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Acoustic detection of ice and water velocities on the Peace River during the 2008-2009 Winter

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Frazil ice detection and water velocity profile instruments were deployed in the Peace River in Northern Alberta, which is hydraulically regulated by upstream hydroelectric projects. The data are being collected to support studies related to ice jam occurrences and winter hydropower operations.

Concurrent deployment of two Shallow Water Ice Profiling Sonars (SWIPS) of two different frequencies and an Acoustic Doppler Current Profiler (ADCP) was successful on the Peace River during the winter of 2008-2009. The paper describes the freeze-up, mid-winter and break-up ice processes in context with the ADCP and the higher of the two SWIPS frequency instruments and environmental parameters.

Insights into the surface and suspended ice runs, ice cover stabilization and formation process, and ice cover frazil slush transport throughout the ice season were provided by the ADCP and SWIPS instruments.

The formation of a grounded out freeze-up ice jam close to the instruments' location allowed for the collection of data on the erosion of this blockage over the course of the winter.

1. Introduction

Floating frazil ice pans and suspended individual or aggregated crystals of frazil ice in fresh water bodies often have significant impacts upon water supply, hydro electric, fisheries and other management activities. Effective detection and quantitative characterization of such ice can provide direct input to operational decision-making and for formulating numerical river ice and flow models (Shen et al., 1995; Shen, 2006) underlying modern flow management (Jasek, 2006).

The results presented here were obtained in freshwater during BC Hydro's and Alberta Environment's 2008-2009 winter Peace River monitoring programs utilizing SWIPS (Shallow Water Ice Profiler Sonar) instruments developed by ASL Environmental Sciences Inc. and a Teledyne RDI ADCP (Acoustic Doppler Current Profiler). The SWIPS is an upward looking sonar instrument that acquires acoustic backscatter data from, roughly, 1.1 cm deep, horizontal, slices of an insonified water column. Suspended particles such as frazil ice crystals, the bottoms of floating frazil ice pans and the water surface can be detected. The location of the monitoring program and the basic instrument set-up and components are depicted in Jasek et al. 2005. The SWIPS and ADCP are deployed on the river bottom in about 5 m depth about 50 m offshore into the 350 m wide river and the former is linked to an instrument shelter on shore via a communications cable for data transfer. The ADCP is attached to the same mooring platform but data from it is not retrieved prior to the spring recovery of the instrument. A steel mooring cable and a power supply cable for an onboard heater to prevent anchor ice from forming on the SWIPS instruments are also connected to the shore. The ADCP did not have a heater due to practical difficulties.

2. Instrumentation

The Shallow Water Ice Profiler (SWIP) is a real-time acoustic ice thickness measurement (ice draft) instrument for shallow water river and lake applications. The underwater components include an acoustic transducer, a tilt sensor, and a temperature sensor, all providing suitably high resolution for shallow water measurements. The instrument can be operated in an internal recording mode with a connection to an underwater battery pack for power, or with RS-422 serial output for real-time operation using an underwater cable which also allows for external power. The SWIP is a shallow water version of the Ice Profiler Sonar developed for ocean applications (Melling et al., 1995). This instrument has recently been upgraded to provide additional data capacity and improved resolution and accuracy (Fissel et al., 2008). The use of the shallow water version has been used in river applications since 2005 (Jasek et al., 2005, Marko and Jasek, 2008). The bottom-mounted SWIP instrument can be programmed to provide measurements of ice targets and/or measurements of the acoustic backscatter return throughout the water column at measurement intervals of 1 s or longer.

A 235 kHz and a 545 kHz SWIPS unit were deployed during the 2008-2009 ice season but to reduce the scope this study, only data from the latter unit was presented in this paper. The units sampled at 1 Hz for the entire ice season and provided data at 1.1 cm intervals throughout water column.

The Acoustic Doppler Current Profiler (ADCP), Sentinel Workhorse series, manufactured by Teledyne RD Instruments of Poway, California, USA was used for measurement of the vertical profiles of the river flow. The ADCP technology is widely used for oceanic and freshwater environmental monitoring applications. Mounted on the river bottom, the ADCP unit provides precise measurements of ocean currents (both the horizontal and vertical components) at 0.25 m vertical spacing within the water column, from near surface to near-bottom at five minute sampling intervals. The ADCP also provides time series measurements of the velocity of the river ice moving at the surface, as well as near-bottom temperature data. The ADCP instruments measure velocity by detecting the Doppler shift in acoustic frequency, arising from water current (or ice) movements, of the backscattered returns of upward (20^o from vertical) transmitted acoustic pulses.

3. Description of the 2008 – 2009 ice season

Figure 3.1 shows the time dependence of the location of the leading edge of the stationary ice cover (ice front) in terms of distance along the length of the Peace River. The SWIPS and ADCP measurement site and water and air temperature time series are also included in the Figure. It can be seen that water temperatures reached the supercooling point at the SWIPS site on Dec 14, this initiated the formation of suspended frazil ice and surface frazil ice pans. This frazil ice run continued until freeze-up of the ice cover that occurred on Dec 28. Due to cold weather in the -20 to -40 ^oC range, the ice front continued to rapidly advance 165 km upstream of the SWIPS location until mid January. Milder weather with only occasional cold spells caused the ice front to remain relatively stable in a zone 160 to 190 km upstream of the SWIPS location from mid January to mid March, 2009. After mid-March the weather warmed significantly and the ice front retreated downstream and a thermal break-up occurred at the SWIPS location on Apr 13. Although the Smoky River (a significant tributary of the Peace River about 1 km upstream of the SWIPS location) broke up dynamically, the dynamic break-up front stalled short of the confluence and then melted thermally. This dynamic break-up did send a surge of water into the Peace from Apr 10 – 14 but it was not enough to trigger a dynamic break-up event on the Peace River.

4. Pre freeze-up

This was the first year that an ADCP was deployed on the Peace River along with the two SWIPS instruments and therefore some assessment of its performance during ice conditions is warranted. Figure 4.1a shows the water levels from barometrically compensated pressure transducer as well as depth- and time (30 minute)-averaged water velocities from the ADCP corresponding to open water and pre-freeze-up period. Water temperature data are also included in the plot to delineate between the supercooled period initiated on Dec 14 from prior, ice free, conditions. As expected water level and velocities are well correlated in the ice free period but, at times between Dec 14 and 18 the water velocities vary well outside of the ranges anticipated from the contemporary water level fluctuations. This lack of correlation is believed to be a consequence of anchor ice formation on the unheated ADCP instrument. The consequent blockage of the acoustic beam was particularly unfortunate since the observed fluctuations in water levels suggest that there may be something interesting going on during this period. The fluctuations, with an amplitude of about 10 cm, cannot be explained in terms of water discharge changes at the Peace Canyon Hydroelectric facility or a gauge 226 km upstream of the SWIPS instrument. As well, in December all tributaries are contributing base flow and would not be capable of introducing fluctuations of the observed magnitude. Consequently, the fluctuations must have been introduced by the ice formation process itself. Possible driving mechanisms would include the formation and release of anchor ice from the bed of the river as well as border ice growth and decay. Had reliable ADCP data been available during this fluctuation period it would have been possible to asses if the observed changes were due to a shift in the rating curve as opposed to having their origins in an actual water storage and release mechanism connected to anchor ice formation and release. It is therefore recommended that a heater be added to the ADCP in future deployments.

Figure 4.2 shows the 545 KHz SWIPS data during the pre-freeze-up period associated with the first appearances of ice on Dec 14 to just prior to the buildup of a backwater from an approaching ice front on Dec 26. Variations in ice pan thickness (red) and surface ice concentration as well as the presence of ice suspended in the water column are evident in this image. Figure 4.3a quantifies this information from the raw data and Figure 4.3b shows the ADCP water velocity, air and water temperature during this same time period.

Unsurprisingly, air temperature was the dominant controlling variable for the observable amounts of suspended and surface ice. Suspended ice return strength and surface ice concentrations and ice pan thicknesses coincidentally increase sharply at the onset of supercooling on Dec 14. The tendency for surface ice prevalence to inversely track air temperature is evident in comparisons of results from the brief Dec 15 to 18 warming period relative to those from the preceding and following cold periods. However, the SWIPS returns from suspended ice not only appear to be sensitive to air temperature but also to surface ice coverage. As expected, given the same air temperature, the strength of the returns from suspended ice decreases with increasing surface ice concentration. To the extent that SWIPS signals from frazil are proportional to the amount of frazil ice presence (Marko and Jasek, 2010), this result shows the insulating effects of surface ice which reduces the supercooling and, thereby, frazil generation rates. Similar results were reported by Jasek and Marko (2007) for Jan 2006 but anchor ice problems precluded more definitive observations of the effect.

5. Freeze-up

In terms of ice processes and hydraulic conditions, freeze-up can be divided into two distinct periods: associated with the approach of the backwater curve; and ice cover formation which includes ice cover shoving events.

5.1 Approach of the backwater curve

As frazil ice pans travel downstream they can stop and freeze together at a constriction to form an ice cover. As additional frazil pans arrive and accumulate this stopping point moves further upstream, and is designated as the ice front. Due to its thickness and frictional forces the ice exerts on the water flow, water levels at and downstream of the ice front are much higher than for an identical discharge rate under open water conditions. This increase in water levels is typically 3 to 5 m on the Peace River.

As the ice front approaches any particular location (like the SWIPS site), water levels increase prior to ice front arrival: producing a distinct transition zone upstream of the ice front which is typically about 10 to 15 km in length. This transition region between the ice covered and open water water levels is called a backwater curve. Since the ice front can be typically traveling 5 to 15 km/day (depending on the supply of frazil ice pans arriving from upstream) the increase in water level (or stage-up) can typically take 1 to 3 days.

Figure 5.1a shows the rise in water levels produced by the approaching ice front. As expected, the depth-averaged water velocity measured by the ADCP decreases as the water level and the corresponding river cross-sectional area increases. The ADCP also provided ice pan or ice cover velocity data through its “bottom tracking” feature. Prior to and during most of the stage-up process the ice velocity is about 10% higher than the depth-averaged water velocity and the two decrease in unison. This is as expected, as under open water conditions, higher water velocities tend to occur near the water surface. However, at some point as the surface ice concentration increases the ice should begin to slow down due to bank and border ice friction forces and due to collisions between the ice pans themselves. This did not appear to happen for surface ice concentrations between 90 and 95% (Figure 5.1a,b), with detectable slowing confined to ice concentrations very close to or at 100%. It would be interesting to conduct further analysis and compare velocity profiles without and with ice at various surface concentrations to determine the effect of ice concentration on channel conveyance. Shen et al (1990) developed a theoretical relationship that shows that the conveyance capacity starts to be affected by surface ice concentrations greater than about 60%. More detailed analysis of our Peace River data could establish this relationship directly.

Figure 5.1b shows that the strength of the SWIPS returns from suspended ice decreases as water velocity decreases. This could be due to the reduced turbulence in the backwater that is no longer strong enough to keep frazil ice in suspension. On the other hand, the effect could also be attributed to lower air temperatures (Figure 5.1c). However, it is notable that the frazil ice pan thicknesses in Figure 5.1b increase substantially prior to surface ice concentrations going above 0.95 early on Dec 28, possibly due to accretion of frazil ice coming out of suspension. Later on Dec 28, further thickening could be caused by the compression of the surface ice run in a narrower reach upstream of the SWIPS location.

One weakness of the surface ice concentration and thickness data in Figure 5.1b is that after about 1100 hrs on Dec 28 is that they were no longer representative of conditions further out in the river. The ice over the SWIPS stopped moving at this time and a shear line separated it from the moving and stationary ice forms further out in the river. This circumstance accounted for continued rises in local water levels in response to the approaching ice front even though ice velocities were predominantly zero over the SWIPS. Between 14:25 and 16:25 hrs a small lead formed over the SWIPS and ADCP before closing again. These data suggest that deployments of instruments 30 to 50 m further out into the river could provide more representative data.

5.2 Ice cover shoving events or consolidations

Figure 5.1a includes evidence for a shoving event in the approaching ice cover downstream of the SWIPS/ADCP site. Such an event is suggested by the sharp drop in water level and comparably strong rise in water and ice velocities late on Dec 28. Figure 5.2 also contains evidence of this event in the SWIPS acoustic and the ADCP water velocity profiles. The latter Figure also highlights two other shoving events: one early on Dec 30 and one on Jan 1. The Dec 30 event reached the instrument location as the ice cover thickened in response to water level and velocity increases. The Jan 1 shoving event coincided with only a temporary rise in water level and velocity, indicating that the shoving displacement stopped short somewhere upstream of the instrument site.

Unfortunately, the SWIPS profile data between Dec 28, 19:46 hrs and Jan 2, 21:04 hrs were somewhat compromised by reduced return signal strengths in this period (Figure 4.2). The start of the reductions coincided with a sudden late Dec 28 water level drop. It is suspected that the shielding of the SWIPS communications cable may have been compromised at the shore ice hinge line at this time or perhaps a pebble had been deposited by released anchor ice on the SWIPS transducer face. In any case, the problem was self-corrected on Jan 2 as indicated by the apparent and continued increase in suspended ice concentration. The observed instantaneous increase (over 1 second) in suspended ice return strength could not reflect true changes in this ice component since even highly dynamic events tend to require times ranging from a fraction of a minute to several minutes to produce comparable changes. Also, the thickness of the region adjacent to the transducer face associated with saturated signal levels was substantially reduced during the suspected period, favouring instrument- as opposed to ice character- origins of the problem. Nevertheless, useful qualitative interpretations can be gleaned from this time period.

The consolidation event on Dec 30 is interesting as it produced a permanent increase in water velocity from 0.4 to 1.2 m/s (Figure 5.2b) even though the river discharge was unchanged after decay of the dynamic component transient. An examination of the ice cover after this event, as captured in Figure 5.3, offers relevant insights into these results. The photograph taken encompasses the width of the river at the SWIPS/ADCP location and shows a very rough ice cover in the central portion of the river offshore of the instrument location. This rough ice is the downstream end of the ice shove (toe) and, since the toe of these events have been previously been measured to be grounded (Andres et al. 2005); it is possible that the associated ice consolidation created a local restriction in the river thereby increasing the water velocities. Unfortunately, the significance of this was not realized until weeks later when downloaded SWIPS data were suggestive of the presence of unusually large amounts of frazil ice being transported in suspension. A cross section across the toe of this consolidation was measured on Mar 16 which indeed indicated that ice was grounded 6 to 7 m to the bed (Figure 5.4a) but locally thinner thermal ice existed over the SWIPS location. In contrast, a cross section measured in a different year (Feb 8, 2010) showed a more uniform thickness of the ice cover (Figure 5.4b) as well as evidence for a typically thick layer lower layer of slush ice. It is likely that initially the restriction was even larger at the time of formation on Dec 30 relative to the Mar 16 measurement data due to erosion in the interim.

6. Mid-Winter and break-up

The locally thickened ice cover that formed on Dec 30 (described in the previous section) near the SWIPS/ADCP site had an impact on the local frazil transport and velocities measured by the two instruments for the remainder of the ice covered season. The collected data were not typical of this river section on the basis of measurements made in other years associated with more uniform distributions of ice thickness across the channel. However, the data still provided valuable insight into the mid-winter frazil transport and erosion processes.

Figure 6.1 shows the vertical velocity profiles before, during (Dec 28 to Apr 13), and after the ice covered season. The two black lines indicate the water level and the bottom of ice level. In the first week or so after freeze-up there appeared to be about a metre of slush which eroded fairly quickly. Eventually, only a solid thermal ice layer remained over the SWIPS/ADCP location through the remainder of the winter. This situation was confirmed by holes drilled through the ice on Feb 11 when the thermal ice thickness was found to range between 0.34 to 0.45 m in 13 holes drilled over and close to the SWIPS location. This relatively thin ice with no slush underneath was a local phenomenon and was likely caused by frazil slush erosion due to the high velocities caused by the main channel blockage of the flow further out in the river (Figure 5.4a).

Figure 6.2a shows the vertically integrated average velocity as well as the water level and bottom of the ice cover. Apparent is the sudden rise in water velocity on Dec 30 from 0.4 to 1.2 m/s when the blockage of the channel formed. The water velocity then settled quickly down to a value of about 1 m/s and then rose steadily until Jan 19 to a value of 1.5 m/s. The frazil transport shortly after freeze-up implied by Figure 6.2b (early January) is maximal for the entire winter period. The fact that the contemporary water velocity was increasing may indicate that the water way area on the left side of the consolidation toe was expanding and allowing more water and higher conveyance through the left side of the channel. Figure 6.2e shows that the discharge from Peace Canyon Dam was constant at about 1450 m^3/s from Dec

25 to Jan 11 (1600 m^3/s Dec 27 to Jan 13 at the SWIPS location due to the flow travel time and additional tributary inflows) indicating that water velocity increase during this period was not due to increased releases from the Peace Canyon Dam but that it may had been due to the flow redistribution around the toe of the consolidation. One may argue that the flow withdrawal due to the moving upstream ice front puts water into storage and could be the source of observed velocity and discharge variations at the SWIPS site. Generally, this would be true as a moving ice front can add or subtract a few hundred m^3/s of flow to/from the Peace River. However, the ice front was moving at a fairly constant rate during this period (Figure 6.2f). Further evidence to support that the discharge was constant is that the water level remained relatively flat during this time (Figure 6.2a).

Following the steady flow period, the discharge from Peace Canyon was gradually increased over a few days up to 1700 m^3/s for a total discharge of about 1950 m^3/s at the SWIPS site. The weather moderated in the same period, slowing ice front movement and reducing the amount of water going into storage. These two effects increased the flow and water level between the Jan 13 to Jan 21 period but the frazil transport rate continued to drop (Figure 6.2 b,c) likely because the source of local frazil supply was diminishing through erosion. The inferred frazil transport rate continued to decrease until late February after which it varied in unison with water level, velocity and discharge fluctuations. There was no longer a steady fall of water levels as in late January and all of February, indicating that the locally high erosion rates of the frazil slush was largely completed. However, since the relationship between the SWIPS return strength from suspended ice targets and actual volumetric ice concentrations is not linear and both frequency- and particle size-dependent (Marko and Jasek, 2010), more definitive inferences from these results will require additional analyses. It is sufficient to note that previously observed (Marko and Jasek, 2008) correlations between return strength and river water levels were again strong and present at times after, roughly, Jan. 30, the end of the period associated with “anomalous” suspended frazil properties (Marko and Jasek, 2010).

Figure 6.2d shows the air temperature during the ice covered period and the frazil transport. One may be tempted to conclude that there is increased frazil transport for higher air temperatures but the underlying relationship is almost certainly indirect. Higher air temperatures cause the ice front to slow down or even recede thereby increasing the flow in the river (less water going into storage or water being releases from storage) raising water velocities and frazil transport rates.

Figure 6.2g shows the ice velocity and depth-averaged water velocity as well as the suspended ice return strength. Since overall the ice cover is stationary after freeze-up, the ice velocity is presumably the speed of the ice particles bouncing along the underside of the ice cover. During the ice-covered season, the ice velocity ranged from 5 to 25% of the mean water velocity which is what may be expected from a logarithmic velocity profile and for ice particles travelling with the water velocity close to the ice undersurface. The plot shows that there appears to be a higher correlation between the ice velocity (rather than water velocity) with the suspended ice return strength.

On Apr 9 there is an instantaneous doubling of suspended ice counts and a corresponding instantaneous increase in water velocity from 1.3 to 1.7 m/s. Yet there is no substantial increase in water levels which, in fact start to drop slowly after this point in time. It could be that there was a localized shift in the velocity distribution due to a sudden frazil mass release and reconfiguration of the consolidation toe. Contribution from the Smoky River which comes into the Peace River just upstream of the SWIPS location were not significant enough to cause the increases on Apr 9 as the dynamic break-up did not occur until Apr 11-12.

7. Conclusions

Concurrent deployment of a SWIPS and an ADCP was successful on the Peace River during the winter of 2008-2009 and yielded insights into the ice processes that occur prior to, during and after freeze-up.

This was the first ice season in which an ADCP was added to the SWIPS measurement program in order to gain insights into the role played by water velocity in the many observed ice processes. However, despite its plastic housing, the ADCP was not immune to data interruption due to anchor ice formation on its transducer surfaces. It is recommended that a heater be installed in future deployments to duplicate our previously demonstrated successes in maintaining SWIPS measurement continuity. Reliable velocity measurements during the active frazil period should give insights into the source of water level fluctuations that cannot be accounted by hydroelectric or tributary inflow variations. It is important to distinguish if these water level fluctuations are simply due to a shift in the rating curve due to anchor/border ice formation and release or represent actual changes in discharge due to the same factors. The latter interpretation would be indicative of water storage withdrawal and release over long reaches and would have larger effects on the stability of forming ice covers.

As expected, the suspended ice acoustic return strength increased with decreasing air temperature and decreased when surface ice coverage increased. The former result is due to increased heat loss from the water surface and the latter arises from the insulating effects of the surface ice. However, further work on quantifying the composition of the suspended ice on the basis of the acoustic signal returns will be needed before these relationships can be established and used to improve river ice models.

Suspended ice return strengths dropped off as the backwater from the ice front approached the SWIPS site indicating that ice was coming out of suspension. This effect could have been due to 3 factors; decreasing velocity and associated turbulence; increased water surface insulation from increasing surface ice concentration; and an increase in air temperature. Unfortunately, the air temperature warmed slightly during the stage-up period so this factor could not be discounted. However, the suspended ice return signal was lower than observed during comparable periods of similar air temperature and surface ice concentration. Additional years of data associated with approximately constant or cooling air temperatures during the stage-up period are needed to support drawing firmer conclusions on relative importance of the cited three alternative mechanisms affecting suspended ice concentrations under the backwater curve of an approaching ice front.

The SWIPS data showed the thickness of the ice run in the backwater curve to be thickening as the ice front approached: providing a possible indication that the suspended ice was coming out of suspension in this period. Later on, under higher surface ice concentrations, further thickening could have been caused by compression of the surface ice run in a narrower reach upstream of the SWIPS location.

During the ice cover formation period the SWIPS and ADCP were located under the ice cover formation shear line indicating that future deployment should be another 30 to 50 m further out in the river in order to collect data which are more representative of overall ice processes. Nevertheless, the instruments did record interesting ice cover shoving events where increasing velocities coincided with thickening of the ice cover.

After freeze-up was complete over the instrument location, the SWIPS and ADCP provided insights into the erosion of a localized restriction (a toe of a consolidation that formed during the freeze-up process) over the remainder of the ice covered season. Frazil transport rates were maximal after freeze-up and diminished gradually over a 2 month period as the toe of the consolidation eroded. Later on in the ice season, the suspended ice return strength increased with increases in water level, discharge and water level velocities as expected. Ice velocities under the bottom of the ice appeared closely correlated with suspended frazil intensities. Additional analyses are needed to quantify and, hopefully, explain these correlations.

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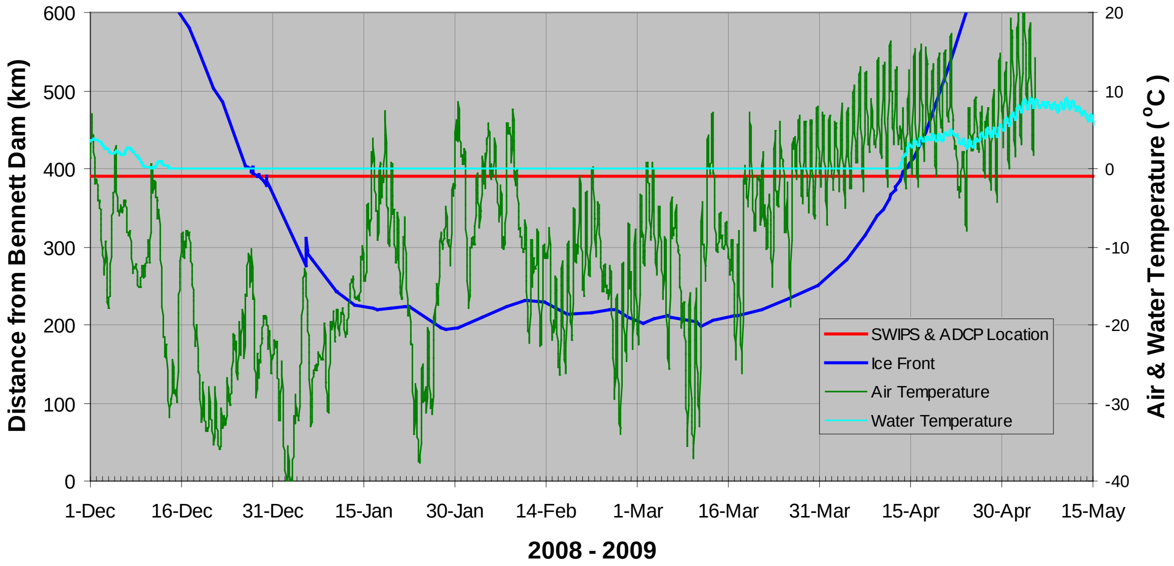


Figure 3.1. Location of SWIPS, ice front, air and water temperatures. (Stationary ice cover present above dark blue line).

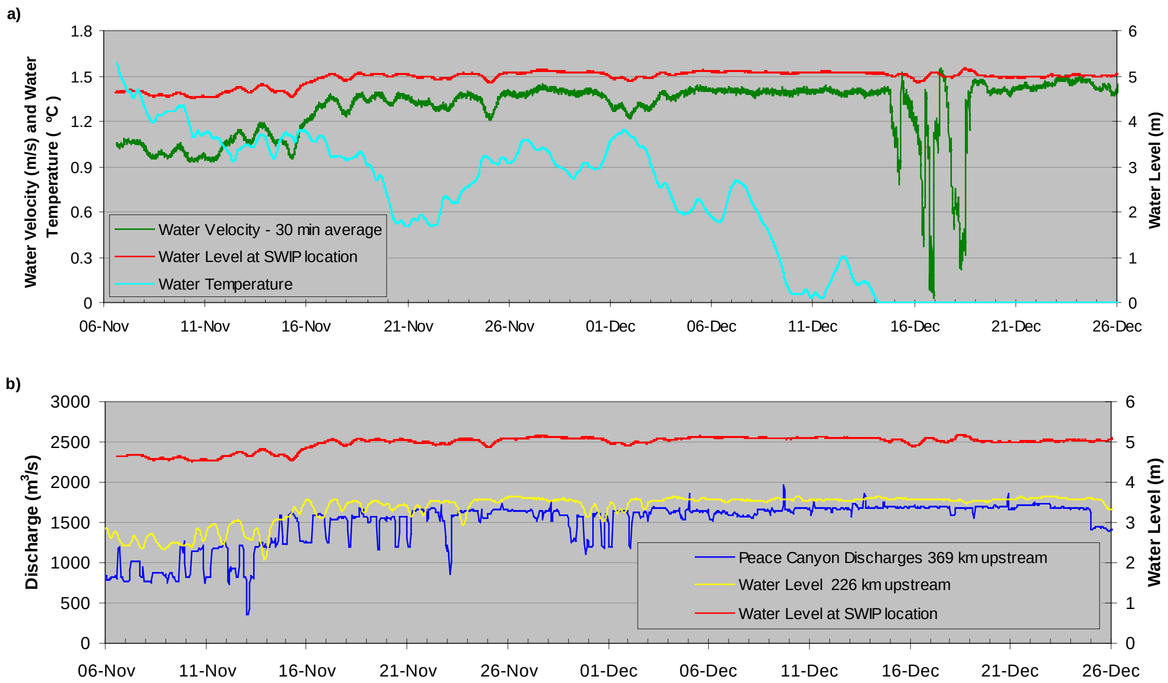


Figure 4.1. a) Vertically and 30 minute time-averaged ADCP water velocity, water level and water temperature at the SWIPS location. Some anchor ice build-up gave inaccurate ADCP readings Feb 14 – 18. b) Hourly water discharge from the Peace Canyon generating facility 369 km upstream, water level 225 km upstream of the SWIPS and water level at the SWIPS location.

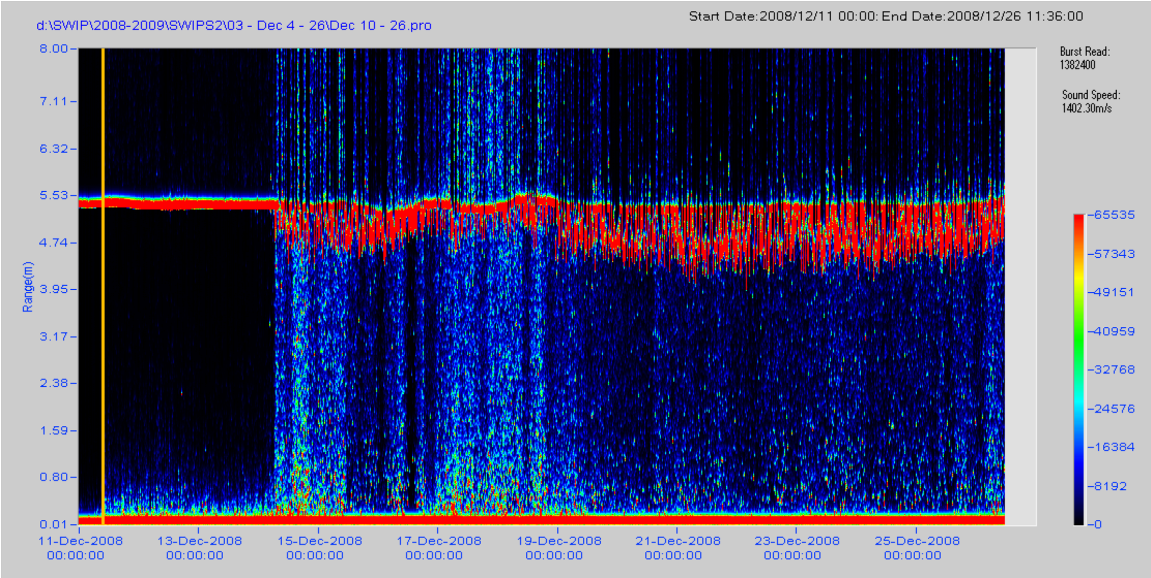


Figure 4.2. SWIPS 545 KHz profile data shown suspended and surface ice during the ice formation period. The last data shown on Dec 26 is just prior to the start of stage-up from an approaching ice front.

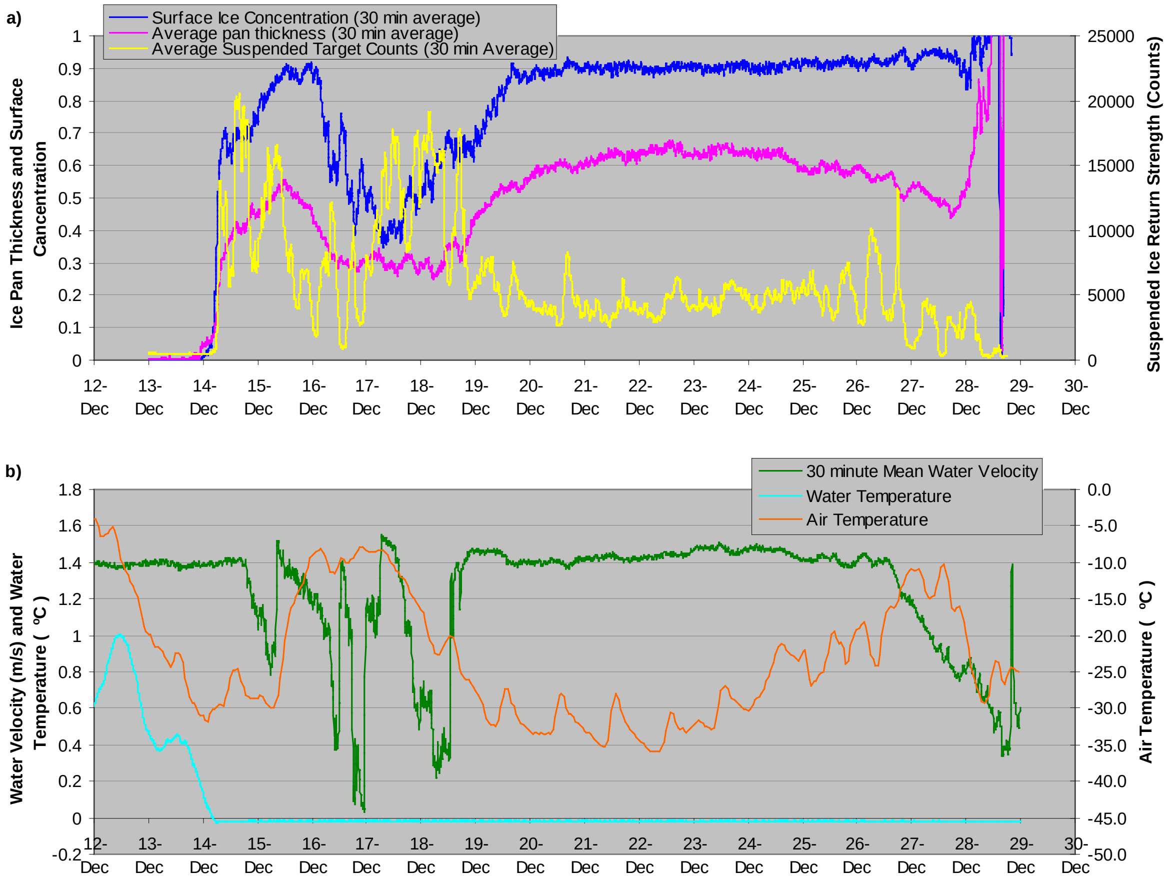


Figure 4.3 a) Surface ice concentration, ice pan thickness and suspended ice derived from the SWIPS data. **b)** ADCP water velocity data, air and water temperature. Data shown after Dec 26 shows the effect of increasing depth and lowering velocities as the backwater increases due to and approaching ice front.

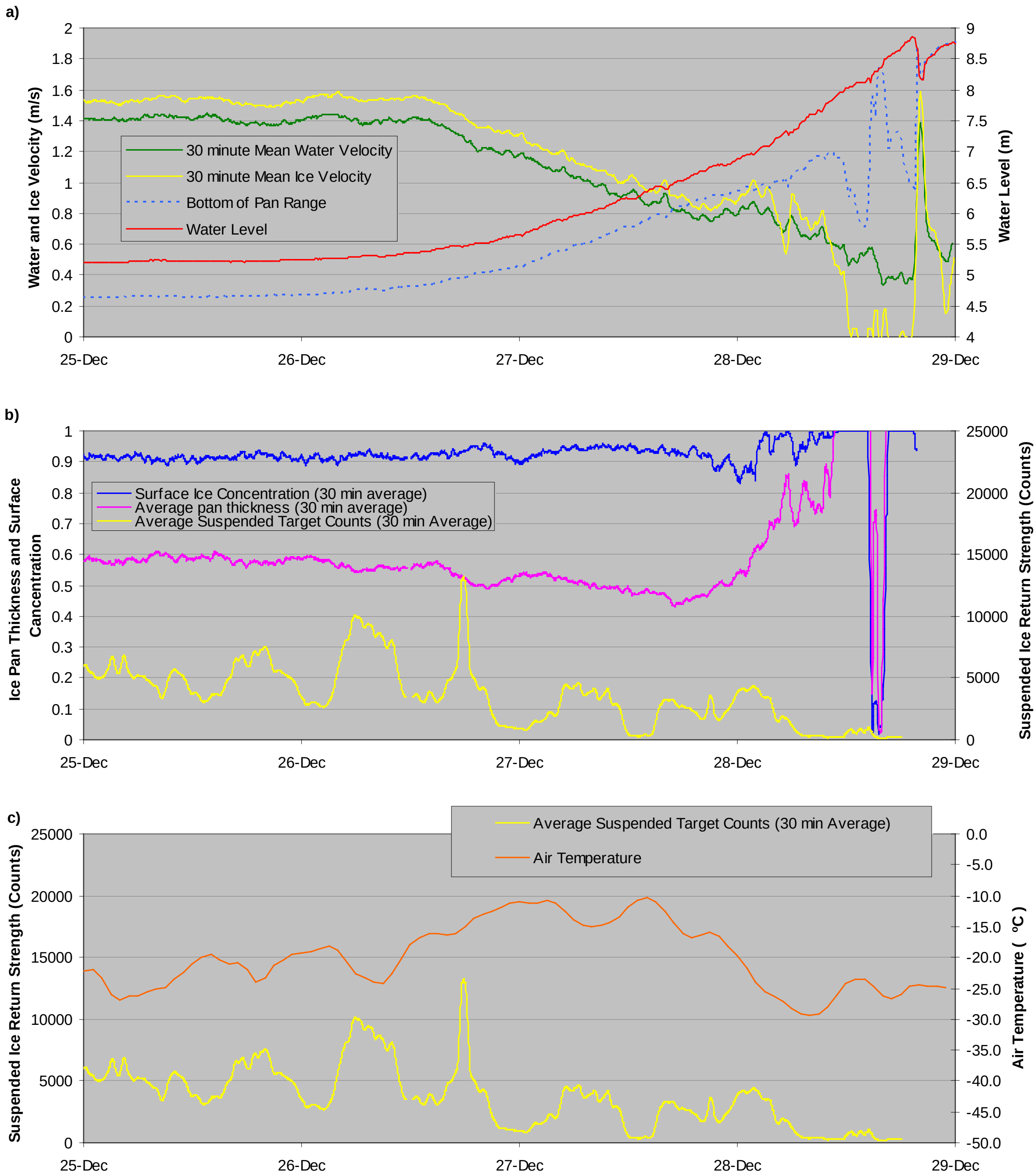
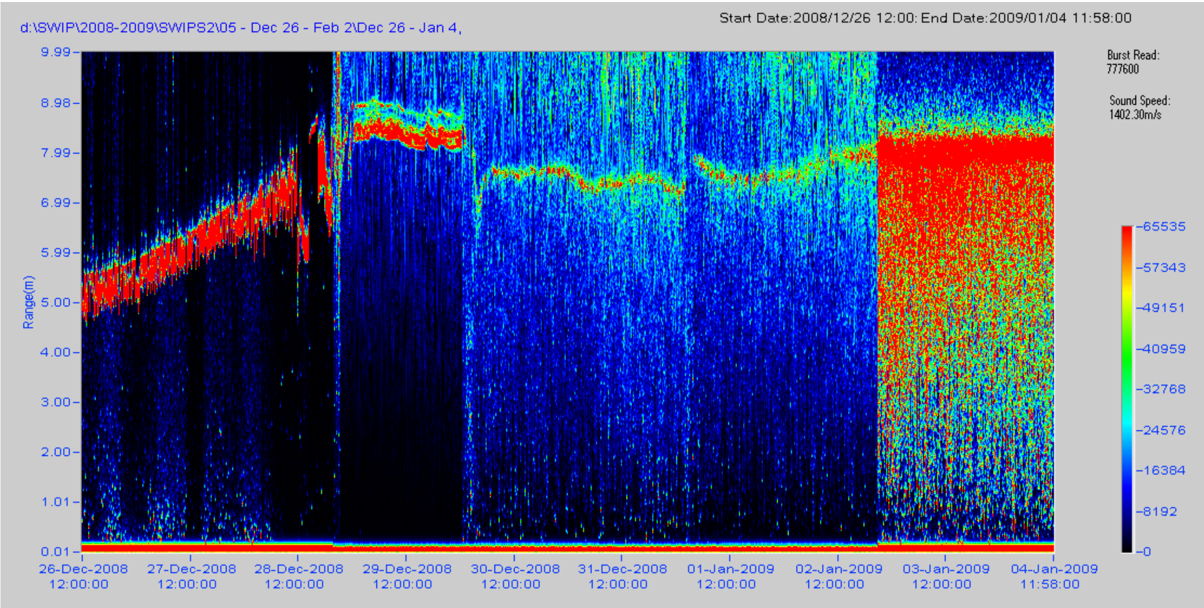


Figure 5.1 a) Water level, mean depth-averaged water velocity and ice velocity as backwater approaches due to advancing ice front and during the first instance of ice stabilization of the ice cover. **b)** Surface ice concentration, ice pan thickness and suspended ice from SWIPS data during the same time period. **c)** Air and water temperature

a)



b)

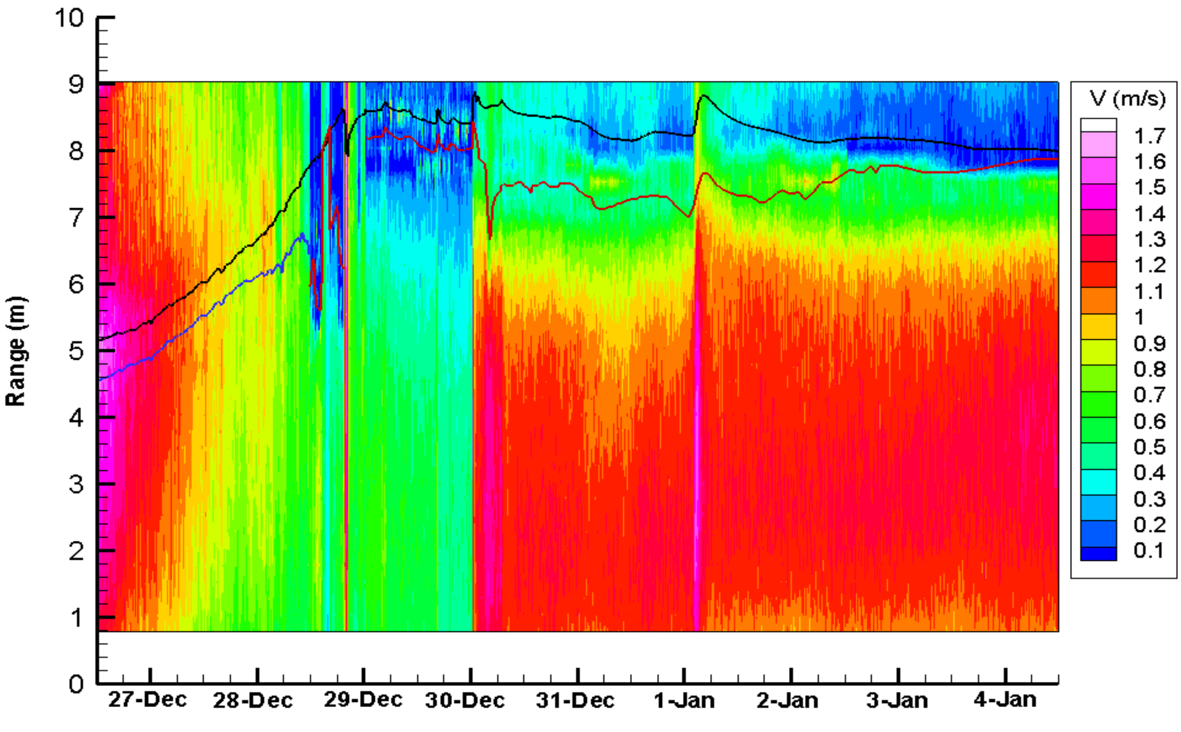


Figure 5.2 a) SWIPS 545 KHz acoustic profiles and **b)** ADCP velocity data during the ice cover formation period, black line is the water level, the red line is the bottom of stationary ice, the blue line is the bottom of frazil ice pan floes. ADCP data above these lines is reflected and not valid. Note: SWIPS signal in a) is partially blocked or weakened Dec 28, 19:46 hrs to Jan 2, 21:04 hrs as suspended frazil returns appear weaker, bottom of ice detection is more subtle, thickness of saturated signal near Range = 0 m is thinner.

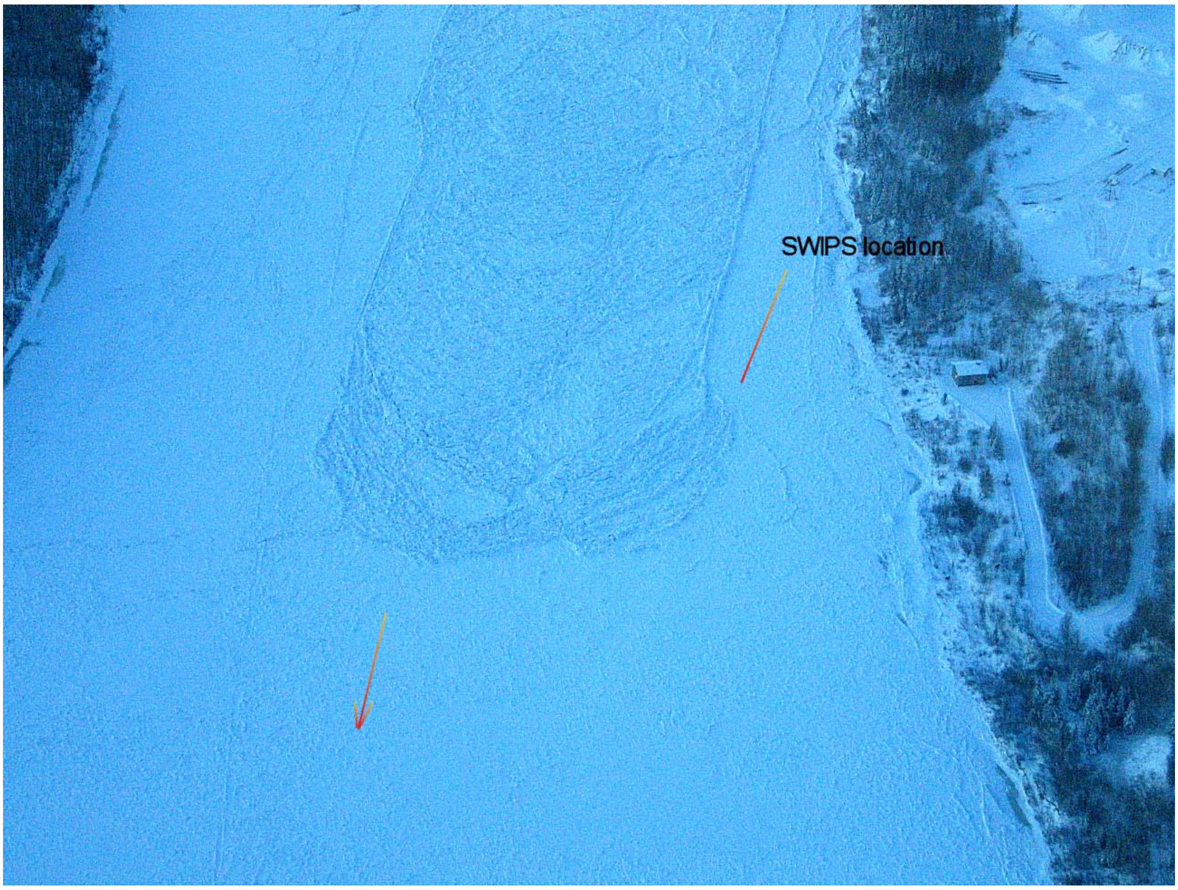
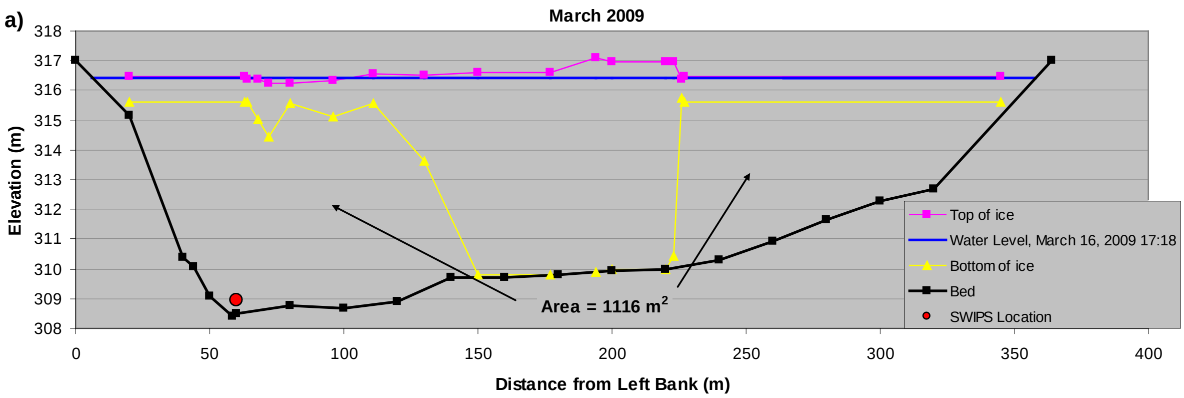


Figure 5.3. Looking upstream at the toe of a consolidation near the SWIPS site.



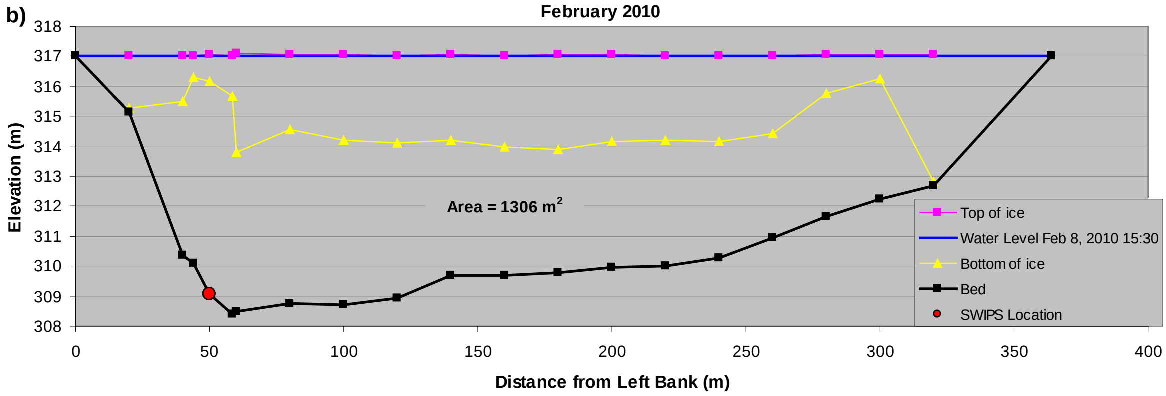


Figure 5.4 a) Cross section at SWIPS site in March 2009 through the toe of the consolidation showing that ice was grounded **b)** For comparison a cross section in Feb 2010 showing a very different and more typical ice cover (more uniform thickness).

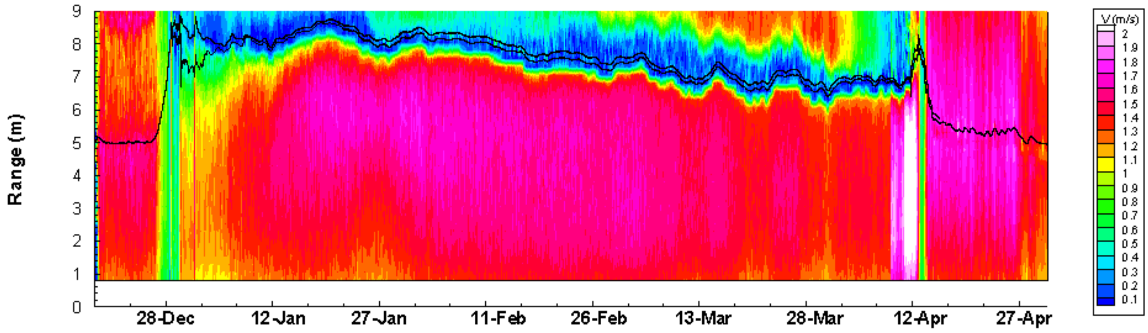


Figure 6.1 ADCP velocity data for the 2008-2009 ice season. Black lines indicate water level and bottom of ice. Data shown above these lines is reflected (unusable) data.

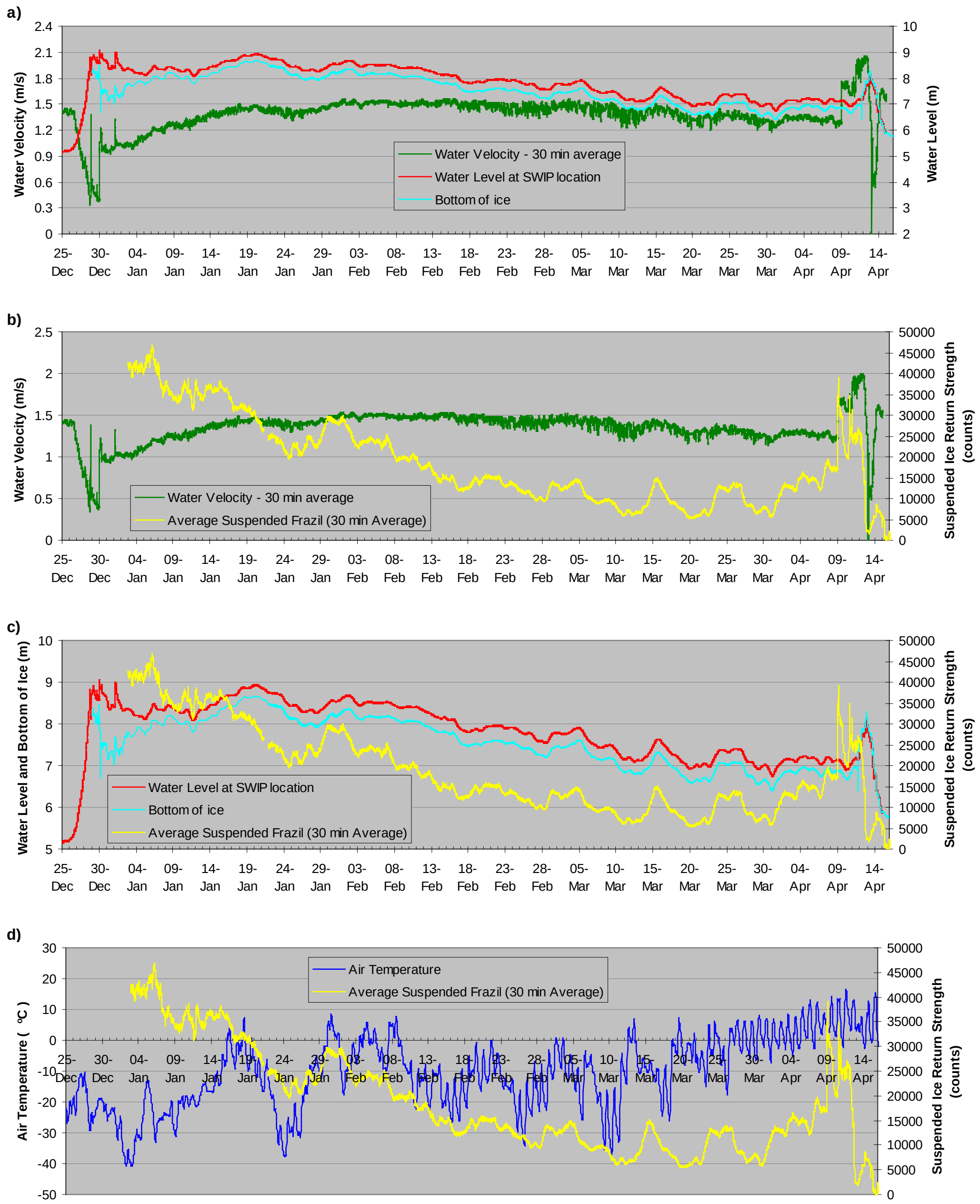


Figure 6.2 a) mean velocity, water level, bottom of ice. **b)** Depth and 30 minute averaged suspended ice 545 kHz SWIPS signal return strength. **c)** SWIPS suspended ice return strength, water level and bottom of ice level. **d)** Suspended ice return strength and air temperature.

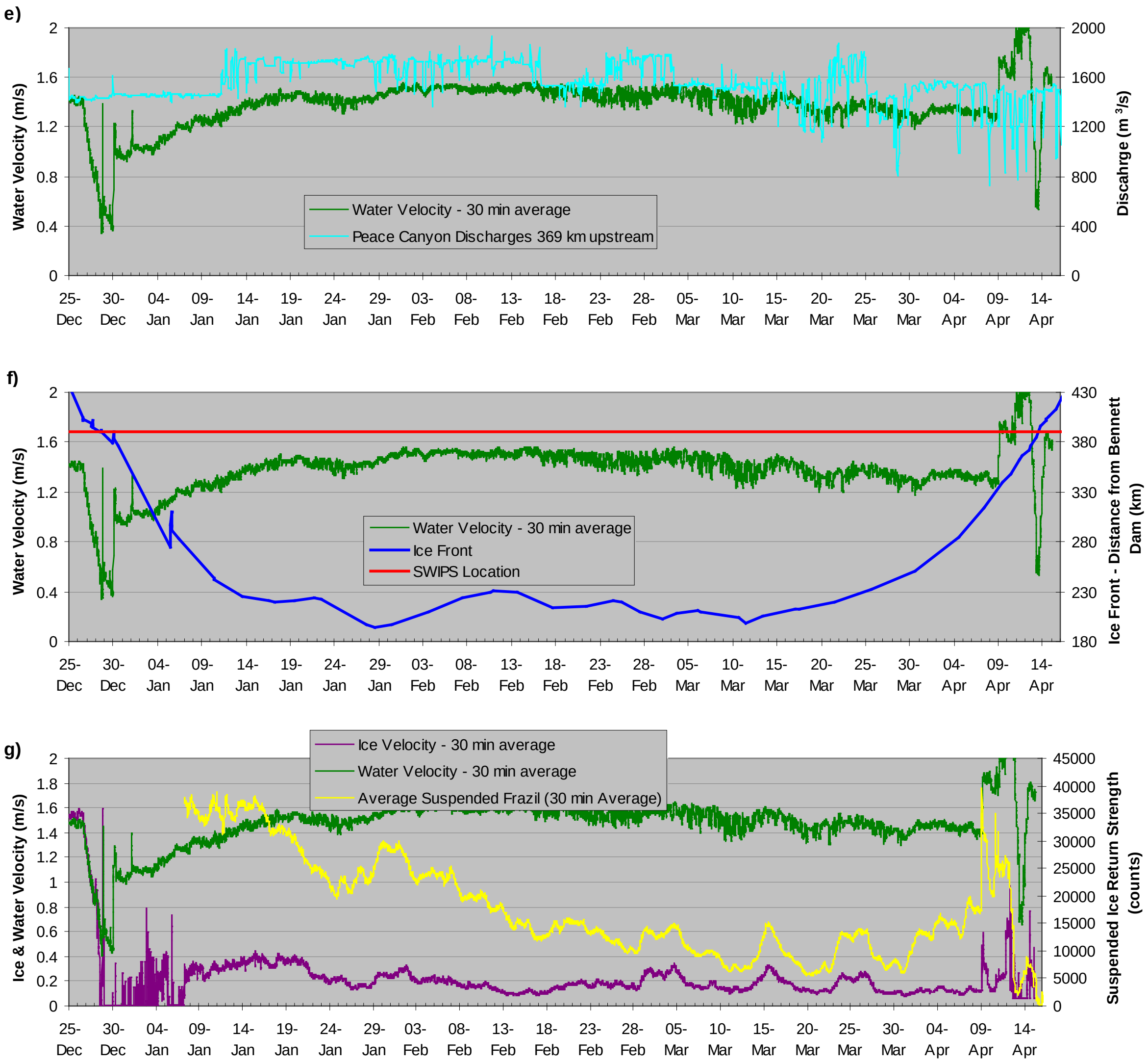


Figure 6.2 continued e) Hourly discharge at Peace Canyon Hydroelectric facility, water velocity. **f)** Ice front location and water velocity. **g)** Ice and water velocity and suspended ice return strength.