CLIMATE CHANGE IMPACTS ON WATER BALANCE AND UNFROZEN WATER CONTENT AND THE IMPLICATIONS FOR TAILINGS MANAGEMENT IN NORTHERN CANADA

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ABSTRACT
Climate change is predicted to be amplified in the northern hemisphere and it will have a significant impact on permafrost ice content and water balance (storage in tailings ponds). Using synthetic scenarios of climate change, the water balance and permafrost unfrozen water contents were determined for 2050 and 2100 for two weather stations in Northern Canada. The results showed a future trend of decreasing water balance, increasing future permafrost unfrozen water content and greater seasonal fluctuations in the water balance.

1 INTRODUCTION

There is an increasing agreement among the scientific community that the globe is warming compared to the preindustrial revolution (Futter et al. 2014; IPCC 2014). Most studies point to the fact that the Northern Hemisphere is warming faster than the rest of the globe (IPCC 2014). For instance, studies conducted by Callaghan et al. (2010) showed that a subarctic community in Sweden has had its mean annual temperature above 0^{o}C since 2000, compared to -0.3^{o}C in the 1940s. Similarly, Furgal and Prowse (2008) discovered Northern Canada has been warming since 1960, with increasing precipitation, in the form of more rain than snow, and more days of extremely warm temperatures than extremely low temperatures.

Unless future greenhouse gas emissions are curtailed below current levels, the warming trend should continue beyond 2100 (IPCC 2014). The predicted climate will have significant impacts on both biotic and abiotic systems (Callaghan et al., 2010). In the mining industry the impacts of climate change on tailings management is already being experienced. Azam and Ali (2010) reported that extreme precipitation accounted for only 25% of all tailings dam failures from 1910 to 1999, but accounted for 40% all such failures between 2000 and 2009. In the cold regions, the loss of ice in permafrost due to increasing temperature has been reported in various studies (Hong et al. 2014; Instanes 2003). Loss of ice (increasing unfrozen water content) in permafrost represents decreasing strength of permafrost (Kokorev et al. 2016) which could cause significant defects to tailings storage facilities sited on it.

This paper therefore analyses the loss and gain of water (water balance) in a tailings pond and the permafrost unfrozen water content for a region of Northern Canada for 2050 and 2100. The potential implications of these changes on tailings management in the region are also discussed.

2 METHODOLOGY

2.1 Study Area

Northern Canada comprises the Yukon, Northwest Territories and Nunavut, as shown in Figure 1. The region lies north of latitude 60^{o}N and extends to the North Pole. It is characterized by low average annual precipitation and temperature. For the purpose of studies related to mining, the region between latitude 60°N and 66°N is examined. Two weather stations in Nunavut were selected and for which historic climate data from 1971 to 2004 were obtained from the Environment Canada Database. The Baker Lake station with ID 2300500 is located at 64.3^{o}N and 96.08^{o}W and the Iqaluit A station with ID 2402590 is located at 63.75°N and 68.55°W.

Figure 1. Map of Northern Canada showing Baker Lake and Iqaluit in dark circles (Furgal & Prowse 2008)

2.2 Water Balance

The daily water balance (△S) was determined for the two weather stations using the historical data. The general water balance is determined as the difference between water input (I) and water output (O) as expressed in Equations 1 and 2 (Liu & Shaake 1989; Peters 2014).

$$\Delta S = I - O \quad [1]$$

Equation (1) can be expanded as

$$\Delta S = (P + Rin) - (E + S) \quad [2]$$

where
P is precipitation (mm),
R_{in} is runoff into the pond (mm),
E is evaporation (mm), and
S is seepage (mm).

Evaporation is calculated using the Priestly-Taylor method describe by Reid (2005) as

$$E = \propto \frac{\Delta}{\Delta + \gamma} E_R \quad [3]$$

where
E is evaporation (mm/day)
α is the sensible heat flux (W/m^2),
Δ is the slope of the temperature-saturated vapour pressure curve (kPa/ ^oC)
γ is the psychrometric constant (kPa/ ^oC), and
E_R is the energy balance coefficient (mm/day).

Δ and γ are obtained from formulas from Allen et al. (1998) and Reid (2005) as shown in Equations 4 and 5

$$\gamma = \frac{C_P P}{0.622 l_v} = 0.665 * 10^{-3} * P \quad [4]$$

$$\Delta = \frac{4098 * (0.6108 * e^{(\frac{17027 * T}{(237.3 + T)})}}{(T + 237.2)^2} \quad [5]$$

where
C_p is constant pressure specific heat of air (MJ kg^{-1} $°C^{-1}$),
lv is latent heat of vaporization (2.45MJkg^{-}),
P is atmospheric pressure (kPa) and
T is air temperature (°C).

The energy balance coefficient is defined by Reid (2005) in Equation 6

$$E_R = 0.0353 * Rn \quad [6]$$

where Rn is the net solar radiation ($MJm^{-2}day^{-1}$).

The values of Rn are estimated based on guidelines provided by the Food and Agriculture Organization (Allen et al. 1998) and Reid (2004) and the runoff into pond component, Rin, is obtained from Reid (2004)

$$R_{in} = \frac{0.5 * A_L * P}{A_p} \quad [7]$$

where
A_L is the undiverted catchment area of the pond (m^2), excluding the pond itself, and
A_p is the Pond Area (m^2).

Based on the dimensions of the tailings pond studied by Reid (2004), a conservative value of 0.2096 for the A_L:A_p ratio was used to simplify the runoff calculation.

The daily water balance was therefore obtained from the historical values of temperature and precipitation and the generated values of runoff and evaporation.

To simplify the calculation of water balance, seepage (S) was assumed to be negligible. As well, evaporation was taken to be zero whenever T was at or below the freezing point.

2.3 Unfrozen Water Content

The near surface permafrost is a mixture of ice and water in equilibrium (Burn and Osterkamp 2003), and the values of the frozen and unfrozen water content depend on the temperature and soil properties (Arenson et al. 2008). To determine the value of the unfrozen water content (θu), a formula proposed by Burn and Osterkamp (2003) is applied for temperatures below 0^oC. Above 0^oC, the near surface ice is assumed to have completely melted.

$$\ln \theta u = 0.2618 + 0.5519 \ln S + 1.119 S^{-0.264} \ln Ts \quad [8]$$

where
θu is amount of unfrozen water (%),
S is soil specific surface area (m^2g^{-1}), and
Ts is soil temperature (°C).

Based on air and soil temperature obtained from the Nunavut Impact Review Board, NIRB (2012) shown in Table 1, a 30-day moving average was used for the Ts. Taking the soil to be mostly clay, a value of $444.4 m^2g^{-1}$ can be used as the soil specific surface area.

To simplify the calculation, assumptions were made that there was minimal snow cover on the soil surface (Burn & Osterkamp, 2003). Therefore, the effects of thermal and vegetation insulation were ignored.

Table 1. Average monthly air and soil temperatures at Baker Lake (NIRB, 2012)

Month	Air Temperature (^oC)	Soil Temperature (^oC)
Jan	-29.1	-25.5
Feb	-27.8	-28.1
Mar	-22.3	-24.9
Apr	-17	-18.1
May	-3.1	-8.0
Jun	7.6	2.0
Jul	7.6	10.5
Aug	16.8	9.3
Sep	5.7	3.6
Oct	-5	-2.8
Nov	-14.8	-11.7
Dec	-22.3	-19.9

2.4 Future water balance and unfrozen water content

Eight synthetic scenarios were generated based on climate change projections published by the IPCC under two representative concentration pathways (RCPs), RCP 6.0 and RCP 8.5 under the Coupled Model Intercomparison Project (CMIP) 5 ensemble. RCP 8.5 represents the highest possible GHG emission scenario with no curbing beyond 2100. The RCP 6.0 represents a moderate rate of increase in GHG emissions with very minimal curbing, ending in 2100. The modelling is Excel based and therefore synthetic scenarios are useful because of limited computing power (Cattle et al., 2005). Projections are made for 2050 and 2100 based on the projected mean global changes as shown in Table 2.

Table 2. Projected temperature and precipitation changes for Northern Canada, adapted from IPCC (2014)

	Global Temperature Change (%)		Precipitation change (% per ^oC)
Scenario	2050 Range	2100 Range	
RCP 6.0	1.3 – 1.8	2.2 – 3.1	3
RCP 8.5	2.0 – 2.6	3.7 – 4.8	

Since the arctic region is projected to warm faster than the rest of the planet (IPCC, 2014), it was assumed that the region of Northern Canada would experience temperature changes between the mean and maximum values of global projections. Also since global precipitation changes are likely to be from 1% to 3% per ^oC, and the northern hemisphere should experience higher precipitation changes, precipitation changes of 3% per ^oC were used for future arctic projections.

Using a simplified method described by Xu (2000), adjustments were made to the historic temperature and precipitation by applying the future scenarios shown in Table 2.

In further sections of this paper, the projections are simply denoted by the RCP notation and the projected temperature increase. For example, RCP 6.0-1.3 indicates an increase of 1.3^oC under RCP 6.0.

3. RESULTS

The results for annual and seasonal water balance (∆s) and unfrozen water content (θu) are presented for historic (1971-2004) and future projections (2050 and 2100). The seasons are defined in terms winter (December, January and February), spring (March, April and May), summer (June, July and August) and fall (September, October and November).

3.1 Unfrozen water Content

3.1.1 Annual Unfrozen water Content

The historic annual unfrozen water contents for the two stations are shown in Figure. 2. There is an upward trend at both stations which reflects increasing temperature over the historic period (1971-2004). At both stations, the graphs showed three distinct phases, an initial upward trend followed by a minimal downward trend followed by a final upward trend. Analysis of the data showed that the slope of the downward trend was very small (1.8%) compared to the two upward trends from 1971 to 1982 and 1992 to 2004 (≈16%). The unfrozen water content could therefore be said to be increasing throughout the period.

The statistical analysis of the relationship between surface soil changes (derived from air temperature) generated R-squared values of 0.64 and 0.63 for Baker Lake and Iqaluit, respectively. Even though the response of ice changes to climate (temperature) is medium as denoted by the R-squared values, the relationship is still statistically significant with p-values less than 0.001 at a 95% confidence level, for both stations, as summarised in Table 3.

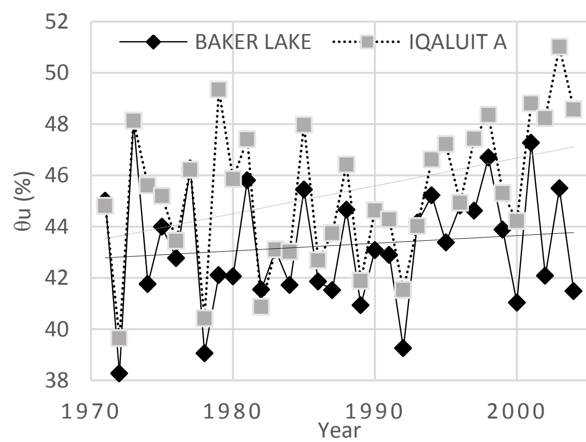

Figure 2. Annual unfrozen water balance for Baker Lake and Iqaluit for 1971-2004. A 9-year running mean was used for Iqaluit in 1993 since the raw data was missing.

Table 3. Summary of average annual unfrozen water contents from 1971-2004 for Iqaluit and Baker Lake weather stations

		Baker Lake	Iqaluit	Average
Average Soil Temperature (^oC)		-11.6	-9.4	-10.5
Unfrozen water content (%)	Avg.	43.3	45.3	44.3
	Max.	48.1	51.0	46.0
	Min.	38.3	39.6	39.0
R-squared		0.64	0.63	
Significance (p-value)		<0.001	<0.001	

The values of the unfrozen water content showed an increase for the 2050 and 2100 projections. The maximum θu values were recorded at the highest temperature projections for both years, as shown in Tables 3 to 6. The θu rose to an average of 50.3% at Iqaluit and 47.0% at Baker Lake. In 2100, it increased to 54.5% and 50.0% at Iqaluit and Baker Lake, respectively. The responses of θu to temperature were linear and therefore any increase in temperature causes a corresponding increase in θu.

Table 4. Average annual θu (%) for 2050 and 2100 under different climate change projections compared to 1971 to 2004 values at the two weather stations

		Baker Lake	Iqaluit A
1971-2004		43.3	45.3
2050	RCP 6.0-1.3	45.2	48
	RCP 6.0-1.8	45.9	48.9
	RCP 8.5-2.0	46.1	49.2
	RCP 8.5-2.6	47	50.3
2100	RCP 6.0-2.2	46.4	49.6
	RCP 6.0-3.1	47.7	51.3
	RCP 8.5-3.7	48.5	52.3
	RCP 8.5-4.8	50	54.5

3.1.1 Seasonal Unfrozen Water Content

Based on the projections used, the seasonal average θu increased for 2050 and 2100 (Figures 3 to 6). However, there were only minimal changes in winter and spring. Significant changes in unfrozen water content in the Summer and Fall were mainly due to the increases in June and October. Figures 3 to 6 also show the historic seasonal values to allow for easy comparison.

In 2050, the maximum predicted θu values for winter, spring, summer and fall respectively were 14.6, 16.8, 94.6 and 62.2 for Baker Lake and 15.3, 19.3, 96.1 and 70.1 for Iqaluit. All maximum values for every season occurred under RCP8.5-2.0 where the maximum temperature projections were used.

In 2100, where the highest projected temperature increase occurred under RCP8.5-4.8, the maximum values recorded in winter, spring, summer and fall respectively were 14.5, 19.34, 97.6 and 68.0% for Baker Lake and 16.0, 23.9, 98.7 and 78.6% for Iqaluit.

3.1 Water Balance

3.1.1 Annual Water Balance

The annual water balance (Δs) (Figure 7) for the two weather stations follows a common trend in most years. It is positive in all years for Iqaluit, except 1998 (-77mm). For the 1971-2004 period the average Δs for Iqaluit is very high, at 236.3mm (ignoring 1993) compared to that of Baker Lake, which is 43.45mm.

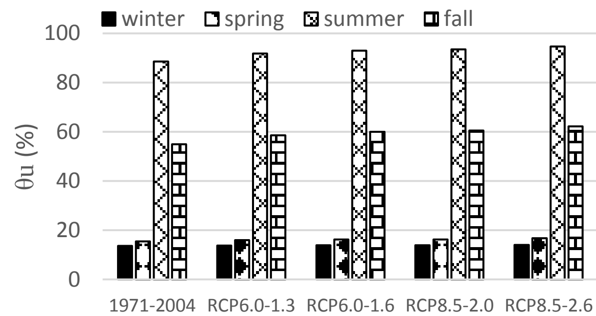

Figure 3. 2050 Seasonal θu for Baker Lake

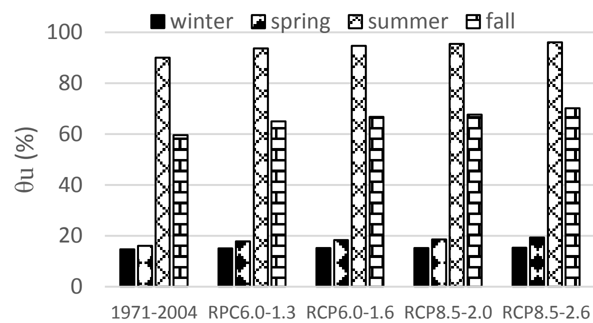

Figure 4. 2050 Seasonal θu for Iqaluit

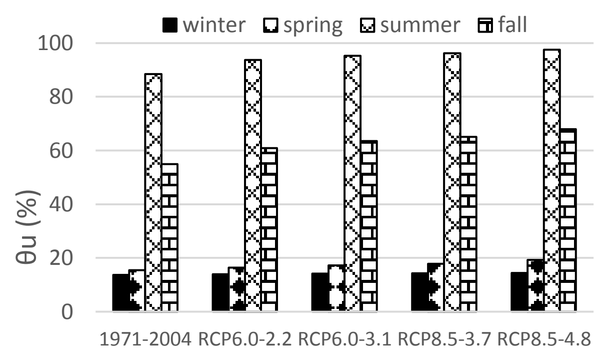

Figure 5. 2100 Seasonal θu for Baker Lake

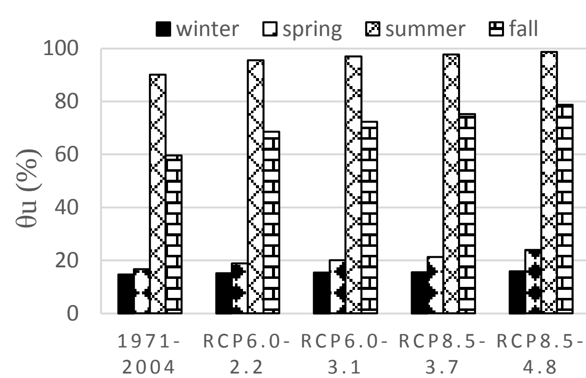

Figure 6. 2100 Seasonal θu for Iqaluit

At Iqaluit, the maximum Δs of 489.1mm occurred in 1979 and the minimum Δs of -135.8mm occurred in 1998. At Baker Lake, the maximum Δs of 152.2mm was recorded in 1985 and the minimum Δs of -89.5mm occurred in 1993. The general trend analysis shows that Δs decreased from 1971 to 2004.

At both stations, the years from 1971-1998 exhibited higher average annual water balance values of 66.5mm and 265.7mm than from 1998-2004, which were 21.6mm and 200.8mm respectively, for Baker Lake and Iqaluit. Analysis of the Environment Canada Annual Climate Trend Bulletin shows that the precipitation has been decreasing since 1988 while the temperature has been rising. This could explain the much steeper decreasing trend in water balance for the period after 1998.

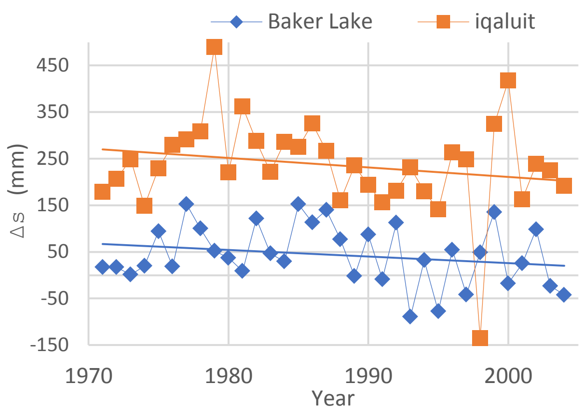

Figure 7. Average annual water balance for Baker Lake and Iqaluit from 1971 to 2004. A 9-year running average was used for Iqaluit in 1993.

Statistical analysis shows that, the R-squared values of how well the water balance was predicted by air temperature and precipitation were 0.88 and 0.99 respectively for Baker Lake and Iqaluit A stations (Table 5). At a 95% confidence level, the relationships were found to be statistically significant (p<0.001).

The projections for 2050 in Table 6 show different trends for the two weather stations. At Baker Lake, the response to changes in temperature and precipitation is uniform. As the temperature and precipitation increase, the average water balance decreases significantly, relative to the historical average.

At the Iqaluit weather station, the 2050 projections show only a marginal difference from the historical data. The effect of temperature on the water balance is significantly minimised by the high average annual precipitation, as shown in Table 6. Major change is only observed RCP6.0-1.8 where a decline of 7.1mm occurs.

In 2100, Baker Lake continued to show a decline in water balance for all projections (Table 7), and showed more response to temperature increase than precipitation increase. Similar to the 2050 projections the changes to average annual water balance for 2100 was marginal. The maximum decline in water balance was only 3.1mm.

Table 5. Summary of average annual unfrozen water contents for 1971-2004 for Baker Lake and Iqaluit A weather stations

		Baker Lake	Iqaluit A*
Average temperature (^{o}C)		-11.6	-9.4
Average precipitation (mm)		264.0	408.2
Water Balance (mm)	average	43.7	236.3
	maximum	152.2	489.1
	minimum	-89.5	-135.8
R-squared values		0.88	0.97
Significance (p-values)		<0.001	<0.001

* Average values for Iqaluit A do not include 1993.

Table 6. Average annual Δs (mm) for 2050 under various RCP projections

		2050			
		RCP 6.0-1.3	RCP 6.0-1.8	RCP 8.5-2.0	RCP 8.5-2.6
Baker Lake	Avg.	35.7	29.3	31.7	27.3
	Max.	150.3	141.5	144.0	144.2
	Min.	-95.6	-103.7	-102.5	-105.2
	(σ)	65.5	65.4	66.3	67.3
Iqaluit A	Avg.	234.6	229.1	234.4	233.6
	Max.	494.8	489.0	310.8	503.9
	Min.	-151.6	-151.4	-160.4	-155.8
	(σ)	104.2	104.8	106.4	108.3

Table 7. Average annual Δs (mm) for 2100 under various RCP projections

		2100			
		RCP 6.0-2.2	RCP 6.0-3.1	RCP 8.5-3.7	RCP 8.5-4.8
Baker Lake	Avg.	30.3	25.5	23.0	17.1
	Max.	143.4	143.7	142.0	144.0
	Min.	-94.4	-109.0	-113.0	120.2
	(σ)	66.6	68.2	69.8	71.8
Iqaluit A	Avg.	234.3	233.2	233.0	235.0
	Max.	500.9	507.2	513.0	523.7
	Min.	-155.8	-164.3	-175.2	-186.9
	(σ)	107.0	110.2	112.3	115.3

Tables 6 and 7 also contain the value of the standard deviation (σ) for each scenario and at each site and these numbers show that there are wide variations in the possible outcomes between the maximum and minimum annual water balances.

3.1.2 Seasonal Water Balance

The seasonal water balance for 1971-2004 and 2050 projections are presented in Figures 8 and 9 for Baker Lake and Iqaluit respectively. In general, summer has the least Δs and fall has the highest. The water balance in summer is negative, showing more response to temperature than precipitation. In the summer of 2050 Δs was more negative for all projections at both stations. Similarly, the spring projections also decreased relative to the years from 1971-2004 at both sites.

Fall and winter projections however increased. This is because the winter temperatures are generally below the freezing point, resulting in minimal evaporation, and therefore Δs was largely dependent on precipitation. In fall the Δs was largely dictated by precipitation because the temperatures in October and November were significantly lower compared to those of the summer.

In 2100, the predicted seasonal Δs values (Figures 10 and 11) for Baker Lake were very similar to those for 2050, for all seasons. In summer and spring, they decreased while in winter and fall they increased. Baker Lake has a relatively low precipitation and therefore at very high temperature, the water balance decreased. The decrease in spring was largely dependent on the above 0^{o}C temperature experienced during most days in May in 2100, which would cause increased evaporation. In the fall, the temperatures in October and November were predicted to still be very low and hence, increase in precipitation caused an increase in the water balance.

The predicted Δs values decreased in summer and spring and increased in fall and winter showing more fluctuations in the future, which is one of the symptoms of climate change (IPCC, 2014).

The projections for 2100 for Iqaluit and Baker Lake were similar as predicted Δs values decreased for summer and spring and increased for fall and winter. However, by comparison, the values of Δs for each season were higher at Iqaluit than Baker Lake. Higher precipitation at Iqaluit was responsible even though the expected temperature would be higher at Iqaluit. In the summer of 2100, the predicted Δs values at Iqaluit were negative for all projections with a minimum of -6.23mm under RCP 8.5-4.8.

4. DISCUSSION AND CONCLUSION

4.1. Climate Change Impacts on Unfrozen Water Content- Implications for Regional Tailings Management

Both historical and future projections point to increasing unfrozen water content under increasing temperature conditions on an annual basis and on a seasonal basis. The intensity of changes is more evident in summer and fall, where the changes in temperature would be more profound. This is due to the fact summer and fall generally have higher temperatures than winter and spring.

Winter and spring remain largely near or below 0^{o}C for most of these two seasons and hence the projected increases in temperature have little impact on the permafrost ice content. However, in summer, the region experiences higher temperatures, mostly above 0^{o}C, and especially in summer.

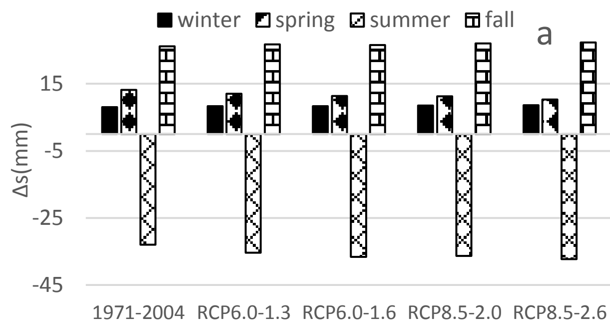

Figure 8. Seasonal water balance at Baker lake for 2050

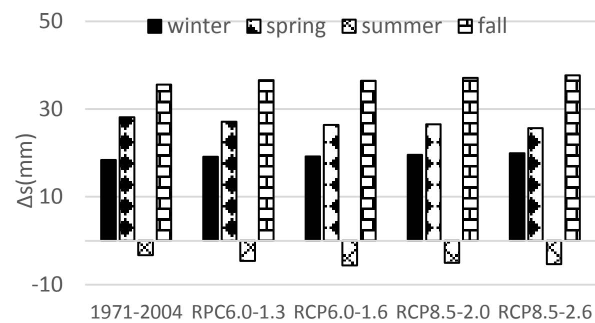

Figure 9. Seasonal water balance at Iqaluit for 2050

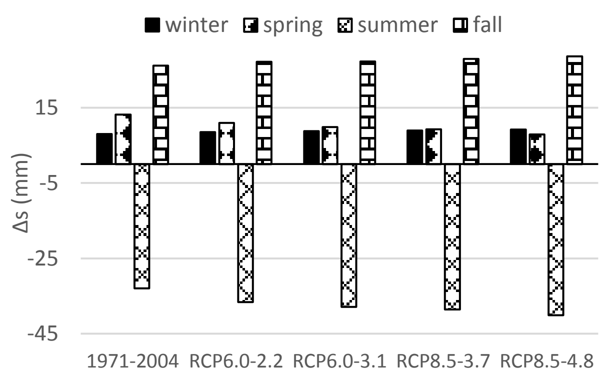

Figure 10. Seasonal water balance at Baker lake for 2100

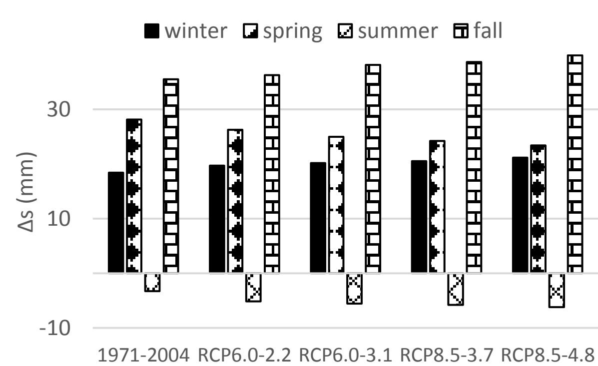

Figure 11. Seasonal water balance at Iqaluit for 2050

During the fall, the region generally experiences early onset of cold weather. However, based on the historical data and projected temperature increases, the onset of cold weather in fall would be delayed which would contribute to a further decline of ice content in the permafrost.

Confirmation of loss of ice due to climate change has been proven in some studies. A study in Russia by Nelson et al. (2012) confirmed that increasing air temperature had caused loss of permafrost ice, thickening the active permafrost layer from 1963 to 2010. Instanes (2003) also projected an increasing air thawing index and decreasing air freezing index for the permafrost region of Svalbard, which technically means permafrost in the region would lose more ice than it would gain.

The implications of decreasing permafrost ice content for tailings management are wide and varied. Foundations of tailings dams and other supporting structures would be are at risk of failure under increasing permafrost unfrozen water content. According to Hong et al. (2014), Kokorev et al. (2016) and Nelson et al. (2012), the bearing capacity of a permafrost is directly related the ice content. The higher the ice content, the higher the bearing capacity and vice versa. Loss of ice therefore reduces the ability of permafrost to support foundations sited on them. This puts tailings dams and other tailings storage facilities constructed from raised embankments at risk of failure in the future.

The studies by Nelson et al. (2012) built a direct relationship between increasing air temperature and reduction in permafrost bearing capacity. Failure of structures related to reduction in permafrost ice has been proven in some studies. Jin et al. (2015) found that highway embankments in permafrost regions of China were settling due to increasing air temperature. As well, Kokorev et al. (2016) discovered foundation deformations in buildings located in the Russian arctic due to increasing temperature.

An important function of permafrost to tailings management is its ability to minimize seepage under tailings storage facilities. The Government of Nunavut (2012) highlights that tailings dams built on permafrost which are subjected to thawing will likely experience increased seepage underneath them. This hazard could be more detrimental to tailings dams on abandoned and orphaned mine sites (Beaumier et al., 2011).

In a typical example, thawing permafrost caused excessive seepage under the tailings dump at the Clinton Creek Asbestos mine in Yukon which operated between 1967 and 1978 (Beaumier et al., 2011). The dam eventually failed and further assessment showed that climate change was not adequately factored into the construction of the tailings dam, since the assumption that permafrost would be permanently frozen was used (Beaumier et al., 2011). Reductions in permafrost ice therefore present a clear risk of increased seepage under tailings dams and potential pollution of groundwater.

4.2 Climate Change Impacts on Water Balance-Implications for Regional Tailings Management

Both the historical and projected average annual water balances showed decreasing trends into the future. Northern Canada is generally cold and hence has low average annual temperature. Statistical analysis showed that water balance was more dependent on temperature than precipitation. Therefore, an increase in temperature would cause an increase in evaporation and a reduction in the water storage in tailings ponds.

However, due to the low average temperature of the region, the quantity of precipitation commands a significant impact on the water balance. Generally, the region will follow the pattern exhibited by Baker Lake because of the similarities in temperature and precipitation since Whitehorse and Yellowknife are similar to Baker Lake. The trends exhibited at Iqaluit however showed that at places of high precipitation, the water storage or balance could be high, overcoming to a greater extent the impacts of temperature.

The average annual water balances for all projections were positive. However, the variations in water balances for 2050 and 2100 were wide, as shown in Tables 5 and 6, raising the possibility of numerous outcomes under any given projection. Chances of dry and flooded ponds are possible under all projections considered, which could impact on tailings management in the region variedly. Under seasonal projections, the summer and spring will become drier while the fall and winter will be wetter. Assessment of the primary data shows that summer is generally warm and hence the negative water balance would be expected. Spring on the other hand remained relatively cold for March and April but got warmer in May which accounted for the drop in the water balance.

The impacts of the changing water balance on regional tailings management can be assessed in two main forms, drying and flooding as stated earlier. Based on the results of this study, tailings facilities experiencing average precipitation are not at risk of flooding since water balance decreases under such a circumstance. The results however point to the possibly of an extremely high maximum water balance, raising the chances of flooding.

Seasonally, flooding is much more possible in winter and fall where water accumulates. However, the occurrence of flooding is dependent on the severity of unusual precipitation, which could occur during any season. Analysis of the primary data showed that such events would be possible under increasing precipitation in the future. For instance, in 1994, the Baker Lake station recorded 80.1mm of precipitation, over a 2-day period from September 23 to 24 which represented 30% of the average annual precipitation for the 1971 to 2004 period. September 1 to 3, 1999 also recorded 68.1mm of precipitation which was equivalent to 26% of the average annual precipitation for the 1971 to 2004 period.

Such high precipitation events, coupled with projected increasing water balance in the fall could expose tailings ponds to the possibility of flooding. However, as stated earlier, such high precipitation events are not limited to only the fall season. The primary data from both stations showed that high unusual precipitation incidence in summer was not very uncommon and overtopping could equally occur then. High water levels resulting from extreme precipitation have accounted for about 40% of all tailings dam (pond) failures since 2000 (Azam & Ali. 2000).

Dust pollution from a tailings facility usually results from a drought event where water lost though evaporation, for example, is higher than the water gained. Based on the annual water balance projections for 2050 and 2100, it is safe to say that dust pollution would be minimal since the average Δs values were positive for all scenarios considered.

However, there are chances that precipitation could be very low and cause tailings ponds to dry and create dust pollution. The minimum average annual water balance was -88mm for 1971 to 2004 at Baker Lake. This minimum value decreased to -105mm and -120mm in 2050 and 2100, respectively. The minimum value, together with the standard deviation under each scenario (Tables 6 and 7) showed the wide variation of possible outcomes and a strong indication that the drought-like conditions could be experienced in a tailings pond situated in Northern Canada. Under such drought-like conditions, dust pollution is a possible challenge during windy conditions. Dust pollution is usually a major concern for mining communities in Northern Canada. For instance, it was one of the biggest concerns when a sub-aqueous tailings disposal method was proposed for the Meadowbank gold mine in Nunavut (Government of Nunavut, 2012).

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