DEPARTMENT OF THE ARMY
U.S. Army Corps Engineers
Washington, DC 20314-1000

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Technical Letter
No. 1110-2-576

1 May 2011

EXPIRES 30 APRIL 2016

Engineering and Design

ICE-AFFECTED STAGE FREQUENCY

1. Purpose. This engineer technical letter (ETL) provides guidance on the development of ice-affected stage frequency (SF) relationships and includes a literature review of advances made in the last two decades, as well as case studies illustrating the various methods.

2. Applicability. This guidance applies to all HQUSACE elements, major subordinate commands, districts, laboratories, field operations, and related agencies having responsibility for development of ice-affected flood frequency analyses.

3. Distribution. Approved for public release, distribution is unlimited.

4. General. Over half the rivers and waterways in the continental U.S. experience ice covers and ice jams, which can cause dramatic increases in stage above open water levels for an equivalent discharge. Because of the prevalence of ice on many rivers, flood plain mapping, land use planning, and the design of riverine structures may require estimates of ice-affected SF. Ice-affected SF analyses have been used to quantify benefits of ice control structures both before and after construction, as well as predicting the ice impacts of dam removals or contaminated sediment remediation projects. This ETL describes currently used methods to develop ice-affected SF relationships, incorporating more recent techniques. Covered are the direct method of estimating ice-affected SF from observed stage data and the more common indirect method where ice-affected stage distributions are synthesized from hydro-meteorological data with knowledge of the local ice regime. The ETL also describes recent efforts to estimate the uncertainty of ice-affected SF relationships.

FOR THE COMMANDER:

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CHAPTER 1
Introduction

1-1. Purpose. Over half the rivers and waterways in the continental U.S. experience ice covers and ice jams that can cause dramatic increases in stage above open water levels for an equivalent discharge. Owing to the prevalence of ice on many rivers, flood plain mapping, land use planning and the design of riverine structures may require estimates of ice-affected stage-frequency (SF). Ice-affected SF analyses have been used to quantify benefits of ice control structures both before and after construction, as well as for predicting the ice impacts of dam removals or contaminated sediment remediation projects.

a. In the open water case, SF at sites along a river relates closely to discharge frequency, which may be estimated from stream gage data or the use of rainfall-runoff models. With discharges known for desired return intervals, corresponding stages can be calculated using rating curves or gradually varied flow models such as HEC-RAS. Because of the close relationship between open water stage and discharge, calculated or observed open water peak stage populations are often fit directly to probability distributions, such as normal or log normal, and statistical parameters such standard deviation used for confidence intervals for the SF curves.

b. In contrast, ice-affected water levels depend not only on discharge but on ice conditions, which can be variable and unpredictable. Ice jam floods are generally more site specific than open water ones and the added resistance of the ice means that high stages can occur at a fraction of the discharge needed to cause an equivalent open water flood. Furthermore, while open water stage continues to rise with discharge, slowing somewhat when flow goes out of bank, ice jam stage typically rises to the point of jam release followed by a rapid return to the open water stage for that discharge.

c. Because ice jams result from variety of factors besides discharge (river geometry, ice conditions, etc.), ice-affected peak stage populations do not fit well to standard probability distributions such as normal or log normal, making uncertainty estimates and extrapolation to extreme events by conventional statistical methods more difficult than for the open water case.

d. As a result of these issues, techniques for estimating ice-affected SF are relatively recent. Guidance can be found in Gerard (1989), FEMA (2003), EM 1110-2-1612, White and Beltaos (2008), and Beltaos (2010). Previously, calculation of ice-affected stage was often left out of studies to predict flood levels and design river structures. In some cases this is not a problem as the ice-affected peak stages were dwarfed by the open water ones. In other cases the omission of ice or difficulties in calculating its effect on stage has caused major problems.

e. An ice-affected SF analysis may require considerable effort, resources, and data and the latter two may be limited. A first step is to assess the need and feasibility of doing an ice-related SF analysis. Where data and resources are limited, an ice-related SF analysis may not be possible and a severe ice jam flood may have to serve as the design event. An initial review of historical information and hydro-meteorological data may reveal that the impact of ice jams on annual peak stages is minimal and a detailed analysis of ice-affected SF may not warrant the cost and effort.

f. This ETL describes currently used methods to develop ice-affected SF relationships, building on selected publications and incorporating more recent techniques. Covered are the direct method of estimating ice-affected SF from observed stage data and the more common indirect method where ice-affected stage distributions are synthesized from hydro-meteorological data with knowledge of the local ice regime. The ETL also describes recent efforts to estimate the uncertainty of ice-affected SF relationships.

1-2. References.

EM 1110-2-1612
Ice Engineering, 2005.

U.S. Army Corps of Engineers (1962)
Beard, L.R., *Statistical Methods in Hydrology*. U.S Army Engineer District, Sacramento, 1962.

U.S. Army Corps of Engineers (1978)
Donchenko, R.V., *Conditions for Ice Jam Formation in Tailwaters*, Draft Translation 669, U.S. Army Cold Regions Research and Engineering Laboratory, 1978.

U.S. Army Corps of Engineers (1999)
White, K. D., *Hydraulic and Physical Properties Affecting Ice Jams*, CRREL Report 99-11, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.
White, K. D. and Eames, H. J., *CRREL Ice Jam Database,* CRREL Report 99-2, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 1999.
https://rsgis.crrel.usace.army.mil/icejam/

U.S. Army Corps of Engineers (2000a)
White, K., Pederson, K. J., and R. T. Pomerleau, *Ice Affected Stage Frequency*, Ice Engineering Bulletin No. 24, U.S. Army Cold Regions Research and Engineering Laboratory, January, 2000.

U.S. Army Corps of Engineers (2000b)
Daly, S. F., White, K. D., Zufelt, J. E., Lever, J. H., and J. J. Gagnon, *Ice-affected flooding, Oahe Dam to Lake Sharpe, SD*. Contract report to the U.S Army Engineer District, Omaha, by U.S. Army Cold Regions Research and Engineering Laboratory, 2000.

U.S. Army Corps of Engineers (2002)
HEC-RAS Hydraulic Reference Manual Version 3.1, 2002.

U.S. Army Corps of Engineers (2001)
White, K. D., Tuthill, A. M., and A. M. Smith, *Engineering Support for Section 205 Flood Control Study, Salmon River, East Haddam, CT*. Contract report to the U.S Army Engineer District, New England, by U.S. Army Cold Regions Research and Engineering Laboratory, 2001.

FEMA
Guidelines and Specifications for Flood Hazard Mapping, Appendix F: Guidance for Ice Jam Analysis and Mapping, April, 2003.

Adamowski, K. (1981)
Plotting formula for flood frequency, *Water Resources Bulletin*, 17(2): 197–202.

Alcoa (2004)
Addendum to the Comprehensive Characterization of the Lower Grasse River, Grasse River Study Area, Massena, NY, Alcoa Inc.

Beltaos, S. (1983)
River ice jams: theory, case studies, and applications, *ASCE Journal of Hydraulics Division*, 109(HY10): 1338–1359.

Beltaos, S. (1996)
Users Manual for the RIVJAM Model, National Water Research Institute Contribution 96-37, Burlington, Canada.

Beltaos, S. (2008)
Chapter 7. Ice Jams. Chapter 7 In *River Ice Breakup* (S. Beltaos, ed.), Water Resources Publications, Highlands Ranch, CO: 207–246.

Beltaos, S. (2010)
Assessing Ice Jam Flood Risk: Methodology and Limitations, In *Proceedings IAHR 20th International Symposium on Ice, Lahti, Finland*, June 14–18, 2010.

Gerard, R. and Karpuk, E. (1979)
Probability analysis of historical flood data, *Journal of the Hydraulics Division, ASCE*, (HY9): 1153–1165.

Flato, G. and R. Gerard (1986)
Calculation of ice jam thickness profiles, *Fourth Workshop on the Hydraulics of River Ice*, NRCC Montreal.

Gerard, R. (1989)
Ice Jam Floods, Chapter 10 in: *Hydrology of Floods in Canada* (W.E. Watt, ed.), National Research Council of Canada, Ottawa, Ontario, Canada, 169–184.

Shen, H.T., J. Su, and L.W. Liu. (2000)
SPH simulation of river ice dynamics, *Journal of Computational Physics*, 165(2): 752–770.

Shen, H.T., Jayasundara, N.C. and A.M. Tuthill (In review)
Occurrence of Breakup Ice Jams on the Grasse River, *ASCE Journal of Cold Regions Engineering*.

Tuthill, A.M., J.L. Wuebben, S.F. Daly, and K.D. White (1996)
Probability Distributions for Peak Stage on Rivers Affected by Ice Jams, J *ASCE Journal of Cold Regions Engineering*, 10(1): 36–57.

Tuthill, A.M., Vuyovich, C.M., and K. D. White (2003)
Ice-Affected Stage Frequency Distributions Along the Connecticut River, In *Proceedings, 12th Workshop on River Ice Processes and the Environment*, Edmonton, AB, 19–20 June 2003.

White, K. D., and Beltaos, S. (2008)
Development of Ice-affected Stage Frequency Curves, Chapter 9 In: *River Ice Breakup* (S. Beltaos, ed.), Water Resources Publications, Highlands Ranch, CO: 305–332.

CHAPTER 2
River Ice Processes and Ice Jam Flooding

2-1. Background. Ice begins to form on rivers in late fall or early winter as the water cools to the freezing point or slightly below. The first ice typically appears in low velocity (≤ ~1 ft/s) pool areas and along the channel sides (border ice). This smooth-surfaced ice which forms in-situ is often termed thermal ice. In most rivers the ice initiates as tiny crystals (frazil) in super-cooled moving water. The crystals stick together (flocculate) into frazil slush, which in turn congeals into floes or pans, increasing in size as they move downstream with the flow. The drifting frazil stops as its concentration exceeds the conveyance capacity of the water flow or the floes reach an obstruction such as an intact ice cover, or a dam. As additional frazil continues to arrive, the ice cover progresses upstream. In areas of relatively low water velocity (≤ ~2-1/4 ft/s) the frazil floes tend to accumulate edge to edge (juxtapose) to form a single layer accumulation. Where flow velocity is faster, the floes may tilt and under-turn to form a thicker, "shoved" ice accumulation. This loose ice mass may further collapse or shove-thicken as additional floes arrive and the downstream forces increase. At some point the interstitial water freezes and the progressing ice cover solidifies. If conditions are right, additional floes and slush may be drawn beneath the initial ice cover to deposit there in the form of a hanging dam. In rapids sections where water velocity is very fast (≥~5 ft/s), an ice cover may never establish, and open water will persist all winter. In some cases, freezeup ice covers may attain sufficient thickness to cause upstream flooding. These freezeup ice jams, if they remain in place all winter, may block the breakup ice run to cause severe jams and flooding later on.

a. Barring mid-winter freshets and breakups, by mid- to late-winter, the ice cover reaches its maximum extent and thickness and the open water frazil-producing areas reach their minimum. In temperate regions, final breakup typically occurs in the late winter or early spring, as river discharge increases to the point where the ice cover releases and moves downstream as an ice run. In the case of extended gradual thaw, the ice cover may melt in place with little movement, known as a thermal breakup. At the other extreme, rapid thaw and a quick rise in discharge and stage may trigger a dynamic breakup and ice run. These events often occur as a downstream progressing breakup front with the ice running and jamming at downstream locations. Once sufficient head builds behind these jams, they may release and the sequence repeat itself.

b. Although the breakup process and ice jamming are variable and unpredictable, patterns emerge from year to year in terms of ice jam location, pre-breakup ice thickness, breakup discharge magnitude, and the characteristics of the breakup hydrograph. Research of historical ice events and hydro-meteorological data to identify these patterns and characteristics is critical to an ice-affected SF analysis.

c. Because winter discharges are typically close to base flow levels, the elevation of the freezeup ice cover is usually low and well within banks. With the onset of breakup, as river discharge and stage increase, the ice cover typically lifts and fractures from the banks as river top-width increases. During this period, river stage rise follows a path more or less parallel to the open water rating curve. Water surface elevation with a fixed ice cover can be related to discharge using open channel flow equations (EM 1110-2-1612) or numerical models such as HEC-RAS with a fixed ice cover (U.S. Army Corps of Engineers 2002).

d. At some discharge the ice cover may release, causing a return to open water levels, or an ice jam may form, causing an abrupt rise in stage. While breakup processes are complex and difficult to model (Beltaos 2008), a simple rule of thumb says that the ice cover will release once stage has increased 3–4 times the pre-breakup ice thickness (U.S. Army Corps of Engineers 1978). Once an ice jam is in place, further discharge increase, plus the arrival of more ice, will continue to push up stage until water and ice begin to escape into the floodplain or the ice jam releases. Figure 2-1, shows an ice jam rating curve to illustrate this process.

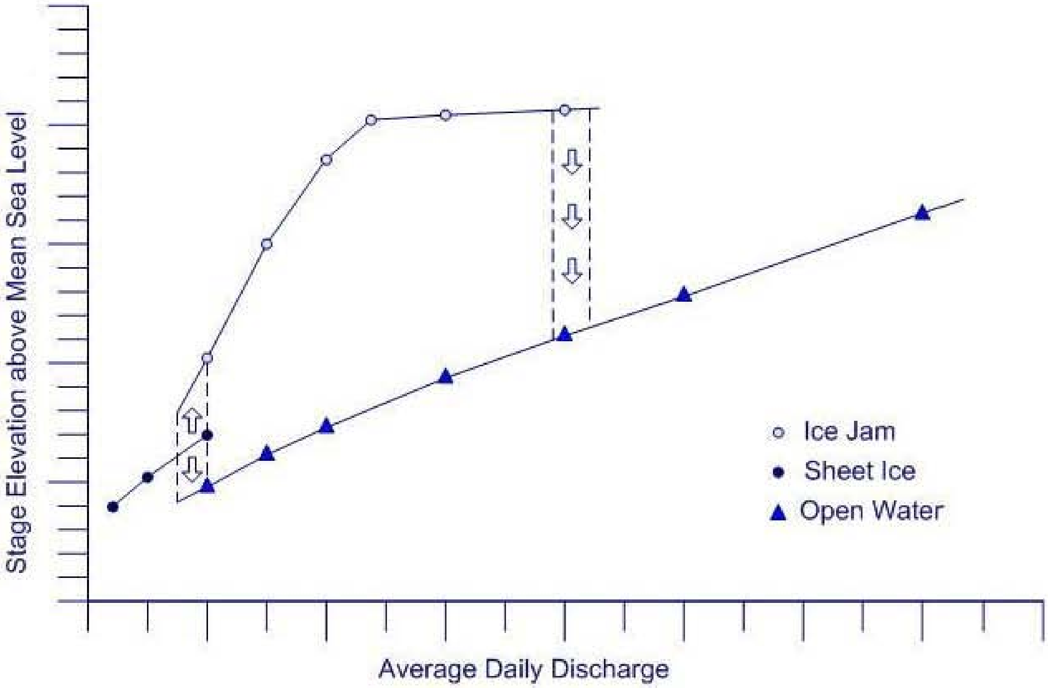

Figure 2-1. Composite open water and ice-affected rating curve (after Tuthill et al. 1996).

2-2. <u>Calculation of Ice Jam Profiles and Ice-Affected Water Levels</u>. While ice jams are natural phenomena occurring at many locations along a river, they are considered a problem mainly where they flood or damage settled areas. Ice jam floods differ from open water ones in that they are usually more site specific and local in extent. If an ice-affected SF analysis is required, ideally the ice jam location and extent will be known and some peak stage data will be available.

a. Lacking water level observations, ice jam stage can be estimated using open channel flow equations adapted for ice (EM 1110-2-1612), or ice routines within numerical models such as HEC-RAS. These equations and models predict ice jam thickness by treating the ice accumulation as a granular material and using a force balance to transfer downstream forces of water drag and gravity via internal ice stresses to the resisting forces of bank friction. Many ice jams exhibit an “equilibrium section” where the ice thickness is relatively constant and the ice-affected water level is at its maximum, and more or less parallel to the river bed. Figure 2-2 shows the profile of a theoretical ice jam with an equilibrium section.

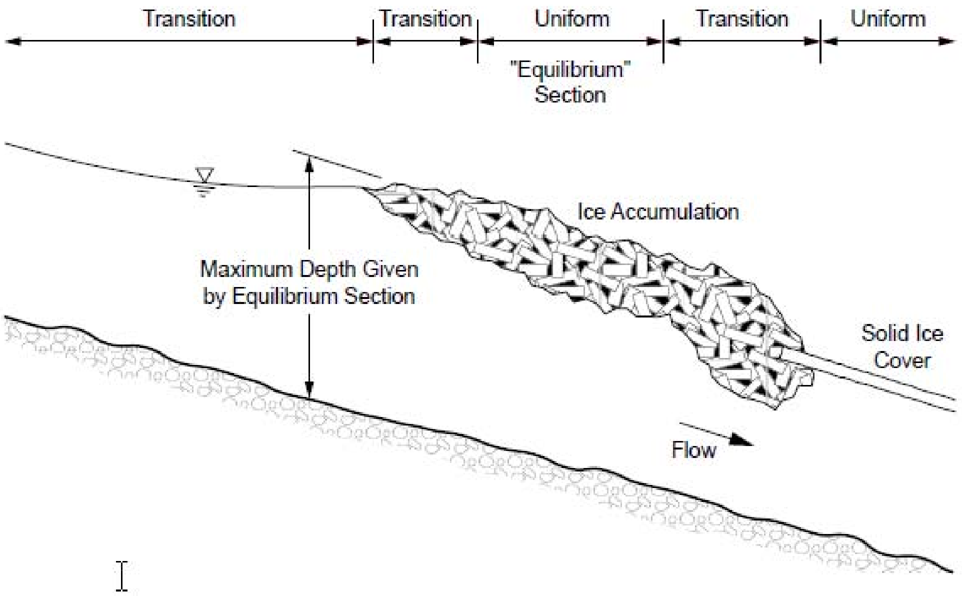

Figure 2-2. Typical breakup ice jam profile showing equilibrium section.

b. The ice jam force balance is expressed as:

$$\frac{d(\sigma_x t)}{dx} = \rho' g S_w t + \tau_i - \frac{2\tau_b t}{B} \tag{2-1}$$

where

σ_x = longitudinal stress within the ice accumulation
t = ice accumulation thickness
τ_b = shear resistance along the banks
B = ice accumulation width
ρ' = ice density
g = acceleration due to gravity
S_w = water surface slope
τ_i = water shear force on the ice underside

c. EM 1110-2-1612, Gerard (1989), and White (U.S. Army Corps of Engineers 1999) provide additional background on Equation 1 as well as other techniques for calculating ice-affected stage. For the constant thickness of the equilibrium section of the jam with $dt/dx = 0$ Equation 2-1 reduces to:

$$t = \frac{BS_f}{2\mu(1-s_i)}\left[1+\sqrt{\frac{4\mu(1-s_i)R_j}{s_i BS_f}}\right] \tag{2-2}$$

where

s_i = specific gravity of ice
R_i = hydraulic radius with an ice cover
μ = coefficient related to the internal strength of the ice accumulation ranging from 1 to 1.2.

d. Equation 2-2 can be used to predict the ice thickness within the equilibrium section of the jam, provided the jam is not grounded and the location of interest is far enough above the toe of the jam for equilibrium conditions to have established. The equilibrium ice thickness and open channel flow theory are then used to predict the maximum ice-affected water level, assuming reasonable values of ice jam roughness, porosity, and internal strength, which can be found in U.S. Army Corps of Engineers (1999). Gerard (1989) also explains calculation methods for ice jam stage, presenting a dimensionless rating curve for equilibrium ice jam conditions developed by Beltaos (1983).

e. A number of other ice hydraulic models exist besides HEC-RAS, including RIVJAM, ICEJAM and DynaRICE. The HEC-RAS ice option (U.S. Army Corps of Engineers 2002), which is similar in structure to ICEJAM (Flato and Gerard 1986), has the advantage of its wide use and a good graphical user interface. Unlike HEC-RAS, RIVJAM (Beltaos 1996) can simulate porous flow through the ice jam, which is important in the ice jam toe region where the water surface slope may be quite steep. The two-dimensional DynaRICE (Shen et al. 2000), with unsteady hydraulics and ice dynamics, simulates ice transport, ice jam initiation, and ice-affected water surface profiles, but has greater data needs and a steeper learning curve.

2-3. Data Sources. Owing to the site-specific nature and short duration of ice jam floods, event data are often scarce. Possible data sources include river gages, historical information such as flood studies, newspapers, photographs, and anecdotal evidence from local residents.

a. Gages. Ideally, a stream gage with a long period of record lies close to the site but in reality this is rarely the case. Even with a gage nearby, the record of winter peak stages may contain gaps resulting from frozen equipment or damage to the gage as a result of ice events. Although annual peak stages are readily available from the USGS, along with event dates, it is not always clear whether a winter season peak resulted from an ice jam. Another problem is that non-peak stage data are typically archived and more difficult to obtain than daily average discharge data. Inaccuracies also arise from the discharges associated with ice events being difficult to estimate. In addition to the USGS, the Corps of Engineers and other organizations also maintain gages and records from which ice-affected peak stages are archived.

b. Reports, Historical Information, Ice Jam Database. Historical data may serve to fill in for missing gage data or supplement existing gage records. Examples include photographs showing ice jam levels with respect to buildings or landmarks, or anecdotal accounts of peak ice jam flood levels at various locations. For many locations with a history of ice jam flooding, reports from previous studies by Corps Districts and other government organizations may be available. The USACRREL *Ice Jam Archive* and the USAERDC-CRREL *Ice Jam Database*

(White and Eames, U.S. Army Corps of Engineers 1999), with over 18,000 entries, contain much information on ice jams in the U.S. including event descriptions, peak stages, discharges and damages. Flood insurance studies available from FEMA may also contain ice event jam information.

c. Environmental data. Environmental clues to past ice jams and ice elevations include ice tree scars and vegetation trim lines. The lack of woody plants below a specific bank elevation may result from frequent ice passage or ice jams. River bathymetry surveys may reveal bank failures or scour holes resulting from ice jams. In the case of the Grasse River in northern NY, evidence from river bed sediment stratigraphy, tree scars and growth rings, and historical observations were combined to estimate the frequency and severity of past ice jam events (Alcoa 2004).

2-4. Perception Stage and Multiple Data Sources. When combining incomplete data sets from different sources and time periods, the concept of "perception stage" is useful. By this method, described by Gerard and Karpuk (1979), the record length N of a data set is equal to the time period m over which the observed stages apply. For an observed event to have a rank, its stage must exceed a perception stage for that data set, defined as the water level above which an event would be noticed. In the case of gage data, the record length would equal the record length of the gage and all measured stages would be ranked. In the case of single historical stage being reported as "the worst event in 30 years," in the absence of any other information, m would = 1 and $N = 30$ years. By this means of assigning record length and rank to various data sources, plotting positions can be calculated for a single combined data set.

CHAPTER 3
Estimating Ice-Affected Stage Frequency

3-1. General. Ice-affected SF may be estimated by two approaches. The first and simplest is the direct method, whereby ice-affected peak stage data are ranked, their probabilities calculated and a SF curve is fit graphically to the data. If the record of annual peak flows is treated as a single population regardless of ice effects, then the analysis is considered a mixed population one. It is often advantageous to separate the record of observed peak stages into open water and ice-affected sub-populations, in the form of a combined population frequency analysis. Where observed ice-affected stage data are lacking or SF relationships are required at multiple locations along the river, the indirect method may be required whereby winter period peak stages are synthesized from hydro-meteorological data and available ice information.

3-2. Direct Method for Estimating Ice-affected Stage Frequency. If sufficient data exist, an ice-affected SF analyses may be done directly from the observed peak stage data. This approach is termed the "direct" method. In a mixed population frequency analysis, the annual peak stages are ranked and exceedance probability P calculated using a plotting position formula of the form:

$$P = \frac{m-a}{N+b} \tag{3-1}$$

where P = exceedance probability corresponding to the m^{th} ranked peak stage and a and b are coefficients that range from 0 to 1, depending on the desired probability distribution. For the Weibull formula, a = 1 and b = 0. Standard probability distributions seldom fit ice-affected stage data; however, favoring a distribution-free pair (a = 0.25 and b = 0.5; Adamowski (1981), Beltaos (2010).

a. Current practice favors plotting ice-affected peak stage vs. exceedance probability graphically on linear axes, although standard probability distributions, such as normal and log-normal, have been used in the past. Because ice jam stage data are considered non-parametric, care should be taken when extrapolating the curves beyond the limits of data. Inaccuracies from extrapolation to rare events arise from factors such as ice jam release and out of bank flow, which limit the maximum ice jam stages.

b. Gerard and Karpuk (1979) provide a practical example of the application of the direct method for developing ice-affected SF distributions.

c. Though the simplest, the mixed population approach is often inappropriate for peak stage populations that include both open water and ice-affected peaks because the characteristics of their SF curves may be quite different, as shown in Figure 3-1. A combined frequency analysis may better address the effects of ice. This requires dividing the population of annual peak stages into independent open water and ice-affected subpopulations. In some cases, ice-affected annual peak stages provided by the USGS are listed separately which facilitates the task. The general equation for combining multiple frequency curves from n independent annual series is:

$$P_c = 1-(1-P_1)(1-P_2)...(1-P_n) \tag{3-2}$$

where P_c is the exceedance probability of the combined frequency curve for a given stage and P_1, P_2 ...P_n are the exceedance probabilities for subpopulations 1 through n associated with that stage. If only two curves are to be combined, Equation 3-2 simplifies to

$$P_c = P + P_2 - P_1 P_2 \tag{3-3}$$

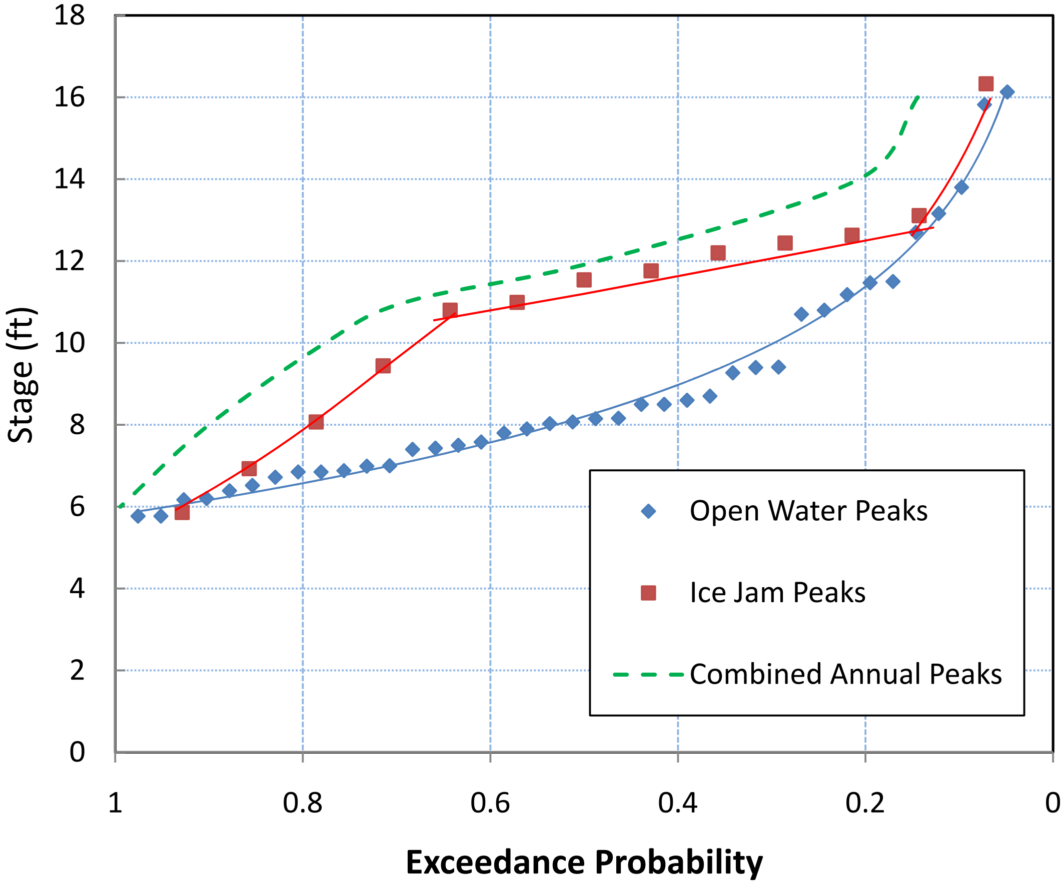

Figure 3-1. Stage frequency curves for ice jam open water peak stages. USGS Gage Vermilion River, OH. Green dashed lines represents combined frequency curve.

3-3. Indirect Method for Estimating Ice-affected Stage Frequency. In many cases, a lack of ice-affected peak stage data will preclude use of the direct method. In this case an "indirect" method may be employed, whereby ice-affected peak stages are synthesized by theoretical means or the use of ice hydraulic models. Important model inputs are discharge, pre-breakup ice thickness, and some knowledge of the ice conditions at the time of a historical or assumed breakup event. This ice information may be gained from historical research or inferred from hydro-meteorological data, such as daily air temperature, precipitation, and pre-breakup ice thickness calculated from accumulated freezing degree days (AFDD) (EM 1110-2-1612).

a. The basic approach for the indirect method is to divide the record of daily discharges into open water and winter seasons, the later being the period when the peak stage might result from the presence of ice. For the open water season, SF curves can be developed by hydraulic modeling of river profiles for desired return interval discharges. For the winter season, decision criteria are developed to sort peak discharges into ice jam and open water subpopulations, and the appropriate equations or models are used to synthesize peak stages at desired locations.

b. The first step is to plot daily average discharge, air temperature, AFDD, and precipitation for each winter of record. Figure 3.2 shows an example of these data for Cazenovia Creek near Buffalo, NY for the ice jam winter of 1996 plotted using HEC-DSSVue. The AFDD data can be obtained for suitable National Weather Service stations by using the following web-based application: https://maps.crrel.usace.army.mil/apex/f?p=AFDD .

From the hydro-meteorological data and historical record, tabulate known ice jam events, associated discharges, and ice thicknesses. If possible obtain hourly stage and flow data for known events and estimate the levels at which the ice cover breaks up, jams, and releases to construct composite rating curves similar to Figure 2-1. Antecedent events, such as mid-winter breakups or gradual warming that may have melted or weakened the ice cover prior to breakup, should be noted. Other important characteristics of the known breakup events include the magnitude of the discharge increase from baseflow to peak, ΔQ, and the hydrograph time to peak T_p. Long-term records of daily average discharge may be all that is available for modeling ice-affected peak stage. This is acceptable, assuming that the jam stayed in place for awhile because the instantaneous peak flow may, in fact, correspond to the release of the jam rather than with the period of equilibrium conditions. Ratios of the daily average discharge and instantaneous peaks may be useful in selection of an ice jam modeling flow.

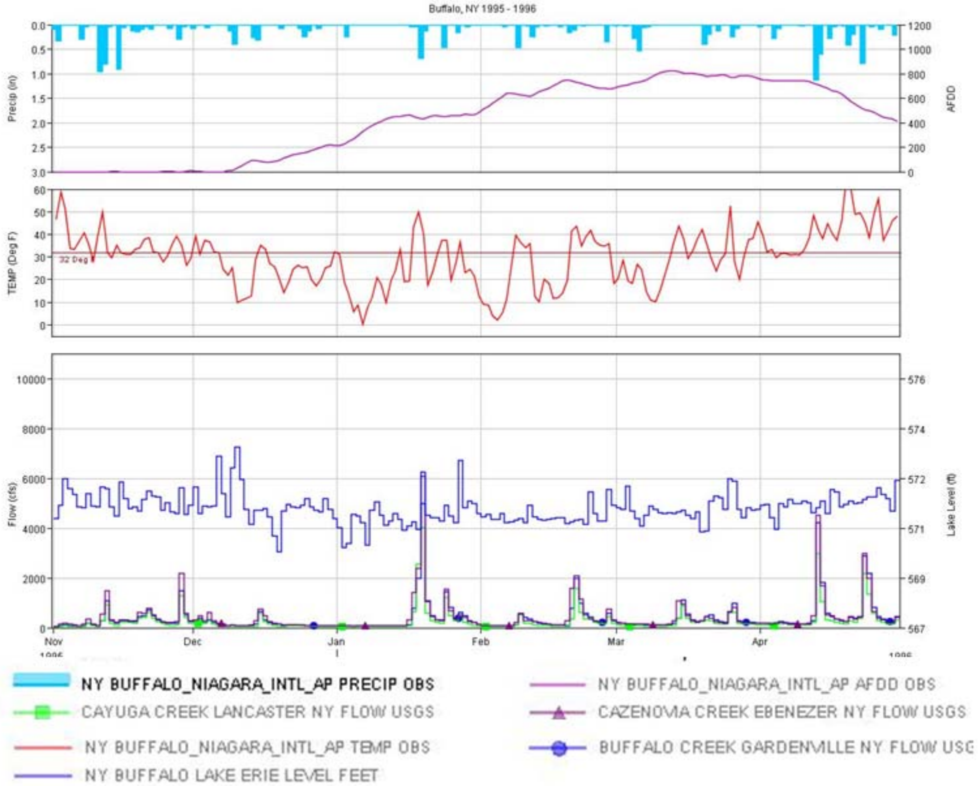

Figure 3-2. Hydro-meteorological data for Cazenovia Creek near Buffalo, NY plotted using HEC-DSSVue.

c. The pre-breakup ice thickness t_{i0} is important as the release of thicker ice requires a greater stage rise and usually results in a more dynamic ice run and more severe jams. Based on the characteristics of the known ice jams, one can develop criteria to identify winters where ice jams probably formed but were not recorded. Plots of Q vs. t_{i0} may reveal fields of jam and no-jam events as shown in Figure 3-3. Tuthill et al. (1996), White et al. (U.S. Army Corps of Engineers 2001), and Tuthill (2003) use a variety of decision criteria to sort the winter record of peak flows into jam and no-jam events. It is important to realize that these decision criteria are site-specific and usually not transferable from one location to another.

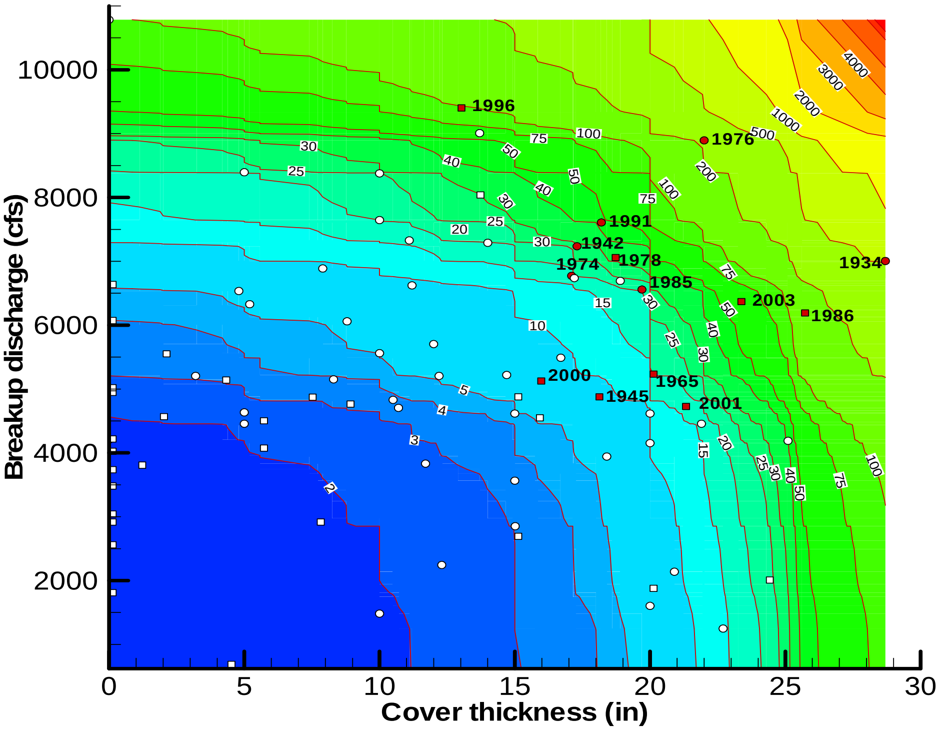

Figure 3-3. Discharge vs. ice cover thickness for observed and hindcast ice breakup events on the Grasse River at Massena, NY. Red squares with dates are known ice jams, white squares are likely ice jams, and white circles are hindcast no-jam breakups. Contours are combined probabilities of discharge and ice thickness. (After Shen et al., in review).

d. Using a jam, no-jam decision criterion, divide the record of winter peak discharges into likely ice jam and open water events. With knowledge of where the ice typically jams and the upstream source reach for the ice, simulate ice jam or open water profiles for each year of record using the HEC-RAS ice routine or similar. If possible, use historical ice jam events with observed stages and ice extent to calibrate and validate the ice jam model. For more basic analyses with limited bathymetry data, ice jam stages may be estimated using Equation 2-2 and the methods outlined in Gerard (1989), U.S. Army Corps of Engineers (1999), and EM 1110-2-1612.

e. When modeling ice jam profiles, an important input is ice jam volume, as it affects jam length and thickness and the magnitude and extent of upstream stage rise. A simple approach to estimating ice jam volume is to calculate the ice volume of an historic jam used for model calibration[1] V_{jc}, and then estimate the volume of simulated ice jams V_j by

$$V_j = \frac{t_{io}}{t_{ioc}} V_{jc} \tag{3-4}$$

where t_{io}/t_{ioc} is the ratio of pre breakup ice thickness of the simulated and calibration jams, respectively. Other methods for estimating ice jam volume as a function of the assumed pre-breakup source reach minus en-route losses are described in White (U.S. Army Corps of Engineers 1999).

f. The synthesized ice-affected and open water subpopulations of peak stages are then ranked, and plotting positions $P(S/J)$ and $P(S/O)$ calculated using Equation 3-1 or similar. The probability of the peak stage resulting from an ice jam $P(S)j$ during any given winter is

$$P(S)_j = P(J) \times P(S/J) \tag{3-5}$$

where $P(J)$ is the probability of a jam occurring and $P(S/J)$ is the stage probability if a jam occurs. $P(J)$ can be estimated as the fraction of the total years of record that an ice jam was observed or hindcast.

g. Similarly, the probability of the peak stage resulting from an open water event $P(S)_o$ during any given winter is

$$P(S)_o = P(O) \times P(S/O) \tag{3-6}$$

where $P(O)$ is the probability of an open water peak and $P(S/O)$ is the stage probability if the winter season peak occurs under open water conditions. $P(O)$ can be estimated as the fraction of the total years of record that an open water winter peak stage was observed or hindcast and

$$P(O) = 1 - P(J) \tag{3-7}$$

The winter period peak stage probability $P(S)_w$ is then

$$P(S)_w + P(S)_j + P(S) \tag{3-8}$$

The annual stage probability curve is then the combination of the open water season and winter SF curves using Equation 3-3.

h. Stages for desired recurrence intervals are taken from the combined curve. Figure 3-4 shows an example. Daly et al. (U.S. Army Corps of Engineers 2000b) developed an interpolation routine to automatically combine SF curves which is useful in studies that include many locations.

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[1] HEC-RAS calculates cumulative ice jam volume.

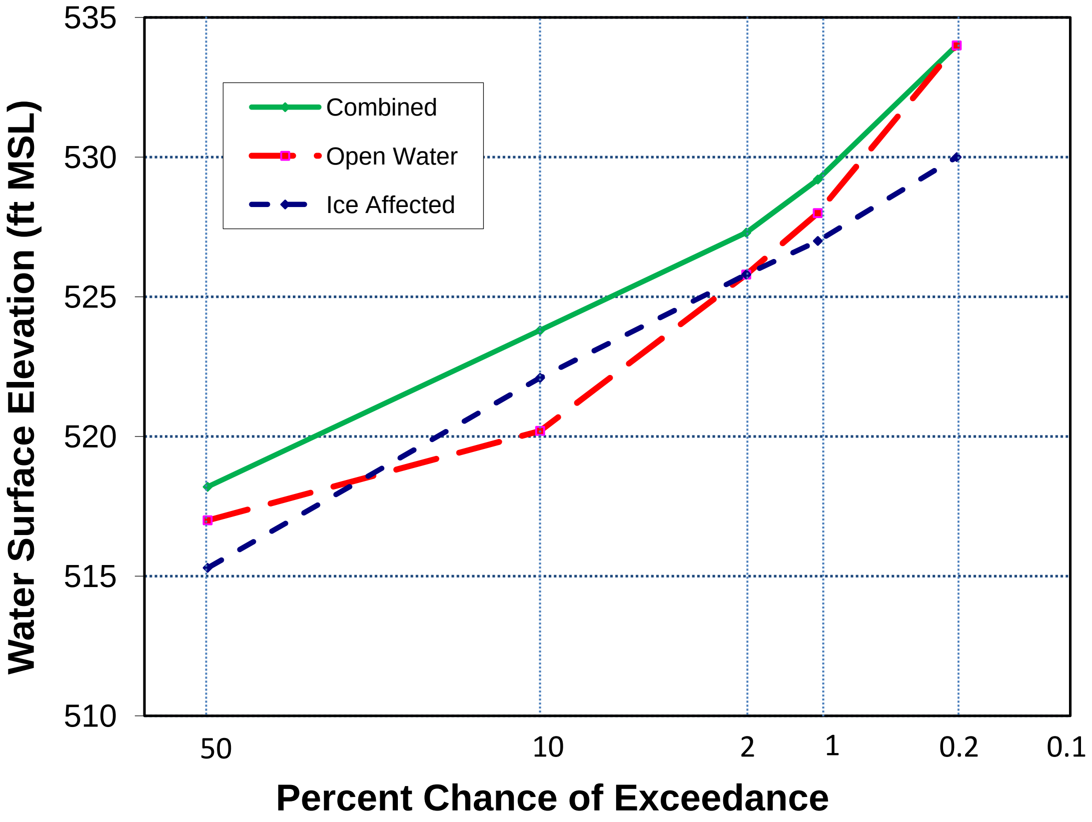

Figure 3-4. Stage frequency curves for ice-affected and open water seasons and annual combined for the Winooski River at Montpelier, VT (from Tuthill et al. 1996).

i. Tuthill et al. (1996), White et al. (U.S. Army Corps of Engineers 2000a and 2001), and Tuthill (2003) describe variations on the indirect method including illustrative case studies.

3-4. Estimating Uncertainty for Ice-Affected Stage Frequency Curves. Because ice-affected stage distributions do not fit well to standard probability distributions, such as normal and lognormal, statistical parameters such as standard deviation cannot be used to estimate confidence bands or extrapolate beyond the data to extreme events. The process of synthesizing ice-affected stage with assumptions about ice jam location and whether or not a jam occurs introduces additional uncertainty that is difficult to quantify. In spite of this, ice-affected SF curves have been fit to standard probability distributions and confidence intervals estimated by multiplying the standard deviation by coefficients such as those developed by Beard (U.S. Army Corps of Engineers 1962).

a. Non-parametric methods, such as order statistics, have been used to calculate the uncertainty of ice-affected SF developed by graphical methods. White and Beltaos (2008) mention a study of ice-affected SF for the Missouri River at Pierre, SD, by Daly et al. (U.S. Army Corps of Engineers 2000b) that estimated confidence intervals using a non-parametric application of the binomial test and order statistics. The order statistics method was applied within the limits of the observed (or synthesized data) while an asymptotic approximation was use to estimate the uncertainty of extreme events. White and Beltaos (2008) suggest a bootstrapping technique involving sampling with replacement to create a large sample ($N \geq 10^3$) from an original, non-parametric small one ($N \leq 10^2$). Provided the larger sample can be fit to a parametric distribution, confidence intervals may be estimated directly. It is not clear if this method has been used to estimate the uncertainty of ice-affected SF distributions.

b. A final and possibly simpler method for estimating the uncertainty of ice-affected SF curves is proposed. Unlike ice-affected peak SF, which is typically non-parametric, the annual series of peak winter discharge Q_p and maximum ice thickness t_i may well be normally distributed. This being the case, confidence intervals can be calculated for the Q_p and t_i SF curves by methods described by Beard (U.S. Army Corps of Engineers 1962), or similar. In the above-described indirect method, winter peak stages are synthesized for each year of record using inputs of Q_p and ice jam volume, which is estimated from the pre-breakup ice thickness t_i. For each (Q_p, t_i) pair used to calculate the maximum ice-affected water surface profile for a given winter, upper and lower bound profiles may be simulated using the (Q_p, t_i) pair plus and minus the appropriate confidence intervals taken from the Q_p, and t_i SF curves. Although somewhat labor intensive, the modern availability of numerical models and automated calculation methods make this approach more reasonable than it would have been in the past.

CHAPTER 4
Conclusions

Assessing flood risk on ice-affected rivers is more difficult than on those where peak stages result solely from open water events. The occurrence of ice jams, which are usually site-specific and unpredictable, may cause the annual peak stage at a fraction of the discharge of the equivalent open water peak. While open water SF can be related directly to discharge frequency, and fit to standard probability distributions, ice-affected SF cannot. The non-parametric nature of ice jam peak stages makes it difficult to estimate uncertainty and to extrapolate beyond the limits of the observed data. Ideally, ice-affected SF curves may be developed directly from observed ice jam stage data by the “direct” method. More commonly however, “indirect” methods are required whereby winter peak stage must be synthesized from winter peak discharge using analytical equations or models. The success of these techniques requires a good understanding of the local ice regime. This ETL describes current methods and the inherent challenges of developing ice-affected SF curves. Methods for estimating confidence intervals are also discussed. The ETL draws on the existing guidance and case studies referenced.