ICE JAM FLOODING NEAR THE CONFLUENCE OF THE MISSOURI AND YELLOWSTONE RIVERS

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ABSTRACT

This investigation focused on ice-related flooding along the Missouri River, just below the confluence with the Yellowstone River near Williston, North Dakota. This area is at the upper end of Lake Sakakawea. With the closure of Garrison Dam in 1953, Lake Sakakawea began filling, reaching operational levels in 1965. Changes in the hydraulics, sedimentation and ice regime of the Missouri River caused by the impoundment have led to an increase in the potential for overbank flooding. This paper presents an evaluation of the ice regime of the Missouri and Yellowstone Rivers using historical and recent information on ice processes and ice-related flooding. A scheme for estimating the potential for ice-related flooding based on a correlation of weather and hydraulic data is outlined. The method has been used in two subsequent winters to estimate the timing and severity of river ice breakup.

INTRODUCTION

Although the prediction of ice jam occurrence and severity is still beyond the state-of-the-art, it is sometimes possible to rate the likelihood of ice jam occurrence based on historical data. Such a prediction mechanism could prove useful in estimating the potential for ice jam formation in a given year, both for early warning of potential flooding and for determining whether advance measures to limit ice-related flood damage are advisable. This paper will focus on the application of such a technique to the Missouri River near Williston, North Dakota. On the basis of interviews with local residents and a review of literature, six significant ice jam events were identified during the period from 1952 to 1992. In order to develop a predictive scheme, weather and hydrologic data for both jam and non-jam years were reviewed. Factors examined included air temperature, snowfall, water discharge, and the water surface elevation in a downstream reservoir. The method has been used in two subsequent winters to estimate the timing and severity of river ice breakup.

SITE DESCRIPTION

The Buford-Trenton Irrigation District is located along the Missouri River about 24 km upstream of the City of Williston, North Dakota, on the extreme western edge of the state. A map of this area is presented in Figure 1, along with cross sections used in the hydraulic analysis. These cross sections, whose numbers correspond to river miles, will be used to identify specific locations later in this report. The study area is at the the upper end of the Garrison Dam-Lake Sakakawea Project, within the Omaha District of the U.S. Army Corps of Engineers.

The Missouri River above Williston has a drainage area of approximately 426,055 km^2, with roughly 181,300 km^2 contributed by the Yellowstone River basin and 233,100 km^2 by the Missouri above the confluence with the Yellowstone. The

Missouri River discharge below the confluence, based on daily mean values, ranges from about 85 to 625 cms during the fall freezeup and mid-winter periods. Mean flows for the the months of December through February are on the order of 300 cms. At this flow the Missouri River has a water surface width on the order of 150 to 300 m, a thalweg depth of 3 to 6 m, and water velocities of 0.3 to 1 m/s. Water surface slopes are relatively flat, 0.00002 or less, below the Route 85 bridge (cross section 1552.7). Above the Route 85 bridge the water surface slope is on the order of 0.00011, while on the lower Yellowstone River it is about 0.00018.

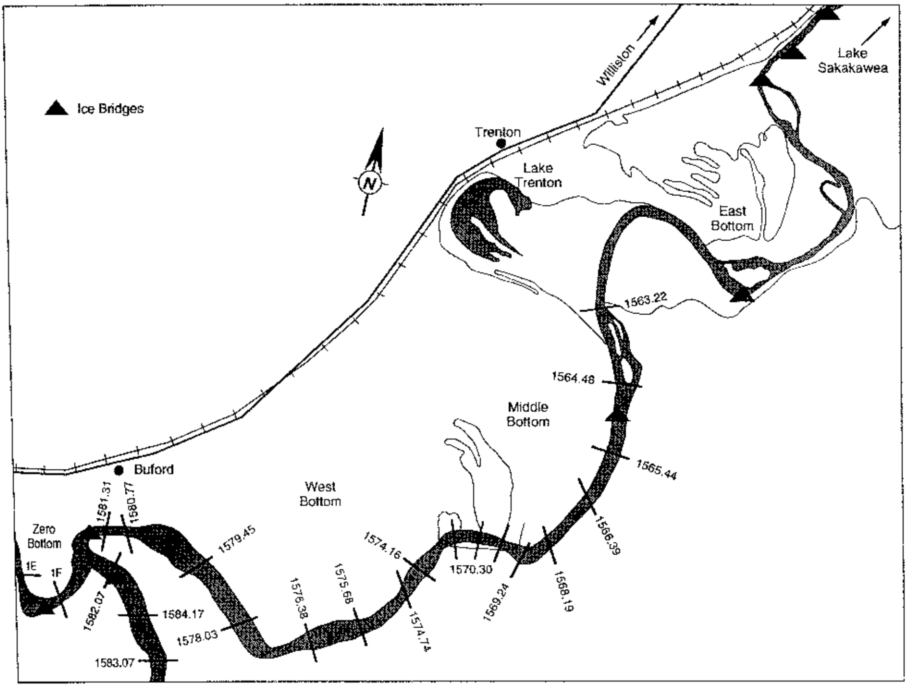

Figure 1. Map of Buford-Trenton Irrigation District.

Hydrology

An analysis of open water conditions along the Missouri River from Fort Peck Dam to Garrison Dam was conducted by the Omaha District (USACE, 1978). USGS discharge records are available for the Missouri River at Williston for the period from 1929 to 1965 after which gaging at the site was discontinued. The flow record was extended through 1975 by transposing the combined flow records for the Missouri River at Culbertson, Montana and the Yellowstone River at Sidney, Montana. The Culbertson gage is 62 km above the confluence, while Sidney is 49 km upstream. The results of an annual peak discharge frequency analysis based on those records are summarized in Table 1. The results of the 1978 discharge-frequency analysis have since been extended through 1984, again using the Culbertson and Sidney gage data (R. Kay, personal communication). These values, also presented in Table 1, show that extending the record has resulted in a lowering of predicted discharge values, ranging from about 5% at a 2-year event to 9% at the 500-year event. Both sets of values are presented for comparison, since an analysis of peak discharges occurring during the month of March contained in the 1978 report (USACE, 1978) will be used later in the report.

Table 1. Missouri River annual peak discharge frequencies.

Return Interval (years)	Discharge * (cms)	Discharge ** (cms)
2	2,690	2,550
5	3,680	3400
10	4,530	4250
25	5,950	5,380
50	7,360	7,110
100	9,630	8,500
500	12,460	11,330

* after USACE (1978)

** Based on data provided by Roger L. Kay, Omaha District (personal communication, June 1992).

While these discharge values are appropriate for determining open-water flood flows, the analysis of spring breakup related flooding requires information on flow magnitudes during past breakup events. Unfortunately, the actual flows or even the exact dates when ice cover breakup and ice jamming have occurred in the past are unknown. In the absence of more detailed historic information, spring breakup flows were taken to be the first major peaks in flow occurring during March or early April sufficient to cause ice cover breakup.

The estimated breakup discharge frequencies presented in Table 2 were developed by ranking these combined flows, plotting them on log-probability paper and fitting a curve by eye. The period of record ranged from 1966, when Lake Sakakawea reached its maximum normal pool elevation, through 1990. For comparison, discharge-frequency values for peak flows in the calender month of March, developed by the Omaha District (USACE, 1978), are also included. The March values are somewhat higher than the estimated breakup discharges since they consider the maximum discharge in the calendar month rather than the first significant discharge peak. Further, the March discharge frequencies were developed using data from 1929 to 1975. As discussed previously, when the all-season discharge-frequency relationship was extended to include the period from 1975 to 1984, the predicted 10-year discharge value was reduced by about 5%.

Table 2. Missouri River Breakup Period Discharge Frequencies.

Return Interval (years)	Discharge (cms)	March Discharge (USACE, 1978)
2	910	1,020
5	1,900	2,270
10	2,600	3,450
25	3,680	4,810
50	4,530	6,230
100	5,520	7,930

Ice Conditions

A field study of the ice regime was conducted during the winter of 1991-92 (Wuebben and Gagnon, 1995). Observations and discussions with residents during that study showed that, with rare exceptions, the winter ice cover in the study area was a smooth, single-layer ice sheet not too unlike that formed on a lake. In some areas the ice was clear, black ice that was apparently formed in place. In other areas, the ice cover was made up of large pans of ice that had formed elsewhere, floated downstream, and gently accumulated through juxtaposition to form a single layer of floes which subsequently froze together to form a smooth ice cover. On the basis of interviews with local residents, it would appear that such ice conditions are typical for this section of the Missouri River. Ice thickness estimates by those residents were generally on the order of 0.6 to 0.75 m, although some residents reported thicknesses as high as 0.9 and 1.2 m on occasion.

Thermal ice growth calculations based on the long term record of accumulated freezing degree days indicate that ice thickness in this area might reach 0.75 m about once in five years, and 0.9 m less than once in 50 years. The 50% exceedance ice thickness would be just over 0.6 m. It is possible that these thicker estimates were made in areas where ice floes have, in some years, accumulated to form a multi-layer cover.

Breakup

In most years, breakup on the Missouri River in the vicinity of Williston, N.D. is driven by events on the tributary Yellowstone River. In response to warmer weather and increasing runoff, the ice on the Yellowstone begins to break up and run several weeks prior to breakup on the Missouri. The breakup of the Yellowstone River then proceeds downstream in a series of ice jamming and release events. Eventually the breakup front on the Yellowstone reaches the Missouri and proceeds further downstream through the area of the Buford-Trenton Irrigation District towards Williston. During an ice run, it was reported that very large ice floes pass down river. One resident commented that the ice floes typically appeared to be 0.75 to 0.9 m thick and "....gym-size in area."

The ice on the Missouri River upstream of the confluence area typically remains in place for approximately two weeks after the Yellowstone River runs, in large part due to the small, steady discharges maintained by the release schedule of Fort Peck Dam in Montana. While spring runoff on the Yellowstone River rises to values on the order of 600 to 1,200 cms, the Missouri River at Fort Peck is typically held below 300 cms until after the Yellowstone River flood peak has passed.

Ice Jam Locations

A number of residents commented that ice jams form in the vicinity of the Buford-Trenton Irrigation District form in the same locations year after year, but with varying severity. Since the ice normally starts running (and jamming) on the Yellowstone River two or three weeks before the ice run begins on the Missouri River, ice runs from the upstream portion of the Missouri River were felt to be of little consequence to the Buford-Trenton area.

Once the ice run on the Yellowstone River reaches the Missouri River, it often jams in the confluence area. This jam causes few problems in the District. As on the Yellowstone River, however, the ice marches downstream on the Missouri River in a series of jam and release events. Once a jam in the confluence area releases, subsequent jams are likely to occur in the vicinity of Ryder Point on the West Bottom (at about cross section 1577.15 as shown in Figure 1), and the Hurley Bend in the Middle Bottom (about cross section 1569.24). Ice jams were reported to be normally between two and ine-half and four kilometers in length, but as long as seven kilometers on occasion.

Ice Jam Events

There were six severe jams reported in the forty years preceding the study. The earliest was in 1952, the most recent in 1986. Based on six jams in forty years, the frequency of significant jamming would be 6/40 = 0.15, or about once in seven years. Since the backwater condition caused by the formation of Lake Sakakawea can have a significant impact on ice jam formation and since some long-past events may not have been recorded or recalled, we might instead use only the last twenty years of record. In that case, jam frequency would be 5/20 or once in four years. Prior years with significant ice-related flooding include 1952, 1972, 1975, 1976, 1978, and 1986. The study was conducted during the winter of 1991-92. Spring of 1992 and 1993 were uneventful. Spring of 1994 brought severe jamming conditions.

ANALYSIS

Ice-related flooding tends to be local and highly site specific. Without prior field observations, it is difficult to predict where, or even if, ice jams will form along a river. The first step in the analysis was a year-by-year review of flow records to determine the expected breakup discharge. Ice-afffected water surface elevations lie somewhere between the limiting conditions of open water, a solid cover of sheet ice, and a fully developed equilibrium ice jam. The solid ice cover case would represent the minimum ice-affected stage, while the equilibrium ice jam case would represent the maximum stage possible for a given discharge. If we consider the range of possible Missouri River discharges during the breakup period, we can categorize ranges of flow from discharges too low to cause breakup of the ice cover to discharges where all ice would move downstream without jamming. These categories might be based on personal observations, observations by local residents, notes on nearby gaging records, sharp breaks in the trend of continuous stage measurements, or other sources of information.

Based on a typical freezeup flow of about 300 cms, a spring discharge on the order of 700 cms or greater would be required to initially dislodge a strong ice cover. This value is based a review of historic events along with a rule-of-thumb that the stage must rise three to four ice thicknesses above the freezeup stage to initiate the breakup and run of a strong ice cover. An increase from 300 to 700 cms would result in an increase in stage on the order of 1.5 m in most areas within the District. A deteriorated ice cover can release with lesser increases in flow, but such events do not normally result in significant ice jams. Below that discharge, then, it might be assumed that the stage-discharge relation would follow the sheet ice curve. Above that discharge, stages would tend towards the ice jam curve, assuming that conditions approaching an equilibrium jam were possible.

At a somewhat higher discharge, the trend of increasing stage with discharge would begin to flatten out. Due to the wide floodplains throughout most of the area, once the raised lateral ditches were overtopped, the channel stage would be substantially stabilized. For example, we know that the 1986 jam nearly overtopped the irrigation lateral near cross section 1567.44 with an estimated discharge of 1,680 cms. The rise in stage would certainly have leveled off once the elevation of the lateral was exceeded, or even dropped if breaching of the lateral had occurred, had the jam not collapsed and released first. Further, if discharge continues to increase after a jam forms, a discharge magnitude would eventually be reached where a stable jam would no longer be possible, the jam would release and the ice would pass downstream. Stages would then return to the open water curve.

The jam release discharge remains unclear, as it depends not only on water discharge, but also the quantity of ice and strength of the ice accumulation. In

1986 we know that two jams released with discharges no higher than about 1,700 cms. Five of the six known jams occurred with discharges between 850 and 2,200 cms. The 1952 event had a mean daily flow of 3,400 cms and a peak discharge of 4,800 cms in the same time frame as the jam event, but it is unclear whether the jam was still in place or had (more likely) released prior to that peak flow. Experience and data from other rivers indicate that the maximum discharge during an ice jam event is usually no more than a two-year open water flow, which in this area would be 2,550 cms. A ten-year breakup period discharge is approximately 2,600 cms. It is suggested here that the maximum ice jam discharge should lie at or below this ten-year, breakup period flow. Beyond that level, ice jams should become unstable and the water levels would return to near-open water levels.

Ice Jam Potential

Predicting ice jam occurrence and severity can be a challenge, even on rivers where detailed, long term data has been collected. Lacking such information makes the problem far more difficult, but it is sometimes possible to rate the likelihood of severe ice jams based on a correlation of weather and flow data with information on significant prior ice events. Such a prediction mechanism could prove useful in estimating the potential for ice jam formation in a given year, both for early warning of potential flooding and for determining whether advance measures to limit ice-related flood damages are advisable. Based on interviews with local residents and a review of literature, six historical ice jam events were identified in the Buford-Trenton area during the forty years preceding the study. Five of these events occurred between 1972 and 1986. In order to review the winter season characteristics leading up to significant ice jam events, weather and hydrologic data from 1970 through the present were reviewed. Two years preceding the filling of Garrison Reservoir, the ice jam year of 1952 and the randomly selected year of 1960, were also included.

As shown in Table 3, factors examined included freezing degree days, snowfall, water discharge, and Lake Sakakawea stage. Freezing degree days and snowfall are used to reflect the thickness and strength of ice on the river. Freezing degree days can be used in a relatively simple equation to predict ice thickness:

$$h = c \ (AFDD)^{0.5} \tag{1}$$

where h is the calculated solid ice thickness in meters, $AFDD$ is the accumulated degree-days of freezing (Celsius), and c is an empirical constant to account for wind exposure and snow cover. This constant was calibrated to the Williston area during the essentially snowless winter of 1991-92 to a value of 0.02. Using this same value for the winter of 1952 resulted in a predicted ice thickness of just under 0.8 m. The measured ice thickness in 1952 was 0.81 m, and there was about 0.25 m of snow on the ground one week prior to breakup (USDOC, 1953). For winters with greater snowfall this value might vary, and the calculated thickness values are used only as an index.

The next term in the table, $AFDD_{max}$, is the water year Julian day (days since October 1st) when the $AFDD$ term began to decrease, taken as an indicator of net melting of the snow/ice cover. Low values of this term often indicate that the weather warmed earlier in the spring and that significant ice deterioration/ melting may have occurred prior to any large increase in runoff. The term in the next column indicates the estimated date of the spring runoff causing breakup in a given year. Lacking direct field observations of ice breakup for the period of record, this term had to be estimated from discharge records, an approach that leaves some uncertainty as to the actual breakup date. The date of the maximum river discharge, $Qmax$, when compared to the date of maximum $AFDD$, $AFDD$max, can be used to reflect the arrival of significant spring runoff relative to warm weather in the District.

Table 3. Ice jam potential analysis.

Year	Known Jam	AFDD (°C-D)		h (m)	$AFDD_{max}$ (JD)		Q_{max} (JD)		Q_{max} - $AFDD_{max}$ (JD)		Q_b (cms)		Snowfall (m)		Snow timing (E/L)		Garrison Stage (m)		+	–	+/-
1952	x	1528	++	.80	178	+	180	+	2	++	3510	-	.64		E	-	Low	-	6	3	2.0
1960		1111		.68	165		174	+	9		2830	-	.38	--			548.03	-	1	4	.25
1970		1128		.69	182	+	160		-22	--	750		.96		L	+	559.92		2	2	1.0
1971		1358		.75	177	+	166		-11	--	1640	+	.44	--	L	+	561.44	+	4	4	1.0
1972	x	1444	++	.78	160		167		7	++	2120		.83				562.05	+	5	0	*
1973		917	--	.62	147	-	157		10		850	+	.17	--	E	-	561.81	+	2	6	.33
1974		1256		.72	180	+	186	+	6	++	880	+	.51				560.47		5	0	*
1975	x	1000		.65	180	+	175	+	-5	++	850	+	1.22	++	L	+	560.41		8	0	*
1976	x	1000		.65	165		175	+	10		1220	+	.71		E	-	560.98	+	3	1	3.0
1977		1056		.66	140	-	170		30	--	710		.38	--	E	-	559.61		0	6	-
1978	x	1667	++	.83	170	+	176	+	6	++	2210		.38	--	E	-	557.17	-	6	4	1.5
1979		1833	++	.88	180	+	170		-10	--	1700	+	.94		L	+	559.46		5	2	2.5
1980		1056		.66	165		151	-	-14	--	740		.64				560.10		0	3	-
1981		611	--	.51	135	-	145	-	10		790		.13	--	E	-	557.75	-	0	8	-
1982		1278		.73	160		147	-	-13	--	1130	+	1.52	++	L	+	557.54	-	4	4	1.0
1983		790	--	.58	174	+	166		-8		590	-	.73		V L	++	561.17	+	3	3	1.0
1984		1089		.68	168	+	174	+	6	++	550	-	.75		L	+	560.56		5	1	5.0
1985		1282		.73	158		156		-2	++	710	-	.46	--	L	+	560.34		3	3	1.0
1986	x	1111		.68	145	-	152	-	7	++	1680	+	.89		L	+	559.70		4	2	2.0
1987		566	--	.49	179	+	168		-11	--	480	-	.53		E	-	560.92	+	2	6	.33
1988		843	--	.59	167	+	176	+	9		480	-	.41	--	E	-	558.67	-	2	7	.29
1989		1278		.73	175	+	167		-8		1150	+	.81		E	-	554.95	-	2	2	1.0
1992		510	--	.46	147	-	158		11	--	740		.46	--	E	-	555.19	-	0	9	-

In the Williston area, the local weather which governs the thickness and strength of the river ice is relatively uncoupled from the weather in the mountains that governs the snowmelt runoff that produces most breakup discharges. If the weather warms up in the Buford-Trenton area well in advance of snowmelt runoff in the mountains, the ice is likely to be too thin and/or rotten to pose a significant flood threat. On the other hand, an increase in runoff from upstream early in the winter may encounter a strong, resistant ice cover requiring a greater, more rapid discharge increase to initiate breakup.

As mentioned previously, it takes a certain magnitude of discharge and stage increase to release an ice cover and allow it to move downstream. If the increase in discharge is rapid or the ice deteriorated, the required increase in stage may be slight, but for gradually rising discharges the required increase in stage may be equivalent to 3 or 4 ice thicknesses. For the typical freezeup and midwinter discharge of about 300 cms in the study area, a spring runoff event in excess of 700 cms should be required to break up a strong ice cover. The required breakup discharge, *Qb*, varies, however, with the actual freezeup discharge for a given year as well as variations in the other terms listed in Table 3.

Two terms are included to account for snowfall characteristics. Ideally the snow-related portion of the prediction scheme would use the depth of snow remaining on the ground prior to breakup as an index, but historic records of this parameter are not available. Instead we have used two terms, total snowfall for the season and the timing of the snowfall as an indicator. The timing of the snowfall is listed as being E for early, L for late, or VL for very late. The climate of the Williston area is such that, in many years, the snow has completely melted from the river ice surface prior to breakup. In addition to potential thinning of the ice cover through thermal melting, this allows solar radiation to penetrate and decay the internal structure of the ice. In this manner, even a relatively thick ice cover can be weakened to reduce or eliminate ice jam flooding potential.

A factor is also included in the table to reflect the elevation of Lake Sakakawea (Garrison Reservoir stage) since the most common location for ice jam formation is the transition from relatively steeper to a relatively milder energy slope such as that presented by a river flowing into a lake or reservoir. Garrison Reservoir reached its normal operating levels in 1965, and since that time has been a potential factor in the occurrence and location of ice jam formation.

In addition to listing the magnitudes of these various terms, an effort was made to discriminate whether the values indicated a high, low, or medium potential for ice related flooding. The criteria for ranking the terms are provided in Table 4 below. Based on these criteria, values for the various terms that would indicate a high correlation with ice jamming are indicated by a "+" in the table, while values associated with a lesser risk are denoted with a "-". Note that three terms, *AFDD*, *Qmax-AFDDmax*, and snowfall magnitude are double weighted.

In the final three columns the total "+" and "-" symbols have been tabulated and a ratio calculated. Values less than one would indicate relatively lesser ice jam flooding potential, while values greater than one would indicate a greater potential. The lowest ratio value for a known ice jam event is 1.5 in 1978, but three years in which no jams were reported (1974, 1979 and 1984) have values greater than 1.5. In 1984 the ratio was a very high 5.0, indicating severe ice jam potential in a year with no reported jam. However, the discharge peak was 550 cms, less than the threshold of 700 cms required to cause a dynamic breakup of the ice cover. While these criteria are empirical and approximate (there is no precedent for this prediction scheme), their correlation with past ice jam events is quite clear. More importantly, tabulating these or comparable terms during future winter seasons should give a useful indication of the potential for ice-related flooding in the spring.

Table 4. Ice Jam Potential Rating Factors

Term	Range	Indicated Potential Low	 High
AFDD (°C-days)	510/1833	<940	>1440
$AFDD_{max}$ (days)	135/180+	<150	>165
Q_{max} (days)	145/175	<155	>170
Q_{max} -$AFDD_{max}$ (days)	-22/+30	<-8 or $>+10$	>-5 or $<+7$
Q_b (K cms)	480/3510	<700 or >2500	>850 or <2000
Garrison stage (m)	548/562	<559	≥ 561
Total snowfall (m)	0.13/1.5	<0.5	>1.0
Snowfall timing	---	<0.1 m after JD = 90	>0.25 m after JD=90 >0.10 m after JD=120

Recent Winters

As the winter of 1992-93 developed, it appeared that it could result in severe spring breakup conditions. Of the five ice jam events recorded since 1970, the *AFDD* total by 20 January was the second coldest. By 27 February, however, the *AFDD* total was only about average for years with ice jams. By 3 March, the *AFDD* total had peaked at 1259. On Monday 22 March, using gage information upstream on the Missouri and Yellowstone Rivers, discharge was anticipated to cross the threshold for breakup by the evening of 23 March. Due to the extended warming period prior to breakup, no significant ice problems were expected. Ice began to move on the Yellowstone River during the morning of 24 March at Sidney, Montana (about 48 km upstream of Williston). Ice breakup in the Williston area occurred during the morning of 25 March.

In 1994, the *AFDD* total reached a maximum of 1263 on 28 February. Discharge rose rapidly above the breakup threshold on Friday 5 March. Although the winter had not been extremely cold, the ratio of ice jam potential rating factors was 6, higher than any recorded in Table 3. Ice jams and ice-related flooding developed on Saturday 6 March. Flood levels peaked on 8 March exceeding any recorded in the events in Table 3.

SUMMARY

This report has reviewed work conducted to analyze the ice regime and develop an ice jam potential prediction scheme for the Missouri River near Williston, North Dakota. Although the prediction of ice jam occurrence and severity is still beyond the state-of-the-art, it was possible to put together a scheme based on a correlation of historic events, flow and weather data that allows an estimation of the likelihood of ice jam occurrence and relative severity. In the two years following the original study, the scheme was able to correctly predict a non-event year in 1993 and a severe event in 1994.

REFERENCES

USACE (1978) "Buford-Trenton Irrigation District: Backwater and Drainage Problems", Design Memorandum MGR-146, U.S. Army Corps of Engineers, Omaha District, Omaha, Nebraska, January.

Wuebben, J.L. and John J. Gagnon (1995) "Ice jam flooding on the Missouri River near Williston, North Dakota", USA Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, CRREL Report 95-19.

DISCUSSION

David Andres,
Trillium Engineering and Hydrographics, Inc.:
What implication does the aggradation have on the thickness of the ice jams? One would think that as the channel aggrades, the slope is reduced and the thickness of the ice jams would be reduced, thereby reducing the ice-related water levels.

Reply: I agree that a lessening of river slope should decrease ice jam thickness since slope is a primary force driving an ice run and governing the stability of an ice accumulation. Indeed, as a reservoir fills, locations previously subject to jamming may no longer see thickened accumulations at all. In areas still subject to ice jamming the ice accumulations may indeed be thinner, but the resulting water levels are also influenced by the reduction in channel capacity due to sedimentation. In the time since Garrison Dam was closed in 1953, the stage necessary to pass a two-year flood during open water conditions has increased by over 3 meters in the East Bottom area shown on Figure 1, and by over 2 meters near the confluence of the Yellowstone and Missouri Rivers. Further, deposition on the river bed elevates the channel relative to valley features and can result in a change in the width of the river that the ice has to bridge across. Since the river banks provide confining pressure for jam development, an increase in river width would indicate an increase in jam thickness.

Another question is the location of jamming. As the deposits continue to evolve, the location of the change in slope from the reservoir backwater to the natural stream slope will progressively move upstream. Since a transition from the steeper slope to a milder one is a primary factor controlling the occurrence and location of ice jam formation, the locations where ice jams form may also propagate upstream. The actual response of the Missouri River is hard to judge, however, since there are no measurements of ice jams thickness through time as the deposition occurred.

Paul Doyle,
British Columbia, Ministry of Environment:
Did you test other indicators for predicting ice jam severity besides those shown on the tables in the paper? If so, what were they? How did they compare to those used?

Reply: The selection of indicators was limited in two ways, availability and imagination. In order to make this system useable as a practical tool, we had to select data that were meaningful and readily obtainable. The factors that we felt were most important to include were hydraulic conditions, ice quantity and ice strength. Water discharge is obvious, with some modification due to the elevation of the pool behind Garrison Dam. Discharge during breakup and jamming would be quite useful, but there was no local gage data available. The discharge data cited is derived from gages some distance upstream on the Missouri and Yellowstone Rivers. All of the other factors serve as indices of ice conditions, particularly those related to the integrity of the ice. Measured ice thickness and strength would be ideal, but such data do not exist. In their place, we used measurements of the magnitude and timing of freezing degree days and snow cover. As indicated in the text, the depth of snow on the ice would be preferred to information on snowfall, but this data was not available. Thus, the selection of factors was reduced to selecting available data to represent factors of importance to ice jam formation and severity, and assigning weighting factors according to their significance. The weightings of the factors given in the paper are a first, and admittedly rough, attempt to quantify their influence. There is no strong basis to assume that the date of maximum freezing degree days, water discharge and reservoir elevation should have equal influence on ice jam formation. Future work will surely modify the weighting scheme. Further, it may be preferable to use a scheme in which the ratings are summed rather than used as a ratio to avoid ratings of zero and infinity.

Sylvester Petryk,
Petryk Consultants, Inc.:
Your observation that breakup occurs at a lower discharge with increased aggradation is interesting because, as Dave Andres said, you would expect the opposite to happen because of the reduction in slope. Possible reasons for earlier breakup with aggradation are: 1) The ice cover loses its bank support earlier and floats onto the floodplain to break up, or 2) The river width increases and therefore reduces the stability of the ice cover.

Reply: If the slope of the river was reduced while other characteristics of the system were held constant, then the forces acting on the ice cover in the direction of flow would be reduced. However, for a similar increase in discharge, the stage would increase more on the milder slope. For situations in which the ice cover breakup is dominated by an increase in stage (loss of bank support), breakup would occur at lower discharges on a mildly sloping stream. Further, if deposition primarily occurs on the river bed, then the width that the ice has to bridge across can be increased as the channel is raised relative to its former cross section.