CRREL REPORT 92-14

Effects of Severe Freezing Periods and Discharge on the Formation of Ice Jams at Salmon, Idaho

Jon E. Zufelt and Michael A. Bilello

August 1992

Abstract
Major ice jams on the Salmon River have reached Salmon, Idaho, and resulted in major flood damage during 16 winters since the winter of 1936–37. Two recent ice jams, in February 1982 and January 1984, caused flooding that resulted in damages of $1 million and $1.8 million respectively. A detailed analysis of the winter air temperature records from 1936–37 through 1991–92 revealed a strong relationship between the duration and intensity of severe cold periods, the air temperature record prior to the severe cold periods, and the occurrence of ice jams reaching the city of Salmon that result in flooding. A threshold condition is identified from which the probability of ice jams reaching the city can be determined from inspection of forecasted air temperatures. It was found that once an ice jam reaches the city, average daily air temperatures of approximately 18°F are necessary to keep the jam in place. While the effects of discharge on ice thickness, and therefore ice jam length, are significant, no relation could be found in this study. An ice control structure located upstream of the city of Salmon appears to be helping alleviate ice-jam flooding.

Cover: Ice on the Salmon River, Idaho.

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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US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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August 1992

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Jon E. Zufelt, Research Hydraulic Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, and Michael A. Bilello, Consultant. Funding was provided under CWIS 31355, *Field Studies of Ice Jams*.

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CONVERSION FACTORS: U.S.CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4	millimeter
mile	1.609344	kilometer
$foot^3$/second	0.02831685	$meter^3$/second
degree Fahrenheit	$t_{°C} = (t_{°F} - 32)/1.8$	degree Celsius

Effects of Severe Freezing Periods and Discharge on the Formation of Ice Jams at Salmon, Idaho

JON E. ZUFELT AND MICHAEL A. BILELLO

INTRODUCTION

The city of Salmon, Idaho, has been plagued by ice-jam flooding from the Salmon River. At least 33 ice-related floods have occurred since 1899. Two recent ice jams, in February 1982 and January 1984, caused flooding that resulted in damages of $1 million and $1.8 million respectively (Zufelt 1987). While there is minor flooding damage downstream of Salmon, the majority of the damage is caused within the city limits by flooding along both the Salmon and Lemhi rivers (Fig. 1).

The Salmon area is fairly dry, with less than 10 in. of precipitation per year, falling mostly as snow during the winter and rain during spring. Aside from the melting of the snowpack in the surrounding mountains in May and June, the flow in the Salmon River is primarily from the release of groundwater. As a result, the discharge during the winter is fairly uniform, with minor increases caused by winter rains or snowmelt during warmer periods, and minor decreases attributable to severe cold periods. Because of the groundwater flow and several warm water springs in the area, frazil ice does not appear in the river until the mean daily air temperature, θ, falls to approximately 20°F. As the air temperature decreases further, larger volumes of frazil ice are produced, which accumulate in an area known as Deadwater, about 30 miles downstream of the city, causing an ice jam to build and progress upstream. When air temperatures are very low, the frazil ice is quite cohesive and nearly all of the frazil reaching the upstream edge of the jam contributes to its further progression. When the air temperature rises, however, the frazil ice becomes less cohesive and the "capture efficiency" of the jam is reduced, with much of the frazil ice carried beneath the jam and transported downstream. Thus, the jam progresses at the greatest rates during the severe cold periods because of the larger volumes of frazil ice produced and its greater capture efficiency. Field observations have shown that the jam's progression is halted when the mean daily air temperature rises above 20°F and at higher temperatures (even though below 32°F), the jam will recede. In winters that experience periods of severe subfreezing air temperatures, the ice jam can progress all the way upstream to the city of Salmon, causing flooding.

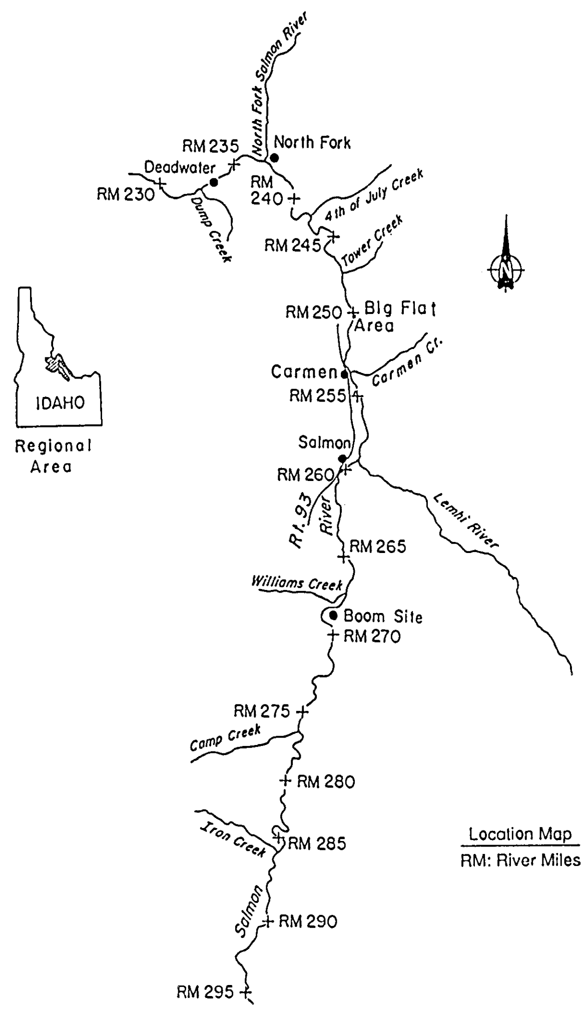


Figure 1. Salmon River area of Idaho.

Several studies have examined the flooding and damage at Salmon from these ice jams (U.S. Army Corps of Engineers 1975, 1984, 1986; Cunningham and Calkins 1984; Earickson and Gooch 1986). These reports include historical summaries of past floods and the associated financial losses in the region, as well as descriptions of the river system and its tributaries, hydrology and ice-jam characteristics. Methods for reducing the damage or controlling the buildup of ice on the river have been suggested by Earickson and Zufelt (1986), Zufelt (1987) and Axelson (1990).

Earickson and Gooch (1986) and Zufelt (1986) discuss the meteorological conditions associated with the ice jams that result in high stages at Salmon. Earickson and Gooch found that the number of freezing degree-days accumulated by the time the leading edge of a jam reaches Salmon can vary widely and has little relationship to the total number of freezing degree-days recorded during the entire winter. In other words, they found that while there is a general trend for ice jams to reach Salmon in colder years, ice jams can also cause flooding in seemingly mild winters, and that a much stronger correlation exists between extreme cold periods and ice-jam potential. All of the jams that they noted occurred during severe cold snaps when the mean daily air temperature fell below 15°F for several days. Their findings infer that the slope of the freezing degree-day curve, or simply the mean daily air temperature during these cold periods, serves as a much better indicator of ice-jamming potential than the total number of Accumulated Freezing Degree-Days (AFDD).

This apparent relationship between the major ice-jam events and intense cold periods of relatively short duration was further investigated in this study.

DATA SOURCES AND ANALYSIS

Ice jam flooding events listed by U.S. Army Corps of Engineers (1986) were jams that were severe enough to cause a noticeable rise in water surface at the U.S. Geological Service stream gage at Salmon, Idaho. These are shown in Table 1, with the corresponding dates of the start and end of the period of high stage. Earickson and Gooch (1986) used only the date of the ice jam's peak stage in their analysis. However, the date of the peak stage does not necessarily coincide with the date that the ice jam initially reached Salmon. In this study, the starting and ending dates of the high stage period were used, since the objective was to predict not only the arrival of the ice jam at Salmon but also the duration of the problem.

Ice jam records, dating back to 1899, recorded at least 33 ice-jam flooding events. However, ice jam floods prior to 1936 are not considered here since the concurrent daily air temperature data required for this study were not available. Since 1936, two winters have experienced two separate periods of high stage (or two ice-jam events). Also, no information exists for 1971–72, other than a record of the fact that an ice jam had reached Salmon. From an inspection of discharge and air temperature records and newspaper accounts, the likely period of high stage for the winter of 1971–72 was estimated. The ice jams at Salmon from the winter of 1936–37 through the winter of 1991–92 are analyzed in this study.

Table 1. Period of high stage (after U.S. Army Corps of Engineers 1986).

Jam year	*Start date*	*End date*	*Duration (days)*
1988–89	6 Feb 1989	10 Feb 1989	4
1984–85	4 Feb 1985	9 Feb 1985	5
1983–84	24 Dec 1983	31 Dec 1983	7
1983–84	15 Jan 1984	18 Feb 1984	34
1981–82	7 Feb 1982	17 Feb 1982	10
1978–79	1 Jan 1979	24 Feb 1979	54
1973–74	8 Jan 1974	15 Jan 1974	7
1972–73	12 Dec 1972	23 Dec 1972	11
1972–73	8 Jan 1973	19 Jan 1973	11
1971–72	3 Feb 1972	10 Feb 1972	7
1962–63	20 Jan 1963	3 Feb 1963	14
1961–62	20 Jan 1962	13 Feb 1962	24
1956–57	27 Jan 1957	23 Feb 1957	27
1955–56	3 Feb 1956	23 Feb 1956	20
1949–50	4 Feb 1950	5 Feb 1950	1
1948–49	29 Dec 1948	23 Feb 1949	56
1941–42	7 Jan 1942	13 Mar 1942	65
1936–37	9 Jan 1937	7 Mar 1937	57

Air temperature records

Daily minimum and maximum air temperature data recorded at Salmon from October through March for the winters of 1936–37 through 1991–92 were obtained. These data were used to calculate the mean daily air temperature, θ, and the AFDD from the first day of sub-freezing θ after 1 October. A Freezing Degree-Day (FDD) is obtained by subtracting the mean daily air temperature in degrees Fahrenheit from 32°F, e.g., 32°F – (–3°F) = 35 FDD.

Table 2 lists the starting date of sub-freezing air temperatures, the maximum AFDD and its date, and, as a measure of the winter's severity, the number of days for which θ was below 0°F for all 56 winters.

Air temperature curves

To determine if there were any general similarities between the winters in which the leading edge of ice

Table 2. Freezeup discharge and air temperature data for all 56 winters.

Year	*Start of freezing*	*AFDD*		*No. days*	*Freezeup Q**
		Max	*Date*	$\theta < 0°F$	*(ft^3/s)*
1936–37	2 Nov 1936	1628	27 Feb 1937	11	850
1937–38	30 Nov 1937	768	2 Mar 1938	0	750
1938–39	11 Nov 1938	948	9 Mar 1939	1	825
1939–40	18 Dec 1939	768	24 Feb 1940	2	825
1940–41	9 Nov 1940	1086	21 Feb 1941	1	750
1941–42	19 Nov 1941	1543	21 Mar 1942	15	950
1942–43	19 Nov 1942	1458	23 Mar 1943	3	1050
1943–44	5 Dec 1943	1229	15 Mar 1944	6	975
1944–45	16 Nov 1944	895	7 Mar 1945	4	1000
1945–46	6 Nov 1945	970	24 Feb 1946	0	900
1946–47	20 Nov 1946	815	10 Feb 1947	2	1100
1947–48	14 Nov 1947	797	14 Feb 1948	0	875
1948–49	16 Nov 1948	2131	15 Feb 1949	29	1075
1949–50	3 Dec 1949	793	11 Feb 1950	2	850
1950–51	8 Nov 1950	1033	18 Mar 1951	6	875
1951–52	3 Dec 1951	1462	23 Mar 1952	1	1150
1952–53	20 Nov 1952	554	7 Jan 1953	1	850
1953–54	2 Dec 1953	363	11 Feb 1954	0	1150
1954–55	28 Nov 1954	1345	27 Mar 1955	0	950
1955–56	11 Nov 1955	1214	16 Mar 1956	9	1000
1956–57	14 Nov 1956	1340	22 Feb 1957	10	925
1957–58	15 Nov 1957	776	15 Feb 1958	0	1000
1958–59	14 Nov 1958	571	14 Feb 1959	2	950
1959–60	4 Nov 1959	1487	13 Mar 1960	7	925
1960–61	27 Nov 1960	738	29 Jan 1961	0	850
1961–62	12 Nov 1961	1229	15 Mar 1962	8	850
1962–63	23 Nov 1962	696	31 Jan 1963	7	800
1963–64	21 Nov 1963	1293	25 Mar 1964	0	825
1964–65	12 Nov 1964	600	26 Mar 1965	2	925
1965–66	25 Nov 1965	579	9 Mar 1966	0	1100
1966–67	23 Nov 1966	375	24 Feb 1967	0	900
1967–68	25 Nov 1967	922	17 Feb 1968	0	1000
1968–69	13 Nov 1968	862	14 Mar 1969	1	900
1969–70	17 Nov 1969	500	13 Jan 1970	1	975
1970–71	21 Nov 1970	815	7 Mar 1971	4	950
1971–72	26 Nov 1971	1121	26 Feb 1972	7	1125
1972–73	20 Nov 1972	1090	24 Feb 1973	10	925
1973–74	20 Nov 1973	549	13 Jan 1974	11	900
1974–75	28 Nov 1974	896	27 Feb 1975	2	1025
1975–76	17 Nov 1975	938	12 Mar 1976	1	1000
1976–77	26 Nov 1976	1093	10 Feb 1977	5	1000
1977–78	17 Nov 1977	518	19 Feb 1978	1	900
1978–79	10 Nov 1978	1768	9 Jan 1979	18	800
1979–80	12 Nov 1979	722	17 Feb 1980	4	775
1980–81	13 Nov 1980	334	13 Feb 1981	0	1025
1981–82	26 Nov 1981	964	13 Feb 1982	7	725
1982–83	12 Nov 1982	573	9 Feb 1983	0	1000
1983–84	21 Nov 1983	1486	8 Mar 1984	10	1275
1984–85	22 Nov 1984	1530	16 Mar 1985	4	1175
1985–86	9 Nov 1985	1394	13 Feb 1986	2	1075
1986–87	30 Nov 1986	669	25 Jan 1987	0	1075
1987–88	18 Nov 1987	654	7 Feb 1988	1	750
1988–89	12 Nov 1988	1262	5 Mar 1989	8	800
1989–90	28 Nov 1989	405	20 Feb 1990	0	775
1990–91	27 Nov 1990	1141	10 Feb 1991	13	975
1991–92	28 Oct 1991	850	10 Feb 1992	0	850

*Q = discharge.

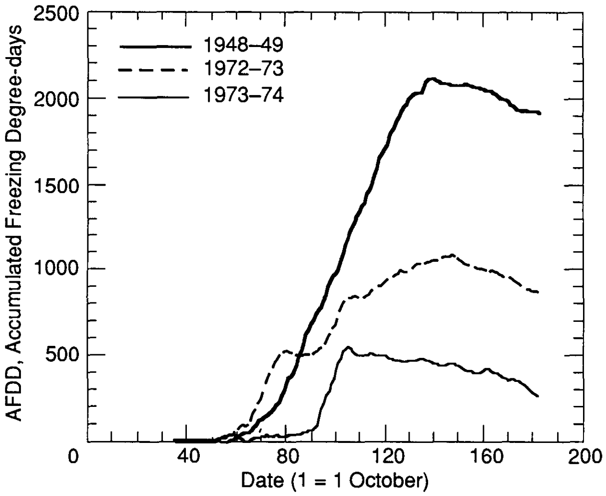


Figure 2. AFDD vs time plots for ice-jam winters of 1948–49, 1972–73 and 1973–74.

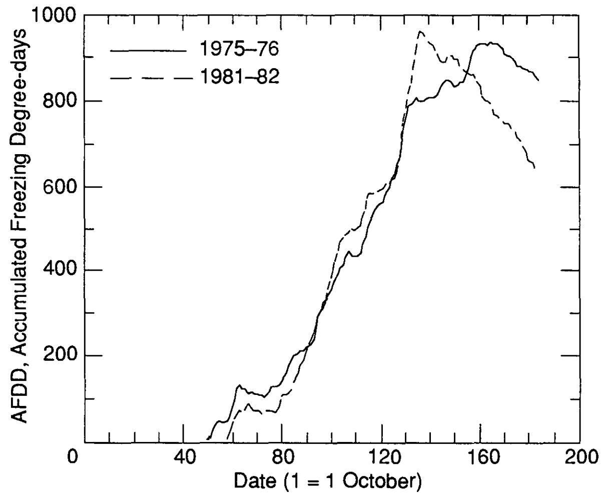


Figure 3. Comparison of AFDD vs time for the winters of 1975–76 (no ice jam) and 1981–82 (ice jam).

jams reached Salmon, the AFDD were plotted against time for the winters listed in Table 1. Examples of these plots for 3 of the 16 ice-jam winters are shown in Figure 2. These curves reveal the variability in the air temperature regime that can be expected at Salmon throughout the winter. For example, the maximum AFDD for the ice-jam winters varied from over 2000 (1948–49) to less than 500 (1973–74). Also, the beginning of the continuous period of freezing temperatures at Salmon started as early as mid-November (1972–73), or as late as January (1973–74). It is also evident that the AFDD curve can be either gradual and smooth (1948–49), erratic with brief mid-winter thaws (1972–73) or rapid and steep (1973–74).

Since the three temperature regimes illustrated in Figure 2, as well as the 13 additional winters listed in Table 1, all resulted in ice jams reaching Salmon, it was necessary to analyze each of the air temperature records in detail to see if a possible common feature existed among them. It was also necessary to examine the air temperature records for the years in which there was no ice jam at Salmon to identify differences between jam and non-jam years. Figure 3 shows the plots of AFDD vs time for 1975–76 (when there was no jam) and 1981–82 (when there was a jam). Differences in the air temperature regimes of these two winters are not very apparent from inspection of the AFDD vs time plots. Therefore, the air temperature records for each winter were analyzed as described below.

Air temperature record analysis

Inspection of the air temperature records indicated that the 16 ice-jam winters could be logically separated into the following consecutive chronological sections:

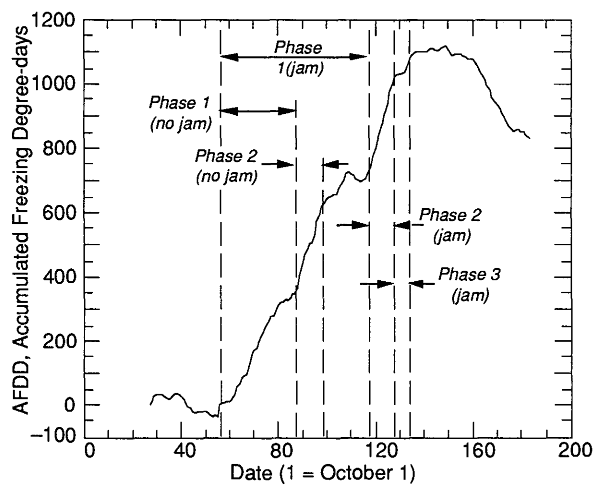


Figure 4. Air temperature phases for 1971–72, which experienced a cold spell that did not produce an ice jam followed by a cold spell that did produce an ice jam.

1. Phase 1—the period from the start of continuous freezing air temperatures to the start of a major cold snap, defined as a period when the *minimum* daily air temperatures are 0°F or lower.
2. Phase 2—From the beginning of the major cold snap to the starting date of the reported high water stage at Salmon, Idaho.
3. Phase 3—The period between the start and end of high stages at Salmon, Idaho.

Winters that did not experience ice jams would not contain a phase 3. The end of phase 2 for the winters without ice jams was determined in a similar manner as the beginning of phase 2—when the minimum daily air

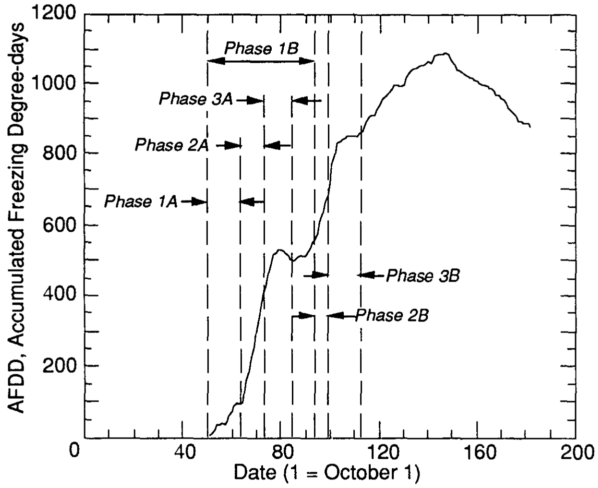


Figure 5. Air temperature records for 1972–73, which experienced two separate ice jam events.

temperature rose above 0°F. Not every winter (whether ice jams were experienced or not) was separable into only two or three distinct phases because some winters experienced two or more severe cold periods.This resulted in multiple data sets for some winters. For example, a cold snap that did not result in an ice jam reaching Salmon was considered a non-jam data set, even if a second cold snap (in the same year) did result in a jam reaching Salmon. In such a case, the phase 1 of the data set for the jam reaching Salmon included the cold snap of the data set for which there was no ice jam. This is illustrated in Figure 4 for the winter 1971–72.

Also, two winters experienced two separate ice-jam and related high-stage events. Each ice-jam event was considered to be a separate ice-jam data set, with the phase 1 including everything up to the cold snap that resulted in high stages for that particular ice jam. Figure 5 depicts the phases of both ice-jam events of 1972–73.

Table 3. Air temperature data sets.

	Phase 1		*Phase 2*		*Phase 3*	
Year	*No. days*	*AFDD*	*No. days*	*AFDD*	*No. days*	*AFDD*
1936–37	65	635	3	154	57	811
1937–38	56	466	6	156	—	—
1938–39	90	630	3	79	—	—
1939–40	64	224	5	155	—	—
1940–41	53	465	4	114	—	—
1940–41	53	465	13	306	—	—
1941–42	37	141	13	387	65	981
1941–42	42	229	8	299	65	981
1942–43	36	264	3	74	—	—
1942–43	45	354	11	251	—	—
1942–43	59	624	3	106	—	—
1943–44	18	21	9	207	—	—
1943–44	43	500	10	277	—	—
1944–45	36	323	7	218	—	—
1945–46	37	200	7	149	—	—
1945–46	80	605	5	96	—	—
1946–47	41	145	8	209	—	—
1946–47	51	386	11	250	—	—
1947–48	45	235	3	79	—	—
1947–48	73	495	4	94	—	—
1948–49	30	241	14	485	56	1364
1948–49	34	390	9	335	56	1364
1949–50	57	597	6	177	1	11
1950–51	80	637	7	253	—	—
1951–52	28	317	10	252	—	—
1952–53	5	38	7	168	—	—
1952–53	34	309	4	107	—	—
1953–54	21	92	5	69	—	—
1953–54	49	255	2	33	—	—
1953–54	49	255	7	63	—	—
1954–55	21	148	6	116	—	—
1954–55	36	418	7	152	—	—
1954–55	67	888	4	81	—	—
1955–56	75	429	10	377	20	329
1956–57	68	628	13	391	27	317
1957–58	45	234	10	240	—	—

Table 3 (cont'd). Air temperature data sets.

Year	*Phase 1* No. days	*Phase 1* AFDD	*Phase 2* No. days	*Phase 2* AFDD	*Phase 3* No. days	*Phase 3* AFDD
1958–59	49	246	4	118	—	—
1959–60	70	572	9	301	—	—
1959–60	114	1205	6	194	—	—
1960–61	9	49	12	201	—	—
1960–61	54	584	9	149	—	—
1961–62	57	440	12	320	24	303
1962–63	48	160	11	311	14	217
1964–65	34	163	4	130	—	—
1965–66	20	75	7	132	—	—
1966–67	29	108	7	135	—	—
1967–68	17	106	10	219	—	—
1967–68	62	695	4	90	—	—
1968–69	47	292	3	78	—	—
1969–70	48	332	5	137	—	—
1970–71	42	418	6	205	—	—
1971–72	31	349	5	142	—	—
1971–72	31	349	11	268	—	—
1971–72	61	722	10	284	7	72
1972–73	14	96	9	304	11	104
1972–73	44	575	5	151	11	123
1973–74	41	73	9	315	7	120
1974–75	31	183	6	141	—	—
1974–75	60	493	6	165	—	—
1975–76	78	637	6	155	—	—
1976–77	40	431	7	220	—	—
1976–77	60	814	7	149	—	—
1977–78	54	260	3	94	—	—
1978–79	46	507	7	254	54	983
1979–80	75	359	6	201	—	—
1980–81	89	291	2	43	—	—
1981–82	70	636	4	152	10	149
1982–83	26	100	5	115	—	—
1982–83	46	285	6	159	—	—
1983–84	25	201	9	319	7	130
1983–84	55	827	7	258	34	292
1984–85	62	840	12	302	5	90
1984–85	68	954	6	188	5	90
1984–85	9	42	6	174	—	—
1985–86	14	133	4	104	—	—
1985–86	32	425	5	125	—	—
1985–86	43	634	10	246	—	—
1986–87	47	467	6	138	—	—
1987–88	45	249	4	114	—	—
1988–89	81	826	6	227	4	124
1989–90	78	327	2	34	—	—
1990–91	22	114	7	295	—	—
1990–91	32	466	9	283	—	—
1990–91	54	832	3	74	—	—
1990–91	63	1006	3	86	—	—
1991–92	47	162	3	66	—	—
1991–92	85	670	2	46	—	—

Table 3 includes the data sets generated by the above process. The year, number of days and AFDD for each phase are given (no phase 3 for non-jam data sets).

Discharge records

The stage of the Salmon River is recorded by U.S. Geological Survey stream gage 13302500 at the city of Salmon, just upstream of the Salmon's confluence with the Lemhi River. These stages are converted to average daily discharge values and published by the USGS. The gage is often affected by ice during the winter and especially during ice jams, resulting in gaps in the stage and discharge records. The ice-affected stage can also be mistakenly interpreted as an increase in discharge and thus reported as such.

The thickness of an ice jam, and thus the stage, usually depends on discharge. Therefore, the average discharge during the ice cover progression (or severe freezing period of phase 2) was of interest. One would normally expect a higher open water discharge to result in a greater open water width. The Salmon River valley is steep and narrow, however, and an increase in discharge does not significantly increase the width (or area of open water) nor consequently the amount of frazil ice generated. Therefore, in any given winter, a higher discharge may result in a thicker jam and higher stages, but since the total ice volume would be nearly constant, the jam might not progress as far upstream. Conceivably, the jam might not reach Salmon at a higher discharge when it would have at a low discharge, and thus there would be no flooding in the city. Also, low discharges could result in thinner jams that would cause a smaller stage increase and only minor flooding.

The average discharge for the freezeup period in each ice-jam year was taken as the mean of the daily discharges during the severe cold period prior to the time of high stage at Salmon (or during phase 2). For the years without ice jams, it was taken as the mean of the daily discharges during the severe cold periods (again during phase 2). The average discharge values thus calculated are listed in Table 2.

RESULTS

As stated earlier, the objective of this study was to see if a relationship existed between major cold snaps and ice jams reaching the city of Salmon. Such a relation could be useful in assessing the probability of an ice jam reaching Salmon in any given year, based on the forecasted air temperatures. The effectiveness of proposed ice control measures might also be assessed through such a relation.

Phase 1

Phase 1 is the period from the start of continuous freezing air temperatures to the beginning of a severe cold spell. For the years with ice jams, phase 1 ranged from 14 to 81 days and experienced 73 to 954 AFDD. For the years without ice jams, phase 1 ranged from 5 to 114 days and had 21 to 1205 AFDD. No relation existed between ice jams reaching the city and the phase 1 characteristics alone.

Phase 1 could be considered the establishment of the initial ice conditions, with ice being generated and accumulated very slowly prior to the cold snap of phase 2. As mentioned above, the ice jam accumulates and progresses when mean daily air temperatures fall below 20°F. While this temperature is not considered severe, significant amounts of ice could build over long periods of time. Thus, one would expect that a phase 1 lasting 70 days accompanied by 900 AFDD (or a mean daily air temperature of 19°F) could result in a considerable amount of ice contributing to the jam progressing several miles upstream. Conversely, a shorter or warmer phase 1 might result in no jam progression at all. For these warmer first phases, phase 2 would have to be colder or longer for an ice jam to reach Salmon. Therefore, while no direct relation exists between the length or severity of phase 1 and an ice jam reaching the city, phase 1 does influence the ice regime of the river.

Phase 2

The start of phase 2 was taken as the beginning of a severe cold spell when the minimum daily air temperature is at or below 0°F. For the years with ice jams, phase 2 ended with the beginning of high water stages at the Salmon USGS gage, signifying that the ice jam had reached the city. In many years, the severely low air temperatures lasted several days beyond the onset of high water stages. This would indicate that the ice jam progressed farther upstream of the city, as has been corroborated by historic newspaper accounts. For the years without ice jams, there were no high water stages and the end of phase 2 was identified as the time when the minimum daily air temperature rose above 0°F. In either case, if there was a minor warming of the air temperature (1 or 2 days) in the middle of a cold spell, it was included as part of the cold spell. If the warming trend lasted any longer, however, the period was treated as two separate cold spells. Phase 2 for the ice-jam years ranged from 3 to 14 days with 152 to 485 AFDD and for the years without ice jams ranged from 2 to 13 days, accompanied by 33 to 354 AFDD.

When a jam does occur, its progression is a function of many variables, some of which are unknown or difficult to quantify. One of the most important variables is the ice supply (volume of ice generated), which is directly influenced by the intensity and duration of low air temperatures. This can be seen from the equation for the volume of ice produced per unit time, V_i

$$V_i = \frac{h_s A_o \Delta T}{\rho_i \lambda_f} \tag{1}$$

where h_s = heat transfer coefficient of water to air
A_o = area of open water
ΔT = difference between the air temperature and the freezing point of water
ρ_i = density of ice
λ_f = latent heat of fusion of water.

The data showed that the progression of the ice jam depended heavily on the duration and severity of phase 2, and also, but to a lesser extent, on the AFDD of phase 1, which represented the antecedent ice-jam conditions. A rather weak dependence on the freezeup discharge was expected owing to the fairly narrow range of discharges experienced. Therefore, the variables of interest were, first, the duration of the severe low air temperatures of phase 2; second, the intensity of the severe cold represented by the average daily freezing degree-days over phase 2; third, the antecedent ice-jam conditions represented by the AFDD of phase 1; and fourth, the average freezeup discharge.

The existing data were plotted as the average daily freezing degree-days over the period of severe low air temperatures of phase 2 vs the duration of phase 2. We found that the data could be separated into two distinct groups: those events with a phase 1 of less than 500 AFDD and those with a phase 1 of greater than 500 AFDD. The corresponding plots are presented in Figure 6. Shown on the figures is a limiting curve describing the threshold conditions for an ice jam to reach the city. The function that best described this limiting curve for both groups of data was found to be

$$FDD2_t = 24.5 + 34.83 \exp\left[-0.37\,(T_2 - C_o)\right] \qquad (2)$$

where $FDD2_t$ = threshold value of the average daily freezing degree-days of phase 2

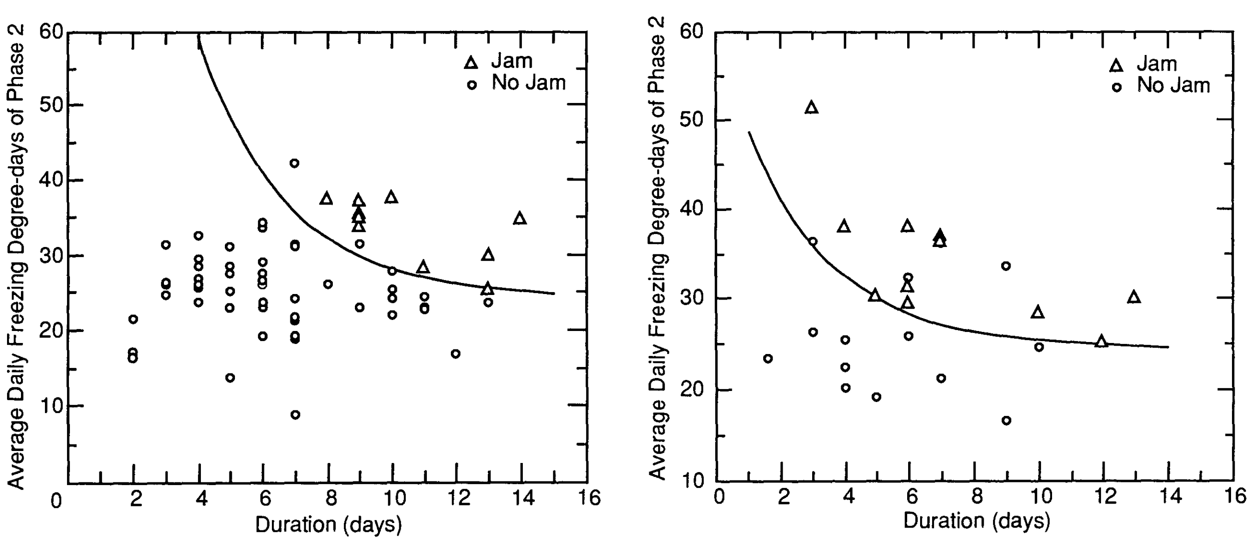
T_2 = duration of phase 2

C_o = coefficient describing the offset of the curve based on the AFDD of phase 1.

For eq 2 above, the value of C_o is 4 for Figure 6a (AFDD1 < 500) and 0 for Figure 6b (AFDD1 > 500), indicating an offset of 4 days for the higher AFDD of phase 1. The relation fits the data points very well, with all the ice-jam events on or above the threshold value of eq 2. For Figure 6a, two events without ice jams plot above the threshold value. These are for two separate severe cold periods during the winter 1990–91 for which the ice regime in the river was altered by an ice control structure. This is discussed in a later section. For Figure 6b, three events without ice jams plot above the threshold value; two are for two separate severe cold periods in 1959–60 and one for 1950–51. Two of these three points can be partially explained by the effects of freezeup discharge, but it is probable that an ice accumulation formed in the river upstream of the city and reduced the ice supply to the Deadwater ice jam. Historic records have indicated that ice covers do form upstream of the city on rare occasions, but no dates are given.

Figures 6a and 6b and eq 2, which separate ice jam events from events without ice jams at the city of Salmon, can be physically interpreted as follows. Once the *minimum* daily air temperatue is 0°F or below and a phase 2 cold spell has begun, the average daily freezing degree days, FDD2, must be greater than 24.5, i.e., the average mean daily air temperature of phase 2, $\bar{\theta}_2$, must remain below 7.5°F for a minimum number of days if the ice jam is to progress as far as the city of Salmon. This minimum duration of phase 2 can be obtained from eq 2 and can be expressed by

$$T_2 \geq C_o + 2.7\ \ln\left[\frac{34.83}{7.5 - \bar{\theta}_2}\right]. \qquad (3)$$



a. With phase 1 having fewer than 500 AFDD. *b. With phase 1 having more than 500 AFDD.*

Figure 6. Average daily freezing degree-days of phase 2 vs duration of phase 2.

The dependence on the average mean daily air temperature during the cold spell, $\overline{\theta}_2$, is attributed to lower air temperatures giving rise to greater production of frazil ice and increased cohesion of that frazil ice, resulting in a faster progression of the jam. Also, a greater AFDD1 implies that the leading edge of the jam was further upstream at the onset of the cold spell, resulting in a shorter distance to the city, i.e., a lower volume of frazil ice needs to be generated. For example, a cold spell with a $\overline{\theta}_2 = 0°F$ should last between 4 and 5 days if AFDD1 >500 or between 8 and 9 days if AFDD1 <500 for the jam to reach the city of Salmon.

The two values of C_0 for the data in Figures 6a and 6b correspond to average values of AFDD1 of 250 and 750 respectively. A general form of C_0 was then assumed to be

$$C_0 = \frac{750\text{–AFDD1}}{125} \quad \text{for AFDD1} \leq 750$$
$$C_0 = 0 \quad \text{for AFDD1} \geq 750 \qquad (4)$$

The actual and threshold values of FDD2 were computed for all the data points using eq 2 and 4 and are plotted in Figure 7 along with an equality line. The zone above the equality line should indicate years in which an ice jam reached the city, below the line indicating years in which one didn't. The relation fits the data points well, with most of the outliers being the same data points as those mentioned above. The two ice-jam events that lie below the line are the second ice jams of 1973 and 1984, when significant precursor ice existed from the first ice jam of those years. This form of the threshold relation includes the three most important variables and provides a quick test of whether an ice jam might be expected to reach the city in any given year.

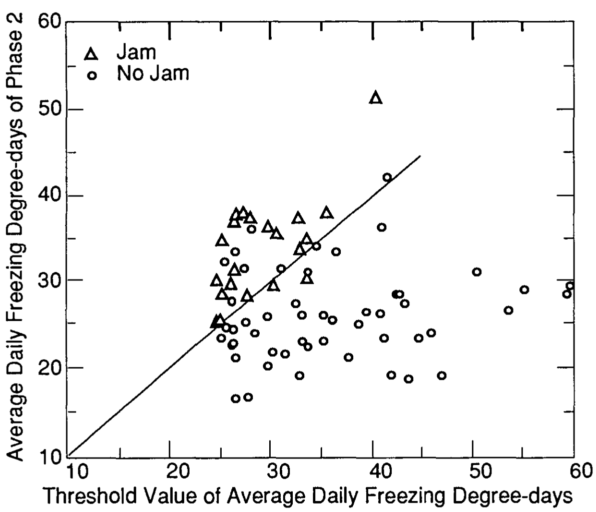


Figure 7. Actual vs threshold values of average daily freezing degree-days for phase 2.

Phase 3

Phase 3 only occurred during the years when an ice jam reached the city. It was defined as the period between the beginning and end of high water stages at the Salmon USGS gage. Information was not available on the location of the leading edge (most upstream point) of the ice jam during phase 3 for every event. The ice jam may have progressed several miles upstream of the city or possibly only several hundred yards. Higher air temperatures would cause the jam to recede and reduce water levels at the gage. The object of the phase 3 analysis was to determine the intensity and duration of low air temperatures that would cause the ice jam and the subsequent high water stages to persist. Also, if an ice jam had reached the city, it would be possible to forecast the necessary warming trend that would cause it to recede.

Phase 3 ranged from 1 to 65 days accompanied by 11 to 1365 AFDD. The air temperature pattern of phase 3 varied widely, especially for the years with a long phase 3. Some years showed a gradual warming trend, while others showed warming followed by severe cold periods and sudden warming. As stated previously, the severe cold spell lasted several days into phase 3 for many of the winters.

The mean daily FDD for all the jam years during phase 3 was 14 with a standard deviation of 3. This corresponds to a mean daily air temperature of 18°F to sustain the jam and high-water stages in the city. This value is close to field observations of a mean daily air temperature of 20°F or less for the jam to progress.

Effects of discharge

Many researchers have presented formulae for the equilibrium thickness of an ice jam—the ice thickness that would be expected in a uniform channel under steady flow conditions. An adaptation of the formula given by Ashton (1986) is

$$(1-s_i)\,\mu\rho_i g t^2 - \rho_i gSBt + 2C_i t - \tau B = 0 \qquad (5)$$

where s_i = specific gravity of ice
μ = coefficient based on the porosity and angle of internal friction that describes the internal strength of the cover
ρ_i = density of ice
g = gravitational acceleration
t = cover thickness
S = energy slope
B = top width

C_i = cohesive intercept of the Mohr–Coulomb relation

τ = shear stress on the underside of the cover.

Equation 5 represents the force balance on a unit length of ice cover. The first and third terms represent the internal and cohesive forces, respectively, resisting downstream movement. The second and fourth terms represent the downstream component of the weight of the cover and the shear on the underside of the cover respectively.

One can see from eq 5 that as discharge or velocity increases, the shear on the cover increases, requiring the cover to collapse and thicken to resist downstream movement. Thus, for a constant volume of ice generated, a higher discharge will produce a thicker and therefore shorter length of ice jam. For steep, shallow rivers, however, the jam thickness relies more on slope and width than on discharge. One can also see from eq 5 that cohesion is important in determining the thickness of an ice cover. Colder air results in a higher value of cohesion and consequently a thinner ice cover. Attempts have been made to measure the cohesive intercept in the laboratory and field values have been inferred from other measurements of ice jams that have frozen in place. The interaction of cohesion, air temperature and discharge is very complex and has not yet been sufficiently explained. Most investigations dealing with ice-jam thickness simply treat the jam as cohesionless, which appears to be valid for breakup type ice jams. The Salmon River ice jam, however, is a freezeup jam and cohesion is important.

The discharge values given in Table 2 are the freezeup values—the average discharge during phase 2. These values range from 725 to 1275 ft^3/s for the years in which an ice jam progressed to the city of Salmon. The discharges during this phase in the years having no ice jams also fall within this range, providing no simple explanation of the effect of discharge. Since phase 2 is the period of severe cold, cohesion is also important in determining the thickness of the jam as it progresses. Zufelt (1990) provides a solution of eq 5 for the case of a cohesionless jam by substituting

$$\tau = \rho g R_i S \quad (6)$$

where ρ is the density of water and R_i is the hydraulic radius of the ice affected portion of the flow area. Ice jam thickness is given as

$$t = \frac{BS}{2(1-s_i)\mu}\left\{1+\left[1+\frac{4R_i(1-s_i)\mu}{s_i BS}\right]^{1/2}\right\}. \quad (7)$$

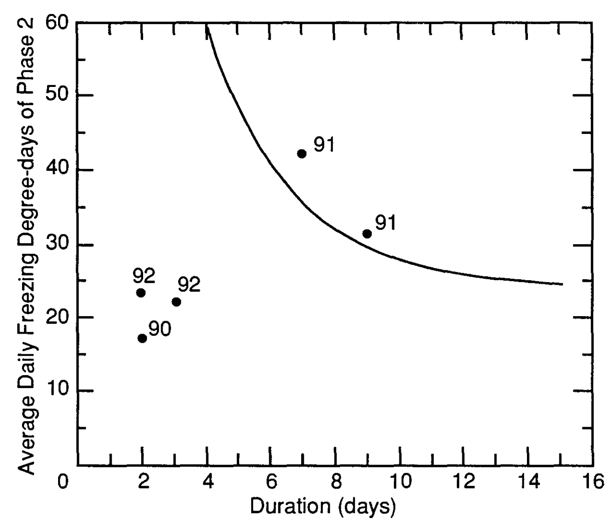


Figure 8. Threshold condition for ice jams to reach Salmon plotted with winters of 1989–90 through 1991–92 when the ice control structure was in place.

Equation 7 can be used to determine the effects of an increase in discharge on jam thickness. Using average values of B and S for the Deadwater to Salmon reach and solving Manning's equation for R_i, we can show that in the range of discharges experienced for phase 2, a 50% increase in discharge translates to only a 4% increase in jam thickness. Therefore, the theoretical importance of discharge is minor. The data were examined to find jam and non-jam events that experienced similar phase 2 intensities and durations such that the freezeup discharges could be compared. For example, the jam event of 1979 and the non-jam event of 1951 experienced almost identical phase 2 conditions. The freezeup discharge of 1979 was 800 ft^3/s while that of 1951 was 875 ft^3/s. While this comparison supports the hypothesis that higher freezeup discharges result in thicker ice jams that would not progress as far, other sets of jam and non-jam data show the opposite. The problem of comparing the data arises from differences in the AFDD1 and the cohesion value during phase 2. While the cold of phase 2 would result in cohesion, the function of air temperature and cohesion is not linear. Thus, a comparison of events that have the same duration and AFDD of phase 2 may not be valid because of the variation in mean daily air temperature within this phase. Since the effects of freezeup discharge have been shown to be theoretically minor and other factors such as cohesion and the AFDD1 are highly variable, no relation between discharge and ice jams reaching the city could be found.

SALMON RIVER ICE CONTROL

Several reports such as Cunningham and Calkins (1984) or Earickson and Zufelt (1986) have suggested that locating an ice control structure upstream of Salmon could catch frazil ice floating down the river and reduce the supply of ice that contributes to the Deadwater ice jam. The U.S. Army Engineer District, Walla Walla, and CRREL designed and installed an ice boom at river mile 268.5, approximately 8.5 miles upstream of the city center. The boom—described in a report by Axelson (1990)—was deployed during the winters 1989–90 through 1991–92. The object of the ice boom was to capture enough ice so that the Deadwater ice jam would not reach the city during severe winters when it otherwise would. These three winters provided a good test of the ice control concept.

Figure 8 shows the function describing the threshold condition for ice jams reaching the city of Salmon in Figure 6a. Also plotted are the severe cold periods (phase 2) of the winters of 1989–90 through 1991–92. The winter of 1989–90 was not very severe at all, while the winter of 1990–91 experienced two separate periods of severe cold. The winter of 1991–92 fell between these two extremes, with two short periods of severe cold. Figure 8 shows that an ice jam was not expected to reach the city during 1989–90 or 1991–92 but that an ice jam should have reached the city on both occasions during 1990–91. Since an ice jam did not reach the city during 1990–91, it would appear that the ice boom performed as expected.

During 1989–90 there were no extended periods of severe cold, nor did the boom accumulate any ice. During the winter of 1990–91, however, the boom did accumulate ice and formed an ice cover that extended several miles upstream during the first phase 2 period. While the velocities at the boom are higher than those normally found acceptable to create an ice cover, the cohesion that is experienced during very cold weather gives the cover the strength required to resist downstream movement. In other words, the ice boom collects ice and performs as expected only during periods of severe cold, which are coincidentally the times when it is necessary for the boom to work. In this light and since the Deadwater ice jam did not reach the city in 1990–91, the ice boom at Salmon is a success.

CONCLUSIONS

A method has been presented in which the likelihood of ice jams reaching the city of Salmon, Idaho, in any given winter can be assessed by inspection of the air temperature record. The analysis of the historical winter air temperatures and record of ice jams has shown that there is a relationship between the intensity and duration of severe cold, the air temperature record prior to the severe cold periods and ice jams reaching the city. The function that describes the threshold condition can be used with temperature forecasts to determine if an ice jam will reach the city in any given year. The analysis also showed that a mean daily air temperature of approximately 18°F is needed to retain an ice jam in place once it has reached the city. The theoretical importance of freezeup discharge on the thickness and consequently the length of the ice jam is discussed, and is shown to have a very minor effect on the Salmon River. An ice boom placed upstream of the city has prevented an ice jam from reaching the city during 1990–91 when it would have without the upstream ice control.

This technique should be applied to other rivers where a freezeup ice jam builds through the winter and periodically results in flooding, such as the Missouri River below several of the main stream dams. Field observations and measurements of ice jams should continue to determine the effects and values of cohesion in relation to air temperature. The ice boom at Salmon should be monitored during future winters to verify its operation and effects.

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Large ice jams on the Salmon River have reached Salmon, Idaho, and resulted in major flood damage during 16 winters since the winter of 1936–37. Two recent ice jams, in February 1982 and January 1984, caused flooding that resulted in damages of $1 million and $1.8 million respectively. A detailed analysis of the winter air temperature records from 1936–37 through 1991–92 revealed a strong relationship between the duration and intensity of severe cold periods, the air temperature record prior to the severe cold periods, and the occurrence of ice jams reaching the city of Salmon that result in flooding. A threshold condition is identified from which the probability of ice jams reaching the city can be determined from inspection of forecasted air temperatures. It was found that once an ice jam reaches the city, average daily air temperatures of approximately 18°F are necessary to keep the jam in place. The effects of discharge on ice thickness, and therefore ice jam length, are shown to be minor and no relation could be found in this study. An ice control structure located upstream of the city of Salmon appears to be helping to alleviate ice-jam flooding.

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