Forecasting Systematic Ice Jam Occurrence along the Yukon River, Alaska

Kathleen D. White, PE
Research Hydraulic Engineer, Ice Engineering Research Division,
US Army Cold Regions Research and Engineering Lab, Hanover, NH 03755
kwhite@crrel.usace.army.mil

Many long northern rivers experience a single, snowmelt-driven, ice-cover breakup that progresses downstream and results in the occurrence of ice jams. For example, the ice jams that form annually on the Yukon River generally occur during May and June and progress from east (upstream) to west (downstream). In some years, the jamming progresses in an orderly, systematic fashion, and in others the jam occurrence is marked by long delays. Since most development in the Yukon River basin is clustered along the river, the ice jams may cause flooding and damage to structures as well as disrupt transportation. Long-term empirical forecasts of the likelihood of spring ice-related flooding are made by the National Weather Service Alaska River Forecast Center. Combining this long-term forecast of jam likelihood with near-term forecasts of jam occurrence could improve ice jam mitigation and reduce damages. This paper presents a forecast matrix based on observed jam dates that can be used in preparing near-term forecasts of systematic ice jam occurrence along the Yukon River.

1. Introduction

Many large northern rivers experience single, snowmelt-driven, ice-cover breakup that progresses downstream and can result in the occurrence of ice jams. Because many of these rivers are located in sparsely populated regions (e.g., Athabaska River, and St. John River, Maine), development is often clustered along the rivers, which often serve as a major transportation link as well as a source of food and water. Such is the case for residents along the Yukon River in Alaska, for whom the breakup of the river ice cover means the end of frozen highways and the start of open water transportation (Fountain 1984). According to Woerner

(1986), most of Alaska's 16,000 km of road are south of the Yukon River, which has only one road bridge. Air transport is vital, and damage to airfields can be critical, during the breakup period when transportation is largely limited to aircraft.

The Alaska River Forecast Center (AKRFC) makes relatively long-term forecasts of the potential for spring breakup floods (Nibler 1994). They also actively monitor ice cover breakup and ice jamming in close cooperation with local officials (Rundquist 1994). However, ice jams can still take towns by surprise and cause flooding and ice damage. This was the case in 1971, when a sudden ice jam accompanied by a rapid rise in water level at Alakanuk damaged every structure in the village and residents were forced to await rescue via helicopter from rooftops and boats (Newsminer 1971). In these situations, a near-term ice jam occurrence forecast could be quite useful, in addition to the longer-term forecast provided by the AKRFC. This paper presents a forecast matrix based on observed jam dates that could be used in preparing near-term forecasts of ice jam occurrence along the Yukon River. The method could also prove useful in developing jam forecasts for other northern rivers that behave in a similar fashion.

2. Historical Ice Data

Ice cover breakup along the upper Yukon River from Rampart (approximate river mile (RM) 758) to Eagle (RM 1204) between 1896 and 1978 has been chronicled by Stevens et al (1979a). They also collected data on the timing of ice cover breakup along the lower river from Alakanuk (RM 10), within the Yukon delta, to Tanana (RM 694) for the period 1883 to 1978. In a summary and analysis of this data as well as data from other sources, Fountain (1984) reported that river ice cover breakup patterns can vary widely from year to year but that breakup generally proceeds from upstream to downstream. Following a qualitative analysis of breakup trends, Fountain proposed three general categories of breakup: progressive, staggered, and static. Ice cover breakup that progresses downstream without significant delays is termed progressive. Staggered breakup is characterized by significant delays in the downstream progression of breakup, and static breakups show no discernible trend in progression. Breakup may occur nearly simultaneously at several locations before progressing downstream for both systematic and staggered breakups. Referring to the underlying mechanism controlling breakup, Nibler (1996) proposed two categories of breakup: dynamic breakup corresponding to Fountain's progressive breakup, and thermal breakup, corresponding to Fountain's staggered and static breakup. In his paper, the terms "systematic" and "nonsystematic" have been selected to describe these two patterns of breakup and subsequent jamming.

As might be expected, ice jam occurrence along the river is closely related to breakup. Ice jam data for the Yukon River obtained from the US Army Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database includes the location and date of the reported jam (Figure 1). For the purpose of this study, it is assumed that jams occurred on the date that they were first reported although it is possible that some jams formed earlier

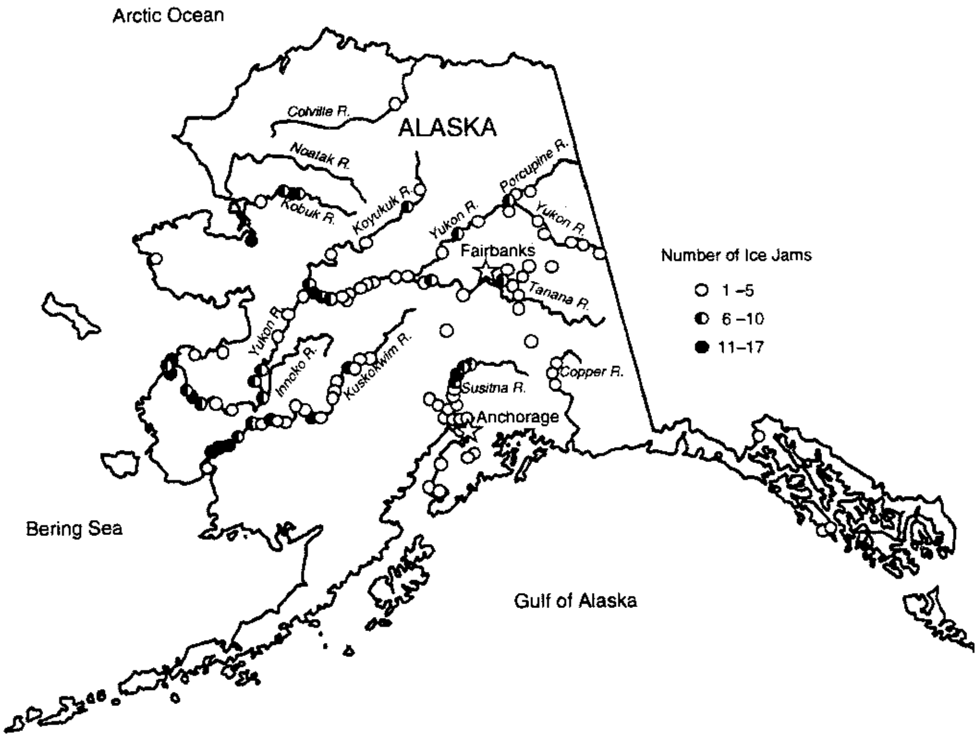


Figure 1. Alaskan ice jam locations included in the CRREL Ice Jam Database.

than the reported jam date, since jams often go unnoticed until reaching some stage at which a problem is perceived. An evaluation of the dates of reported breakup (from Stevens et al. 1979a, 1979b) and jamming (from the CRREL Ice Jam Database) in the four years for which both types of published data are available (1971, 1972, 1975, and 1976) shows little difference in the timing of these events. Therefore, the error associated with this assumption is presumed to be small.

In general, the ice jams are first reported at upstream locations before downstream locations. Of the known Yukon river ice jams reported since 1959, ice jam data (i.e., location, ice jam date) for at least five different locations along the river locations is available for 19 years: 1971, 1972, 1975, 1976, and 1981-95. Ice jam occurrence can be described as systematic in 11 of these years and as nonsystematic (i.e., exhibiting significant delays) in the remaining eight years. No years with jam occurrence behavior similar to Fountain's static breakup were identified in the sample population with five or more locations. Years with fewer than five reported jams may exhibit this type of behavior possibly due to errors associated with smaller sample size. However, it is possible that the years with very few jams represent an extreme condition resulting from a largely thermal breakup, for which little downstream movement of jams is expected.

A comparison of the behavior of the mean annual jam occurrence of systematic and nonsystematic jams is shown in Figure 2. Simultaneous jamming (i.e., the downstream

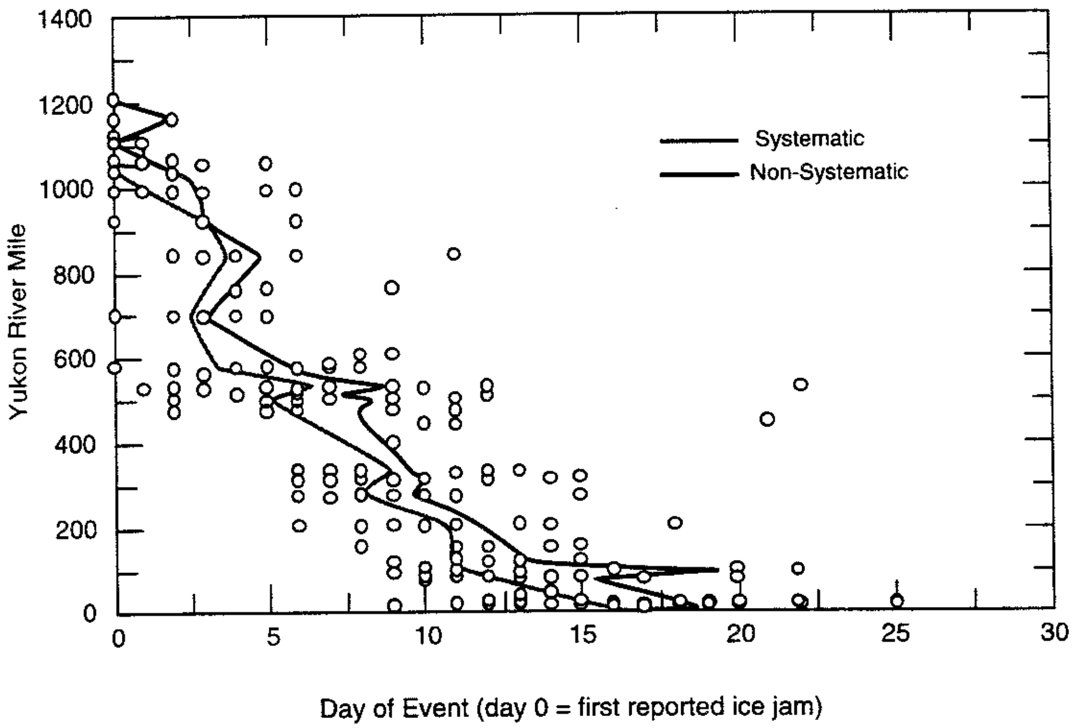


Figure 2. Mean values of daily jam occurrence for systematic and nonsystematic jams.

location experiences a jam at the same time as or before the upstream location) occurs at several locations, primarily river confluences. These locations include Tanana (RM 694), where jams are reported before Rampart (RM 758), probably due to the influence of the Tanana River, which can break up before the Yukon River and jam at the confluence. Jams also tend to occur at Nulato and Koyukuk (RM 470 and 497 respectively) before they are observed at Bishop Rock and Galena upstream (RM 510 and 525 respectively), again possibly due to the influence of the Koyukuk River, which joins the Yukon River at Koyukuk. Holy Cross (RM 272), located near the confluence with the Innoko River, also tends to report ice jams earlier than its upstream neighbor Anvik (RM 310).

The two types of jams exhibit the same behavior between about Twentytwo Mile Village (RM 1040) and Pilot Station (RM 115). Deviations above this reach are probably due to small sample size, while downstream deviations may be affected by tidal influences as well. Although visual observation suggests that nonsystematic jams occur more slowly than systematic jams (Figure 5), a Kruskal-Wallis test of the means indicates that there is no significant difference between the timing of systematic and nonsystematic jams (i.e., the mean nonsystematic jam occurrence is not statistically significantly later then the mean systematic jam occurrence). The statistical results imply that jam occurrence along the Yukon in any given year may fall along a continuum of jam behavior, from purely systematic to purely nonsystematic. For the purpose of developing a model to forecast the progression of ice jams along the Yukon River, all jams can be included in a single population.

3. Forecasting Yukon River Jam occurrence

Forecasts can be based on deterministic, stochastic, or empirical models, or combinations of the three, and can have varying degrees of uncertainty depending on the underlying model. Limitations in the development of deterministic models of ice jam processes (e.g., ice cover breakup, transport, jamming, and jam failure) prevent a wholly deterministic forecast. The long-term spring breakup flood forecast developed for the Yukon River (Nibler 1994) is empirical in nature. This forecast is based on calculation of a breakup index, developed from measurements of the snow pack and ice thickness on 1 April each year combined with the seasonal air temperature. The near-term forecast of ice jam occurrence along the Yukon proposed here is based on observed ice jam dates at locations with at least five reported ice jams and is stochastic in that at each of these locations, it is the distribution of the date of jam occurrence that provides the basis for the forecast.

Although a near-term forecast of jam occurrence based on calendar date is desirable, an examination of the data suggests that forecasting progression by calendar date would have a level of uncertainty too large for beneficial use. Much less variability is apparent when the annual jam progress is compared in terms of daily progression within each year, where day 0 would be the day when the first jam was reported each year. While sophisticated curve-fitting procedures could be used to construct a jam occurrence model, use of mean jam occurrence values is preferred for several reasons: 1) mean values preserve information on simultaneous jamming, 2) confidence intervals that provide information about the risk and uncertainty of the forecast can be easily constructed around the mean, and 3) use of mean values allows the forecast model to be easily updated on an annual basis. In practice, the near-term forecast could be used to refine predictions made by the long-term empirical forecast. Note that the near-term forecast is used to predict *when* a jam might not occur, not *if* the jam will occur, and thus assumes that hydraulic, hydrologic, and ice conditions favor jam formation.

Mean ice jam occurrence along the Yukon River, including the 95% confidence interval around the mean, is shown in Figure 3 and tabulated in Table 1 for locations with at least five reported ice jams were included. These locations are shown in Figure 4. Continued collection of ice jam occurrence data will allow refinement of the forecast, both in terms of reducing uncertainty at locations presently included in the forecast and through the inclusion of additional locations. For example, Rampart (RM 758) and Bishop Rock (RM 510), each with four reported jams, could potentially be included in the forecast model following the next ice jam season.

The mean jam occurrence data form the basis for the near-term ice jam occurrence forecast. Table 2 contains a matrix of mean progression times as well as the 95% confidence interval around each mean. This matrix is used to forecast the expected time of jam occurrence between locations; that is, it does not address the likelihood of jam formation, but rather when a jam might form relative to jams that have formed upstream, if indeed it does form. The occurrence of simultaneous jamming has been preserved in the forecast matrix and can be seen at several locations; for example, if a jam forms at Saint Marys, it is likely to have

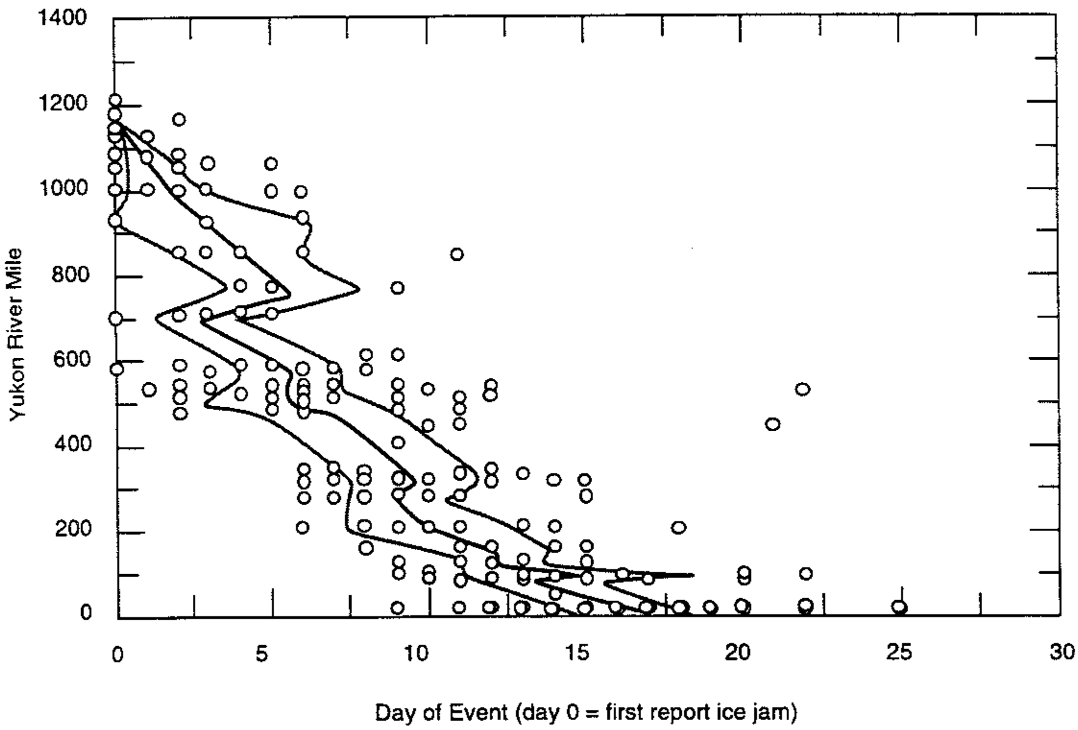


Figure 3. Mean ice jam occurrence shown with 95% confidence interval.

Table 1. Mean jam occurrence and 95% confidence limits for locations with ≥ five reported jams.

Location	*Approximate river mile*	*Mean day after first jam reported*	*Standard deviation*	n	*Lower 95% confidence*	*Upper 95% confidence limit*
Eagle	1204	0	0	5	—	—
Circle	1057	1.14	1.51	14	0.35	1.93
Fort Yukon	990	1.73	2.10	11	0.49	2.97
Stevens Village	836	4.22	2.77	9	2.41	6.03
Tanana	694	2.67	1.75	6	1.27	4.07
Ruby	575	5.71	2.21	7	4.07	7.35
Galena	525	5.40	3.68	15	3.54	7.26
Koyukuk	497	5.71	3.82	7	2.89	8.54
Nulato	470	7.00	2.98	8	4.94	9.06
Grayling	327	9.57	2.82	7	7.48	11.66
Anvik	310	9.60	3.17	10	7.64	11.56
Holy Cross	272	9.00	2.58	10	7.40	10.60
Russian Mission	200	10.18	4.69	11	7.41	12.95
Marshall	150	12.14	2.41	7	10.36	13.93
Pilot Station	115	12.33	1.94	9	11.07	13.60
Saint Marys	92	14.71	4.75	7	11.19	18.23
Mountain Village	79	13.50	3.10	10	11.58	15.42
Emmonak	15	15.94	4.11	18	14.05	17.84
Alakanuk	10	16.35	3.86	17	14.52	18.19

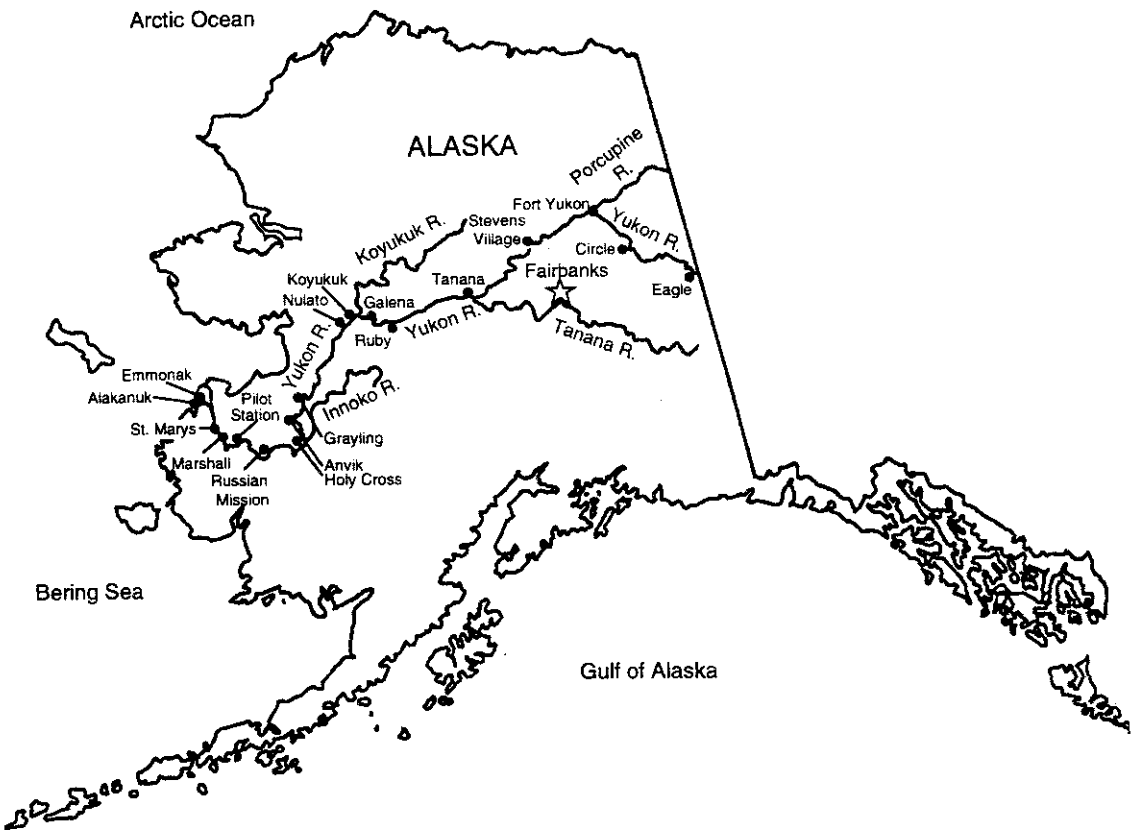


Figure 4. Locations along the Yukon River with at least five reported ice jams.

formed an average of 1.2 days earlier at Mountain Village. Some locations have very small mean progression times, such as from Galena to Koyukuk (0.3 days) and Ruby to Koyukuk (essentially simultaneous jam formation).

Progression at other locations may be interpolated between known locations; however, the uncertainty associated with such interpolations may be large, due to the potential for simultaneous jamming.

The confidence intervals given in the table should always be provided with the mean forecast to reduce the possibility that a jam forms without adequate warning. Although the ideal forecast would fall within the confidence limits, a jam that occurs later than forecast is preferable to one that occurs earlier, without warning. The risk of jams that occur earlier or later than predicted is inherent in forecasting, but may be minimized by adjusting the forecast according to locally monitored ice and hydraulic conditions. More complete monitoring of ice jam formation and progression in the future will increase both the accuracy of the forecast and the number of locations for which forecasts are available.

The forecast matrix can be used in two ways: to provide a forecast for a single location, or

Table 2. Forecast matrix for mean Yukon River ice jam occurrence between locations (95% confidence interval in parentheses).

Reported jam → / Forecast desired ↓	RM	Eagle	Circle	Fort Yukon	Stevens Village	Tanana	Ruby	Galena	Koyukuk	Nulato	Grayling	Anvik	Holy Cross	Russian Mission	Marshall	Pilot Station	Saint Marys	Mountain Village	Emmonak	Alakanuk
	RM	1204	1057	990	836	694	575	525	497	470	327	310	272	200	150	115	92	79	15	10
Eagle	1204	0																		
Circle	1057	1.1 (1.9,0.4)	0																	
Fort Yukon	990	1.7 (3.0,0.5)	0.6 (-0.7,1.8)	0																
Stevens Village	836	4.2 (6.0,2.4)	3.1 (1.3,4.9)	2.5 (0.7,4.3)	0															
Tanana	694	2.7 (4.1,1.3)	1.5 (0.1,2.9)	0.9 (-0.5,2.3)	-1.6 (-3.0,-0.2)	0														
Ruby	575	5.7 (7.4,4.1)	4.6 (2.9,6.2)	4.0 (2.3,5.6)	1.5 (-0.1,3.1)	3.0 (1.4,4.7)	0													
Galena	525	5.4 (7.3,3.5)	4.3 (2.4,6.1)	3.7 (1.8,5.5)	1.2 (-0.7,3.0)	2.7 (0.9,4.6)	-0.3 (-2.2,1.5)	0												
Koyukuk	497	5.7 (8.5,2.9)	4.6 (1.7,7.4)	4.0 (1.2,6.8)	1.5 (-1.3,4.3)	3.0 (0.2,5.9)	0.0 (-2.8,2.8)	0.3 (-2.5,3.1)	0											
Nulato	470	7.0 (9.1,4.9)	5.9 (3.8,7.9)	5.3 (3.2,7.3)	2.8 (0.7,4.8)	4.3 (2.3,6.4)	1.3 (-0.8,3.3)	1.6 (-0.5,3.7)	1.3 (-0.8,3.3)	0										
Grayling	327	9.6 (11.7,7.5)	8.4 (6.3,10.5)	7.8 (5.8,9.9)	5.3 (3.3,7.4)	6.9 (4.8,9.0)	3.9 (1.8,5.9)	4.2 (2.1,6.3)	3.9 (1.8,5.9)	2.6 (0.5,4.7)	0									
Anvik	310	9.6 (11.6,7.6)	8.5 (6.5,10.4)	7.9 (5.9,9.8)	5.4 (3.4,7.3)	6.9 (5.0,8.9)	3.9 (1.9,5.9)	4.2 (2.2,6.2)	3.9 (1.9,5.9)	2.6 (0.6,4.6)	0.0 (-1.9,2.0)	0								
Holy Cross	272	9.0 (10.6,7.4)	7.9 (6.3,9.5)	7.3 (5.7,8.9)	4.8 (3.2,6.4)	6.3 (4.7,7.9)	3.3 (1.7,4.9)	3.6 (2.0,5.2)	3.3 (1.7,4.9)	2.0 (0.4,3.6)	-0.6 (-2.2,1.0)	-0.6 (-2.2,1.0)	0							
Russian Mission	200	10.2 (13.0,7.4)	9.0 (6.3,11.8)	8.5 (5.7,11.2)	6.0 (3.2,8.7)	7.5 (4.7,10.3)	4.5 (1.7,7.2)	4.8 (2.0,7.6)	4.5 (1.7,7.2)	3.2 (0.4,6.0)	0.6 (-2.2,3.4)	0.6 (-2.2,3.4)	1.2 (-1.6,4.0)	0						
Marshall	150	12.1 (13.9,10.4)	11.0 (9.2,12.8)	10.4 (8.6,12.2)	7.9 (6.1,9.7)	9.5 (7.7,11.3)	6.4 (4.6,8.2)	6.7 (5.0,8.5)	6.4 (4.6,8.2)	5.1 (3.4,6.9)	2.6 (0.8,4.4)	2.5 (0.8,4.3)	3.1 (1.4,4.9)	2.0 (0.2,3.7)	0					
Pilot Station	115	12.3 (13.6,11.1)	11.2 (9.9,12.5)	10.6 (9.3,11.9)	8.1 (6.8,9.4)	9.7 (8.4,10.9)	6.6 (5.4,7.9)	6.9 (5.7,8.2)	6.6 (5.4,7.9)	5.3 (4.1,6.6)	2.8 (1.5,4.0)	2.7 (1.5,4.0)	3.3 (2.1,4.6)	2.2 (0.9,3.4)	0.2 (-1.1,1.5)	0				
Saint Marys	92	14.7 (18.2,11.2)	13.6 (10.1,17.1)	13.0 (9.5,16.5)	10.5 (7.0,14.0)	12.0 (8.5,15.6)	9.0 (5.5,12.5)	9.3 (5.8,12.8)	9.0 (5.5,12.5)	7.7 (4.2,11.2)	5.1 (1.6,8.7)	5.1 (1.6,8.6)	5.7 (2.2,9.2)	4.5 (1.0,8.1)	2.6 (-0.9,6.1)	2.4 (-1.1,5.9)	0			
Mountain Village	79	13.5 (15.4,11.6)	12.4 (10.4,14.3)	11.8 (9.9,13.7)	9.3 (7.4,11.2)	10.8 (8.9,12.8)	7.8 (5.9,9.7)	8.1 (6.2,10.0)	7.8 (5.9,9.7)	6.5 (4.6,8.4)	3.9 (2.0,5.9)	3.9 (2.0,5.8)	4.5 (2.6,6.4)	3.3 (1.4,5.2)	1.4 (-0.6,3.3)	1.2 (-0.8,3.1)	-1.2 (-3.1,0.7)	0		
Emmonak	15	15.9 (17.8,14.0)	14.8 (12.9,16.7)	14.2 (12.3,16.1)	11.7 (9.8,13.6)	13.3 (11.4,15.2)	10.2 (8.3,12.1)	10.5 (8.6,12.4)	10.2 (8.3,12.1)	8.9 (7.0,10.8)	6.4 (4.4,8.3)	6.3 (4.4,8.2)	6.9 (5.0,8.8)	5.8 (3.9,7.7)	3.8 (1.9,5.7)	3.6 (1.7,5.5)	1.2 -0.7,3.1)	2.4 (0.5,4.3)	0	
Alakanuk	10	16.4 (18.2,14.5)	15.2 (13.4,17)	14.6 (12.8,16.5)	12.1 (10.3,14.0)	13.7 (11.9,15.5)	10.6 (8.8,12.5)	11.0 (9.1,12.8)	10.6 (8.8, 12.5)	9.4 (7.5,11.2)	6.8 (4.9,8.6)	6.8 (4.9,8.6)	7.4 (5.5,9.2)	6.2 (4.3,8.0)	4.2 (2.4,6.0)	4.0 (2.2,5.9)	1.6 (-0.2,3.5)	2.9 (1.0,4.7)	0.4 (-1.4,2.2)	0

as an overall progression forecast, both of which can then be updated as more jams are reported. The first type of forecast is an isolated forecast for one location based on jam occurrence at another location; for instance, if an ice jam is reported at Tanana and an isolated forecast for Pilot Station is desired. In this case, the forecast is obtained from Table 2 by following down the Tanana column to its intersection with Pilot Station. At this point, the forecast matrix indicates that an ice jam will occur at Pilot Station an average of 9.7 days later in the presence of conditions favoring ice jam formation. Based on available data, the 95% confidence interval is (8.4, 10.9), indicating that, if a jam forms at Pilot Station, there is a 95% chance that it will do so as early as 8.4 days after, or as late as 10.9 days after jam formation at Tanana.

The overall progression forecast can be made as soon as the first jam is reported each season. For example, if a jam was first reported at Circle, the overall progression can be forecast by following vertically down from the point where the column designating a reported jam at Circle intersects the row designating a desired forecast at Circle. Thus, on average, jams would be expected at Fort Yukon 0.6 days after the first observed jam at Circle, followed by Tanana (1.5 days), Stevens Village (3.1 days), Galena (4.3 days), Ruby (4.6 days), and so on to Alakanuk (15.2 days). Both the overall and isolated forecasts can (and should) be updated whenever a new jam is reported. The new location and day become the new starting point for the forecast. For example, in 1988 the first reported jam was at Fort Yukon. The date of this jam would become day 0, and an overall forecast would be made downstream from this location. The next reported jam was at Galena on day 3. Updated forecasts would be made with Galena as the reported jam site, and progression time from Table 2 would be added to day 3 to arrive at an updated forecast jam occurrence. Example updated forecasts are given in Table 3 for a systematic-type jam (1988 data) and in Table 4 for a nonsystematic-type jam (1989 data). Ice jam occurrence for these two years is shown in Figure 5. Note that at the locations shown in Figure 5 that have less than five reported jams, no forecast was made.

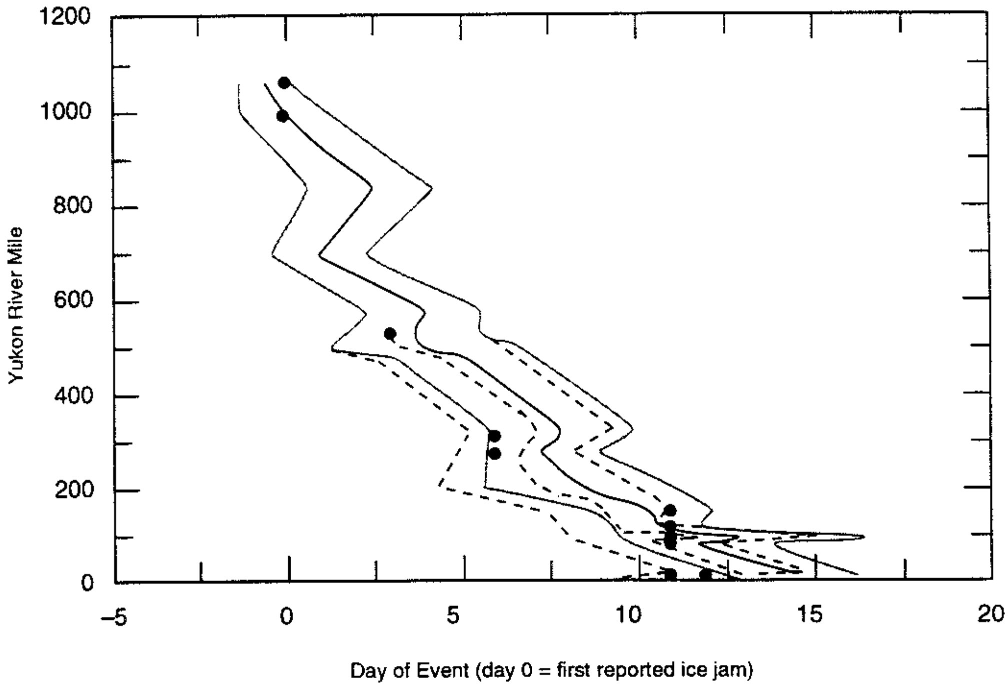
When the forecast is compared to reported progression data for the years 1971 through 1995 (except 1978, which was erratic and had less than five reported jams), it is evident that as Fountain (1984) noted in the case of ice cover breakup, systematic-type jams can be predicted more accurately than nonsystematic-type jams. Nonsystematic-type jams are more likely to result in jams occurring outside the confidence interval about the mean. In the systematic-type jamming of 1988, the overall forecast with an ice jam first reported at Fort Yukon was within the 95% confidence interval for Galena, Anvik, Holy Cross, Marshall, Pilot Station, Saint Marys, and Mountain Village, a distance of about 975 miles (Table 3). Jams occurred 1.3 and 0.8 days earlier than the lower confidence limit forecast for Emmonak and Alakanuk, respectively. Following the updated forecast that reflected jamming at Galena, all of the reported jams at the downstream locations were within the confidence interval. The next update, after jamming at Holy Cross, was slightly conservative in that reported jams occurred 0.1 and 0.4 days later than the upper confidence limit forecast at Marshall and Pilot Station. In general, both the overall and the updated forecasts would have provided adequate warning in 1988, with the overall forecast performing better than

Table 3. Sample updated forecast for data from 1988 (systematic-type jam). Forecast accuracy is determined for 95% confidence interval.

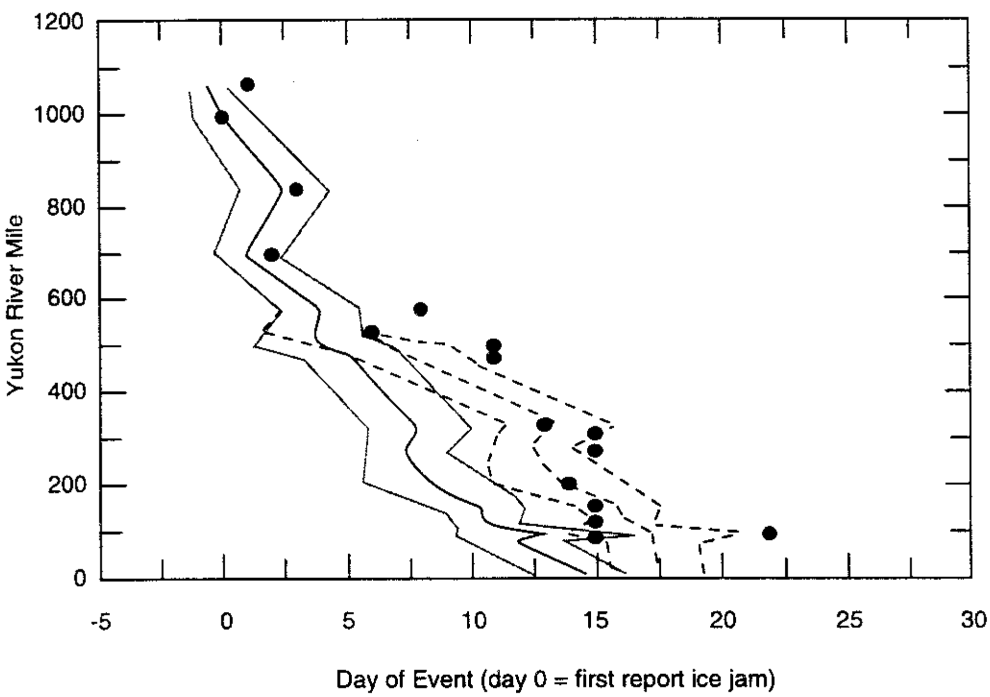
Location	*River mile*	*Actual Jam day*	*Overall forecast Jam day*	*Overall forecast accuracy*	*Forecast update after Galena jam*	*Forecast update after Holy Cross Jam*	*Forecast update after Emonak Jam*	*Final updated forecast*	*Updated forecast accuracy*
Fort Yukon	990	—	—	—	—	—	—	—	—
Galena	525	3	3.7 (1.8,5.5)	within confidence limits	— —	— —	— —	3.7 (1.8,5.5)	within confidence limits
Anvik	310	6	7.9 (5.9,9.8)	within confidence limits	7.2 (5.2,9.2)	— —	— —	7.2 (5.2,9.2)	within confidence limits
Holy Cross	272	6	7.3 (5.7,8.9)	within confidence limits	6.6 (5.0,8.2)	— —	— —	6.6 (5.0,8.2)	within confidence limits
Marshall	150	11	10.4 (8.6,12.2)	within confidence limits	9.7 (8.0,11.5)	9.1 (7.4,10.9)	— —	9.1 (7.4,10.9)	*jammed 0.1 days later*
Pilot	115	11	10.6 (9.3,11.9)	within confidence limits	9.9 (8.7,11.2)	9.3 (8.1,10.6)	— —	9.3 (8.1,10.6)	*jammed 0.4 days later*
Saint Marys	92	11	13.0 (9.5,16.5)	within confidence limits	12.3 (8.8,15.8)	11.7 (8.2,15.2)	— —	11.7 (8.2,15.2)	within confidence limits
Mountain Village	79	11	11.8 (9.9,13.7)	within confidence limits	11.1 (9.2,13.0)	10.5 (8.6,12.4)	— —	10.5 (8.6,12.4)	within confidence limits
Emmonak	15	11	14.2 (12.3,16.1)	— —	13.5 (11.6,15.4)	12.9 (11.0,14.8)	— —	12.9 (11.0,14.8)	within confidence limits
Alakanuk	10	12	14.6 (12.8,16.5)	— —	14.0 (12.1,15.8)	13.4 (11.5,15.2)	11.4 (9.6,13.2)	11.4 (9.6,13.2)	within confidence limits

Table 4. Sample updated forecast for data from 1989 (nonsystematic-type jam).

Location	*River mile*	*Actual day of event*	*Overall forecast*	*Forecast update after Tanana jam*	*Forecast update after Galena jam*	*Forecast update after Nulato jam*	*Forecast update after Grayling jam*	*Forecast update after Russian Mission jam*	*Forecast update after Mountain Village jam*	*Final updated forecast*	*Updated forecast accuracy*
Fort Yukon	990	-	-								
Stevens Village	836	3	2.5 (0.7,4.3)	—	—	—	—	—	—	2.5 (0.7,4.3)	within confidence limits
Tanana	694	2	0.9 (-0.5,2.3)	—	—	—	—	—	—	0.9 (-0.5,2.3)	within confidence limits
Ruby	575	8	4.0 (2.3,5.6)	5.0 (3.4,6.7	—	—	—	—	—	5.0 (3.4,6.7	*jammed 1.3 days later*
Galena	525	6	3.7 (1.8,5.5)	4.7 (2.9,6.6)	—	—	—	—	—	4.7 (2.9,6.6)	within confidence limits
Koyukuk	497	11	4.0 (1.2,6.8)	5.0 (2.2,7.9)	6.3 (3.5,9.1)	—	—	—		6.3 (3.5,9.1)	*jammed 1.9 days later*
Nulato	470	11	5.3 (3.2,7.3)	6.3 (4.3,8.4)	7.6 (5.5,9.7)	—	—	—		7.6 (5.5,9.7)	*jammed 1.3 days later*
Grayling	327	13	7.8 (5.9,9.9)	8.9 (6.8,11.0)	10.1 (8.1,12.3)	13.6 (11.5,15.7)	—	—		13.6 (11.5,15.7)	within confidence limits
Anvik	310	15	7.9 (5.9,9.8)	8.9 (7.0,10.9)	10.2 (8.2,12.2)	13.6 (11.6,15.6)	13.0 (11.0,15.0)			13.0 (11.0,15.0)	within confidence limits
Holy Cross	272	15	7.3 (5.7,8.9)	8.3 (6.7,9.9)	9.6 (8.0,11.2)	13 (11.4,14.6)	12.4 (10.8,14.0)			12.4 (10.8,14.0)	*jammed 1 day later*
Russian Mission	200	14	8.5 (5.7,11.2)	9.5 (6.7,12.3)	10.8 (8.0,11.2)	14.2 (11.4,17.0)	13.6 (10.8,16.4)	—		13.6 (10.8,16.4)	within confidence limits
Marshall	150	15	10.4 (8.6,12.2)	11.5 (9.7,13.3	12.7 (11.0,14.5)	16.1 (14.4,17.9)	15.6 (13.8,17.4)	16.0 (14.2,17.5)		16.0 (14.2,17.5)	within confidence limits
Pilot Station	115	15	10.6 (9.3,11.9)	11.7 (10.4,12.9)	12.9 (11.7,14.2)	16.3 (15.1,17.6)	15.8 (14.5,17.0)	16.2 (14.9,17.4)		16.2 (14.9,17.4)	within confidence limits
Saint Marys	92	22	13.0 (9.5,16.5)	14.0 (10.5,17.6)	15.3 (11.8,18.8)	18.7 (15.2,22.2)	18.1 (14.6,21.7)	18.5 (15.0,22.1)		18.5 (15.0,22.1)	within confidence limits
Mountain Village	79	15	11.8 (9.9,13.7)	12.8 (10.9,14.8)	14.1 (12.2,16.0)	17.5 (15.6,19.4)	16.9 (15.0,18.9)	17.3 (15.4,19.2)	—	17.3 (15.4,19.2)	*jammed 0.4 days earlier*
Emmonak	15	25	14.2 (12.3,16.1)	15.3 (13.4,17.2)	16.5 (14.6,18.4)	19.9 (18.1,21.8)	19.4 (17.5,21.3)	19.8 (17.9,21.7)	17.4 (15.5,19.3)	17.4 (15.5,19.3)	*jammed 5.7 days later*
Alakanuk	10	25	14.6 (12.8,16.5)	15.7 (13.9,17.5)	17.0 (15.1,18.8)	20.4 (18.5,22.2)	19.8 (17.9,21.6)	20.2 (18.3,22.0)	17.9 (16.0,19.7)	17.9 (16.0,19.7)	*jammed 5.3 days later*



(a)



(b)

Figure 5. Actual jam occurrence (•) compared to overall (—) and updated (- - -) forecast mean jam occurrence with confidence limits (a) in 1988, a systematic jam year, and (b) in 1989, a nonsystematic jam year.

the updated forecast for this systematic jam (Table 3).

The ice jam occurrence shown in Figure 5b for 1989 is typical of a nonsystematic-type jam, which often progresses more slowly and with longer delays than a systematic jam. The 1989 jam occurrence also exhibits the simultaneous jamming at several locations—Galena, Russian Mission, and Mountain Village—that is typical of nonsystematic jams. This year was also marked by extremely late jams, well outside the upper 95% confidence limits, that were reported at Saint

Marys, Emmonak, and Alakanuk. The overall forecast and the first two updated forecasts predicted much earlier jamming for locations between Ruby and Alakanuk than actually occurred, with differences reduced at each update. By the time the forecast was updated after jamming at Nulato, its accuracy had increased to the point that half of the 10 predictions were within the confidence intervals. However, a jam would have occurred 0.4 days earlier than the lower 95% confidence interval forecast at Pilot Mountain Village. Adjustment of the forecast based on local ice and hydrologic conditions might have decreased the error in this case.

4. Conclusions

Yukon River villages rely heavily on air transport during the ice cover breakup season. Because many air strips are located in or near the villages, along the river's banks, some early warning of the potential for ice jamming is desired. Ice jams on the Yukon River in Alaska generally progress from upstream to downstream and are monitored by the villages and by the AKRFC. Long-term forecasting of ice jams is given by AKRFC spring flood potential forecasts, however, near-term forecasting could provide additional warning, mitigating some potential ice jam-related damages. This paper presents a forecast matrix containing mean progression data and 95% confidence intervals around the means for locations with more than five reported ice jams.

The stochastically based ice jam occurrence forecast matrix presented here can be used to make both overall and isolated predictions of jam occurrence along the Yukon River. The forecast matrix utilizes mean jam occurrence values for several reasons: 1) mean values preserve information on simultaneous jam occurrence, 2) confidence intervals that provide information about the risk and uncertainty of the forecast can be easily constructed around the mean, and 3) use of mean values allows the forecast model to be updated easily on an annual basis.

Although the timing of systematic and nonsystematic-type ice jams was not found to be statistically significantly different, the forecast matrix appears to be more accurate for systematic-type jams than for nonsystematic-type jams. Forecast updating generally improves the jam occurrence forecast accuracy for nonsystematic jams.

5. References

Eames, H.J. and K.D. White (1997) "Ice jams in Alaska." Ice Engineering Information Exchange Bulletin No. 16, US Army Cold Regions Research and Engineering Laboratory: Hanover, NH.

Fountain, Andrew G. (1984) "Yukon River breakup: The 82-year record." *The Northern Engineer*, Vol. 16, No. 1, p. 20-24.

Newsminer (1971) "Yukon forces village evacuation." *Newsminer* [Fairbanks, AK], June 4, 1971.

Nibler, G.J. (1994) "Forecasting spring breakup flood potential." Proceedings, National Weather Service River Ice Seminar [17-18 November, 1994, Minneapolis, MN], p. 135-142. National Weather Service Central Region: Kansas City, MO.

Nibler, G. J. (1996) Written communication. National Weather Service River Forecast Center: Anchorage, AK.

Rundquist, L.A. (1994) "Ice breakup reconnaissance approach in Alaska." Proceedings, National Weather Service River Ice Seminar [17-18 November, 1994, Minneapolis, MN], p. 81-85. National Weather Service Central Region: Kansas City, MO.

Stevens, C.A., A.G. Fountain, and T.E. Osterkamp (1979a) "Break-up dates for the Yukon River, I. Rampart to Whitehorse 1896-1978." University of Alaska Geophysical Institute: Fairbanks, AK.

Stevens, C.A., A.G. Fountain, and T.E. Osterkamp (1979b) "Break-up dates for the Yukon River, II. Alakanuk to Tanana 1893-1978." University of Alaska Geophysical Institute: Fairbanks, AK.

USGS (1985) "National water summary 1985 - hydrologic events and surface-water resources." USGS Water-Supply Paper 2300, US Geological Survey: Washington, DC.

Woerner, R.K. (1986) The Alaska Handbook. McFarland & Company Inc., Publishers: Jefferson, NC.

Van der Leeden, F., F.L. Troise, and D.K. Todd (1990) *The Water Encyclopedia, 2nd Edition.* Lewis Publishers, Inc.