Evaporation Calculations at the Salmita-Tundra Mine Site, 1993 to 2004

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Summary

Weather data for evaporation modelling have been collected since 1993 at the Salmita-Tundra mine site, located 250 km northeast of Yellowknife. Evaporation rates are modelled with mean daily weather data using the Penman Combination and the Priestley-Taylor methods. Evaporation data are used to improve water balance calculations for site remediation plans. The average annual evaporation rate for Salmita is 286 mm (Penman) and 285 mm (Priestley-Taylor).

Introduction

Climate data, including air temperature, precipitation and evaporation, are important for designing water management facilities at mine sites, assessing the operations of mine tailings containment areas, and determining long-term stability of tailings areas for mine site restoration and abandonment. Proper mine-site water management can prevent uncontrolled releases of potentially contaminated waters and can help minimize acid-rock drainage potential.

The purpose of the evaporation study at the Salmita-Tundra mine site in the Northwest Territories is to assist water balance calculations for mine site remediation activities and final abandonment. An array of weather instrumentation was installed in 1992 at the tailings pond and evaporation rates have been calculated using standard energy budget methods. The study site is located at the tailings pond of the abandoned Salmita-Tundra gold mine, 250 km northeast of Yellowknife (Figure 1).

Salmita-Tundra Site Description

The Salmita-Tundra site (64° 03' N, 111° 11' W) is about 250 kilometres northeast of Yellowknife. The region is characterized by low relief, complex drainage and a typical low arctic tundra vegetation in the Precambrian Shield. Salmita-Tundra is located between two large lakes, Mackay Lake (1060 km^2), five kilometres to the south and Courageous Lake (250 km^2), nine kilometres to the north. Numerous smaller lakes surround the study site.

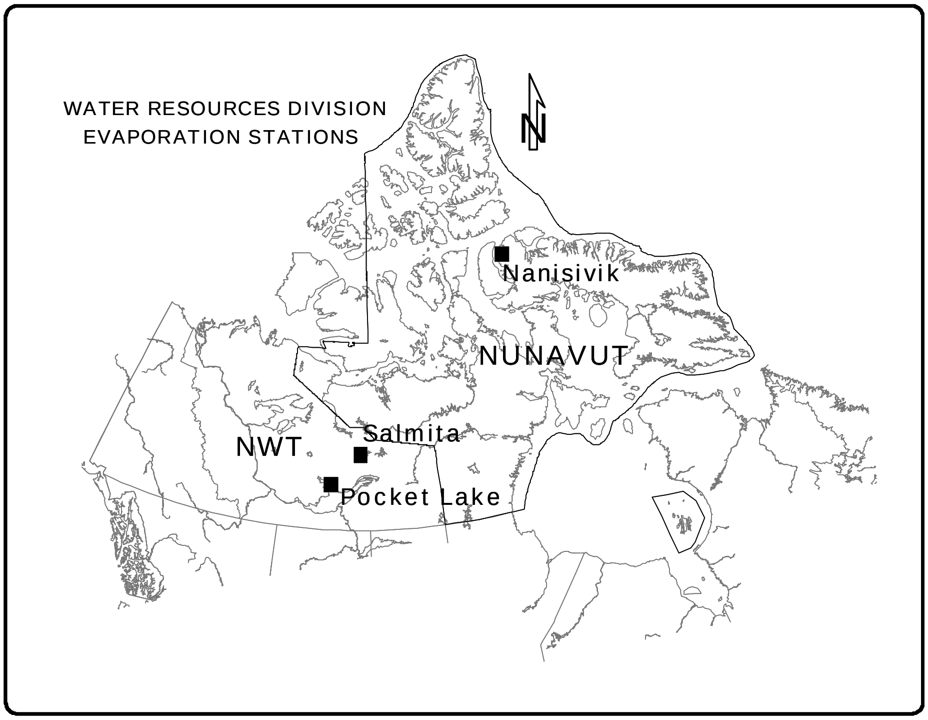

Figure 1. Evaporation Study Site Locations

Gold mining and milling operations began at the Tundra Gold Mines Ltd site in 1964 but ceased in 1968 due to low ore grades. Tailings were deposited in Russell Lake, a small lake adjacent to the mill. Operations at the Tundra mill resumed in 1983 with ore from the Salmita deposit, five kilometres to the northwest. When mining operations ceased at Salmita in 1986, the Russell Lake tailings pond was separated into upper and lower cells with a dyke constructed from waste rock and esker material. The dyke was built to maintain the water level over the tailings solids to limit the acid rock drainage potential. An interception ditch was also constructed on the north side of the tailings pond to minimize surface runoff to the Lower Pond of the tailings containment area.

The Water Resources Division evaporation program was initiated in 1992 with the installation of an automatic weather station at the Russell Lake tailings pond. Instrumentation was located on the small point on the west shore of the lower tailings pond. Damage to the equipment occurred in the spring of 1995 and 1996 by wind-shunted ice during breakup. In 1997, the station was relocated approximately 400 metres southward to an area protected from ice by a shallow beach (Figure 2).

The catchment basin and lake areas of the tailings area were mapped in July 1996 using differentially corrected GPS. The area of the upper pond basin was determined as 13.8 hectares, of which the water surface is 8.3 hectares (60%). The lower pond catchment basin was determined to be 48.6 hectares with a water surface area of 40.3 hectares (83%). Bathymetry of the lower pond was mapped with a depth-sounder interfaced with the GPS system. A maximum depth of six metres was measured on the west side of the pond, adjacent to the weather station and a mean depth of three metres was determined. A water volume of 1.24 * 10^6 cubic metres was calculated for the lower pond. At the time of the mapping survey, there was 1.1 hectares of tailings solids in the upper pond basin exposed to the atmosphere.

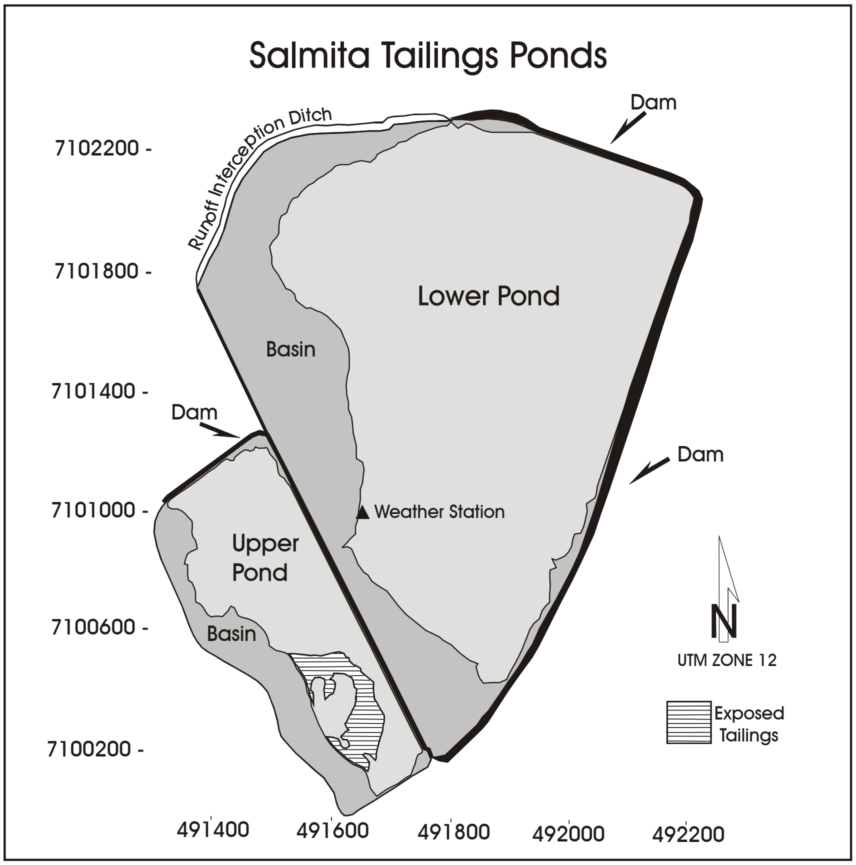

Figure 2. Salmita Evaporation Study Site

Study Site Instrumentation

The instrumentation at the site consists of a tripod-mounted, automatic weather station located in shallow water at the edge of the pond. Air temperature and relative humidity are measured with Vaisala HMP35CF sensors at approximately 2.5 metres above the water surface. Accuracy of the temperature sensor is ± 0.2°C and accuracy of the humidity sensor is ± 2 % between 0 and 90% RH and ± 3 % between 90 and 100% RH (Campbell Scientific, 1997). The

Vaisala sensor is changed each spring for calibration by the supplier. Wind speed is measured at 2.5 metres with a MetOne 013A or 014A sensor which has an accuracy of ± 0.11 m/s (Campbell Scientific, 1990). Wind direction is measured with NRG 200P wind vanes. Net solar radiation is measured with Radiation & Energy Balance Systems Q6/Q7 net radiometer at approximately one metre above the water surface. The protective domes on the radiometers are replaced each spring and the sensor has been calibrated and upgraded periodically. Corrections are made for wind speed effects as specified for the sensor type.

Water temperature is measured with a 107B thermistor placed on the lake bed in approximately 0.5 m of water (sensor accuracy is ± 0.2 °C). Water levels are measured with a submersible depth transducer are verified with level surveys in spring and fall. Rainfall is measured with a tipping bucket gauge which are accurate to ± 1% at the rainfall intensities typical in the study areas. The electronic weather sensors are controlled with a Campbell Scientific 21X datalogger. The sensors are sampled on 60 second intervals and hourly and daily averages are written to final data storage. The station is powered by a 12 volt gel-cell battery charged by a solar (photo-voltaic) panel. A collector rain gauge is located near the weather station to collect rainwater for isotope analysis and to verify tipping bucket gauge data.

Site maintenance trips are scheduled to correspond with the open water season as closely as possible. Field observations of ice-off and freeze-up dates are recorded where available or estimated from the weather data. The estimated dates of breakup and freezeup, the estimated duration of the open water season and the periods of data recovery are recorded in Table 1. The open water period at the study site occurs from mid-June until late September for an average duration of 108 ± 10 days.

Evaporation Calculations

Evaporation rates were calculated with the Penman Combination and the Priestly-Taylor methods using mean daily weather data (Chow *et al*., 1988). Modifications were made to air and water density constants to account for lower ambient temperatures in the study areas relative to the values used in the reference examples. The Penman Combination Method is a combined energy balance/aerodynamic mathematical model defined by the general equation:

$$E(PC) = \frac{\Delta}{\Delta+\gamma} E_R + \frac{\gamma}{\Delta+\gamma} E_A$$

where **)** is the slope of the temperature-saturated vapour pressure curve in Pa/^{o}C and **(** is the psychrometric constant in Pa/^{o}C, calculated respectively by:

$$\Delta = \frac{4098 e_{as}}{(237.3+T)^2} \qquad \gamma = \frac{C_p P_A}{0.622 l_v}$$

where e_{as} is the saturated vapour pressure at air temperature T in ^{o}C;

$$e_{as} = 611 \exp\left(\frac{17.27 * T}{237.3+T}\right)$$

the specific heat of air C_P is 1006 J/kg ^{o}C; air pressure P_A at 20^{o}C is 101.3* 10^3 Pa; and the latent heat of vaporization l_V is 2.501 * 10^6 - 2370T J/kg.

The energy balance component E_R in mm/day is determined by the equation:

$$E_R = \frac{R_n - H - G}{l_v \rho_w} \quad (*\ 8.64 * 10^7\ \textit{unit conversion})$$

where R_n is the net solar radiation measured over water in W/m^2, and H and G are the sensible heat flux and water heat flux in W/m^2,

$$H = -k_a \left(\frac{\delta Ta_2}{z_2}\right) \qquad G = -k_w \left(\frac{\delta Tw}{z_w}\right)$$

where *****Ta_2 and *****Tw are the change in mean daily air and water temperatures from the previous day, as measured at height z_2 and depth z_w in metres from the water surface. The thermal conductivity of air k_a and water k_w at 10^{o}C are 0.0241 and 0.615 W/m/^{o}C, respectively (Yarwood and Castle,

1970) and the water density $\mathbf{D}_w$ at 10°C is 999.73 kg/m^3.

The aerodynamic component E_A in mm/day is calculated as:

$$E_A = \left(\frac{0.1062u}{[\ln(z_2/z_0)]^2} \right) * (e_{as} - e_a)$$

where u is wind speed in m/s measured at height z_2 in cm. The surface roughness height z_0 is 0.01 cm (Brutsaert, 1982). The difference between saturated $\mathbf{e_{as}}$ and actual $\mathbf{e_a}$ vapour pressure (in Pa) is calculated with $\mathbf{e_a = RH * e_{as}}$ where (0 #RH #1).

The Priestly-Taylor method is similar to the Penman Combination method and is defined by the general equation:

$$E(PT) = \alpha \quad \frac{\Delta}{\Delta + \gamma} E_R$$

where the weighted aerodynamic component E_A is replaced by the constant **"**, and the sensible heat flux term H is omitted from the energy balance term E_R (Shuttleworth, 1993; Chow *et al*., 1988). The constant **"** = 1.26 is used for subarctic regions (Stewart and Rouse, 1977; Gibson *et al*., 1996).

Discussion

Evaporation rates were calculated with the Penman and the Priestley-Taylor methods using daily weather data. Calculations were repeated with both methods with a simplified equation for the energy balance component, $\mathbf{E_R = Rn/lvDw = 0.0353 * Rn}$, which uses a constant rather than calculating sensible and water heat fluxes. The sensible heat flux and water heat flux terms are omitted as it is assumed they are negligible (Chow, *et al*, 1988). This assumption is justified as data collection at all sites extends over the entire open water period, thus the net changes in lake heat storage and sensible heat flux are both zero. There were no differences in the results when the constant was used. The results of the evaporation calculation methods are included in Table 2.

Year	Penman	Priestley-Taylor
1993	135*	132*
1994	336	311
1995	261	244
1996	283	286
1997	243	237
1998	348	344
1999	295	301
2000	278	284
2001	296	304
2002	232	242
2003	327	332
2004	242	249
mean	**286**	**285**
std dev	**40**	**38**
maximum	348	344
minimum	232	237
*** incomplete data record: 1993 excluded in mean and standard deviation**		

Table 2. Salmita/Tundra Evaporation Rates in mm

Conclusions

Evaporation rates were calculated for the Salmita/Tundra study site using the Penman Combination method and the Priestley-Taylor method, both of which are energy balance methods. The calculation of the energy balance component in the equations was simplified by omitting the sensible heat flux and water heat flux terms and using a constant for the latent heat of vaporization. The results from the simplified calculation were no different from the original calculation. The mean annual evaporation rate calculated with the Penman method is 286 mm and 285 mm with Priestley-Taylor method.

Acknowledgements

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Appendix 1. Break-up and Freeze-up Field Observations.

	Ice-off Date	Freeze-up Date	Open Water (# of Days)	Data Record (# of Days)
1992	n/a	~ 30 Sept	n/a	56
1993	~ 26 June	~ 03 Oct	100	79
1994	~ 01 June	~ 28 Sept	120	110
1995	~ 19 June	~ 06 Oct	110	110
1996	~ 18 June	~ 03 Oct	108	105
1997	~ 17 June	~ 29 Sept	105	104
1998	~ 01 June	~ 02 Oct	124	124
1999	~ 20 June	~ 29 Sept	102	102
2000	~ 22 June	~30 Sept	101	101
2001	~11 June	~ 4 Oct	116	108
2002	~23 June	~ 25 Sept	94	84
2003	~10 June	~30 Sept	121	114
2004	~26 June	~30 Sept	98	95
mean	16 June	1 Oct	108	103
std dev	9 days	3 days	10.0	12.4

Table 1. Field Observations of Break-Up and Freeze-Up Dates, Open Water Period

Appendix 2. Water Budget Calculations

	-)S (mm)	P (mm)	)S + P (mm)	R= A_L*P*.5/A_P (mm)	E=)S+P+R (mm)
1992	170	38	208	4	212
1993	106	93	199	10	209
1994	253	92	345	10	355
1995	3	153	156	16	171
1996	85	147	232	15	248
1997	153	149	302	16	318
1998	145	164	309	17	326
1999	126	171	297	18	314
2000	139	128	267	13	280
2001	163	134	297	14	311
2002	42	171	213	18	231
2003	203	127	330	13	343
2004	40	134	174	14	188

Table A1-1. Salmita Water Budget Data

where

)S = change in storage (i.e. lake level)

P = precipitation

R = runoff

A_L = Land Area

A_P = Pond Area