CGU HS Committee on River Ice Processes and the Environment
19th Workshop on the Hydraulics of Ice Covered Rivers
Whitehorse, Yukon, Canada, July 9-12, 2017.

Impacts of Climate Warming on River Ice Break-up and Snowmelt Freshet Processes on the Porcupine River in Northern Yukon

J Richard Janowicz[1]
[1] *Water Resources Branch, Yukon Department of Environment, Box 2703, Whitehorse, YT, Y1A2C6*
richard.janowicz@gov.yk.ca

Because of the history of river transportation most Yukon communities are situated on the floodplain and subsequently are prone to flooding. Potential flooding mechanisms include spring ice jams, snowmelt, rain on snow, intense summer rain, glacier melt and surges, and freeze-up ice jams. The earliest Yukon flooding events in the annual cycle are triggered by spring ice jams which typically occur in late April or May. Ice jam flooding is also the most severe mechanism in terms of impact. With respect to timing spring break-up and associated flooding is followed by the snowmelt freshet several weeks later, typically at the end of May or early June. The village of Old Crow in Yukon's Arctic region has had several significant ice jam flooding events where substantial portions of the community have been inundated by flood waters. A change in spring snowmelt dynamics has been observed throughout Yukon in recent decades. Snowmelt and associated runoff is occurring earlier and has a shorter duration resulting in a compressed runoff period. Spring river ice break-up and the snowmelt freshet on the Porcupine River have been normally separated by up to several weeks. With changing snowmelt dynamics overlapping river ice break-up and snowmelt freshet events are becoming more common. The combined processes are generally producing more severe events which has significant implications respecting public safety and impacts to infrastructure.

1. Introduction

River ice is an important component of both socio-economic and environmental features of cold regions. Of significant importance in remote, sparsely populated areas, frozen rivers are frequently used for transportation purposes for the construction of ice bridges and as transportation networks. In northern North America river ice is frequently relied upon to act as a platform for fishing and trapping purposes. Freeze-up and break-up processes often produce ice jams which may result in flooding with significant implications for public safety, and economic impacts associated with damage to property and infrastructure, road and rail networks and hydroelectric operations. Ice jams and subsequent backwater and ice jam release waves (javes) also affect aquatic ecosystems through impacts on biological and chemical processes. This paper attempts to provide a summary of climate warming impacts on the river ice regimes of the Yukon Territory with specific reference to the Porcupine River at Old Crow.

2. Geographic and hydrologic setting

Yukon Territory is situated in northwestern Canada, bounded by Alaska and the Northwest Territories to the west and east, respectively, and the 60th parallel of latitude and the Arctic Ocean to the south and north, respectively (Figure 1). The climate is characterized as subarctic in the south and arctic in the north, with some maritime influence from the Gulf of Alaska in the southwest regions (Wahl *et al.*, 1987). Annual mean daily air temperatures range from -1ºC in the south to -10ºC in the north. While, annual precipitation amounts are significant in the Coast and Saint Elias Mountains with amounts up to 2000 mm, precipitation throughout much of the Territory ranges from 300 to 600 mm, with annual amounts declining to approximately 150 mm on the Arctic coast. Much of the Yukon is underlain by permafrost subdivided into continuous, discontinuous and sporadic zones, representing approximately 30, 45 and 25 percent of Yukon, respectively (NRC, 1995). Streamflow response is controlled by the underlying permafrost or lack of it (Janowicz, 2004). The response is characterized by a rapid increase in discharge in the late spring in response to snowmelt at lower elevations followed by runoff from higher elevations with peak freshet flows generally occurring in early June. Hydrologic response is closely tied to the relative extent and location of the three permafrost zones. Peak flow volumes are directly proportional to the amount of underlying permafrost. Greater amounts of permafrost shorten the pathways to the stream channel as a result of limited infiltration rates (Janowicz, 2008). The controlling influence of the underlying permafrost on hydrologic response is extreme in Arctic regions. Peak flows exhibit very quick response times because of the shallow active layer. Secondary peak flows throughout Yukon occur during the summer months as a result of rainfall. Occasionally smaller systems will have the dominant peak resulting from rainfall. Annual minimum discharge occurs in March or April, coinciding in timing with minimum annual groundwater inputs. Annual minimum flows decrease moving northward due to lesser groundwater contributions to winter streamflow. Many smaller streams within the continuous permafrost zone have no observed flow during the latter part of the winter.

3. Climate and River Ice Trends

Annual, winter and summer temperatures have generally increased in all regions, with greater increases observed in central and northern regions. Annual precipitation trends are not consistent. Winter precipitation has generally increased in northern regions and decreased in southern regions whereas summer precipitation has generally increased slightly throughout, with greater increases in southeast and central areas (Janowicz, 2010).

Climate warming is affecting the ice regimes of cold regions. In subarctic regions break-up is typically a spring event, with the timing generally a function of latitude. The length of the ice cover season has shortened, with later occurrence of freeze-up and earlier break-up events. Freeze-up observations were sporadically made in Yukon Territory since the 1890s primarily for river transportation reasons (Fountain & Vaughn, 1984). The data was initially collected by the transportation shipping companies, with the Atmospheric Environment Service taking over this role in later years. This practice was discontinued in the mid-1990s. Freeze-up of the Yukon River at Whitehorse has been delayed by approximately 30 days since 1902 (Janowicz, 2010).

Because of the river transportation history there is an excellent record of break-up dates for the Yukon River at Dawson. Break-up signaled the end of winter isolation for Dawson, which would be followed by the arrival of the first steamship from the south in about two weeks. A lottery to predict the exact minute of break-up has been held in Dawson since 1896 and continues today. Over the period of record, break-up at Dawson has ranged from 23 April to 29 May, with a mean date of 8 May (Janowicz, 2010). Jasek (1999) carried out an assessment of the data to 1998 and observed that the break-up date advanced 5 days per century. The last two decades have seen an unprecedented advancement of the break-up date. Prior to 1989, only two April break-ups had been observed, while after 1989, eight April break-ups have been observed, including the 2016 April 23 event which shattered the previous record by five days . A similar trend is noted for the Porcupine River at Old Crow, though the record begins in 1961. The break-up date ranges from 2 May to 30 May, with an overall mean of 16 May. The mean break-up date has advanced from 18 May during the first 20 years of record to 14 May in the last 20 years. (Janowicz, 2010)

Mid-winter break-ups have also occurred in recent years. Dawson experienced the warmest winters in the 115 year record during 2002–3 and 2016-17. Unusual periods of warm weather and rain during December resulting in an early winter break-up event and subsequent formation of an ice jam on the Klondike River. There was minor winter flooding in both years, but after the earlier event, the 3 km long jam subsequently refroze, creating "jumble" ice with thicknesses up to 3 m. During spring break-up at the end of April 2003, the lower Klondike valley experienced one of the most severe break-up floods on record, with a number of residences, businesses and the Klondike Highway affected.

Winter ice cover is becoming thinner as a result of increased winter temperatures, reducing thermal ice thickening and frazil ice generation. Increased winter discharge may also contribute to a thinner ice cover through the downstream transport of frazil away from typical accumulation areas. In some cases greater snow cover is contributing to the development of thinner ice covers through its insulating effect (Michel, 1971). There is some evidence to suggest that duration and severity of break-up events are also being affected. The ice cover period is becoming shorter; with the break-up period likewise, shorter (Janowicz and Hinzman, 2017). Break-up severity is a function of ice cover strength and integrity balanced by hydrometeorological conditions which control streamflow discharge and water level. At the lower range of severity, a thermal break-up occurs when the ice cover has deteriorated sufficiently by radiation from above and erosion from below to allow it to break up with little increase in discharge (Andrishak & Hicks, 2005). In contrast, a mechanical break-up occurs when streamflow discharge and water level increase rapidly, causing the ice cover to break its bond with channel banks while it is still strong and competent. Such events occur when a colder-than-normal period is followed by the rapid melt of a greater-than-normal snowpack and subsequent runoff. The most common break-up events occur somewhere between the two extremes; however, these shorter and more dynamic events appear to be increasing in severity in some regions of Yukon Territory (Janowicz, 2010). Numerous Yukon communities have historically experienced ice jam flooding, with the most severe floods having occurred at Dawson City on the Yukon River and Old Crow on the Porcupine River. Dawson City and Old Crow have experienced six and four major ice jam floods in the last century, respectively. There appears to be a trend of increasing elevations from the early 1970s to the present, possibly exhibiting the influence of climate warming. Though there is both considerable range and scatter, the trend of increasing elevations is evident at both low and high elevations (Figure 2). A similar trend is not evident for the Porcupine River at Old Crow, possibly due to the paucity of data; however, the characteristics of the break-up event appear to be changing. Greater energy inputs, as represented by higher winter and spring air temperatures, are producing an earlier onset of, and more rapid snowmelt events, resulting in a compressed runoff with higher peak flows in some regions (Janowicz and Hinzman, 2017). Figure 3 is a graphical illustration of a pair of streamflow hydrographs. The flatter hydrograph is typical of a nival streamflow regime prior to climate warming. The post climate warming hydrograph shows the peak to be greater and to occur sooner. With this scenario it is possible to have greater peak events even when the streamflow volume is less, due to the more rapid (compressed) runoff period.

There is some indication that these observed changes in runoff and streamflow dynamics are affecting the relationship between river ice break-up and the snowmelt freshet in northern Yukon. Typically these events are quite distinct. The timing of river ice break-up in Yukon occurs in early to mid-May, which is then followed by the snowmelt freshet peak two to four weeks later. Figures 4 and 5 illustrate typical spring and summer hydrographs for the Porcupine River at Old Crow. In 2009 the break-up peak occurred on May 7 followed by the larger freshet peak on May 24. In 2010 the break-up peak occurred on May 2 followed by the much smaller freshet peak on May 20. It is noted that the 2010 annual peak water level was generated by a rainfall event in August.

Figures 6 and 7 illustrate the summer hydrographs for 2011 and 2015. In 2011 and 2015 the combined break-up and freshet peaks occurred on May 23 and 15 respectively. A detailed illustration of the 2011 and 2015 events are presented in Figure 8 and 9 respectively. The 2011 local break-up at Old Crow occurred at 0915 on May 20, with the shifting of the ice in front downstream of the community. Previous to this event, the Porcupine River water level had risen 1.8 m since the minimum winter level on April 13. Break-up was initiated by rapid snowmelt produced by significantly above normal air temperatures which resulted in a rapid water level rise. After the onset of break-up the water level rose 3.8 m as a result of a bank to bank ice run over the next 5 hours which was backing up behind a major ice jam at the Bluefish River approximately 40 km downstream. A second major ice run beginning 0400 May 21 brought the water level up slightly. The water level dropped slightly with release of the Bluefish ice jam and the passage of the ice run. Continuous running ice with snowmelt contributions over the next 24 hours maintained the water level at a high level. A maximum ice related water level of 16.65 m occurred at 0500 on May 22 with snowmelt runoff contribution to this peak. Snowmelt runoff produced a slightly higher peak of 16.69 m at 1900 on May 23.

The 2015 local break-up at Old Crow occurred at 1215 on May 12. Prior to this event, the Porcupine River water level had risen 1.95 m since the minimum winter level on April 18. The 2015 break-up event was very rapid in progression. The local break-up was initiated by rapid snowmelt produced by above normal temperatures for the five days preceding break-up. This caused the water level to drop by 0.33 m as a result of the release of a downstream ice jam. This was followed by a 3.1 m water level increase to the peak break-up water level of 14.58 m at 0615 on May 13. This event was initiated by the simultaneous release and movement of the ice cover from the 147 km reach of river downstream of the Bell River. The passage of the ice run past Old Crow was followed by a 0.7 m drop in water level which was initiated by the release and movement of ice cover as far downstream as the Bluefish River (the traditional anchor point for severe ice jams). A heavy bank to bank ice run subsequently moved past the community for approximately 14 hours, slowly bringing the water level up to a new peak, ice related level of approximately 14.7 m at 0045 on May 14. By May 15 ice from above the Bell River, as well as the Bell and Old Crow Rivers, moved past the community maintaining high water levels. After break-up the weather became significantly warmer than normal, with air temperatures 5 to 15 degrees above the seasonal mean. These temperatures produced a very rapid melt of record high snowpack; which, on top of the break-up javes, resulted in a gradual and sustained water level increase to a combined break-up and snowmelt peak of 16.22 m at 1450 May 15. This event resulted in minor flooding of parts of Old Crow.

4. Interrelationship Between River Ice Break-up and the Snowmelt Freshet

Recent observations indicate that there is an increasing frequency of overlapping river ice break-up events and freshet peaks. Snowmelt dynamics can be described in various forms. The rate and quantity of snowmelt is determined by the amount of energy provided to the snowpack. The heat content of the snowpack over time is dependent on the summation of incoming solar radiation, sensible and latent heat transfer, the heat transfer through advection, and ground heat transfer (Pomeroy et. al., 2003). Solar radiation accounts for the greatest portion of heat flux, followed by combined sensible and latent heat fluxes (NEH, 2004). These heat fluxes are often represented by air temperature (Gray and Prowse, 1992). Energy inputs, as represented by air temperature, are increasing significantly in northern regions. While summer and winter temperatures are increasing in most Yukon regions, summer (April to October) temperatures at Old Crow are increasing at a greater rate than most Yukon communities having increased 2.5 degrees in the last sixty years, while April, May and June temperatures have increased 4.5, 5 and 3 degrees respectively (Janowicz, 2010). Both river ice break-up and the snowmelt freshet are occurring earlier, often both in mid to late May with overlapping events.

Figures 10 to 15present air temperature trends from 1969 to 2015 for consecutive five day periods from May 1 to May 30. May 1 to 5 and May 6 to10 indicate there is no visible change in air temperate during these periods. The five day periods between May 11 and 30 all exhibit a progressive increase. The average date of break-up has advanced from May 19 to May 13, while the average date of the freshet peak has advanced from May 28 to May 22.

5. Conclusions

Yukon air temperatures have increased significantly in the last five decades century. Precipitation trends are not as consistent with greater precipitation in some regions and less in others. The length of the ice cover period is becoming shorter with later freeze-up and earlier break-up dates. Mid-winter break-up events and associated flooding have been observed on two occasions. Break-up water level trends on the Yukon River suggest that break-up severity is increasing. There is also some indication that changes in runoff and streamflow dynamics are affecting the relationship between river ice break-up and the snowmelt freshet. Where these events have been quite distinct, recent observations indicate that there is an increasing frequency of overlapping river ice break-up events and freshet peaks as presented in this paper for the Porcupine River at Old Crow. The observed changes have significant implications associated with public safety and economic impacts to property and infrastructure, transportation networks and hydroelectric operation. In addition there are potentially serious environmental impacts on fish and wildlife habitat.

References

Andrishak, R. & Hicks, F. 2005. Impact of climate change on the winter regime of the Peace River in Alberta. Prepared for: Climate Change Research Users Group Alberta Environment. Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB.

Fountain, A.G. & Vaughn, B.H. 1984. *Yukon River Ice: Freeze-up Data (1883-1975)*. US Geological Survey Open File Report 84-601, Tacoma, WA.

Gray, D.M., Prowse, T.D. 1992. Snow and floating ice. In:Maidment DR (ed) Handbook of hydrology. McGraw-Hill, Inc., New York, pp 7.1–7.58.

Janowicz, J.R. 2004. Yukon overview: watersheds and hydrologic regions. In: *Ecoregions of the Yukon Territory – Biophysical Properties of Yukon Landscapes* (Smith, C.A.S., Meikle, J.C. & Roots, C.F. (Eds.)). PARC Technical Bulletin 04-01. pp 15–18.

Janowicz J.R. 2008. Apparent recent trends in hydrologic response in permafrost regions of northwest Canada. *Hydrology Research* **39**(4), 267-275.

Janowicz J.R. 2010. Observed trends in the river ice regimes of northwest Canada. *Hydrology Research* **41**(6), 462-470.

Janowicz, J.R. & Hinzman, L. 2017. In: Sesser, A.L. ., Rockhill, A. P., Magness, D. R., Reid, D., DeLapp, J., Burton, P., Schroff, E., Barber, V., Markon, C., editors (In press). Drivers of landscape change in the northwest boreal region of North America: Implications on policy and land management. U.S. Geological Survey Circular.

Jasek, M.J. 1999. 1998 break-up and flood on the Yukon at Dawson – did El Nino and climate play a role? In: *Proc. 14th International Ice Symposium, Potsdam, NY, A.A. Balkema, Rotterdam,* 761–768.

Michel, B. 1971. *Winter Regimes of Rivers and Lakes*. Cold Regions Science and Engineering Monogram III-Bla. Cold Regions Research and Engineering Laboratory, US Army, Hanover, NH.

National Engineering Handbook 2004. Part 630 hydrology, chapter 11 (snowmelt). United States Department of Agriculture, Natural Resources Conservation Services.

Natural Resources Canada 1995. *National Atlas of Canada* 5th edn, MCR 4177. Geological Survey of Canada, Terrain Sciences Division, Ottawa.

Pomeroy JW, Toth B,Granger RJ, Hedstrom NR, & Essery RLH 2003. Variation in surface energetics during snowmelt in a subarctic mountain catchment. J Am Meteorol Soc 4(4):702–719

Wahl, H.E., Fraser, D.B., Harvey, R.C. & Maxwell, J.B. 1987. *Climate of Yukon*. Environment Canada, Atmospheric Service, Climatological Studies Number 40, Ottawa.

Figure 1. Location Plan

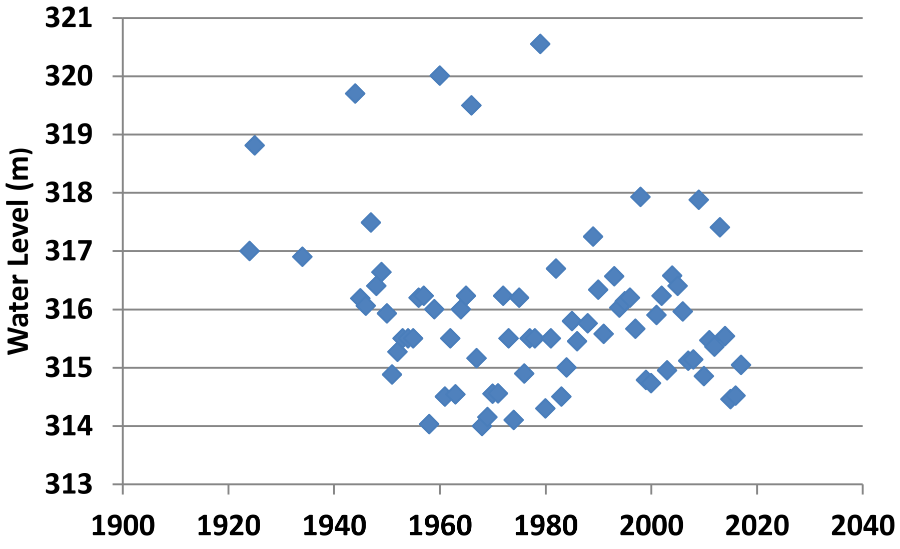

Figure 2. Yukon River at Dawson Annual Peak Ice Related Water Levels

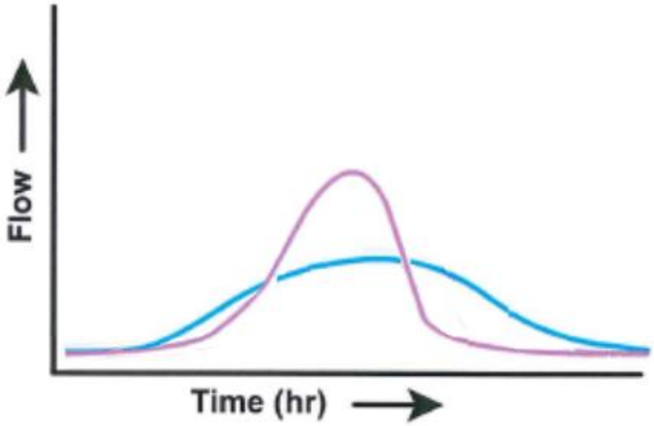

Figure 3. Typified hydrographs – pre-climate warming (blue); post warming (pink).

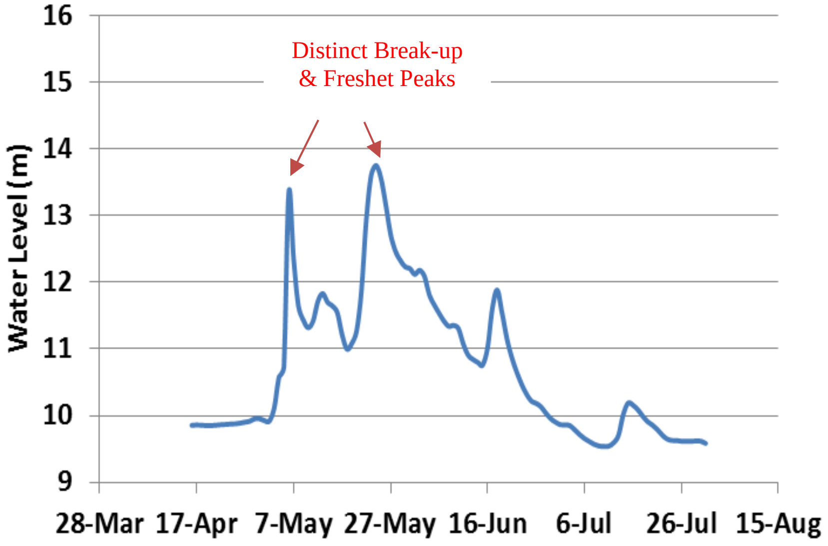

Figure 4. Porcupine River at Old Crow hydrograph – 2009.

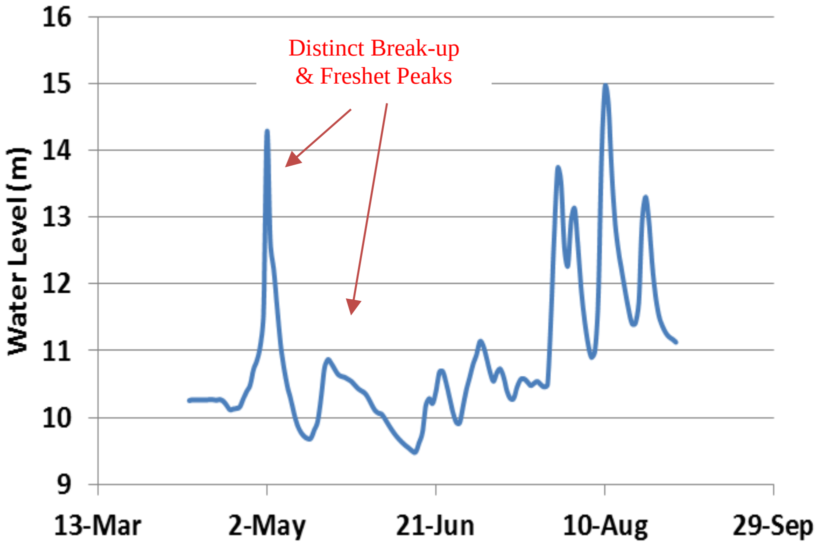

Figure 5. Porcupine River at Old Crow hydrograph – 2010.

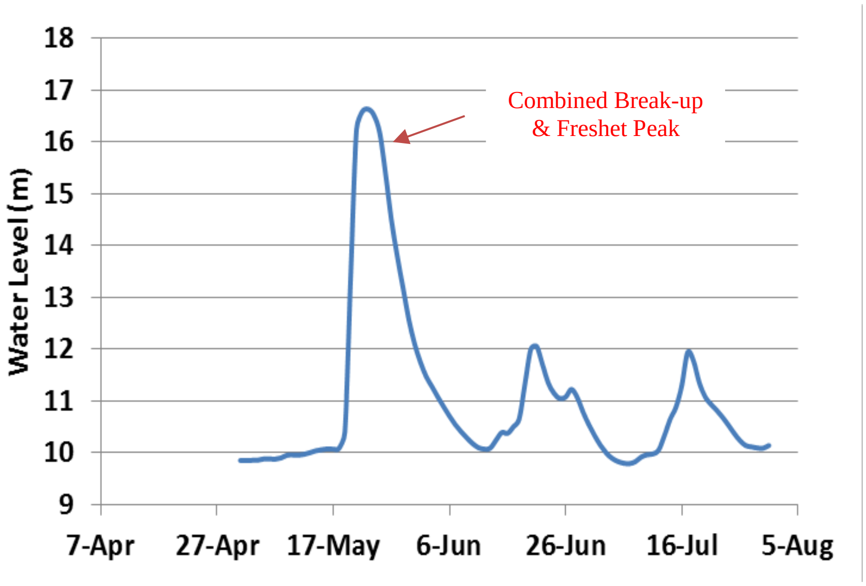

Figure 6. Porcupine River at Old Crow hydrograph – 2011.

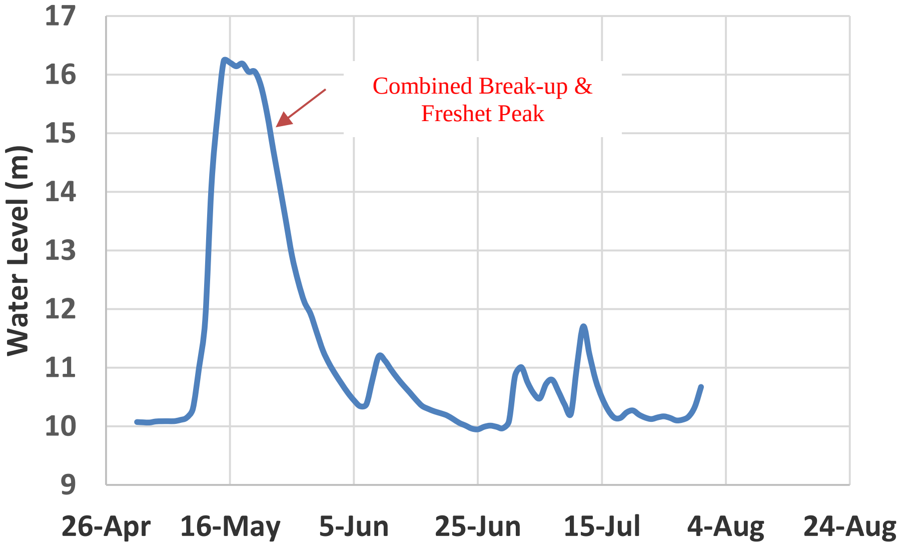

Figure 7. Porcupine River at Old Crow hydrograph – 2015.

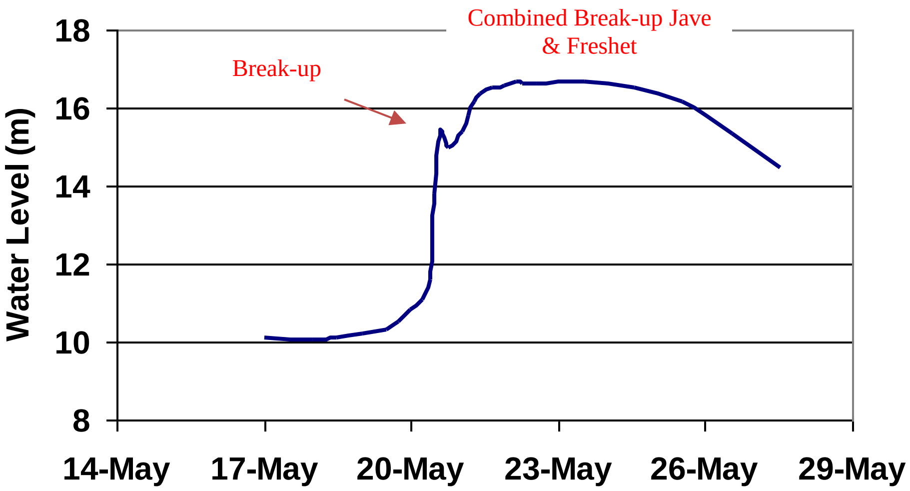

Figure 8. Porcupine River at Old Crow break-up hydrograph – 2011.

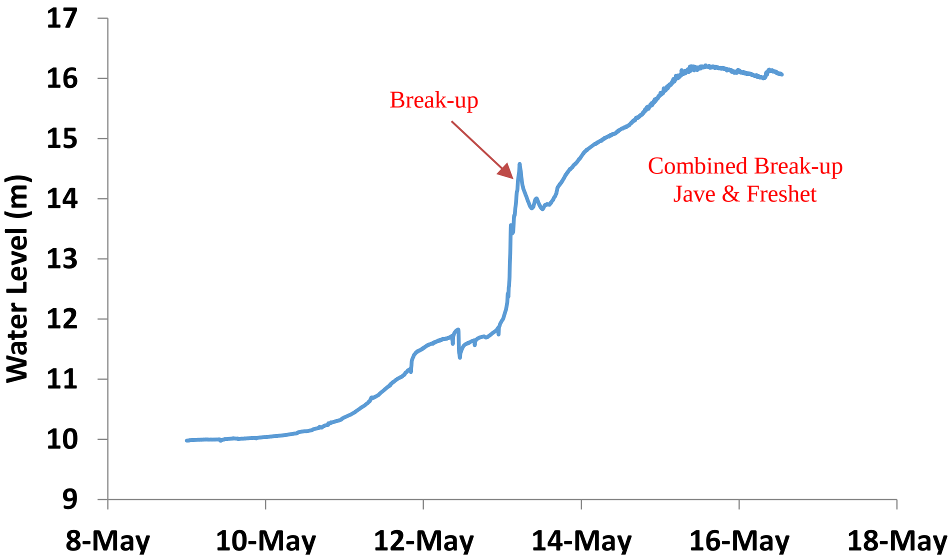

Figure 9. Porcupine River at Old Crow break-up hydrograph – 2015.

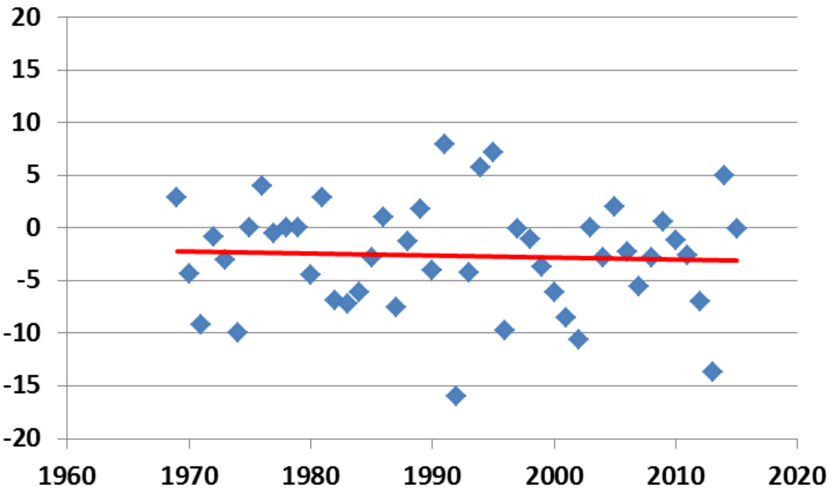

Figure 10. Old Crow Daily Air Temperature (May 1 – 5).

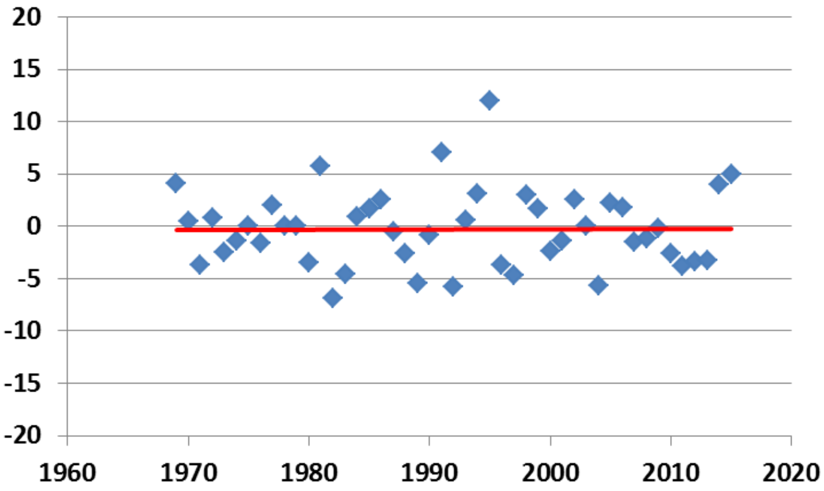

Figure 11. Old Crow Daily Air Temperature (May 6 – 10).

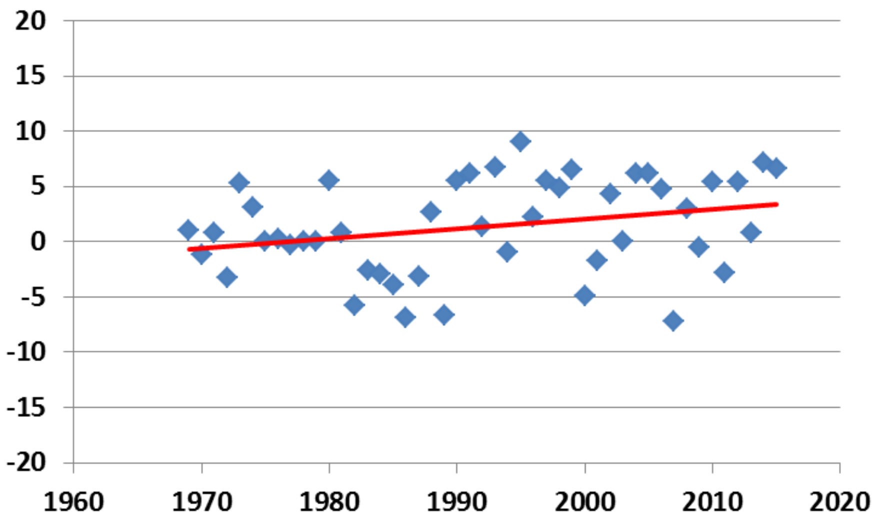

Figure 12. Old Crow Air Temperature (May 11 – 15)

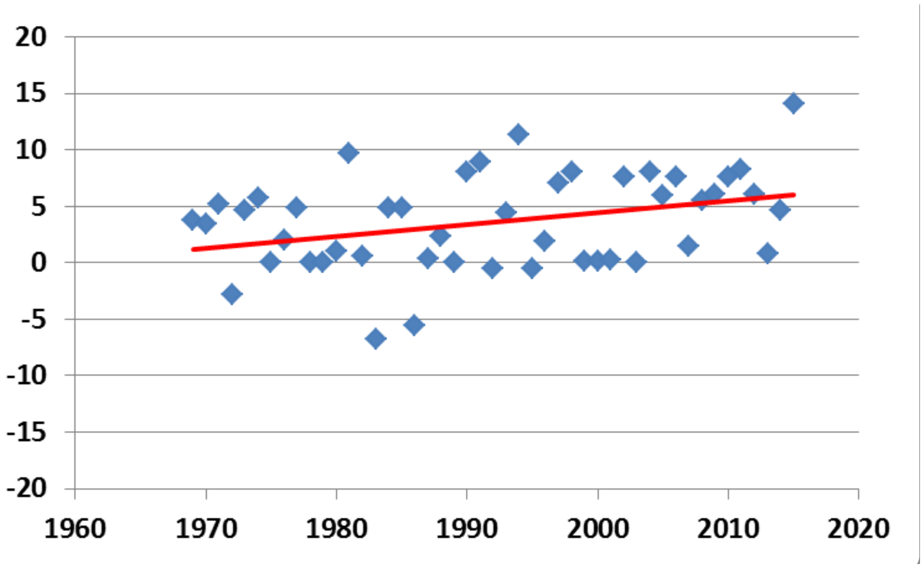

Figure 13. Old Crow Air Temperature (May 16 – 20)

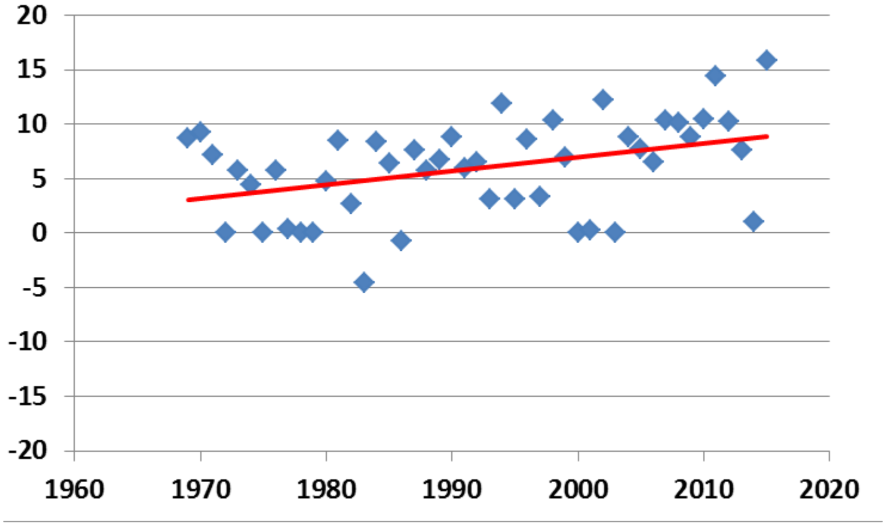

Figure 14. Old Crow Air Temperature (May 21 – 25)

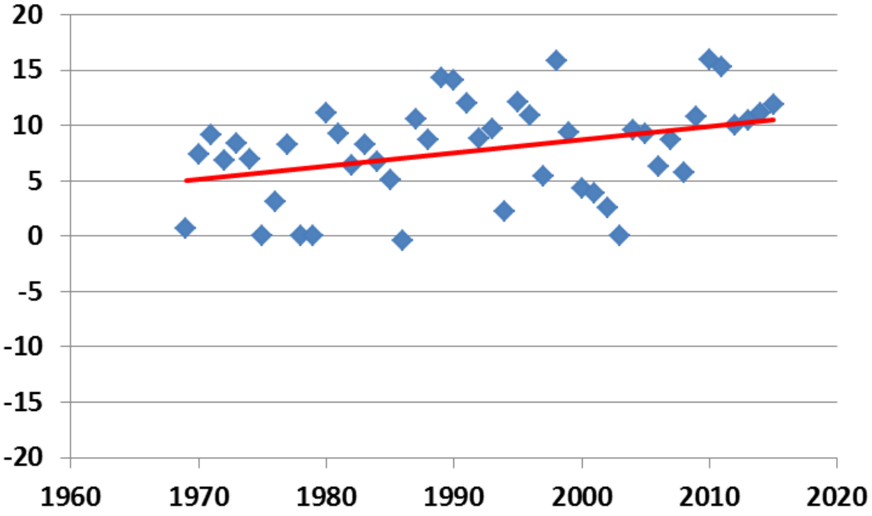

Figure 15. Old Crow Air Temperature (May 26 – 30)