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Mt Nansen Mine Site
Melt Estimates
for a
Man-made Snowpack

Prepared for

G. J. Bull & Associates

Prepared by

Soilcon Laboratories Ltd.

January 7, 2000

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Mr. Greg Bull
c/o Yukon Engineering Services
#1 - 151 Industrial Road
Whitehorse, Yukon Y1A 2V3

Dear Mr. Bull:

Melt Estimates for a Proposed Made-made Snow Pack at Mt. Nansen City Yukon

Soilcon Laboratories Ltd. is pleased to provide the climate based estimate of the speed of melting of a man-made snow pack which might be construct at Mt. Nansen mine site, Yukon. Estimates are provided for three possible locations, a flat site, a 10^{o} (18%) south-facing slop and a north-facing 10^{o} (18%) slope. The north-facing slope is favored above the flat and south-facing slopes.

There are preliminary estimates only. Recommendations are made to improve the data available upon which the estimates are based.

Please call with any questions or comments.

Yours truly,

Michael Goldstein, M.Sc., P.Ag.
President

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E	*evapotranspiration rate*	*mm/day*
s	*slope of saturation mole fraction function*	C^{-1}
Rn	*net radiation*	W/m^2
G	*soil heat flux*	W/m^2
$\gamma*$	*apparent psychrometric constant*	*C-1*
λ	*latent heat of vapourization*	*J/mol*
g_v	*conductance for vapour*	$mol\ m^{-2}s^{-1}$
D	*vapour deficit of air*	*kpa*
p_a	*atmospheric pressure*	*kpa*
L	*latent heat of vapourization*	*J/kg*
α	*Priestly and Taylor constant*	*unitless*
α_s	*absorptivity for radiation*	*unitless*
$K\downarrow$	*incoming short-wave radiation*	W/m^2
$L*$	*net long-wave radiation*	W/m^2
Ta	*mean daily air temperature*	*C*
Ta_{max}	*maximum daily air temperature*	*C*
ε_a	*emissivity of air*	*unitless*
ε_s	*emissivity of surface*	*unitless*
u	*horizontal windspeed*	*m/s*
h_r	*relative humidity*	*unitless*
A	*elevation*	*m*
m	*mass of a single ice particle*	*g*
t	*time*	*s*
r	*radius of ice particle*	*m*
σ	*water vapour deficit with respect to ice*	
Q_s	*short-wave radiation adsorbed by ice particle*	W/m^2
λ_T	*thermal conductivity of atmosphere*	$Jm^{-1}\ s^{-1}\ K^{-1}$
Nu	*Nusselt Number*	*unitless*
h_s	*latent heat of sublimation*	*J/kg*
M	*molecular weight of water*	*kg/kmole*
R	*universal gas constant*	*J/kmoleK*
D_w	*diffusivity of water vapour*	m^2/s
ρ_s	*saturation density of water vapour*	*kg.m3*
Sh	*Sherwood Number*	*unitless*
E_s	*sublimation rate*	*mm/month*
h	*height*	*m*
F_d	*fetch distance*	*m*
u_{10}	*mean monthly wind speed at 10 m*	*m/s*
T_{max}	*monthly mean of daily maximum air temperature*	*C*
RH_{max}	*monthly mean of daily maximum relative humidity*	*%*
P_m	*mean monthly snowfall*	*mm water equiv.*
d	*mean monthly snow depth*	*mm water equiv.*

Introduction

Mr. Greg Bull, P.Eng. of G. J. Bull & Associates requested a estimate of melting rates of snow from a man-made snowpack located in Mt. Nansen mine site, Yukon. The speed of melt is important as the snowpack is being used to store and treat tailings water that might otherwise enter a fisheries stream. The estimates are first-cut, “arm chair” estimates for this feasibility phase. Recommendations are made for the work required to improve these estimates and complete an annual water balance.

General Approach

The melt of a snowpack is determined by an energy balance of the snow pack. That is the amount of energy entering and leaving the snow pack. The energy balance of the snowpack is complicated by phase changes within the pack. (freezing, melting, sublimation evaporation and condensation). For example, if rainwater falls on snow and freezes it releases the latent heat of fusion.

At this feasibility stage, we make several simplifying assumptions. Recommendations are made for monitoring the actual snow pack. The collected data will allow much more accurate predictions of man-made snow pack melt rates to be made in the future.

We assume that the there is no horizontal energy flow. This would be true for an extensive flat surface, but a man-made snow pack may have horizontal energy flows. The second assumption is that the snow equilibrates quickly and can be treated as a single block. This may be more true of man-made snow than natural snow due to the higher density of the snow. The third assumption is that heat conduction to the soil is minimal. This is a safe assumption in this northern environment. The energy balance becomes (Oke 1996)

Equation 1

$$R_n + Q_R = H + LE + \Delta S \quad + \Delta Q_M$$

where Rn is net radiation, Q_R is the energy exchange due to rainfall. H is the sensible heat exchange to the air; LE is the latent heat exchange to the air included the sublimation of snow to water vapour; S is the storage of sensible heat, and Q_M is the storage to latent heat. The speed of melting can be estimated by estimating the change in latent heat:

Equation 2

$$\Delta Q_M = L_f \Delta r$$

where Lf is the latent heat of fusion and Δr is melt water in mm/day

1 The Melt Period

There are two very distinct types of snow from an energy perspective. During winter the snow pack is entirely frozen. The snow packs temperature depends on the diurnal fluctuation of air temperature . These fluctuations are reduced (damped) with depth in the snow pack. During this winter period, snow pack temperatures are below freezing. In the spring snow pack warms until the freezing point is reached (0^oC). The snow pack then becomes iso-thermal at 0^oC. During this period, a portion of the pores in the snow hold liquid water. Changes in energy content of the snow pack result in melting or freezing with little or no temperature change.

Based on the 1999 data from the Carcross climate station, snow became isothermal about March 15. For our calculation we will assume that snow making operations are complete on March 15, and that little loss of snow has taken place prior to March 15. The use of the iso-thermal model simplifies estimating snow melt.

The following section derive monthly average values for each term in the energy balance equation (1).

2 Energy Balance

2.1 *Radiation*

The net radiation (Rn) is calculated from equation 3, 4 and 5 based on Spittlehouse, D.L. and M.J. Goldstein (1989)**.**

$$Rn = (1-\alpha_s)K\downarrow + L^*$$ **Equation 3**

$$L^* = \left(0.2 + 0.9\frac{K\downarrow}{K\downarrow_{\max}}\right)(\varepsilon_a - \varepsilon_s)\sigma Ta^4$$ **Equation 4**

$$\varepsilon_a = 1 - \left\{0.261\exp\left(-0.000777 * T_a^2\right)\right\}$$ **Equation 5**

The albedo (α) or reflectivity of snow should be measured for the man-made snow. At the feasibility phase, a value of 0.8 is used for new snow and a value of 0.4 is used for old snow based on Oke (1996). Albedo varies linearly from March to June between these values. This indicates that melt rates can be reduced if new snow is made to cover the pile frequently.

Short-wave radiation (K↓) is taken form published tables (Hay 1979). Net longwave radiation (L*) is calculated from equation 4. The emissivity of snow is estimate as 0.99 for new snow and 0.82 for old snow based on Oke (1996).

Air temperature data come from the single year of data measured at the site. The value of mean air temperature in May is unreasonable as the climate equipment on the site was only operational for 3 days. The average daily temperature for May was taken from longterm data form the Whitehorse climate station.

Table 1 gives the radiation estimates for three different slopes. This first is a 10 degree (18%) north facing slope, the second is a flat area, and the third is a 10 degree (18%) south facing slope. It is assumed there is no shading of the snow pack ant that there in no vegetation overtopping the snowpack.

Table 1 Radiation Balance

	Kd	**Kdmax**	**Albedo snow**	**emissivity snow**	**Ta**	**Tamax**	**ea**	**L***	**Rn**
North	**MJ/m2 day**	**MJ/m2 day**	**unitless**	**unitless**	**C**	**C**	**unitless**	**MJ/m2 day**	**MJ/m2 day**
March	5.66	9.3	0.8	0.99	-7.9	4.2	0.75	-3.74	-2.61
April	13.18	17.61	0.67	0.93	-1.1	7.8	0.74	-4.02	0.37
May	18.33	24.77	0.53	0.88	6.6	12.7	0.75	-2.96	5.60
June	19.83	27.56	0.4	0.82	11	23.2	0.76	-1.37	10.53
July	17.73	24.4	0.4	0.82	14	20.3	0.78	-1.11	9.53
Flat									
March	9.51	13.15	0.8	0.99	-7.9	4.2	0.75	-4.34	-2.43
April	15.05	19.48	0.67	0.93	-1.1	7.8	0.74	-4.13	0.88
May	19.77	26.21	0.53	0.88	6.6	12.7	0.75	-3.01	6.22
June	20.84	28.57	0.4	0.82	11	23.2	0.76	-1.39	11.12
July	18.87	25.54	0.4	0.82	14	20.3	0.78	-1.12	10.20
South									
March	11.26	14.9	0.8	0.99	-7.9	4.2	0.75	-4.50	-2.25
April	16.64	21.07	0.67	0.93	-1.1	7.8	0.74	-4.21	1.33
May	20.82	27.26	0.53	0.88	6.6	12.7	0.75	-3.04	6.68
June	21.53	29.26	0.4	0.82	11	23.2	0.76	-1.40	11.52
July	19.65	26.32	0.4	0.82	14	20.3	0.78	-1.13	10.66

2.2 *Energy from Rainfall*

Rainfall data from the site is minimal. Rainfall at the Carmacks climate station (Lat. 62^{o}N, Long 136^{o}W, Elev. 525 m) averages 0.2 mm in March, 1.1 mm in April and 18.3 May and 34 mm in June. Rainfall is not an important energy source for natural snow, but if a man made snowpack lasts into May, rainfall will become important in the melt. QR is estimated from the following equation.

Equation 6

$$Q_R = L_F P$$

Where L_f is the latent heat of fusion and P is the precipitation rate.

Table 2 shows the estimates of the energy input due to rain. The monthly precipitation data is from the site with the exception of May which is from Whitehorse.

Table 2 Energy from Rain

	Precipitation		**QR**
	mm3/mm2 month	**kg/m2 day**	**MJ/m2 day**
March	5.1	0.165	0.055
April	3.6	0.116	0.039
May	18.3	0.610	0.204
June	67.3	2.171	0.725
July	38.5	1.242	0.415

2.3 *Sensible Heat Flux*

Sensible heat Q_H is calculated from.

Equation 7

$$H = -C_a K_H \frac{(T_a - T_s)}{\partial z}$$

In the iso-thermal period snow temperature Ts is taken to be 0^oC. The height increment ∂z is taken a 1 m. The heat capacity of air (Ca) is 1.20E-09 MJ/m^3K. Thermal eddy diffusivity is harder to estimate. A value of 1000 m^2/s is used at the feasibly phase. This value represents moderately turbulent conditions. Improvement to this estimate are recommended for future phases of the project.

Table 3 Sensible Heat Flux

	KH	**KH**	**Lf**	**H**
	m2/s	**m2/day**	**MJ/m3K**	**MJ/m2day**
March	1000	8.64E+07	1.20E-09	0.82
April	1000	8.64E+07	1.20E-09	0.11
May	1000	8.64E+07	1.20E-09	-0.68
June	1000	8.64E+07	1.20E-09	-1.14
July	1001	8.65E+07	1.20E-09	-1.45

2.4 *Sublimation*

Sublimation is the direct conversion of ice and snow to water vapour. Negative values of sublimation occur when water vapour turns to ice. This is responsible for “rime” ice that forms on poles and wires. Sublimation is calculated from the following equation (Pomeroy and Gray 1995)

Equation 8

$$LE = L_s g_v \frac{e_s - e_a}{p_a}$$

In isothermal snow, water both sublimates from ice and evaporates from water held in the pores in the snow. The net evaporation and sublimation rate in Spring are low. Based on humidity and wind speed recorded at Whitehorse Airport, the sublimation rate directly from the snow surface was calculated from Equation 8. The rate of sublimation in March and April is estimated at 0.3 mm, which is insignificant in the annual water balance.

A more important loss of snow is from sublimation of blowing snow. The physics of predicting the amount of blowing snow and sublimation of this mass is complex. The basic theory was developed by Schmidt (1972, 1991). Equation 9 needs to be solved for the column of blowing snow.

$$\frac{dm}{dt} = \frac{2\pi r\sigma - \frac{Q_s}{\lambda_T T_a Nu}\left(\frac{h_s M}{RT_a} - 1\right)}{\frac{h_s}{\lambda_T T_a Nu}\left(\frac{h_s M}{RT_a} - 1\right) + \frac{1}{D\rho_s Sh}}$$

Equation 9

A more practical approach is to base sublimation estimates on empirical models. The closest well-developed model is the Prairie Blowing Snow Model PBSM (Pomeroy and Gray 1995). Pomeroy (1988, 1989) found that sublimation from blowing snow could be modeled by estimating the sublimation rate at a “fetch” of 1 km using Equation 10, then applying this to specific sites by adjusting for the fetch of the site using **Equation 11**. Fetch is the distance measured in the upwind direction across a uniformly rough surface. Fetch is estimated as 5 km on the site. The site where the snow is to be placed has only short vegetation which will not overtop the snowpack.

$$E_s(1,1) = 7.21 + 1.76u_{10} - 0.16T_{\max} - 0.18RH_{\max} + 0.19P_m$$

Equation 10

Equation 11

$$E_s(h, F_d) = E_s(h,1)\left(-0.457 + 1.37F_d + 0.125F_d^2\right)$$

where $E_s(1,1)$ is the sublimation rate of blowing snow in mm/month from a bare surface with a 1 km fetch, u10 is the average monthly wind speed in m/s at a height of 10 m, and P_m is the monthly snowfall in mm of water equivalent.

Table 4 shows the inputs and results of Equations 10 and 11. The wind speed and maximum air temperature data is from the site (1998) with the exception of May. May wind speed was estimated at 9 km/hr. May air temperature, and maximum relative humidity come from Whitehorse Airport (Environment Canada 1993). Snow fall data is from the Carmacks climate station (Environment Canada 1993). There is a limited amount of wind speed and temperature data from the site, and the height of measurement is not stated. Some of the energy from the sublimation of snow may be taken away for the site by advection. This would lower Qe.

Table 4 Sublimation from Blowing Snow

	site	**site**	**site**	**White-horse**	**Car-macks**				
	u10	**u10**	**Tmax**	**RH max**	**P**	**Es(1,1)**	**Es(1,5)**	**Es(1,5)**	**LE**
	km/hr	**m/s**	**C**	**%**	**mm**	**mm/month**	**mm/day**	**kg/m2 day**	**MJ/m2 day**
March	7.9	2.19	4.2	75	6.8	-0.46	-4.41	-0.14	-0.40
April	9.5	2.64	7.8	69	5.4	1.71	16.26	0.54	1.53
May	9	2.50	12.7	67	1.1	1.79	17.05	0.55	1.56
June	8.6	2.39	23.2	68	0	2.89	27.47	0.89	2.51
July	9	2.50	20.3	71	0	2.08	19.78	0.64	1.81

2.5 *Sensible Heat Storage*

Since the snow pack during melt is expected to be iso-thermal, the change in sensible heat storage is expected to be small, (i.e., $\Delta S = 0$).

3 Melt Rate

Using the above model, the rate of snow melt in mm/day was calculated for three situations. A flat surface, a surface with a 10° (18%) north facing slope and, for a surface with a 10°(18%) south facing slope. Note that this applies to the top surface of the snow. Table 5 shows the result of the these estimates.

Table 5 Estimated Melt Rates

	Rn	**QR**	**H**	**LE**	**ΔS**	**ΔQM**	**Δr**
North	**MJ/m2day**	**MJ/m2day**	**MJ/m2day**	**MJ/m2day**	**MJ/m2day**	**MJ/m2day**	**mm/day**
Mar	-2.61	0.05	0.82	-0.40	0.00	-2.97	-8.89
Apr	0.37	0.04	0.11	1.53	0.00	-1.24	-3.70
May	5.60	0.20	-0.68	1.56	0.00	4.93	14.75
June	10.53	0.73	-1.14	2.51	0.00	9.88	29.59
July	9.53	0.41	-1.45	1.81	0.00	9.59	28.73
Flat							
Mar	-2.43	0.05	0.82	-0.40	0.00	-2.79	-8.37
Apr	0.88	0.04	0.11	1.53	0.00	-0.73	-2.17
May	6.22	0.20	-0.68	1.56	0.00	5.55	16.62
June	11.12	0.73	-1.14	2.51	0.00	10.47	31.36
July	10.20	0.41	-1.45	1.81	0.00	10.26	30.73
South							
Mar	-2.25	0.05	0.82	-0.40	0.00	-2.61	-7.82
Apr	1.33	0.04	0.11	1.53	0.00	-0.28	-0.83
May	6.68	0.20	-0.68	1.56	0.00	6.01	17.99
June	11.52	0.73	-1.14	2.51	0.00	10.88	32.57
July	10.66	0.41	-1.45	1.81	0.00	10.72	32.10

4 Conclusion

Based on these results the estimated cumulative melt is plotted on Figure 1 for the three aspects.

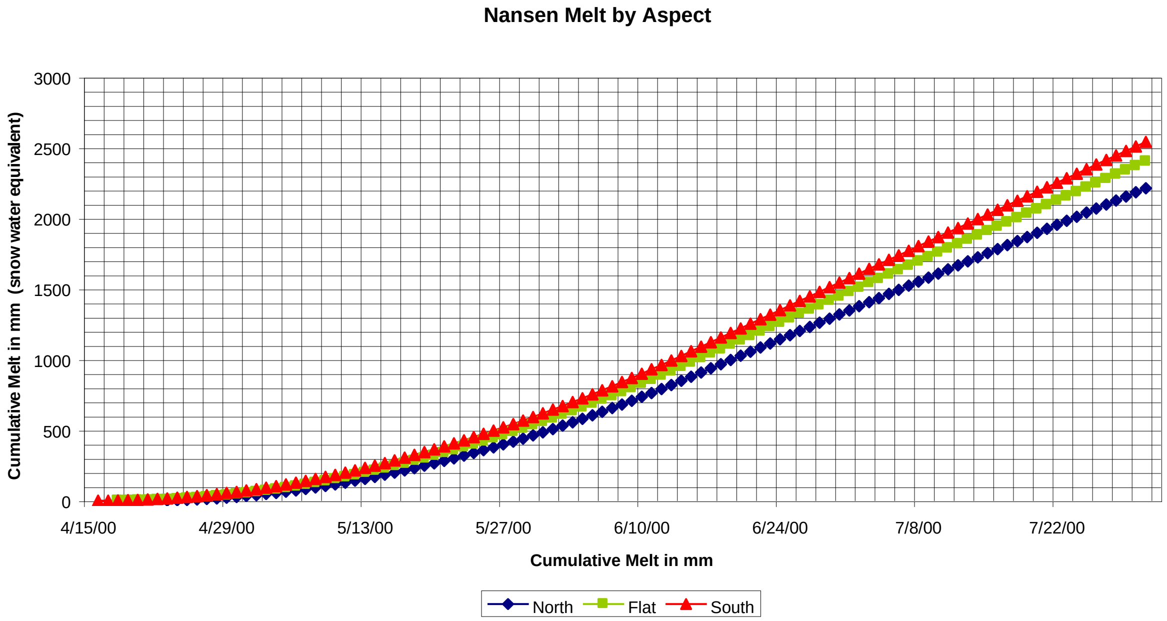

Figure 1Cumulative Melt Water Graph

Figure 1 shows the cumulative melt rate from the south aspect at a 10^{o} (18%) slope is slighlty more rapid than that on a flat surface. This is reasonable give the latitude of the site. The north aspect lags about 6 days behind the south. This would seem contrary to the visual observation that snow patches persist on the north aspect 4 weeks longer than snow on the south aspect. There may not be a contradiction. “Patches” of snow could be in small areas with locally steeper slopes than the 10^{o} (18%) used in our calculations. Also patches could be shaded by local obstructions. It may be possible to find shade for a large snow patch, but it may be unwise to place a snow pack on a slope greater than 10^{o} (18%). The real question is by how many weeks does the mass of snow on the north-facing slope remain after the mass of snow has gone from the south-facing and flat areas. It would also be interesting to know if the mass of snow left on the flat and south-facing areas melt on about the same date.

If a snow pack had a snow water equivalent height of 1000 mm it would be expected to complete its melt on June 20 on the north aspect, and on June 16 on a flat surface and June 14 on a south facing area.

It should be remembered that these are first estimates only. The greatest errors are expected in heat eddy diffusion, albedo of the snow, air temperature and cloud cover. The use of monthly estimates also weakens the analysis. Ideally melt should be estimated hourly. Having said this the estimates are reasonable based on values in the scientific literature.

5 Recommendations

It is recommended to use a series of satellite photos to determine the dates of snow melt over the past 10 years.

The limited amount of climate data for the site have several large gaps. It also appears that relative humidity was not monitored. It also appears that the hour values were not recorded. It is recommended that a complete climate station be established on site and operated for a least two years if the project lasts this long. If the snow making program goes forward, temperature sensors should be placed in the pack.

The albedo (reflectivity of the snow should be determined. This could be accomplished by placing a net shortwave radiometer on the snowpack.

Air temperatures over the snow pack could be lower than those measured by a climate station away from the snow pack. If the snow making program goes forward, air temperature sensors should be placed over the snow pack.

Estimated melt rates should be calculated on a hourly basins using the above data.

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