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Dam Removal Ice Hydraulic Analysis and Ice Control Alternatives

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Removal of many dams in the United States are being considered, often as a means of improving habitat and increasing spawning ground for migratory fish species. Investigation of the impact of such dam removals on the local ice regime is important in areas where river ice jams are a concern. Ballville Dam, on the Sandusky River in Ohio, US, is a 10.5-m-high concrete structure, located 2.5 km upstream of the city of Fremont, which is being considered for removal, particularly to increase spawning grounds for the walleye. Because Fremont is located where the Sandusky River transitions into the backwater of Lake Erie, the town has experienced many ice jam floods, some very severe. A recent study by Vuyovich (2008) found that the dam has most likely reduced the frequency of ice jam floods at Fremont and recommended further investigation to quantify the that risk for existing dam-in and dam-out conditions.

In the current study, a hindcasting analysis is conducted and the results are used to determine combined probabilities of paired breakup discharge and ice thickness associated with severe ice events. Based on the above analyses, combinations of ice jam volume and breakup discharge are used to define recurrence intervals for simulated ice jam profiles under existing and dam-out conditions. For selected recurrence intervals, the HEC-RAS model is used to simulate ice jam profiles and develop stage frequency relationships at key locations. Comparison of these stage frequencies with and without the dam in place is used as a guide in the selection of potential ice control alternatives. A discussion of the success of several recent ice control alternatives in place in the US will also be presented.

1. Introduction

Interest in dam decommissioning, including dam removal, has increased significantly throughout the United States over the past 20 years as older dams reach the end of their design life, and awareness of environmental, recreational and economical issues concerning dams increases Before a dam can be decommissioned an analysis of the hydraulic impacts is often necessary. Dams alter the natural conditions of a river by changing the timing and peak values of flood hydrographs, causing sediment to accumulate in the impoundment, and impacting the ice regime (White and Moore 2002). As most dams remain in place for decades, the geography of the surrounding land, the habitat of the stream, and the population that lives along the river adjust to the new conditions. Removing a dam can result in a possible increase in ice jams, flooding or sedimentation in downstream areas. These effects need to be well understood prior to removal to prepare for and minimize future damages.

There are a number of examples of dam removals impacting and increasing the frequency and severity of damaging ice jam floods (Tuthill and White 1997, White and Moore 2002, Vuyovich and White 2006, Tuthill et al. 2007). One important way dam removal can modify the river ice conditions is by allowing ice at breakup to travel farther down river. Ice that was held upstream of the dam, either by the dam itself or by the solid ice cover formed on the impoundment, can contribute to ice jams downstream. As a result, development and infrastructure, such as bridges, may be susceptible to ice damage. Another way dam removal can affect river ice conditions is to increase frazil ice volume in downstream reaches (White and Moore 2002). Frazil ice is formed in steep turbulent reaches at sub-freezing temperatures. As they drift downstream, the frazil ice crystals adhere to each other and form "flocs" or slush which develop into larger floes. Frazil slush and floes may transport and deposit beneath the thermally grown ice, thickening and strengthening the ice cover, or they may accumulate upstream of the thermal ice in the form of a freezeup ice cover or ice jam. This common dynamic ice forming process is known as ice cover progression. The pools upstream of dams are favorable locations for frazil ice to accumulate on steep rivers. Once a dam is removed, the frazil ice can be transported farther downstream until another thermally grown ice cover is encountered. Significant frazil ice accumulations can result in freeze-up jams (USACE 2002).

2. Site Description and Data

Removal of the Ballville Dam (Figure 1) on the Sandusky River in Ohio is being considered as a means of improving habitat and increasing spawning ground for migratory fish species, particularly walleye. This 35-ft-high concrete structure, located 1.5 miles upstream of the Fremont, OH was built in 1911. Because Fremont is located where the Sandusky River transitions into the backwater of Lake Erie, the town has experienced many ice jam floods, some very severe. Fremont is located on the Sandusky River where a relatively steep section of river meets the backwater from Lake Erie. This is a location where ice jams can typically be expected. The Ballville Dam, located immediately upstream of the steep section, is ideally located to protect Fremont from damaging ice jams.

Figure 1. Balville Dam near Fremont, OH.

2.1 *Ice Formation on the Sandusky River*

Ice formation on the Sandusky River is heavily influenced by the river's geomorphology and its location in northern Ohio. The Sandusky River flows from south to north, traveling about 127 miles with a mean gradient of 0.00074 ft/ft (Evans et al 2002). The steepest portion of the river is a series of rapids with exposed bedrock between the Ballville Dam and downtown Fremont, with a mean gradient of 0.003 ft/ft. Fremont, OH is located near the downstream end of the Sandusky River, approximately 10 miles before the river empties into the Sandusky Bay of Lake Erie. The water surface between Fremont, OH and the Sandusky Bay is essentially flat, as the backwater from the bay reaches almost all the way to town. The location of Fremont, at the upstream extent of the Sandusky Bay backwater is a likely location for ice jams to occur. A strong, thermal ice cover grows during the winter in the slow-moving backwater of the Sandusky Bay. Frazil ice generated in the steep section between the Ballville Dam and downtown Fremont can accumulate against and deposit beneath the thermally grown ice cover and contribute to the ice thickness in this reach.

In the case of the Sandusky River, the thicker ice in the backwater downstream of town stops the breakup progression and causes a jam to form. As ice accumulates the jam extends upstream, reducing the channel flow area and causing sudden rises in water level. The severity of flooding is a function of the volume of ice contributing to the ice jam, the ice strength, the discharge rate, and the riverbed geometry (USACE 2002). A similar ice formation process occurs behind the Ballville Dam. A thermally grown ice cover forms behind the dam, which is likely thickened by frazil ice from upstream. Break-up ice traveling downstream impacts the solid ice cover and forms an ice jam.

2.2 *History of Ice Jams at Ballville and Fremont*

A recent study by Vuyovich (2008) reviewed historic ice events at Fremont going as far back as 1833 and analyzed causal factors. There are 58 recorded ice events on the Sandusky River near Fremont. Forty-seven jams were reported upstream of the Ballville Dam. Small ice jams have been reported at the United States Geological Survey (USGS) gage upstream of the Ballville Dam on the Sandusky River on average every three years. The orientation of the river, flowing from south to north may contribute to the frequency. Ice formed on the southern, warmer reaches upstream is likely to break up first and flow downstream until it impacts the stronger, intact ice sheet behind the dam. Most ice jams on the Sandusky River are minor and cause little or no flooding.

In historical accounts of ice jams before the dam was in place, ice was described as coming from miles upstream and piling many feet high in Fremont. After the Ballville Dam was constructed, ice upstream of the dam remained in place during the most significant events and did not contribute to the ice jams in town. Prior to construction of the dam small, frequent events were reported downstream in Fremont (Thomas 1913). High water due to ice was recorded five times in downtown Fremont in the 7 years between when the stage gage was installed on the State Street Bridge in 1904 until the Ballville Dam was constructed in 1911. Four ice jams caused extensive damage and flooding in downtown Fremont prior to the dam construction; the jams of 1833, 1843, 1883 and 1904, found. Two major ice jams caused flooding in downtown Fremont after the dam construction; in 1959 (when two separate flooding events occurred) and 1963. In 1972, flood walls were constructed to protect downtown Fremont from flooding and ice jam flooding has not been reported since that time.

2.3 *Hindcasting Analysis*

The major causal factors for severe ice jam formation were investigated for the purpose of discrimination of Ice Jam and Non-Ice Jam Events on the Sandusky River. Daily air temperature and daily precipitation were recorded at National Weather Service Gage 332974 in Fremont from 1901-present (NCDC, 2011). Some high water event stages were also recorded at this gage. Average daily discharge and stage for high water events was recorded at USGS Gage 04198000, Sandusky River at Fremont from 1939-present (USGS, 2011). For each year of flow record the maximum daily winter flow, time to peak of the hydrograph, magnitude of and time since last peak flow, and pre-breakup ice thickness based on accumulated freezing degree-days (AFDD) were analyzed. A hind-casting analysis was used to sort the period of record of Sandusky River discharge and air temperature data into ice jam and non-ice jam winters (Tuthill et al., 1996). T the following criteria were determined:

1. Ice-jam period: December 15 through March 35
2. Average daily flow greater than 9.3 kcfs
3. Ice thickness greater than or equal to 14 inches.
4. Time to peak less than 6 days (base flow to local peak)
5. No local discharge peaks greater than 9.3 kcfs in the previous 14 days

Hind-casting captured all 4 major ice jam events and identified 23 jams and 58 non-jam winter maximums. The probability of an ice jam winter maximum event was therefore 28.4%.

3. Model

The HEC-RAS model was used to simulate ice cover using composite roughness and wide river ice jams by balancing the ice jam force balance equation (USACE, 2008). At each cross-section, the ice cover was defined with a roughness and pre-jam ice thickness. The location of the jam was based on historical information and the length of the jam was simulated to match the pre-breakup ice volume.

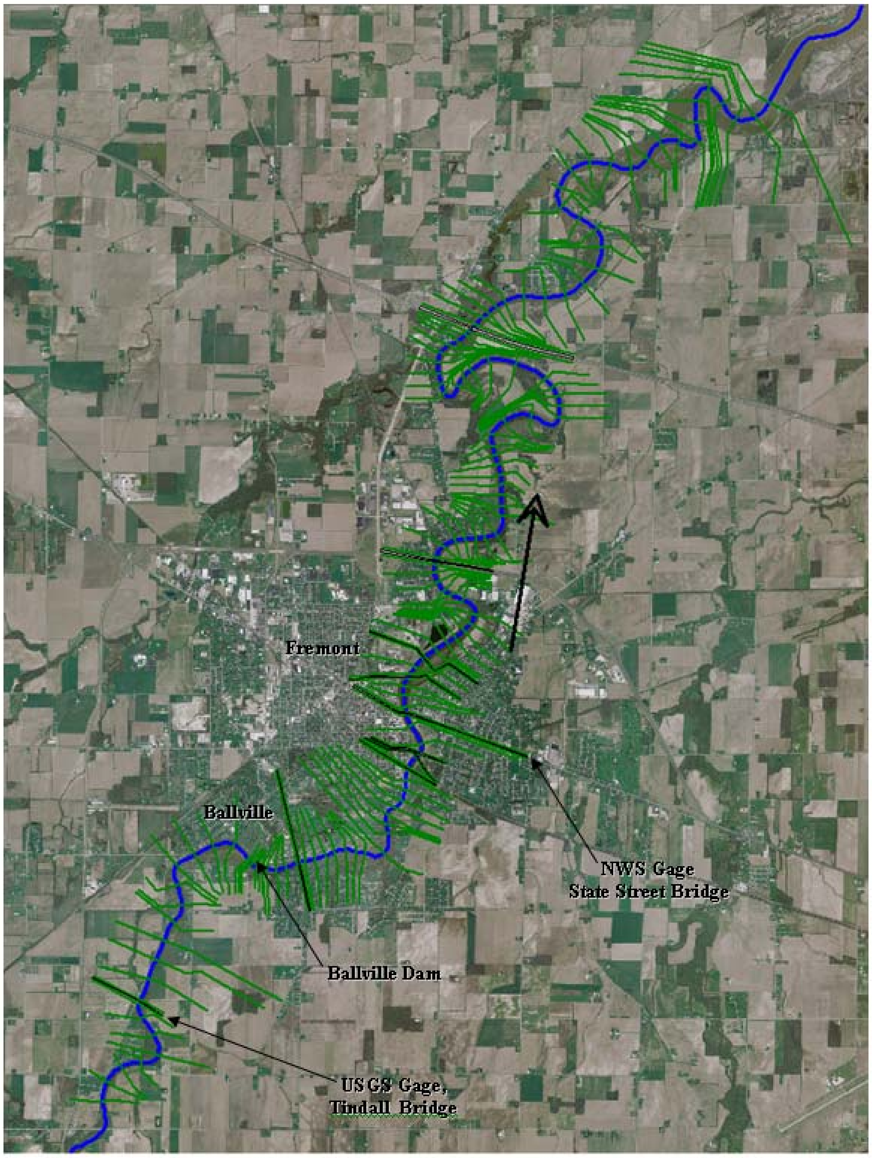

Figure 2. Model Geometry

Buffalo District provided CRREL with HEC-RAS geometry for the Sandusky River (Figure 2). The downstream boundary condition was normal flow with a slope of 0.002. Distance between cross sections was typically 1000 ft with more detail near structures. The model was calibrated to a range of open water flows using USGS gage data and stage data at a NOAA gage at the State Street Bridge.

3.1 *Ice Formation and Pre-breakup Ice Volume*

The history of the freezeup ice regime of the Sandusky River was examined and winter ice cover profiles simulated using the HEC-RAS ice routine. For each ice jam year, freezeup was assumed to occur at or around AFDD = 100 ºF-day, an ice thickness of 6 inches, and a Manning's roughness of 0.012 (White, 1999). The freezeup flow was taken as the average flow from the start of the winter season to the date of AFDD = 100 ºF-day. Velocities for this reach of the Sandusky River range from thermally grown sheet ice velocities less than 1 ft/s in the flat sections downstream of town to close to 5 ft/s in the steeper sections. Freeze-up profiles were calculated for each jam year for both existing dam-in and dam-out conditions (Figure 3). The profiles were used to generate cumulative ice volume vs. river distance to the jam curves for use in the calculation of ice volume supplying breakup ice jams. Because jams upstream of the dam have been described to extend far upstream of the dam and above the upstream end of the model domain, the volume contribution above the dam was estimated from a 0.50 loss coefficient, pre-breakup ice thickness, an average top width of 525 ft, and a contributing river length of 25.3 miles upstream to the next flat section of the river.

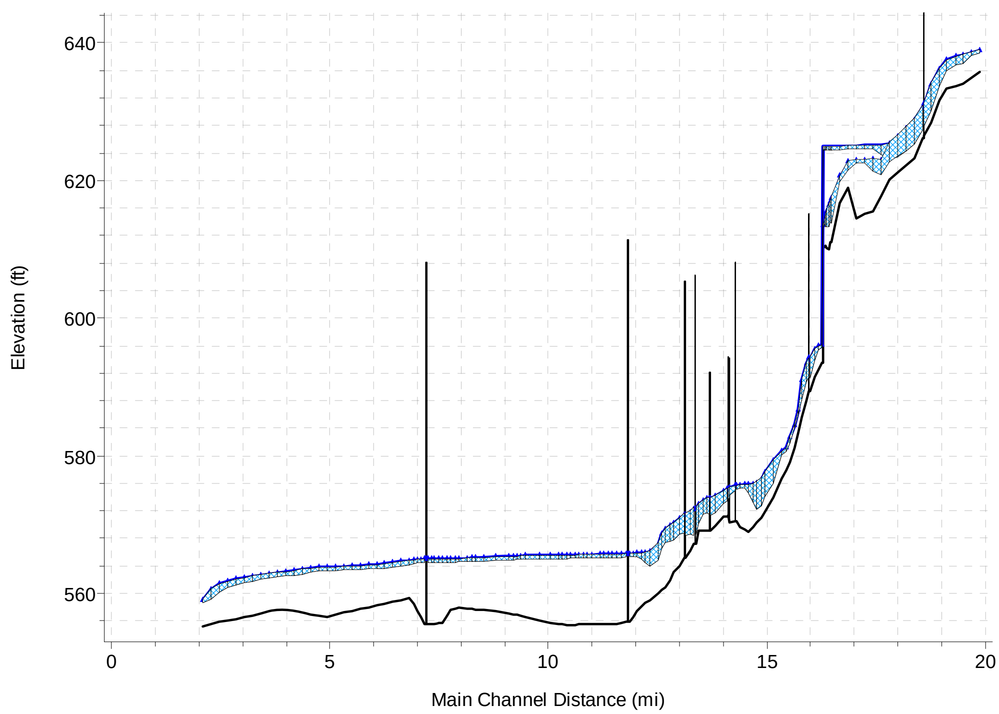

Figure 3. Freezeup Ice Profile, 1959. Upper profile is with dam in place, lower profile is with dam removed, ice shown in hatched blue.

3.2 *Breakup Ice Jam Simulation*

The HEC-RAS model was used to simulate ice jam profiles for existing dam-in and dam-out conditions for the for the 23 jams and 58 sheet ice events of record identified in the hind-casting analysis. The model was calibrated to the stages at State Street and the Fremont gages for severe ice events of 1959 and validated with the event of 1963, for which less data was available. For the existing conditions, a jam was initiated several thousand feet upstream of the dam and another at the historic location about 1 mile downstream of Fremont (RM 10.42). The length of each jam was matched to the appropriate pre-breakup ice volume determined in the ice formation analysis. The calibrated values were 0.07 for Manning's n and 0.49 for loss coefficient

From these simulated ice jam profiles, stage discharge relationships were developed at several key locations for jam, sheet ice and non-ice winter season maximum flows. Figure 4 shows the stage discharge relationship for the with and without-dam condition at the State Street Bridge gage. Typically, the with-dam ice jam curve is on the order of 5.5 ft above the open water winter max curve, and the dam removed ice jam curve is about another 6.5 ft above that.

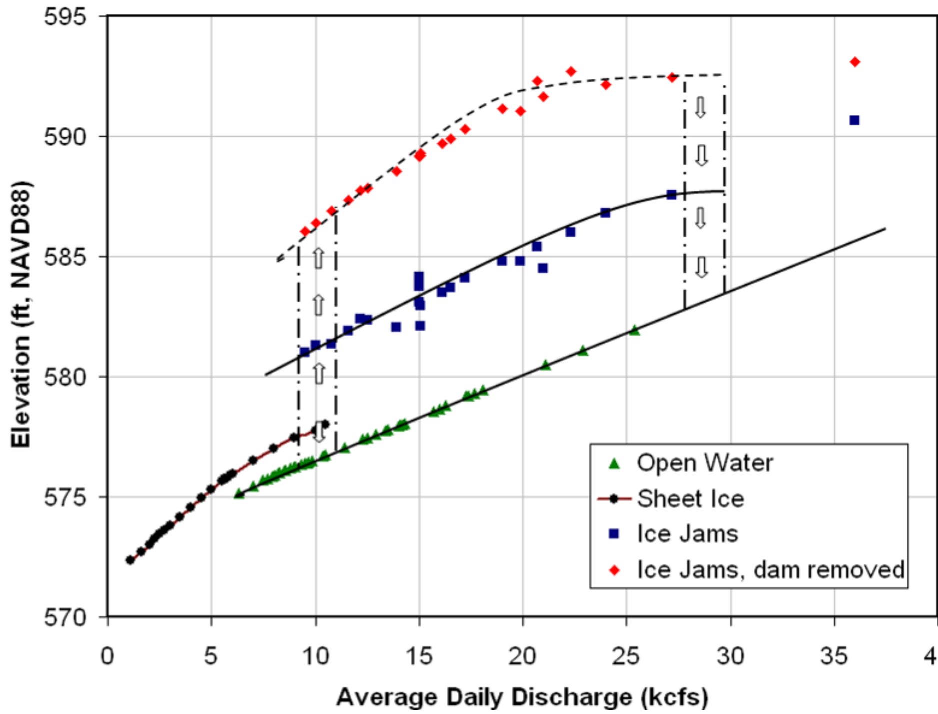

Figure 4. Ice Affect Stage Discharge at State Street, with and without Dam.

3.3 *Ice Affected Stage Frequency*

Ice jam and no ice jam winter season stage probabilities were calculated using Weibull plotting positions for key locations at for pre and post-dam removal conditions and stage frequency curves developed. To combine these synthesized ice jam and no ice jam curves (USACE, 2011) the probability of a winter season maximum stage was evaluated as,

$$P(S)_w = P(J) * P(S/J) + P(O) * P(S/O) \quad [1]$$

Where *P(J)* is the probability of a jam occurring and *P(S/J)* is the stage probability if a jam occurs, 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(J)* and can be estimated as the fraction of the total years of record that an ice jam was observed or hind-cast and *P(O)=1-P(J).*

Figure 5 shows the combined winter season stage frequency plots at State Street Bridge for the current condition and post dam removal condition. Due to the larger ice jams that would occur if the dam is removed, much higher stages occur at higher probabilities (or shorter return periods). The annual stage probability curve was calculated from the combination of winter season and non-winter season stage frequency curves. Since these series are independent, the combined curve, P_c, was evaluated as (USACE, 2011)

$$P_c = P(S)_{nw+} P(S)_w - P(S)_{nw*} P(S)_w \quad [2]$$

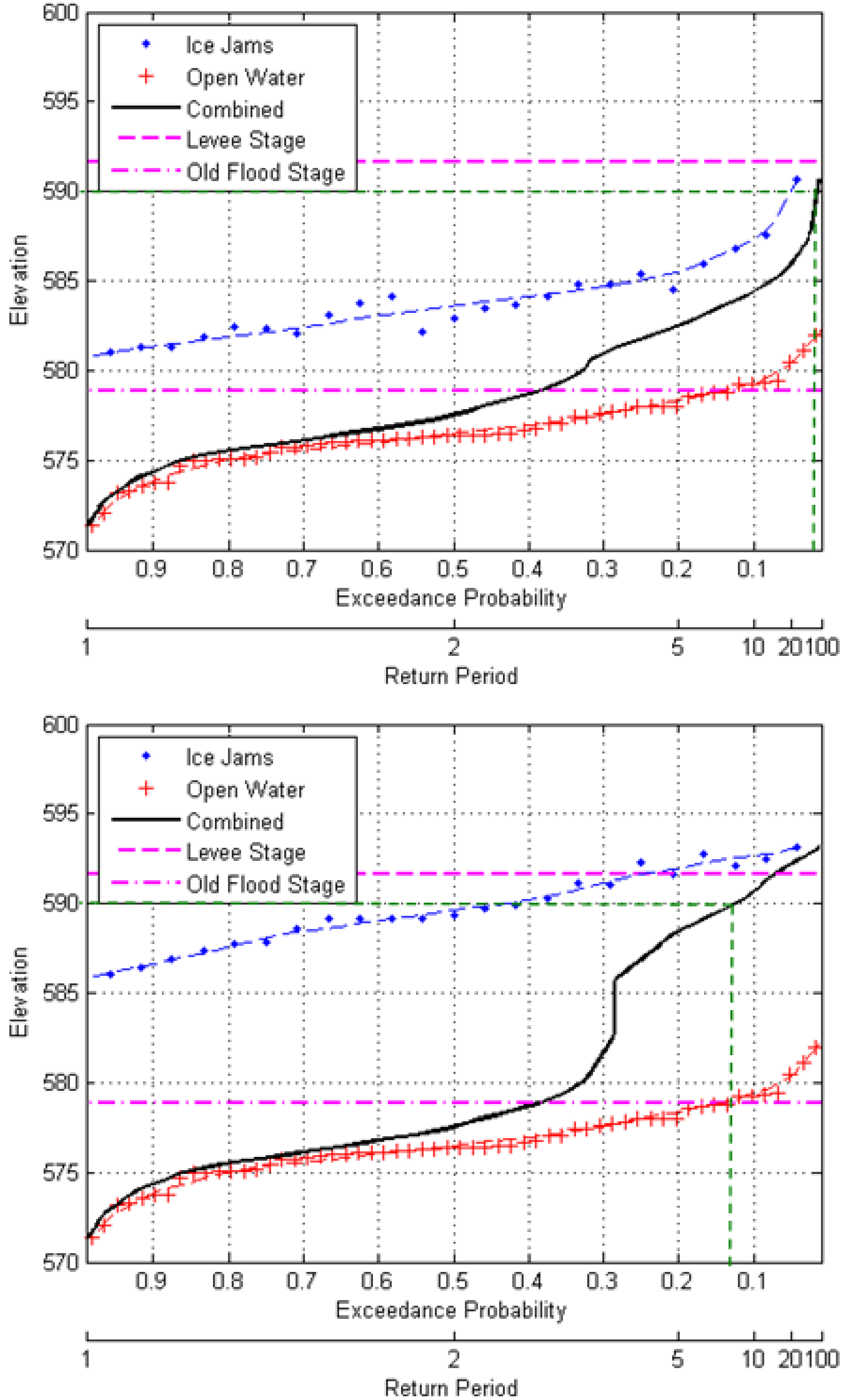

Figure 5. Maximum Winter Season Stage Frequency Curve at State Street Bridge.
Top Panel: current conditions, Bottom Panel: dam removed.
Green Line indicates the probability of the 590 ft winter season maximum stage event.

where $P(S)_{nw}$ is the probability of non-winter stages and $P(S)_w$ is the probability of winter stages. The annual stage probability curve at State Street is shown in Figure 5. The removal of the dam causes a marked increase in the stage for a given probability at State Street while the stage was decreased upstream at the USGS gage.

4. Potential Ice Control Alternatives at Ballville

The results above show that the removal of the Ballville Dam will require some type of breakup ice control in order to maintain the level of ice jam flood protection currently provided by the dam. An alternative under consideration is ice retention at a location upstream of the dam which provides an area for floodplain relief flow. The design of the Cazenovia Creek ICS located in West Seneca, NY is based on this concept (Lever et al, 2000). This type of ICS consists of piers spaced apart to provide for through-flow and a relief flow channel. Construction could possibly coincide with the proposed removal of sediment from the dam impoundment. Such a pier setup would provide for passage of fish open water flood flows and sediment. The structure would catch the breakup ice run and cause a jam with a well grounded toe region (Tuthill and Lever, 2006). Intercepting the ice run at this location would significantly reduce ice-jam flood damages downstream. Only the section of river downstream of the structure would supply ice jams that form in town. Design issues included erosion of the banks, plans for the floodplain relief flow, shape of piers to best retain ice and allow debris passage, and maintenance of the structure.

A stage frequency analysis, conducted as above, was also completed for the dam removed with ICS case. The with-ICS curves are very similar to the current condition dam-in curves, with lowered stages for a given probability at State Street and raised stages for a given probability that are close to current condition water levels at the USGS gage. It is possible that the structure will retain ice at higher flows than the dam currently retains ice, which may result in elevated flood levels in upstream areas, a possibility that should be further studied and designed for as data becomes available. These results are preliminary, due to limited design and bathymetry data, but they suggest that if a site can be found near the proposed location, an ICS would likely be successful in reducing ice jam flooding in town and have little effect upstream.

5. Summary

A hind-casting analysis was used to find discriminating criteria for ice jam occurrence in Fremont, including criteria for minimum flow, ice thickness, time to peak, and time since a major peak. Jams events were hind cast for 23 of 81 years of record, or 28.4 % jams for winter season maximum flows.

Using HEC-RAS geometry provided by the Buffalo District, freezeup ice profiles were developed for each of the jam event years. The breakup ice jams were then calibrated using volume and observed stages for the two 1959 events and validated using the 1963 event. The 23 breakup jams, 58 open water winter season maximums, and 82 non-winter season maximums were evaluated in HEC-RAS for the with dam and dam removed conditions Simulations were also conducted for a possible ice control structure alternative located several thousand feet upstream of the dam site.

Annual stage exceedence probability plots were developed for each case at key locations. Table 1 summarizes the impact on stages at the 2- , 5- 10- and 100-year return periods for the dam removed and ICS in place cases as compared to the current condition. For the 5 year return period, the impact in town can be from 5-11 feet if the dam is removed, while less than ½ foot if the ICS is installed. Upstream of the dam, removal of the dam and installation of an ICS results in lowering of stages. The removal of Ballville Dam will cause much larger jams to form in town, though the levees may still succeed in protecting some areas as in the example shown in Figure 6.

Table 1. Difference in Stage (NAVD88 ft) from Current Condition on the Sandusky River .

Return Period (year)	**Combined Exceedence Probability**	**Location**	**State Street Bridge**	**Roger Young Park**	**USGS Gage**	**Indian Creek**
		River Mile	13.72	14.49	18.58	19.32
2	0.5	dam removed	0.03	0.09	-0.73	-0.24
		ICS in place	0.01	0.01	-0.39	0.00
5	0.2	dam removed	5.69	10.54	-3.53	-1.29
		ICS in place	0.36	0.20	-0.75	-0.02
10	0.1	dam removed	6.06	10.45	-3.16	-1.52
		ICS in place	0.35	0.30	-0.34	0.00
100	0.01	dam removed	1.63	5.93	-4.36	-3.61
		ICS in place	0.48	0.41	-0.34	-0.04
Average		*dam removed*	3.35	6.75	-2.95	-1.67
		ICS in place	0.30	0.23	-0.45	-0.01

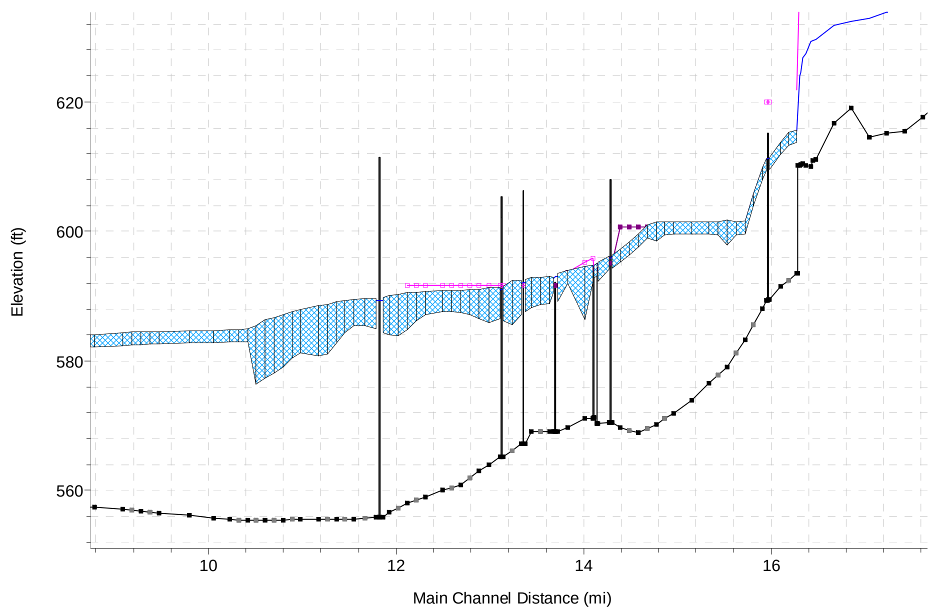

Figure 6. No Dam Ice Jam Profile, showing levees in magenta, 1978 event.

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References

Evans, J. E., N.S. Levine, S.J. Roberts, J.F. Gottgens, and D.M. Newman (2002), Assessment Using GIS and Sediment Routing of the Proposed Removal of Ballville Dam, Sandusky River, Ohio, Journal of the American Water Resources Association, Vol. 38, No. 6, December 2002

National Climatic Data Center (2011), Climate Data Online, Available at http://cdo.ncdc.noaa.gov/CDO/cdo, Accessed April 2011

Thomas, S.E. (1913) Compared with Other Floods, Historical Souvenir of the Fremont Flood, March 25-28, 1913, Published by the Finch Studio, 1913

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. Cold Regions Engineering*, **10**(1), 36-57.

Tuthill, A. M., and K.D. White (1997) Breakup ice control structure for the Salmon River in Connecticut. Proceedings, 9th Workshop on River Ice, Fredericton, NE, 125–139.

Tuthill, A.M., K.D. White, and C.M. Vuyovich (2007) Ice Jams, Contaminated Sediment, Dam Removal, and Bridge Scour on the Clark Fork River, Montana. 14th Workshop on Ice Covered Rivers, 19–22 June 2007, Quebec, Canada.

USACE (2002) Engineering and Design – Ice Engineering. U.S. Army Corps of Engineers Engineer Manual 1110-2-1612, http://www.usace.army.mil/inet/usacedocs/eng-manuals/em1110-2-1612/toc.htm.

USACE (2008) HEC-RAS Hydraulic Reference Manual Version 4.0, US Army Corps of Engineers Hydraulic Engineering Center, Davis, CA.

USACE (2011) Ice Affected Stage Frequency, US Army Corps of Engineers ETL, in press.

U.S. Geological Survey, 2011, Streamflow Data: Sandusky River near Fremont, OH, Station 04198000. Available at http://waterdata.usgs.gov/oh/nwis/uv?04198000 , last accessed May, 2011

Vuyovich, C. A. (2008) *Impact of the Ballville Dam on Ice Jams in Fremont, Ohio,* CRREL Report to the Buffalo District, January, 2008.

Vuyovich, C.A. and White, K. D. (2006) Assessment of the Effectiveness of the Israel River Ice Control Structure, Lancaster, NH. US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, NH, Technical Report ERDC-CRREL TR-06-01.

White, K.D. (1999) Hydraulic and Physical Properties Affecting Ice Jams, CRREL Report 99-111, December, 2009.

White, K.D. and J.N. Moore (2002) Impacts of Dam Removal on Riverine Ice Regime, ASCE Journal of Cold Regions Engineering, Vol 16, No. 1, March 2002