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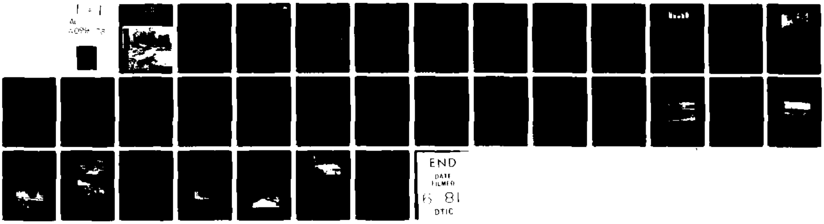

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## REPORT 81-1

# *Analysis of ice jams and their meteorological indicators for three winters on the Ottauquechee River, Vermont*

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*Cover: Ottauquechee River, east of Woodstock, Vermont.*

# Analysis of ice jams and their meteorological indicators for three winters on the Ottauquechee River, Vermont

Roy E. Bates and Mary-Lynn Brown

February 1981

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Prepared for
DIRECTORATE OF CIVIL WORKS
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The formation of ice jams and their meteorological indicators were studied in detail for the winters of 1975-76, 1976-77 and 1977-78 on the Ottauquechee River at and east of Woodstock, Vermont. Meteorological data are presented for nearby National Weather Service Co-Operative Stations as well as for CRREL sites on the Ottauquechee River. The severity of each winter is discussed, as are the effects of a heavy rainfall on a high water-equivalent snow cover. The resultant runoff and subsequent ice jamming that occurs is discussed. Continuous monitoring of water temperature before, during and immediately after an ice cover formed on the river during the winter of 1977-78 is included. The report includes a section on warm sewer outfall effects on the ice at and below

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20. Abstract (cont'd)

a municipal treatment plant. Retrieved data will assist in future modeling studies to help predict ice formation, growth, decay and jamming of river ice covers.

## PREFACE

This report was prepared by Roy E. Bates, Meteorologist, and Mary-Lynn Brown, Science Aid, of the Geophysical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was conducted under DA Program *Ice Engineering*, Work Unit CWIS 31332, *Fundamental Mechanics of Ice Jams*. Richard K. Haugen and Steven Daly of CRREL technically reviewed the manuscript.

The U.S. Army Atmospheric Sciences Laboratory (White Sands, New Mexico) meteorological detachment based at CRREL furnished and installed the meteorological instrumentation and tabulated the meteorological field data for the three winters of study (1975-1978).

The authors thank Bryan Harrington of the Engineering and Measurement Services Branch, Technical Services Division, for his assistance in the design and installation of the electronic water temperature collection system and Dr. George Ashton and Darryl Calkins for their helpful suggestions throughout the project.

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## CONTENTS

## ILLUSTRATIONS

## TABLES

# ANALYSIS OF ICE JAMS AND THEIR METEOROLOGICAL INDICATORS FOR THREE WINTERS ON THE OTTAUQUECHEE RIVER, VERMONT

Roy E. Bates and Mary-Lynn Brown

## INTRODUCTION

This report examines meteorological data, ice thickness, ice conditions (including ice jams), and water temperatures for three winters on the Ottauquechee River at and east of Woodstock, Vermont (Fig. 1 and 2). Meteorological variables discussed include air temperatures, precipitation (including water-equivalent snowfall), wind, and solar radiation.

The period of record covered includes three winters: November–March 1975-76, 1976-77, and 1977-78. In addition to a general interpretation of these data, emphasis is placed on the documentation of climatic (cooling and/or warming) trends (App. A) which lead to ice formation and growth as well as to breakup, when ice jamming and flooding are usually a major problem. After examining these climatic conditions, this report attempts to determine the meteorological indicators needed to predict ice formation, jamming, winter flooding, and subsequent breakup. A descriptive account of ice conditions for the three winters studied is given in Appendix B. An additional report, focusing on two major wintertime floods (January 1976, March 1977) is in preparation.

A second phase of the investigation includes a study of river water temperature profiles and ice conditions on the Ottauquechee at and downstream from the Woodstock Sewage Treatment Plant's outflow. The purpose of this part of the project is twofold: first to measure the manner in which warm sewage effluent, with a wintertime temperature between 3° and 7°C, mixes with the 0°C river water; and second, to evaluate the extent of the effect of this warm water (only a small percentage of the total flow) on the ice cover below the plant. The report, *Analysis of Potential Ice Jam Sites, Connecticut River at Windsor, Vermont*[2], shows an aerial photograph of a similar situation caused by warm sewage outfall into the nearby Connecticut River.

The objectives of this investigation can be summarized as follows:

1. To present the meteorological conditions in the Ottauquechee River basin during the winters of 1975-76, 1976-77 and 1977-78.
2. To identify meteorological events leading to ice formation, jamming, winter flooding and ice breakup.
3. To determine the influence of warm sewage effluent on river water temperatures and ice formation and growth.

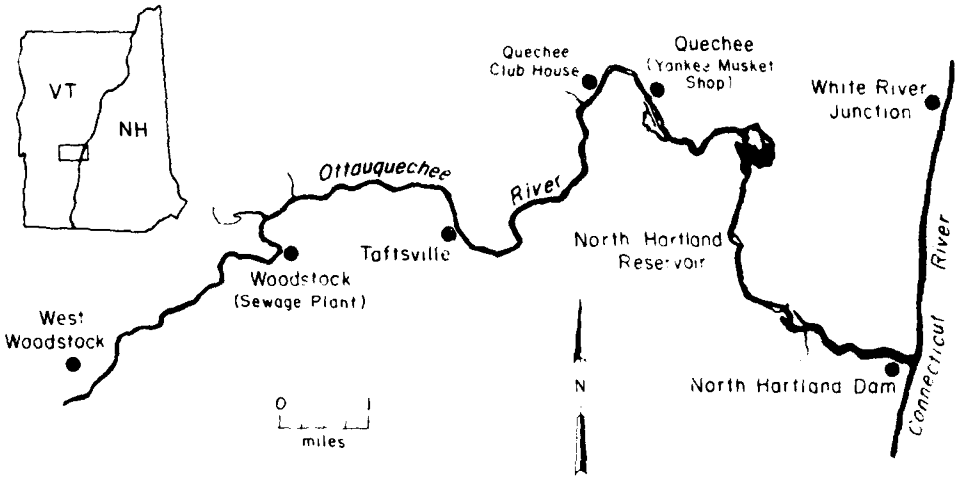


*Figure 1. Vicinity and measurement locations, Ottauquechee River, Vermont.*

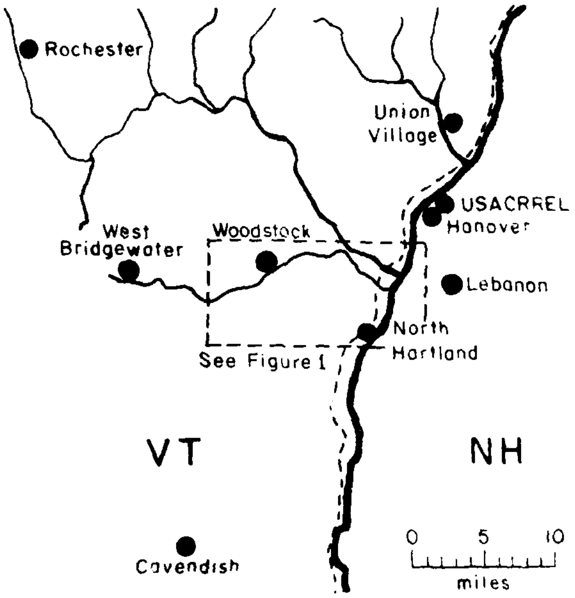


*Figure 2. Meteorological station locations*

## METEOROLOGICAL DATA RETRIEVAL AND MEASUREMENTS

CRREL established a meteorological data collection site on the Ottauquechee River at the Woodstock Sewage Treatment Plant in November 1976. Previous to that time (i.e. during the winter of 1975-76), weekly ice observations and water temperature measurements were made by CRREL personnel. Daily maximum and minimum air temperatures were obtained from the Woodstock Sewage Treatment Plant records[3] and precipitation amounts were taken from the New England Climatological Data (monthly summary) for Woodstock, Vermont[4]. During the 1976-77 winter, air temperatures and winds (speed and direction) were measured continuously at the CRREL site and precipitation data were again taken from the Woodstock Climatological Station monthly summaries[5]. However, for the winter of 1977-78, a precipitation recording gage was added to the instrumentation

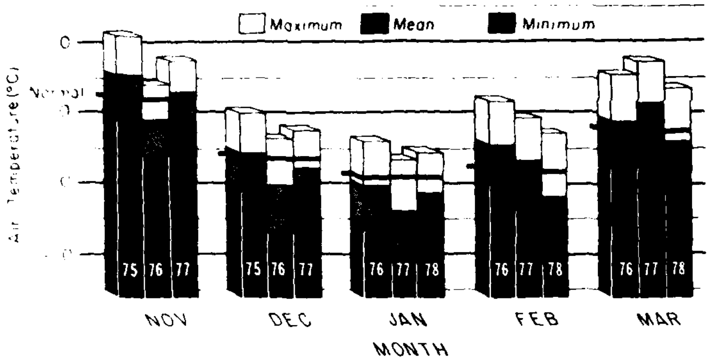


*Figure 3. Winter air temperatures at Woodstock, Vermont: 1975-78.*

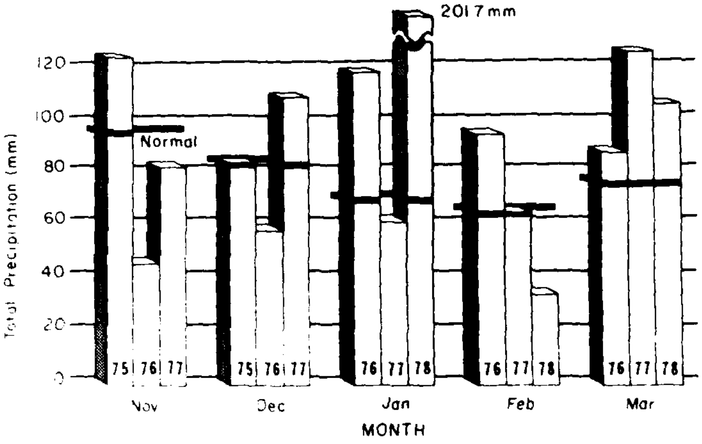


*Figure 4. Winter precipitation totals at Woodstock, Vermont: 1975-78.*

These data are summarized and compared to long term normals in Figures 3 and 4, and Tables 1 and 2. The accumulated freezing degree days (0°C base) were calculated for each winter period from the Woodstock Sewage Treatment Plant temperature data. The number of freezing degree days per month are summarized in Table 3. An accumulated freezing degree day curve for each winter period, plus the average curve, is illustrated in Figure 5. In determining a long-term average (30-year mean, 1941-1970), the normal temperatures (taken from the New England Climatological Data summaries for Woodstock) were assumed [illegible] represent the Woodstock Sewage Treatment Plant area. Actually the Woodstock [illegible] station was located nearer [illegible] the ma[illegible]

[illegible] mplete [illegible] site

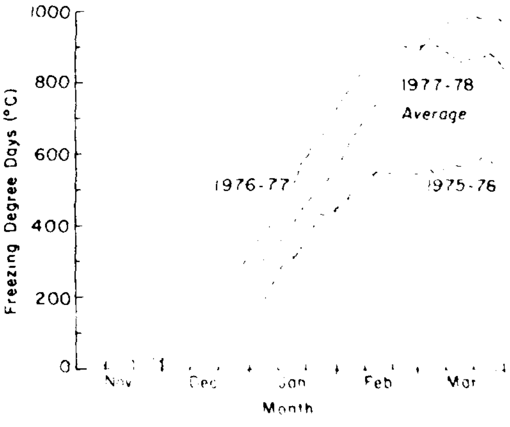


*Figure 5. Accumulated freezing degree days, Woodstock, Vermont.*

**Table 1. Air temperature comparison (°C), Woodstock, Vermont.**

| Month | Long-term average | 1975-76 | Departure | 1976-77 | Departure | 1977-78 | Departure |
|---|---|---|---|---|---|---|---|
| November | 2.4 | 6.1 | +3.7 | -0.4 | -2.8 | 3.2 | +0.8 |
| December | -5.7 | -5.1 | +0.6 | -9.4 | -3.7 | -7.0 | -1.3 |
| January | -8.3 | -9.7 | -1.4 | -13.0 | -4.7 | -10.5 | 2.2 |
| February | -7.4 | -3.3 | +4.1 | -6.3 | +1.1 | -11.5 | -4.1 |
| March | -1.4 | -0.4 | +1.0 | 1.9 | -3.3 | -3.3 | -1.9 |

Winter 1975-76 data from N.E. Climatic Survey for Woodstock, Vermont
Winter 1976-77 data from N.E. Climatic Survey for Woodstock, Vermont
Winter 1977-78 precipitation data from meteorological site near sewage plant in Woodstock, Vermont.

**Table 2. Precipitation comparison (mm), Woodstock, Vermont.**

| Month | Normal | 75-76 | % Normal | 76-77 | % Normal | 77-78 | % Normal |
|---|---|---|---|---|---|---|---|
| November | 96.2 | 122.9 | 127.8 | 45.7 | 47.5 | 82.1 | 85.3 |
| December | 84.3 | 83.6 | 99.2 | 58.2 | 69.0 | 108.0 | 128.1 |
| January | 71.4 | 117.6 | 164.7 | 61.5 | 86.1 | 201.7* | 282.2 |
| February | 65.8 | 94.7 | 143.9 | 65.1 | 98.9 | 33.3 | 50.6 |
| March | 76.7 | 86.9 | 113.3 | 125.5 | 163.6 | 105.1 | 137.0 |
| Total | 394.4 | 505.1 | | 356.0 | | 530.2 | |

*Reported precipitation data (72.4 mm) at the CRREL site were rejected as invalid as compared to amounts recorded by other nearby stations. The amount used (201.7 mm) was recorded by the Woodstock, Vermont, Cooperative Station Site.

Winter 1975-76 data from N.E. Climatic Survey for Woodstock, Vermont
Winter 1976-77 data from N.E. Climatic Survey for Woodstock, Vermont
Winter 1977-78 precipitation data from meteorological site near sewage plant in Woodstock, Vermont

**Table 3. Number of freezing degree days (°C).**

| | 1975-76 | | 1976-77 | | 1977-78 | | Normal | |
|---|---|---|---|---|---|---|---|---|
| | Month | Accumulated | Month | Accumulated | Month | Accumulated | Month | Accumulated |
| November | 2 | 2 | 28 | 28 | 20 | 20 | 5 | 5 |
| December | 151 | 153 | 291 | 319 | 217 | 237 | 177 | 182 |
| January | 292 | 445 | 403 | 722 | 320 | 557 | 257 | 439 |
| February | 99 | 544 | 177 | 899 | 322 | 879 | 207 | 646 |
| March | 12 | 556 | 8 | 907 | 98 | 977 | 48 | 694 |

was installed on the Ottauquechee River. Temperatures, precipitation, and wind (speed and direction) were recorded on a daily basis. In addition, water temperatures were electronically monitored at two sites one near the Woodstock Sewage Treatment Plant (Fig. 6) and the other near Quechee at the Yankee Musket Shop (Fig. 1). Because of recorder and thermistor cable difficulties, only one site (the Woodstock Sewage Treatment Plant) continuously recorded water temperatures in January 1978.

Climatic data (temperatures, precipitation, snowfall, and snow depth) for eight other local stations—Hanover, Lebanon, and CRREL in New Hampshire and Woodstock, N. Hartland Dam, Union Village Dam, Rochester, and Cavendish in Vermont—were examined as a means of verifying meteorological conditions for the entire Ottauquechee River drainage basin[4,6,7,8]. The tables in Appendix A summarize these data. These additional climate records were especially valuable during the two significant winter ice

*Figure 6. Water temperature measurement device near the Woodstock Sewage Treatment Plant.*

jam floods that occurred in January 1976 and March 1977. In addition, photographs were taken of various areas along the river during the three winters. These photographs (App. B) provide a record of ice formation, growth, jamming and decay as well as the effects of thermal effluents on the ice cover.

## METEOROLOGICAL EFFECTS ON RIVER ICE COVER

### Winter 1975-76

In comparison to the winters of 1976-77 and 1977-78, the winter of 1975-76 was warm. Compared to the long term average air temperatures, however, the winter of 1975-76 was closer to normal than the following two winters. Air temperatures in November 1975 and February 1976 were significantly higher than normal (Table 1), and freezing degree days did not begin to accumulate until early December. In mid-February 1976 the number of accumulated freezing degree days began to differ noticeably from the long-term average (Fig. 5 and Table 3).

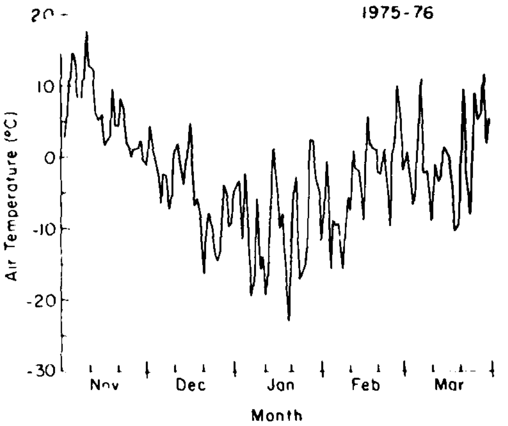
With the exception of December 1975, and to a lesser extent March 1976, there was abnormally high precipitation (Table 2 and Fig. 4). Table 2 shows that in November, January, and February precipitation amounts were, respectively, 27.8, 64.7, and 43.9% higher than average.

The most notable meteorological event of the 1975-76 winter was a thaw, accompanied by heavy rains, from 26 to 28 January. Within a few days, temperatures rose well above freezing (Fig. 7a), *disrupting the winter regime.* During the subsequent ice jam and flooding period, the maximum air temperatures at local sites rose to approximately 8°C (App. B), well above January's mean maximum temperature of approximately -2°C[9].

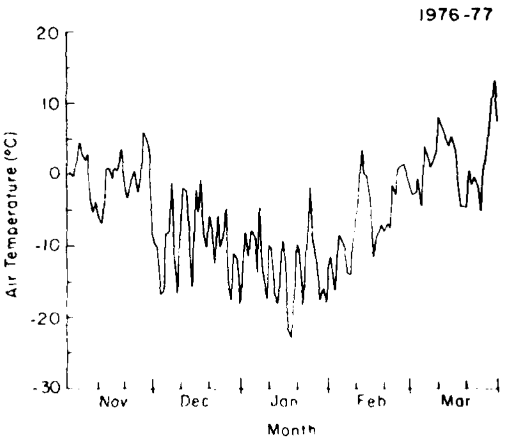
Coinciding with the rapid increase in temperature was heavy rainfall which accounted for over one-half of January's precipitation[1]. The combination of temperatures above freezing and heavy precipitation on an already high water-equivalent snow cover[7,8] caused extensive flooding and jamming of ice on the Ottauquechee River (Fig. B1).

The period of 4-7 February witnessed a quick end to the January thaw as temperatures rapidly dropped (Fig. 7a) and ice re-formed around the jammed and rafted ice (App. B).

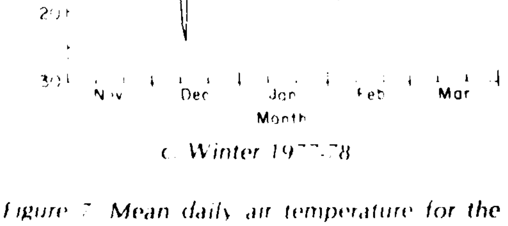
However, the remainder of February 1976 was extremely warm, with a mean daily air temperature of -3.3°C, 4.1°C above the long-term average. Because of the higher temperatures and no heavy rainfall, the ice jam on the Ottauquechee River disappeared gradually with no further damage by 1 March (App. B), two weeks earlier than during the two following winters.



*a. Winter 1975-76*



*b. Winter 1976-77*



*c. Winter 1977-78*

*Figure 7. Mean daily air temperature for the winters of 1975-78.*

## Winter 1976-77

In contrast to the previous winter, 1976-77 was typified by extremely low air temperatures (Fig 3 and 5, Tables 1 and 3) and below-normal precipitation (Fig. 4 and Table 2). Temperatures in November 1976 were 2.8°C below the long-term average, with a mean monthly temperature below freezing (-0.4°C, Table A2). Freezing degree days began to accumulate on 8 December, 17 days earlier than normal (Fig 5). In addition, precipitation in November was less than 50% of normal. The lack of significant precipitation, coupled with below average temperatures, led to an early freeze-over of the Ottauquechee River. Ice was first observed flowing in the river on 11 November, and by 30 November freeze over occurred on the Taftsville Pond (App B).

In December, the mean temperature was 4°C below normal (-9.4°C), and over 290 freezing degree days were recorded (Table 3) even though daily temperatures rose above average for a week in mid-December. Average daily maximum temperatures approached 0°C during this week, and a maximum temperature of 7.2°C was recorded on 12 December. This warming trend caused slight rafting and jamming of the ice in the Ottauquechee River (which later froze in place) (Fig B2), especially behind the Taftsville and Quechee Dams. However, because of the low amount of rainfall, these small jams caused only minimal flooding.

The remainder of the month was cold and dry and this trend persisted into January. January was the coldest month of the winter with a total of 403 freezing degree days (vs the normal of 257) (Table 3). The mean daily temperature was -13°C (Table 1) the largest departure from normal of the winter (-4.7°C below the long term average). The daily maximum temperature rose above freezing on only three occasions (2, 20 and 25 January). In addition, precipitation in January remained 14% below normal (Table 2). These meteorological conditions caused a rapid increase in ice thickness on the river during January (App B).

The severe cold, dry start of the winter of 1976-77 moderated in February. Precipitation was near normal (Table 2) and air temperature was 1.1°C above normal (Table 1). Because of the winter's low temperatures and the December 1976 ice jam, considerable amounts of rafted ice, frozen frazil, anchor ice and congelation (river water) ice were reported in the river from the Quechee dam upstream to west of Woodstock.

Less than normal precipitation from November to February was followed by 125 mm of precipitation in March, 163.6% of the normal 77 mm (Table 2). Of this precipitation, 52.8 mm (42% of the month's total) fell from 13 to 16 March[1]. Several days *prior to the rain, temperatures* soared 5-7°C above the monthly mean of 1.9°C (Fig. 7b), which was itself 3.3°C above the long-term average for March (Table 1). As in January 1976, the high temperatures, coupled with abnormally high precipitation, caused extensive ice jams and subsequent flooding (Fig. B3, B4, and B5). Snow disappeared virtually overnight, not only at Woodstock, but at sites throughout the local area. For example, at Hanover, New Hampshire, 13 cm of snow melted overnight in the period from 9-10 March[4].

It can thus be hypothesized that heavy rain, preceded or accompanied by a sudden increase in air temperature and combined with an existing high water-equivalent snow cover,[7,8] causes not only jamming and rafting of the ice cover, but also flooding. High temperatures alone can cause jamming and rafting (e.g. in December 1976), but the severity of the problem is increased when high temperature is combined with excessive rain (e.g. 26-28 January 1976, 13-16 March 1977).

### Winter 1977-78

The winter of 1977-78 could best be described as a winter of oscillation, in terms of both temperature and precipitation. Freezing air temperatures commenced slightly later than in 1976-77, however, spring breakup was late in arriving. The 1977-78 winter (November-March) was colder than normal, with the low temperatures (Fig. 3 and 5) accompanied by above normal precipitation (Fig. 4), especially in January. Temperatures were not as low as those experienced through January of the previous winter. However, in contrast to the relatively early arrival of spring in February 1977, temperatures remained significantly below normal in February and March 1978. The late arrival of higher temperatures is evidenced by the 25 March ice breakup date vs 1 March in 1976 and 16 March in 1977.

In addition to the daily air temperature and wind data previously monitored at the CRREL site, precipitation and water temperature were continuously recorded during the winter of 1977-78. Water temperatures were electronically monitored at two sites on the Ottauquechee River (Woodstock Sewage Plant and Yankee Musket Shop, Fig. 1). However, water temperature measurements at the Yankee Musket Shop were unsuccessful because of recorder problems and destruction of the sensor by ice movement.

November 1977 was near normal, with no extreme climatological variations. Temperatures were slightly above normal (+0.8°C, Table 1) and precipitation slightly below normal (85.3%, Table 2). Ice was first observed flowing in the Ottauquechee River on 27 November (vs 11 November the previous winter), but it was not until the major cold spell of 8-12 December (Fig. 7c) that the Taftsville Pond completely froze. As illustrated in the observational records (App. B), ice rapidly formed at many Ottauquechee River locations during this period. Significant snowfall also occurred during December and January.

Although recorders broke down in December, water temperature data were obtained for approximately one-half of the month. The mean maximum temperature of the water for that time period (20 days of data) was -0.01°C. The mean minimum water temperature (only 13 days of data) was -0.28°C, giving a monthly mean water temperature of -0.14°C. This negative temperature can be attributed to three possible factors. First, the recording device experienced mechanical difficulties and electrical interference during the early winter period. Second, slush ice formation around the sensors could have caused incorrect water temperature readings. Third, frazil ice was observed and the existence of supercooled water (<0°C), in conjunction with the turbulent flow of a river, is associated with this frazil ice formation[2]. Figure 8 gives a plot of the average daily water temperature obtained during the period January-March 1978.

Although December 1977 could be considered a wet month, with precipitation 128% of normal (Table 2), January 1978 definitely experienced abnormally high precipitation. For example, the Woodstock, Vermont, Cooperative Weather Station (data incomplete at the CRREL meteorological site) recorded 282% of January's average precipitation. This figure is compared to that of three other local stations in Table 4.

Two minor thaws occurred in January 1978 (4-9 January, 24-26 January), causing slight jamming and rafting of the ice (App. B). The second thaw was the more serious one. According to the observational report "thaw and heavy rain caused flooding and a new ice jam at Woodstock" (Fig. B6).

On 9 January 1978, the water temperature recording system at Woodstock was put back in operation. Water temperatures oscillated slight-

*Figure 8. Average daily water temperature near the Woodstock Sewage Treatment Plant: winter 1977-78.*

**Table 4. Local precipitation: January 1978.**

| *Station* | *% of normal precipitation* |
|---|---|
| Hanover | 231.5 |
| Woodstock | 282.2 |
| Rochester | 266.1 |
| Cavendish | 271.5 |
| Average | 262.8 |

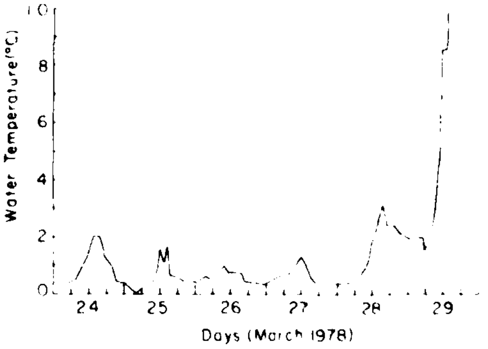


*Figure 9. Average daily water temperature near the Woodstock Sewage Treatment Plant: 24-29 March 1978.*

ly during the month, hovering barely above 0°C, and rising slightly with high air temperatures prior to the rains of 24-26 January (Fig. 6).

The Ottauquechee River refroze in early February. In terms of climate February varied more from normal than January. Not only was the mean daily temperature 4.1°C below normal (Table 1) with over 100 more freezing degree days (Table 3), but precipitation was even more significant when it is noted that most of it (88.8%) fell in a two-day period (8-9 February) during a severe snow storm, while the remainder of the month was dry.[4] The combination of low temperatures and lack of precipitation allowed the ice cover to quickly re-form (App. B).

Water temperature continued to fluctuate slightly, rising to a maximum daily mean of 0.06°C on 7 February, and then decreasing to 0°C on 14 February. The end of the month saw the beginning of slightly higher water temperatures, the start of the seasonal warming trend.

March 1978 continued to be cooler than average (air temperatures 1.9°C below the long-term average). Freezing degree days accumulated into early March, surpassing the total number of freezing days of the previous winter (Fig. 5). The freezing degree day curve reached its peak during the month and started to decline as a noticeable warming trend began (Fig. 3). As in the previous year, precipitation was above average (137%), although not to the same extreme (Table 2). No significant additional jamming and flooding of the river were observed as the ice gradually melted, despite the precipitation. This can be attributed to two factors. First, the slow warming trend (i.e. air temperatures slightly above freezing during the day with freezing temperatures at night) permitted gradual melting of the ice. The associated gradual warming of the water, evident late in the winter (Fig. 8) and detailed for the last week of March in Figure 9, aided this process. Second, because of jamming and melting of the ice cover earlier in the winter, the ice thickness was less than expected. However, a completely open river channel was not reported until 25 March 1978 (later than the previous two winters), following two days of heavy rain.[6]

## ANALYSIS OF ICE FORMATION AND DECAY

### Mechanism of ice formation

As air temperatures drop below 0°C, a water body responds to the heat loss by forming ice. The water must be cooled below the equilibrium point of 0°C before ice appears. A slight degree of supercooling was apparent in the Ottauquechee River, as evidenced by measurements of water temperatures during the 1977-78 winter. Ashton contends that "in rivers supercooling is seldom more than a few hundredths of a degree below 0°C when ice first appears."[10] Although the temperature sensors installed during the 1977-78 winter were accurate to 0.05°C, electronic noise difficulties with the strip chart recorder and frazil ice collection around the thermistor at Woodstock prevented accurate continuous measurement of the water temperature during the critical ice formation period. A mean water temperature of -0.14°C was recorded for approximately one-half of December, indicating either supercooled water or an ice-coated sensor.

After the temperature sensors and recorders became fully functional on 9 January 1978, continuous monitoring of water temperature was possible. The water temperature beneath the ice cover remained extremely close to 0°C (0.0°-0.1°C) from 9 January until nearly all ice melted in late March 1978 (Fig. 8).

Air temperature is not the only meteorological element controlling ice formation. Other meteorological variables that influence ice cover formation on both stationary and moving bodies of water include snow cover, precipitation, radiation and wind. On a moving body of water, such as the Ottauquechee River, the physical features of the channel also play an important role. The size and velocity of the river influence the amount of mixing that occurs. Furthermore, influx from tributaries, the quality of which is heavily dependent on precipitation, sediments, and water impurities from sources such as the atmosphere, power plants, highway salt and sewage treatment plants, influences ice formation and decay rates.

Finally, because of the dynamic nature of the Ottauquechee River, uninterrupted natural ice growth is rarely recorded over periods longer than 60 days. For example, during the three winters under consideration, high temperatures, accompanied by heavy rains on several occasions, caused melting, ice floes and jamming of the ice cover.

### Ice growth and decay on the Ottauquechee River, 1975-76, 1976-77, 1977-78

During the 1975-76 winter, data were not available regarding the date of initial freeze-over above the Woodstock Sewage Treatment Plant. However, the date of the appearance of frazil ice was recorded (17 December). In contrast, during the following two winters flowing frazil and slush ice were reported on the Ottauquechee River on 11 and 27 November respectively. Solid ice was reported by 15 December 1975, 30 November 1976, and 10 December 1977.

The physical characteristics of the river remained nearly the same during the three winters, as did the amount of effluent flowing into the river. Thus, assuming that meteorological variables such as radiation and wind are negligible in comparison to the effects of temperature and precipitation, ice formed relatively late in 1975-76 because of higher air temperatures and, to a lesser degree, precipitation. In contrast to the following two winters, temperatures in November and December 1975 were above the long-term average. In addition, precipitation during this same time period was at or above normal (Table 2). This rainfall led to increased flow in the river, preventing earlier ice formation.

However, November and December 1976 experienced temperatures significantly below normal, accompanied by below average precipitation. As a result, ice formation and growth were accelerated.

The precipitation and air temperature during the beginning of the 1977-78 winter season were near the average of those of the two previous winters (see Tables 1 and 2) and this period was thus more typical of the expected conditions. This is also reflected in the date of ice formation, which was the approximate average of the two previous winters.

The relationship of precipitation and air temperature with river ice formation and breakup continued throughout the remainder of the three winters. For example, in comparison to the following two winters, the maximum amount of ice recorded at any of the sites along the Ottauquechee River (Fig. 1) was significantly less in the 1975-76 winter. The maximum amount of ice measured in 1975-76 was 58 cm at the Taftsville Pond on 12 February. In contrast, 91 cm of frozen frazil ice (nearshore ice) or 76 cm of mid-channel ice was measured near the Quechee Village Green on 2 February 1977. Even during the 1977-78 winter, which experienced two thaws in January, 74 cm of ice remained on 7 March 1978, 6 m from shore above the Woodstock Sewage Treatment Plant (App. B).

The winter of 1975-76 also experienced an early ice-out date. Ice had virtually disappeared by the end of February 1976, whereas normal river ice was still 41 cm thick on 16 March 1977. During the winter of 1977-78, the ice was 43 cm thick in the middle of the river near the Yankee Musket Shop on 20 March. Even after considerable precipitation during 20-25 March 1978, some ice (~3 cm) still remained at several sites (App. B).

Higher than normal late February and early March air temperatures, accompanied by above average precipitation, accelerated the ice-out date in the winter of 1975-76. Another important factor in the early ice-out was the severe ice jam and the subsequent flood that occurred on 26-28 January 1976.

In the following two winters, small ice jams, unaccompanied by rain, formed during 11-12 December 1976 and 4-9 January 1978. Another jam formed late in January 1978 (24-26 January) as a result of a heavy rain storm; however, as in the other two small ice jams, not all areas were affected because air temperatures rose only slightly above freezing. As opposed to the January 1976 ice jam, below-normal air temperatures immediately followed these ice jams, facilitating complete freeze-over (Table 1), a condition which was not present after the 1976 ice jam.

Prior to the ice jam flooding of January 1976, more ice was observed in the Ottauquechee River than at similar times during the following two winters. Again, this reduced ice depth can be attributed to the early ice jams in December 1976 and early January 1978.

The severity of the rafting and jamming ice in January 1976 and the resulting high water cleared out the majority of the ice, as it also did in March 1977. Although the ice re-formed in February 1976, significant ice growth was not reported. The relative lack of ice growth can be attributed to the absence of the necessary meteorological conditions (i.e. low temperatures of long duration and little precipitation).

What causes the ice to jam and what determines the severity of the ice jam? Channel morphology is a significant determinant. As defined by Calkins et al. "areas ... where ice jams generally form are: 1) constrictions, 2) exposed rock outcrops and man-made structures (bridge piers), 3) long, low velocity, deep water pools, and 4) shallow sections across portions of the channel where grounding of ice floes could be initiated."[2] Areas along the Ottauquechee River which are susceptible to grounding and jamming of ice are outlined as follows (from App. 2):

1. Bridges
   Elm St. bridge in Woodstock
   Quechee Lakes bridge (golf course)
2. Dams
   Taftsville and Quechee
3. Near Woodstock Sewage Treatment Plant (double oxbow)
4. Lakes/Ponds
   Quechee Lakes/Taftsville Pond

The question remains as to what meteorological conditions cause ice jams at these locations. While sudden high air temperatures can cause rafting and jamming of ice, a sharp rise in air temperatures accompanied by heavy rainfall (which increases the influx of water from tributaries) on a high water-equivalent snow cover increases the likelihood of severe ice jamming and high water. The available data indicate that 3 cm (approximately 1 in.) of wintertime rainfall in the Ottauquechee River drainage basin in a 24-hr period on a high water-equivalent snow cover causes significant flooding and ice jamming. Some grounding, rafting, and jamming of the ice cover typically occurs each spring, as the rapid arrival of warm weather does not normally allow the ice cover time to melt in place. For example, the spring of 1978 experienced a gradual rise in temperatures followed by normal rainfall. Thus, flooding and jamming did not cause serious problems, a definite contrast to March of 1977 when heavy rain and a rapid increase in the air temperature occurred simultaneously.

However, as demonstrated in January 1976 and to a lesser extent in December 1976 and January 1978 (App. B), ice jamming is possible at any time during the winter, given the appropriate meteorological and physical conditions.

## INFLUENCE OF WARM SEWAGE EFFLUENT ON RIVER WATER TEMPERATURES AND ICE CONDITIONS

Another objective of this report is the examination of the extent and effect of thermal effluent outflow from the Woodstock Sewage Treatment Plant on the Ottauquechee River's ice cover. The amount of this flow is insignificant when compared to total river flow. Approximately 400,000 gal. is discharged daily into the river, less than 2% of the river's total flow.[3] However, as illustrated in the photographs (Fig. B7 and B8), the significance of this warm water input cannot be underestimated. The effluent combines vertically with the river water and proceeds downstream. The warmer effluent then expands laterally by turbulent mixing, as explained by Ashton[10] and Engmann[11]: "in the open surface area the lateral mixing is similar to that during non-ice periods, but beneath the ice cover the mixing rate is approximately one-half that in open water conditions."[11] Thus, the lateral mix

**Table 5. Water temperatures* as influenced by the influx of warm (approx. 6°C) sewage effluent: 1975-76 winter.**

| *Date* | *Water temp (°C) near outflow pipe* | *Water temp (°C) 5.7 m below pipe* | *Remarks* |
|---|---|---|---|
| 17 Dec 1975 | 3.4 | 1.5 | |
| 2 Jan 1976 | 0.25 | 0.05 | Open channel of water 1 m wide along shore extends 30 *m down river* |
| 14 Jan 1976 | 1.5 | 0.6 | |
| 21 Jan 1976 | 2.45 | 0 | |
| 12 Feb 1976 | 1.2 | 0.03 | A few days after ice jam small open water area 60 cm wide, 4 m long, thawed by warm water input |
| 27 Feb 1976 | 2.3 | | |
| 3 Mar 1976 | River ice thawed | | |

*Temperature of water above sewage plant was *near 0°C during this time period.*

ing and other secondary effects) cause the characteristic open water area to be much narrower than it is long, by a factor as great as several hundred. This is supported by measurements made during the *three winters under* consideration. Although CRREL did not continuously monitor the extent of open water caused by the sewage outflow, occasional references appear in the ice thickness observational records (App. B). For example, on 2 January 1976 an observer reported that an open water channel 1 m wide extended 20 m downstream *along the shore* (Table 5).

In addition to visual observations of the influence of warm sewage effluent on the ice cover, CRREL also measured water temperatures above *the sewage outfall at various times during the* three winter periods at the outfall pipe and approximately 6 m below the pipe. Water temperatures were accurately monitored during the 1975-76 winter and these results are presented below (see App. B for data from the other two winters).

Without the thermal effluent discharge, the temperature of the water beneath the ice cover would be expected to be quite close to 0°C. However, the available data demonstrate that the discharge of the 6°C wastewater into the river disrupts the ice-water equilibrium. In fact, even during the large ice jams of January 1976 and March 1977, an area of open water is formed below the sewage outflow pipe within a few days.

Thermal effluents released into the Ottauquechee River by the Woodstock Sewage *Treatment* Plant disturb the winter regime of the river downstream of the outflow by slightly raising the temperature of the surrounding water and delaying or preventing the formation of a uniform ice cover.

## CONCLUSIONS

Several conclusions can be drawn from studying the winter regime of the Ottauquechee River. The winter of 1975-76 was the least severe of the three winters in terms of precipitation, temperature and ice growth. The winters of 1976-77 and 1977-78 had comparable severity, with the 1976-77 winter having the earliest ice cover and being coldest through the month of January. However, the winter abruptly ended in March 1977 with a severe ice jam and flooding. The 1977-78 winter was longer, having the greatest number of freezing degree days (Fig. 5) and the latest ice-out date.

These data provide a base for modeling of *wintertime rivers.* The conditions controlling ice formation, jamming and melting can be more accurately determined from these records. For example, this study provided the impetus for a subsequent report concentrating on the identification of the factors causing the two major jams/floods on the Ottauquechee River during the last three winters. Precipitation measurements in dicate that 3 cm of rainfall in 24 hr on a high *water-equivalent* snow cover causes ice jams and subsequent flooding

Second, the daily continuous *monitoring of* water temperatures during the 1977-78 winter provided a useful addition to the study of the river From this report and from the work of other investigators, it appears that supercooling of the river occurred immediately prior to freezeover However, this hypothesis could not be completely validated because of mechanical instrumentation problems Additional measurements are necessary for more accurate evaluation

Continuous measurements demonstrated that the water temperature below the ice cover averaged approximately 0.03°C With the arrival of higher air temperatures and increased solar radiation in early March the ice cover deteriorated open water areas appeared and the water temperature became more responsive to air temperature fluctuations During March the water temperatures gradually rose and greater daily temperature oscillations were evident Fig 8 and 9

Finally the influence of sewage effluent on the Ottauquechee River ice was also observed during the three winters Although it is only 2% of the total flow this warm water outflow affected the thermal regime and ice cover in the immediate area Water temperatures at and below the outfall pipe were frequently monitored and measurements of the size and shape of the open water channel below the outfall pipe were completed Extensive work is needed regarding the effect of warm water input sources on ice cover near large municipal *power plants* and at industrial and municipal wastewater outfalls where thermal regimes are disturbed

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# APPENDIX A: CLIMATOLOGICAL OBSERVATIONS

Table A1: Climate 1975-76 Winter

| Station | Mean max | Mean min | Mean temp | Departure | Amt. precip | Departure | Max snow depth | Snow-fall | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | (°C) | (°C) | (°C) | (°C) | (mm) | (mm) | (cm) | (cm) | |
| | | | | | Nov 1975 | | | | |
| Hanover | 10.3 | 0.3 | 5.3 | 2.7 | 115 | 25 | 8 | 4 | |
| Lebanon | 11.2 | 0.2 | 5.7 | - | 121 | - | 3 | 3 | |
| CRREL | 10.0 | 0.0 | 5.0 | - | 107 | - | T | T | |
| Woodstock | 10.2 | -2.8 | 3.7 | 1.3 | 123 | 27 | 10 | 10 | |
| Sewage Plant | 11.4 | 0.7 | 6.1 | - | | | | | |
| N. Hartland Dam | 10.6 | -0.6 | 5.1 | - | 104 | | - | 14 | |
| Union Village | 10.7 | -2.5 | 4.1 | - | 106 | | 3 | 8 | |
| Rochester | 10.6 | -1.1 | 4.8 | - | 131 | 25 | 10 | 23 | |
| Cavendish | 10.8 | -0.6 | 5.1 | 3.0 | 135 | 31 | 10 | 13 | |
| AVG | 10.6 | -0.7 | 5.0 | - | 118 | - | | 9 | |
| | | | | | Dec 1975 | | | | |
| Hanover | -0.8 | -10.7 | [illegible] | 1.6 | [illegible] | 6 | 38 | [illegible] | |
| Lebanon | [illegible] | -11.0 | [illegible] | - | [illegible] | - | [illegible] | [illegible] | |
| CRREL | [illegible] | -12.8 | [illegible] | - | [illegible] | | [illegible] | | |
| Woodstock | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | | |
| Sewage Plant | [illegible] | [illegible] | [illegible] | | - | - | - | | |
| N. Hartland Dam | [illegible] | [illegible] | [illegible] | - | [illegible] | - | | | |
| Union Village | [illegible] | [illegible] | [illegible] | - | [illegible] | - | [illegible] | [illegible] | |
| Rochester | [illegible] | [illegible] | [illegible] | - | [illegible] | | [illegible] | | |
| Cavendish | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| AVG | [illegible] | [illegible] | [illegible] | | [illegible] | | - | [illegible] | |
| | | | | | [illegible] | | | | |
| Hanover | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Lebanon | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | [illegible] | [illegible] |
| CRREL | [illegible] | [illegible] | [illegible] | | [illegible] | - | [illegible] | - | [illegible] |
| Woodstock | [illegible] | | | | [illegible] | [illegible] | | | |
| Sewage Plant | [illegible] | [illegible] | [illegible] | | | | | | |
| N. Hartland Dam | [illegible] | [illegible] | [illegible] | - | [illegible] | | 61 | - | [illegible] |
| Union Village | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] |
| Rochester | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Cavendish | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| AVG | [illegible] | -18.2 | -11.1 | - | 106 | - | | 67 | |
| | | | | | Feb 1976 | | | | |
| Hanover | [illegible] | -9.6 | -2.9 | [illegible] | 78 | 17 | 48 | | |
| Lebanon | [illegible] | -10.[illegible] | -3.6 | - | 60 | - | 41 | 10 | |
| CRREL | [illegible] | -11.1 | [illegible] | - | 87 | - | 36 | | |
| Woodstock | [illegible] | -11.6 | [illegible] | [illegible] | 95 | 29 | 86 | [illegible] | |
| Sewage Plant | [illegible] | [illegible] | [illegible] | | - | - | - | - | |
| N. Hartland Dam | [illegible] | [illegible] | [illegible] | | 83 | - | | - | |
| Union Village | [illegible] | [illegible] | [illegible] | | 133 | [illegible] | 66 | [illegible] | |
| Rochester | [illegible] | [illegible] | [illegible] | [illegible] | 103 | [illegible] | 58 | [illegible] | |
| Cavendish | [illegible] | [illegible] | [illegible] | | [illegible] | | 51 | [illegible] | |
| AVG | [illegible] | [illegible] | [illegible] | - | [illegible] | - | | [illegible] | |
| | | | | | Mar 1976 | | | | |
| Hanover | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 20 | [illegible] | [illegible] | |
| Lebanon | [illegible] | [illegible] | [illegible] | - | [illegible] | - | 23 | [illegible] | |
| CRREL | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | | |
| Woodstock | [illegible] | [illegible] | [illegible] | | [illegible] | 10 | 91 | [illegible] | |
| Sewage Plant | [illegible] | [illegible] | [illegible] | | | | | | |
| N. Hartland Dam | [illegible] | [illegible] | [illegible] | | [illegible] | - | | [illegible] | |
| Union Village | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | [illegible] | |
| Rochester | [illegible] | [illegible] | [illegible] | | 99 | 14 | [illegible] | [illegible] | |
| Cavendish | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13 | [illegible] | [illegible] | |
| AVG | [illegible] | [illegible] | | | [illegible] | | | [illegible] | |

[illegible]

Table A2: Climate 1976-77 Winter

| Station | Mean max (°C) | Mean min (°C) | Mean temp (°C) | Departure (°C) | Amt. precip. (mm) | Departure (mm) | Max snow depth (cm) | Snow-fall (cm) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | November 1976 | | | | | |
| Hanover | 4.8 | -3.5 | 0.7 | -2.0 | 46 | -5 | 5 | 9 | |
| Lebanon | 4.8 | -3.9 | 0.5 | -- | 38 | -- | 5 | 11 | |
| CRREL | 3.8 | -4.6 | -0.4 | -- | 46 | -- | -- | -- | |
| Woodstock | 4.3 | -4.9 | -0.3 | -2.8 | 46 | -50 | 10 | 18 | |
| MEI Site | [illegible] | -5.2 | -0.4 | -- | -- | -- | -- | -- | |
| N. Hartland Dam | 4.3 | -3.8 | 0.4 | -- | [illegible] | -- | -- | -- | |
| Union Village | 4.8 | [illegible] | -0.6 | -- | [illegible] | -- | -- | -- | |
| Chester | [illegible] | [illegible] | -0.1 | -- | [illegible] | [illegible] | 16 | 15 | |
| Cavendish | [illegible] | -3.4 | [illegible] | -1.6 | 29 | [illegible] | [illegible] | 15 | |
| Avg. | 4.6 | [illegible] | [illegible] | -- | [illegible] | -- | - | 14 | |
| | | | | December 1976 | | | | | |
| Hanover | [illegible] | -14.[illegible] | -8.[illegible] | [illegible] | [illegible] | -23 | 17 | 2[illegible] | |
| Lebanon | -2.[illegible] | -14.2 | -8.1 | -- | [illegible] | -- | 1[illegible] | 2[illegible] | |
| CRREL | -[illegible].1 | -1[illegible] | -9.[illegible] | -- | [illegible] | -- | -- | -- | |
| Woodstock | [illegible]* | -1[illegible]* | -9.2* | [illegible] | [illegible] | [illegible] | 1[illegible] | [illegible] | *2 days data missing |
| MEI Site | [illegible] | [illegible] | [illegible] | -- | [illegible] | - | [illegible] | - | |
| N. Hartland Dam | [illegible] | [illegible] | [illegible] | - | [illegible] | -- | [illegible] | [illegible] | |
| Union Village | [illegible] | [illegible] | [illegible] | -- | [illegible] | [illegible] | [illegible] | 30 | |
| Chester | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | -- | |
| Cavendish | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| Avg. | [illegible] | [illegible] | [illegible] | [illegible] | | | [illegible] | [illegible] | |
| | | | | January 1977 | | | | | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] |
| [illegible] | | [illegible] | [illegible] | | | | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | | | | | | |
| [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | | | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | |
| | | [illegible] | [illegible] | | | | | | |

Table A3: Climate 1977-78 Winter

| Station | Mean max (°C) | Mean min (°C) | Mean temp (°C) | Departure (°C) | Amt. precip. (mm) | Departure (mm) | Max snow depth (cm) | Snow-fall (cm) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | November 1977 | | | | |
| Hanover | 8.5 | 0.2 | 4.3 | 2 | 81 | -8 | 2 | 3 | |
| Lebanon | 8.7 | 0.2 | 4.4 | -- | 63 | -- | 3 | 3 | |
| CRREL | 8.3 | -0.7 | 3.8 | -- | 73 | -- | -- | -- | |
| Woodstock | 7.9 | -1.4 | 3.2 | 1 | 73 | -23 | -- | 11 | |
| MET Site | -- | Incomplete Data | | | | | | | |
| N. Hartland Dam | 8.9 | -0.3 | 4.3 | -- | 91 | -- | 3 | -- | |
| Union Village | 8.6 | -1.8 | 3.4 | -- | 71 | -- | 3 | 3 | |
| Rochester | 8.7 | -1.2 | 3.8 | -- | 104 | -2 | 15 | 23 | |
| Cavendish | 8.1 | -0.9 | 3.6 | 1 | 94 | -10 | 5 | 9 | |
| AVG | 8.5 | -0.7 | 3.8 | -- | 81 | -- | -- | 9 | |
| | | | | | December 1977 | | | | |
| Hanover | -0.8 | -9.5 | -5.2 | 0 | 92 | 18 | 41 | 61 | |
| Lebanon | -0.9 | -9.7 | -5.3 | -- | 75 | -- | 48 | 60 | |
| CRREL | 0.0 | -9.0 | -4.5 | -- | 68 | -- | 33 | -- | |
| Woodstock | -2.0 | -12.4 | -7.2 | -2 | 133 | 49 | 69 | 71 | |
| MET Site | -1.9 | -12.1 | -7.0 | -- | 108 | -- | -- | -- | |
| N. Hartland Dam | -0.2 | -10.6 | -5.4 | -- | 86 | -- | -- | -- | |
| Union Village | -0.9 | -13.2 | -7.0 | -- | 91 | -- | 51 | 66 | |
| Rochester | -0.9 | -11.1 | -6.0 | -- | 142 | 50 | 46 | 77 | |
| Cavendish | -1.5 | -12.7 | -7.1 | -2 | 136 | 48 | 51 | 86 | |
| AVG | -1.0 | -11.1 | -6.1 | -- | 104 | -- | -- | 70 | |
| | | | | | January 1978 | | | | |
| Hanover | -3.2 | -13.2 | -8.2 | 0 | 149 | 85 | 75 | 90 | |
| Lebanon | -3.1 | -13.4 | -8.3 | -- | 143 | -- | 66 | 75 | |
| CRREL | -3.5 | -14.5 | -9.0 | -- | 110 | -- | -- | -- | |
| Woodstock | -3.5 | -15.1 | -9.3 | -1 | 202 | 130 | -- | 117 | |
| MET Site | -4.9 | -16.2 | -10.5 | | - | | | | |
| N. Hartland Dam | -2.0 | -13.2 | -7.6 | -- | 154 | -- | -- | -- | |
| Union Village | -2.4 | -15.6 | -9.0 | -- | 143 | -- | 79 | 99 | |
| Rochester | -2.7 | -15.3 | -9.0 | -- | 184 | 115 | 91 | 137 | |
| Cavendish | -2.4 | -15.2 | -8.8 | -1 | 204 | 129 | 102 | 107 | |
| AVG | -3.1 | -14.6 | -8.8 | -- | 161 | -- | -- | -- | |
| | | | | | February 1978 | | | | |
| Hanover | -2.2 | -17.8 | -10.0 | -3.7 | 56 | 0 | 99 | 65 | |
| Lebanon | -2.2 | -18.6 | -10.4 | -- | 70 | -- | 104 | 89 | |
| CRREL | -2.0 | -20.0 | -11.0 | -- | 20 | -- | 95 | -- | |
| Woodstock | -3.4 | -21.4 | -12.4 | -5.0 | 35 | -31 | -- | 80 | |
| MET Site | -1.9 | -21.1 | -11.5 | -- | 33 | -- | -- | -- | |
| N. Hartland Dam | -2.9 | -18.9 | -10.9 | -- | 23 | -- | -- | -- | |
| Union Village | -2.7 | -23.2 | -13.0 | -- | 22 | -- | 81 | 73 | |
| Rochester | -2.1 | -14.2 | -11.7 | -- | 28 | -35 | 122 | 64 | |
| Cavendish | -2.9 | -20.9 | -11.9 | -5.2 | 33 | -45 | 112 | 66 | |
| AVG | -2.5 | -19.6 | -11.4 | -- | 37 | -- | -- | 69 | |
| | | | | | March 1978 | | | | |
| Hanover | 4.3 | -8.9 | -2.3 | -1.8 | 43 | -24 | 76 | 23 | |
| Lebanon | 3.4 | -8.6 | -2.6 | -- | 56 | -- | 38 | 18 | |
| CRREL | 3.5 | -9.5 | -3.0 | -- | 30 | -- | 56 | -- | |
| Woodstock | No Data Available | | | | | | | | |
| MET Site | 3.6 | -10.0 | -3.3 | -- | 65 | -- | -- | -- | |
| N. Hartland Dam | 4.4 | -8.3 | -2.0 | -- | 47 | -- | -- | -- | |
| Union Village | 3.4 | -12.7 | -4.6 | -- | 40 | -- | 76 | 38 | |
| Rochester | 3.5 | -11.2 | -3.8 | -- | 79 | -5 | 86 | -- | |
| Cavendish | 3.5 | -10.4 | -3.4 | -2.4 | 64 | -22 | 94 | 41 | |
| AVG | 3.7 | -10.0 | -3.1 | -- | 53 | -- | -- | 30 | |

## APPENDIX B: ICE CONDITIONS, FIELD REMARKS AND PERTINENT PHOTOGRAPHY

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| | | 1975-76 WINTER |
| 17 Dec | ---------- | Frazil ice flowing. Water temperature at Quechee Clubhouse 0-0.1°C. Possibly some super-cooled water near shore. Water temperature near Woodstock Sewage Treatment Plant outfall, 3-4°C. River temperature 5-7 m below outfall, 0.5°C. Temperature of effluent at plant, 6°C. |
| 2 Jan | ---------- | Ottauquechee River at Golf Course almost completely frozen over, covered with 3-5 cm snow. Small open area near bend at clubhouse, water temperature 0.05°C. Frazil ice in water. Clear day, air temperature -18 to -12°C. |
| | | At Woodstock Sewage Treatment Plant the ice and snow conditions the same as at clubhouse. Open river channel at outfall pipe and downstream 30 m. Open channel 1 m wide. Water temperature probe placed at outfall pipe. Water upwelling, temperature ≈7.5°C, 2 m downstream temperature 2.5°C, 9 m downstream temperature 0.05°C. |
| 14 Jan | ---------- | Quechee Lakes: Air temperature ≈-18°C. Sunny. River covered with wet snow. Water temperature 0°C. |
| | 54 | At Woodstock Sewage Treatment Plant open water extends 450 m downstream. Ice thickness measured 6 m upstream from outfall pipe; water temperature 0°C. At pipe water temperature 1.5°C. Downstream ≈6 m temperature 0.6°C (temperature readings taken near outfall pipe depend on where probe was placed with respect to pipe. Readings on successive days vary due to difficulty of finding the same location when heavy fresh snow covers reference points). |
| | | At treatment plant and Quechee Lakes, frazil ice flowing in open water. |
| 21 Jan | ---------- | Quechee Lakes: Little change in overall conditions. Water temperature 0°C. Ice unsafe. |

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| | 61-64 | Woodstock Sewage Treatment Plant: Two holes drilled 6 m apart. Ice measures 61 to 64 cm. Water temperature 0.05°C. |
| | | At outfall pipe opening in ice ≈61 cm downstream, water temperature 2.45°C. 8 m below pipe water temperature 0°C. (For last three weeks ice surface consists of small soft snow hillocks 1 to 4 cm deep below which is ice and soft slush.) |
| 26-28 Jan | ---------- | High air temperature coupled with heavy precipitation caused heavy flooding and severe ice jamming along the Ottauquechee River. High water caused by over 6 cm of rain in a three-day period. Air temperature rose as high as 8°C (Fig. B1). |

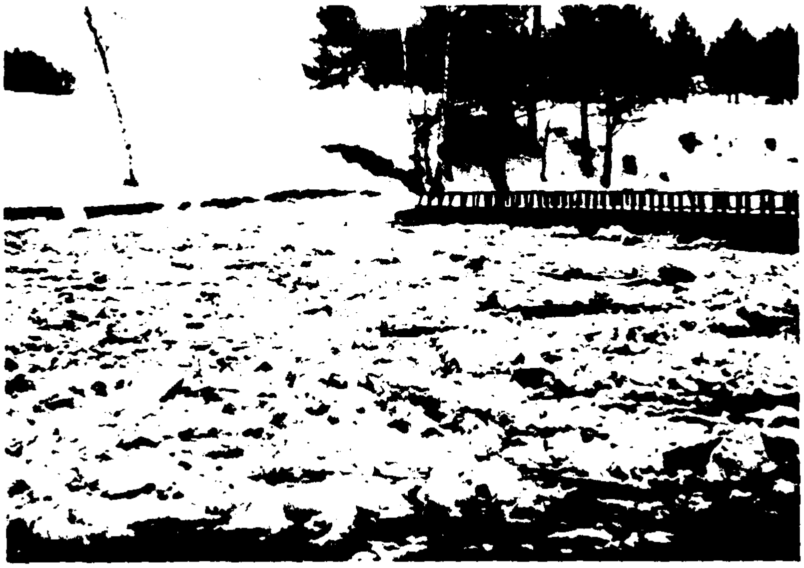

Figure B1. Ice jam at Quechee Golf Course bridge, 26-28 January 1976.

| | | |
|---|---|---|
| 12 Feb | 13-18 | At Quechee Lakes new ice formed between and around old ice jam conglomerate that settled. Water flowing between ice layers and underneath ice jam. Water channel flow restricted. |
| | 43-51 | Quechee Lakes Mill Pond ice covered. |
| | | Woodstock Sewage Treatment Plant: Ice jam entirely around sewage outfall area that extends 1 mile upstream and 1 mile |

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| | | downstream to Taftsville Pond. Small area in the jam near outfall pipe is thawed. Area is ≈60 cm wide, 3.5-4.5 m long. Water temperature around pipe 1-2°C both slightly upstream and downstream. Water temperature 2.5 m downstream 0-0.3°C. |
| | 45-58 (variable) | Taftsville Pond: Dirt layer observed in ice indicative of the flood. River ice temperature isothermal at 0°C, measured at 10, 30 and 50 cm below ice surface. Ice closer to dam of variable thickness. |
| 27 Feb | ---------- | Ice jam has rotted out downstream from Elm St. Bridge in Woodstock to 250-350 m above Woodstock Sewage Treatment Plant. Water flowing through new river channel cut across Billings Farm field immediately below sewage treatment plant. |
| | 20-46 | At Taftville Pond the water has started flowing along shore. |
| | | Water temperature near Woodstock Sewage Treatment Plant outfall 2-3°C. |
| | | Water flowing over and through portions of jam. Water partially open upstream from jam. Water rising in Ottauquechee and White rivers as air temperatures on 25-26 February 10-18°C. |
| 1 Mar | ---------- | Ice at Woodstock Sewage Treatment Plant melted as far as 180-270 m below plant by 28 Feb. Jam completely melted out of Ottauquechee River down to Taftsville Pond by 29 Feb. Ice remains on Taftsville Pond. |
| 2 Mar | ---------- | Ice balls flowing in river. Frazil ice. Ice or slush balls (8-13 cm in size) caused by heavy snowfall at -7°C air temperature on open water. Frazil ice flowing beneath flowing ice balls. |
| | | 1976-77 WINTER |
| 11 Nov | ---------- | Slush ice flowing in river at Taftsville. |
| 12 Nov | ---------- | First ice cover forming at Taftsville. At Woodstock Sewage Treatment Plant water temperature 0°C. |
| 29 Nov | ---------- | Ice along shore of Taftsville Pond. |

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| 30 Nov | ---------- | Freeze-over of Taftsville Pond. |
| 1 Dec | ---------- | Solid ice cover on Taftsville Pond. |
| 11-12 Dec | ---------- | Ice jam on Taftsville Pond caused by warmer weather and rain. |
| 16 Dec | ---------- | Ice jam area rafted along eastern shore of Ottauquechee River, 120-150 cm high (Fig. B2). |
| 19 Jan | ---------- | Woodstock Sewage Treatment Plant: Air temperature -27°C. Bottom water temperature at outfall pipe 0.8°C. Water temperature at surface 0.7°C. Temperature upstream of outfall pipe 0°C. Temperature 3 m downstream from outfall (mixing taking place) 0.1-0.3°C. Open hole (1-1.5-m diameter) at site. |
|  | 33 | 90-140 m downstream of outfall: Open water area in fast waters 180-220 m downstream from plant. |
| 2 Feb | 76 | Mid-channel, Quechee Green. |
|  | 91 | Near shore Quechee Green (mid-channel): 30 cm snow cover, 96 cm water depth under ice. Water temperature 0.1-0.3°C. Ice temperature -2.5°C. |

Figure B2. Jamming and rafting of ice behind the Taftsville Dam, 16 December 1976.

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
|  | 41 | Quechee Clubhouse: 5 cm snow, 66 cm water depth beneath ice. Ice in area grounded and rafted. Ice temperature -1.5°C. Water temperature 0-0.2°C. |
|  | 48.3 | Ice measured above partial jam at Taftsville. 122 cm water under ice, 20 cm snow cover. Water temperature 0.1-0.3°C. Ice temperature -0.5°C. In general, considerable amounts of ice rafting, frozen frazil, and anchor ice as well as new ice formation in river. |
| 12 Mar - 15 Mar | ---------- | Ice jams in river above Taftsville Pond and above Quechee Mill Pond Dam in addition to other areas. High water on river 12, 13, 14 March from snow melt induced by over 4 cm rain and warm weather. Ice jam formed upstream immediately above Taftsville Pond. Jam caused by remains old ice jam which formed in late Dec. 1976. Old ice jam, new ice formation and frazil flow caused ice jam in river. Many areas frozen to bottom. Ice flowed over river road. Huge ice jam also formed above Quechee Mill Pond Dam.<br>Quechee Lakes: Quechee Golf Course Bridge taken out when ice moved in night of 13 March (Fig. B3). River so jammed with ice |

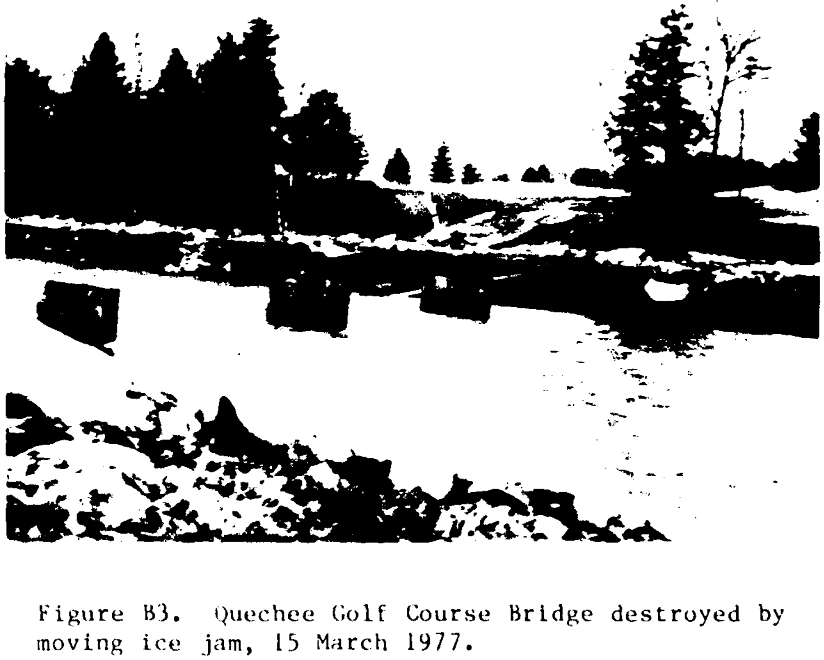

Figure B3. Quechee Golf Course Bridge destroyed by moving ice jam, 15 March 1977.

Figure B4. Ice rafted on Quechee Golf Course, 15 March 1977.

Figure B5. Ice blocks, 91-151 cm on shore of Ottauquechee River, 15 March 1977.

that water overflowed all low areas. Ice rafted and flowed over many areas of golf course (Fig. B4). Ice blocks 91-151 cm [illegible] on shore (Fig. B5).

[illegible] at North Hartland Flood Control [illegible] control [illegible] of [illegible]. [illegible] rafted [illegible]

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| | | struck the solid ice behind the dam, it shoved the sheet of ice forward, destroying a log boom across the river. |
| 16 Mar | ---------- | Jam just above Quechee Lakes office and above Taftsville Dam. Blocks from old jam piled and refroze in river. Some blocks up to 1.5 m thick. |
| | | Normal river ice (41-46 cm thick) rafted on shore. Ice sample 36-cm long taken on shore. |
| | | 1977-78 WINTER |
| 27 Nov | ---------- | First ice flowing in river. Ice was generated by snowfall and contains slush ice with small amounts of frazil. Water temperature 0°C near shore and ≈0.5°C at mid-channel. Overnight air temperture -12°C. |
| 28 Nov | ---------- | Taftsville Pond: Ice along shore. Slush and frazil ice in river. |
| | | Temperature sensor installed 46 cm beneath water surface at Woodstock Sewage Treatment Plant. |
| 29 Nov | ---------- | Less ice at Taftsville than previous day. Higher air temperatures overnight. Water temperature 0-1°C. |
| 2 Dec | ---------- | Water temperature 3°C at Woodstock Sewage Treatment Plant outfall. |
| 5 Dec | ---------- | Water temperature 0.15°C. |
| 6 Dec | ---------- | Water temperature 0.05-0.1°C. |
| 10 Dec | ---------- | Ice dam near Quechee sewer outfall pipe. Solid ice above Quechee Mill Pond Dam. Ice and frazil flow above dam. Frazil and anchor ice at Taftsville and downstream through golf course in areas of rapidly moving water. Solid ice along shore of river and upstream from Taftsville Pond. Taftsville Pond mostly frozen over. |
| | | Frazil and anchor ice at Woodstock Sewage Treatment Plant. Solid ice along shore (1.5 m out from shore). |

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| | | River frozen solid upstream of Quechee Mill Pond Dam to old water level recorder site (where road splits to W. Hartford). |
| | | Recorder fixed at Woodstock Sewage Treatment Plant. Water temperature -0.2 to 0.3°C. Ice formed around thermistor, necessitating removal and placement elsewhere in area. |
| 11 Dec | ---------- | Freeze-over at Woodstock Sewage Treatment Plant. |
| | | Frazil and anchor ice in open river areas. |
| 12 Dec | ---------- | Ice formation due to a major cold spell in local area 8-12 December. |
| 29 Dec | 5-25 | Woodstock Sewage Treatment Plant: Ice unstable and variable. Water temperature on recorder -0.1°C. Air temperature -3°C. Water temperature 0-0.5°C at sensor. |
| | 22 | Yankee Musket Shop: Water temperature 0.05°C. Air temperature 2°C. Ice temperature 0°C. |
| 4-9 Jan | ---------- | Minor thaw, slight jamming and rafting of ice cover. |
| 13 Jan | ---------- | Ice re-forming along river, especially at dam sites. |

Figure B6. Ice jam at Woodstock, east of Sewage Treatment Plant, 26 January 1978.

| DATE | ICE THICKNESS (cm) | ICE CONDITIONS AND REMARKS |
|---|---|---|
| 25-26 Jan | ---------- | Thaw and heavy rain caused flooding and a new ice jam in Woodstock (Fig. B6). Solid ice remained in Quechee Lakes Mill Pond and Taftsville Pond. Ice jam extends from just below Woodstock Sewage Treatment Plant upstream to Woodstock Union High School. |
| 9 Feb | 25-38 | New ice formation. Ice rafted and jammed at Woodstock and Quechee. |
| 7 Mar | 56 | Water temperature at bridge near Yankee Musket Shop 0°C or slightly below. Water samples appear silty. Snow depth on ice 30 cm. Ice same thickness 3 m from shore and in center of river at shop. 51 cm water beneath ice in center of river; 66 cm water near sensor. |
|  | 71 | Woodstock Sewage Treatment Plant: 3 m beyond temperature sensor, water samples nearly clear, 33 cm water beneath ice. Water temperature 0°C. (See Fig. B7 and B8.) |
|  | 74 | 6 m from shore: 3 m water beneath ice, water temperature 0°C. |
| 9 Mar | ---------- | Some open water at Yankee Musket Shop and upstream. Water temperature 0.05-0.1°C beneath ice cover. |

Figure B7. Effect of sewage effluent at Woodstock Sewage Treatment Plant (looking upstream).

Figure B8. Effect of sewage effluent at Woodstock Sewage Treatment Plant (looking downstream).

| | | |
|---|---|---|
| 10 Mar | ---------- | 450 m below Taftsville Dam: Water temperature 0.2-0.35°C. River starting to open. Open channel in many areas from Taftsville Dam to Quechee Lakes Golf Course Bridge.<br>Yankee Musket Shop: Water profile beneath ice; 0-8 cm down, 0°C; below 9 cm, 0.1°C. |
| 17 Mar | 48-50 | Ice measured at Yankee Musket Shop. Water temperature 0-0.05°C. |
| | 46 | Ice measured at Woodstock Sewage Treatment Plant. Water temperature 0-0.05°C. Open water channels observed along shore between Taftsville Dam and Yankee Musket Shop. |
| 20 Mar | 44 | Near shore at Yankee Musket Shop. |
| | 43 | Center of river at Yankee Musket Shop. |
| 23-24 Mar | ---------- | Considerable rain (29 cm in 18 hrs) at Ottauquechee sites. |
| 25 Mar | ---------- | River open at Quechee Clubhouse. Temperatures in open water 0.1-0.4°C from Quechee Clubhouse up to Taftsville Dam. |

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Bates, Roy E.
Analysis of ice jams and their meteorological indicators for three winters on the Ottauquechee River, Vermont / by Roy E. Bates and Mary-Lynn Brown. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1981.
iv, 33 p., illus., 28 cm. ( CRREL Report 81-1. )
Prepared for Directorate of Civil Works - Office of the Chief of Engineers / by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory under CWIS 31332.
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