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Ice Impact Evaluation for the Lower Connecticut River

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The Connecticut River within Hampden County in Massachusetts, and Hartford and Middlesex Counties in Connecticut, is the subject of a Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) update as part of the FEMA Map Modernization Program. Significant ice jams on the lower Connecticut River are the basis of a FEMA request for a detailed review of historical events to determine whether they should be included in the updated hydraulic analysis. An extensive look into historical ice events on the lower Connecticut River found 15 recorded jams. The conditions that led to the known events were analyzed to develop an understanding of the ice jam characteristics along this reach. Ice-affected stage frequency was analyzed at Hartford and Middletown, CT, where historical stage data are available, to determine the probability of a significant ice event occurring in any given year. The winter season probability distribution did not affect the combined probability distribution beyond the 10% annual exceedence probability. The winter season probability distributions and peak ice-affected stages reported at other locations were compared to recurrence interval flood levels taken from the FIS flood profiles. In no instance did the ice-affected stage surpass the 1% annual probability (100-year return period) flood. The 10% annual probability flood stage was exceeded at two locations.

1.0 Introduction

The Connecticut River within Hampden County in Massachusetts, and Hartford and Middlesex Counties in Connecticut is the subject of a Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) update as part of the FEMA Map Modernization Program. In the past, this 83-mile-long reach of river between Holyoke, MA, and the mouth of the river has experienced significant ice jams and ice jam flooding, however, the existing flood insurance studies address open water flooding only. Concerns that ice jams on the lower Connecticut River could significantly alter the peak water surface elevations for the 1% chance annual exceedence probability (100-year return period) flood led to this study to investigate the impacts of flooding attributable to ice along this reach and to determine whether ice-affected flooding should be included in the updated flood insurance study.

The Connecticut River begins in northern New Hampshire and flows about 390 miles southward, forming the border between New Hampshire and Vermont, before flowing across Massachusetts and Connecticut and emptying into Long Island Sound. The watershed encompasses approximately 11,250 square miles of land within these four states. In the middle part of the last century, flood control projects were constructed on major tributaries of the Connecticut River to reduce main stem discharge during large runoff events (USACE 1966). Fairly small increases in discharge, however, can cause thick ice covers along the river to break up and form ice jams, resulting in rapid upstream stage rise and damaging floods.

2.0 Method

Flooding caused by ice jams on the Connecticut River in Hampden, Hartford and Middlesex Counties was evaluated by completing the following tasks:

- Review historical ice jam events to identify common ice jam locations, dimensions, causes, frequency, extent of flooding, and other contributive factors.
- Compile and plot historical discharge, air temperature, and calculated ice thickness for winter months over the period of record.
- Identify probable ice jam events using specific test criteria developed from historical ice jam information and hydrometeorological data.
- Estimate to what extent ice jams could significantly impact peak water surface elevations for various return period floods presented in FEMA flood insurance studies.

To compare the impacts of ice-related flooding to open-water flooding, ice-affected stage frequency distributions were developed at two gage sites along the reach. Historical stage data at Hartford and Middletown, CT, were divided into peak winter season and peak open water populations. Probability distributions were developed for each season and combined into an annual peak stage frequency distribution. These results were compared to the calculated open-water return interval flood levels, taken from the original FIS flood profiles.

3.0 Overview of Ice-Affected Stage Frequency

To determine what impact ice-affected flooding will have on the lower Connecticut River flood analysis, it is necessary to establish a stage-frequency relationship for ice jam events. For open-water events, standard methods exist for developing stage-frequency distributions from historical discharge data (e.g., Water Resources Council 1982, Schuster and Yakowitz 1985, Adamowski 1985, Hydrologic Engineering Center [HEC] 1992). On northern rivers, flood stage resulting from ice jams often exceeds open-water stage for the same discharge. To establish a flood profile at a location prone to significant ice events, it is necessary to determine the stage resulting from ice jam events.

In open-water flow, there is generally a correlation between discharge and stage, from which stage-discharge rating curves can be developed. In contrast, very high stages associated with ice-affected flooding can occur at relatively low discharges. An ice jam impedes flow by changing the hydraulic conditions (i.e., roughness coefficient, hydraulic radius, and flow area), causing water to back up behind the jam and localized flooding to take place. Ice jams can happen rapidly and cause significant damage at discharges that would not result in flooding without the presence of ice. However, at high discharge levels, the ice jam becomes unstable and eventually fails, returning the river stage to open-water levels. As a result ice-affected flooding impacts only a portion of the stage-frequency distribution.

The Federal Emergency Management Agency (FEMA) provides two methods for developing ice-affected stage-frequency relationships: the direct method and the indirect method (FEMA 1995). The direct method is used when sufficient historical stage data are available at the ice jam location. At least three significant ice jam events and 25 years of historical stage data are necessary to perform the analysis. To develop an ice-affected stage-frequency distribution using the direct method, the water year is separated into winter and open-water seasons. A peak annual stage for each season (two per year) is determined when data are available. Probability distributions are developed for each season by assigning Weibull plotting positions to each point. The annual peak stage probability distribution (P_c) is determined for each location by combining the two seasons:

$$P_c = P_{ow} + P_w - (P_{ow})(P_w) \qquad (1)$$

where P_{ow} is the open water season peak stage probability distribution, and P_w is the winter season peak stage probability distribution.

When only annual maximum stage data are available, the peaks are separated into winter and open-water season events. The winter season probability distribution (P_{wp}) is multiplied by the fraction of the total record that the winter season peaks represent, by:

$$P_w = (n_w / N)(P_{wp}) \qquad (2)$$

where n_w is the number of annual peak stages occurring during the winter and N is total number of years that annual peak stage data are available. A similar formula is used to determine the open-water season peak stage probability distribution. The two seasons are then combined to form the annual peak stage probability distribution using equation 1.

The indirect method is used when sufficient historical stage data are not available. In this method, a standard step-backwater analysis is conducted to develop a discharge-frequency relationship at each cross section along the reach. The water year is again separated into winter and open-water seasons and a stage-discharge relationship is developed for each season at each location. Peak winter season discharges are modeled assuming an ice cover is in place. The combined annual peak stage probability distribution is then determined using equation 1.

Peak winter stage could be the result of a jam or an open-water event. Based on extensive research, CRREL has modified these approaches by separating the winter season peak stages into jam, no-jam events based on a set of ice jam criteria. The ice jam criteria are developed from historical ice event information, including estimated ice thickness from accumulated freezing degree days (AFDD) and daily discharge data. The jam and no-jam events are assigned Weibull plotting positions and multiplied by the fraction of total winter events that each type represents. The combined winter season probability distribution (P_w) is determined by combining the probability distribution for the jam (P_{wj}) and no-jam (P_{wnj}) events, using:

$$P_w = P_{wj} + P_{wnj} \quad (3)$$

As an initial investigation into the impacts of ice on the lower Connecticut River, the CRREL-modified direct method was used to develop ice-affected stage-frequency distributions at two USGS gage sites along the reach: Hartford and Middletown, CT. At both of these locations several ice jam events have been recorded and historical stage data are available. The results of this investigation were used to determine whether a more detailed analysis, using the indirect method to develop stage-frequency distributions for additional locations, is necessary.

4.0 Historical Ice Events on the Lower Connecticut River

Ice-affected stage frequency analysis requires recorded ice event information. Ice jams are highly localized and can be triggered by such factors as changes in river slope or configuration, bridges and other structures obstructing flow, or upstream jam releases. Temperature and discharge also contribute to ice jam formation, all of which makes them difficult to predict without prior observations. Often historical ice event data are not readily available or reported. One reason for the under-reporting of ice events involves *perception stage* (Gerard and Karpuk 1979), which is defined as the minimum stage at which a source will perceive an event. If an ice jam occurs, but does not exceed the perception stage, the event is not reported by most observers. The USGS reports peak annual stages in its annual gage summary, *Water Resource Data* books. USGS gage information is generally held to be a highly reliable indicator of stage. However, if an open-water event resulted in a greater stage than an ice event occurring in the same water year, the ice event might not be included. In some cases, it is not specified whether the annual peak stage is attributable to an ice-related or open-water event and some analysis of the data is required. Another reason for an ice jam to go unreported is if the location is particularly rural and structures or roads are unaffected by any flooding.

This study used various sources to gather ice event information on the lower Connecticut River. The CRREL Ice Jam Database (White 1996) holds over 14,000 records and is a good source of information for ice analyses. All of the historical ice jams used in this study were obtained from the IJDB. Additional sources, including the United States Geological Survey (USGS), Connecticut Department of Environmental Protection (CT DEP), and local newspaper accounts, were searched but no additional ice jams were found. For this study, it is assumed that a number of lesser magnitude ice events have occurred that were not reported. Figure 1, a map of the study area, shows the ice event locations as well as the discharge and temperature gages used in the study.

The review of historical events found 15 ice jams reported since 1910 on the Connecticut River south of Holyoke, MA (Table 2). Two significant events were responsible for 10 of the 15 jams. A January thaw in 1910 caused rivers to rise and breakup jams to form in at least five places along this reach. Another major ice event in March 1936 caused jams in five additional locations, before the major open water floods that occurred about a week later. These events are described in detail below. Of the 15 recorded jams, an ice jam in Hartford, CT, in 1996 was the only one to occur after 1957. Flood control structures built after significant floods in the early part of the century are one possible explanation for the lack of recent ice jams. Natural conditions may have become less conducive to ice jam formation along the study reach in recent years. In addition, operation of the Millstone Nuclear Power Generating Station in Waterford, CT, may have affected the downstream ice regime owing to a slight elevation in temperature of the receiving waters beginning in 1970.

5.0 Review of Hydrological and Meteorological Data

River stage data were obtained from USGS gages. The Thompsonville gage, located north of Hartford on the Connecticut River, has a long period of record, 1928–present. The gage in Holyoke, MA, has reported peak annual and daily river discharge data since 1983. The Hartford, CT, gage has been reporting daily average discharge since 1996 and peak annual data dates back to 1828. At Middletown, annual peak discharge and stage data are available since 1927. The USGS provided 15-minute stage data for Middletown, CT, from 1996 to the present and stage-discharge rating curves for the Middletown, Hartford, and Holyoke gages. Additional daily river stage data for Holyoke, MA, and Hartford, CT, were found in *Daily River Stages for Principal Rivers of the United States* (USDA, 1910–1947).

Daily maximum and minimum air temperature data were retrieved from National Weather Surface (NWS) meteorological stations. Temperature data were used to estimate ice thickness along the Connecticut River based on accumulated freezing degree days (AFDD) (White 2004). Owing to its long period of record, the Hartford, CT, station was the primary source used in this analysis. For earlier years, the Storrs, CT, station provided a reasonable estimate of AFDD.

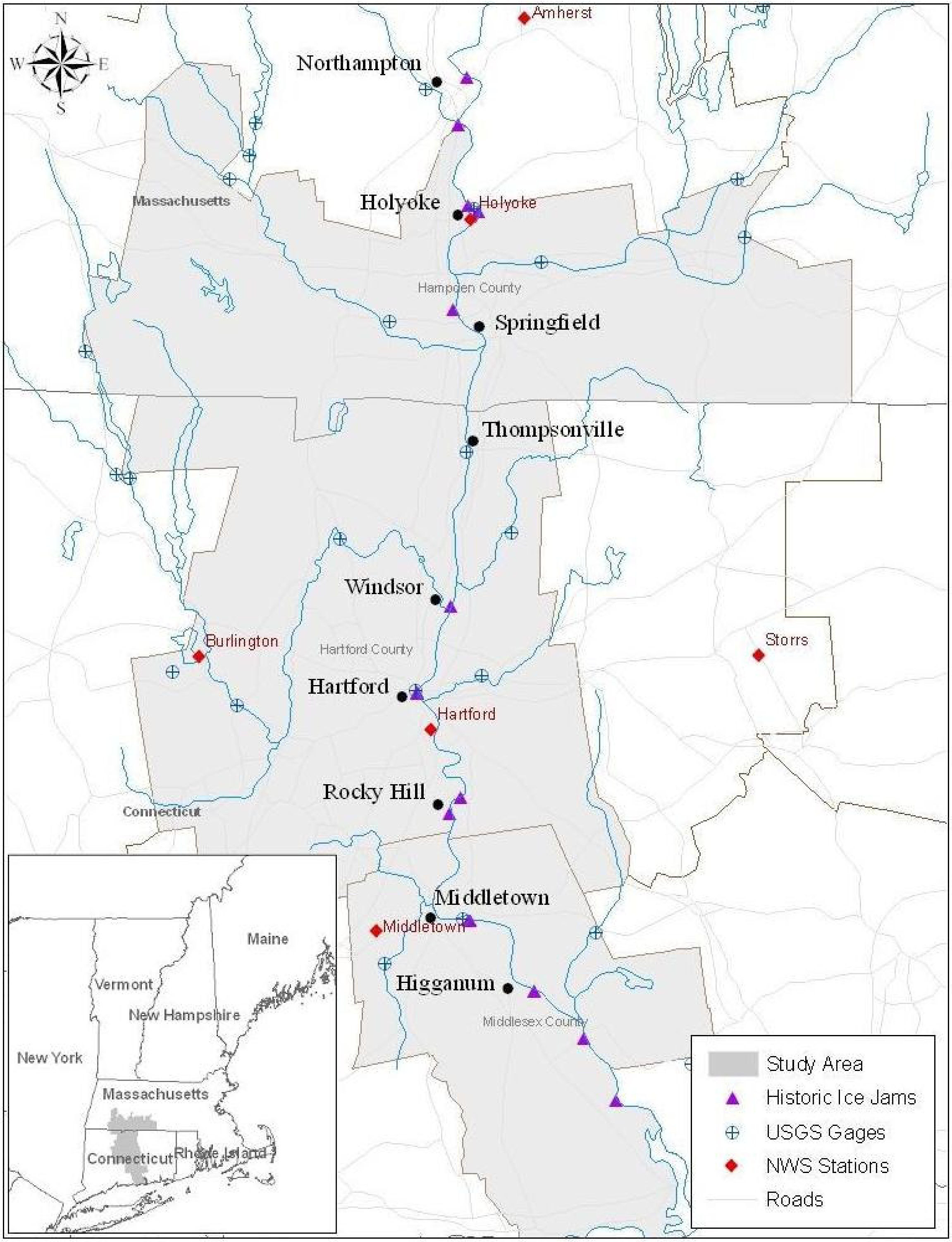

Figure 1. Study Area.

River discharge and temperature data, along with the historical ice event information, were used to develop jam criteria for the lower Connecticut River. Table 1 shows the

USGS and NWS gages used in this study and their periods of record. A summary of all the ice events and the hydrometeorological data associated with each is given in Table 2.

Table 1. Available meteorological and hydrological data on the lower Connecticut River

Station	Drainage Area (m^2)	Data Type	Source	POR
		Annual Peak Flow	USGS	1983–2003
		Daily Flow	USGS	1983–2003
Holyoke, MA	8,332	Daily River Stage	USGS, USDA	1910, 1928–47
Thompsonville, CT	9,660	Daily Flow	USGS	1928–2003
		Annual Peak Flow	USGS	1828–2003
		Daily Flow	USGS	1996–2003
Hartford, CT	10,487	Daily River Stage	USGS, USDA	1910, 1928–47
		Annual Peak Flow	USGS	1927–2003
Middletown, CT	10,887	15-min River Stage	USGS	1997–2004
Hartford, CT		Temperature	NWS	1920–2004
Storrs, CT		Temperature	NWS	1888–2002

5.1 Estimation of Ice Thickness

Ice growth on a water surface is a function of heat transfer at the ice/water interface. Ice thickness can be estimated on a given date during the winter using temperature data in the months leading up to this date. Freezing degree-days (*FDD*) represent the difference between the average daily air temperature (T_a) and 0°F, where temperature below freezing is positive and a temperature above freezing is negative. FDD can be calculated by:

$$FDD = (32 - T_a) \tag{4}$$

The net accumulation of FDD (*AFDD*) over a winter season is a good indicator of winter severity. Accumulation begins in the fall when temperatures drop below freezing. AFDD can provide an estimate of ice thickness (t_{ice}) in inches on a particular day using the modified Stefan equation presented in USACE (2002):

$$t_{ice} = C\sqrt{AFDD} \tag{5}$$

where C is a coefficient, usually ranging between 0.3 and 0.6, and AFDD is in °F-days. A coefficient of 0.37 was determined from ice thickness measurements on the Connecticut River between Vernon and Wilder Dams (Tuthill et al. 2004). Photos taken by the Connecticut Department of Environmental Protection during the 1996 event in Hartford confirmed that this was a reasonable value for C. While this method provides a reasonable estimate, it is important to note that the ice thickness may be underestimated because of other factors, such as water velocity and the presence of a snow cover on top of the ice. Additionally, frazil ice deposition under an ice cover can contribute to ice thickness.

Table 2. Recorded historical ice events on lower Connecticut River.						
Date	**Location**	**Description**	**Max Stage (ft)**	**AFDD**	**Estimated Ice Thickness (in)**	**Q (cfs)**
23Jan1910	Middletown, CT	Jam occurred 22 Jan at Bodkin Rock and other locations. Blowout on the 23rd. Buildings, boats, and trees carried down with ice	13.0	297.5*	6.38	105,000[a]
24Jan1910	Hartford, CT	Boats and possibly lives lost.	19.5	297.5*	6.38	95,000[a]
24Jan1910	Rocky Hill, CT	Jam below town. Some boats and a scow lost.		297.5*	6.38	95,000[a]
24Jan1910	Higganum, CT	Jam at Rock Landing. No damages reported.	11.0	297.5*	6.38	105,000[a]
24Jan1910	Deep River, CT	Jam between island and west shore. Boats lost.		297.5*	6.38	105,000[a]
05Jan1928	Hartford, CT	Ice gorge 10 miles below Hartford	12.9	125.0	4.14	31,000[a]
12Mar1936	Higganum, CT	Flooding in several homes.	12.0	567.5	8.81	57,400[b]
13Mar1936	Holyoke, MA	Jam at Mt. Tom Junction. Tightly packed jam forced water to flood Hockanum Meadows. Blowout occurred on 15 Mar	9.5	560.5	8.76	61,900[b]
13Mar1936	Windsor, CT	Jam formed at junction of Connecticut and Farmington Rivers. Summer cottage carried away.	20.0	560.5	8.76	98,600[b]
13Mar1936	Hartford, CT	Jam at Bulkeley Bridge.	22.4	560.5	8.76	98,600[b]
08Jan1938	Middletown, CT	Jam at Bodkin Rock. Tugs used to break through ice.	0.0	173.5	4.87	18,700[b]
21Dec1945	Holyoke, MA	Jam downstream from Holyoke gage	2.7	222.0	5.51	10,500[b]
01Mar1947	Springfield, MA	Jam upstream from Springfield gage	4.5	489.5	8.19	10,300[b]
25Jan1957	E. Haddam, CT	Jam extends from E Haddam bend upstream to Rock Landing. Coast Guard ice breaker used to break through		253.0	5.89	41,100[a]
07Feb1996	Hartford, CT	Jam between Founders and Bulkeley bridges.	10.9	518.5	8.43	38,000[c]

* Temperature data from Storrs, CT, station (All other temperatures from Hartford, CT, station).
[a] Discharge estimated from rating curves.
[b] Discharge from Thompsonville gage.
[c] Discharge from Hartford gage.

6.0 Ice Jam Criteria for Hartford and Middletown

Ice jam criteria were established for two USGS Gage locations along the Connecticut River: Hartford and Middletown, CT, and are detailed below. Hydrometeorological conditions that were found to contribute to ice jam formation at these locations were based on the recorded ice events and historical discharge and temperature data. Experience in other locations has shown that the higher-magnitude, low frequency events of the type identified in Table 3 are not the only ice jams that occurred. The criteria established were used to uncover ice events that may have been below perception stage. Criteria used to identify possible ice events were based on the time of year, minimum and maximum discharge, and ice thickness. The winter season was considered to be 01 January through 31 March, which is consistent with when a solid ice cover will be in place at these locations.

6.1 Hartford

In Hartford there are two scenarios favorable to the formation of ice jams. The first situation occurs when an ice cover on the order of 6–8 in. thick exists and discharge rises significantly over a 3–5 day period. This took place during the 1910 and 1936 events. During the few days leading up to the jams, the flow increased by at least 85,000 cfs, causing the ice cover to break up and jam downstream. At about 120,000 cfs, the ice accumulation is no longer capable of withstanding the force of the upstream backwater and the jam releases suddenly.

The second ice jam scenario at Hartford occurs when the discharge increases by 18,000 to 20,000 cfs, within a short period of time (e.g., 1–2 days). This took place during the 1996 event in Hartford and the 1928 event just downstream of Hartford, in Rocky Hill.

The test criteria determined for Hartford are:

- Ice jam period of 1 Jan–31 March.
- Ice thickness at time of break-up > 4 in.
- No previous breakups have occurred within 30 days.
- Discharge > 31,000 and < 120,000 cfs.

6.2 Middletown

In Middletown, the highest reported stage of 13 ft occurred during the 1910 event. Ice tends to jam just downstream of the city at Bodkin Rock, where the channel narrows. Reported discharge during peak winter events was used to determine the discharge criteria.

The test criteria determined for Middletown are:

- Ice jam period of 1 Jan–31 March
- Ice thickness at time of break-up > 4 in.
- No previous breakups had occurred within 30 days.
- Discharge > 54,000 and < 106,000 cfs.

7.0 Estimating Stage Frequency at Hartford and Middletown

A peak stage probability distribution was developed for peak annual winter and open-water season events for each year that peak stage data were available. In Hartford, annual peak winter and open-water season stages were determined for 75 years of record, 1910, 1928–2002. During these years, temperature and discharge data were available to select possible jams during winter peak events.

For Middletown winter and open-water seasons, peak stages were determined for each year since 1997 when consistent stage data are available. Annual peak stage data, from 1936– 1997, were sorted into either winter season or open-water season events. As either season is based on only a portion of the total record, the probabilities had to be adjusted to represent the entire period of record, as described above. The winter season events were sorted, based on the criteria, into jam and no-jam subpopulations. Figures 3 and 4 show the jam and no-jam peak stage probability distributions with the combined winter peak stage probability distributions (P_w) at Hartford and Middletown, respectively.

A peak annual stage probability distribution was created by combining the winter season and open water seasons together. The combined annual stage-frequency distribution for Hartford is presented in Figure 4, along with the open-water and winter season distributions. Figure 5 is a similar plot for the Middletown results. Note that ice-affected peak stage does not affect the combined probability distribution beyond the 10% chance of exceedence at either location.

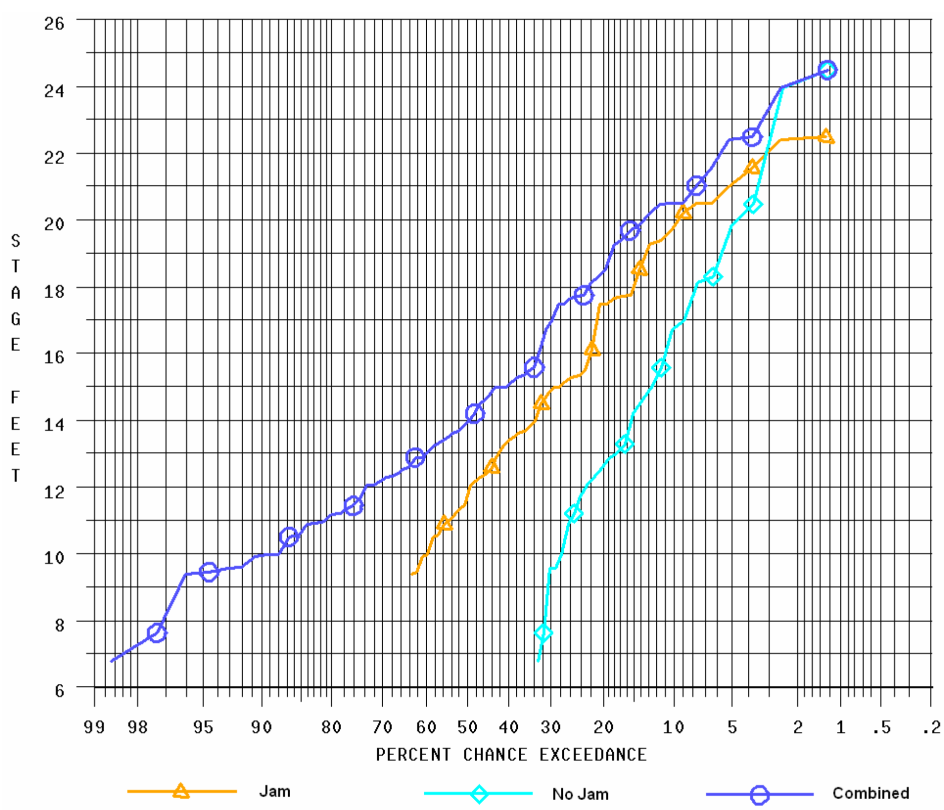

Figure 3. Hartford winter season peak stage probabilities.

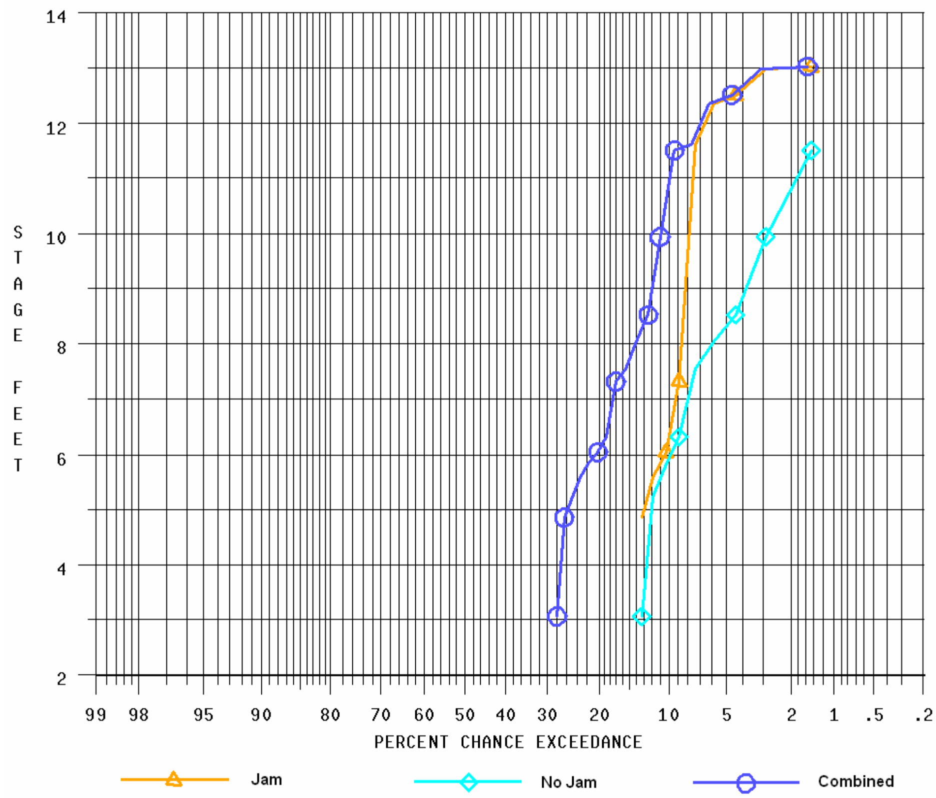

Figure 4. Middletown winter season peak stage probabilities.

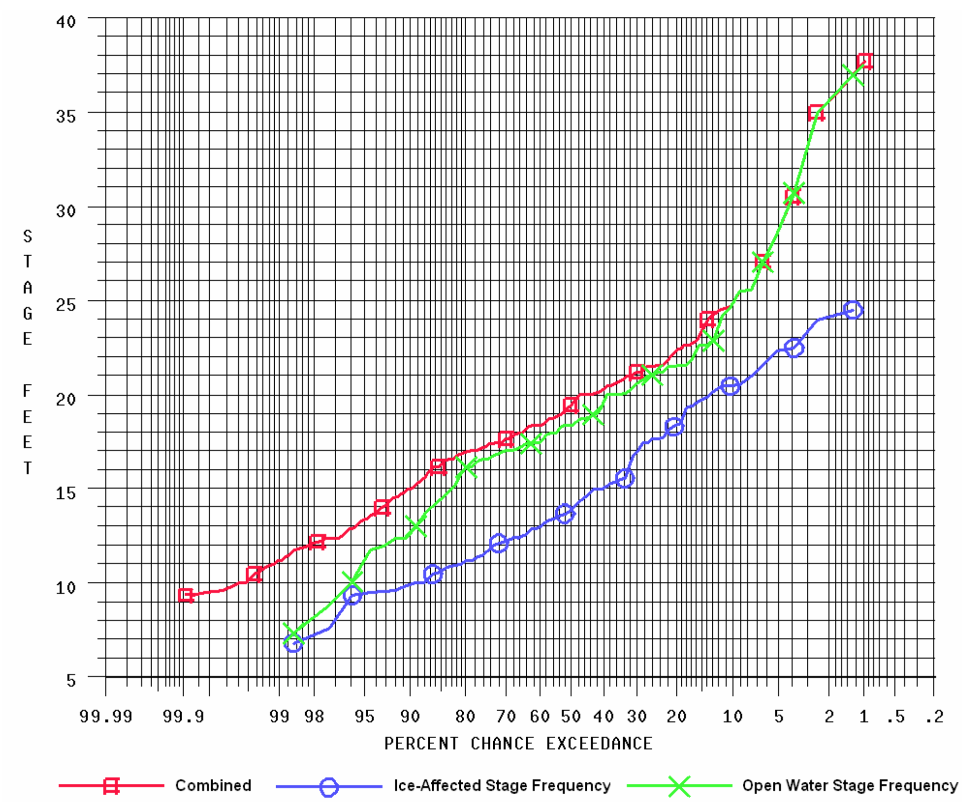

Figure 5. Hartford annual peak stage probability distribution.

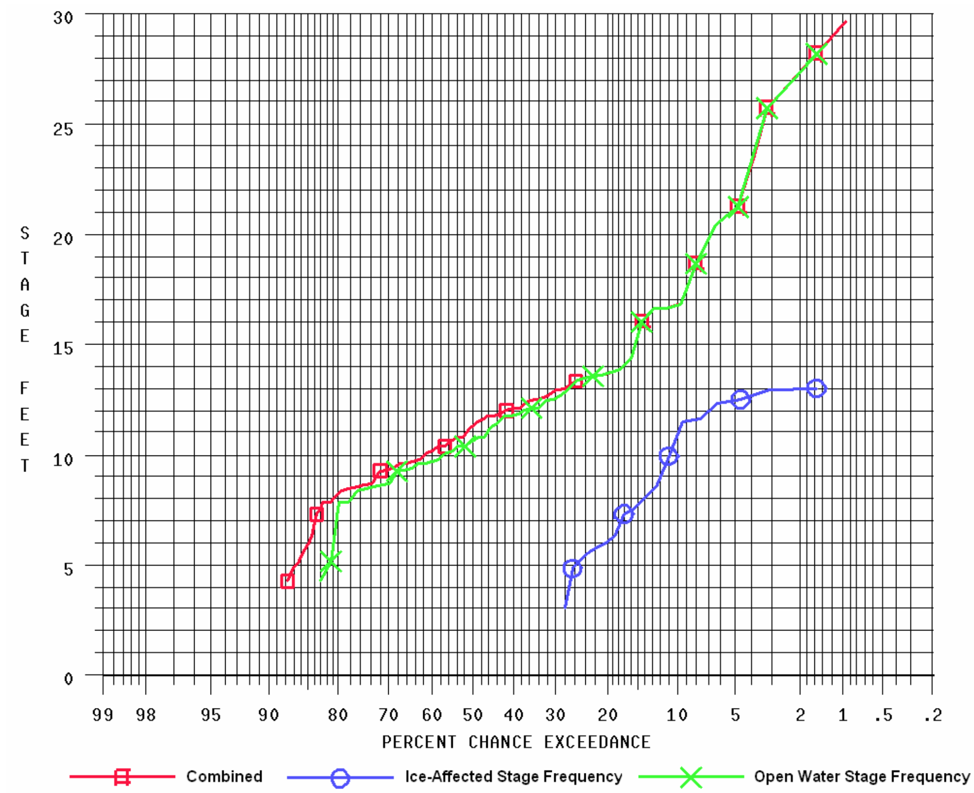

Figure 6. Middletown annual peak stage probability distribution.

8.0 Comparison to FIS return interval flood elevations

The winter season probability distributions at Hartford and Middletown were compared to FIS return interval flood profiles. The 1% chance annual winter event at Hartford reaches a stage of 24.5 ft, which is greater than the FIS 10-year flood elevation. Ice jam criteria at Hartford predicted that the larger winter events were not caused by ice. These events were likely included in the original flood insurance study as open-water events and then reduced as described above. No ice-affected peak stage exceeded the FIS return interval flood levels. The Middletown winter peak stage probability distribution had no impact on the FIS return interval flood levels.

Table 4 compares the highest recorded stage at locations along the study reach to the FIS 10-, 50-, 100- and 500-year stage, which were taken from the flood profile charts. Of the locations where a stage value is available, two have experienced flooding greater than the 10-year level. During the 1936 event, water and ice from the blowout of a jam in Holyoke flowed 9.5 ft above the crest of the dam, where the 10-year flood level is 9 ft. In Higganum the ice-affected stage reached during the 1936 event was estimated using USGS topographic maps and the description of the flooding. The historical record seems to support the conclusion that flood levels exceeded the 10-year return interval open-water flood stage. No ice jam location observed a water surface elevation higher than the 50-year open-water level.

Table 4. Comparison of ice-affected and open-water flood stage.					
Location	Highest Recorded Stage	10-year	50-year	100-year	500-year
Higganum	12.0	11.0	14.7	16.3	19.0
Middletown	13.0	15.0	19.5	21.2	24.7
Hartford	22.4	23.2	28.0	29.8	33.4
Holyoke	9.5	9.0	12.0	13.5	17.0

9.0 Summary

This study analyzed the impacts of ice jams on peak water surface elevations along the lower Connecticut River, from Holyoke, MA, to the mouth to determine whether updates to the FEMA Flood Insurance Studies on this reach should include ice. To do this, historical ice events on the lower Connecticut River were thoroughly reviewed. Historical discharge and temperature data were also collected and used to determine under what conditions ice jams are likely.

An ice-affected stage frequency analysis was completed at Hartford and Middletown, CT, where several there have been significant ice events and where historical stage data exist. Both locations experienced jams during the largest ice events recorded on the lower Connecticut River, 1910 and 1936. To understand the significance of these events, the ice-affected probability distributions were compared to the FIS return interval flood levels at these two locations. In neither location did the winter season probability distribution impact the FIS flood profile above the 10% chance annual flood event.

Additional locations along the study reach reported peak stages during ice events. These water surface elevations were compared to FIS open-water flood levels. In two locations the ice-affected stage has exceeded the 10-year open-water stage. In no locations has the ice-affected stage ever topped the 50-year or greater open-water events. To fully understand how ice impacts the probability distribution at these locations for smaller, more frequent events, a more detailed hydraulic analysis is required.

This report finds that ice jams along the lower Connecticut River do not significantly impact the 1% chance annual peak water surface elevation. Ice jams do occur on the Connecticut River below Holyoke, MA, and can cause considerable damage to stream banks and infrastructure. However, flooding during open water events has historically been far in excess of flooding caused by ice jams.

Acknowledgements

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