AREVA

Kiggavik Project
Final Environmental Impact Statement

Tier 3 Technical Appendix 5H:
Waste Rock Water Balance

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Waste Rock Water Balance - Volume 5H

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1.0 INTRODUCTION

This report provides the refinement of climatic parameters for application in the water transport modelling with emphasis on precipitation and evaporation (mean and ranges), and snow accumulation and redistribution near the Kiggavik waste rock piles. The specific objective of the climate data refinement was to assemble a complete set of daily climate data for a long-term period of record with several climate elements such as precipitation rainfall, snowfall, temperature, humidity, wind speed, net radiation and evaporation.

From the compiled data, representative wet, dry and average precipitation years were determined. The year with the highest annual precipitation was considered a wet year, while the year with the lowest annual precipitation was considered a dry year. An average year was the year with the annual precipitation closest to the mean of all the annual precipitations in the record.

Melting snow can be an important component of the overall water balance on waste rock piles. The determination of the amount snow remaining on the waste rock pile and available for melting, and subsequent infiltration, is an important element in the waste rock water balance. This report provides a description of the physical process related to snow transport by wind and methods developed for its estimation in northern Canada. Empirical expressions were employed to estimate snow accumulations and redistribution of snow potentially available for infiltration on the waste rock piles.

2.0 CLIMATE DATA SOURCE

Local climate data collected near the Kiggavik Project (the Project) has been sporadic and sparse. In various years between 1983 and present, short-term climate stations were installed by several different consultants for research purposes (Roulet and Woo 1986; Beak 1987; Beak 1989a; Beak 1989b; EcoMetrix 2006). Data collected from these short-term climate stations do not provide an adequate period of record for modelling water transport. The nearest long-term climate station is located at Baker Lake, approximately 80 km east of the Project. The Baker Lake climate station is part of Environment Canada's National Climate Data and Information Archive and includes daily climate data from 1946 to present.

There is not enough coincident data available at the Project site to provide a statistical assessment or comparison of means between the Project site and Baker Lake data. However, data collected from May 7 to August 31 of 2009 at the Project site were compared to the data collected at the Baker Lake climate station. Figures 1 to 4 show the mean daily data plotted against one another for temperature, atmospheric pressure, relative humidity and wind speed. The comparisons suggested that temperatures and pressures at Baker Lake and the Project are similar. Mean relative humidity and wind speeds show more scatter over the measurement period. The mean wind speeds over the measurement period were 19.8 km/h at the Project site and 17.0 km/h at Baker Lake. Therefore, mean wind speeds were approximately 16% higher at the Project site than Baker Lake. Despite the difference in wind magnitudes, Baker Lake climate station provides the most reasonable climate data for use at the Project site. The mean relative humidity at the Project site over the measurement period was 79.3% compared to 77.7% at Baker Lake. Therefore, the mean relative humidity was 2% higher at the Project site than Baker Lake. This climate comparison uses a very limited record of data; therefore, the relationships given in Figures 1 to 4 may not be truly representative long-term climate differences and/or similarities between the Project site and Baker Lake. Differences in instrumentation at the two locations could also account for some variability between the sites. As such, the data presented in this analysis is from the Baker Lake climate station, and the data have not been adjusted to represent the climate at the Project site.

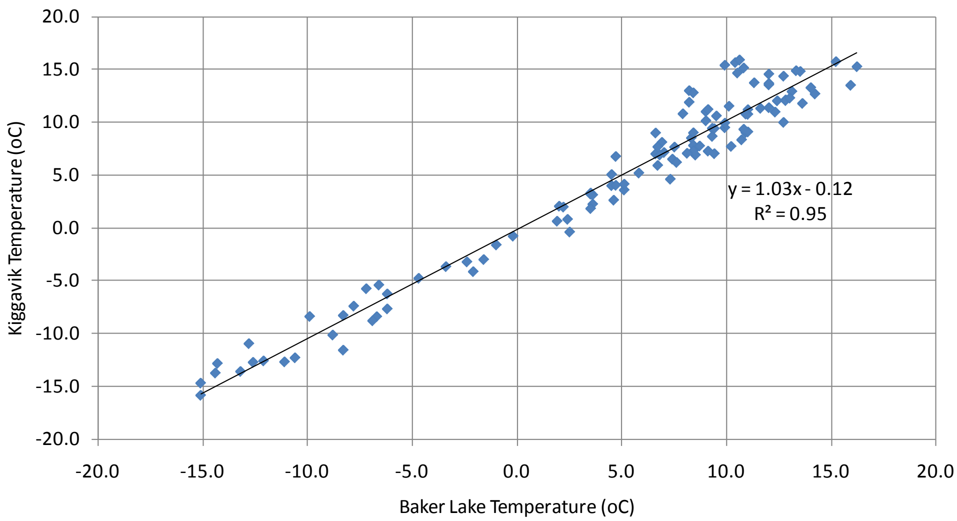


Figure 1: Kiggavik versus Baker Lake mean daily air temperatures, May to August 2009

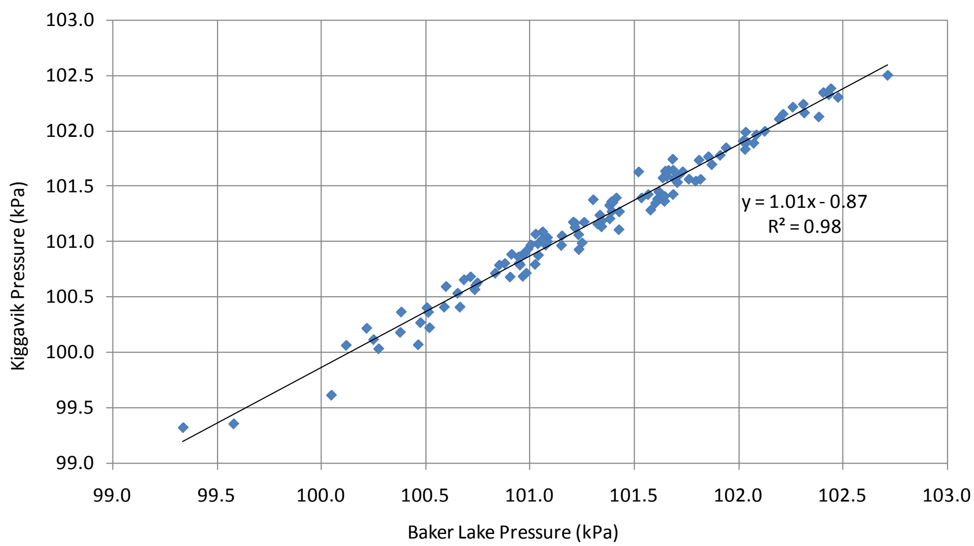


Figure 2: Kiggavik versus Baker Lake mean daily atmospheric pressure, May to August 2009

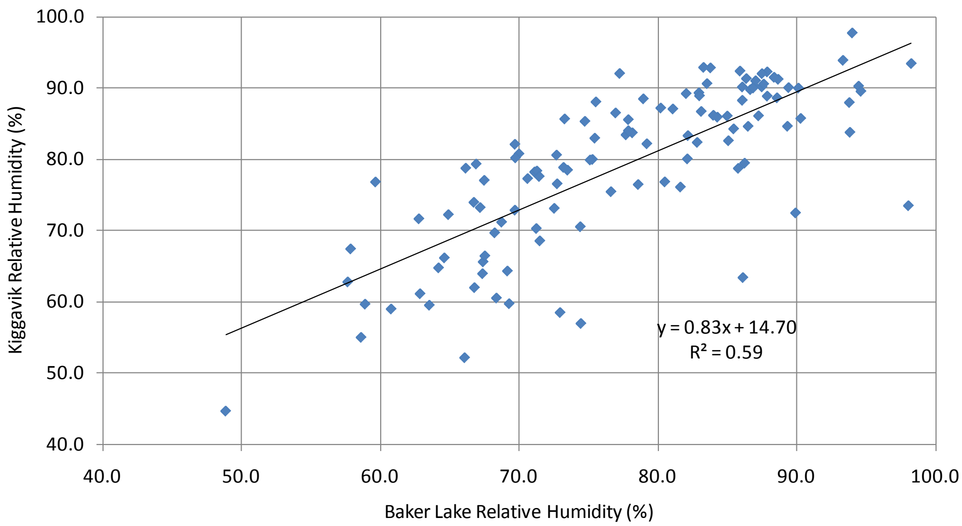


Figure 3: Kiggavik versus Baker Lake mean daily relative humidity, May to August 2009

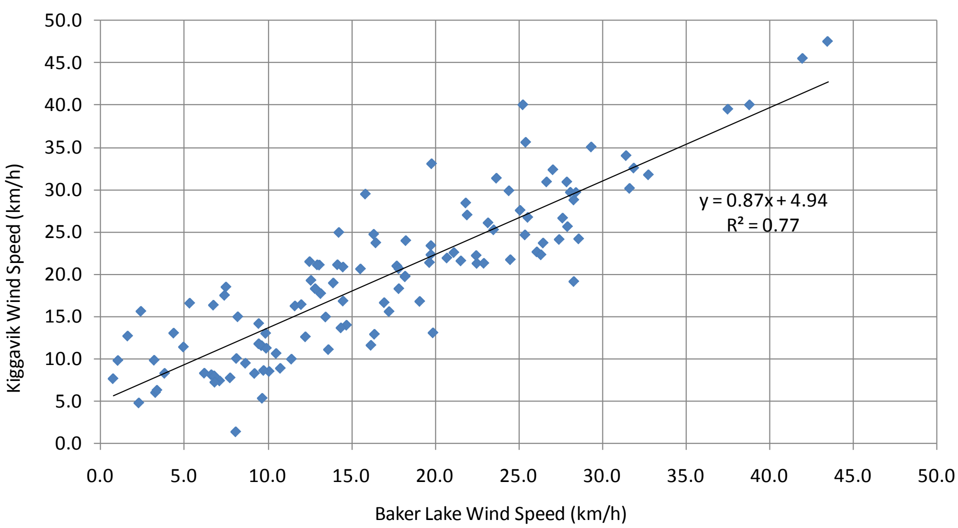


Figure 4: Kiggavik versus Baker Lake mean daily wind speed, May to August 2009

3.0 REVIEW AND REFINEMENT OF BAKER LAKE CLIMATE DATA

Baker Lake daily climate data was compiled from 1959 to 2009. Climate elements compiled included air temperature, precipitation, wind speed, relative humidity, station pressure and net radiation. Within the period of record compiled, several data gaps existed. Table 1 lists the percentage of data that was missing for each climate element. Net radiation had the most missing data with 59% missing.

Table 1: Percentage of measured daily data that was missing for each climate element from 1959 to 2009 at the Baker Lake climate station

Climate Element	Data Missing (%)
Mean, maximum and minimum air temperature	1.0
Total rainfall, snowfall and precipitation	2.0
Mean, maximum and minimum wind speed	1.9
Mean, maximum and minimum relative humidity	3.7
Mean, maximum and minimum station pressure	2.4
Mean net radiation rate	59

Typically for modelling purposes, there must be a value for each climate element for each day of the record. In order to reduce the amount of data that required estimating, each year of the record was examined to determine the amount of data that was missing. Because net radiation had the most missing data but can be estimated using other available climate elements, it was not considered “missing” if measured data was not available. The number of days missing during each year ranged from 0 days to 354 days. It was found that 30 years of the entire record had less than 10 days of missing data. These years were 1975 to 2008, excluding 1979, 1989, 1992 and 1993. During these 30 years of data, approximately 94 days of data were missing. In other words, only 0.7% of the days were missing and required estimating. These 30 years are used for this climate data refinement and compilation.

Missing temperature, wind speed, relative humidity, and station pressure were estimated by averaging the value of the day before and after the gap. Missing precipitation data was filled by using precipitation measured at either Environment Canada’s Robertson Lake or Yathkyed Lake climate station. Although, these stations are a distance of approximately 300 m from Baker Lake, it was decided that measured data was better than trying to estimate a precipitation event from other climatic variables. Net radiation was estimated using the methods outlined in Irmak et al. (2003) where net radiation can be estimated using the following equation:

$$R_n = (-0.09T_{\max}) + (0.203T_{\min}) - (0.101RH) + (0.687R_{s(predicted)}) + 3.97 \qquad [1]$$

where R_n is the net radiation (MJ/m²/d), T_{max} is the maximum daily air temperature (°C), T_{min} is the minimum daily air temperature (°C), RH is the mean daily relative humidity, and $R_{s(predicted)}$ is the predicted total incoming solar radiation (MJ/m²/d).

To summarize, a complete daily record of mean, maximum and minimum air temperatures; total rainfall, snowfall and precipitation; mean, maximum and minimum wind speed; mean, maximum and minimum relative humidity; mean, maximum and minimum station pressure; and mean net radiation rate were compiled from 1975 to 2008, excluding 1979, 1989, 1992 and 1993. Excluding net radiation, approximately 1% of this data was estimated. Approximately 43% of the net radiation was estimated using Equation 1.

4.0 PRECIPITATION AND EVAPORATION

4.1 Precipitation

Environment Canada provides adjusted and homogenized climate data for many climatological stations in Canada, including the Baker Lake climate station. These data were created for use in climate research including climate change studies. They incorporate a number of adjustments applied to the original station data to address shifts due to changes in instruments and in observing procedures. The methodology follows the steps described in Mekis and Hogg (1999). Adjustments were applied on daily values for rain and snow separately. For each rain gauge type, corrections to account for wind undercatch, evaporation and gauge specific wetting losses were implemented. The details of rain gauge corrections are further explained in Devine and Mekis (2008). For snowfall, density corrections based upon coincident ruler and Nipher measurements were applied to all snow ruler measurements (Mekis and Hopkinson 2004). All rainfall, snowfall and precipitation data used in this climate refinement and compilation are values adjusted by Environment Canada.

4.2 Evaporation

Evaporation is the process where liquid water is converted to water vapour and removed from sources such as soil surface, wet vegetation, and water bodies. Potential evaporation (*PE*) is defined as the evaporation that would occur from a vegetated surface when moisture supply is not limiting. Actual evaporation drops well below its potential level as the soil dries out.

Estimated daily evaporation off the Kiggavik waste rock piles were calculated using the modified FAO Penman-Monteith Evaporation method presented by Neuner (2009). The original FAO Penman-Monteith method extends the Penman (1948) method to non-saturated cases. The FAO Penman-Monteith method takes into account vapour transport and aerodynamic effects and uses climate elements that are readily available from the Baker Lake climate station, such as mean air temperature, mean relative humidity, mean wind speed, and net radiation. The FAO Penman-Monteith equation is defined as follows (Zotarelli et al. 2010):

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad [2]$$

where ET_0 is the reference evapotranspiration (mm/day), Δ is the slope of the saturation vapour pressure versus temperature curve (KPa/°C), R_n is the net radiation flux (MJ/m^2/d), G is the sensible heat flux into the soil (MJ/m^2/d), γ is the psychrometric constant (KPa/°C), T is the mean air temperature (°C), u_2 is the wind speed at 2 m above the ground, e_s is the saturated vapour pressure (kPa), e_a is the vapour pressure (kPa), C_n is the numerator constant for the reference crop type and C_d is the denominator constant for the reference crop type. C_n and C_d depend on the reference crop.

Neuner (2009) modified the FAO Penman-Monteith method by using two coefficients as follows:

$$E = K_f K_{bs} ET_0 \qquad [3]$$

where K_f is the frozen soil coefficient used to allow evaporation or limits evaporation based on mean air temperature and K_{bs} is the bare soil coefficient used to account for the moisture content of the waste rock near the surface.

For this analysis, a short reference crop was chosen; therefore, the C_n and C_d values were 900 and 0.34, respectively. K_f was set to 1 for mean air temperatures above 0°C and set to 0 for mean air temperatures below 0°C. K_{bs} allows E to equal ET_0 or to limit E based on an estimation of the moisture content of the waste rock near the surface. K_{bs} is a function of infiltration depth, reference evaporation, and the number of days since the last rainfall. This coefficient ranges from 0 to 1 and changes daily depending on the three variables. A detailed description of how this coefficient is calculated is provided by Neuner (2009). At the Diavik Diamond Mine research site, this modified FAO Penman-Monteith method of calculating evaporation was found to match lysimetry measurements over a 40 day period.

The psychometric constant, slope of the saturation vapour pressure versus temperature curve, saturated vapour pressure, vapour pressure and latent heat of vaporization can be found using the following equations (Mays 2001; Chow et al. 1988):

$$\gamma = \frac{C_p K_h p}{0.622 l_v K_w} \qquad [4]$$

$$\Delta = \frac{4098 e_s}{(237.3 + T)^2} \qquad [5]$$

$$e_s = 0.6108 \exp\left(\frac{17.27T}{237.3 + T}\right) \qquad [6]$$

$$e_a = (RH/100) e_s \qquad [7]$$

$$l_v = 2.501x10^6 - 2370T \qquad [8]$$

where C_p is the specific heat at constant pressure (assumed to be 1005 J/kg.K for air), K_h/K_w is the ratio of heat to vapour diffusivities and assumed to be 1, l_v is the latent heat of vaporization (J/kg), p is atmospheric pressure (Pa), and the other variables have previously been defined.

4.3 Calendar Year Results

Daily precipitation and evaporation data has been compiled for a 30 year period from 1975 to 2008, excluding 1979, 1989, 1992 and 1993. The mean annual precipitation and total evaporation for each calendar year are provided in Table 2 and plotted in Figure 5. The maximum precipitation of 530 mm occurred in 1999, while the minimum precipitation of 263 mm occurred in 2004. The mean precipitation during the 30 year period was 387 mm. The maximum and minimum evaporation occurred in 2001 with 296 mm and 2007 with 152 mm, respectively. The mean annual total evaporation was 195 mm. It should be noted that precipitation data is available for Baker Lake over the period 1949 to present and the mean precipitation is 344.4 mm when all the data is used.

Table 2: Total precipitation and potential evaporation based on calendar year

Year	Total Precipitation (mm)	Total Evaporation (mm)	Net (mm)
1975	434	237	197
1976	323	227	97
1977	479	208	271
1978	364	174	189
1979	n/a	n/a	
1980	346	192	154
1981	326	187	139
1982	401	201	201
1983	362	211	150
1984	345	214	131
1985	468	222	246
1986	444	193	251
1987	509	154	355 (maximum)
1988	497	181	317
1989	n/a	n/a	
1990	408	181	227
1991	331	200	130
1992	n/a	n/a	
1993	n/a	n/a	
1994	337	163	174
1995	265	179	86 (minimum)
1996	400	174	227
1997	351	173	179
1998	403	232	171
1999	530 (maximum)	212	318
2000	325	177	147
2001	383	296 (maximum)	87
2002	387	211	176
2003	341	179	162
2004	263 (minimum)	160	103
2005	484	200	284
2006	374	194	180
2007	323	152 (minimum)	171
2008	410	169	241
MEAN	**387**	**195**	**192**

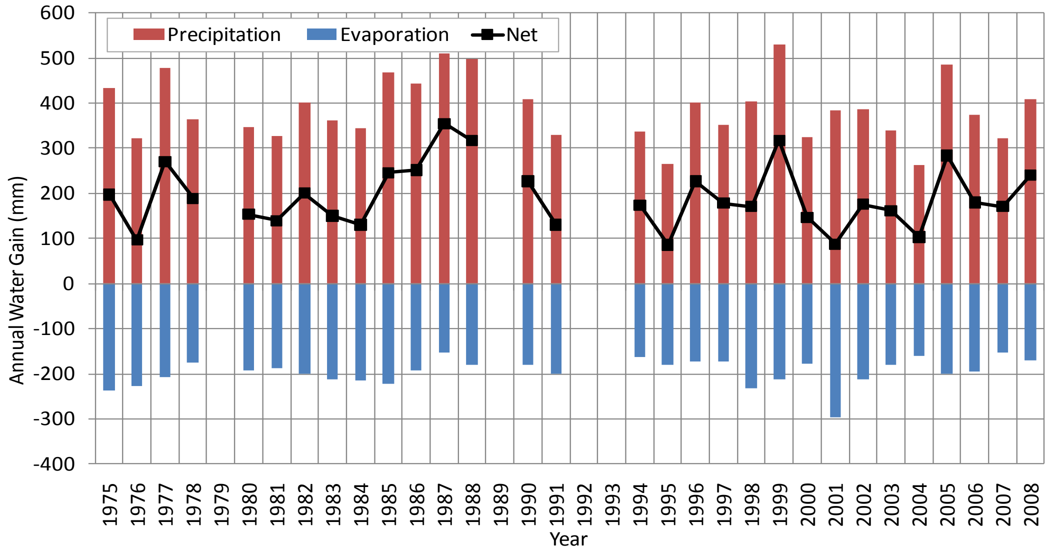


Figure 5: Precipitation, evaporation and net values for each calendar year using Baker Lake climate station data.

4.4 Water Year and Seasonal Results

The hydrologic water year was defined as the 12-month period from October 1 through September 30. This interval was used because the hydrological system is typically at its lowest levels near October 1. The water year was further divided into the "winter" season and the "summer" season. These seasons were divided based on mean daily temperatures. The date in which the mean daily temperature was consistently above zero was assumed to be the beginning of the summer season, while the date in which the mean daily temperature was consistently below zero was assumed to the beginning of the winter season. The dates in which summer and winter began were determined for each year. On average, the summer season began on June 2 and the winter season began on September 27. Therefore, winter is assumed to be from October 1 to May 31 and summer is assumed to be from June 1 to September 30.

Table 3 lists the total precipitation, evaporation and net values for each water year. The precipitation and evaporation was also divided in the winter and summer season values. Figure 6 illustrates the precipitation, evaporation and net values for each calendar year, while Figures 7 and 8 show the seasonal precipitation and evaporation results, respectively.

Table 3: Total precipitation and evaporation divided into winter, summer and water year.

Water Year	Precipitation (mm)			Evaporation (mm)			Net Water Year (mm)
	Winter	Summer	Water Year	Winter	Summer	Water Year	
1975-1976	247	139	385	8	218	226	159
1976-1977	236	144	380	9	197	206	174
1977-1978	279	164	443	3	174	177	266
1978-1979	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1979-1980	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1980-1981	156	128	284	3	179	183	101
1981-1982	183	204	387	6	196	202	185
1982-1983	218	170	387	5	209	214	174
1983-1984	213	170	384	3	211	214	170
1984-1985	170	280	450	4	218	222	228
1985-1986	190	206	396	9	185	194	202
1986-1987	290	189	479	0	153	154	326
1987-1988	302	193	495	0	178	178	317
1988-1989	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1989-1990	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1990-1991	188	150	338	1	198	199	139
1991-1992	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1992-1993	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1993-1994	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1994-1995	137	122	259	5	176	181	78
1995-1996	158	249	406	4	170	174	232
1996-1997	149	111	259	5	167	171	88
1997-1998	262	238	500	2	229	231	269
1998-1999	192	254	446	4	210	214	232
1999-2000	266	139	404	1	176	177	227
2000-2001	185	153	338	17	277	293	45
2001-2002	208	241	449	3	210	214	236
2002-2003	165	137	303	12	163	175	127
2003-2004	160	138	298	4	160	164	134
2004-2005	212	241	453	10	188	198	255
2005-2006	245	97	342	7	184	191	152
2006-2007	225	162	387	5	147	153	235
2007-2008	160	243	403	10	157	168	236
MEAN	**208**	**179**	**387**	**5**	**190**	**195**	**192**

Notes: Winter is assumed to be from October 1 to May 31; summer is assumed to be from June 1 to September 30; and a water year is assumed to be from October 1 to September 30.

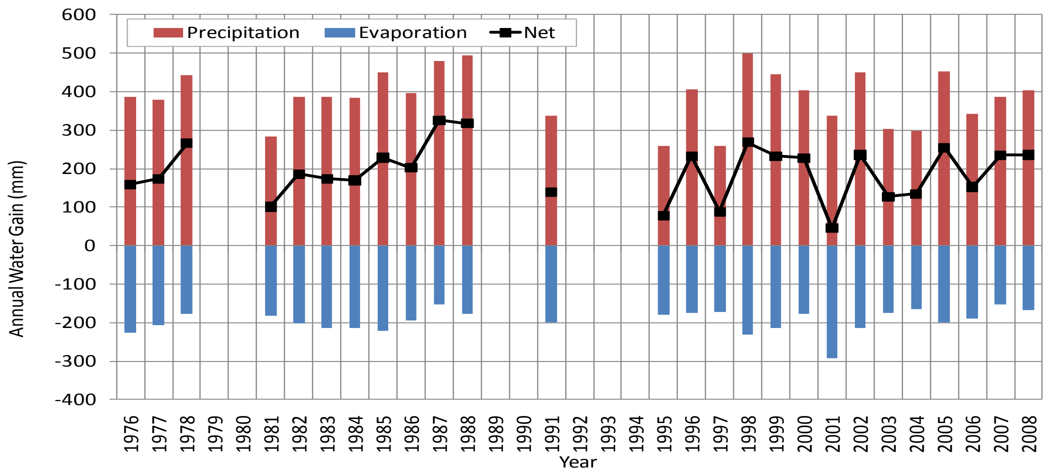


Figure 6: Precipitation, evaporation and net values for each water year using Baker Lake climate station data.

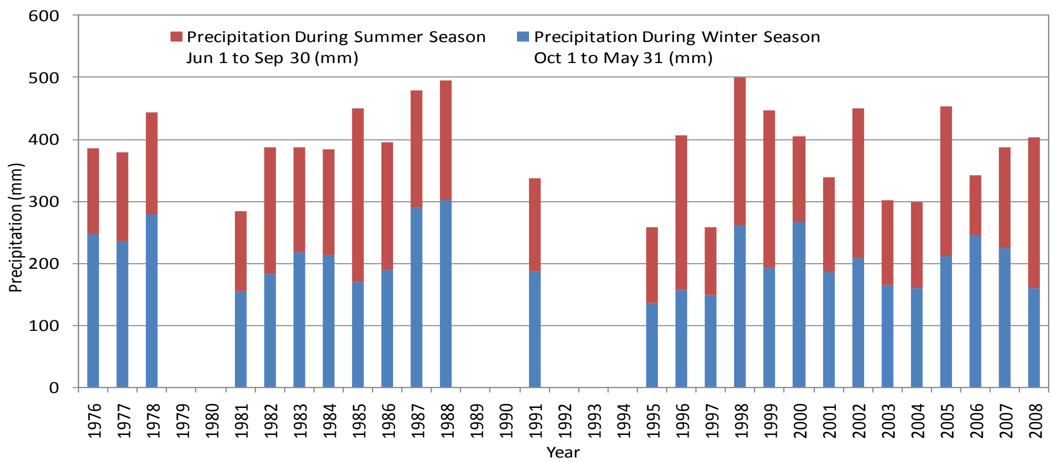


Figure 7: Precipitation divided into summer and winter seasons.

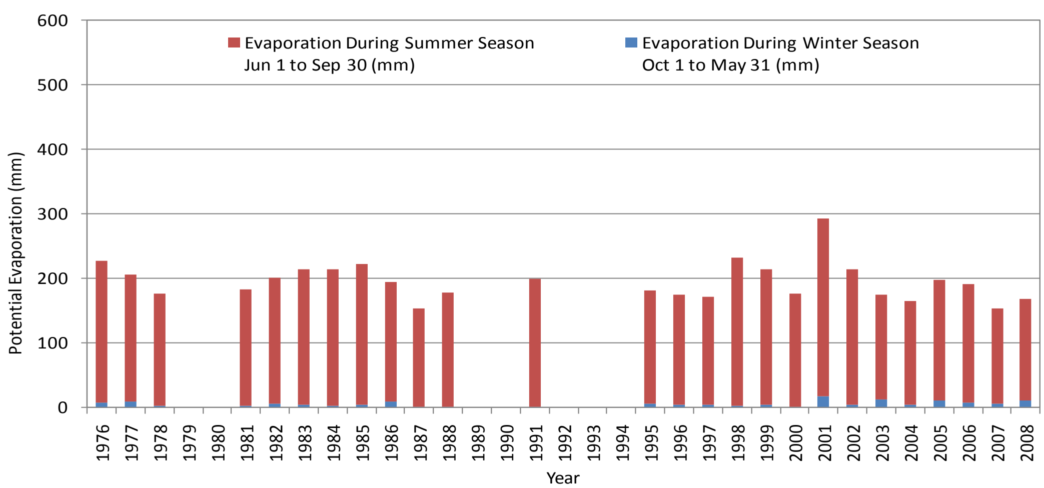


Figure 8: Evaporation divided in to summer and winter seasons.

5.0 SELECTION OF YEARS TO REPRESENT AVERAGE, DRY AND WET CONDITIONS

Representative conditions were based on calendar year precipitation data. The average, wet and dry representative years were determined to be 2002, 1999 and 2004, with total precipitation amounts of 387 mm, 530 mm and 263 mm, respectively. For each representative year, plots were created for each climate element. Figures 9 to 11 show the daily and accumulative precipitation for the average, wet and dry years. Similar graphs were created for evaporation, air temperature, relative humidity, and wind speed, as shown in Figure 12 to 23.

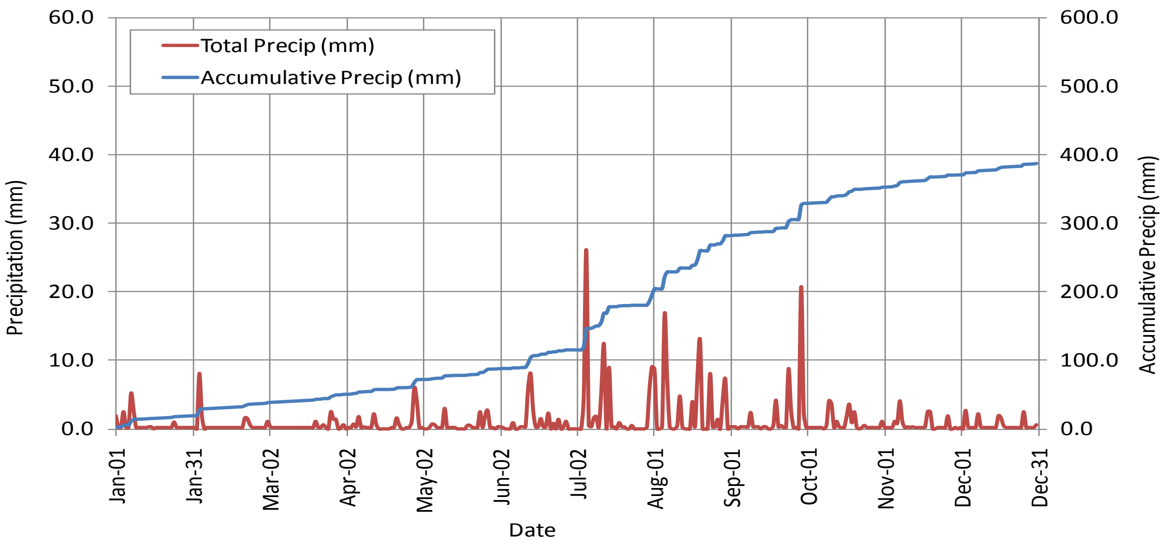


Figure 9: Daily precipitation for 2002 representing an average year.

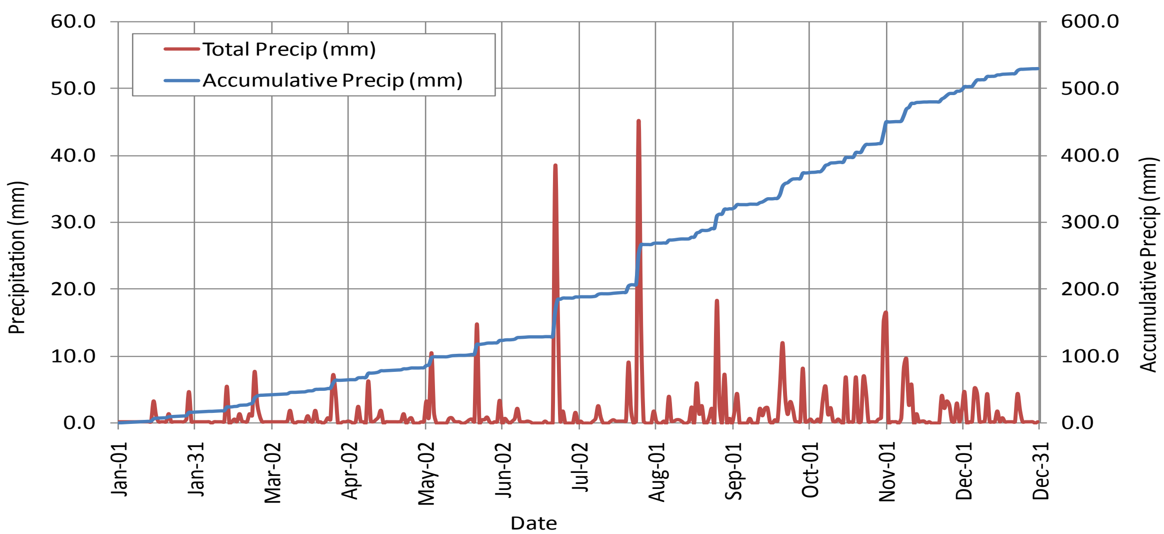


Figure 10: Daily precipitation for 1999 representing a wet year.

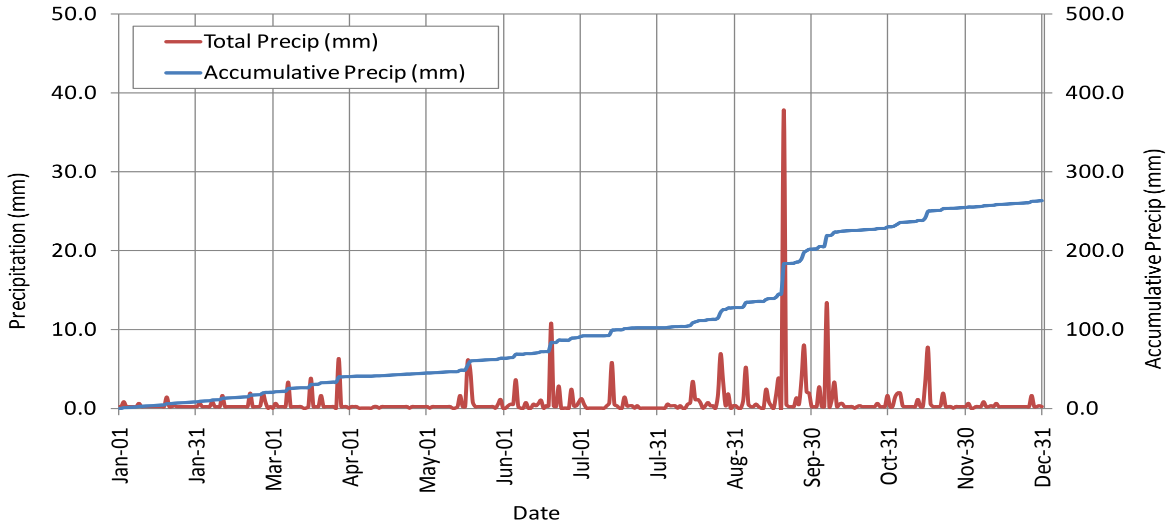


Figure 11: Daily precipitation for 2004 representing a dry year.

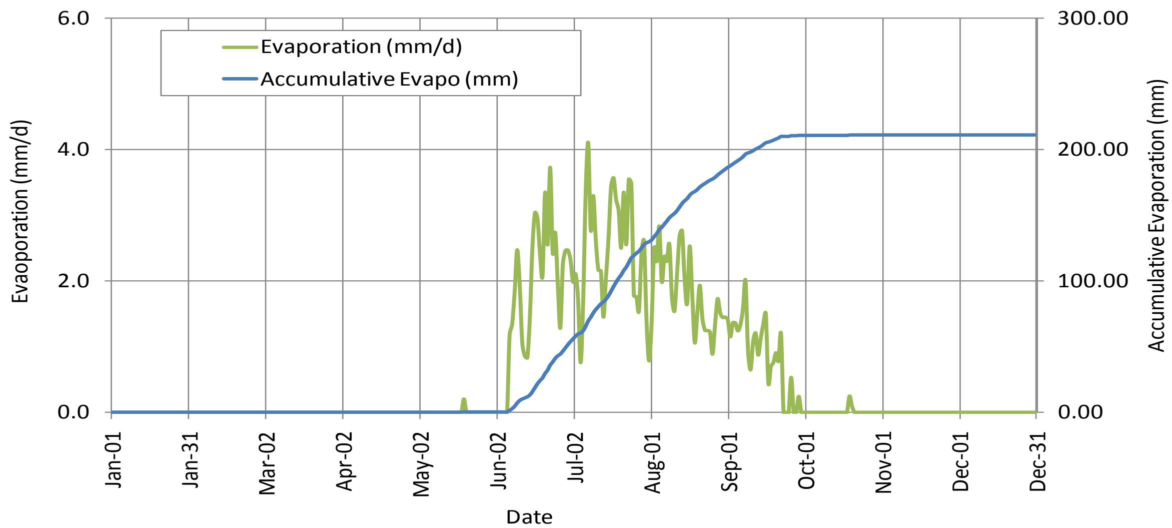


Figure 12: Daily evaporation for 2002 representing an average year.

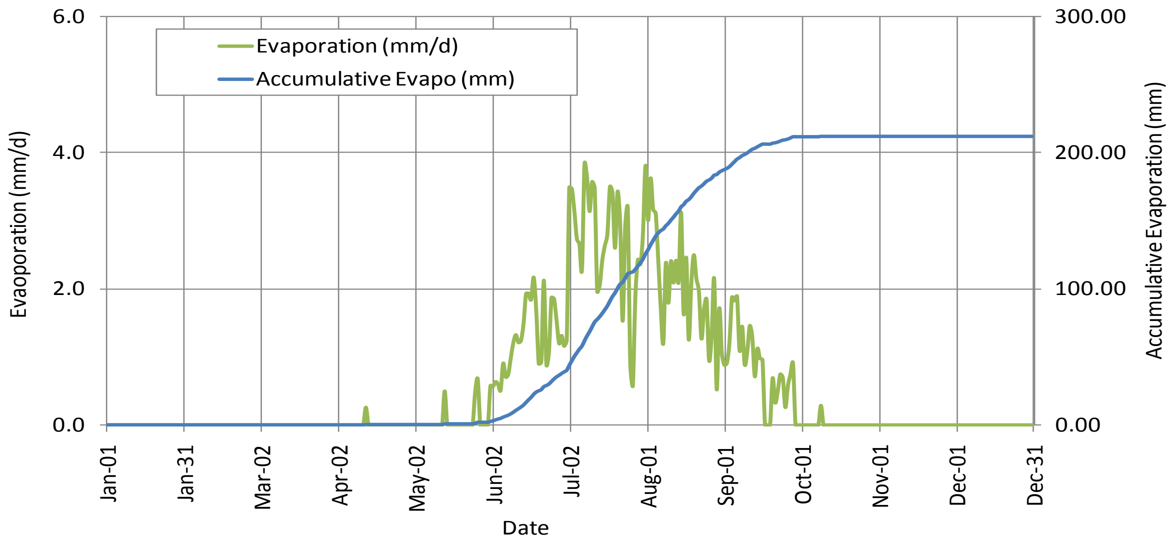


Figure 13: Daily evaporation for 1999 representing a wet year.

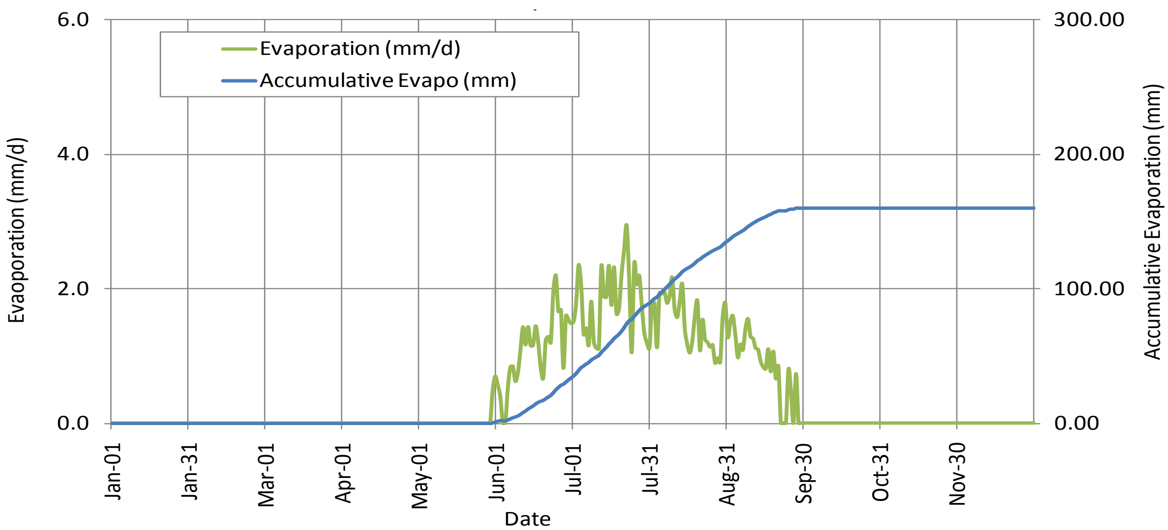


Figure 14: Daily evaporation for 2004 representing a dry year.

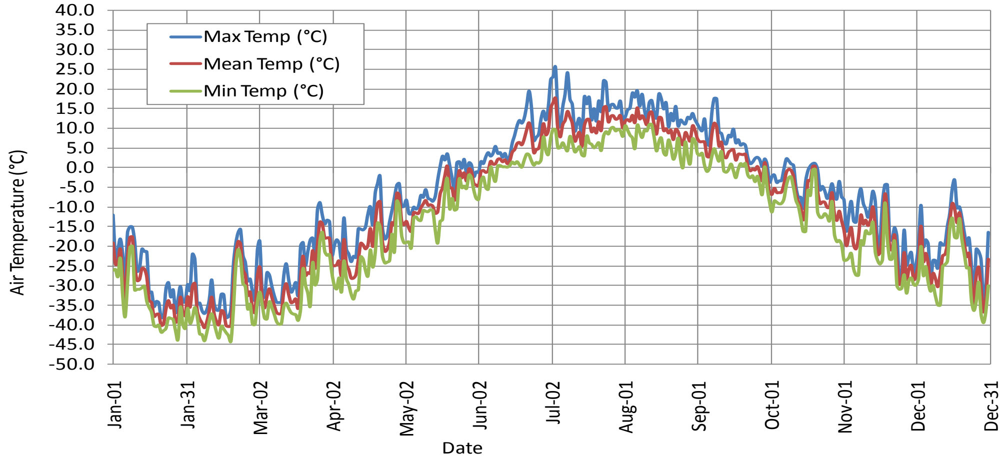


Figure 15: Daily temperature for 2002 representing an average year.

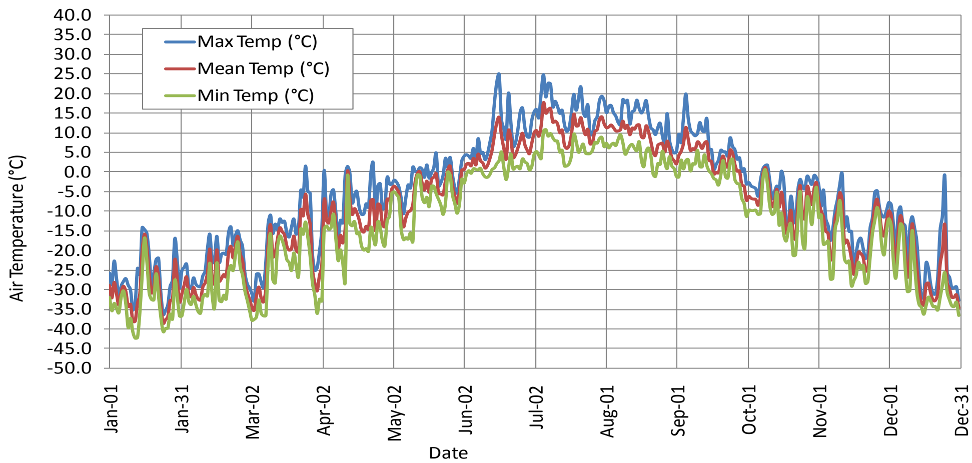


Figure 16: Daily temperature for 1999 representing a wet year.

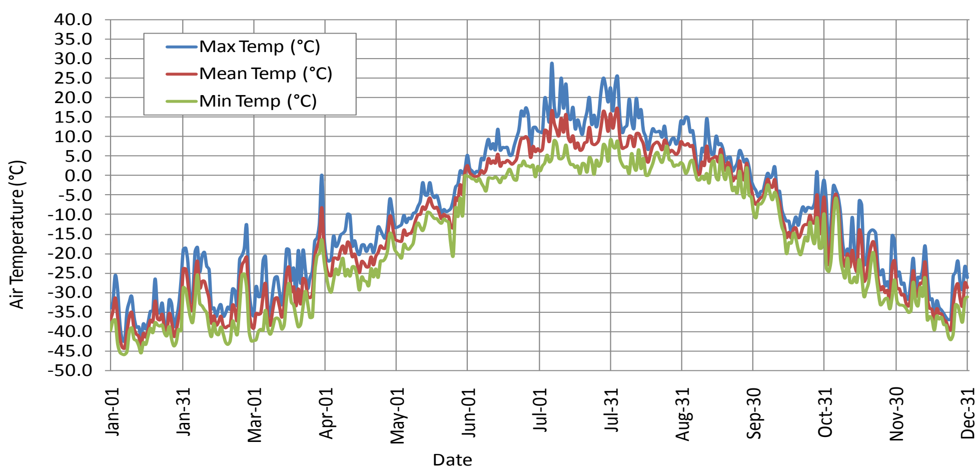


Figure 17: Daily temperature for 2004 representing a dry year.

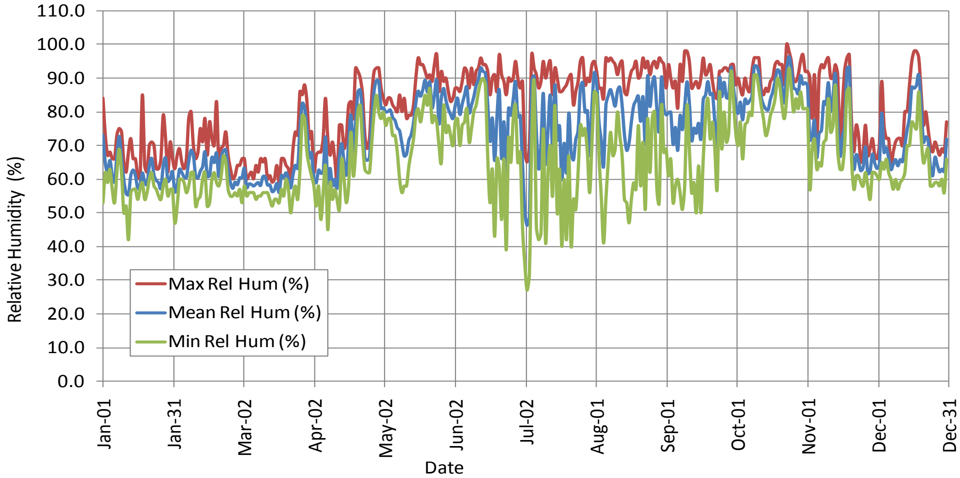


Figure 18: Daily relative humidity for 2002 representing an average year.

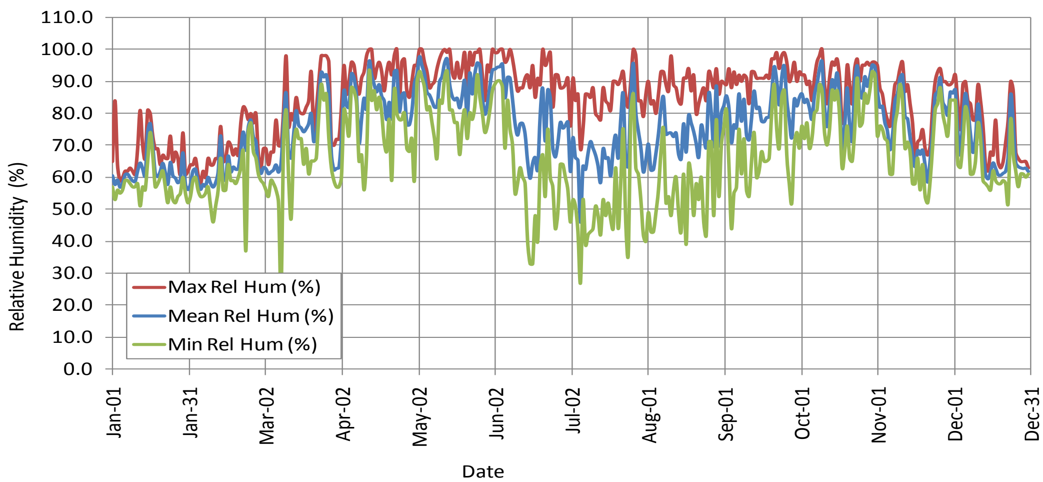


Figure 19: Daily relative humidity for 1999 representing a wet year.

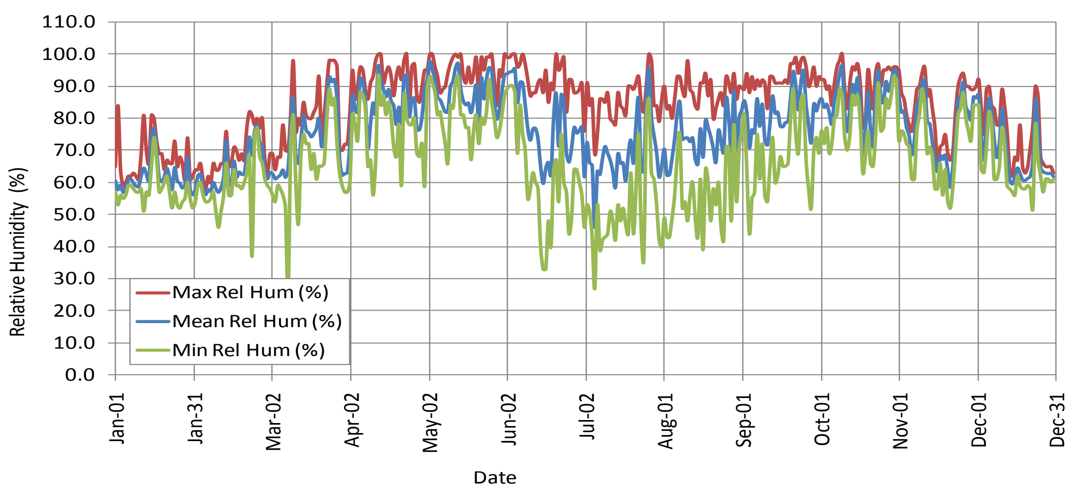


Figure 20: Daily relative humidity for 2004 representing a dry year.

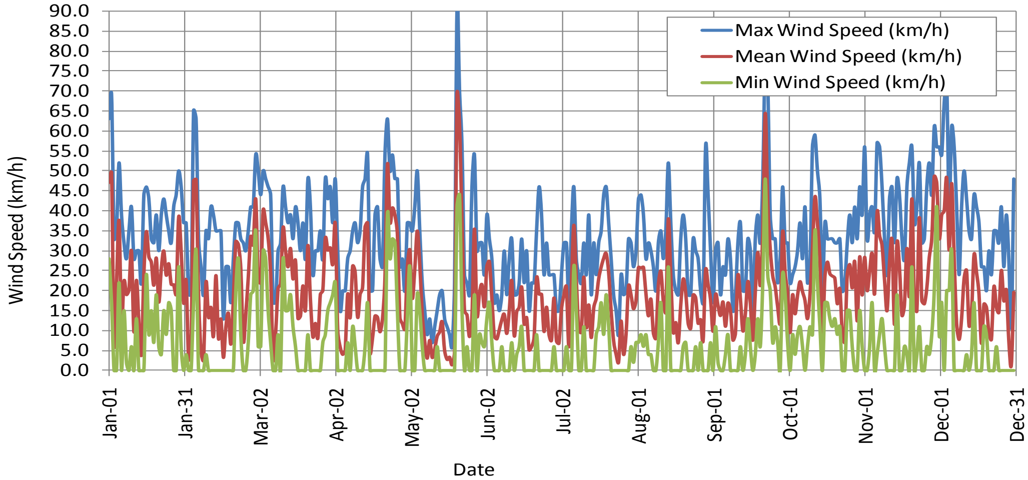


Figure 21: Daily wind speed for 2002 representing an average year.

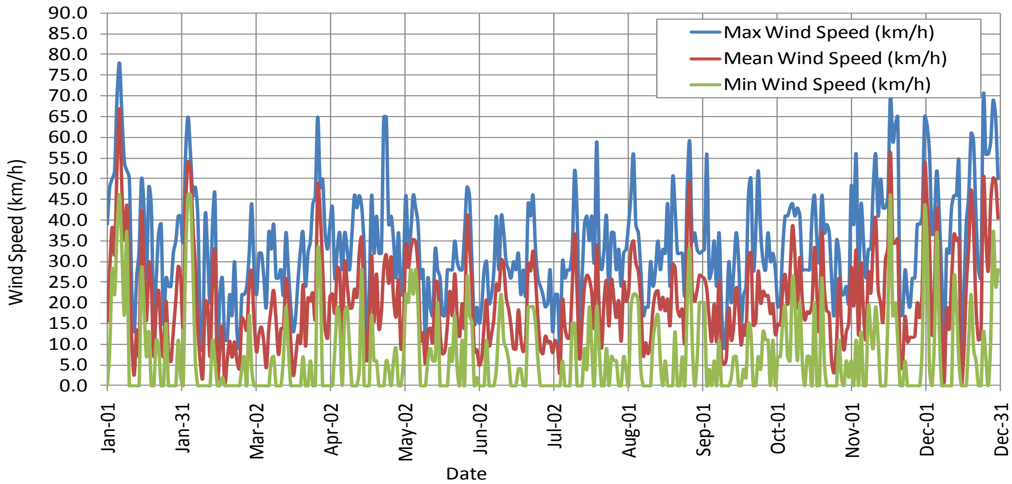


Figure 22: Daily wind speed for 1999 representing a wet year.

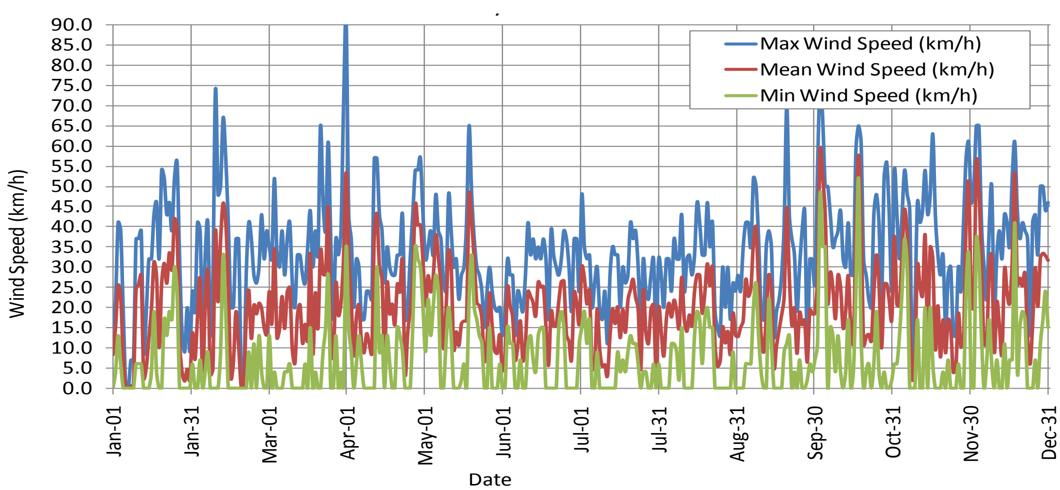


Figure 23: Daily wind speed for 2004 representing a dry year.

6.0 MEAN CLIMATIC YEAR

A mean climatic year is helpful to determine initial conditions for some models. The mean climatic year was created by averaging each daily value for each climate element using the 30 years of record. In other words, each climate element on January 1 of the mean climatic year was found by averaging January 1, 1975; January 1, 1976; January 1, 1977; until January 1, 2008. Similar to average, wet and dry representative years, plots were created for each climate element. Figures 24 to 29 show the precipitation, evaporation, air temperature, relative humidity, wind speed, and net radiation for the mean climatic year.

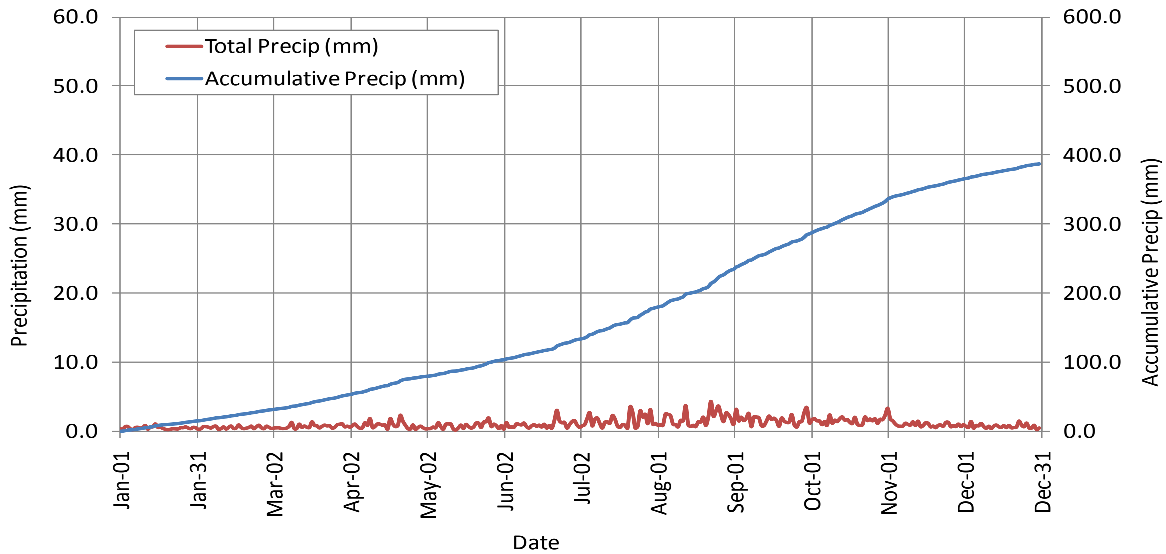


Figure 24: Daily precipitation for mean climatic year.

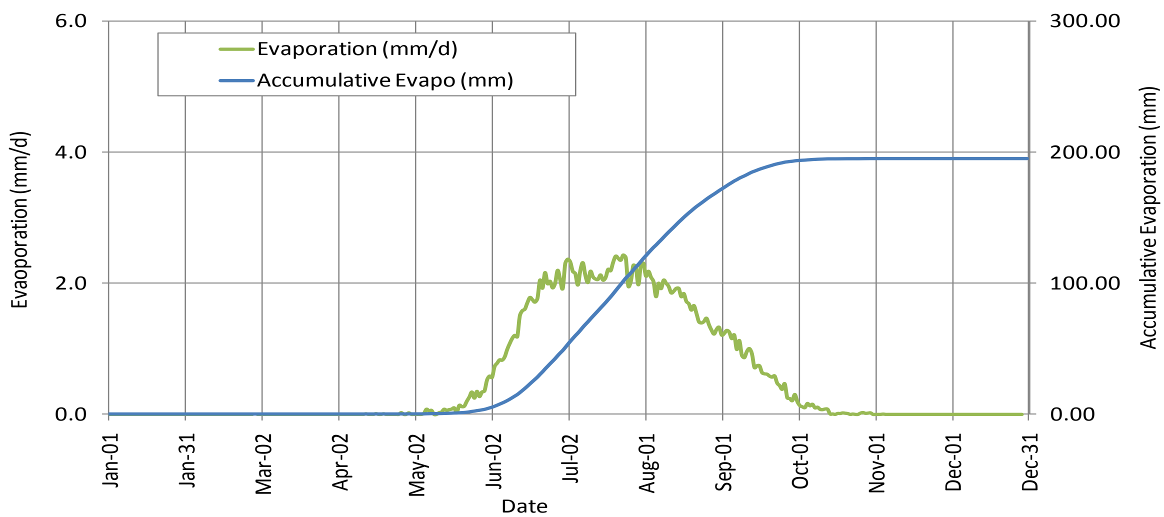


Figure 25: Daily evaporation for mean climatic year.

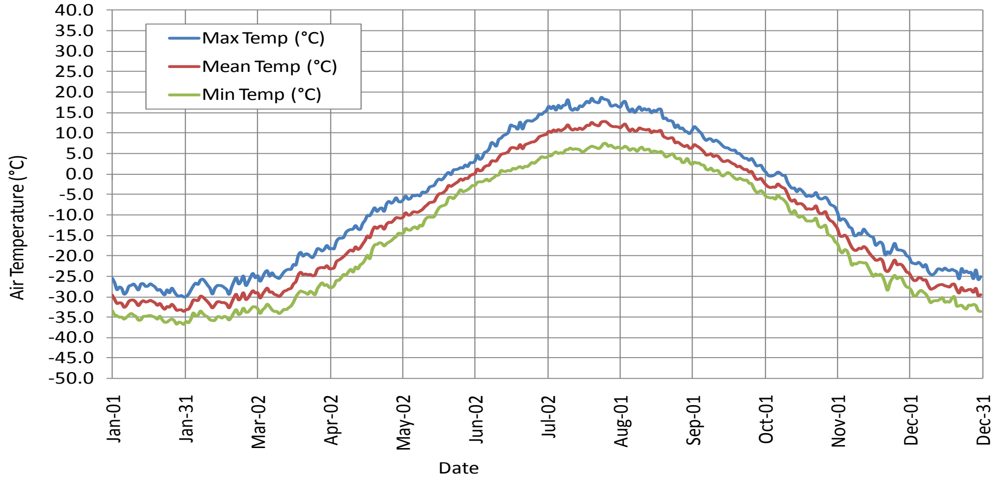


Figure 26: Daily temperature for mean climatic year.

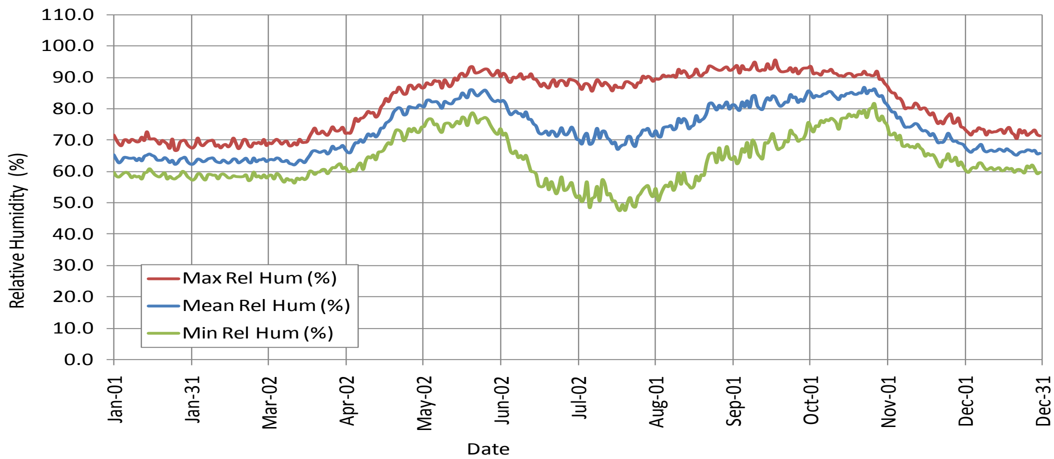


Figure 27: Daily relative humidity for mean climatic year.

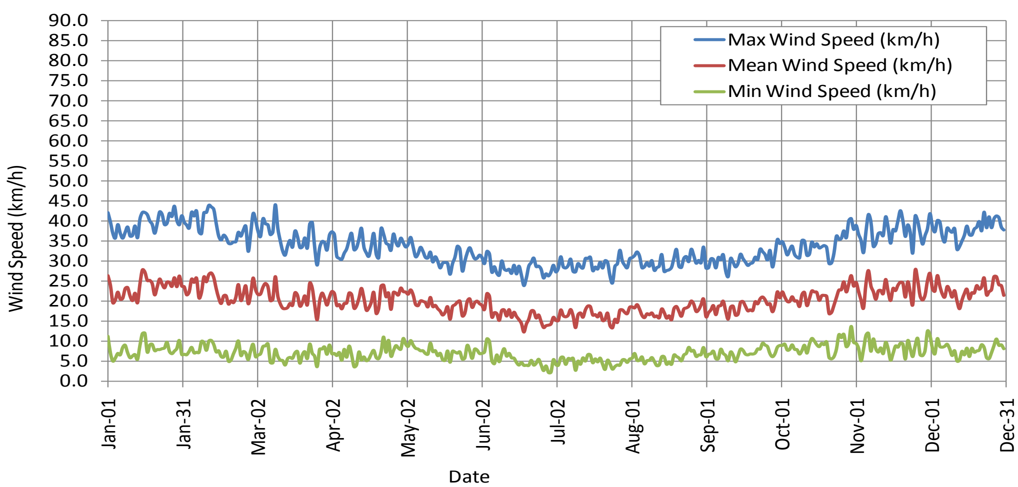


Figure 28: Daily wind speed for mean climatic year.

Figure 29: Daily net radiation for mean climatic year.

7.0 WIND SNOW REDISTRIBUTION

7.1 Wind Transport

Wind has a large effect in the evolution and distribution of the snow, especially in open environments. When the snow is transported by wind there is an effect in its physical properties, such as crystal shapes and sizes. Wind transport studies have focused more on the redistribution of snow, and the effect of this redistribution is spatial variability in snow water equivalent rather than in the loss of water by sublimation that occurs during the movement (Pomeroy and Gray 1995).

The mechanisms that involve the transport of snow by wind can be summarized by three main methods, i.e., creep, saltation and suspension. Creep is defined as the movement of heavier particles by rolling along the surface and this process normally accounts for a very small part of the total wind snow transport. Saltation is the movement of particles by jumping along the snow surface; a typical jump could be 1 cm high and 20 cm long and the maximum trajectory is in the range from few millimetres to 5 cm. Suspension accounts for the particles that are moved in suspended flow at a mean horizontal velocity close to that of the moving air (Maidment 1992, Pomeroy and Gray 1995).

Comprehensive research studies have investigated the physical process associated with snow transport by all of the three methods (Pomeroy 1988, Pomeroy and Gray 1990, Tabler et al. 1990, Pomeroy and Gray 1995, Pomeroy et al. 1997, Déry 2001, and Déry and Yau 2001). Pomeroy and Gray 1995 provide a summary of the main physical process associated with snow wind transport and they also present simple expressions developed in past studies for calculating rate of blowing snow by saltation, suspension, and the total (combined saltation and suspension) as a function of the air velocity under the assumption of a flat non-vegetated land surfaces with complete snow cover (Table 4).

Table 4: Expression for calculating the transport of rate of blowing snow (kg/m/s) perpendicular to the wind speed (m/s) for the specified range of height

Equation, q in (kg/m.s) and , u_{10} in m/s	Height (m)	Reference
$q_{salt} = u_{10}^{1.295} - \frac{1}{17.37\, u_{10}^{1.295}}$		Pomeroy and Gray 1990
$q_{susp} = \frac{u_{10}^{4.13}}{674000}$	5	Tabler et al. 1990
$q_t = 0.0000022\, u_{10}^{4.04}$	0 - 5	Pomeroy et al. 1991

Source: Pomeroy and Gray 1995

For equations in Table 4, $q_{salt},\ q_{susp}\ and\ q_t$ are the transport rate for saltation, suspension and total (saltation plus suspension) respectively in (kg/s) per metre of width perpendicular to the wind, and u_{10} is the wind speed at a height of 10 metres in (m/s). These equations apply for wind speeds equal to or larger than 6.5 m/s.

Pomeroy and Gray (1995) also developed practical empirical expressions for evaluating monthly total transport (saltation plus suspension) and sublimation as a function of the monthly climate data that are collected at the stations of the Atmospheric Environment Service (AES) of Canada. The empirical expressions were obtained by statistical regression using information from AES stations in the Canadian Prairies and suitable for crop stubble and fallow land under the assumption of a 1 km fetch length. The expressions for fallow land are as follows:

$$t_{trans(m)} = -14.33 + 2.26\, u_{10} - 0.25\, T_{max} + 0.046\, RH_{max} + 0.079\, S_{max}$$

$$sub_{(m)} = 7.21 + 1.76\, u_{10} - 0.16\, T_{max} - 0.18\, RH_{max} + 0.19\, S_{max}$$

Where:

$t_{trans(m)}$:	mean monthly snow transport, (mm of snow water equivalent)
$sub_{(m)}$:	mean monthly sublimation, (mm of snow water equivalent)
u_{10}:	mean monthly wind speed at 10 m height, (m/s)
T_{max}:	monthly mean of daily maximum air temperature, (°C)
T_{min}:	monthly mean of daily minimum air temperature, (°C)
RH_{max}:	monthly mean of daily maximum relative humidity, (%)
RH_{min}:	monthly mean of daily minimum relative humidity, (%)
S_m:	mean monthly snowfall (mm of snow water equivalent)

These equations, suitable for the Canadian Prairies, assume a direct relationship between blowing snow fluxes and wind speed while the relationship with the temperature is inversely related. Though the relationship between temperature and sublimation rate for an ice sphere is directly related, the inverse relationship in the empirical prairie expressions could be explained by the large number of hours of blowing snow that occurs during the winter in the region.

7.2 Topographic and Mechanical Barriers

Topographical and mechanical barriers play a large role in snow drift formation by wind. Some work has been done for estimating snow drifts formed by topographic features and those formed by mechanical barriers such as fences, shelterbelts and snow ridging (e.g., Tabler and Schmit 1986, Tabler et al. 1990). Specifically, for mechanical barriers, the drifts grow until reaching the equilibrium state and the maximum growth is a function of the length, height and the porosity of the barriers. In general the dimensions of the drift are a function of the barrier height, providing that the barrier is of sufficient length (i.e., more than 30 times the height). Once the snow drift reaches its equilibrium, the capacity of the barrier for trapping snow tends to zero (Pomeroy and Gray 1995).

For a solid fence, the drift length once the equilibrium is reached is approximately 24 times the height of the fence (24h) equally divided between the windward and leeward sides (12h each). The volume of the snow in the drift can be approximated as 3 times $h^{2.2}$ in cubic metres per metre of fence (m^3/m) with h in metres (m) (Tabler et al. 1990).

8.0 HYDROLOGY OF MINE WASTE ROCK PILES IN THE ARCTIC

A summary of hydrologic studies of mine waste rock piles located in the Arctic and mine waste rock piles located in the Sub-arctic were reviewed. Ongoing studies are in Diavik, Ekati, Cluff Lake and Cliff Lake. Unfortunately none of these studies have undertaken surveys of snow redistribution by wind surrounding piles and on the piles (top and slopes) but qualitatively the studies have shown that wind plays an large role in the redistribution of the snow at the top and slopes of the piles (Golder Technical memorandum: Hydrology of Waste Rock Piles in Cold Climates, Oct 2010).

Quantitative results from a comprehensive research program at Diavik have indicated, based on results from 2006 and 2007, that snow depth prior to melt had been from 0 cm to 5 cm at top of pile while the piles slopes were accumulating approximately 150 cm (Neuner 2009). This study does not highlight differences between the windward and leeward slopes of the piles. Taking into account that the annual snowfall in millimetres of snow water equivalent at Diavik is approximately 187 mm, these results are an indication that the snowfall at the top of the piles is transported downwind likely to the leeward slope of the pile while the windward slope trap snow until a drift in equilibrium is formed. Similarly, the leeward slope will also trap snow until a drift is in equilibrium is formed.

8.1 Wind Snow Transport at Kiggavik

The Project is located 80 km west of Baker Lake, Nunavut, in a region of continuous permafrost with a mean annual temperature of approximately -12°C (1946 to 2008; Environment Canada). Mean annual precipitation at Baker Lake is 344 mm, of which 175 mm is snowfall.

Climate variables at Diavik are comparable with climate variables at Baker Lake (Table 5). Consequently the findings from the hydrology studies at Diavik are reasonably representative for the Project, i.e., it will be expected that future waste rock piles at the Project will have large proportion of snow transported from the top to the leeward slopes of the piles, but there will not likely be large differences between the snow deposited in the windward and leeward slopes. The explanation of this could be the topographic characteristic surrounding the piles, which is basically a flat, tundra non-vegetated land surface where the only major topography feature is the pile. It means that most of the blowing snow from the land on the site of the windward slope will deposit on that slope forming a drift that eventually will reach the equilibrium while the snow from the top will be transported to the leeward side and farther when the drift formed on that slope reaches equilibrium. The fetch for the blowing snow at the top is the average width of the pile top perpendicular to the dominant wind direction.

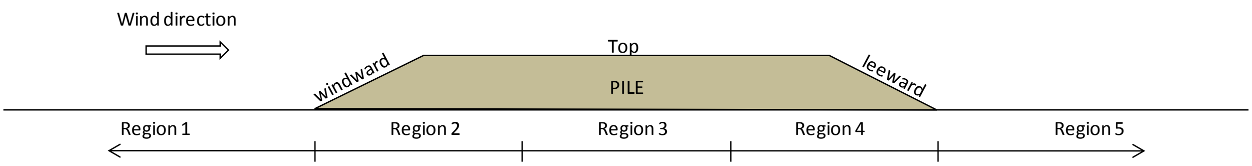
Table 5: Relevant Climate variables for Diavik and Baker Lake

Parameter	Baker Lake	Diavik
Temperature (ºC)	-12 (1946 – 2008)	-11 (1959 – 2006)
Rainfall (mm)	169	184
Snowfall water equivalent (mm)	175	177

8.2 Estimation of Wind Snow Transport at Kiggavik Piles

A preliminary estimation of the snow transport at the waste rock piles is undertaken by using the expression for the total transport rate of blowing snow (kg/m/s) developed by Pomeroy et al. 1991 (Table 4), while an approximate estimation of sublimation is undertaken using the monthly empirical equation developed for the prairies. Though these expressions were developed for areas warmer than Project area, some of the assumptions used in its development compares well with the expected conditions at the Project site, i.e., a flat non-vegetated land surfaces with complete snow cover can be assimilated with the land surrounding the piles and with the top of the piles.

The expected situation in full developed waste rock pile at Kiggavik is presented in the figure below, i.e.:



The surrounding land where the waste rock piles are can be divided in five regions for the purposes of the snow wind transport, i.e.:

Region 1: relative flat land on the windward side with a large fetch (larger than 500 m), i.e., open snow blowing zone.

Region 2: windward slope (3H: 1V) with likely depositional effects and blowing snow from Region 1.

Region 3: top of the waste rock pile relatively horizontal and with a fetch equal to the average width of the pile (500 m). Eventually, this region will have blowing snow from region 2 once the deposition on that region reaches the equilibrium.

Region 4: leeward slope (3H: 1V) with likely depositional effects and open blowing snow from region 3.

Region 5: relative flat land on the leeward side with a large fetch (larger than 500 m). Eventually, this region will have blowing snow from the pile once the deposition on Region 4 reaches the equilibrium. Open snow blowing zone far from the leeward side.

Data

Daily climate for the period 1953 to 2009 from Baker Lake has been used for this assessment. As it was mentioned in a previous section, Baker Lake is approximately 80 km east of the Project with comparable climate variables. For the purposes of defining the fetch at the site the most frequent monthly wind directions are used (Table 6).

Table 6: Monthly Wind Speed and Direction Baker Lake

Month	Wind Speed (km/h)	Most Frequent Direction
January	23.7	NW
February	22.9	NW
March	21.6	NW
April	20.5	NW
May	19.4	NW
June	16.5	E
July	16.6	N
August	17.7	NW
September	19.4	NW
October	21.8	NW
November	22.3	NW
December	22.7	NW
Annual	20.4	NW

Source: Environment Canada

Assumptions

- The slopes of the piles (windward and leeward) are assumed to be similar to a solid fence which has partially developed a snowdrift equivalent to the 3H:1V sideslopes. The studies that have been undertaken for modeling snow trapped for a fence have assumed fences are perpendicular to the wind velocity. For the relatively flat terrain surrounding the waste rock piles at the Kiggavik site, it is reasonable to consider a horizontal wind. Consequently, the triangle formed between the vertical from the toe to the top and the slope of the pile, can be considered similar to the initial drift formation forced by a vertical solid fence. Snow deposition in the slopes will continue until reaching the drift size in equilibrium as a function of the pile height.

- Deposition on both slopes will stop once the volume of the material underlying the slope (pile material plus snow) reaches the drift equilibrium volume. For simplicity, the volume is considered equally distributed on both slopes.

- The affect of site infrastructure including snow fences, buildings and open pits which occur generally on the windward side of the two clean waste rock piles at the Kiggavik site has not been considered in this assessment. It is understood that snow management controls are planned (fences) to be located at the north and west side of the core facilities area to reduce the accumulations of blowing snow. These snow controls will likely intercept some of the blowing snow from the northwest (Region 1 in the previous sketch) reducing the amount of snow reaching the waste rock piles. Consequently the windward slope will accumulate mainly local snowfall and may eventually develop a drift in equilibrium, but it will not be a main source for blowing snow to reach the top of the piles

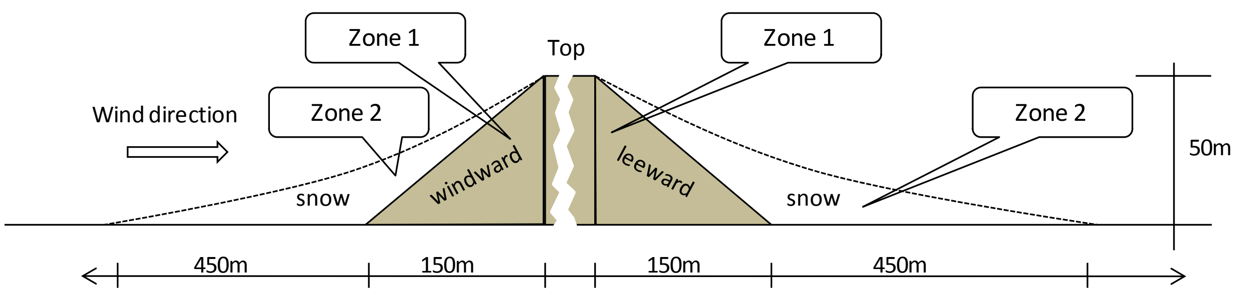
- Snow accumulation on the windward side is equal to the snowfall plus the snow transported from the windward side under the assumption of a fetch length equal to 1000 m. The snow drift to be formed at the windward side is assumed to have a length of approximately twelve times the height of the pile.

- Snow on the top of the pile (Region 3) is equal to the snowfall minus the snow lost from transport and sublimation.
- Snow on the leeward is equal to the snowfall plus the snow transport from Region 3. The snow drift formed on the leeward is assumed to have a length of approximately twelve times the height of the pile.
- The wind will reach the piles from the northwest and consequently the fetch for the top of the piles will be variable but on average, is assumed to be between 500 m and 1000 m.
- Data collected at Baker Lake climate station is considered representative for applying at the top of the piles.

9.0 RESULTS

The following results provide an estimate of the amount of snow remaining on the waste rock pile surface prior to the spring snowmelt period. In this assessment the height of the waste rock piles is assumed to be 50 m and the length of the pile is assumed to be 30 times the height or larger. Maximum length of the drifts formed at the windward and leeward slopes is assumed to be 12 times the height of the piles, i.e., 600 m from the edge of the pile crest.

The maximum snow volume that can be trapped on the pile slopes, under the assumption of a solid vertical barrier, could be evaluated as 3 times $h^{2.2}$ in cubic metres per metre of pile (m^3/m) length with the height of the pile, h, in metres. This volume includes the volume of the pile slope measured with respect to the vertical at the edge of the pile crest. For simplicity, the volume is considered equally distributed on both slopes.



According to the above sketch:

- Zone 1: Volume of each slope pile. Assuming a slope gradient is defined by 3H: 1V, the volume per metre is 3,750 m^3/m.
- Zone 1 and Zone 2: Maximum volume per metre required to form a drift in equilibrium in both slopes. This volume is equal to $3h^{2.2}$, i.e., 16,400 m^3/m. Consequently, the maximum volume at each slope is equal to 8,200 m^3/m.
- Zone 2: Remnant volume to potentially fill with snow at each slope. This volume is equal to the difference between the maximum volume at the slope for having a drift in equilibrium (8,200 m^3/m) minus the volume already filled by the slope pile (3,750 m^3/m) which is equal to is 4,450 m^3/m.

9.1 Remnant Snow on the Top of the Piles Prior to the Snowmelt Period

The expected blowing snow is evaluated based on Baker Lake historical climate data from 1953 to 2008 using the following procedure:

Step 1: Using the empirical expressions for evaluating monthly total transport and sublimation as a function of climate variables (Pomeroy and Gray 1995), a monthly ratio between sublimation and snow transport is estimated.

Step 2: By using the expression developed by Pomeroy et al. (1991) presented in Table 4, the historical total snow transport is estimated on a daily basis for the period 1953 to 2008. Then sublimation is estimated on daily basis as a function of the daily total transport using the ratio obtained in Step 1. The fetch for estimating the transported snow in millimetres of snow water equivalent is 500 m.

Step 3: A simulation is undertaken applying the total snow loss (total transport plus sublimation) to the historical snowfall from 1953 to 2008. Snow is blown and sublimated depending of the snow availability. If the potential loss in a day is less than the snow availability, the remnant snow is accumulated for the next day. If the potential loss is greater than the snow availability then the remnant snow is zero.

Remnant snow at the end of the winter months expressed in percentiles obtained from results of the simulation to the historical period (1953 to 2008) are presented in Table 7. For example, for the last day of May,75% of the years analyzed had a remnant snow water equivalent of 0.48 mm or less, 90% had 3.15 mm or less and 95% of the year had 12.34 mm or less.

Table 7: Remnant Snow at the last day of each winter month in (mm) of snow water equivalent

Percentile	October	November	December	January	February	March	April	May	June
5	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0
50	0.99	0.1	0.2	0.4	0.2	0.4	0	0.2	0
75	7.40	1.73	0.87	0.95	1.69	2.22	1.81	0.48	0.05
90	13.82	5.97	4.22	4.28	6.56	6.44	11.33	3.15	7.27
95	18.50	11.91	6.36	6.06	13.08	7.80	15.43	12.34	11.84

In conclusion, the results provided in Table 7 indicate that the expected amount of snow on the top of the waste rock piles prior to the snowmelt at the Project site, which typically occurs in late May or early June will be close to zero for average winters (percentile 50), zero for dry winters (percentile 25) and less than 5 mm for wet winters (percentile 75).

9.2 Accumulated Snow on the Slopes of the Piles Prior to the Snowmelt Period

The accumulation of snow on the windward side is estimated based on the following procedure:

Step 1: It is assumed that the windward side is open for blowing snow with a fetch of 1000 m, i.e., open tundra. Consequently the snow sources for the windward slope are the snowfall plus the snow transported from the windward region.

Step 2: By using the expression developed by Pomeroy et al. (1991) presented in Table 4, the historical total snow transport is estimated on a daily basis for the period 1953 to 2008.

Step 4: A simulation is undertaken by applying the potential total transport of snow to the historical snowfall from 1953 to 2008. No simulation for sublimation is required because the sublimation loss does not contribute to the snow deposited on the slope. Snow is transported depending of the snow availability. If the potential transport in a day is less than the snow availability, the remnant snow is accumulated for potential transport the next day. Alternatively if the potential transport exceeds snow availability then the remnant snow is zero.

Step 5: No losses for sublimation are considered from the windward.

The accumulation of snow on the leeward slope is estimated using the same procedure used for the windward slope. In this case the snow transported to the slope comes from the top of the pile; therefore the fetch is 500m.

Accumulated snow at the end of the winter months is expressed in percentiles obtained from results of the simulation over the historical period (1953 to 2008), and are presented in Table 8 for both slopes. At the end of May, 75 percent (75%) of the years analyzed had an amount of snow on the windward slope equal to 381 mm of SWE while the leeward had 401 mm of SWE.

Table 8: Trapped Snow on the windward and leeward slopes in (mm) of snow water equivalent

Percentile	Windward Slope		Leeward Slope	
	May	June	May	June
5	165	169	165	169
10	210	215	213	219
25	254	263	257	269
50	299	309	307	331
75	381	387	401	407
90	431	450	489	491
95	483	501	510	537

The expected amount of snow on the slope of the waste rock piles before snowmelt at the end of May will be less than 307 mm for average winters (percentile 50), less than 257 mm for dry winters (percentile 25) and less than 401 mm for wet winters (percentile 75). Note that if these amounts exceed the maximum equilibrium volume, the amount trapped will be the maximum volume.

Report Signature Page

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