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Mitigation of Elevated River Freeze-up Levels by Revised Flow Regulation

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Northern rivers affected by hydroelectric operations generally have higher than natural winter flows as well as an altered ice regime. Freeze-up levels are also higher, as a consequence of the increased flow regime. During typical winter conditions, these freeze-up levels are within acceptable bounds. When freeze-up events produce higher than expected river levels, it has been common operational practice to reduce reservoir releases, if necessary, to mitigate the elevated river levels.

On the Peace River in northwest Alberta, Canada, four unusually high freeze-up events have occurred over the past forty years. Mitigation efforts during the 2005 event suggested that increased, rather than reduced, flows had a greater effect in lowering river levels. A series of tests during the 2008 event yielded the same result. The tests showed that a modulated flow regime could decrease river levels by a greater amount than a reduced flow regime.

1. Introduction

The Peace River, in northwestern Canada, has been regulated since 1968 with the start of construction of the W.A.C. Bennett Dam. Ice jam flooding did occur at the Town of Peace River prior to the dam construction (1963 and 1965). In 1974, after two severe breakup jams in 1973 and 1974, the Alberta-British Columbia Joint Task Force on Peace River Ice (JTF) was formed to study and develop mitigation strategies for breakup jams. That mandate was later expanded to include freeze-up processes after the high freeze-up ice jam of January 1982.

Since then, the Peace River at the Town of Peace River (TPR) has experienced three other high freeze-up events: 1992, 2005 and 2008. The event in 2005 highlighted a need to better understand the possible mitigation strategies following such an event. The 2008 event offered an opportunity to test a possible strategy; of modulating flows to enhance the smoothening of the underside of the ice cover. This paper presents the results of that testing and compares it to the strategies employed in 2005.

2. Background

The TPR is located about 396 km downstream of the W.A.C. Bennett Dam. Another regulation facility, the Peace Canyon Dam (PCN), lies 20 km downstream of WAC Bennett and serves as reference for dam releases into the Peace River. Figure 2.1 shows the location of the TPR in relation to the two BC Hydro facilities and Figure 2.2 shows freeze-up at TPR in 2008.

The National Research Council of Canada (1990) summarized typical ice problems for rivers in Canada affected by hydro-electric facilities. The report also mentions a possible mitigation strategy for high freeze-up events of using ‘flow control to assist in smoothing the ice cover to reduce head losses’. Breland (1995) found for the particular case studied, that moderate peaking operations over the formation discharge are possible, but dependant on the ice cover conditions. Tuthill (1999) reviewed the use of flow control methods to manage river ice and provided guidelines to the limits on river levels during peaking operations.

3. Comparison of the 2005 and 2008 seepage mitigation strategies

Figure 3.1 shows the hourly water levels at the Lower West Peace River Subdivision and daily Peace Canyon Discharges during the 2005 and 2008 winters. For a better comparison the 2005 dates are shifted forward by 5 days and the water level data is adjusted upward from the WSC data since LWPR is 2.5 km upstream of the Water Survey of Canada gauge.

The mitigation strategy initially for the 2005 event was to reduce Peace Canyon Discharges. As shown in Figure 3.1, the flow releases were reduced from about 1600 m^3/s down to 1200 m^3/s This provided a nearly instantaneous decrease the water level of about 0.65 m. However, despite that low flows were maintained for about 1.5 months, the long term water level trend experienced no further reduction until much later in the season when natural inflows caused discharges to increase (Friesenhan and Mahabir 2005).

The mitigation strategy for the 2008 water levels was to increase the Peace Canyon discharges once the thermal ice cover was thick enough to resist further secondary consolidations. Discharges were increased from 1425 m^3/s to 1850 m^3/s to almost 1900 m^3/s in a weekly series of discharge pulses. The flow was backed off for two days between the discharge pulses back to the original 1425 m^3/s to operationally determine if this strategy was reducing water levels. It is evident that the long term trend of the 2008 water levels in Figure 3.1 that the channel conveyance capacity was increasing and water levels were dropping. This was in stark contrast to the 2005 event where the long term trend in the water level was flat despite lower discharges. It was the results of this operational test that initiated the more comprehensive study described in this paper.

There was further evidence that water levels did eventually decrease in 2005, but only after significant warm spell and subsequent cooling in March that produced snowmelt from the unregulated portion of the Peace River Basin. This caused an unusual high discharge event during the March 5-16 period. Jasek et al. (2005) estimated that this raised the total flow in the river at the TPR from 1600 to 2100 m^3/s, even though Peace Canyon releases were reduced from 1500 down to almost 700 m^3/s during this time. After the tributary inflows returned to normal winter levels, Figure 3.1 shows that the water level in the LWPR were reduced by almost 1 m.

4. Analysis of 1972-1973 to 2008-2009 water levels

Comparisons of the daily Peace Canyon discharge releases and daily water levels at the Water Survey of Canada gauge in the TPR were made for 37 ice seasons from 1972 to 2009. Tributary inflows between Peace Canyon and the TPR in the winter are of the order of 10% of the Peace Canyon flow (Water Survey of Canada data) and change only by about 5% of the Peace Canyon flows over the course of the winter (other than during rare mid-winter warm spell events such as in 1992 and 2005). It was therefore deemed appropriate to make a comparison to the more precise discharges obtained from a hydroelectric facility rather than one from the less precise backwater (ice) affected discharge estimates available at the TPR.

Using a two-day travel time and operational knowledge that about 600 m^3/s change on the Peace River during ice conditions equates to about a 1 m change in the water level, an assessment of the change in the conveyance capacity of the channel could be made more effectively. Figure 4.1 shows the Peace Canyon discharges and the measured water level at the TPR for the 2008-2009 ice season. The yellow line shows calculated water levels that have been corrected by the discharge difference between the 2-day lagged discharge from Peace Canyon at freeze-up and the discharge on any particular day. This removes some of the variability in water levels attributed to the regulation of the Peace River. The corrected water levels show that there is a reduction in the water level over the course of the winter. This is most likely due to the increase in the channel conveyance capacity attributed to the redistribution of the frazil by erosion from high velocity areas to deposition in low velocity areas (deep channel portions, side channels, and shallow areas) and also transport of frazil out of the area. It is difficult to separate out these two effects and therefore the change in the water level over a time period will be referred to as erosion (and deposition in some cases) even though some of the change could be attributable to redistribution.

Another source of discharge variation (but which was not considered) was that resulting from the movement of the ice front in the upstream and downstream directions; water goes into channel storage as the ice front travels upstream and water comes out of storage as the ice front travels downstream. Assuming a typical stage-up due to ice resistance of 4 m, a typical channel width of 400 m, and ice front celerities ranging from 0 to 25 km/day, these discharge contributions (or sinks) can be quite large on the Peace River, anywhere from 0 m^3/s to as high as 460 m^3/s when the ice front is travel very quickly upstream during a cold spell. Typical ice front speeds are about 5 to 10 km/day corresponding to discharge contributions/sinks of 180 to 280 m^3/s. It is difficult to incorporate these changes into water level corrections as daily ice front observations are not available. One could use modeled discharges from a river ice model such as CRISSP and this could be a part of a later study. However, since generally at the beginning of the ice season the ice front is advancing and near the end it is receding, the error in the frazil erosion rate (or increase in channel conveyance) calculated from the beginning to later in the ice season from year to year should be somewhat systematic. Furthermore, neglecting a channel storage effect should give a more conservative frazil erosion rate since the ice front traveling upstream in the beginning of the winter depresses the water level (downstream of the ice front) and the ice front traveling downstream later in the winter increases the water level (downstream of the ice front). Nevertheless, neglecting this effect is likely to be responsible for much of the scatter in any correlation between discharge and the frazil erosion rate.

The other, but smaller source of error, is the change in travel time from Peace Canyon due to variable lengths of the ice cover. The 2-day travel time from Peace Canyon to the TPR was assumed in the analysis. The travel time could be as long 3 days in the case of lengthy ice cover.

Care was taken to avoid the rare late winter warm weather events from the erosion rate calculations since the inflows were likely substantially greater than 10% of the regulated flows and were of an unknown quantity.

Figure 4.2 shows the calculated erosion rates as a function of the average Peace Canyon discharge (lagged 2 days) for the period of the erosion rate calculation. The first day was generally taken as the first day after freeze-up or the day after a secondary consolidation if there was one. Although there is considerable scatter, the 4 high water level events do show an increase in erosion rates with increased in Peace Canyon discharge.

An investigation into the outliers in Figure 4.2 was undertaken, especially those that exhibited frazil deposition rather than erosion. Two of the stronger deposition years were 1988 and 1998 and are potted in Figure 4.3. It is evident from Figure 4.3 that significant deposition (of the order of 0.5 m and lasting several weeks) occurred prior to the onset of the erosion. In some years, like 2008-2009, no initial deposition occurred (Figure 4.1). Examining the other 35 years indicated that initial deposition had a wide range between these two extremes.

It was therefore deemed appropriate to treat the later ice season separately from the earlier portion that had potential deposition; the starting day of the erosion calculation was taken as the last deposition day. Figure 4.4 shows the results of this analysis and shows a much improved and again a positive correlation between discharge and the erosion rate.

Although a large portion of the remaining scatter could be attributable to the discharge variation from the channel storage affect, other and more easily available variables were looked at that could explain the remaining variability. One obvious analysis would be to look at the erosion rate as a function of the air temperature, since frazil could be generated upstream of the ice front during colder weather and provide a source of frazil for deposition and redistribution. This data is plotted in Figure 4.5. This correlation appears to be fairly weak. Another variable tested was the initial freeze-up level (or the water level at the beginning of the erosion calculation period). This data is plotted in Figure 4.6. This appears to have a positive and a more significant correlation than air temperature, but should be considered not as a deterministic variable, but rather an envelope limiting one. Note that there are no high erosion rates for low freeze-up elevations, but a very wide range of erosion rates for high freeze-up levels. The likely reason for this is that low freeze-up levels occur with a juxtaposed ice cover where the thickness of frazil slush below the solid thermal ice is relatively thin, less than a metre compared to the normal 2 to 4 metres. This reduces the amount of slush that can be moved and redistributed placing a limit on the amount of erosion. Table 4.1 shows results of single and multi-variable regression analyses. The analyses show that the Peace Canyon discharge accounts for the largest portion of the variability and air temperature and starting stage only marginally improve the correlations. The P-Values which should be less than 5% to have a 95% probability of being significant also demonstrate that the Peace Canyon discharge is the most influential variable.

There is also some evidence of cross-correlation between the average post-freeze-up discharge and the initial stage. This would explain the apparent improvement when adding the latter variable. However, since the latter variable describes more of an envelope rather than a linear relationship, it should not be incorporated into any predictive equation.

Since the initial frazil deposition period was removed from the above analysis to make an improvement in the correlation equations, it was thought prudent to look into what could be causing this initial deposition to occur (or not). Figures 4.7, 4.8 and 4.9 show the deposition rate compared to the Peace Canyon discharge, average air temperature and the initial freeze-up elevation. None of the variables appear to show a significant correlation.

One possibility for this is that the freeze-up level process is likely somewhat random. As the ice cover forms in an upstream direction it shoves and consolidates even when Peace Canyon flow are being held constant. This causes some reaches of the river to form with a thicker frazil slush layer and some locations with a thinner one. This shoving process is so random that two years with the same flows and air temperatures will cause the ice cover to be thicker or thinner in different reaches. After the ice cover forms, the thicker locations tend to erode out more due to higher velocities and the thinner location to erode out less, or even experience deposition rather than erosion. This may take place in the first few days or weeks after freeze-up. Once this initial redistribution is complete, further redistribution and erosion can start to occur for all reaches.

Figure 4.10 shows the total deposition amount (rather than a daily rate) plotted against the starting freeze-up level. It is notable that the 4 high freeze-up years had only low to medium total deposition values, all less than 0.3 m. i.e. No higher than normal depositional increases occurred after secondary consolidation events made the river already high in the first place. This supports the hypothesis that initial the frazil slush moves from reaches with a locally thick ice cover to reaches that are locally thin. But the scatter in the data for lower freeze-up elevations shows that this is not necessarily always the case.

Several studies using an acoustic instrument on the Peace River (Jasek and Marko, 2007, Marko and Jasek 2009) show that suspended frazil ice in the water column below a stabilized ice cover increases with increases with flow. This supports the results found in this study.

5. Conclusions

Correlations between frazil erosion and various environmental factors were investigated. In order to improve these relationships the ice season had to be split up into two portions. The early phase (occurring a few days to a few weeks after freeze-up and could exhibit deposition or erosion) and the latter phase (occurring from the peak water level to towards the end of the ice season and always showing erosion).

The Peace Canyon discharge was determined to be a significant factor for affecting the frazil erosion rate and the corresponding water level decrease on the Peace River in the latter phase.

Frazil erosion and the corresponding decreases in water level were positively correlated with discharge. Other variables such as air temperature were much less significant. Nominal erosion rates from 0.005 m/day to 0.025 m/day were evident for historical discharges ranging from 500 to 1800 m^3/s respectively (Figure 4.4) (Extremes ranging from 0.004 to 0.031 m/day were found in this 37-year data set). This suggests that a possible strategy to mitigate high water levels during high freeze-up years is to increase Peace Canyon flows rather than decreasing them. There was some scatter in the data which is likely the result of the discharge uncertainty due to the moving ice front subtracting and releasing water from channel storage. Variable travel time from Peace Canyon to the TPR due varying lengths of the ice cover upstream of the TPR was also likely to be a cause of further variability.

No significant correlations could be found between the early phase ice season deposition rate and discharge or air temperature. This was likely because the initial ice thickness formation on the Peace River has a strong stochastic component where frazil redistribution takes a few days to a few weeks to even out the frazil deposits before systematic erosion for a longer reach of the Peace River can occur.

Acknowledgments

Willi Granson and Kevin Osowetski provided information on and photographs of the 2008-2009 freeze-up event. Wuben Luo, BC Hydro provided advice for the statistical analysis.

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Table 4.1. Results of single and multi-variable regression analysis for determining the frazil erosion rate.

Analysis#		**Discharge (m^3/s)**	**Initial Stage (m)**	**Air Temperature (^oC)**	**R Square**
1		Yes	No	No	0.425
2		No	Yes	No	0.224
3		No	No	Yes	0.034
4		Yes	Yes	No	0.462
4	P-Value	0.041%	18.0%		
5		Yes	No	Yes	0.432
5	P-Value	0.00051%		12.4%	
6		Yes	Yes	Yes	0.504
6	P-Value	0.046%	9.3%	6.6%	

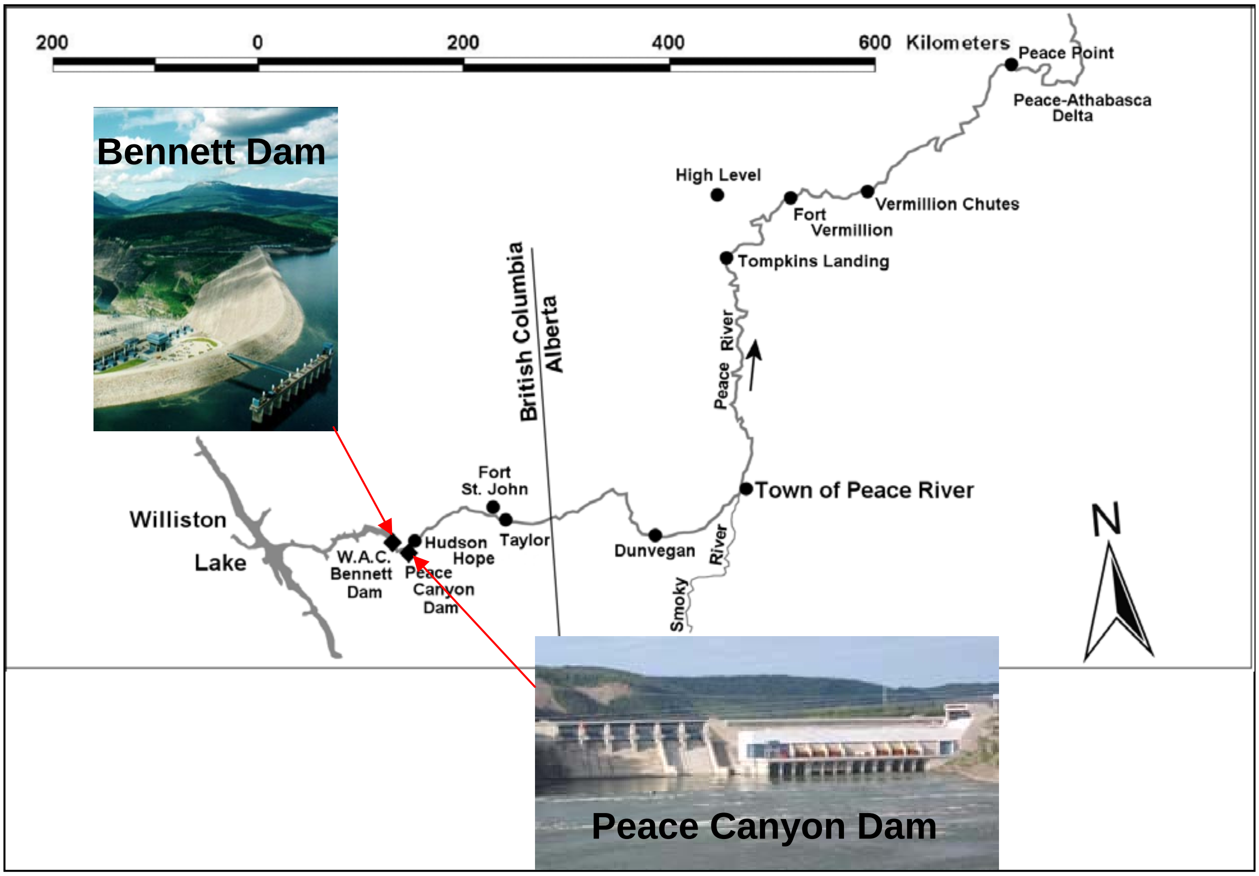

Figure 2.1 Map of Peace River showing locations of interest.

Figure 2.2. Freeze-up at the Town of Peace River on Jan 14, 2008, Alberta Environment.

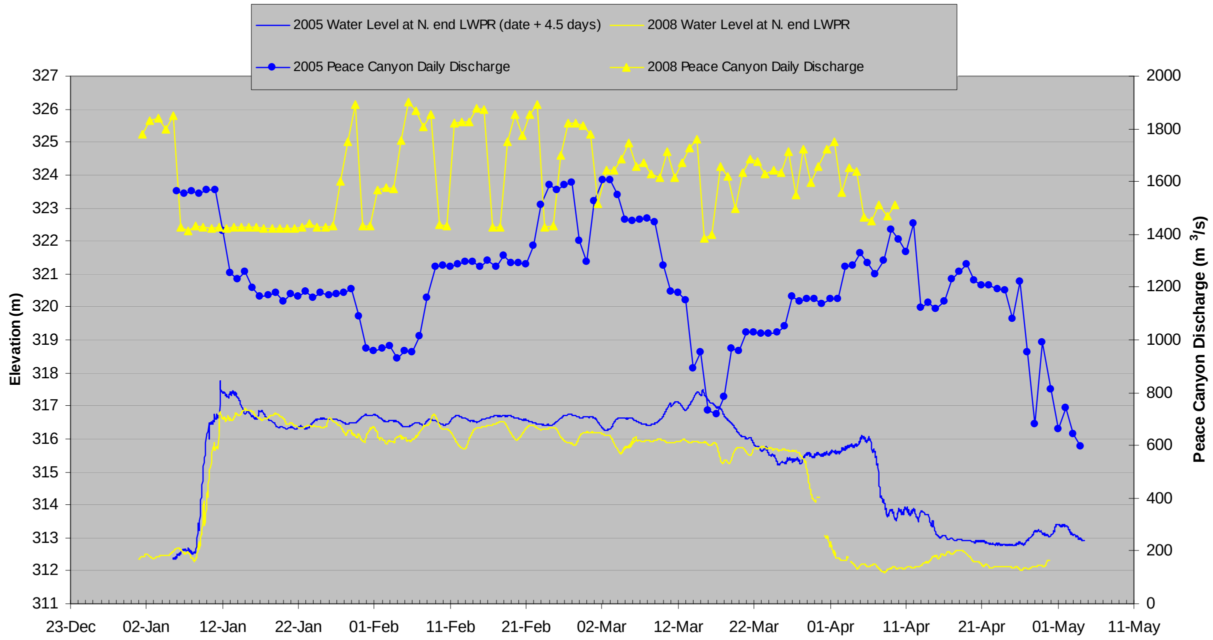

Figure 3.1. Water levels at the Town of Peace River and daily Peace Canyon discharges for the 2004-2005 and 2007-2008 winters.

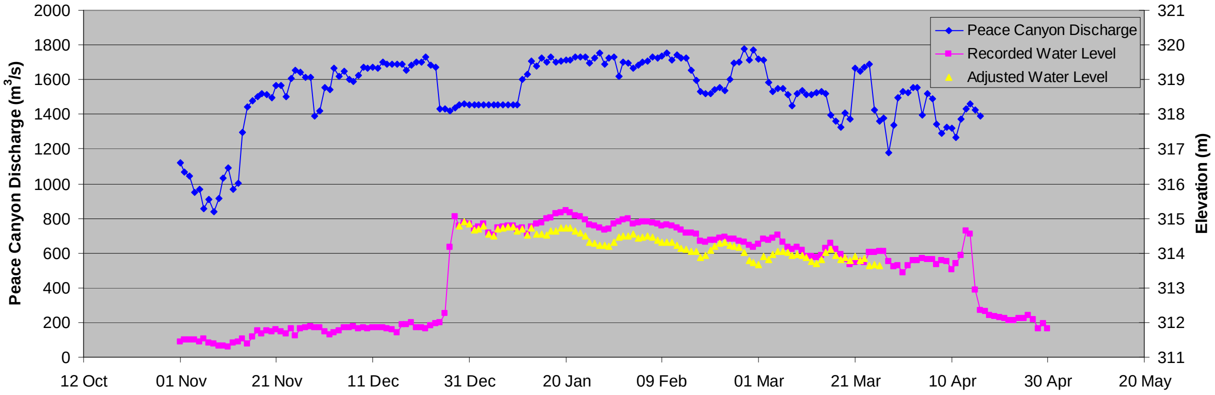

Figure 4.1. Recorded Water levels at the Town of Peace River and daily Peace Canyon discharges for the 2008-2009 winter. Also shown is the adjusted water level to compensate for changes in Peace Canyon discharge releases.

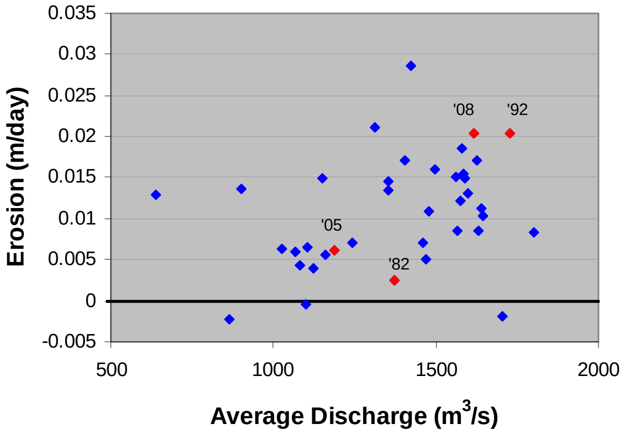

Figure 4.2. Calculated erosion rates from the start of freeze-up to late winter as a function of the average Peace Canyon Discharge. Red points indicate high freeze-up events.

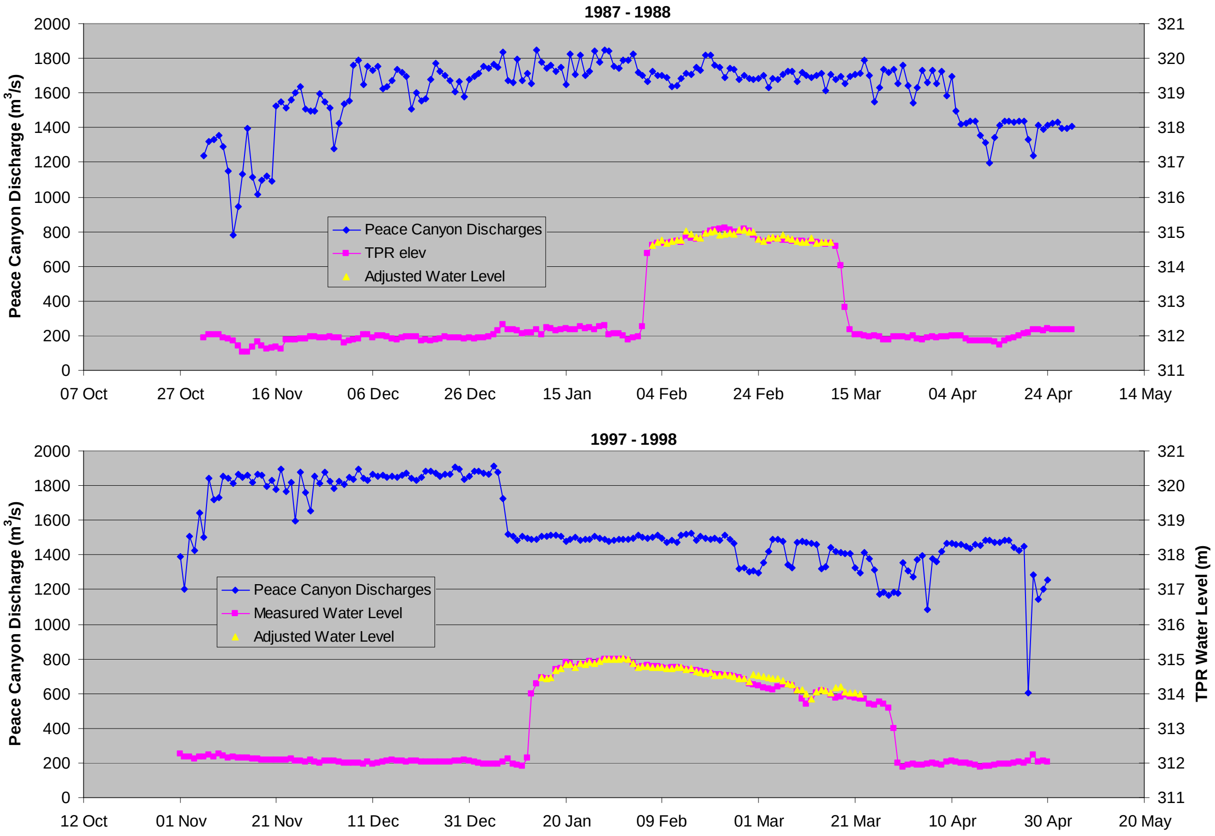

Figure 4.3. Peace Canyon Discharges and TPR measured and discharge adjusted water levels for the 1987-1988 and 1997-1998 winters. These two years showed significant deposition in the earlier part of the ice season before erosion took over.

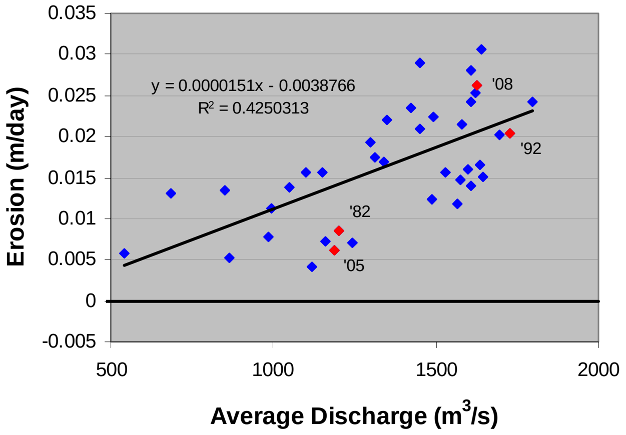

Figure 4.4. Calculated erosion rates from the start of the erosion phase to late winter as a function of the average Peace Canyon Discharge. Red points indicate high freeze-up events.

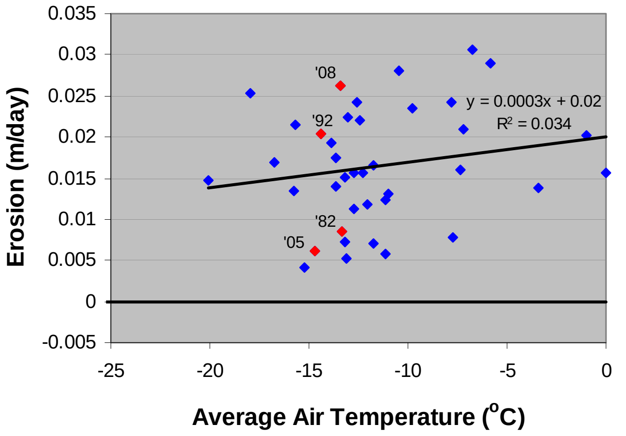

Figure 4.5. Erosion rate compared with average air temperature. Red points indicate high freeze-up events.

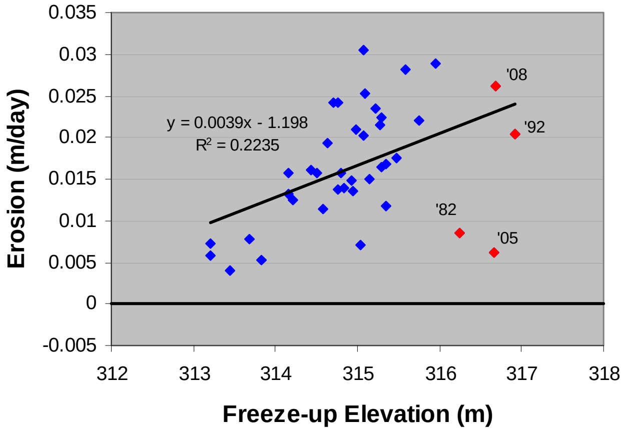

Figure 4.6. Erosion vs. initial water level at the start of the erosion phase.

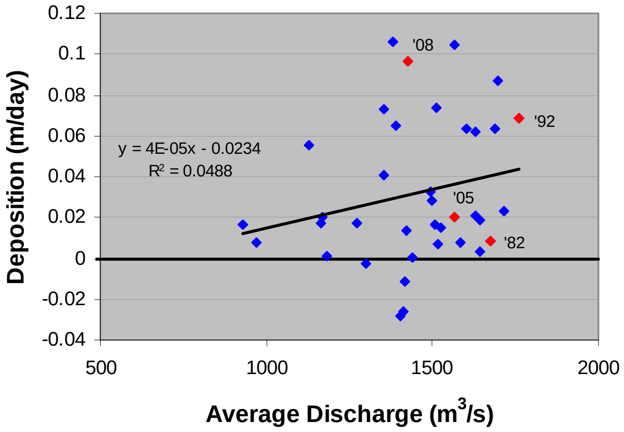

Figure 4.7. Deposition rate vs. average Peace Canyon discharge.

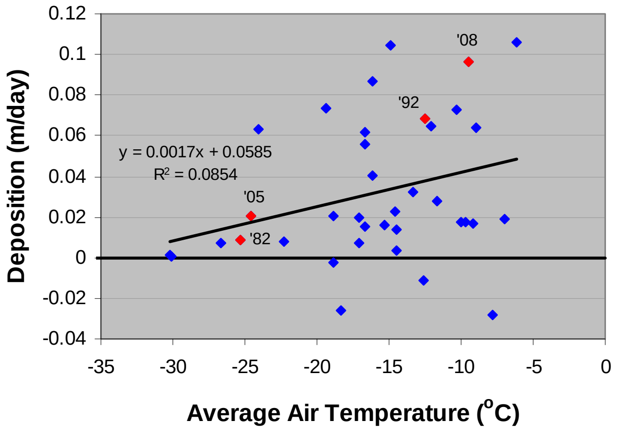

Figure 4.8. Deposition rate vs. average air temperature.

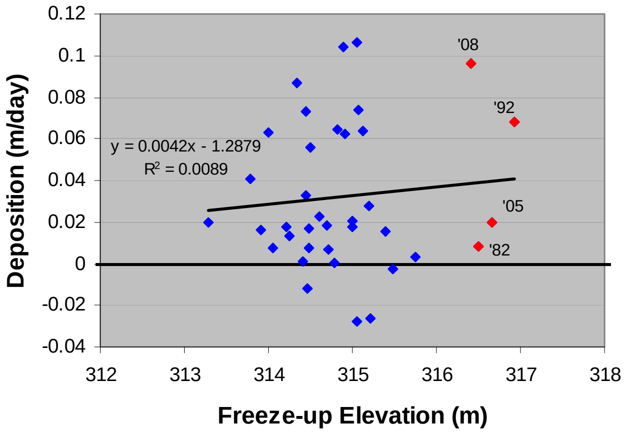

Figure 4.9. Deposition rate vs. freeze-up elevation.

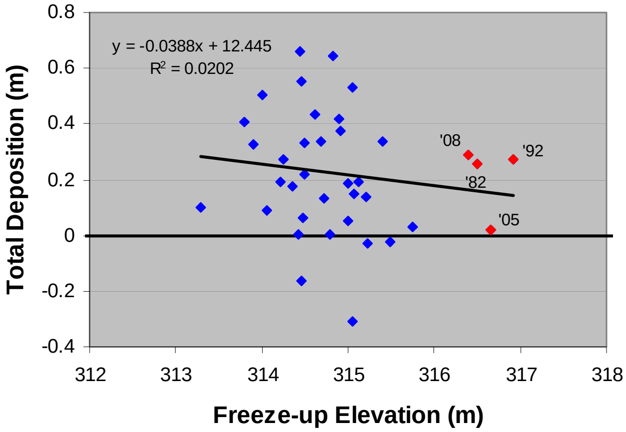

Figure 4.10. Total deposition vs. freeze-up elevation.