CGU HS Committee on River Ice Processes and the Environment
12th Workshop on the Hydraulics of Ice Covered Rivers
Edmonton, AB, June 19-20, 2003

Ice-Affected Stage-Frequency Development Along the Connecticut River

Andrew M. Tuthill, PE, Carrie M. Vuyovich, and Kathleen D. White, PhD, PE
US Army Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory
72 Lyme Road, Hanover, NH 03755
Andrew.M.Tuthill@erdc.usace.army.mil
Carrie.M.Vuyovich@erdc.usace.army.mil
Kathleen.D.White@erdc.usace.army.mil

Breakup ice jams affect annual peak stages at many locations along the Connecticut River between Vernon Dam and Hanover, NH. The flood insurance studies in this 70-mile reach are being updated to incorporate ice-affected flood levels. This report details the work undertaken to carry out the portion of this study leading up to the hydraulic modeling of the study reach. The study involved review of historical ice data from many sources to identify the causes and locations of ice jams in this reach, their dimensions, estimates of ice volumes in the jams, frequencies of occurrence, and lateral and upstream extent of flooding. Long-term winter temperature data for winter months at NWS stations near the study reach were used to estimate ice thickness from accumulated freezing degree days. Long-term daily average discharges at gages in the reach were used to identify river stages and discharges associated with the ice jams. Peak annual ice-affected conditions (discharge, ice thickness, jam locations) were developed for input to the HEC-RAS hydraulic model, which can then be utilized to develop ice-affected stages. A statistical analysis of the model results will provide the required ice-affected stage-frequency curves.

1.0 Introduction

The Connecticut River arises at First Connecticut Lake in northern New Hampshire and flows southward forming the border between New Hampshire and Vermont. (Figure 1). Ice covers form annually on this reach of the Connecticut River through a combination of thermal and dynamic processes. Normal winter operations of the hydroelectric dams at Dalton, NH, Waterford, VT, McIndoe Falls, VT, Wilder, VT, Bellows Falls, VT and Vernon, VT maintain a relatively steady daily average discharge on the portion of the river between Hanover, NH and Vernon Dam. Flood control projects on most of the major tributaries of the upper Connecticut significantly reduce main stem discharge during large runoff events, but in spite of this, inflow from thaws and snowmelt, combined with precipitation, can increase river discharge to the point that the ice covers break up and begin moving downstream. The moving ice can stop and form ice jams, resulting in rapid upstream stage rise and damaging floods. The moving and jammed ice can also cause bank erosion as well as structural damage to dams, roads, bridges, and other nearby structures.

The 70-mile-long reach of river between Hanover, NH and the dam at Vernon, VT is currently the subject of a Federal Emergency Management Agency (FEMA) Flood Insurance Study update. Except for the Town of Charleston, NH (USACE 1998, Dewberry & Davis 1998), the existing Flood Insurance Studies address open-water flooding only despite the fact that ice jams have been known to cause severe flooding within this reach. As result, the current Flood Insurance Study update includes ice effects. This paper briefly describes the ice jam analysis carried out in preparation for ice-affected hydraulic modeling of the study reach. The ice analysis involved review of historical meteorological, hydrologic, and ice data from many sources to identify the locations of the dominant ice jams in the study reach. This entailed research into the causes of the various jams, estimates of their dimensions and associated ice volumes, high stages and extent of flooding. Peak annual ice-affected conditions (discharge, ice thickness, jam locations) were developed for input to the HEC-RAS hydraulic model, which will later be used to perform the hydraulic modeling of the river. Following hydraulic modeling, a statistical analysis will be performed to develop final ice-affected stage-frequency information for the study reach.

2.0 Review of Historic Ice Jam and Hydrometeorological Data

Historic ice jam information from a variety of sources was reviewed to identify and characterize ice jamming in the study reach. Sources of historic ice jam information include the U.S. Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database (http://www.crrel.usace.army.mil/ierd/ijdb/), gage records and reports from the U. S. Geological Survey (USGS), the Section 206 Study Report: "Historic Ice Jam Flooding in Maine, New Hampshire and Vermont" (USACE, 1980), and the archives of the former New England Power Company, now known as US Generating Company, a subsidiary of Pacific Gas and Electric.

The review of historic data indicates four general ice jam locations on the Connecticut River between Hanover and the Vernon Dam (Figure 1). Listed from upstream to downstream, ice jams were found to form downstream of the West Lebanon USGS gage, below Windsor, VT, in the pool of the Bellows Falls Dam, and upstream of the Vernon Dam in the vicinity of Brattleboro, VT. A total of 33 ice jams were reported at the four general ice jam locations. Many more jams undoubtedly occurred but either went unrecorded or happened so long ago that records no longer exist.

2.1 West Lebanon, NH – Hartford, VT.

The jams located near West Lebanon, NH (across from the village of White River Junction, VT) have the most complete information due to the density of bridges, roads and structures along the ice jam reach. Another reliable and detailed information source is the West Lebanon USGS gage, which is located just upstream of the common ice jamming locations. Since 1959, eight peak annual stages at this gage have been attributed to ice jams or backwater from ice. These events do not coincide with the annual peak discharges, which occurred during the open water season. Although the West Lebanon gage record starts in 1927, there is no mention of annual peaks due to ice before the 1959 entry. The perception level for ice jam flooding has likely increased since the 1960's when commercial development began in the floodplain near the West Lebanon gage, thus it is probable that many ice jams occurring before that time went unrecorded.

Although ice jams occur at West Lebanon on a semi-annual basis, the ice jam events of 1964, 1970, and 1990 were memorable. On 6 March 1964, the White River Junction Bridge was swept away by ice, several houses were wrecked, 12 families evacuated, and Route 14 was buried in ice as far upstream as West Hartford. The bridge was replace by a temporary structure. On 12 February 1970, an ice jam that froze in place flooded several commercial buildings before it was partially removed by blasting. The next summer, ledges were blasted from the channel of the White River at Hartford in an effort to improve ice conveyance through this reach, although it is unclear what effect these physical changes had on ice jam severity downstream at West Lebanon. An ice jam on 27 January 1990 again caused the failure of the White River Junction Bridge, when ice-induced scour cause the failure of one of its 26-year-old "temporary" wooden piers, causing a portion of the bridge –and several cars – to fall into the river (Figure 2).

The White River is the main ice source for jams at the West Lebanon gage. The Connecticut River above the confluence and the Mascoma River's ice contributions are relatively minor by comparison. Ice covers on the White River and its tributaries consist of thermally grown sheet ice and border ice combined with thick accumulations of frazil ice produced in the numerous steep, turbulent reaches of the river. The White River, which is one of the few major uncontrolled rivers remaining in New England drains a steep mountainous watershed that has a rapid runoff response to snowmelt and rainfall events. Due to its flashy nature, it is not uncommon for most of the White River ice cover to break up and run in a single event. Jams commonly form on the Connecticut River in the reach 0.5 to 3 miles below the confluence with the White River. Common jam locations are the sandbar near the confluence with the Mascoma River, the bend below the I-89 Bridge and the head of Johnston Island.

Whether or not the ice from the White River jams at West Lebanon, and for how long, depends to some extent on the event hydrographs for both rivers. The thickness and strength of the White River ice floes and the thickness and strength of the Connecticut River ice cover are also important factors. If discharge is still increasing when the breakup front reaches West Lebanon, the ice may keep on moving past the West Lebanon jam initiation points to jam at Windsor, as it did on 11 Mar 1992, or even Bellows Falls, as occurred on 19 Jan. 1996. In some cases, the ice stalls for only a brief period at West Lebanon before moving downstream, as happened on 12 March 1936.

2.2 Windsor, VT.

Although recorded ice jams at and downstream of Windsor, VT are less frequent than those at West Lebanon, NH, they are usually more severe in terms of impacts and damages. The village of Windsor lies just upstream of the normal head of pool of the Bellows Falls Dam. The reduction in water surface slope from the free-flowing river to the impoundment, as well as two bridges and a channel bend, make this a natural location for ice jamming and deposition of sediment. According to USACE (1980), the three common ice jam locations are Chase Island and two sandbars 0.7, 1.2 and 2.5-miles downstream of the covered bridge respectively. When discharges are high, ice moves past these sites to jam about 7 miles downstream of Windsor in a bend below the Ascutney Bridge. A submerged mid-channel gravel bar upstream of the Cornish-Windsor Covered Bridge slows the ice run and, to some extent, protects the structure. In spite of this natural barrier, the ice has damaged the bridge at least three times (1979, 1964 and 1936).

Sections of roads and highways around Windsor, including NH Route 12A and VT Route 5, have flooded during nearly all events listed in Table 2. During the most recent serious ice jam on 11 March 1992, the high water came to within two ft of the low chord of the Cornish-Windsor Covered Bridge (326.1 ft MSL, with a resulting water level of about 324 ft MSL), low-lying portions of the Grand Union parking lot were submerged up to three ft, and 14 homes were evacuated. An ice jam in February 1973 had similar impacts, with flooding reported at the wastewater treatment plant (WWTP) as well. The ice events of 7 March 1979, 6 March 1964 and 13 March 1936 were more severe, and damaged the Cornish-Windsor Covered Bridge. On 9 March 1946, a 4.5-mi-long jam formed 2.5 miles below Windsor that extended upstream to a point near the Windsor Country Club (Figure 3). Peak stages were 319.3 ft MSL at the Cornish-Windsor Covered Bridge (Figure 4), 324.46 ft MSL where Rt. 5 crosses Hubbard Brook (Figure 5) and 325.3 ft MSL at the upstream end of the jam. In addition to flooding of roads and structures, the moving ice and flow scoured and eroded long sections of bank on both sides of the river (NE Power, 1946). The jam released on 15 March and passed the Bellow Falls Dam without further difficulty. On 13 March 1936, the ice jammed six miles below Windsor causing a peak stage of 323.7 ft MSL at the Cornish-Windsor Covered Bridge. This ice released 17 March and jammed briefly at Bellows Falls before passing over the dam.

2.3 Bellows Falls, VT.

Although some impressive-looking ice jams have occurred in the pool of the Bellows Falls Dam, they are typically less severe in terms of flooding and damage than the jams below Windsor. The most recent ice jam occurred on 19 January 1996, when an extreme thaw accompanied by rain caused nearly all the ice from the White River and the Connecticut River below Wilder Dam to run and jam at in the bend 0.7 mi upstream of the Bellows Falls Dam (Figure 6). The jam froze in place for over a month and flooded a section of VT Route 5 near the Cheshire Bridge (302.3 ft MSL), as well as some mobile homes in Charlestown, NH (298.5 ft MSL) (Figure 7). This event was unique since the ice did not jam at any of the usual upstream locations on its way to Bellows Falls. The extremely rapid rise of the hydrograph and the thinness of the pre-breakup ice cover (8-10 inches) are the probable reasons for this unusual behavior. Following this event, at the request of FEMA the New England District of the Corps used the direct method to recalculate the 100-year flood profiles to account for ice jams (USACE, 1998). Based on records from New England Power Company the study identified 9 ice jam locations between Bellows Falls and Windsor[1]. USACE (1980) compiled ice jam high stage data from 1927 to 1996 for Bellows Falls Dam and the Cheshire Bridge, as well as breakup discharges at the dam. These data also include observed ice jam high stages at the Charlestown Trailer Park (7.5 mi upstream of the dam) of 303.0 ft MSL on 24 March 1968 and 298.5 ft MSL on 27 Jan. 1996.

In 1936, the ice jammed on 13 March at a point 6 miles upstream of the Bellows Falls Dam flooding low lying areas near the Cheshire Bridge and in Charlestown. The jam released on 17 March, and, after stalling for 1.5 hours at Bellows Falls, passed the dam just ahead of the ice from the Windsor jam which released at about the same time (NE Power, 1936).

2.4 Brattleboro, VT.

Considering the potential volume of the upstream ice, severe ice jams at Vernon and Brattleboro have not been that frequent. Possible causes are ice volume losses into over bank areas, and water temperatures that are sufficiently warm to melt much of the ice as it floats downstream or stalls in jams along the way. In 1936 the White River ice that released on 12 March did not pass the Vernon Dam until five days later. In 1946, six days elapsed before the White River ice reached Brattleboro, sufficient time for significant melting to occur.

On 19 January 1996, a 2.2 mile-long jam at Brattleboro formed and froze in place in the reach between the Route 119 and the Route 9 Bridges. On 14 March 1946, an ice jam formed four miles upstream of the Vernon Dam and extended several miles upstream to Brattleboro. The jam washed out the next day, along with ice from the release of upstream jams, destroying the flashboards on the dam. Parts of Brattleboro were flooded due to an ice jam in January of 1935, and on 17 March 1936, a five-mile-long jam above Vernon Dam caused some flooding of roads and cellars. The release of major ice jam on 28 March 1920 destroyed the Brattleboro Bridge.

The records indicate that, except for the White River, ice runs from tributaries do not appear to significantly impact the ice jamming processes on the main stem Connecticut River. Possible reasons are flood control dams on tributaries such as the Ompompanoosuc, Ottaqueechee, Black, and West Rivers, which delay breakup until stages have risen on the main stem of the Connecticut. Another factor is the presence of numerous milldams that stop or delay tributary ice

---

[1] Jam Locations were 0-1.0, 4.0, 7.4, 10 (Cheshire Bridge), 12.5, 17, 20.5, 24, and 26 miles upstream of the Bellows Falls Dam (the Windsor Covered Bridge is located 26.8 miles upstream of the Bellows Falls Dam).

runs, examples being the Mascoma, Sugar and Black Rivers. Finally, where tributaries drain into impounded reaches of the Connecticut, obstructions to flow caused by deposited sediment as well as man-made barriers such as bridges and embankments stop the ice run short of the main river channel. The Black, Williams and West Rivers are examples of this type of confluence.

2.5 Hydrometeorological Data

Hydrometeorological information was obtained from four USGS gages and two NWS meteorological stations. Data for the period 1927 to 2001 was available at the USGS gages White River at West Hartford, VT and Connecticut River at West Lebanon, and the NWS station at Hanover, NH. Data from the NWS station at Keene, NH and the USGS gage Connecticut River at North Walpole, NH were used for the period 1942 to 2000. Data from the USGS gage Connecticut River at Vernon for the period 1945 to 2000 was also used. Meteorological data was used to estimate of maximum pre-breakup ice thickness. Historical hydrometeorological data was also plotted for ease in developing of jam-no jam decision criteria (Figures 8 and 9).

3.0 Estimation of Ice Thickness

Hydraulic modeling of ice-affected rivers using the Hydrologic Engineering Center (HEC) model HEC-RAS (HEC 1998) requires an estimation of the ice thickness. Ice covers may form and thicken further through heat transfer processes, or by mechanical process such as shoving or deposition of frazil or snow ice. However, the ice thickness used in hydraulic modeling is generally that developed through heat transfer, unless specific information regarding frazil deposition or other mechanical processes is known for a given river reach. Ice thickness in inches (t_i) resulting from heat transfer processes can be estimated from the net accumulated freezing degree-days (net AFDD). Freezing degree-days (FDD) are first calculated for each day of the winter season:

$$FDD=(32-T_a) \qquad (1)$$

where T_a is the average daily air temperature in ºFahrenheit. A negative freezing degree-day value represents a temperature warmer than freezing, while a positive freezing degree-day represents temperatures below freezing. The FDD values for each day of the winter are summed to determine the net AFDD each day. Ice thickness in inches is then estimated using the modified Stefan equation presented in USACE (1999):

$$t_i = C\,(\text{net AFDD})^{0.5} \qquad (2)$$

where C is a coefficient, usually ranging between 0.3 and 0.6 and net AFDD is in °F-days. The zero AFDD point is assigned to the point in time in late fall or early winter when the AFDD curve goes from a negative to a consistently positively slope. Snow cover on top of the ice can insulate it, decreasing the heat transfer and effectively lowering the coefficient used in equation 2. After comparing AFDD to selected observed ice thicknesses, a coefficient of 0.37 was chosen for use throughout the study reach. This coefficient value produced calculated ice thicknesses in the 7 to 14 inch thickness range for the computed AFDD, which is reasonable for sheet ice covers on northern New England Rivers. However, due to the importance of frazil in ice cover formation on the Connecticut River and its tributaries, the ice thickness may be underestimated using equation 2.

4.0 Estimation of Ice Jam Volume

Unless otherwise limited, the HEC-RAS model will assume an unlimited ice supply. Therefore, estimates of ice jam volume are important, since they used to adjust the length of the modeled ice jams, which in turn affects stages and potential flood areas. The ice jam volumes developed in this study are estimated by considering potential source reaches for historic jams of known extent. These estimates assume that during an extreme ice breakup, nearly all the ice on the White River will break up and run, and a large percentage of this ice will travel at least as far as the Connecticut River.

Ice source reach area, *A*, is calculated from:

$$A = \sum_{i=1}^{n} L_i W_i \qquad (3)$$

where L_i and W_i are the length and average width of individual contributing reaches. The following equation calculates V_0, which is the pre breakup ice volume (in ft^3) for a specific year

$$V_0 = \frac{t_{io}}{12} A \qquad (4)$$

where t_{io} is the pre breakup ice thickness in inches calculated from net *AFDD* using the method described above.

For the purposes of ice volume estimation, the White River was broken into the five reaches shown in Table 5. Assuming the ice is 12 inches thick, the potential pre-breakup ice volume V_0 is about 55 million ft^3. This includes the pre-breakup ice cover on the Connecticut River from the mouth of the White River to an assumed jam site 1.5 mi downstream of the West Lebanon USGS gage. Assuming an ice jam porosity of 0.5 results in a potential total ice jam volume V_t of 110 million ft^3 using:

$$V_t = V_0 / (1 - e) \qquad (5)$$

Historic ice jams at West Lebanon have extended as far up the White River as West Hartford, a distance of nine miles. Estimated jam dimensions of 2 mi long, 550 ft wide, and 6 ft thick on the Connecticut River and 7 miles, 350 ft wide, and 4 ft thick on the White River give a calculated ice jam volume of 87 million ft^3. The difference can reasonably be attributed to variations in actual vs. estimated ice thickness, losses due to melting and stranding of ice along the channel sides in the form of shear walls, and losses due to stranding when ice that is carried overbank is deposited in the floodplain. Ice loss due to melting and stranding can decrease the ice supply available for downstream jamming and thus is of interest when estimating ice jam volume. Ice loss during breakup and ice cover movement can be described using an ice loss coefficient, c_l:

$$c_l = \frac{V_t - V_j}{V_t} \qquad (6)$$

where V_t is the total upstream ice supply and V_j is the volume of ice contained in the jam.

The ice loss coefficient calculated here is about 0.21, which can be considered conservative. White (1999) reports a range of between 0.4 and 0.93 for reported ice loss coefficients. However, the ice loss coefficient is expected to be low for shallow, steep rivers with short reaches of contributing ice cover such as the White River and tributaries, and thus this estimate is acceptable.

The same reasoning is used to estimate potential ice jam volumes and losses for the downstream ice jam sites. The calculated ice jam volume for Windsor is based on the 9-mile long jam of 7 March 1979, which extended upstream as far as Sumner Falls. The 19 January 1996 jam provided estimates of volume and losses in the Bellows Falls jam, as did the 1936 and 1920 jams at Brattleboro. Note that in Table 5, the calculated loss coefficients increase in the downstream direction from 21 percent in the White River jam to 77 percent in the Brattleboro jam. This result is not unreasonable as ice floes commonly deposit in the floodplain fields and meadows along this reach of the Connecticut River. In addition, melting that occurs while the ice is stalled in jams can account for significant losses in ice jam volume in relatively short periods of time (Lever et al. 2000).

5.0 Criteria for Identifying Potential Ice Jams

The review of historic hydrometeorological data revealed that at least three scenarios can cause peak stage during the winter period: a peak winter flow with a sheet ice cover in place, an ice jam, or an open-water winter peak flow that occurs either before a strong ice cover ice cover forms or after ice out. The winter period is defined as 1 December through 31 March, since all the historic ice jams occurred between these dates.

Based on the ice jam history, and the plots of daily average discharge (including time to peak, T_p), air temperature, and AFDD (Figures 8 and 9), criteria were developed to predict the occurrence of ice jams at locations in the study reach (Table 6). Review of discharge and air temperature data indicates that, although the occurrence of the peak winter stage with a sheet ice cover in place is possible, it is unlikely. Where the peak stage did not result from an ice jam, then it is assumed that the winter peak stage occurred on the day of the peak winter discharge. In most years, the peak winter discharge occurs either early in the season before a competent ice cover has formed, or during the winter-end thaw, after the AFDD curve has peaked out. In the early season cases it is assumed that the ice cover has released without jamming before the peak discharge is reached. In the late season melt-out cases, it is safe to assume that the ice cover had essentially disappeared by the time of the winter peak flow. In some cases it was uncertain if the peak winter stage was caused by an ice jam or by a separate open water peak flow event. For this reason, the open water peak discharges are listed along with the ice jam events so the higher of the two can be selected using HEC-RAS. Other important modeling variables for the ice jam case are the ice jam location, the pre-breakup ice thickness and ice volume, and the estimated ice volume loss in transit to the jam location.

Four general locations were selected for ice jam modeling with HEC-RAS. The first is in the vicinity of West Lebanon, NH and Hartford, VT, the second downstream of Windsor VT, the third in the Bellows Falls Pool, and the fourth near Brattleboro, VT. Tables 12, 13, 14 and 15 list the predicted ice jam events respectively for the above-mentioned locations. Also listed for each jam year are the calculated pre-breakup ice thickness and the estimated ice jam volume. In the cases of Windsor and Bellows Falls Pool, the criteria select one of two sub locations. The dates and magnitudes of the peak daily average flow for the winter period are also listed since it is possible that during the same winter, an open water discharge event could cause higher water levels than an ice jam event.

5.1 West Lebanon, NH-Hartford, VT

Jams have been observed to form 0.5 to 3.0 miles downstream of the White River Confluence. Because the most common ice jamming location is the bend below the I-89 Bridge, 1.5 mi downstream of the West Lebanon USGS gage, this location was selected for hydraulic modeling. Application of the criteria for selecting potential ice jams resulted in the identification of 48 predicted ice jams for West Lebanon, NH for the 75-year period of record in addition to the 13 observed historic jams listed in Table 1. In all but two cases, the predicted jams fell on or within one day of the reported date of the historic jams. In the 1959 case, the hydraulic data do not support the occurrence of an ice jam on the reported date of 29 January, so the conditions on the predicted date of 22 Jan are suggested for HEC- RAS modeling. In 1970, the criteria selected 4 February as the jam date, while the historic jam occurred on 12 Feb. In this case, hydraulic conditions for the actual event date are provided in Table 12 for hydraulic modeling of the event.

5.2 Windsor, VT

Jams have been observed to form 0.6 to 2.6 miles downstream of the Windsor Covered Bridge and 7 miles downstream of Windsor, below the Ascutney Bridge. The historic record suggests that higher discharge tends to shift the jam location downstream. Application of the criteria for selecting potential ice jams resulted in the identification of 16 predicted ice jams for the Windsor, VT area for the 75-year period, in addition to the 6 observed historic jams listed in Table 2. Fifteen jams were predicted at the location 1.3 miles downstream of the covered bridge while only one was predicted for the location 7 miles downstream of the covered bridge.

5.3 Bellow Falls Dam Pool

Historic jams have formed at locations ¾ and 6 miles upstream of the Bellow Falls Dam. For thick ice (>12 to 14 inches thick) higher discharge tends to shift the jam to the lower site. If the pre-breakup ice is relatively thin (< 10 inches thick), jams can form near the dam at lower discharges. Application of the criteria for selecting potential ice jams resulted in the identification of 9 predicted ice jams for the Windsor, VT reach for the 60-year period, in addition to the 2 observed historic jams within that period listed in Table 3. Note that Table 3 lists four additional jams that occurred before 1942, the start of the North Walpole gage record. Eight jams were predicted at the location 6 miles upstream of the Bellows Falls Dam while only one was predicted for the location 0.7 miles upstream of the dam.

5.4 Vernon Dam Pool

Jams in the vicinity of Brattleboro VT usually form upstream of the Rt. 119 Highway Bridge and causeway. The greatest jam length reported is 5 miles, suggesting that significant melting and over bank losses have occurred by the time upstream ice reaches Brattleboro. In some high flow cases, jams have formed in the pool downstream of the Rt. 119 Bridge, closer to the dam. Application of the criteria for selecting potential ice jams resulted in the identification of 33 predicted ice jams, in addition to the 3 observed historic jams at Brattleboro that occurred within the period of record. Note that all of the predicted jams formed at the Route 119 Bridge. Table 4 also lists four additional historic ice jams that formed downstream of Brattleboro, before the start of the North Walpole Gage record in 1942.

6.0 Summary

Severe breakup on the 70-mile-long study reach of the Connecticut River generally progresses from upstream to downstream, triggered initially by the release of the White River ice. The White River ice usually jams at West Lebanon, and, if discharge continues to rise, releases and jams again downstream of Windsor VT. Jams that form at Windsor may in turn release to re-jam below the Cheshire Bridge or, in higher discharge cases, will form a new jam about 0.5 mi-upstream of the of the Bellows Falls Dam. In rare high flow cases, the Bellows Falls jam will release and pass over the dam. Jams usually form in the Vernon Pool between the NH Route 119 and US Route 9 Bridges. These jams typically contain less ice than the upstream jams due to losses and melting of the ice supply while en-route. In general, the increase in river discharge required to break up the ice cover and the ice jam release discharge increase in the downstream direction.

Review of the historic ice jam and hydrometeorological data revealed three scenarios that can cause peak stage during the winter period (1 December through 31 March). These are a peak winter flow with a sheet ice cover in place, an ice jam, or an open-water winter peak flow that occurs either before a strong ice cover forms or after ice-out. Ice jam-no jam decision criteria for use in selecting the proper scenario for hydraulic analyses during the winter period were developed and applied to daily hydrometeorological records. Meteorological data were used to estimate ice thickness and ice volume for use in hydraulic analyses of the scenarios predicted at each ice jam site.

Acknowledgments

This project was funded by the Federal Emergency Management Agency through a Test and Evaluation Agreement between their contractor, ENSR International, and the ERDC-CRREL Ice Engineering Group. Methods used in this study were developed under several work units funded by the Cold Regions Engineering Program, part of the US Army Corps of Engineers Civil Works General Investigations Research and Development Program.

References

Adamowski, K. (1985) "Nonparametric kernel estimation of flood frequencies." *Water Resources Research*, Vol. 21, No. 11, p. 1585-1590.

Dewberry and Davis, 1998. Review of Ice Jam Analysis for the Connecticut River in Charlestown, NH. Contract Report prepared for the Federal Emergency Management Agency.

Hydrologic Engineering Center, 1998. HEC-RAS R. Analysis System User's Manual Version 2.2. Hydrologic Engineering Center Report CPD-68, U.S. Army Corps of Engineers Hydrologic Engineering Center: Davis, CA.

Lever, J. H, Gooch, G. and S. F. Daly, 2000. Cazenovia Creek Ice Control Structure. Engineer Research and Development Center/CRREL TR-00-15, U. S. Army Corps of Engineers

USACE (1999) Engineering Manual 1110-1612 "Ice Engineering" Department of the Army, U. S. Army Corps of Engineers, Washington, DC 20314-1000

USACE (1998) "Charlestown, NH Ice Jam Flood Analysis", prepared for FEMA by New England District US Army Corps of Engineers.

USACE (1980) "Historic Ice Jam Flooding in New Hampshire and Vermont" Section 206 Study Report, New England District, US Army Corps of Engineers, October 1980.

White, K.D. (1999) "Review of Physical and Hydraulic Properties Important in Ice Jams." USA CRREL Report 99-11.

Table 1. Discharge, Air Temperature and Calculated Pre-Breakup Ice Thickness for Historic West Lebanon, NH Ice Jams

Date	White River at West Hartford			Connecticut River at West Lebanon			Days to Peak	AFDD at Breakup	Ice Thickness (inches)	Peak Stage	Jam Length (mi)
	Q base	Q daily	Delta	Q base	Q daily	Delta					
28-Feb-2000	500	4600	4100	2500	13500	11000	5	880	11.0	20.03	5
18-Mar-1995	900	4800	3900	4000	19000	15000	9	380	7.2	17.33	
27-Jan-1990	900	3000	2100	3500	16000	12500	2	750	10.1	21.56	
12-Feb-1981	500	6000	5500	2000	27000	25000	4		0.0	23.90	
7-Mar-1979	900	9000	8100	5000	40000	35000	2	1250	13.1	22.47	10
12-Feb-1970	700	3000	2300	6000	13500	7500	1	1120	12.4	23.33	4
6-Mar-1964	500	12000	11500	5000	35000	30000	2	1200	12.8		
Feb-1961									0.0		
22-Jan-1959	300	3000	2700	3000	11000	8000	1	850	10.8	23.08	11
8-Mar-1946	600	5000	4400	2500	11600	9100	3	1230	13.0	20.30	
2-Jan-1945	600	4000	3400	2500	13000	10500	1	420	7.6	17.30	
25-Feb-1943	600	3200	2600	2000	6500	4500	3	1280	13.2	17.80	
12-Mar-1936	500	11000	10500	1500	20000	18500	1	1460	14.1	18.50	

[1] $t_{io} = 0.37\sqrt{AFDD}$

Table 2. Discharge, Air Temperature and Calculated Pre-Breakup Ice Thickness for Historic Windsor, VT Ice Jams

Date	White River at West Hartford			Connecticut River at West Lebanon			Days to Peak	AFDD at Breakup	Ice Thickness (inches)	Peak Stage	Jam Length (mi)
	Q base	Q daily	Delta	Q base	Q daily	Delta					
11-Mar-1992	600	10500	9900	3000	26600	23600	2	950	11.4		
7-Mar-1979	900	9000	8100	5000	40000	35000	2	1250	13.1		9
21-Mar-1968											
6-Mar-1964	500	12000	11500	5000	35000	30000	2	1200	12.8		8
9-Mar-1946	600	12000	11400	4000	31000	27000	3	1230	13.0	319.3	4.5
13-Mar-1936	500	17500	17000	1500	20000	44000	1	1460	14.1	323.70	6

[1] At Windsor Covered Bridge Gage

Table 3. Discharge, Air Temperature and Calculated Pre-Breakup Ice Thickness for Historic Bellows Falls, VT Ice Jams

Date	Connecticut River Q at North Walpole			Days to Peak	AFDD at Breakup	Ice Thickness (inches)	Peak Stage	Jam Length (mi)
	Q base	Q daily	Delta					
20-Jan-1996	4500	48000	43500	1	680	9.6		10
21-Mar-1968								
13-Mar-1936	1000	60000	59000	2	1460	14.1	307.5	7
17-Mar-1936	40000	90000	50000	1	1460	14.1		
9-Jan-1935	5000	30000	25000	2	500	8.3		
13-Feb-1925								

Table 4. Discharge, Air Temperature and Calculated Pre-Breakup Ice Thickness for Historic Brattleboro, VT Ice Jams

Date	Connecticut River Q at North Walpole			Days to Peak	AFDD at Breakup	Ice Thickness (inches)	Peak Stage	Jam Length (mi)
	Q base	Q daily	Delta					
20-Jan-1996	4500	48000	43500	2	680	9.6		2.2
24-Jan-1957	5000	21000	16000	2	500	8.3		
14-Mar-1946			40000	4	900	11.1		2
17-Mar-1936	40000	90000	50000	1	1460	14.1	230.0	5
10-Jan-1935	5000	30000	25000	2	500	8.3		
13-Feb-1925								
28-Mar-1920								

Table 5. Ice Jam Source Reaches and Ice Volumes for a Pre Breakup Ice Thickness of 1.0 ft. and an Ice Jam Porosity of 0.5

River	Length L_i (mi)	Width W_i (ft)	Pre-Breakup Ice Volume $V_{1.0}$ (ft^3)		Potential Ice Jam Volume V_{jp} (ft^3)	Calculated Ice Jam Volume V_{jc} (ft^3)	Percent Loss l
				Cumulative			
White River							
Third Branch downstream of Randolph	7	150	5.5E+06				
Second Branch downstream of East Bethel	4	100	2.1E+06				
First Branch downstream of Tunbridge	5	100	2.6E+06				
Mainstem Gaysville downstream to Bethel	5	200	5.3E+06				
Bethel to Connecticut River Confluence	22	300	3.5E+07	5.0E+07			
Connecticut River							
White River mouth to West Lebanon Jam	1.5	550	4.4E+06	5.5E+07	1.1E+08	8.7E+07	20.6 %
West Lebanon Jam to jam 1.3 mi downstream of Windsor	14.6	550	4.2E+07	9.7E+07	1.9E+08	1.5E+08	22.8 %
West Lebanon Jam to jam 7 mi downstream of Windsor	21.6	550	6.3E+07	1.6E+08	3.2E+08	2.2E+8*	26.7%*
Jam 7 mi downstream of Windsor to jam 6 mi upstream of Bellows Falls	13	800	5.5E+07	2.1E+08	4.3E+08	2.8+E8*	34.0 %*
Jam 6 mi upstream of Bellows Falls to 0.7 mi upstream of Bellows Falls Dam	5.3	1000	2.8E+07	2.4E+08	4.9E+08	3.1E+08	37.0 %
Jam at Rt.119 Bridge in Brattleboro	31.5	1000	1.7E+08	4.1E+08	8.2E+08	1.9E+08	77.4 %

* Estimated by linear interpolation

Table 6. Ice Jam Test Criteria

General Location	Ice Jam Criteria
West Lebanon, NH – Hartford, VT	$\Delta Q_{\text{W. Hart.}} \geq 2600$ cfs or $\Delta Q_{\text{West Lebanon.}} \geq 7500$ cfs $t_{io} \geq 7$ in $\Delta Q_{\text{West Lebanon.}} \leq 35{,}000$ cfs $T_{p\ \text{W. Hart}} \leq 5$ days Location: 1.5 mi downstream of West Lebanon Gage Volume for $t_{io} = 1.0$ ft : 5.4×10^7 ft^3
Windsor, VT and downstream	$\Delta Q_{\text{West Lebanon.}} \geq 20{,}000$ cfs $t_{io} \geq 8$ in $\Delta Q_{\text{West Lebanon.}} \leq 44{,}000$ cfs $T_{p\ \text{W. Hart}} \leq 3$days Location: If $t_{io} \geq 12$ in and $\Delta Q_{\text{West Lebanon.}} \geq 30{,}000$ cfs, then jam is 7 mi downstream of Covered Bridge Else jam is 1.3 mi downstream of Covered Bridge
Bellows Falls, VT Dam Pool	$\Delta Q_{\text{North Walpole}} \geq 20{,}000$ cfs $t_{io} \geq 8$ in $Q_{\text{North Walpole}} \leq 90{,}000$ cfs $T_{p\ \text{North Walpole}} \leq 3$days Location: If tio ≤ 12 in and $\Delta Q_{\text{North Walpole.}} \leq 40{,}000$ cfs, then jam is 6 mi upstream of Bellows Falls Dam If $t_{io} \leq 12$ in and $\Delta Q_{\text{North Walpole.}} > 40{,}000$ cfs, then jam is 0.7 mi upstream of Bellows Falls Dam If $t_{io} \geq 12$ in and $\Delta Q_{\text{North Walpole.}} \leq 60{,}000$ cfs, then jam is 6 mi upstream of Bellows Falls Dam If $t_{io} \geq 12$ in and $\Delta Q_{\text{North Walpole.}} > 60{,}000$ cfs, then jam is 0.7 mi upstream of Bellows Falls Dam
Vernon, VT Dam Pool	$\Delta Q_{\text{North Walpole}} \geq 25{,}000$ cfs $T_{p\ \text{North Walpole}} \leq 3$days $t_{io} \geq 8$ in $Q_{\text{North Walpole}} \leq 90{,}000$ cfs

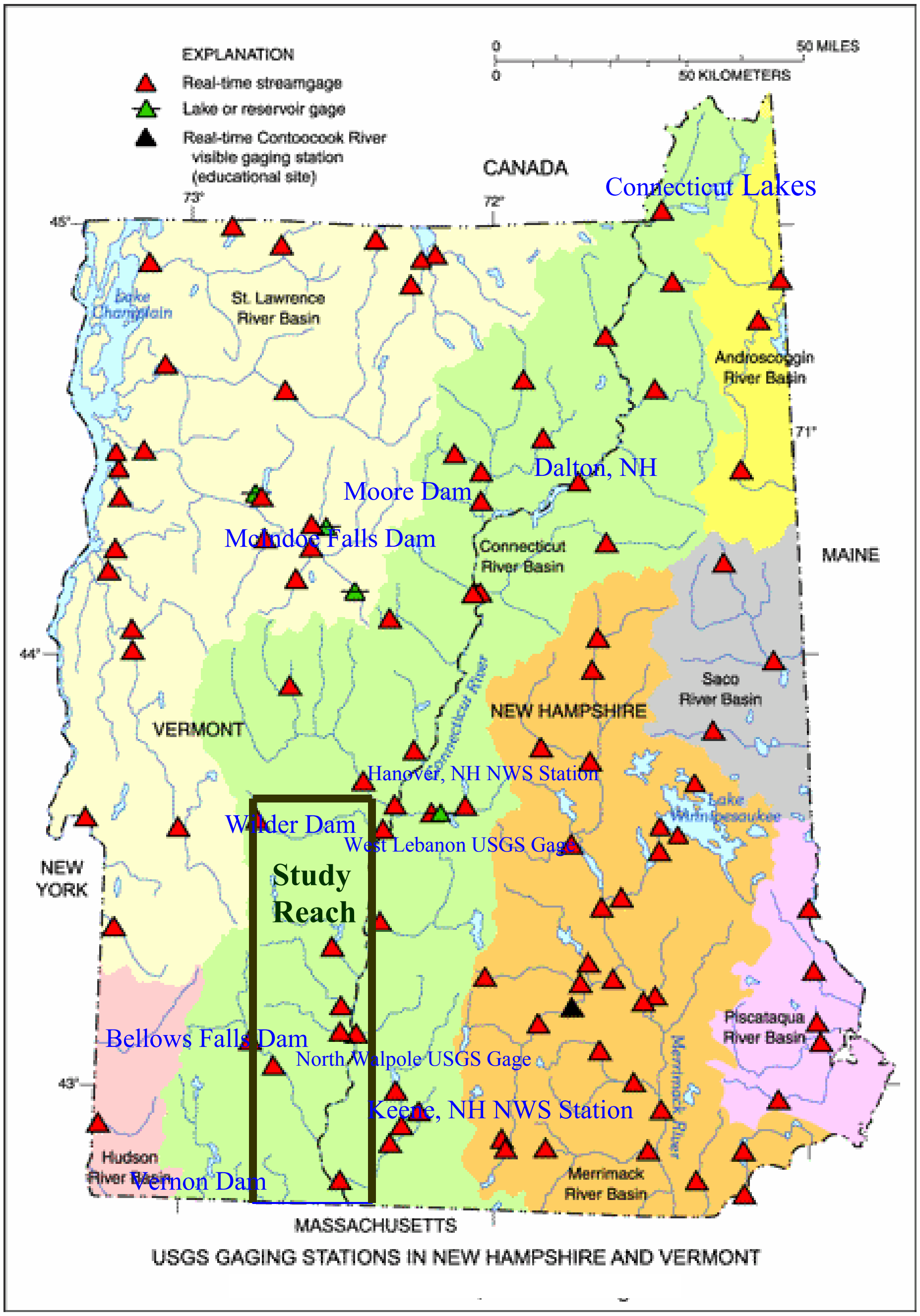

Figure 1. The Connecticut River in New Hampshire and Vermont, with the study reach outlined.

Figure 2. Failure of the White River Bridge, 27 Jan. 1990 as a result of ice jam induced scour around piers.

Figure 3. Windsor, VT ice jam 10 on March 1946. (Photo from New England Power Co. Archives)

Figure 4. Ice upstream of Windsor Covered Bridge on 11 March 1946 (Photo from New England Power Co. Archives).

Figure 5. Ice jam flooding in Windsor, VT on 10 March 1946. (Photo from New England Power Co. Archives)

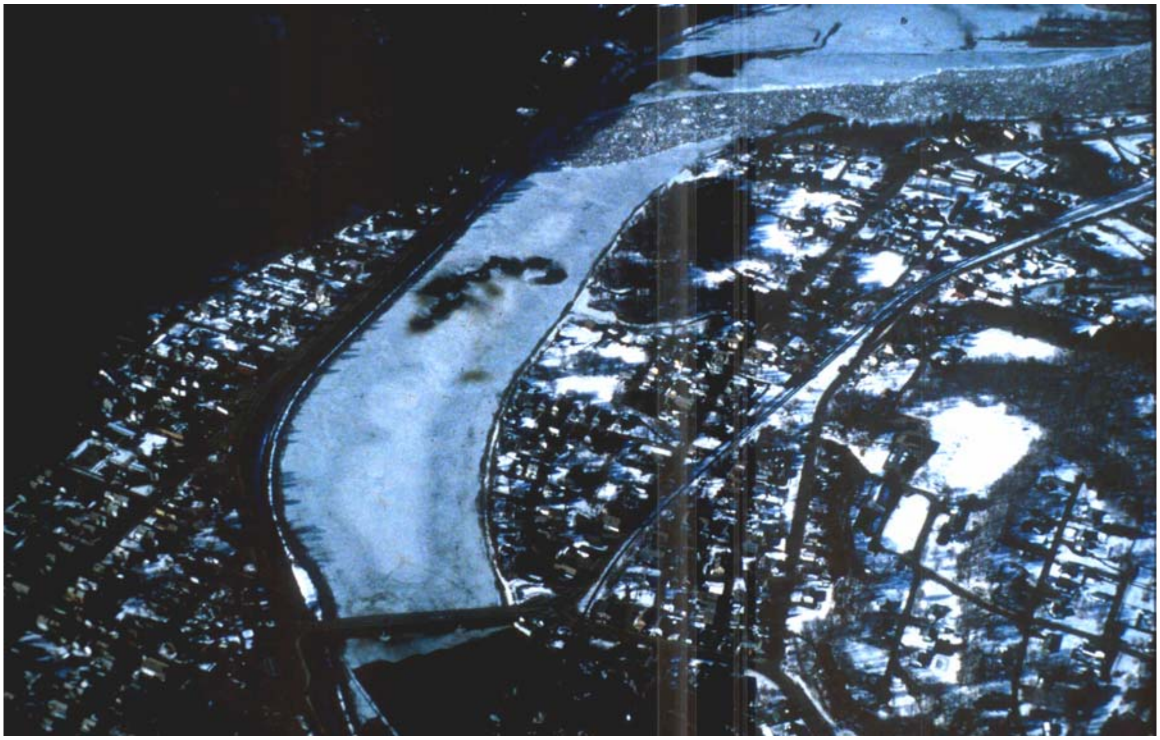

Figure 6. Downstream end of Bellows Falls ice jam on 25 Jan. 1996.

Figure 7. Upstream end of Bellows Falls ice jam on 25 Jan. 1996. Charleston, NH is on the right.

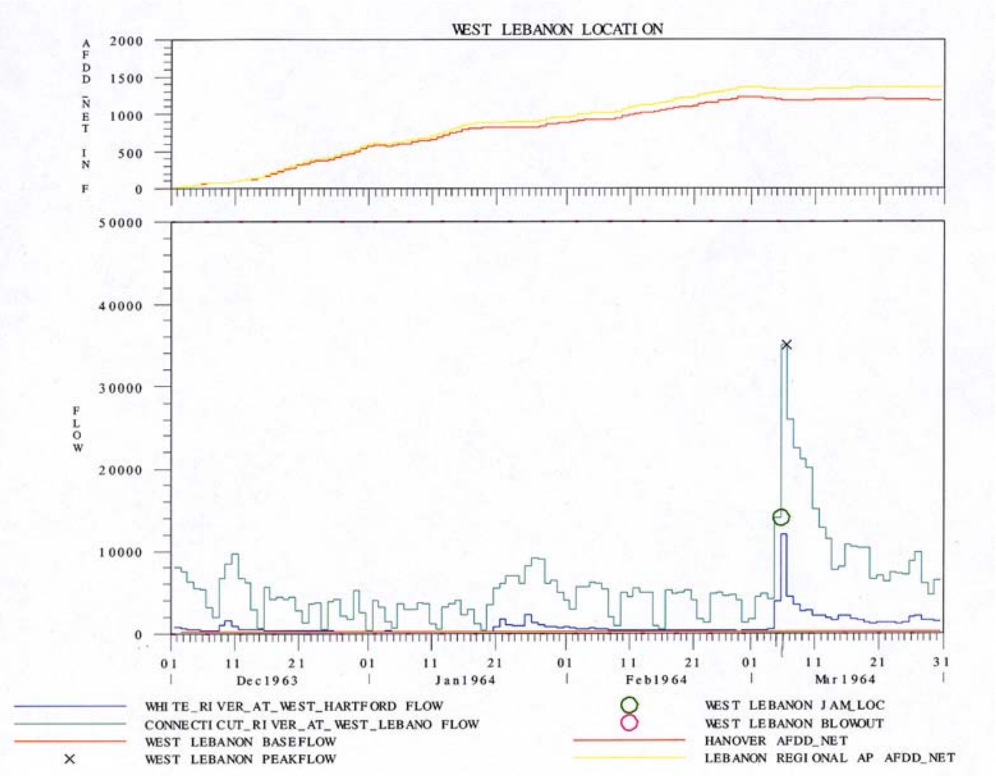

Figure 8. Hydrometeorological plots for West Lebanon, NH, Water Year 1964.

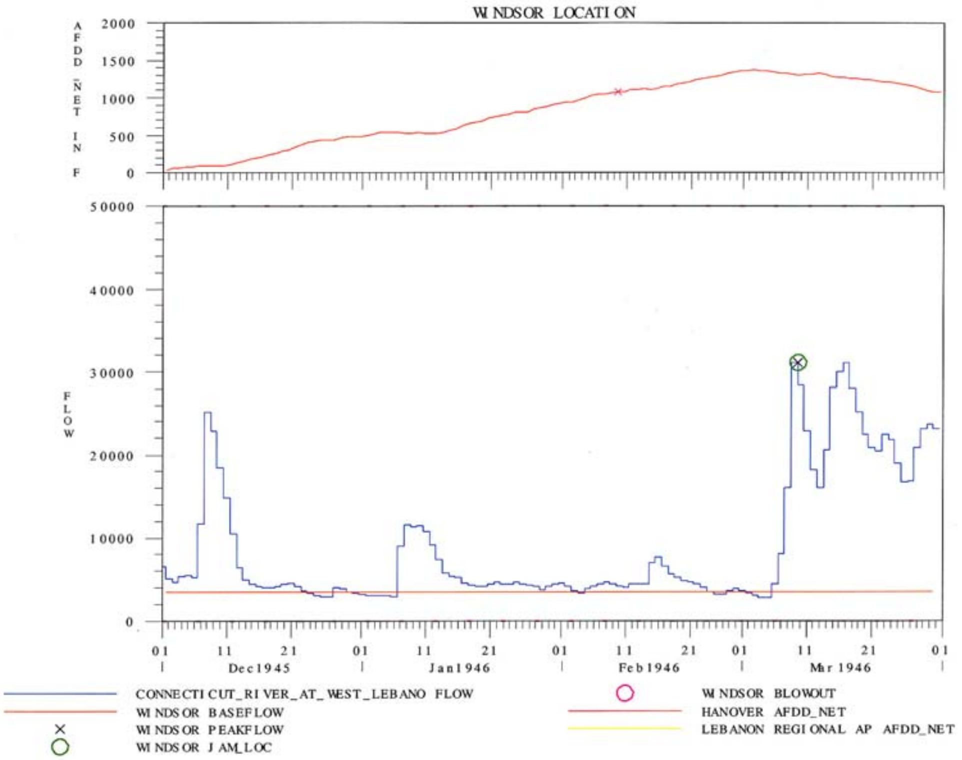

Figure 9. Hydrometeorological plots for Windsor, VT, Water Year 1946.