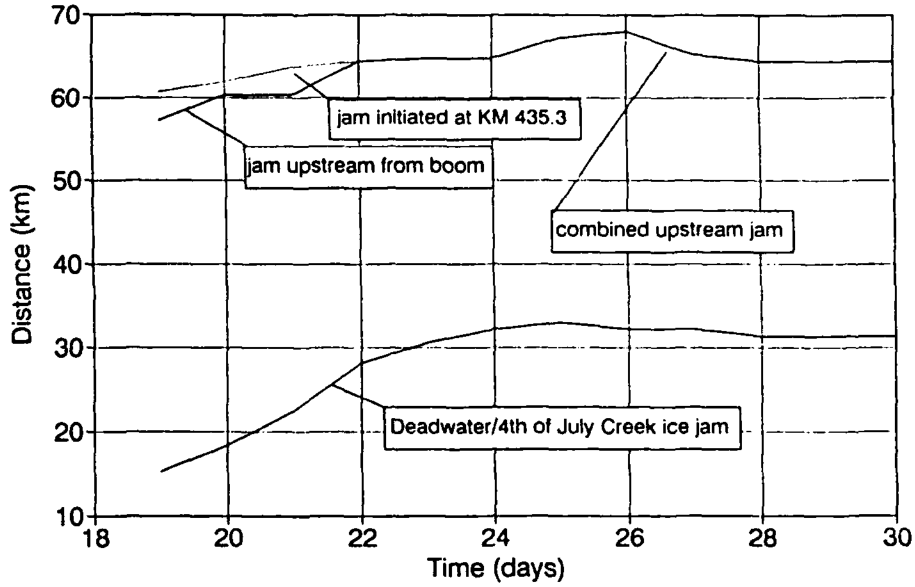


Figure 12. Progression of ice jams near Salmon, Idaho, in December 1990. The Deadwater/Fourth of July Creek jam stabilized on 25 December while upstream jam continued growth through 26 December. Distance is km above Deadwater jam initiation point.

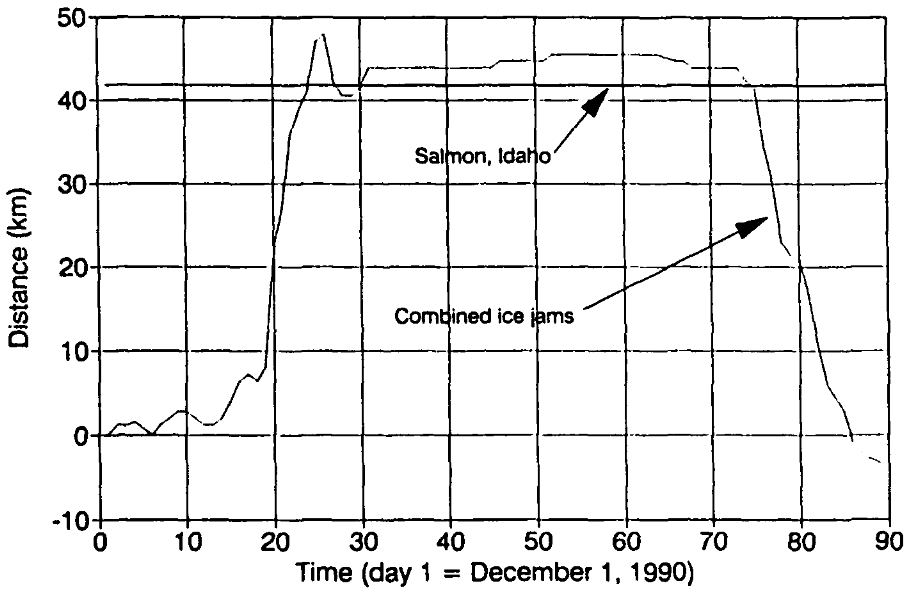


Figure 13. Cumulative ice jam progression at Salmon. Distance given in km above Deadwater jam initiation point.

progressing until 26 December. Even with the additional frazil ice supplied by the Lemhi River, the amount of frazil ice produced in the reach between the boom site and the Deadwater jam was not great enough to allow progression of the Deadwater jam. This was an important observation because earlier calculations made with simplified heat transfer equations and based on rough estimates of temperature and river geometry showed that significant Deadwater ice jam progression would result from frazil ice production in this reach. The observed impact of the upstream jams on the progression of the Deadwater jam during the 1990–91 winter season verified the results of a more recent progression model (Axelson and Zufelt 1990).

Figure 13 shows the cumulative length of the ice jam at Salmon, where the initiation point of the Deadwater ice jam (KM 375) is a distance equal to 0. This figure shows that, without the upstream jams, the Deadwater ice jam would have progressed through Salmon. This is confirmed by the temperature-progression model developed by Zufelt and Bilello (in prep.), which indicated that there were two periods of cold severe enough to have caused ice jam flooding in Salmon if the boom were not present. The boom's performance during the 1990–91 winter seasons shows that an ice cover can form at this hydraulically marginal site under certain conditions. The river discharges were similar to those of the previous season, but the air temperatures were lower. The lower air temperatures led to higher observed surface ice concentrations. The internal strength of the ice appeared to be greater as well. The modified boom configuration and the more continuous surface along the right side of the boom altered the ice accumulation characteristics of the boom. The funneling effect, although still present, tended to move the frazil ice floes toward a lower velocity area with more favorable conditions for deposition. The concept that an upstream ice cover located at the boom site could control enough frazil ice to limit the growth of the Deadwater ice jam suggested by Zufelt and Bilello's (in prep.) analysis was confirmed by the cumulative length of the Salmon ice jams during the 1990–91 winter season.

CONCLUSIONS

The observations during the winter of 1989–90 confirmed that the Salmon River ice boom test site at KM 432.1 was marginal or unacceptable for a formation boom using a conventionally designed boom, although ice jams had been known to progress through the site in the past. Questions were also raised concerning the effects of the internal strength of frazil ice on capture efficiency. We felt that there was some hope that the natural ice jam process could be duplicated even though a boom would provide a smaller initial increase in stage than an ice jam passing through the reach. Our observations led us to conclude that boom configuration is an important design parameter for frazil ice formation booms in marginal hydraulic conditions, and that higher ice capture efficiency might be achieved by changing the shape of the boom to take into account velocity and channel geometry conditions.

Our primary objective in modifying the boom was to minimize the funneling effect and encourage frazil ice floe deposition or accumulation at the boom. After modifications, the boom eventually formed a stable ice cover during the 1990–91 winter season even though the Froude criteria predicted submerging of the frazil floes. This experience implies that the Froude criteria should be reexamined for frazil ice accumulation at booms with configurations designed specifically to encourage ice accumulation. The internal strength, or effective cohesion, of the floes was also much greater during the 1990–91 season, and we feel that this contributed significantly to the improved capture efficiency of the modified boom.

The success of the modified Salmon River ice boom in collecting frazil ice under favorable weather conditions leads us to re-examine the boom's performance: rather than expecting the boom to capture ice under all conditions, it may work only when it needs to work. In other words, the boom needs to work when the Deadwater jam threatens Salmon, but it does not have to capture ice during warm seasons or other times when the Deadwater jam does not threaten the city. Low temperature conditions may be precisely those under which the boom works best, as was the case in the 1990–91 winter season. If it is acceptable for an ice formation boom to work on this basis, we suggest that the Froude criteria may be relaxed for booms specifically designed to capture frazil ice under favorable conditions. However, further study is necessary to determine exactly what these conditions might be, and to what extent the Froude criteria may be relaxed. The ice boom will be reinstalled for testing during the 1991–92 winter season in its present configuration. Ice accumulations at the boom and the Deadwater jam will be closely monitored in order to compare capture efficiencies associated with varying weather and surface ice concentration conditions.

Although the successful performance of the Salmon River experimental ice boom in 1990–91 is heartening, there are still questions to be answered. The most important question is: How will the boom perform with less severe cold temperatures? A related question is: How can we predict the risk of ice jam flooding in Salmon associated with using the boom alone to control frazil ice? Despite the unanswered questions, the past two seasons of testing have provided valuable insights into formation boom design. Chief among these is that the primary design factor for frazil ice formation booms should be the boom configuration, and the configuration should be based on hydraulic and ice conditions rather than equal distribution of the forces expected.

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The city of Salmon, Idaho, is affected by flooding resulting from a frazil ice jam, known as the Deadwater jam, which forms annually on the Salmon River. Because the river has considerable environmental, economic, aesthetic, and recreational value, an innovative approach to frazil ice control is needed. The steep slope and turbulence of the river also add to ice control design constraints. Past investigations have examined a number of different methods to control the ice. This report documents two years of testing of an experimental ice formation boom located upstream from the city of Salmon. The observations show that boom configuration is an important factor in ice capture efficiency, and that conventional boom siting criteria may be modified under certain conditions.

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