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The Impact of Ice Cover Roughness on Stream Hydrology

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While the influence of ice cover on river hydrology has been a focus of river ice research, there has been a lack of field studies that have compared detailed ice cover roughness with velocity profile data. Previous field studies have relied on calculations to estimate the roughness of the ice cover underside surface. A field study began in 2005 on Cazenovia Creek, West Seneca, New York to collect detailed physical measurements of the underside of the ice cover roughness and to document the temporal and spatial variation of the ice cover roughness. Observations of the ice cover roughness were correlated with velocity profile measurements. The observations revealed that ice cover roughness systematically varied over the sampling time-period, but that at any one sampling event the roughness was spatially similar across the stream cross section. Contrary to previous studies, a comparison of velocity profile measurements under smooth and rough floating ice covers indicates that the positions of average and maximum velocities within the height of effective flow are significantly different from one another. The significance of the ice cover dynamics and the resulting flow patterns will be presented and discussed.

Keywords: ice cover; hydrology; ice cover roughness; river hydrology

1.0 INTRODUCTION

While ice cover formation over streams and rivers is common in cold regions during winter months, the influence of ice cover on stream hydrology is not fully understood. During open flow conditions, the average velocity in a stream or river is typically measured at 6/10s the depth of the water column (Rantz et al., 1982). Accurate stream and river discharge measurements can be calculated because the behavior of the velocity profile is well understood during open flow. During ice cover conditions, it is known that an ice cover causes the stream velocity to drop to zero at the ice/water interface (Rantz et al., 1982), but the typical positions of the maximum and average velocity readings within the velocity profile are not well established. The inability to quickly and reliably measure the average velocity under an ice cover hampers winter discharge estimations. It is important to collect field data on ice cover roughness and corresponding velocity profile measurements to develop a better understanding of what influence ice cover has on stream hydrology so winter discharge estimations can be made with greater accuracy.

This paper focuses on the influence of a typical ice cover on stream hydrology. The basic questions represented in this paper are:

- Does the ice cover roughness vary with time and space?
- Does the velocity profile change with ice cover roughness?
- How do average velocity values obtained through typical United States Geological Survey (USGS) methods compare to actual velocity values measured in the field?

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2.0 BACKGROUND

Previous laboratory and field studies indicate that a typical ice cover influences the distribution of flow in the channel, the velocity profile, as well as sediment transport (Lau and Krishnappan, 1985; Wuebben, 1988; Smith and Ettema, 1995 and 1997; Zabilansky et al., 2002; and Ettema et al., 1999 and 2000). Under a typical ice cover, the magnitude of influence that ice formation may have on stream hydrology can vary with the volume of ice formed (Ettema and Daly, 2004), which is determined in part by the cumulative below-freezing time period (White, 2004). Several previous studies have focused effort on quantifying the ice cover underside surface roughness, and understanding the influence of the surface roughness on stream flow and sediment transport (Lau and Krishnappan, 1985; Wuebben, 1988; Smith and Ettema, 1995 and 1997; Zabilansky et al., 2002; and Ettema et al., 1999 and 2000). The ice cover surface roughness (ni) estimations have been back-calculated using velocity profile measurements (White, 1999; Nezhikhovskiy, 1964). Early estimations of the roughness of the bottom surface of the ice cover has been described as smooth as a finished concrete surface or as rough as the natural channel bed when drifting ice blocks exist (Chow, 1959). Chow (1959) listed n (roughness coefficient) values ranging from 0.010 – 0.025 for ice covers in dredged channels; however, later studies have shown a wider variation in roughness, and have noted variation roughness over time (White, 1999). Research studies have determined the roughness of the ice cover surface by measuring the velocity profile under the ice cover and then back-calculating the ice cover roughness coefficient (ni) (White, 1999). No field studies have actually measured the ice cover surface roughness directly, and data on this aspect of the ice cover is needed to fill the data gap.

Nezhikhovskiy (1964) collected 500 ice cover samples from 1936 to 1959 and reported ni of the slush ice cover (now referred to as frazil ice) surface at the time of initial ice cover formation. The ni values ranged from 0.008 to 0.015, with the roughest ice covers occurring during the initial formation of the ice cover and smoother ice cover developing over time (Nezhikhovskiy, 1964). Nezhikhovskiy (1964) noted that frazil ice would distribute non-uniformly in the river channel and further observed that roughness tended to increase or decrease with changes in ice cover thickness and ice cover type (frazil, sheet ice, or consolidated ice blocks). Frazil ice cover tended to smooth as the thickness decreased (accompanied by a higher flow volume underneath) and become rougher as the thickness increased, meanwhile thermal ice cover tended to smooth as the ice thickness increased. Nezhikhovskiy (1964) suggested the use of the Belokon-Sabaneev formula, which uses Manning's ni, for the roughness of the underside of ice, and nb for the roughness of the stream bed to calculate nc, as a total roughness for the channel.

A comprehensive review on hydrologic and physical properties of ice jams by White (1999) reported calculated roughness values of ice covers (covers formed by ice block jams, frazil ice, and sheet ice) and composite roughness coefficient (nc-the roughness of the bed and the ice cover on flow). The calculated roughness values were determined from velocity profile measurements by dividing the flow into two layers at the point of maximum velocity and using standard flow equations such as Manning's equation, the Darcy-Weisbach equation or a boundary-layer theory. The values of ni from these studies ranged from 0.004 to 0.15 (White, 1999). Over half of these roughness coefficient values were calculated for ice jam events rather than typical ice cover.

Previous research (Sayre and Song, 1979; Lau and Krishnappan, 1985; Wuebben, 1988; Smith and Ettema, 1995 and 1997; Ettema et al., 1999 and 2000) studied the influence of ice cover on flow and sediment transport using a laboratory flume. The studies determined that a floating ice cover induces resistance on the flow, which reduces the flow velocity and can dramatically change the form of the vertical velocity profile (see Figure 2-1). Laboratory flume studies do not replicate the natural stream environment for several reasons. One reason for the departure of laboratory results from field results is that in laboratory studies ice cover underside surface roughness is preset and static, while the roughness may vary by location and through time in the natural environment. Another deviation from natural field conditions is the fact that laboratory studies have been conducted in temperatures above 10 oC when realistic conditions often involve temperatures below 10 oC (Ettema and Daly, 2004; Ettema et al., 2000; Muste et al., 2000). The findings of the field study of Zabilansky et al. (2002) indicate that laboratory studies might not accurately represent natural fluvial dynamics and sediment transport and suggest that further field study is necessary to understand ice cover influence on steam hydrology.

The accepted convention of measuring the average velocity of open flow is to measure flow at 6/10s stream depth (Rantz et al., 1982). This is often denoted as 0.6D, where D is the actual flow depth as measured vertically downward from water surface to the stream bed. Within this paper, D is similarly used to denote a particular fractional distance from the bottom of the ice cover surface to the stream bed. DT and DB are used to specifically denote the locations within the velocity profiles of the top and bottom average velocity locations, respectively.

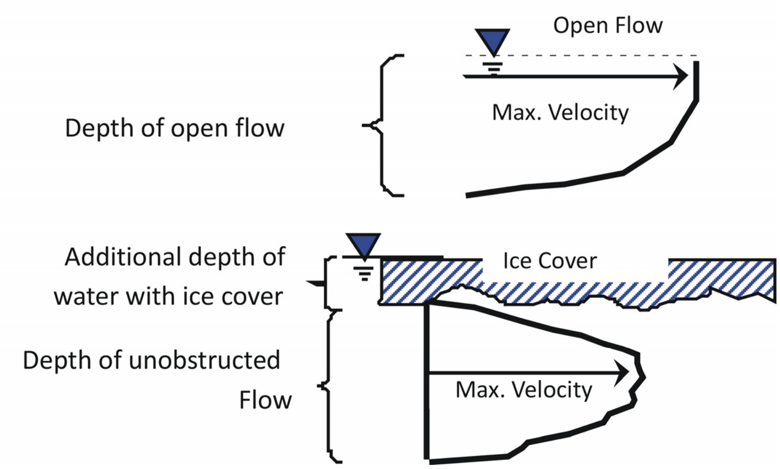

Figure 2-1. Example of open and covered velocity profiles.

The USGS and the Water Survey of Canada (WSC) jointly conducted a large field study measuring velocity profiles under ice cover for the purpose of developing a method of estimating discharge under ice cover. In all, 4100 velocity profiles were collected from 1988 to 1991 in North America. The study collected velocity profiles from under thermal ice cover, but did not sample from areas that had frazil ice or anchor ice due to the inconsistent presence, absence, or volume of either of these types of ice; and subsequently the unpredictable influence both of these conditions might have on stream flow. The study concluded that average velocity under an ice cover could be obtained by one of two methods: 1) averaging the point flow velocities collected at 0.2D and 0.8D (two-point method), or 2) measuring the point velocity at 0.5D or 0.6D (6/10s method) and multiplying by a coefficient (Walker and Wang, 1997; Rantz et al., 1982). Rantz et al. (1982) suggests averaging the 0.2 and 0.8-depth velocities when the stream depth is equal to or greater than 0.76 m, and the 6/10s-depth method when the stream water depth is less than 0.76 m. When the velocity profile is abnormal, Rantz et al. (1982) suggests using a three point method, however this method requires a flowing water depth of greater than 0.76 m. The three point method averages the 0.2-, 0.6- and 0.8-depth velocity measurements. When more weight to the 0.2- and 0.8-depth measurements is desired, the arithmetical mean of the three observations may is used (Rantz et al., 1982). USGS personnel use the 6/10s-depth method with a coefficient of 0.92 to obtain the average vertical velocity at the Cazenovia Creek Ebenezer gage station (personal communication, H. Zajd, 2007). A problem Walker and Wang (1997) had with using the coefficient of the 6/10s method is that the coefficient variability is large at any given station; and the variability among different stations was larger still. Although using the two-point method generally worked better among different field stations, 25% variability still existed among the measured velocity profiles (Walker and Wang, 1997). Although Walker and Wang (1997) suggested instrument calibration, flow meter differences, and measurement techniques to account for some of the variability, the possibility exists that the variation in velocity profiles is from external forces acting on the flow.

3.0 STUDY AREA

The ice cover study was conducted within an 80-meter stream reach of Cazenovia Creek that ends 10 meters upstream of the Ridge Road Bridge in West Seneca, New York (Figure 3-1). This particular stream reach was selected because ice cover was observed to consistently form at this location during winter months, and because the USGS Ebenezer gage station #04215500 is located within this reach. The Cazenovia Creek sub-watershed is approximately 373 square kilometers in size and is one of three sub-watersheds that comprise the Buffalo River watershed. The stream is approximately 48-km in length and has an average slope of 0.0026 or about 2.7m/km for the last 27-km (Lever et al., 2000).

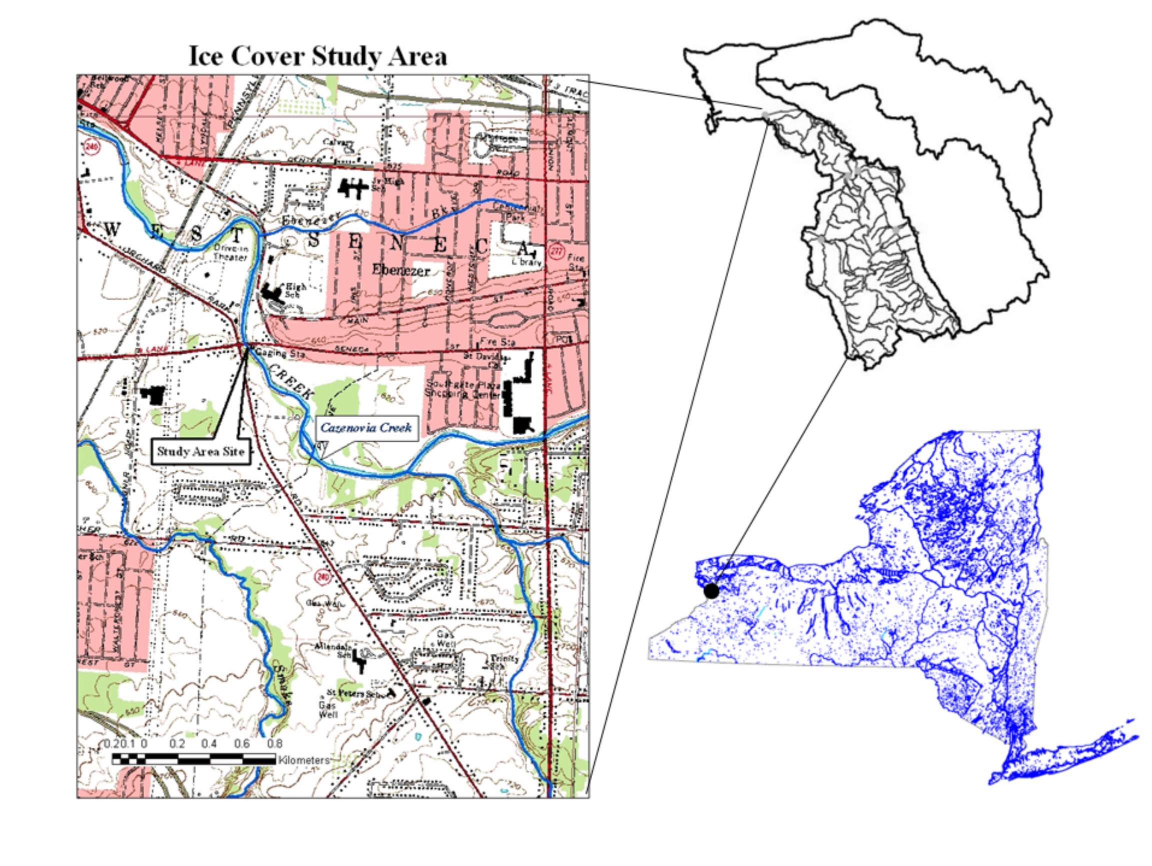

Figure 3-1. The location of the ice cover study within the Buffalo River watershed.

During most winters, ice covers 80–100% of the surface of Cazenovia Creek from the Township of Aurora to its confluence with the Buffalo River (personal communication, A. Tuthill, 2005). The average maximum ice thickness formed on Cazenovia has been estimated to range from 30 to 61 cm (Lever et al., 2000). The study area is recorded as being prone to ice jam flooding. In January of 2006, the United State Army Corps of Engineers completed the installation of an Ice Control Structure approximately 4.5 km upstream of the Ridge Rd Bridge. During the 2005-2006 and 2006-2007 study period, no significant block-ice jams occurred within the study reach.

The USGS records indicate that the average number of days of ice cover between September 2000 and March 2007 is 59 days (Table 3-1). Ice covers generally form sometime between the last week in November and the last week of December, and the last ice cover of the winter breaks up during the month of March (Table 3-1). Photographs of the ice covers for both the 2005-2006 and 2006-2007 sampling seasons are shown in Figure 3-2.

Table 3-1. Dates of ice cover on Cazenovia Creek.

Winter season	Ice cover period	Winter season days with ice cover
Winter 2000-2001	11/20/00 – 3/07/01	88
Winter 2001-2002	12/27/01 – 3/6/02	39
Winter 2002-2003	11/29/02 – 3/18/03	87
Winter 2003-2004	12/8/03 – 3/24/04	70
Winter 2004-2005	12/19/04 – 3/6/05	49
Winter 2005-2006	12/8/05 - 3/8/06	29
Winter 2006-2007	1/21 – 3/13/07	52

Figure 3-2. Ice covers of 2005-2006 (left) and 2006-2007 (right).

4.0 METHODS

4.1 Cross section and sampling location set up for data collection

Ice cover surface roughness and stream flow data were collected during the 2005-2006 and 2006-2007 winter seasons when an intact ice cover of approximately 5 cm thick covered the stream at the study site. Velocity measurements of stream flow under the ice cover and ice roughness observations were taken at six sampling points along two permanent cross sections (cross-sections four and six) (Figure 4-1). The use of the tagged rope for a transect line, as well as sighting between permanent fence posts, ensured that sampling occurred at the same points throughout the winter study period (Figure 4-2).

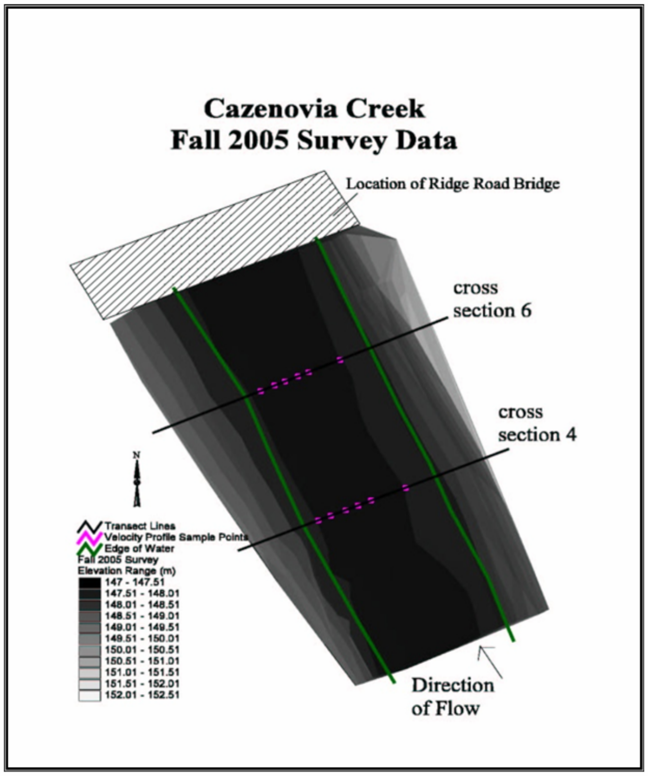

Figure 4-1. Cross section location and study reach morphology.

Figure 4-2. Transect line with tags used to mark locations of velocity profile measurements.

4.2 Tactile ice surface data acquisition

At each sampling point across cross-sections four and six, a tactile observation of the ice surface was recorded to determine ice surface roughness. Tactile surface observations were made by reaching through the sampling hole and feeling the underside of the ice. Tactile observation texture categories were developed from detailed field notes taken during the field study. The observations were categorized as follows:

- Smooth (S) - when the ice felt as flat as a plate of glass
- Smooth with rindles (Swr) - when the ice had a flat surface with small rindles (furrows), (one cm or less deep) eroded into the surface that paralleled the water flow
- Rough (R) - when the ice surface undulated more than three cm and created pockets of small holes in the cover ranging from millimeters to centimeters in size which could cause the surface of the ice to feel as if it had sharp and/or pointed edges
- Bumpy (B) - when the ice surface undulated three centimeters or less and had no sharp edges or points on the surface
- Partial Smooth Partial Rough (SR) - when the ice was smooth on one side of the hole, and bumpy or rough on the other side of the hole
- Frazil Ice (F) - when granular ice was attached to the cover. Sometimes the underside surface of the cover could not be reached for observation due to the amount of frazil ice in the column at the sampling location, preventing a recorded observation
- No Observation (no) - when no observation of the underside of the ice surface was recorded

Tactile observations were recorded on a spreadsheet for each sampling point and sampling event. Ice surface roughness observations were broken into two groups: 1) Smooth and Smooth-with-rindles (n=29) or 2) Rough and Bumpy surfaces (n=25). This division of observations grouped together sufficiently similar surfaces together for the sake of comparing velocity profile differences. The observations of Partial-Smooth Partial-Rough surfaces (n=3) were not used in comparisons because they were not defined distinctly as smooth or rough surfaces.

4.3 Velocity profile data acquisition

Velocity measurements under ice cover were collected using a Global Water velocity meter along both cross sections by drilling holes through the ice cover. The top of the ice cover, bottom of the ice cover, and the water elevation were measured using a metric measuring rod. If frazil ice (unattached granular ice) was present at the sampling location, the amount of frazil ice from the ice cover to the streambed was estimated and recorded. The first velocity reading was taken just under the ice cover by placing the top of the propeller casing up to the bottom of the ice cover. Lowering the flow meter into the current and slowly raising the meter until flow readings stopped verified the ice cover/flow interface. Velocity measurements were taken every 5 cm down to the bottom of the streambed, with the propeller casing sitting on the streambed for the last measurement. Because the casing of the flow meter is 6 cm in diameter with the propeller in the middle of the casing, 3 cm is the closest distance a velocity reading could be taken to either the ice cover or the bottom of the streambed.

Velocity measurement data were transcribed into a spreadsheet and the velocity profiles were graphed by grouping all velocity profiles within a cross section to compare week to week surface roughness differences. The average velocity was calculated by summing the velocity measurements within a profile and dividing by the number of measurements taken. The relative position of the average and maximum velocity was determined by noting the depths at which the average and maximum velocity occurred in the profile and dividing those depths by the effective flow depth. The relative positions of the maximum and average velocities were compared between the smooth (n=29) and rough (n=25) tactile surface data. Velocity profiles that had loose frazil within the water column or aquatic vegetation were not used in calculating the relative positions of the maximum and average velocities. The Mann-Whitney non-parametric testing was used to compare differences between the smooth and rough velocity profile groups with a normal approximation used to determine the critical value for the sample size.

To compare USGS average velocity calculations to the average of measured velocity data, the USGS Two-point, Three-point and 6/10s-depth methods for determining the average velocity were calculated using the velocity measured at the appropriate depth for each velocity profile. The average velocities obtained from the USGS methods were compared with the average velocity of each velocity profile gathered in this study. The position of the average velocity, (relative depth, D), obtained in data collection were compared to the 0.2D, 0.8D, and 0.6D positions used in USGS calculations.

5.0 RESULTS

5.1 Ice cover surface texture data

The roughness of the underside surface of the ice cover ranged from as flat as a piece of glass to a surface that undulated up to 8 cm in height (Figure 5-1), but the ice conditions and the ice roughness temporal variability of the 2005-2006 sampling season was different than the 2006-2007 sampling season.

Figure 5-1. Underside surface of ice cover samples; February 23rd 2006 (left) – rough surface, February 3rd 2007 (right) – smooth flat.

During the 2005-2006 sampling period, frazil ice had not only formed most of the ice cover, but it had also filled most of the area below the ice cover as well (Table 5-1). For both sampling events, the ice cover had a rough texture where the frazil ice had accumulated under the ice cover. The only sampling location that had a smooth surface was T6-6m, which did not have any frazil ice accumulated under the ice cover (Table 5-1).

During the 2006-2007 sampling period, cross-section six had the same texture observation across the width of the stream each week (Table 5-1). Cross-section four had very similar texture observations across the stream width, with some variation in texture towards the stream banks. Although the texture was fairly consistent at all the sampling locations across the cross sections, the texture observations of the ice surface cycled between smooth and rough, week to week through the 2006-2007 sampling period (Table 5-1).

Table 5-1. Ice observations - tactile ice surface roughness.

Ice Observations - Tactile Ice Surface Roughness												
Sample Location/ Date	Cross-section T4						Cross-section T6					
	6m	13m	16m	18m	21m	24m	6m	12m	15m	17m	19m	22m
3/4/06	F-100	F-90	F-90	F-90	F-100	no-0	S-0	F-100	F-100	F-100	F-100	F-100
3/8/06	F-50	F-100	F-100	F-70	F-100	F-100	S-0	F-100	F-100	F-100	no-0	no-0
2/3/07	No	S	no	F-0	No	no	F-0	F-35	F-0	F-85	F-85	F-0
2/10/07	S	S	S	S	R	R	S	S	S	no	no	no
2/17/07	Swr	Swr	Swr	Swr	Swr	R	Swr	no	Swr	Swr	Swr	Swr
2/24/07	SR	R	R	R	SwrR	R	R	R	R	R	R	R
3/3/07	R	B	R	R	R	S	B	B	R	R	R	B
3/10/07	SR	S	S	Swr	S	Swr	S	S	S	S	S	S
S=Smooth; Swr=Smooth with rindles; SR = Part Smooth and Part Rough; B=Bumpy; R=Rough; F=Frazil ice - % loose frazil ice in water column at sampling location; no=no ice cover surface observation recorded												

5.2 Velocity profile measurements under ice cover

Velocity measurements were collected to determine if the ice cover roughness influences the velocity profile. Each week, six velocity profiles were taken in each cross section, and a total of six weeks were sampled for a total of 72 velocity profiles under the thermal ice cover. Since the ice cover surfaces were generally consistent across the cross sections, but varied week to week, the velocity profiles were graphed by grouping all the sample locations in each cross section together for each week. The velocity profiles were keyed to the roughness of ice cover surface that was present at the sampling location (Figure 5-2).

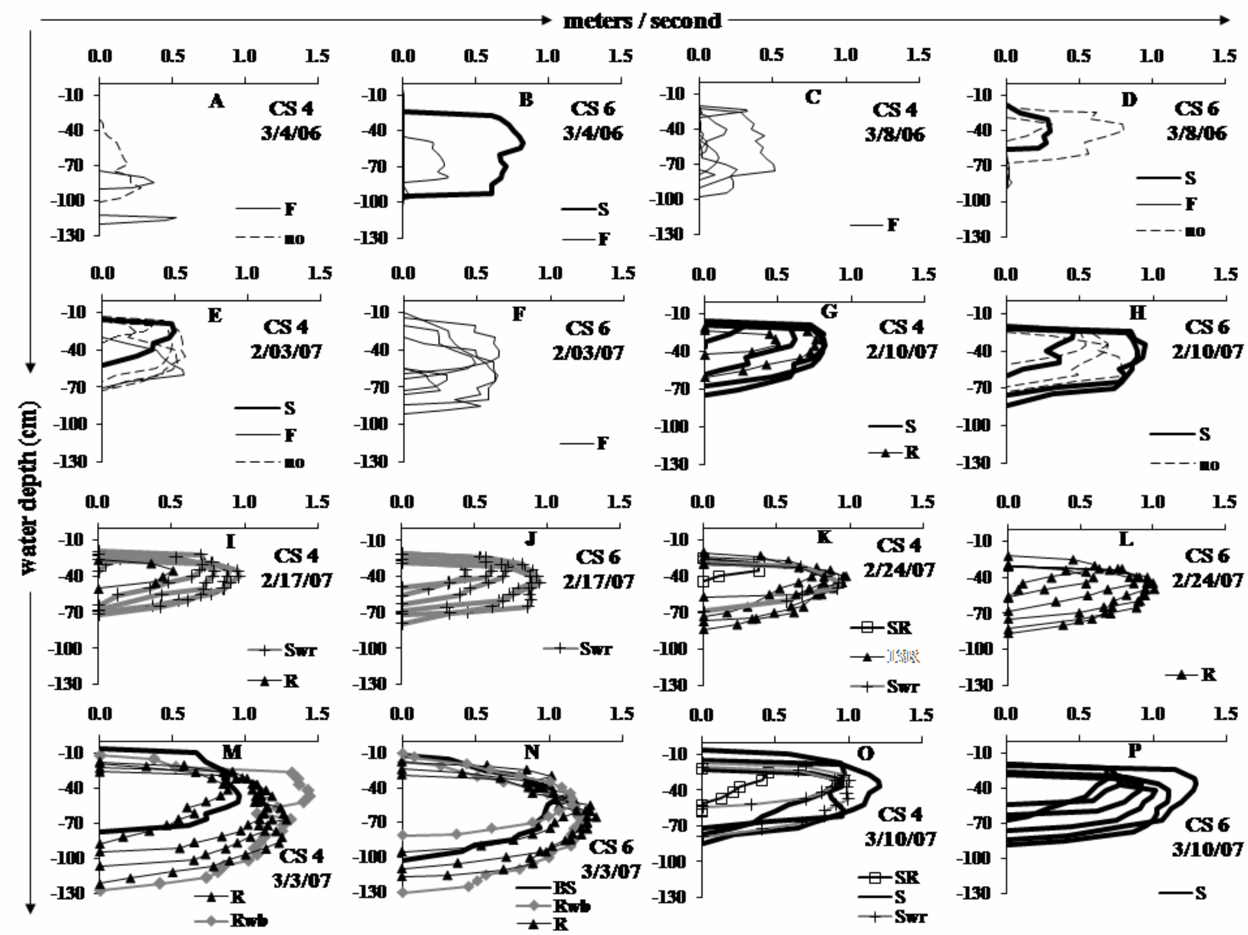

Figure 5-2. Velocity profile graphs A – P.

To determine if the roughness of the ice cover influenced the velocity profile, a comparison was done on the position of the average and maximum velocities between the smooth and rough ice covers (Table 5-2). The flow under the smooth ice surface had a maximum and average velocity that is closer to the ice cover than flow underneath a cover with a rough ice surface. When the cover had a smooth ice surface the relative position of the maximum velocity was 0.26D+/-0.06 (Table 5-2). A rough ice cover had a relative position of the maximum velocity of 0.46D+/-0.15 (Table 5-2). When the ice cover had a smooth ice surface the relative position of the average velocity was at 0.05DT+/-0.01 and 0.76DB+/-0.09 (Table 5-2). A rough ice cover had a relative position of the average velocity at 0.14DT+/-0.10 and 0.82DB+/-0.07 (Table 5-2). An example of the locations of the average and maximum velocities for velocity profiles under a smooth and rough ice cover is given in Figure 5-3.

Table 5-2. Comparison of relative position of average and maximum velocities.

Smooth n=29; Rough n=25 Parameter	Average D_T Velocity		Average D_B Velocity		Maximum Velocity D	
	Smooth Surface	Rough Surface	Smooth Surface	Rough Surface	Smooth Surface	Rough Surface
Mean	0.05	0.14	0.76	0.82	0.26	0.46
Standard Error	0.00	0.02	0.02	0.01	0.01	0.03
Median	0.05	0.11	0.77	0.81	0.26	0.45
Standard Deviation	0.01	0.10	0.09	0.07	0.06	0.15
Sample Variance	0.00	0.01	0.01	0.01	0.00	0.02
Kurtosis	-0.37	1.29	-0.26	-0.77	1.73	0.33
Skewness	-0.32	-1.38	0.19	-0.22	0.91	-0.60
Range	0.05	0.36	0.36	0.25	0.30	0.61
Maximum	0.08	0.40	0.93	0.95	0.37	0.82
Minimum	0.03	0.04	0.57	0.70	0.07	0.21
Confidence Level (95.0%)	0.01	0.04	0.03	0.03	0.02	0.06
t=1.96 Alpha @0.05	**4.83**>1.96 null hypothesis is rejected Position of the Top Average Velocity is different between smooth and rough surfaces		**2.74**>1.96 null hypothesis is rejected Position of the Bottom Average Velocity is different between smooth and rough surfaces		**5.23**>1.96 null hypothesis is rejected Position of the Maximum Velocity is different between smooth and rough surfaces	
D – Relative position in velocity profile. D_T – Relative position of average velocity near the stream surface. D_B – Relative position of average velocity near the stream bed						

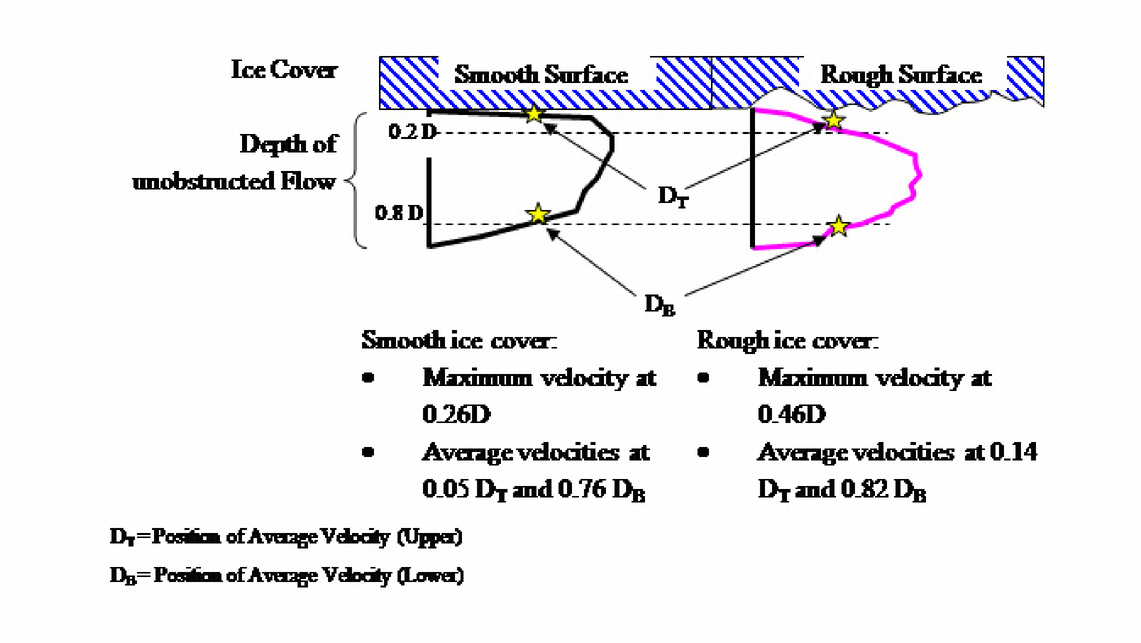

Figure 5-3. Comparison of velocity profiles under smooth and rough surface ice covers.

5.3 USGS average velocity estimation

One objective of this study was to compare the average measured velocity with the method that the USGS uses to determine the average velocity. The comparison between the measured average velocity and the average velocity determined by the USGS methodology for each sampling location is summarized in Table 5-3. The 6/10s method was calculated when the depth of the flow was less than 0.76 m. The two point and three point methods were calculated if the flow was greater than 0.76 m. The 6/10s method was used more than other methods because generally flow depth did not exceed 0.76 m. Seven of 72 average velocities that were estimated using the USGS methodology were within 0.03 m/s of the average value of the measured velocities (Table 5-3 and Figure 5-4). Two USGS estimations were below the average value of the measured velocities by more than 0.03 m/s and sixty-three USGS estimations exceeded the average value of the measured velocities by more than 0.03 m/s (Table 5-3 and Figure 5-4). Typically the coefficient for the 6/10s method is 0.92; however, the optimal coefficient for the velocity data collected was calculated as 0.75. Using 0.75 as a coefficient resulted in 30 out of 72 of the estimated values within +/-0.03 of the measured average velocities, while 42 of the calculated values were above (n=21) and below (n=21) the measured average velocity by more than 0.03 m/s (Figure 5-4).

Table 5-3. Comparison of USGS estimated velocity and measured average velocities.

Average Velocity Calculation Method	#of Calculations	# of Calculations Within +/- 0.03 of Measured Average	# of Calculations More Than 0.03 Above Measured Average	# of Calculations More Than 0.03 Below Measured Average
Measured Average Velocity	72			
USGS Two-Point Method	11	1	9	1
USGS 6/10s Method	72	7	63	2
USGS Three-Point Method	11	0	11	0

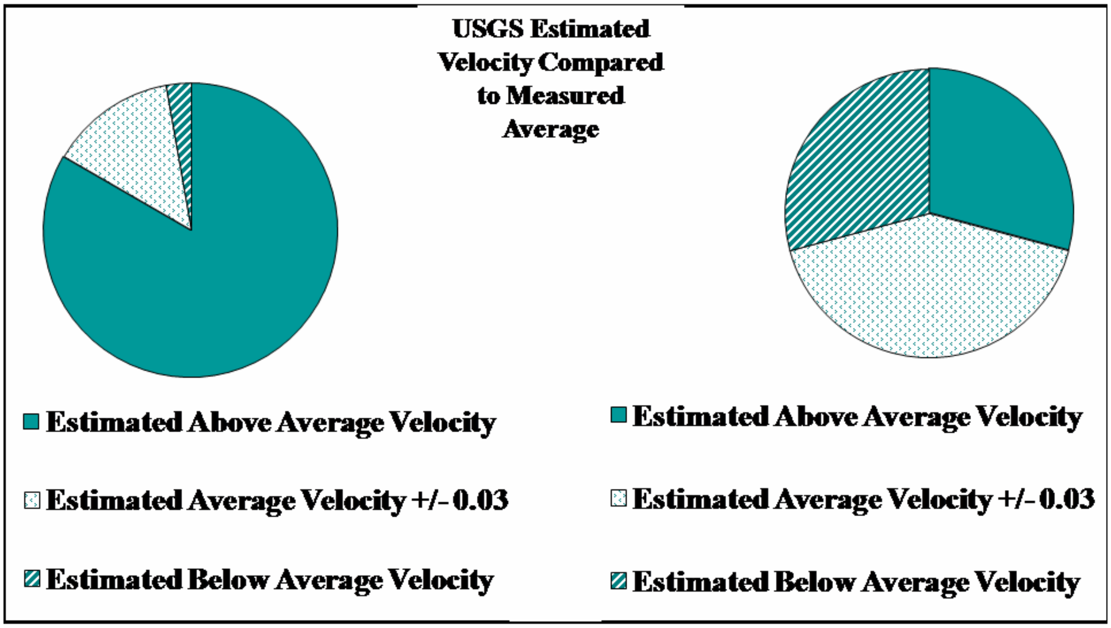

Figure 5-4. Comparison of USGS Estimated Average Velocity using 6/10s method and coefficient of 0.92 (left) and 0.75 (right).

6.0 DISCUSSION

6.1 Does the ice cover roughness vary with time and space?

Velocity profile data and ice surface texture data were collected two times during 2005-2006, and six times during 2006- 2007. During the 2005-2006 season, the ice surface was rough at all locations except T6-6m, which was the last area to form ice cover and did not have frazil ice accumulation under the surface on both sample dates. The accumulated loose frazil ice under the ice cover greatly altered the flow velocity (Figure 5-2 A-D). The velocity profiles that had loose frazil within the water column or aquatic vegetation were not used in calculating the relative positions of the maximum and average velocities because the loose frazil ice and the aquatic vegetation both interfere with analyzing the velocity profile for the influence of the ice cover roughness.

During the 2006-2007 season the texture was fairly consistent spatially, but the texture observations of the ice surface cycled temporally between smooth and rough (see Table 5-1). Cross-section six had the same texture observation across the width of the stream each week (see Table 5-1). Cross-section four had very similar texture observations across the stream width, with some variation in texture towards the stream banks (see Table 5-1). One explanation of how the ice cover could go from rough to smooth is provided by Nezhikhovskiy (1964), who stated that additional frazil ice would come under the ice cover and fill in depressed areas under the cover, smoothing the surface. Areas of smooth ice cover would have a random occurrence (Nezhikhovskiy, 1964), as the frazil ice would randomly attach to the bottom of the ice surface. However, it is not likely that additional frazil ice smoothed the ice surface in the study reach since the formation of frazil ice occurs in areas of open flow and does not travel long distances under an ice cover (Yapa et al., 1986). There were no openings in the thermal ice cover for more than ½ kilometer upstream of the study reach (see Figure 3-2). Other evidence that frazil ice was not smoothing the surface of the study reach ice cover is that the texture observations did not vary randomly, but rather were a gradual progression from a smooth surface, to a smooth surface with rindles parallel to the stream flow, to a bumpy or rough surface texture. The week-to-week change in the thermal ice cover indicates that there was a non-random process that developed the texture of the ice surface.

Another plausible explanation for the variation ice surface texture over time is that the cover may have an initial rough surface due to frazil ice, but water within the interstitial spaces of the frazil ice froze to create a smooth ice cover surface (thermal thickening). Subsequently, the stream flow began to erode the smooth ice cover by flowing in small rindles up to one centimeter deep in the ice cover that run parallel to the flow (the rindles possibly initially formed through stress fractures due to the weight of the ice cover). The flow in these rindles would continue to erode the ice rindle parallel to the flow until it reached an object within the ice (such as bits of vegetation or sediment) that caused the flow to veer left or right. The veering of the flow near the cover could cause the uneven erosion of the ice cover and create a roughened ice surface. Since the thermal ice surface developed in layers, the weaker bonds within the layer interface of the ice cover could eventually give way as more the lower ice layer got eroded. As pieces of the ice cover break off they would float down stream and reattach to the bottom of the ice cover, which could further roughen the downstream ice cover surface. The ice surface could smooth again if temperatures dropped below freezing, similar to the process previously stated, with water within the interstitial space freezing to create a smooth surface. The fresh smooth ice surface would then go through the process of roughening again. White (1999) mentions that ice covers can thicken by a thermal process or by transport and deposition of ice beneath the ice cover. Nezhikhovskiy (1964) mentions the smoothing of frazil ice shortly after ice cover formation coinciding with the thickening of the ice cover. The specific process of the variation of the ice surface over time has not been discussed by other studies, other than brief statements within White (1999) and Nezhikhovskiy (1964).

6.2 Does the velocity profile change with ice cover roughness?

What is perhaps more interesting about the flow under the ice cover is the variation in flow corresponding to the surface texture of the ice cover. Flow under a rough ice cover surface had a maximum velocity relative position that was 2/10ths lower than the maximum velocity position under smooth ice cover (see Table 5-2). The rough ice cover had a velocity profile that suggested the roughness of the ice cover was nearly as rough as the bed, as the relative position of the maximum velocity was 0.46D (approximately mid-depth). The relative position of the maximum velocity under a smooth ice was closer to the cover (0.26D) (see Table 5-2, and Figure 5-2). Zabilansky et al. (2005) and Beltaos (2001) found that maximum velocity of both rough and smooth ice covers remained at approximately mid-depth with floating ice covers. While the finding of the maximum velocity under a rough ice cover at approximately mid-depth (0.46D) is consistent with both Beltaos (2001) and Zabilansky et al. (2005), the finding of the maximum velocity shifted towards the ice cover under a smooth ice cover was different from either study. The smooth ice cover texture in the field was as smooth as a pane of glass, while both Zabilansky (2005) and Beltaos (2001) used plywood to simulate a smooth surface. Although the difference in textures may partially explain the difference between this study and the laboratory studies, further research is necessary to fully understand forces acting on velocity profiles under a smooth ice cover.

The relative positions of the average velocities were also different under smooth and rough ice covers. The average velocity position under a rough ice cover was 1/10th lower than that of a smooth ice cover. The difference between the smooth and rough ice cover in the relative position of the average velocity was larger near the cover than near the bed of the stream (0.05DT and 0.14DT respectively for the top average velocity positions, and 0.76DB and 0.82DB for the bottom average velocity positions) (see Table 5-2, and Figure 5-3). The data indicates that the roughness of the ice cover does influence the positions of the average and maximum velocities, and modifies the velocity profile. The variation in coefficients to calculate an average velocity was noted in Walker and Wang (1997); which would correlate to changes in the position of the average velocity in the velocity profile; however, Walker and Wang (1997) did not mention ice surface roughness as the reason for the fluctuation.

6.3 How do average velocity values obtained through typical United States Geological Survey (USGS) methods compare to actual velocity values measured in the field?

As noted previously, the USGS methodology calls for measuring the velocity at 0.2DT and 0.8DB and averaging these measurements to get the average velocity within the velocity profile; however, since the average velocity DT for both the smooth and rough ice cover was above the 0.2 DT (see Figure 5-3), the calculations are using values greater than the average velocity (the position of 0.2 would be in faster flow, and in fact would be close to the maximum velocity position under smooth cover). This is why the USGS average velocities (see Table 5-3) tended to exceed those of the measured average velocity. Results from this study indicate that the use of 0.8 DB alone to collect an average velocity measurement would be more accurate than the two point method. The USGS 6/10s method typically uses a coefficient of 0.92 to determine average velocity (Rantz et al., 1982) and the 0.92 coefficient is used at the Cazenovia Creek gage station by USGS personnel during ice cover (personal communication with H. Zajd, 2007). This method calculated higher average velocities than average velocities calculated from measured values during this study. If a coefficient of 0.75 is used with the 6/10s method, the results are closer to the average velocity calculations of this study (see Figure 5-4). A large variability in coefficients (0.55 to 1.26) for the 6/10s method is noted in Walker and Wang (1997); therefore, the use of a lower coefficient for closer accuracy with the calculated average of the measured velocities of this study can be justified.

7.0 CONCLUSIONS

This study has contributed to the understanding of the impact of ice cover on stream flow by documenting spatial and temporal patterns of ice cover surface roughness and the corresponding velocity profiles. Major findings of this study indicate the following:

1. The ice cover surface becomes rough due to flow eroding the ice surface unevenly and the ice cover roughness tends to be similar in texture across the stream cross section at any particular time if the ice cover surface is subjected to similar flow conditions across the stream cross section. Similar ice cover texture/velocity relationships were also observed in Nezhikhovskiy's (1964) study. The frazil ice cover remained rough in areas that had relatively low discharge; meanwhile, the ice cover was smooth in areas that had relatively higher flow. The thermal ice cover generally had a similar roughness across the cross sections; however, the surface texture changed week to week. The roughness of a thermal ice cover surface can change over time from smooth to rough, and back to a smooth surface again. Although this study was able to

document a progression of ice surface roughness, further data collection is needed to better understand the ice surface roughness progression process.

2. The velocity profile adjusts as the roughness of the ice cover changes. When the ice cover has a rough surface, the relative position of the maximum and average velocity is shifted closer to the stream bed than when the ice cover has a smooth surface. Numerous field and laboratory studies have also noted that the presence of an ice cover effects flow velocity (Ettema et al., 2000 and 1999; Smith and Ettema, 1997 and 1995; Wuebben, 1988; Lau and Krishnappan, 1985; Sayre and Song, 1979).

3. The typical USGS methodologies for determining average velocity profiles tended to produce average velocities higher than the measured average velocities in this study. The reason for the over-estimation is because the two-point method measures velocities at the 0.2DT and 0.8DB depths; however, the actual average velocities lie above or below these positions in the velocity profiles measured in this study. Flow at the 0.2DT position is faster than the average velocity of the velocity profile; meanwhile, flow at the 0.8DB position is faster than the average velocity under a rough ice cover, but slower than the average velocity under a smooth ice cover. The USGS 6/10s method for determining the average velocity also tended to produce average velocities higher than the measured average velocities in this study. If a coefficient of 0.75 were used rather than 0.92 for the 6/10s method, it would produce average velocity results closer to the average velocity measurements in this study.

Suggestions for Future Research

The work accomplished in this study will help to better understand stream ice cover and its influence on stream flow and channel morphology; however, there is still further work to be done to understand ice cover and flow dynamics. Suggestions for future research include:

- Collection of ice surface roughness measurements to document the average and range of ice surface roughness in many different stream and river locations.
- Collection of more velocity profile data in various field conditions to better understand the influence of surface roughness on the velocity profile.
- Comparisons between roughness coefficients that are back calculated from velocity profile measurements and those that are calculated from ice cover roughness measurements to verify that the values are similar.

Often ice roughness coefficients are back calculated using standard flow equations such as Manning's equation, the Darcy-Weisbach equation or a boundary-layer theory (White, 1999). A method for measuring the roughness of the ice surface should be developed to better understand the influence of surface roughness on the velocity profile. Future laboratory studies may want to gain more knowledge about the ice surface roughness in rivers and streams so that artificial covers can be developed that are similar to natural conditions.

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