THE ICE MOTION DETECTOR: ADVANCE WARNING FOR BREAKUP

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ABSTRACT

Ice jams in the northern United States result in over $125 million in damages annually, and the figure for Canada is equally high. In communities where ice jamming and flooding are a recurrent threat, measures are often taken to predict the occurrence of ice jams and minimize their impact. Advance warning that an ice run has actually begun and that flooding is possible can allow downstream communities to evacuate flood-prone areas, close bridges, and mobilize flood-fighting efforts in a timely manner. Present methods of ice run detection rely on either direct around-the-clock river observations, monitoring of stage gauges, or air temperature and precipitation forecasts. Only direct observation provides definite evidence that an ice run has begun but, due to personnel costs, it is often economically prohibitive. Direct observation is also difficult or impossible during nighttime hours. The other two methods merely indicate a probability that breakup can occur and require a thorough knowledge of the river basin and ice processes. This paper describes an inexpensive, automated, around-the-clock ice motion detection system developed at USACRREL that provides a definite indication of ice breakup. Two variations of system configuration and the results obtained over two breakup seasons are presented.

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THE NEED

Much of the annual cost of ice jams can be attributed to personal property damage due to flooding. Hence, a significant amount of research has concentrated on the stages associated with ice jams and their frequency of occurrence as well as methods of ice jam control and flooding reduction. One area of current research addresses ice jam initiation, development, and release as well as jamming location. Results of this research should assist in the prediction of recurrent ice jamming and flooding in many communities.

Ice control structures and ice jam flooding mitigation plans have successfully reduced damages in many cities and towns. Smaller communities, however, often cannot justify the large capital cost associated with a comprehensive structural solution. Yet advance warning that an ice run has definitely begun and that flooding is possible could allow residents of these smaller communities adequate time to evacuate flood-prone areas, close bridges, and mobilize flood-fighting efforts.

Advance warning of ice breakup could also provide useful information to operators of flood control dams, allowing the dams to be operated in a way to minimize downstream flooding. Ice runs can cause structural damage to navigation and flood control facilities when large, fast-moving ice pieces hit the lock or dam control gates. Knowing that the ice cover upstream of a facility has broken up and is moving downstream would allow operators time to modify operations in order to minimize adverse impacts both at the facility and to downstream reaches.

DETECTING AN ICE RUN

There are two commonly used methods of river ice motion and ice run detection: direct observation and forecasting. Direct observations of the river are usually done by one or more individuals who have some knowledge of river ice processes. Visual inspection tours are made of the river basin ranging in time from infrequent weekly visits during midwinter to around-the-clock watches as spring approaches. Due to the inaccessibility of many rivers and the length of river to be observed, aerial surveys may often be necessary, resulting in the observations becoming very costly and coverage thereby limited. River ice runs may also occur very suddenly, increasing the chance that they go undetected until the ice jams and flood waters rise.

Forecasting river ice breakup and ice runs requires a thorough knowledge of river ice processes and the hydraulic and hydrologic characteristics of the river basin. Midwinter field observations of the river provide estimates of ice thickness and ice strength as well as the water equivalent of the snowpack in the river basin. Coupled with knowledge of the response of the river to precipitation and snowmelt, rough estimates of the probability of river ice breakup can be made. This method requires good air temperature and precipitation forecasts and still can only provide estimates that conditions are suitable for river ice breakup. Forecasting is often used to determine when to send river observers into the field prior to breakup and can therefore result in false alarms or undetected ice runs.

In conjunction with both of the above methods, recording water stage gauges can also be monitored on a near-real-time basis, with rapid rises in stage signaling a possible ice breakup. While stages can be helpful in assessing ice conditions, they provide no positive information on ice movement. Depending on the river characteristics and ice strength, rapid stage rises may or may not induce ice breakup or movement and thus can result in false alarms. A gradual stage rise may induce movement in a sufficiently rotted ice cover, also resulting in undetected ice runs.

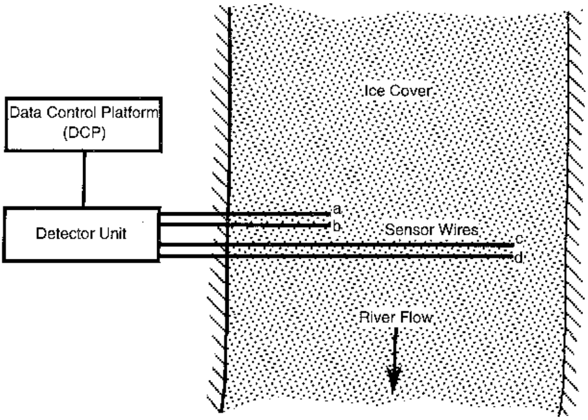
DESCRIPTION OF THE ICE MOTION DETECTOR

The main objective of any breakup warning or prediction system is to provide time for downstream communities to take damage prevention measures. Since many ice-jam-prone rivers are either inaccessible due to marginal road conditions during breakup or because the area of observation is so great, an automated, low-cost monitoring system that can reliably determine when an ice cover is breaking up and beginning to run is desirable. Since time is important in damage prevention, such a system should be able to relay information to downstream communities on as near a real-time basis as possible. Therefore, the use of a proven communications system for information exchange (i.e., satellite, radio, microwave, or telephone) is necessary.

A schematic of the prototype river ice motion detector is shown in Figure 1. The system consists of a detector unit, fused sensor wires placed into the ice cover, and a voltage source/reader. For the prototype system, the voltage source and reading was provided by a satellite Handar 570 Data Collection Platform (DCP). The DCP provides a switched 5 V dc power source that passes through the detector unit and the fused sensor wires, providing two analog inputs (dc voltages) back to the DCP. The level of the analog signal is determined by the integrity of the electrical circuit through each pair of sensor wires connected to the detector unit. The DCP relays the signal to a satellite and downlink on a near-real-time basis.

The detector unit serves as the interface between the DCP and the two pairs of sensor wires. The voltage input received from the DCP is passed to each pair of sensor wires through a series of resistors in the detector unit. A voltage drop occurs depending on whether one, the other, or both sensor wires in each pair has been broken, indicating ice

Figure 1. Schematic of ice motion detector system on St. John River at Ninemile gauge.



movement. The output voltage is then passed back to the DCP, where it is read and recorded.

The resistors are sized to provide distinct voltage drops for each possible condition of the sensor wires. For the prototype unit shown in Figure 1, if both sensor wires *a* and *b* were intact, the signal would be 4.95 V dc. The signal would be 2.58 V dc if wire *a* were broken or 1.86 V dc if wire *b* were broken. If both sensor wires were broken, the signal would be 1.40 V dc. Using a pair of sensor wires for each analog input to the DCP provides redundancy in the system and reduces the likelihood of false indications of ice breakup. The Handar 570 DCP can be programmed to read the circuit voltage at a variety of time intervals, and it stores information for the previous 6 hours. It can transmit to the satellite at a regular time interval (near-real-time) or when a certain condition (such as breakage of the sensor wires) occurs, thereby providing true real-time notification that an ice run has begun. The detector unit also contains four normally closed switches that can be used to test the system (simulate sensor wire breakage) once the sensor wires have been installed into the ice cover.

Each sensor wire is a fused loop of 18-gauge, plastic-jacketed, stranded wire or equivalent, which is placed into a slot cut into the ice cover. The slot is then filled with snow or ice chips and water and allowed to refreeze. The shore ends of the wires are securely fastened to some immovable object and connected to the detector unit. When the ice cover begins to break up and move, the sensor wires will be broken, opening that leg of the circuit. Each sensor wire is fused such that breakage will occur at a predefined location in the loop, reducing the chance that the two broken ends will recontact each other. The fuse is created by removing a small section of the plastic jacket of the 18-gauge wire, cutting 2 or 3 strands of the wire, and then waterproofing with shrink tubing or silicone sealant.

Because it is often difficult to predict exactly where the ice cover will break up first, two pairs of sensors are used, which allows for sensing the ice cover movement at two locations across the river section. Typically, one pair of sensors would be placed at midchannel with the other pair placed halfway between the shoreline and the first pair. This technique helps to determine if the entire cover is in the process of breakup or if the ice is merely undergoing some minor movement in one area.

ADVANTAGES AND ALTERNATIVES

The river ice motion detector described above has several advantages over currently utilized methods of direct observation and forecasting:

- The system provides a definite indication of ice cover breakage and movement that does not rely on extensive scientific knowledge of the river basin and ice processes. Once a suitable location for the sensors has been identified, there is no need for highly trained personnel to interpret the data.
- The system provides around-the-clock monitoring of the ice cover at very minimal operating or maintenance costs. The prototype system was located at a remote site with a battery and solar charger providing power for the DCP and satellite transmission system.
- The unit is installed during midwinter when the ice cover is stable and safe to work on. The sensors can be placed into the cover months before the anticipated breakup. Field safety procedures for working on an ice cover should be followed at all times.
- Installation is quick and easy, and takes about 2 or 3 hours with manually powered equipment (ice chisel or ax). A chain saw can also be used to quickly cut the slot for the sensor wires.
- The system can be tested after sensor wire installation by use of the switches on the detector unit.
- Redundancy in the system reduces the chance of false alarms.
- The system provides near-real-time indication of ice cover movement, allowing maximum notification time.

Several alternatives are possible in the prototype system configuration as described above. The voltage source could be any readable constant dc voltage supply, and any combination of resistors could be used to give distinct outputs to detect which sensor wire has been broken. The instrument used to read the analog signal should typically have a switchable dc voltage supply that could be conveniently used. As an alternative, the resistance of the sensor pair circuit could be read instead of voltage by some type of recording digital voltmeter (DVM).

The number of sensor pairs is only limited by the number of analog input channels available on the reader. A minimum of one pair could be used, with each sensor placed at a different location across the river, eliminating the redundancy of sensor pairs described above.

There are also many configurations of signal reader and transmitter. A data logging instrument could read the data and then relay the information by telephone to communities downstream either actively (the data logger auto-dialing the community) or by inquiry (the community calling the data logger). Where telephone lines do not exist, radio transmission or cellular telephone systems could be used instead of the satellite system described above. The system developed for the City of Montpelier, Vt., described in the next section, used inexpensive burglar alarms that auto-dialed the police dispatcher when the circuit was broken.

PROTOTYPE TESTING

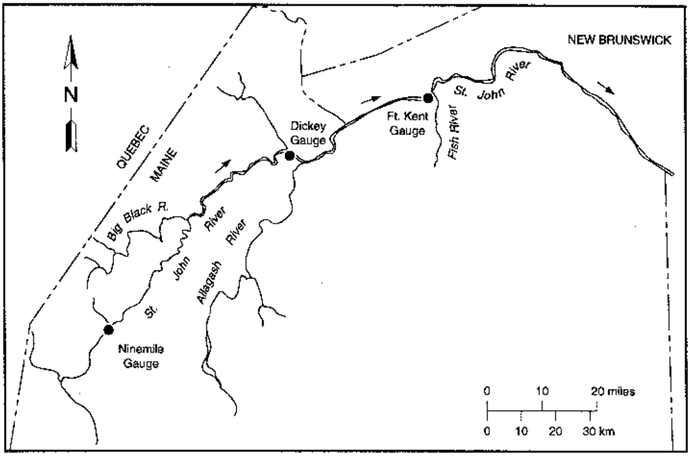
The ice motion detector system was field tested in two locations. The upper St. John River in northern Maine is a remote area where the detector system was linked to a USGS satellite DCP gauge. The gauge is located approximately 100 km upstream of the community of Dickey, which has experienced several severe ice jams and costly flood damages. The City of Montpelier, which lies on the Winooski River in central Vermont, experienced very severe flooding in March 1992. A modified ice motion detection system was employed at several places along the river within the city limits. The advance warning time possible by detecting ice cover movement was less than 2 hours at this location, requiring a direct tie-in to an existing communications system.

Descriptions of the ice motion detection systems for these two locations are given below. The results of two breakup seasons on the St. John River and one breakup on the Winooski River are also presented.

St. John River

Communities along the St. John River in northern Maine and western New

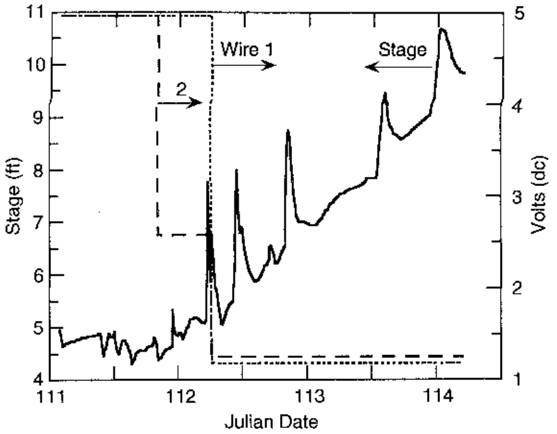
Figure 2. Map of the St. John River basin in northern Maine showing gauge locations at Ninemile, Dickey, and Fort Kent.



Brunswick (Figure 2) experience ice jams from annual ice runs that occur between late March and late April. During severe years, over 150 km of ice cover contribute to massive ice jams at Dickey and Allagash, Maine, which can cause very high stage rises and flooding (USACE, 1993). These ice jams then fail and rejam at many locations downstream where the river forms the international border between the U.S. and Canada, causing disastrous flooding in New Brunswick (Humes and Dublin, 1988). Dickey suffered over $12 million US in damages from an ice jam and run in April 1991. Several residents, caught unaware by the extremely fast rising stage, were stranded as ice and water surrounded their homes and destroyed the only bridge across the St. John River within 60 miles. It was felt that information that the ice cover was moving upstream of Dickey would at least have allowed residents to evacuate dangerous areas.

The prototype system described above was installed in the ice cover of the St. John River at the location of the USGS Ninemile gauge, approximately 100 river kilometers upstream of the community of Dickey, Maine. This was done to take advantage of the USGS satellite DCP station at the gauge site. The sensor wires were placed into the ice cover on 25 February 1992. Two pairs of sensors were used to provide redundancy; one pair of sensors was placed 30 m from the right bank and the other 75 m from the right bank (about midchannel). The snow was first shoveled from the ice, and a slot approximately 8 cm deep and 8–10 cm wide was chiseled into the cover. The sensor wires were placed into the slot and covered with ice chips and water to freeze them back into the cover. The

Figure 3. River state and ice motion detector readings at Ninemile gauge on Upper St. John River for 1992 breakup.



wires were laid loosely up the river bank and secured to a piece of rebar extending from the gaugehouse foundation. The wires were then buried with snow.

The sensor wires were connected to the detector unit at the time they were installed into the ice cover. The connection between the detector unit and the DCP was made on 9 March 1992, by USGS personnel. At that time, the DCP was reprogrammed to read the ice motion detector circuits every half hour. In addition to the ice motion detector circuits, the DCP also read 15-minute river stage, 30-minute precipitation, and hourly air temperature values. The DCP transmits the previous 6 hours of data on a 3-hr time cycle. A mainframe computer at the USGS satellite downlink in Virginia records all data transmissions and can be queried by telephone modem.

Figure 3 presents both the 15-min stage readings and the 30-min ice motion detector readings during ice cover breakup on the St. John River. As can be seen from the figure, it is not evident from the stage record exactly when ice cover breakup occurred. The sensor pair that was installed at the midchannel location shows a signal drop before the shore sensor pair. The level of the signal indicates that one of the midchannel sensors broke about 6 hr before the other midchannel sensor or the ice sensors near the shore. The other three sensor wires broke between 0615 and 0645 on 21 April 1992, shortly after a peak on the stage record that indicates storage and release of water associated with the cover breakup. It can also be seen that several ice runs passed the Ninemile gauge site following the breakup, evidenced by the steep jumps on the generally rising hydrograph.

These are due to the breakup of covers or jams upstream, which then pass the Ninemile gauge.

Observations at the town of Dickey indicated that the ice from the Ninemile gauge breakup passed the town approximately 24 hr after the sensor wires broke. The open water travel time from the Ninemile gauge to Dickey is about 10–12 hr, which implies that the Ninemile ice jammed and released along the way. Other field observations indicated that the Ninemile ice did indeed jam about 9 miles downstream of the gauge and then released approximately 12 hr later.

The above description of events indicates that the town of Dickey could receive advance warning that an ice breakup is occurring at the Ninemile gauge and an ice run is probable within 12–24 hr. Field observations near the town, however, indicated that much of the ice from Dickey upstream to Priestly Bridge (65 river kilometers) broke up and ran prior to the ice breakup at Ninemile. This indicates the need for an additional sensor in the reach between Dickey and Priestly Bridge.

The ice motion detector was again installed at the Ninemile gauge on 23 March, 1993. The same setup as previously described was used, with the two pairs of sensors installed 30 and 75 m from the right bank. The only modification to the installation procedure was the use of a chain saw to cut the slot into the ice cover, which greatly reduced installation time. The ice cover broke up and ran on 10 April 1993, between 1645 and 1715. Figure 4 shows a plot of the 15-min river stage and 30-min ice motion detector readings at Ninemile gauge for the 1993 breakup event. The figure also shows the 15-min stages for the USGS gauge at Dickey. Based on the travel time between the two gauges, it appears that the ice upstream of Dickey ran and jammed prior to the ice cover at Ninemile. Again, this points to the need for at least one additional ice motion detector upstream of the Dickey gauge to maximize the advance warning benefits at Dickey. CRREL identified the most likely site for an additional ice motion detector as just below the mouth of the Big Black River, approximately 44 river kilometers upstream of Dickey.

City of Montpelier, Vt.

Much of downtown Montpelier was flooded on 11 March 1992, when an ice jam formed in the Winooski River just downstream of the center of the city. Flood waters up to 1.6 m deep flowed down streets adjacent to the river, causing a total of $5 million US in damages.

Three tributaries enter the Winooski River in or near Montpelier: the Dog River, below the jam site; the North Branch of the Winooski River, within the extent of the 1992 jam; and the Stevens Branch, upstream of the jammed reach (Figure 5). The USGS

Figure 4. River stage and ice motion detector readings on Upper St. John River for 1993 breakup.

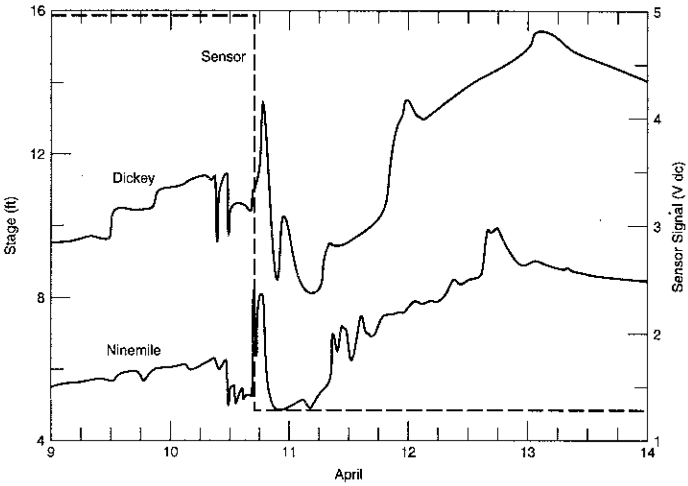
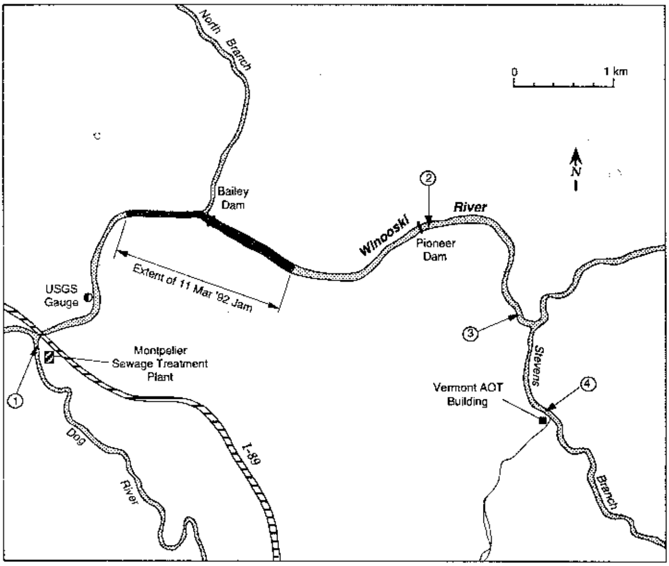


Figure 5. Winooski River basin in vicinity of Montpelier, Vt.



maintains a river stage gauge on the Winooski, 0.65 km upstream of the Dog River confluence. USGS personnel take ice thickness and discharge measurements at this location several times each winter. Two low-head weirs form small pools on the Winooski River within the city, delaying ice movement slightly. A small hydropower station on the Winooski upstream of the confluence with the Stevens Branch typically holds all additional ice from upstream until well after the ice cover on the Winooski River within the city limits is gone.

During the night of 10–11 March, 1992, 1.5 cm of rain fell on a thin, saturated snow cover, causing rapid runoff and a sharp rise in river stage. The ice cover in the Dog River and Stevens Branch ran first, leaving an intact ice cover on much of the main stem of the Winooski River. By early morning of 11 March, the Winooski was open for a short length below the Dog River confluence, but the USGS gauge had risen to about 1 m above its midwinter base flow level, indicating some blockage downstream. Local police reported a jam below Pioneer Dam that moved downstream, contributing to the main jam in the city when the ice between Pioneer Dam and the Stevens Branch ran. Above the confluence with the Stevens Branch, the ice cover remained intact until late afternoon when the ice from the Stevens Branch confluence to the dam at Levesque Station broke up and ran. The resulting surge of ice and water pushed out the Montpelier jam, and the flood waters in the city receded rapidly. The ice in the North Branch remained in place throughout the event.

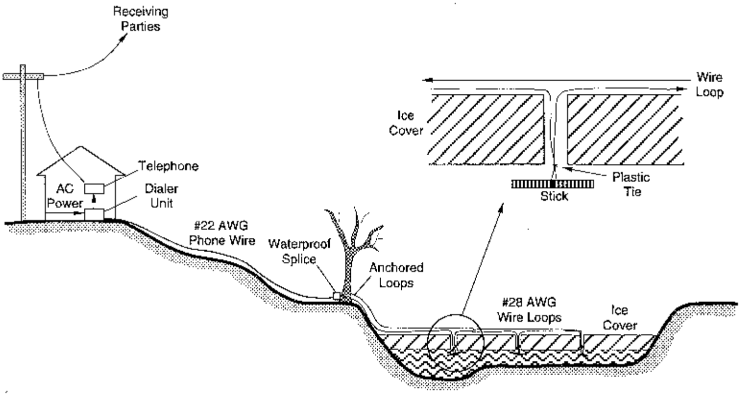
The ice jam flood threat in Montpelier is extremely local since topographic relief is great and travel times are short. It was felt, however, that an early warning system, such as ice motion detectors, coupled with a program to monitor weather and river ice conditions could lessen the impact of future ice jam floods in Montpelier. In particular, knowledge of the timing of the ice run in the various tributaries and reaches of the Winooski River could assist city and state agencies in mobilizing ice removal equipment or evacuating potentially flooded areas.

Based on the course of events during the 1992 jam, it was decided to install four ice motion detector units at key locations: near the mouth of the Dog River, just upstream of Pioneer Dam, 200 m downstream from the Stevens Branch confluence, and on the Stevens Branch 400 m upstream from the confluence. If the ice breakup occurred as it did in 1992, ice motion on the Dog River or Stevens Branch would alert observers to watch the main stem closely. In the case of a dramatic breakup, similar to the 1992 event, the ice motion detector below the Stevens Branch confluence would be the most valuable of the four, in terms of warning the city of a major ice run on the main stem. Knowledge of ice motion above Pioneer Dam would provide the city with shorter-term warning that the ice was on its way. This ice motion detector would also indicate whether or not the ice run was delayed in the pool upstream from Pioneer Dam.

The prototype ice motion detection system design was modified slightly to take advantage of easy access to telephone lines. Instead of a voltage source and reader, auto-dialing burglar alarms were used. At each of the four sites, two closed loops of 28 AGW stranded insulated wire (breaking strength of about 3 kg or 7 lb) were anchored to the ice cover, as shown in Figure 6. At roughly 7-m intervals, the wires were wrapped around 1 by 25 cm wooden sticks, which were then pushed through 10-cm-diameter holes drilled in the ice. After flipping horizontal, the sticks spanned the holes, creating a series of solid anchors for the wire loops. The loops spanned most of the channel width. The two separate loops were connected in a parallel circuit requiring both loops to break in order to trip the alarm. This redundancy would prevent false alarms caused by ice cracking rather than movement of the ice cover en masse. The light-gauge wires forming the loops were anchored to the shore (typically tied to a tree) and connected by a waterproof splice to 22 AGW telephone wire. The telephone wire ran up the river bank to the dialer unit and telephone connection, located in nearby buildings. The longest run was at the Dog River site, where 165 m of telephone line was used to connect the loops on the river to the dialer unit located in the Montpelier sewage treatment plant.

The automatic message dialer units were inexpensive burglar alarms. The dialer unit's normal status was for intact wires (i.e., switch closed). A change from this normal closed condition, caused by breaking both loops, triggered the dialer unit. The unit can be programmed to dial up to three phone numbers (up to 15 digits each) and play a 20-

Figure 6. Schematic of ice motion detector layout at Montpelier, Vt.



second message 5 times to each of the answering parties. When the last digit of a phone number is dialed, the tape begins to play (without waiting for the party to pick up). To fill the 20 seconds allowed for each message and minimize blank message time, two identical 10-second messages were recorded. After the fifth 20-second message is played, the next number is dialed. The unit's battery backup assures operation in the event of a power outage. The auto-dialers were set to call the city police dispatcher, a local volunteer observer, and a CRREL researcher.

Total equipment cost for each detector was about $120 US, mostly for the dialer unit. However, each detector required a telephone connection, which were provided voluntarily by two local businesses, the state Agency of Transportation, and the city's public works department.

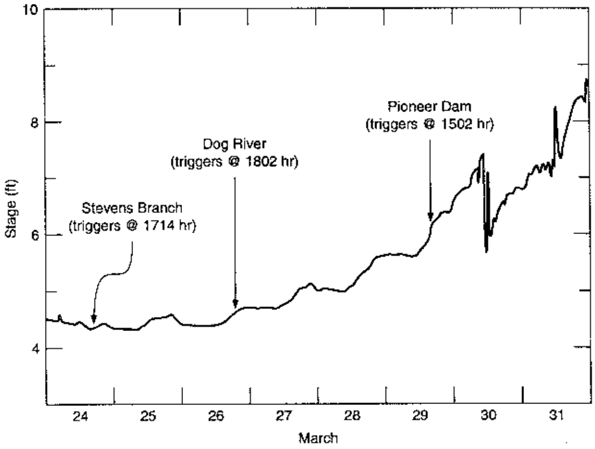
Compared with the previous year, the 1993 breakup was gradual and generally uneventful. The ice motion detector system functioned well, however. As air temperatures moderated in March, the snow cover overlying the river ice gradually melted. Existing open leads slowly enlarged, and new leads began to appear. The actual ice-out occurred as a series of small breakups, taking place over a week-long period, beginning 24 March when the Stevens Branch went out.

The ice motion detector on the Stevens Branch triggered at 1714 on 24 March. Shortly after, the police visually confirmed ice movement at this location. It appears that rapid inflow from Benjamin Falls Brook, entering the Stevens Branch just upstream from the sensor, hastened melting and release of the ice cover in the vicinity of the wires. The main stem of the Winooski River at the Stevens Branch confluence remained ice covered, however.

The Dog River ice motion detector called in at 1802 on 25 March. Follow-up field visits verified the timing of the ice-out, but found no accumulations of ice debris downstream. No significant changes in stage were observed above or below the confluence following the Dog River ice release.

By the evening of 28 March, the Winooski River was mostly open, from the Stevens Branch confluence downstream to an accumulation of large, broken sheets lodged above Pioneer Dam. Immediately upstream of the central section of the spillway, the channel was open. The Pioneer Dam ice detector first triggered at 1502 on 28 March, with police confirming an open channel at this location shortly after. Around midnight, the Pioneer dialer unit began calling the police station, at roughly 15-min intervals. This continued until morning, when the unit was physically disconnected. It is possible that broken loose wires repeatedly opened and closed due to water and ice movement, causing the multiple calls.

Figure 7. Stage record for Winooski River near Montpelier during 1993 breakup.



The ice motion detector on the Winooski River downstream of the Stevens Branch confluence never reported despite observations of an open channel in this area late on 28 March. Later inspection found that the dialer unit had been disconnected and was not active at the time of break-up.

Figure 7 shows the stage record at the USGS Montpelier gauge and the time that the ice motion detector units triggered during the 1993 breakup period. The 1993 breakup was not very dynamic as much of the ice melted in place. For a breakup similar to the 1992 breakup, the Stevens Branch and Dog River ice run would likely occur first but closer in time to the main stem ice run and jamming. The city has agreed to re-install the ice motion detection units again for the 1994 breakup.

SUMMARY

By monitoring the signal from the river ice motion detector through a DCP or similar device, one can determine in almost real time when the ice cover begins to break up at a location. Dissemination of this information through existing communication networks provides time for communities downstream to initiate evacuation, flood preparation, or ice breaking operations. This advance warning should reduce damages to property and improve the effectiveness of flood-fighting efforts. Knowledge of the river system is required, however, to select the proper location of the sensors upstream of the damage areas.

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USACE, 1993. St. John River, Maine—Ice damage control. New England Division, U.S. Army Corps of Engineers, Waltham, Mass.

DISCUSSION

Mike Ferrick:

How is the wire attached to the ice sheet? Is it frozen in? Are there methods to keep solar radiation prior to breakup from destroying the bonding between the wire and the ice sheet?

Reply:

The wires are frozen into the cover on the St. John River. A rather circuitous layout is followed at the fused ends in order to prevent simple pull out. The fuse of the wires is also larger in diameter. The main wire (2-pair) is a light colored wire but could also be white if needed.

The wires for the Winooski River system were tie-wrapped around a wooden dowel and inserted beneath the cover through a small diameter hole. This method provided a definite connection to the cover.

Faye Hicks:

Do you find that the gauge usually fails at the onset of ice movement?

Reply:

The 1992 results indicated that one of the four sensor wires broke about six hours before the other three. This suggests some cracking and minor movement of the ice cover. The stage record indicates several minor fluctuations of ±0.2m at the time the first wire broke. The other three wires broke following a sudden stage rise on 0.8m and subsequent fall of 0.5m. I believe that this sudden rise and fall signifies a water storage (or break-up wave from upstream) and subsequent ice cover failure. The water level also receded (back to the level that it had been prior to cover failure) shortly following failure.