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PHYSICAL MEASUREMENT OF ICE JAMS

1976-77 Field Season

James L. Wuebben
Douglas M. Stewart

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Three shallow stream ice jams which occurred on the Ottauquechee River in Vermont during the 1976-77 winter season are documented. Measurements of the variation in jam thickness along the longitudinal profile of the jams are given along with the variation in surface ice flow sizes. These measurements are compared with those of previous work. All jams were caused to some extent by backwater conditions in the river. The effects of an ice cover and the ice jams on the longitudinal water surface profiles are examined and compared with open water conditions.

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Preface

This report was prepared by James L. Wuebben, Research Hydraulic Engineer, and Douglas M. Stewart, Civil Engineering Technician, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

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Table of Contents

Illustrations

Tables

INTRODUCTION

This report summarizes field work during the 1976-77 winter season related to the continuing program of physical measurement of ice jams on the Ottauquechee River in Vermont. Supporting information on water levels, flows and jamming mechanics is also included.

There were two periods in which jamming occurred, December 1976 and March 1977. During December, two jams occurred almost simultaneously and then froze in place during subsequent cold weather. The March jamming period was not as well documented as the December period since continuing warm weather and rain caused the jam to release shortly after formation.

BACKGROUND

The Ottauquechee River is a shallow stream in the Connecticut River Basin having a drainage area of approximately 572 km^2. The average river discharge for a 45-year period of record is 11 m^3/sec, with a maximum recorded flow of 691 m^3/sec and a minimum flow of 0.082 m^3/sec. The river has a bank-full depth of 3 to 4 m and an average bed slope of 3.0×10^{-3} m/m. The bed material consists of coarse gravel to medium cobble (50-200 mm) with occasional deposits of sand or silt.

An extensive survey of selected portions of the river was previously conducted (Calkins[1]) with river cross-sections profiled at 200-ft (61-m) intervals and benchmarks established for survey control. The locations of the cross sections and benchmarks are shown in Figure 1.

River discharge records were obtained from the U.S. Geological Survey gaging station at North Hartland, Vermont. This station is 1.9 km upstream of the river mouth and 0.5 km downstream of a flood control dam. The ice jam study areas are located approximately 5 to 13 km upstream of the gaging station. Since the gage is located downstream of the dam, data must be corrected for changes in reservoir storage, and unmeasured but possibly significant changes in discharge may occur between the study areas and the gaging station. A discharge rating curve for gaging section below the dam is given in Figure A1 (App. A). The flow records for the past season used in this report are classified as provisional by the USGS and may be subject to revision before official release. Figure A2 is a stage hydrograph of the Ottauquechee for the period October 1975 through April 1977. These records are being received on a continuing basis.

Four water level recorders, using pressure transducers, were constructed and installed at Quechee, Vermont, cross sections 13, 32, 42 and 47. Another four water level recorders have been constructed for future installation at Taftsville cross sections.

Approx. Scale 1:7300

Figure 1. Ottauquechee River, Quechee, Vermont.
17 April 1976

The water level recorders used on the Ottauquechee River employed Endevco Model 8503-40 pressure transducers installed on the riverbed along surveyed river cross sections. The signal cables from the transducers were run underground to an instrument box mounted on a short post. The signal from a pressure transducer was recorded on a battery-operated Gulton Rustrak Model 288 strip chart recorder, set up to measure relative changes in river stage over a range of about 5 m. Figure 2 shows the installation at Quechee cross section 13.

Figure 2. Stage recorder installation.

Several problems with the water level recorders were encountered during the season, including the following:

1. Although the signal cables were buried in the riverbank, the transducers were not adequately anchored and could move around, altering the calibration. In addition, the calibration of the system could drift internally making periodic calibration imperative.

2. The strip chart recorder paper frequently jammed on the takeup reel. It should be possible to prevent this by bypassing the takeup reel and allowing the paper to collect in the base of the instrument box. The boxes must be waterproofed, however, since water was frequently found in the bottom of the boxes this season.

3. Better locations for the instrumentation must be found. During the past season the installations at cross sections 13, 32 and 47 were hit by ice and the latter two would have been destroyed during the March 1977 jam if they had not been removed in time. The recorder at cross section 42 was vandalized early in the season, and was not replaced because of its close proximity to and visibility from the highway.

RESULTS

During December 1976 a flood flow with a total volume of approximately $3.36 \times 10^6 m^3$ (Fig. A3, App. A) and a maximum discharge rate of about 29.7 m^3/s developed on the Ottauquechee River. The rise in stage (about 0.9 m at cross section 13) caused the ice cover to break up and flow down river with ice jams occurring at two locations. The toe of the first jam was located approximately 1.9 km downstream of the Quechee Dam and extended upstream 1160 m. The other ice jam began approximately 45 m above the Quechee Dam at cross section 12, and extended upstream to the tree line above the Ottauquechee golf course bridge at cross section 58 approximately 2800 m. The total volume of ice involved in the upstream jam was estimated to be 72,800 m^3. Employing the initial ice thickness of 16.5 cm and an approximate river width of 45 m yields a rough estimate of the length of the river, on the order of 9800 m, contributing ice to the jam.

The March jamming period is not as well documented as the December period because of the rapidity of events and the timing of ice breakup. The jam took place on the weekend of 12-13 March, and continuing warm weather and spring rains washed the jam downstream prior to Monday, 14 March 1977. Limited data are available for this jam.

The jamming mechanism at the downstream jam was apparently a combination of a 90° bend in the channel, backwater conditions from a small dam, and a constriction in the channel width approximately 80 m after the bend in the channel. There were two very large ice floes (up to 4 m across) located on the bank of the river at this point that had apparently moved little during the breakup of the ice cover.

The jam occurring above the Quechee Dam was held in place because of a combination of backwater of the dam and arching of the ice blocks. Ice floes evidently flowed over the Quechee Dam (and contributed to the ice jam below). This is suggested because of the small block sizes existing in the toe of the upstream jam. The ratio of ice jam thickness to bank-full river depth ranged from 0.22 to 0.09.

A visual examination of ice floes revealed that the initial ice cover was composed of about 4 cm of snow ice along with 12.5 cm of clear ice. Several floes were found with adfrozen soil and vegetation up to 5 cm in thickness.

Descriptive photography of both jamming periods is shown in Appendix B.

Water Surface Profiles

Water surface profiles have been collected along the Ottauquechee River during both open water and ice cover conditions. Figure 3 presents water surface profiles for the Quechee site from the past season as well as open water surface profiles from past seasons for reference. In addition, approximate water surface profiles for various recurrence interval floods are included in Figure A4 (App. A). The water surface profile for the December 1976 jam below the Quechee Dam was also obtained for possible future use if that site is developed.

Figure 3 illustrates the significant increase in river stage due to ice cover roughness in comparison with equivalent open water discharges, as well as the steepening of the water surface profile in the Quechee Dam backwater area.

The untypical water surface profile feature formed in the vicinity of cross sections 25 through 35 during the December 1976 jam appears to persist through the rest of the winter. In addition, the blockage creating this feature in December may have caused or contributed to the jam, creating the large increase in stage in the same area during the March 1977 jam.

A comparison of change in stage at Quechee cross section 13 and the USGS gage below the North Hartland Dam is presented in Figure 4. The reason for the lag time between the rise in stage at North Hartland gage and cross section 13 upstream is not readily apparent, and is not due to problems with time synchronization. It is possible that the ice cover broke up with a relatively small increase in stage and then with subsequent jam development the ice stage reached a maximum at cross section 13 after the peak flow had already passed, or that flow at the USGS gage was affected by operations at the North Harland Dam. However, since the USGS data used here are classified provisional and subject to possible revision this comparison might be unjustified.

Variations in Ice Jam Thickness

Table I lists some measurements of ice jam thickness and distribution from the two December 1976 jams. The variables used in the table are:

Graph	Date	Discharge ft³/s	Discharge m³/s	Remarks
A	30 Jun 73	31,000	877.82	
B	10-11 Feb 76	340	7.89	
C	30 Mar 76	3,000	84.95	
D	1 Apr 76	9,500	269.01	
E	26 May 76	1,090	30.87	
F	15 Jun 76	175	4.96	
G	10 Aug 76	17,900	6.87	Hurricane Belle
H	10 Aug 76	13,000	368.12	After Hurricane Belle
I	8 Dec 76	1,055	29.87	Ice jam
J	5 Jan 77	—	—	
K	26 Jan 77	155	4.39	
L	11 Feb 77	123	3.48	
M	2 Mar 77	171	4.84	
N	14 Mar 77	Provisional discharge (see text)		Ice jam

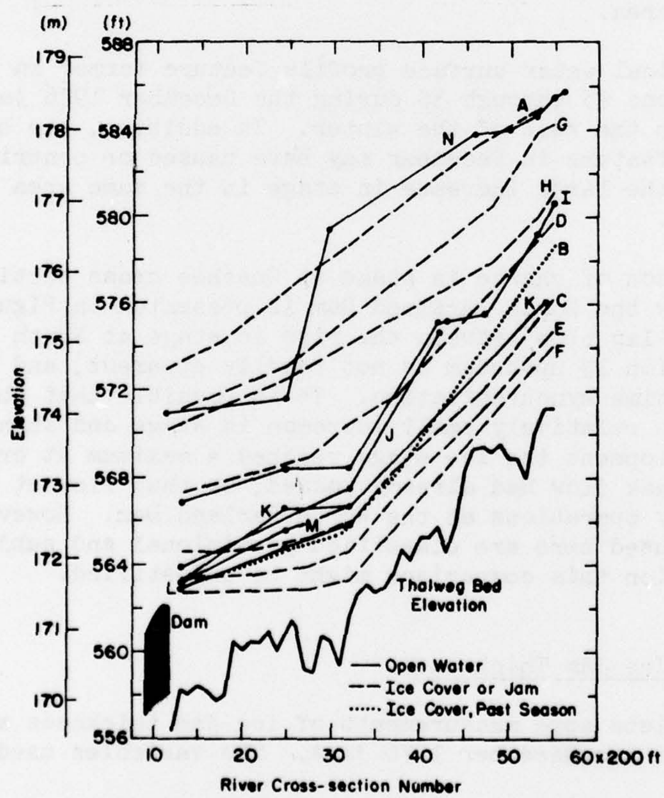

Figure 3. Water Surface profiles, Ottauquechee River.

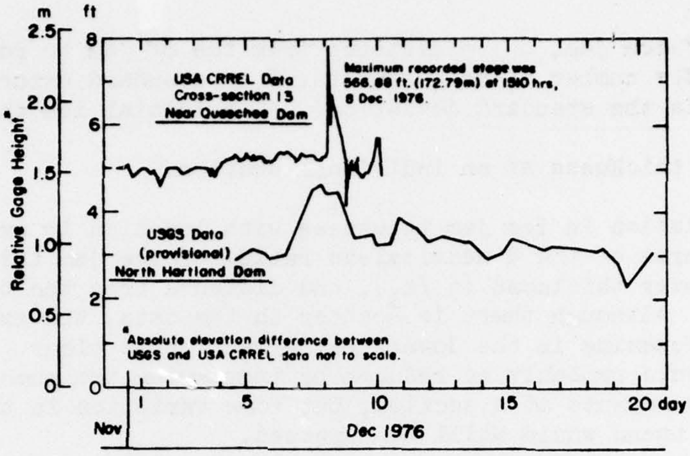

Figure 4. Ottauquechee River stage hydrograph, December 1976.

Table I. Ice Jam Thickness Measurements, Ottauquechee River, Quechee, Vermont, 8 December 1976.

Above dam

Section	N	t_j (ft)	S_e	L_{cu} (ft)	L_{cu}/L_c*	t_j/t_i†
X-13	16	2.58	0.09	200	0.022	4.78
X-15	3	1.89	0.165	600	0.065	3.5
X-20	3	3.03	0.11	1600	0.174	5.61
X-24 + 70	3	1.69	0.136	2470	0.268	3.14
X-32	2	1.25	0.138	4000	0.435	2.31
X-37	2	1.37	0.65	5000	0.543	2.54
X-42	2	1.17	0	6000	0.652	2.17
X-47	2	1.08	0.18	7000	0.760	2.01
X-53	2	2.83	0.68	8200	0.891	5.25

* L_c = 9200 ft

† t_i = 0.54 ft

Below dam

Section	N	t_j (ft)	S_e	L_{cu} (ft)	L_{cu}/L_c*	t_j/t_i†
a	5	2.0	0.254	790	0.21	0.371

* L_c = 3800 ft

† t_i = 0.54 ft

L_c = length of ice jam, L_{cu} = distance from toe of jam to point of measurement, N = number of measurements, S_e = standard error of the mean ($= \frac{s}{\sqrt{N}}$ where s is the standard deviation), t_i = initial ice thickness, t_j = average jam thickness at an individual section.

This variation in ice jam thickness with location is presented in Figure 5 in terms of the dimensionless ratios of ice jam thickness to initial ice cover thickness (t_j/t_i), and distance from the toe of the jam (L_{cu}/L_c). Although there is scatter in the data, the expected trend of the jam thickening in the downstream direction is clear. The scatter in the data would probably be reduced by increasing the number of jam thickness measurements at a section, but some variation in the general jam thickness trend would still be expected.

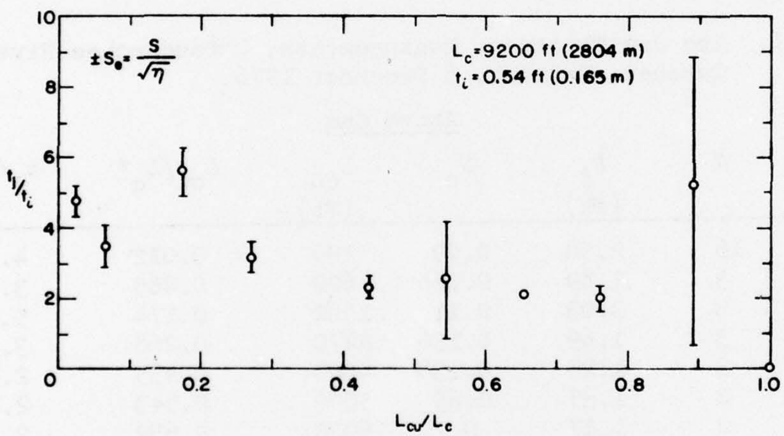

Figure 5. Variation of ice jam thickness.

Figure 6 shows a similar plot by Calkins[1] from jams on the Ottauquechee River near Woodstock, Vermont, and the First Branch of the White River at Tunbridge, Vermont, during January 1976. While it may not be justifiable to draw a curve through such a set of data, a comparison of Figures 5 and 6 shows that the ratio of jam thickness to initial ice thickness near the ordinate is about $3<t_j/t_i<4$ in each case. The standard error of mean of the data points, S_e, is also shown for each point. The term S_e is calculated as the standard deviation S divided by the square root of the number of measurements, η.

As L_{cu}/L_c approaches unity, t_j/t_i has become zero in the field observations to date. However, if a line were to be placed through the data points in Figures 5 and 6, t_j/t_i would be closer to one as L_{cu}/L_c

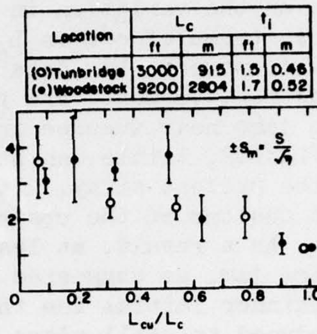

Figure 6. Comparative ice jam thickness variation (after Calkins[1]).

approached unity. This would indicate that if the supply of ice were unlimited, the length of the jam would be controlled by flow conditions, and would require defining the upstream of the jam as the point where ice floes no longer underturned. Thus, for the ice cover above the upstream end of the jam, t_j/t_i would remain at unity unless a flow condition was reached which would cause underturning.

On the relatively small rivers studied to date, however, the ice supply has been the limiting factor in ice jam development and $t_j/t_i = 0$ at $L_{cu}/L_c = 1$.

Variations in Ice Floe Dimensions

Estimates were made of the average floe size $\bar{a}$ at various points along the ice jams. The significance of the data (presented in Table II) is related to the passage of ice through natural or man-made flow constrictions. The floes near the toe of the jam are by far the largest, with size decreasing greatly a short distance upstream. Calkins[1] suggests that passage of the large ice blocks in the initial 20% of an ice run is the critical criterion to prevent jamming.

Table II. Ice Floe Dimensions Along the Jams.

Upstream Jam		Downstream Jam	
L_{cu}/L_c	$\bar{a}$ (ft)	L_{cu}/L_c	$\bar{a}$ (ft)
0.022	2	0	3 to 6
0.268	1 1/2	0.207	1 to 2
0.435	1	0.483	1 to 2
0.467	0.75	0.621	Brash ice 1/2 to 1
0.760	≤ 0.5	1.0	Open water
1.0	Open water		

Calkins[1] presented data on the variation in floe size along a jam as a ratio to river width *B* in terms of $\overline{a}/\overline{B}$ vs L_{cu}/L_c, and suggested an exponential function of the 1/2 power. His data from a jam on the Ottauquechee River near Woodstock, Vermont, are presented in Figure 7 along with data from the two jams near Quechee in December 1976. Because of sparse data at $L_{cu}/L_c < 0.2$, little can be concluded from the more recent information of the present study. An immediate problem is that the larger ice floes at the toe of the upstream jam were apparently pushed over the Quechee Dam. As a result, at least a portion of the critical initial 20% of an ice jam, as suggested by Calkins[1], was unmeasurable. In addition, the thinner initial ice thickness (16.5 cm vs 49 cm) allowed the ice to be reduced to small sizes much more easily, accounting for the difference of about an order of magnitude, as shown by Figure 7.

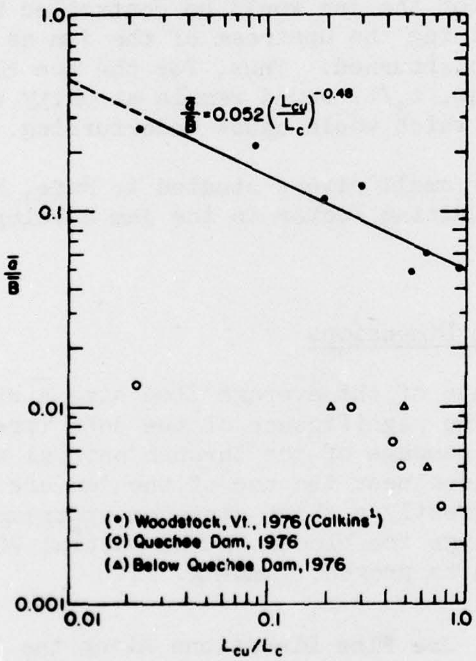

Figure 7. Variation of ice floe dimensions in an ice jam.

SUMMARY AND CONCLUSIONS

Three ice jams occurred on the Ottauquechee River during the 1976-77 winter field season. Depending on their location and stability, they were documented to various degrees with the intent of using the measurements in the development and verification of physical and mathematical models. The cause of the jamming varied from flow constrictions, to dam backwater conditions, to a competent downstream ice cover. The ice jam reached a thickness of roughly four to five times the initial ice thickness at its toe, with a rapid reduction in thickness in the upstream direction. The average surface floe dimension (nondimensionalized by dividing by the average river width) ranged from $\frac{a}{B}$ = 0.03 at the toe to 0.003 at the upstream end. This is roughly an order of magnitude smaller than the dimensions obtained by Calkins[1] and is possibly due to the much thinner initial ice cover. The ratio of ice jam thickness to bank-full river depth ranged from 0.09 to 0.22.

FUTURE WORK

In order to improve the quality of the data in the coming season, several changes in measurement procedure are in order:

1. One or possibly two accurate river gaging stations should be developed. The distance between the study areas and the USGS gage, as well as storage and release activity at the North Hartland Dam, limits the availability and usefulness of the measurements. Possible sites include downstream of the jam site below Quechee, Quechee Dam, and the Taftsville Dam.

2. The water level recorders should be relocated to avoid damage by ice or vandalism. In addition, the takeup reels should be by passed to prevent jamming and the instrument boxes should be waterproofed.

3. The pressure transducers should be firmly anchored in water deep enough to prevent movement by water or ice. Periodic calibration checks should be made to correct for transducer movement or internal calibration drift.

4. In general, more data points should be taken at any one cross section to improve statistical reliability, and cross sections should be chosen to prevent gaps such as on the logarithmic plot in Figure 7.

5. When weather or jam stability prevents a survey crew from physically measuring an ice jam, the jam should be well documented with ground photographs containing a size reference to permit estimates of river stage and block size, etc.

LITERATURE CITED

1. Calkins, D.J. (1977) Ice jam measurements and undercover roughness calculations. U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL) Technical Note. (unpublished).

2. D'Appolonia Consulting Engineers, Inc. (1973) Planned upstream lake approximate water surface during various flood conditions. Drawing prepared for Quechee Lakes Corporation, Quechee, Vermont.

APPENDIX A. RIVER DISCHARGE DATA

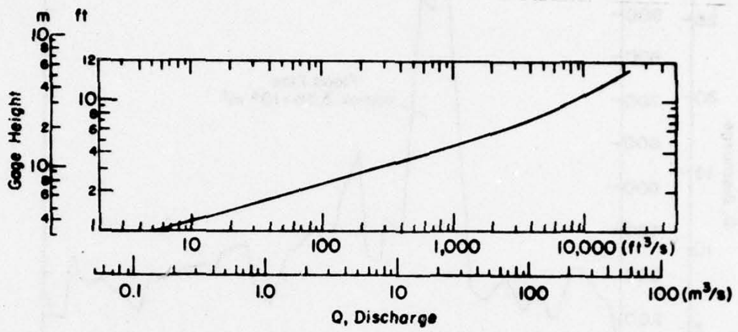

Figure A1. Ottauquechee River discharge rating curve.

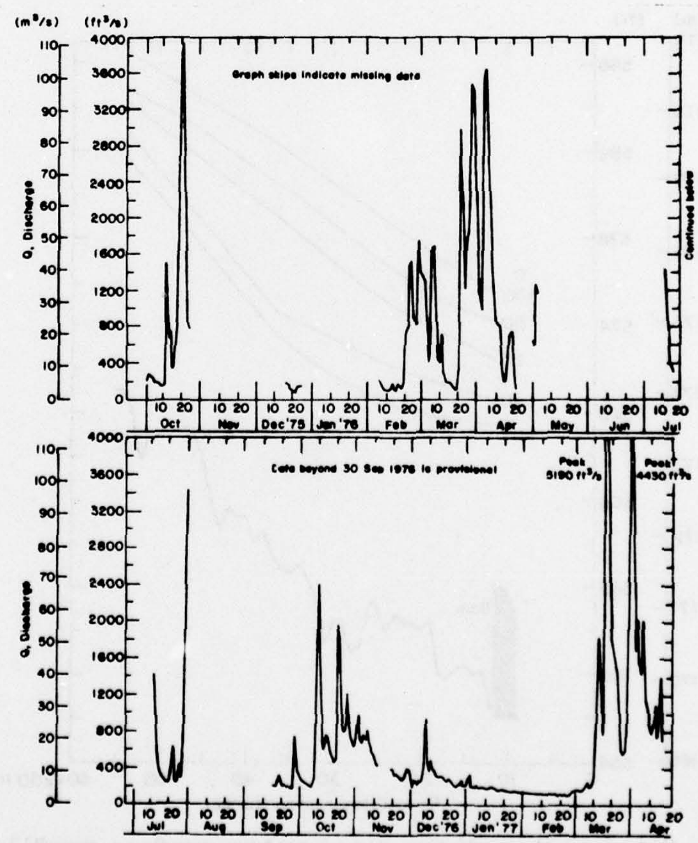

Figure A2. Ottauquechee River hydrograph.

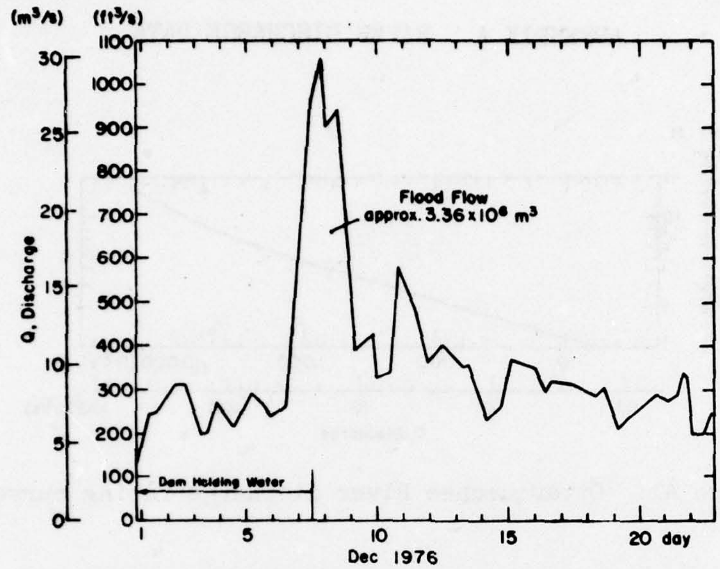

Figure A3. Ottauquechee River flood hydrograph.

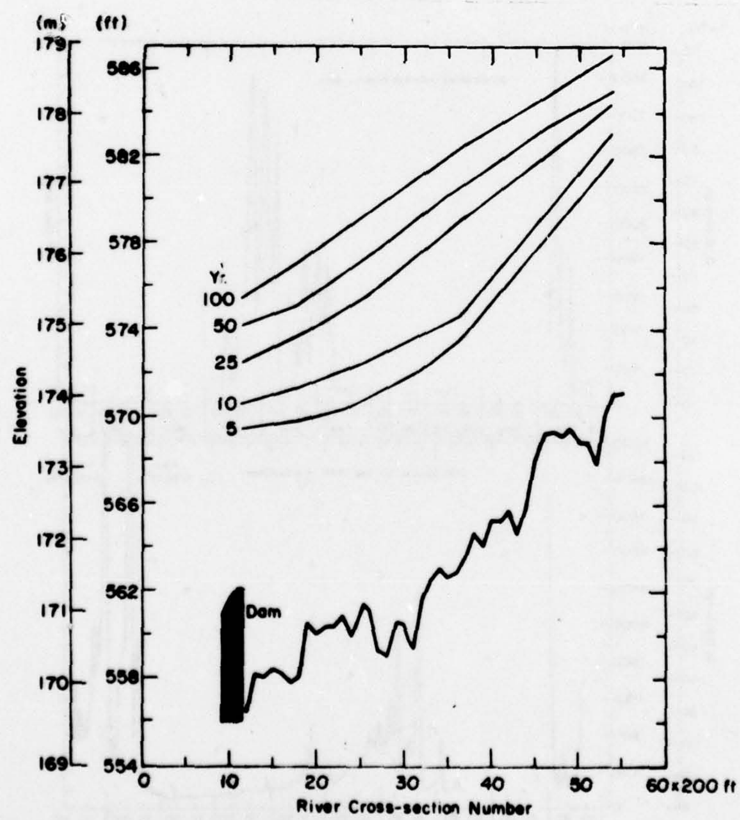

Figure A4. Ottauquechee River flood water surface profiles (after D'Appolonia Consulting Engineers, Inc.[2]).

APPENDIX B. ICE JAM PHOTOGRAPHY

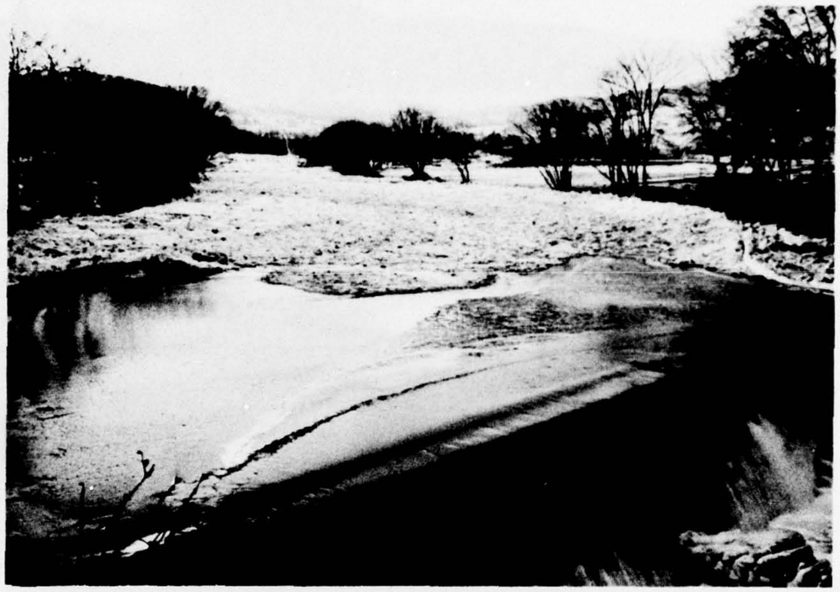

Figure B1. Ottauquechee River upstream of Quechee Dam - December 1976.

Figure B2. Floodplain in vicinity of cross section 25 - December 1976.

Figure B3. Ice run shear wall in contact with soil, near cross section 25 - December 1976.

Figure B4. Ice conditions in vicinity of cross section 45 - December 1976.

Figure B5. Damaged recorder installation, cross section 47 - December 1976.

Figure B6. Ice at Quechee Golf Course bridge - December 1976.

Figure B7. Ottauquechee River upstream of Quechee Dam, cross section 13 - March 1977.

Figure B8. Floodplain near cross section 25 - March 1977.

Figure B9. View downstream of cross section 45 - March 1977.

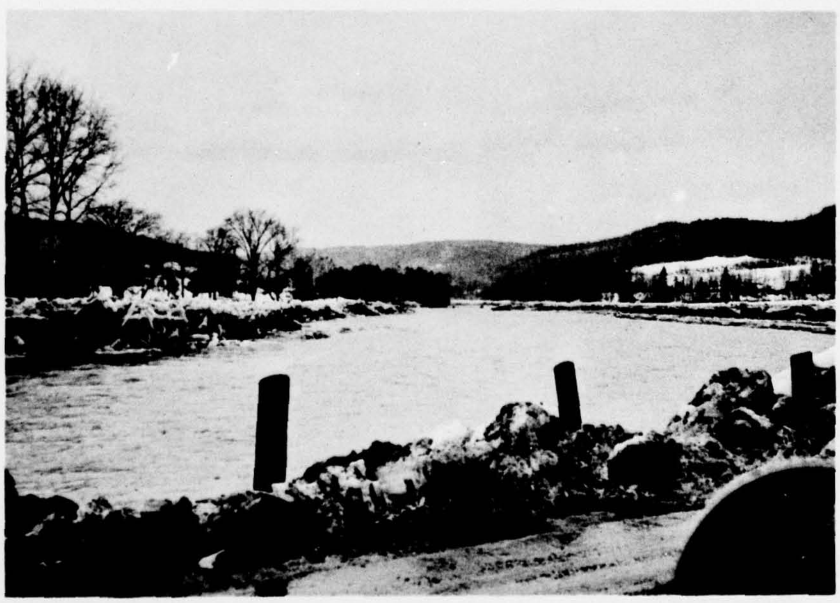

Figure B10. View upstream of cross section 45 - March 1977.