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Performance of a Sloped-Block Ice-Control Structure in Hardwick, VT

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In 1994, we installed an inexpensive ice-control structure (ICS) in the Lamoille River upstream of the village of Hardwick, VT. Developed using model tests, the ICS consists of four sloped granite blocks embedded in a riprap blanket across a channel section with an adjacent treed floodplain. It has performed well during 11 winter seasons, arresting ice runs and retaining them for hours-to-days. Ice-run arrest and jam-holding time improve with increasing ice thickness, and the structure has held three jams throughout the corresponding breakup events. Most importantly, the Village of Hardwick, having experienced 10 ice-jam floods in the preceding 30 years, has not experienced an ice-jam flood since construction of this ICS.

1. Introduction

Ice breakup on small, steep rivers poses difficult challenges for flood mitigation. Flood damages can be significant relative to community resources but insufficient to justify large dam-based control structures. A natural desire for low cost and environmental impact conflicts with the need to reliably arrest dynamic breakup surges and hold the resulting ice jams.

We developed a sloped-block ice-control structure (ICS) that meets these challenges (Lever et al. 1997). Based on encouraging model results, the structure was installed in the Lamoille River upstream of the Village of Hardwick, Vermont, in 1994. The previously flood-prone Village has not experienced an ice-jam flood during the subsequent 11 seasons.

The ice-arrest and holding functions of the ICS depend on breakup-event characteristics such as ice thickness and surge amplitude, with more extreme events producing more reliable ice control at the structure. Here, we compare the compare the pre- and post-ICS event consequences and discuss the reliability of the ICS in terms of ice-run arrest and holding time.

2. Hardwick Ice-Jam History

Figure 1 shows a map of the Lamoille River through Hardwick, VT. Lever et al. (1997) describe the ice-hydraulic conditions of the study reach. The steep reach (0.009 slope) above the Village produces frazil ice throughout the early winter. This frazil forms a thick ice cover along the flatter reach from Hardwick Lake to Cooper Brook. Before ICS construction, breakup ice jams formed most years in the vicinity of the Cottage Street bridge as the breakup ice run encountered the frazil deposits.

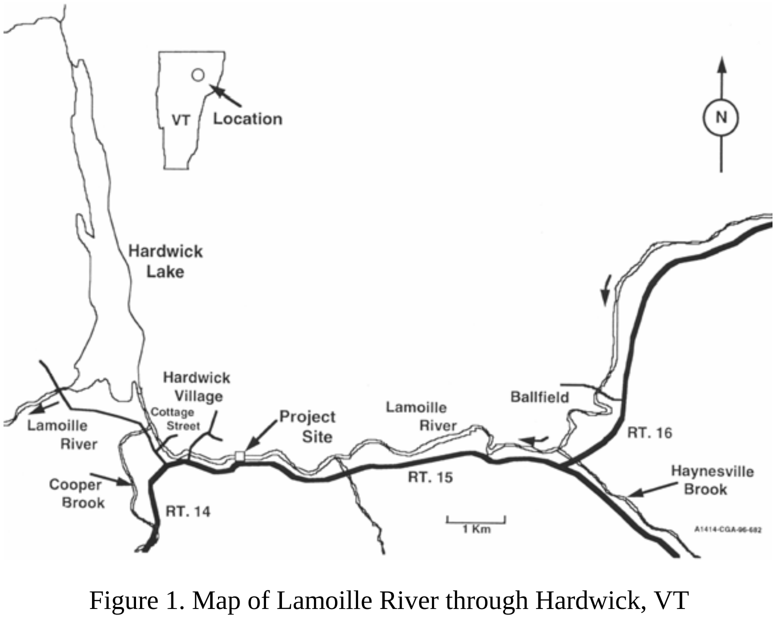

Figure 1. Map of Lamoille River through Hardwick, VT

Information about the formation and consequences of ice jams in Hardwick are available from Calkins (1985), FEMA (1987) and the *Hardwick Gazette* newspaper, whose offices abut the river. We summarized the available information and ranked the events in terms of severity, with 4 being most severe and 0 being of no consequence.

Fairly complete records exist after 1964 when an ice jam destroyed the Cottage Street bridge. Two other ice jams, a freezeup jam in 1976 and a breakup jam in 1981, resulted in more than 1 m of water in the subdivisions and businesses adjacent to the bridge. Extensive property damage, evacuations, road closures and personal injuries resulted during these events, which we rank as category 4.

Category 3 events produced minor flooding (0.3 m or less) but resulted in significant operational effort such as excavation or blasting of the jam. These occurred on seven occasions, the last on 11 March 1992 during a severe breakup event that caused extensive flood damages in nearby Montpelier, VT. During that occasion, emergency excavation work in Hardwick released the jam while flooding was still minor.

Category 2 events produced threatening ice jams but no flooding in the Village. However, they usually provoked an emergency response to mobilize excavation equipment and occupied attention of Town officials for several days at a time. These consisted of both freezeup and breakup jams and occurred on 20 occasions from 1964 to 1990, with some multiple events during the same season.

Category 1 events produced minor ice jams that may or may not have provoked an emergency response. These occurred on 38 occasions since 1965, again with some multiple events during the same season. Four Category 1 events have occurred since construction of the ICS, including two events during which the ICS held ice without releasing it.

Category 0 events produced no ice jams owing to thermal breakup or ice runs that passed through the Village without jamming. During the 30 years prior to ICS construction, only six category 0 events occurred, including a thermal breakup at the end of the 1993-94 season. Since then, 11 Category 0 events have occurred, including eight releases from the ICS that passed cleanly through the Village and three thermal breakups.

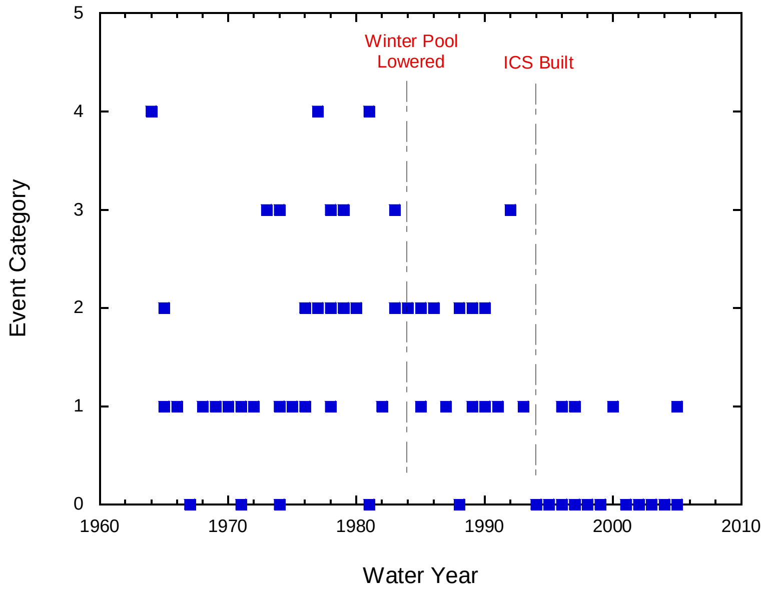

Figure 2. Ice jam event categories for Hardwick since 1964

Figure 2 compiles the event categories by year beginning in 1964. In an effort to reduce flooding, the pool in Hardwick Lake was lowered at the start of each winter beginning in 1984. This had the beneficial effect of moving the location of the frazil deposits about 1 km downstream. Figure 2 suggests that this may have reduced event severities, although the 1992 event had the potential to be Category 4 if the emergency excavation effort had not been successful. No events more severe than Category 1 have occurred since ICS construction prior to the 1994-95 winter season.

3. Ice-Control Structure

The ICS was developed through tests in CRREL's refrigerated hydraulic laboratory and constructed in the Lamoille River in September 1994 (Lever et al. 1997). It consists of four granite blocks embedded in riprap across a 24-m-wide channel section adjacent to a treed floodplain. Each block weighs about 38×10^3 kg, protrudes 1.5 m above the riprap and is about 1.4 m wide. The gaps between blocks are about 4.3 m wide.

Figure 3. ICS during freezeup in 1995 (looking upstream)

Figure 3 shows the ICS during a typical freezeup period as an ice sheet forms on the pool above the structure. The breakup ice run arriving from upstream normally fractures this sheet and shoves the pieces onto the ICS. Arrest of the run then produces a grounded jam at the ICS (Figure 4). Depending on the ice thickness and amplitude of the breakup surge, the ICS will hold the ice jam as waterlevels rise. Most of the flow passes through the grounded jam, but on two occasions water also flowed around the jam on the treed floodplain.

Figure 4. Breakup jam at ICS on 28 Feb 2000 held throughout event

The ICS has experienced 16 breakup events during 11 seasons. Table 1 provides a summary of conditions and the ICS behavior during these events. In all cases, no flooding occurred in Hardwick. The ICS held ice throughout the event on three occasions and released ice held for several hours on six occasions. It did not form a jam during seven breakup events: three thermal breakups and four cases of thin ice. In these latter cases, the ice runs passed harmlessly through the Village.

Because of its flood history and the experimental nature of the ICS, the Town has mobilized equipment to excavate ice jams formed in the Village from the initial ice run downstream of the ICS. They did so during the four Category 1 events listed in Table 1. This behavior is prudent until the ICS demonstrates that it can hold ice throughout extreme breakup events.

Table 1. Summary of breakup conditions and ICS behavior.

Breakup Date	AFDD (°C)	ICS Ice Thickness Sheet (m)	ICS Ice Thickness Pieces (m)	Breakup Weather	ICS Behavior	Released Ice	Event Category
15-Jan-95	194	0.28 ± 0.02	0.20 ± 0.05	T > 10°C, drizzle, snowmelt	jam at ICS, 7.0 hrs	ran through Village	0
16-Mar-95	344	0.30 ± 0.08	0.15 ± 0.05	T > 4°C, drizzle	no jam, slowed run	ran through Village	0
19-Jan-96	444		0.18 ± 0.08	T > 10°C, rapid snowmelt	jam at ICS, 2.8 hrs	ran through Village	0
21-Feb-96	278		0.15 ± 0.13	T ~ 4°C, rain	jam at ICS, 2.8 hrs	pushed Village jam downstream	1
22-Feb-97	518	0.41 ± 0.08	0.30 ± 0.08	T > 4°C, gradual snowmelt	jam in pool, no release	*no release*	1
29-Mar-97	144			T ~ 4°C, gradual snowmelt & drizzle	jam at ICS, 4.8 hrs	ran through Village	0
7-Jan-98	227		0.15 ± 0.08	T < 4°C, rain & drizzle	jam in pool, 1.5 hrs	ran through Village	0
12-Feb-98	204	0.30 ± 0.15	0.18 ± 0.05	T < 4°C, gradual snowmelt & rain	jam in pool, no release	*no release*	0
24-Jan-99	250		0.20 ± 0.08	T ~ 4°C, rain	no jam, slowed run	ran through Village	0
28-Feb-00	453	0.33 ± 0.05	0.38 ± 0.13	T ~ 4°C, rain	jam at ICS, no release	*no release*	1
Mar-Apr 01	840	0.36 ± 0.03		T ~ 0°C, dry	no jam, thermal breakup	thermal breakup	0
10-Mar-02	320		0.08 ± 0.03	T ~ 10°C, rain	no jam, slowed run	ran through Village	0
21-Mar-03	914		0.15 ± 0.05	T ~ 0°C, dry	no jam, thermal breakup	thermal breakup	0
Mar-Apr 04	836			T ~ 0°C, dry	no jam, thermal breakup	thermal breakup	0
14-Jan-05	200		0.15 ± 0.05	T ~ 4°C, rain	jam at ICS, 2 hrs	pushed Village jam downstream	0
2-Apr-05	487		0.25 ± 0.05	T ~ 4°C, dry	jam at ICS, 16 hrs	ran through Village	1

A key parameter governing ice-jam formation and holding time at the ICS is ice thickness. Historical records indicate that ice thickness in Hardwick Village can exceed 0.6 m at the end of a cold winter without a mid-winter breakup event. Pieces excavated from the 1992 Category 3 ice jam approached 1 m in thickness. The maximum ice thickness since 1994 was only 0.41 ± 0.03 m measured for the sheet upstream of the ICS prior to the 22-Feb-97 breakup. For this event and the 28-Feb-00 breakup, average ice-piece thickness at the ICS equaled or exceeded 0.3 m, and the ICS held the jams throughout the events (until flow eroded channels through the jams several days later).

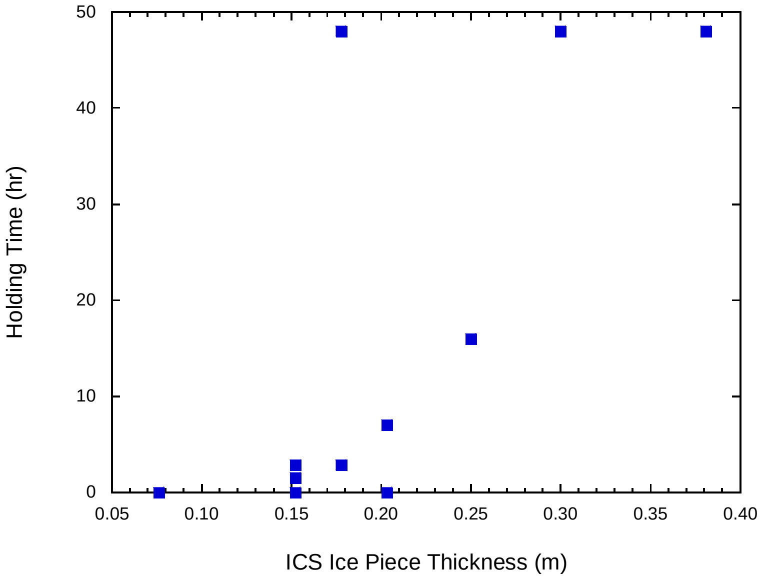

Figure 5. Ice-piece thickness versus ICS jam-holding time.

Figure 5 shows the relationship between average ice-piece thickness at the ICS and jam-holding time. Note that for “no release” we assigned an arbitrary holding time of 48 hours (longer than the typical 24-hour event durations). Generally, holding time increased with ice thickness up to a threshold of about 0.3 m, after which no releases occurred.

4. Discussion

The sloped-block ICS is relatively inexpensive ($3,600/m river width, 1994 dollars) and unobtrusive. These are important characteristics for small communities located on small, essentially undeveloped rivers. The widely spaced blocks, their sloped faces, lack of a dam and presence of an adjoining treed floodplain are all important contributors to keeping cost and environmental impact low. It is clear, however, that the ICS does not arrest all ice runs or hold them indefinitely. Thin ice may not jam at the ICS or it may release after several hours. Provided the reach requiring flood mitigation is fairly limited in extent, ice runs that pass through the structure can also pass through the critical reach without posing a flood threat. This appears to be the case in Hardwick.

We developed the sloped-block ICS with a view to controlling severe breakup conditions on small, steep rivers. These conditions include thick, strong ice, large contributing ice volume and large-amplitude abrupt breakup surges. Model results indicated that the ICS reliably formed and held ice jams for these conditions, and field results to date are consistent with these results. When ice is competent (air temperatures below freezing a week or so before breakup) and ice thickness exceeds about 0.3 m, the ICS will arrest the breakup ice run and hold it throughout the event. The floodplain allows flow to bypass the structure, limiting stage rise and forces on the jam. Most of the flow passes through the structure and warm water melts open the jam as the event proceeds.

Clearly, breakup ice thickness does not solely govern the ICS performance. Ice floe size and strength and surge amplitude must also influence arrest and grounding of the ice run and subsequent jam retention (Lever and Gooch 1998). However, ice thickness is a reasonable surrogate for these other factors. Ice floe size increases with thickness, increasing the likelihood of jamming across the ICS gaps; stage rise required to initiate breakup increases with ice bending strength (and thus thickness) as does the amplitude of the resulting surge; large ice thickness at breakup implies high strength of ice floes and thus high potential to resist rising hydraulic forces in the jam.

Is the sloped-block ICS mitigating ice-jam flooding in Hardwick? Circumstantial evidence suggests yes. There has been a noticeable reduction in ice-jam severity (category values) in Hardwick Village during the past 11 seasons compared with the previous 30 years. The ICS arrests ice runs and holds the resulting ice jams during conditions that pose the greatest flood threat: thick, strong ice and large breakup surges. Nevertheless the large gaps between blocks and their sloped faces permit thin ice to pass through or over the ICS. While thin ice does not pose a serious flood threat to Hardwick, this release behavior must be considered if the sloped-block ICS is a candidate for installation at other sites.

Acknowledgments

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