

# Degree-day snowmelt runoff experiments; Clear Lake Watershed, Riding Mountain National Park

**R.A. McGinn**

Department of Geography, Brandon University, Brandon, Manitoba R7A6A9  
mcginn@brandonu.ca

## Abstract

The Temperature Index model or Degree-Day Melt model estimates snowmelt for a time period (one day) as a linear function of temperature (mean daily). Intrinsic to this model is the melt coefficient, the melt factor, degree-day-factor or degree-day ratio ( $M_f$ ).

The purpose of this study was to empirically determine the degree-day ratios throughout the melt-season for small (< 0.5 ha) open grassland sites in the Clear Lake watershed, Riding Mountain National Park.

A 0.5 ha open relatively flat grassland with full sun exposure was selected for the snowmelt runoff experiments. A 10 m<sup>2</sup> plywood collection platform funneled meltwaters into a collection reservoir. Sample plot runoff was weighed daily. Mean ambient and snowpack temperatures were measured hourly and mean daily values calculated. Degree-days of melt are calculated based on cumulated degree-hours above 0.0 °C for a twenty-four period (degree-hour-days (DHD)).

During the 24-day melt season (March 31 to April 23 2011, degree-day ratios and degree-hour-day ratios are variable. The arithmetic mean DD ratio was calculated to be 7.43 °C day<sup>-1</sup>, a value considerably smaller than the 3.10 mm °C hour-day<sup>-1</sup> calculated mean DHD ratio for the same period. Seven-day running mean smoothing produced a melt season mean DD ratio (3.22 mm °C day<sup>-1</sup>) similar to the seven day smoothing melt season mean DHD ratio (3.38 mm °C hour-day<sup>-1</sup>). The open site 7-day smoothing  $M_f$  values are approximately 19 percent greater than McGuire's 1997 benchmark forested (50%) watershed mean melt ratio of 2.78 mm °C day<sup>-1</sup>. The Martinec 1960 snowpack density function generated an overall melt factor of 3.06 mm °C day<sup>-1</sup>; a value similar to McGuire's benchmark standard and the 7-day smoothing  $M_f$  values.

For shallow ripe snowpacks containing less than 15.0 cm snow water equivalent, that melt over a relatively short period (less than one month), a single degree-day or degree-hour-day melt ratio appears to be acceptable for the snowpack melt phase. Melt ratios however, must be determined for each cover type.

In Riding Mountain National Park, the arithmetic mean degree-day melt ratio tends to overestimate snowpack depletion. Consequently, a 7-day running mean smoothing function combined with a graphically determined mean for the total melt season is preferred. Alternately, Martinec's 1960 density function based on a mean of weekly snowpack density estimations can be used to estimate the degree-day melt ratio.

Keywords: *snowmelt modelling, degree-day index, temperature index*

## Introduction

Snowmelt is a thermodynamic process. Its study should thus consider those factors influencing the transmission of heat to the snowpack: the snowpack radiation heat balance (see Millar 1981, Haan et al. 1982, Bras 1990, Singh 1992). Although energy balance models provide a theoretical background for the applications of snowpack melt equations at specific locales, the estimation of snowmelt-generated runoff from a watershed is more complex.

Grey and O'Neill (1974) found that net radiation was the primary energy source for snowmelt on the Canadian prairies when snow cover is continuous, supplying 93 percent of melt energy. However for discontinuous snow cover, the advection of sensible heat from bare ground towards isolated snow patches provides 44 percent of the melt energy and the net radiation contribution is reduced to 56 per cent. Zuzel and Cox (1975) measured daily values of wind run (velocity times time), air temperature, vapour pressure, net radiation and melt at a continuous snow cover research plot. They found that net radiation, vapour pressure and wind run explained 78 percent of the variation in melt; the autocorrelated air temperature explained 51 percent of variance. Viessman and Lewis (2003) suggested that temperature as an index of melt represents net radiation, sensible and latent heat transfer inputs, and is sensitive to wind. Dingman (1994) supported this argument, indicating that both long-wave radiation and turbulent heat exchanges are approximately linear functions of ambient temperature.

Daily/hourly ambient temperature data is readily available for most watersheds whereas daily radiation, vapour pressures and wind meteorological data may not be available for the watershed of interest. Due to logistics in fulfilling the data requirements for an energy balance approach and the virtual impossibility of collecting spatially representative data in a moderate to large watershed the empirical temperature index or degree-day methodology is incorporated into most snowmelt runoff models e.g. UBC Watershed Model (Quick and Pipes 1977), Snowmelt Runoff Model (Martinec et al. 2008).

The Temperature Index model or Degree-Day Melt model estimates snowmelt for a time period (one day) as a linear function of mean daily temperature (Dingman 1994) and is commonly expressed as:

$$Q = M_f (T_a - T_p) + b$$

Where:

- Q** is the daily melt ( $m^3$ ) or depth of melt (m);
- $T_a$  is the mean or maximum daily temperature ( $^{\circ}C$ );
- $T_p$  is the temperature (mean daily) of the snowpack ( $^{\circ}C$ );
- $T_a - T_p$  is the degree-day value (DD);
- $M_f$ , the slope, is the melt coefficient, melt factor, degree-day factor or degree-day ratio; measured in m, mm or cm of depth per degree-day ( $m^{\circ}C^{-1} day^{-1}$ ,  $mm^{\circ}C^{-1} day^{-1}$  or  $cm^{\circ}C^{-1} day^{-1}$ );
- b**, the intercept, is the volume of melt ( $m^3$ ,  $cm^3$  or  $mm^3$ ) or the depth of melt (m, cm or mm) when  $T_a = T_p$ . This is often assumed to be zero.

A degree-day (DD), is a measure of the departure of

the mean daily temperature from a specified standard; commonly  $0^{\circ}C$ , one degree-day for each  $^{\circ}C$  of departure above the  $0^{\circ}C$  standard during one 24 hour period (Lo 1992).

Intrinsic to the degree-day melt model is the determination of the melt coefficient, melt factor, degree-day factor or degree-day ratio ( $M_f$ ).

## Objective

The purpose of this study is to determine empirically the melt coefficients throughout the melt-season for a small (0.5 ha) open grassland site in the Clear Lake watershed, Riding Mountain National Park.

## Physical Characteristics of a Snowpack

### Cold Content ( $Q_{cc}$ )

Cold Content ( $Q_{cc}$ ) is defined as: the heat required per unit area ( $m^2$ ) to raise a dry snowpack temperature to  $0^{\circ}C$  (Singh 1992).

$$Q_{cc} = - (C_i \rho_s) [d_s (T_m - T_p)]$$

Generally this heat is generated through the refreezing of diurnal meltwater within the snowpack. Consequently, cold content is also defined as a water equivalent depth of snow ( $Dw_{cc}$ ) which on melting and refreezing will generate sufficient latent heat per unit area ( $m^2$ ) to raise a dry snowpack temperature to  $0^{\circ}C$  (Singh 1992).

$$Dw_{cc} = - (C_i / L_f) (\rho_s / \rho_w) [d_s (T_m - T_p)]$$

$$Dw_{cc} = - (C_i / L_f) [d_{swe} (T_m - T_p)]$$

Where:

- $Q_{cc}$  = cold content ( $kJ m^{-2}$ );
- $Dw_{cc}$  = cold content as a water equivalent depth (mm);
- $C_i$  = specific heat capacity of ice =  $2.06 kJ kg^{-1} ^{\circ}C^{-1}$  at  $0^{\circ}C$ ;
- $L_f$  = heat of fusion of ice =  $333.7 kJ kg^{-1}$  at  $0^{\circ}C$ ;
- $\rho_s$  = mean snowpack density ( $kg m^{-3}$ );
- $\rho_w$  = density of water =  $1000 kg m^{-3}$ ;
- $d_s$  = snowpack depth (m);
- $d_{swe}$  = water-equivalent depth of the snowpack (m);
- $T_m$  = melting temperature of snow =  $0^{\circ}C$ ;
- $T_p$  = mean temperature of the snowpack ( $^{\circ}C$ ).

### Thermal Quality ( $\beta$ )

Thermal quality ( $\beta$ ) is defined as: the ratio of the amount of heat required to produce a given amount of water from the snowpack to the amount of heat required to produce the equivalent amount of water from pure ice at  $0^{\circ}C$  (Singh 1992).

$$Q_o / Q_i = \beta$$

$$\beta = (L_s / L_i) + (C_i T_p / L_w)$$

$$\beta = (1 - W_a) L_i + (C_i T_p / L_w)$$

Where:

$Q_o$  = cold content + latent heat in the snowpack (kJ m<sup>-2</sup>)

Latent heat in the snowpack =  $\rho_s d_s L_s$  (kJ m<sup>-2</sup>);

$Q_i$  = Latent heat in the equivalent volume of ice =  $\rho_s d_s L_i$  (kJ m<sup>-2</sup>);

$\beta$  =  $Q_o / Q_i$  = thermal quality;

$L_s$  = heat of fusion of snow < 333.7 kJ kg<sup>-1</sup> (dependent on the liquid water content in the snowpack);

$L_i$  = heat of fusion of ice = 333.7 kJ kg<sup>-1</sup> at 0°C;

$L_w$  = heat of fusion of water = 333.7 kJ kg<sup>-1</sup> at 0°C;

$T_p$  = the mean temperature of the snowpack (°C);

$C_i$  = specific heat capacity of ice (the snowpack) = 2.06 J kg<sup>-1</sup> °C at 0°C;

$W_a$  = the liquid water content of the snowpack =  $\text{mass}_{\text{water}} / \text{mass}_{\text{snow}}$  = zero at temps significantly below freezing.

### Liquid Water Holding Capacity ( $W_{\text{max}}$ ) and Liquid Water Content ( $W_a$ )

A snowpack is assumed to be homogeneous, has a maximum water holding capacity ( $W_{\text{max}}$ ) and fills from the top to the base (Singh 1992). At temperatures equal to or greater than 0°C, liquid water can exist in the snowpack as free water (hygroscopic water and capillary water) and as fringe or gravitational water. The liquid water holding capacity is the maximum liquid water that can be held in the snowpack against gravitational pull at a specified snowpack density and stage of metamorphism (Singh and Singh 2001). The liquid water content in a snowpack ( $W_a$ ) is defined as: the weight ratio of the actual mass of liquid-water (hygroscopic, capillary and fringe) present in the snowpack, to the mass of snow in the snowpack.

$$W_a = (\text{mass}_{\text{water}} / \text{mass}_{\text{snow}}) = M_w / M_s$$

$W_a$  is commonly expressed as a percentage. i.e.  $W_a = (M_w / M_s) 100$ ;

$M_w$  = zero at temps significantly below freezing (< -1.0°C).

The difference between the liquid water holding capacity ( $W_{\text{max}}$ ) and the liquid water content ( $W_a$ ) is referred to as the liquid water deficiency ( $S_d$ ). Once the liquid water deficiency is satisfied, fringe water drains by gravity through the snowpack. This meltwater may evaporate, infiltrate or run off.

## Snowpack Melting Process and Timing

### Warming phase

Absorbed radiant energy raises the isothermal mean snowpack temperature to zero; cold content approaches 0.0 kJ kg<sup>-1</sup>,

thermal quality approaches 1.00 and the snowpack liquid water content is zero.

### Ripening phase

Absorbed radiant energy melts snow, but meltwater is retained in the snowpack as hygroscopic water, capillary water and fringe water. Mean snowpack cold content approximates 0.0 kJ kg<sup>-1</sup>, thermal quality equals 1.00 and the liquid water content ranges from approximately 0% to 8% (Singh 1992).

During the warming and ripening phases, heat energy is generated through the refreezing of diurnal meltwater within the snowpack. Specifically, surface meltwaters percolate downward, refreezing in the lower snowpack layers, releasing latent heat and warming the base of the snowpack.

### Melting phase

Absorbed radiant energy melts snow. Since the ripe snowpack is at the liquid water holding capacity, meltwater drains through the snowpack. Mean snowpack cold content is 0.0 kJ kg<sup>-1</sup>, thermal quality equals 1.00 and the liquid water content ranges from approximately 3% to 15%, depending on the snowpack depth, porosity and density, the size, shape and spacing of snow crystals, the presence of ice layers, snowpack channelization and drainage conditions (Singh 1992).

### The degree-day snowmelt model

The relationship between degree-days (DDs) and snowmelt runoff has been used in North America for over 80 years (Clyde 1931; Collins 1934). The most fundamental formulation relates snowpack water equivalent loss (melt) during a specified time interval (usually one day – 24 hours) to the sum of positive ambient temperatures during that same time interval (Hock 2003). Today, many hydrological models include DD routines to compute snowmelt and snowmelt runoff; e.g. SSARR (Holtan et al., 1975 and US Army Corps of Engineers 1987), USDAHL (US Army Corps of Engineers 1975), UBC Watershed Model (Quick and Pipes 1977), SLURP (Kite 1998), SRM (Martinec et al., 2008). A fundamental input in these DD melt algorithms is the watershed melt coefficient ( $M_p$ ), melt factor ( $M_f$ ) or DD ratio. Melt coefficients and DD ratios are typically recorded in cm °C<sup>-1</sup> day<sup>-1</sup>, or mm °C<sup>-1</sup> day<sup>-1</sup>.

Linsley (1943) demonstrated that the mean DD ratio was not a constant but increased throughout the melt season; ranging from approximately 0.1 cm °C<sup>-1</sup> day<sup>-1</sup> in March to 0.7 cm °C<sup>-1</sup> day<sup>-1</sup> by the end of June in the San Joaquin watershed. Rango and Martinec (1995) attributed these changes to an increase in snowpack liquid water content and decreasing albedos.

Weiss and Wilson (1958) acknowledged that DD ratios change seasonally and recognized the influence of cover type on DD ratios, specifically the effect of forest cover. They recommended a range of DD ratios from 0.185 cm °C<sup>-1</sup> day<sup>-1</sup> to 0.740 cm °C<sup>-1</sup> day<sup>-1</sup> depending on cover type and the time during the ablation season. Granger and Male (1978) observed that the DD ratio increases during the melt season, suggesting that this was due to the effect of radiation during cloud free periods. Bengtsson (1980) in Rango and Martinec (1995) also reported seasonal

increases in DD ratios throughout the melt season at sites in northern Sweden, ranging from 0.3 cm °C<sup>-1</sup> day<sup>-1</sup> in March to 0.6 cm °C<sup>-1</sup> day<sup>-1</sup> in May.

The US Army Corps of Engineers (1960) developed a table of DD factors (ratios) for use in the deep snowpacks of mountainous watersheds and McKay (1968) employed a series of curves to illustrate the variation in DD factors (ratios) for a shallow prairie snowpack. In 1994 the World Meteorological Organization proposed similar temporal and cover type DD ratios.

Rango and Martinec in their 1995 review of the DD model for snowmelt computations stated that there is no excuse for assuming that the DD ratio is constant throughout the melt season and provided guidance for evaluating variable DD ratios (factors). Dingman (1994) stated that the DD ratio or  $M_f$  “varies with latitude, elevation, slope inclination, aspect, forest cover and time of year” and concludes that  $M_f$  must be empirically derived for each watershed.

### Degree-days (DDs) and degree-hour-days (DHDs)

The mean daily temperature, the arithmetic mean of maximum and minimum daily temperatures, may not generate a recorded DD of melt when overnight cooling offsets above freezing daytime hourly temperatures. Consequently, Garstka et al. (1958) in Rango and Martinec (1995) modified the operational definition of a degree-day, using an average of the daily maximum temperature and zero degrees when the minimum recorded daily temperature was below freezing. Bruce and Clark (1966), Brown and Goodison (1993) and Louie and Hogg (1980) argued that maximum daily temperature should be used to determine DDs in Canada as it consistently yields the best model results.

An alternative approach employs the degree-hour concept. Lo (1992) defined degree-hour as the departure of hourly temperature from a given standard (0.0°C). Degree-hours can be accumulated over a 24 hour period to produce a degree-hour-day (DHD). The DHD is commonly employed in European research (Bagchi 1983). See, for example, Hock (1999).

### Snowpack depletion, degree-days and the degree-day ratio

The DD methodology is founded on the linear relationship between the depletion of snowpack mass and daily or hourly temperature. Snowpack depletion generally is evaluated as the reduction in snowpack depth and or snowpack water equivalent depth over a designated time period (commonly one 24 hour day). Relevant examples of studies employing snowpack depletion curves include Martinec 1960, 1975 and 1985, Kane et al. (1997) Alaskan Arctic watershed, and DeWalle et al. (2002) Upper Rio Grande watershed, Colorado. McGuire (1997) employed similar snowpack water equivalent (SWE) depletion measurements at six snowpack survey sites sampling five cover types to determine a mean regional melt ratio ( $M_f$ ) for a small catchment on the Riding Mountain Uplands, Manitoba.

### Degree-days and snowpack density

Martinec (1960) demonstrated that DD ratios ( $M_f$ ) varied considerably over a 35-day continuous period. However when

DD ratios are averaged over a weekly period values become consistent and are linearly related to snowpack density, specifically:  $M_f$  (cm °C<sup>-1</sup> day<sup>-1</sup>) = 1.1 ( $\rho_p / \rho_w$ ). In 1980, Kuusisto derived additional snowpack density degree-day factor relationships:  $DD_f$  cm °C<sup>-1</sup> day = 1.04 ( $\rho_p / \rho_w$ ) - 0.07 for forest cover,  $DD_f = 1.96 (\rho_p / \rho_w) - 0.239$  for open areas. Rango and Martinec (1995) concluded that snowpack density might be a convenient index of DD ratios.

### Areal degree-day ratios

Rango and Martinec (1995) stated that hourly, daily or even weekly snowmelt depths cannot be accurately computed by the DD or DHD method and suggest that this is due to hourly radiation variation responsible for temperature variation, overnight refreezing and associated snowpack water detention. However, they suggest that short term (biweekly) means tend to smooth daily variations particularly for regional watershed responses.

Bagchi (1983) states that point -- or site -- calculated DD factors (ratios) vary in both time and space. Consequently, regional or areal DD factors are of doubtful value for routine prediction of snowmelt runoff in the Himalayas. Hock (1999) pointed out that lumped (regional) temperature index models cannot account for the spatial dynamics of the melt process and are incapable of handling the extreme heterogeneity of complex mountainous topography. Rango and Martinec (1995), however, suggested that a regional (watershed) DD ratio generally agrees with point values under the favorable conditions of non-rugged terrain, a large snow accumulation, and a short ablation period, places such as the Arctic tundra and the Canadian prairies.

### Summary

Rango and Martinec (1995) argued that the classical Degree-day or Temperature Index Methodology for calculating snowmelt will not be easily replaced by more physically-based theoretical radiation balance models. The methodology is reliable for computing snowmelt depth for periods of greater than one week. However, they emphasized that hourly, daily and even weekly computations of snowmelt depths using the degree-hour method are not accurate. Hock (2003) agreed; the DD methodology works for average conditions at the catchment scale for temporal periods greater than several days. Hock (2003) pointed out that DD factors (ratios) vary directly as a function of time of year, physical surface properties and snowpack characteristics and that DD factors need to be adjusted to each application, hence treated as a calibration parameter.

### Methodology

A small (0.5 ha), open, relatively flat grassland was selected for the snowmelt runoff experiments. The site, the “research snowpack lysimeter site,” is located immediately north of Riding Mountain National Park Maintenance Compound; UTM E433270, N5611988, Zone 14, NAD83 at an elevation of approximately 627 metres above sea level (ASL) (Figure 1).

A 10 square metre polygon collection platform constructed out of 0.75 inch plywood with 4” by 4” sides was lined with

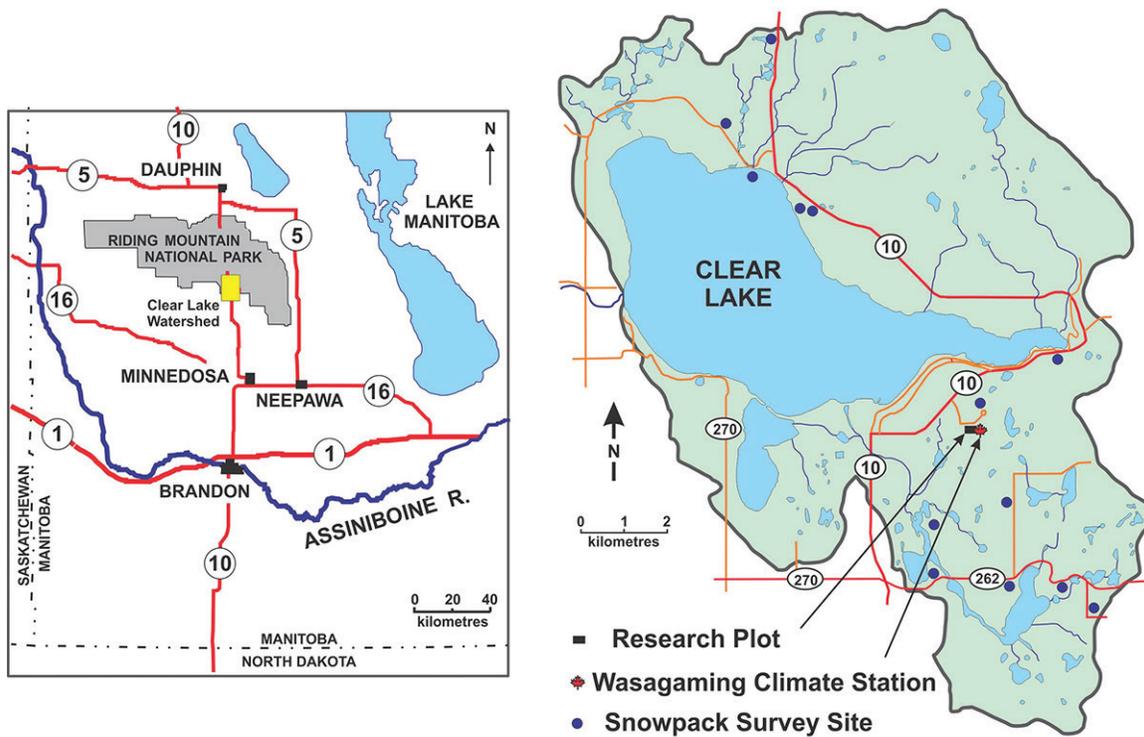


Figure 1: Clear Lake watershed.

high density (10 mm) polypropylene sheeting (Figure 2 and Plate 1). The surveyed slope of the snow lysimeter structure was  $2.82^\circ$  (0.0492) towards the south-southeast (azimuth  $145^\circ$ ) and funneled meltwaters into a dugout pit which contained a “cut down” 20 litre pail (approximately 18 L capacity). Runoff was monitored daily; more frequently during warm melt periods. The collection pail (tare weight = 805 g) and runoff were weighed. A unit (1.0 g) of runoff equals  $1.0 \text{ cm}^3$  volume. Runoff volumes were converted into snowpack water equivalent (SWE) mm depth of melt over the research plot (depth of melt = runoff volume / plot area).

An Environment Canada climatological data collection site (the Wasagaming Climatological Station) is situated in the Clear Lake watershed approximately 150 m east-southeast (azimuth 120) of the research plot (Plate 2). The site is located at the Park

Maintenance Compound near the townsite of Wasagaming (ID. 5013117); UTM E433381, N5611861, Zone 14, NAD83;  $50^\circ 39' 18''$  north,  $99^\circ 56' 31''$  west at an elevation of 627.40 ASL. Since 1966 (48 years) meteorological data have been collected at this site. Hourly temperatures are measured and the daily maximum, minimum and mean ambient temperature values recorded. Daily precipitation (mm water equivalent) and depth of snow (cm) are recorded. Other hourly meteorological variables measured include; standard pressure, dew point temperature, relative humidity, wind direction and velocity.

Two Onset U-series TidbiT v2 temperature loggers (3.0 cm by 4.1 cm by 1.7 cm) were placed near the base of the snowpack in mid-February and secured to framing rebar. This durable, waterproof instrument is designed for extended deployment measuring temperatures in rivers and lakes. The Tidbit v2 temperature logger uses an optical USB communications interface (via a compatible shuttle or base station) for launching and downloading recorded data. The instrument measures temperature from  $-20^\circ\text{C}$  to  $70^\circ\text{C}$  with a  $0.2^\circ\text{C}$  resolution and accuracy. Snowpack temperatures were measured hourly and mean daily values calculated. Table 1 and Figure 3 summarize the data.

## Observations and Results

### The 2010-2011 snowpack

Winter snowpack surveys were conducted at the research snowpack lysimeter site and along thirteen established snow survey courses in the Clear Lake Watershed (Figure 1). The snowpack survey courses sample snowpack depth, snow wa-

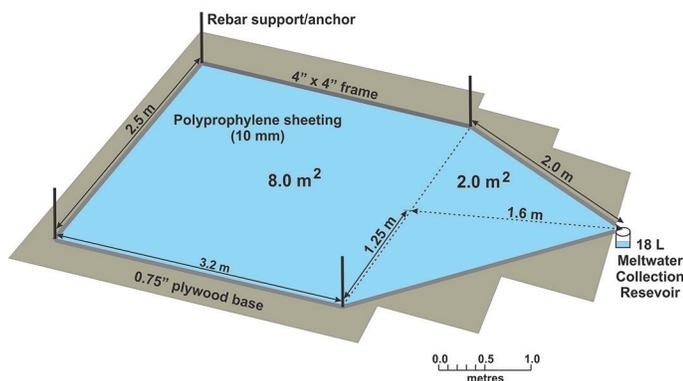


Figure 2: Schematic: snowpack lysimeter.



**Plate 1:** Snowpack lysimeter open site, Clear Lake watershed.



**Plate 2:** Wasagaming climatological station, Clear Lake watershed, Riding Mountain National Park, Manitoba.

Table 1: 2011 snowmelt runoff experimental data.

Ordinal	March	T <sub>max</sub>	T <sub>mean</sub>	T <sub>pack</sub>	Cold	Content	Thermal	DH	Acc DH	DHD	Acc DHD	DD	Acc DD	Melt	Acc Melt	Depth	Melt/DD	Melt/DHD
Date	Date	°C	°C	°C	(kJ m <sup>-2</sup> )	(mm D <sub>sw</sub> )	Quality	(Hours)	(Hours)	(Days)	(Days)	(Days)	(Days)	(g&cm <sup>3</sup> )	(g&cm <sup>3</sup> )	mm	(M)	(M)
60	3/1/2011	-19.6	-26.0	-4.2	921.9	2.8	1.03	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
61	3/2/2011	-14.8	-24.7	-4.4	965.9	2.9	1.03	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
62	3/3/2011	-11.8	-16.0	-4.4	965.9	2.9	1.03	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
63	3/4/2011	-11.5	-16.5	-3.6	790.2	2.4	1.02	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
64	3/5/2011	13.7	-17.1	-3.0	658.5	2.0	1.02	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
65	3/6/2011	-11.5	-21.1	-2.9	636.6	1.9	1.02	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
66	3/7/2011	-14.1	-25.3	-3.5	768.3	2.3	1.02	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
67	3/8/2011	-9.8	-18.4	-4.1	900.0	2.7	1.03	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
68	3/9/2011	-6.8	-14.9	-3.7	812.2	2.5	1.02	0.0	0.0	0.00	0.00	0.0	0.0	0	0	0.000	0.000	0.000
69	3/10/2011	1.9	-11.2	-3.3	724.4	2.2	1.02	2.9	2.9	0.12	0.12	0.0	0.0	0	0	0.000	0.000	0.000
70	3/11/2011	0.6	-9.0	-2.3	504.9	1.5	1.01	0.3	3.2	0.01	0.13	0.0	0.0	0	0	0.000	0.000	0.000
71	3/12/2011	-9.1	-15.3	-2.0	439.0	1.3	1.01	0.0	3.2	0.00	0.13	0.0	0.0	0	0	0.000	0.000	0.000
72	3/13/2011	-4.6	-15.4	-2.6	570.7	1.7	1.02	0.0	3.2	0.00	0.13	0.0	0.0	0	0	0.000	0.000	0.000
73	3/14/2011	4.4	-5.6	-2.8	638.2	2.0	1.02	19.3	22.5	0.80	0.94	0.0	0.0	0	0	0.000	0.000	0.000
74	3/15/2011	2.7	-2.3	-1.4	319.1	1.0	1.01	19.2	41.7	0.80	1.74	0.0	0.0	388	388	0.039	0.000	0.049
75	3/16/2011	3.6	-1.9	-0.3	68.4	0.2	1.00	15.6	57.3	0.65	2.39	0.0	0.0	306	694	0.031	0.000	0.047
76	3/17/2011	-0.7	-7.8	0.1	0.0	0.0	1.00	0.0	57.3	0.00	2.39	0.0	0.0	7982	8676	0.798	0.000	0.000
77	3/18/2011	-4.8	-12.8	0.1	0.0	0.0	1.00	0.0	57.3	0.00	2.39	0.0	0.0	0	8676	0.000	0.000	0.000
78	3/19/2011	2.7	-2.9	0.1	0.0	0.0	1.00	3.6	60.9	0.15	2.54	0.0	0.0	0	8676	0.000	0.000	0.000
79	3/20/2011	-0.9	-2.7	0.0	0.0	0.0	1.00	0.0	60.9	0.00	2.54	0.0	0.0	0	8676	0.000	0.000	0.000
80	3/21/2011	-0.3	-1.8	0.0	0.0	0.0	1.00	0.0	60.9	0.00	2.54	0.0	0.0	604	9280	0.060	0.000	0.000
81	3/22/2011	-1.6	-4.5	0.1	0.0	0.0	1.00	0.0	60.9	0.00	2.54	0.0	0.0	0	9280	0.000	0.000	0.000
82	3/23/2011	-4.5	-13.3	-0.1	22.8	0.1	1.00	0.0	60.9	0.00	2.54	0.0	0.0	0	9280	0.000	0.000	0.000
83	3/24/2011	-0.7	-13.7	-0.8	182.3	0.6	1.00	0.0	60.9	0.00	2.54	0.0	0.0	0	9280	0.000	0.000	0.000
84	3/25/2011	-3.1	-14.4	-1.7	387.5	1.2	1.01	0.0	60.9	0.00	2.54	0.0	0.0	534	9814	0.053	0.000	0.000
85	3/26/2011	-1.2	-12.1	-2.3	524.2	1.6	1.01	0.0	60.9	0.00	2.54	0.0	0.0	0	9814	0.000	0.000	0.000
86	3/27/2011	-2.6	-13.5	-2.6	592.6	1.8	1.02	0.0	60.9	0.00	2.54	0.0	0.0	0	9814	0.000	0.000	0.000
87	3/28/2011	-0.7	-10	-2.5	569.8	1.7	1.02	0.0	60.9	0.00	2.54	0.0	0.0	0	9814	0.000	0.000	0.000
88	3/29/2011	-0.7	-10.7	-2.4	744.6	2.2	1.01	0.0	60.9	0.00	2.54	0.0	0.0	0	9814	0.000	0.000	0.000
89	3/30/2011	0.5	-1.8	-1.8	558.5	1.7	1.01	0.7	61.6	0.03	2.57	0.0	0.0	0	9814	0.000	0.000	0.000
90	3/31/2011	3.7	0.7	-0.8	248.2	0.7	1.00	13.4	75.0	0.56	3.13	0.7	0.7	180	9994	0.018	0.026	0.032

Ordinal	April	T <sub>max</sub>	T <sub>mean</sub>	T <sub>pack</sub>	Cold	Content	Thermal	DH	Acc DH	DHD	Acc DHD	DD	Acc DD	Melt	Acc Melt	Depth	Melt/DD	Melt/DHD
Date	Date	°C	°C	°C	kJ m <sup>-2</sup>	mm D <sub>sw</sub>	Quality	(Hours)	(Hours)	(Days)	(Days)	(Days)	(Days)	(g&cm <sup>3</sup> )	(g&cm <sup>3</sup> )	mm	(M)	(M)
91	4/1/2011	6.8	1.6	-0.1	31.0	0.1	1.00	51.3	126.3	2.14	5.26	1.6	2.3	8539	18533	0.854	0.534	0.399
92	4/2/2011	8.0	-0.6	0.2	0.0	0.0	1.00	60.3	186.6	2.51	7.78	0.0	2.3	6677	25210	0.668	0.000	0.266
93	4/3/2011	2.4	-0.3	0.2	0.0	0.0	1.00	9.3	195.9	0.39	8.16	0.0	2.3	1482	26692	0.148	0.000	0.382
94	4/4/2011	2.3	-4.2	0.2	0.0	0.0	1.00	11.7	207.6	0.49	8.65	0.0	2.3	3924	30616	0.392	0.000	0.805
95	4/5/2011	6.3	-1.7	0.3	0.0	0.0	1.00	40.1	247.7	1.67	10.32	0.0	2.3	24622	55238	2.462	0.000	1.474
96	4/6/2011	5.6	-1.9	0.3	0.0	0.0	1.00	32.3	280.0	1.35	11.67	0.0	2.3	31680	86918	3.168	0.000	2.354
97	4/7/2011	7.8	-0.6	0.3	0.0	0.0	1.00	59.7	339.7	2.49	14.15	0.0	2.3	56430	143348	5.643	0.000	2.269
98	4/8/2011	5.7	-1.2	0.2	0.0	0.0	1.00	43.1	382.8	1.80	15.95	0.0	2.3	40230	183578	4.023	0.000	2.240
99	4/9/2011	5.6	1.6	0.2	0.0	0.0	1.00	52.5	435.3	2.19	18.14	1.6	3.9	68660	252238	6.866	4.291	3.139
100	4/10/2011	12.0	3	0.5	0.0	0.0	1.00	109.9	545.2	4.58	22.72	3.0	6.9	261988	514226	26.199	8.733	5.721
101	4/11/2011	12.9	3.5	0.6	0.0	0.0	1.00	102.3	647.5	4.26	26.98	3.5	10.4	269380	783606	26.938	7.697	6.320
102	4/12/2011	6.5	1.3	0.7	0.0	0.0	1.00	78.4	725.9	3.27	30.25	1.3	11.7	51870	835476	5.187	3.990	1.588
103	4/13/2011	-1.3	-7.1	-2.0	28.8	0.1	1.00	0.0	725.9	0.00	30.25	0.0	11.7	36918	872394	3.692	0.000	0.000
104	4/14/2011	2.0	-5.4	-2.0	287.6	0.8	1.01	5.5	731.4	0.23	30.48	0.0	11.7	23786	896180	2.379	0.000	10.379
105	4/15/2011	2.0	-0.7	-1.3	186.9	0.5	1.01	4.2	735.6	0.18	30.65	0.0	11.7	4420	900600	0.442	0.000	2.526
106	4/16/2011	-0.1	-2.1	-0.3	43.1	0.1	1.00	0.0	735.6	0.00	30.65	0.0	11.7	3480	904080	0.348	0.000	0.000
107	4/17/2011	-1.1	-3.7	-0.7	100.7	0.3	1.00	0.0	735.6	0.00	30.65	0.0	11.7	3210	907290	0.321	0.000	0.000
108	4/18/2011	1.3	-4.2	-0.1	14.4	0.0	1.00	3.5	739.1	0.15	30.80	0.0	11.7	12070	919360	1.207	0.000	8.277
109	4/19/2011	4.3	-4.1	0.3	0.0	0.0	1.00	30.7	769.8	1.28	32.08	0.0	11.7	45760	965120	4.576	0.000	3.577
110	4/20/2011	5.7	-2.3		0.0	0.0	1.00	45.3	815.1	1.89	33.96	0.0	11.7	121690	1086810	12.169	0.000	6.447
111	4/21/2011	8.8	1.5		0.0	0.0	1.00	53.3	868.4	2.22	36.18	1.5	13.2	116020	1202830	11.602	7.735	5.224
112	4/22/2011	7.4	1.7		0.0	0.0	1.00	63.6	932.0	2.65	38.83	1.7	14.9	46760	1249590	4.676	2.751	1.765
113	4/23/2011	10.4	1.9		0.0	0.0	1.00	96.1	1028.1	4.00	42.84	1.9	16.8	7850	1257440	0.785	0.413	0.196
114	4/24/2011	12.1	4.6					117.5	1145.6	4.90	47.73	4.6	21.4					
115	4/25/2011	8.8	4.4					108.5	1254.1	4.52	52.25	4.4	25.8					
116	4/26/2011	16.5	8.1					168.2	1422.3	7.01	59.26	8.1	33.9					
117	4/27/2011	17.4	7.8					183.4	1605.7	7.64	66.90	7.8	41.7					
118	4/28/2011	16.3	7.5					205.1	1810.8	8.55	75.45	7.5	49.2					
119	4/29/2011	11.7	5.9					159.6	1970.4	6.65	82.10	5.9	55.1					
120	4/30/2011	0.0	-4.2					0.0	1970.4	0.00	82.10	0.0	55.1					
<b>Totals</b>								<b>1028.1</b>		<b>42.84</b>		<b>16.8</b>		<b>1257440</b>		<b>125.74</b>	<b>36.169</b>	<b>65.475</b>
<b>Mean</b>		<b>0.4</b>	<b>-7.1</b>	<b>-1.3</b>													<b>4.02</b>	<b>2.85</b>

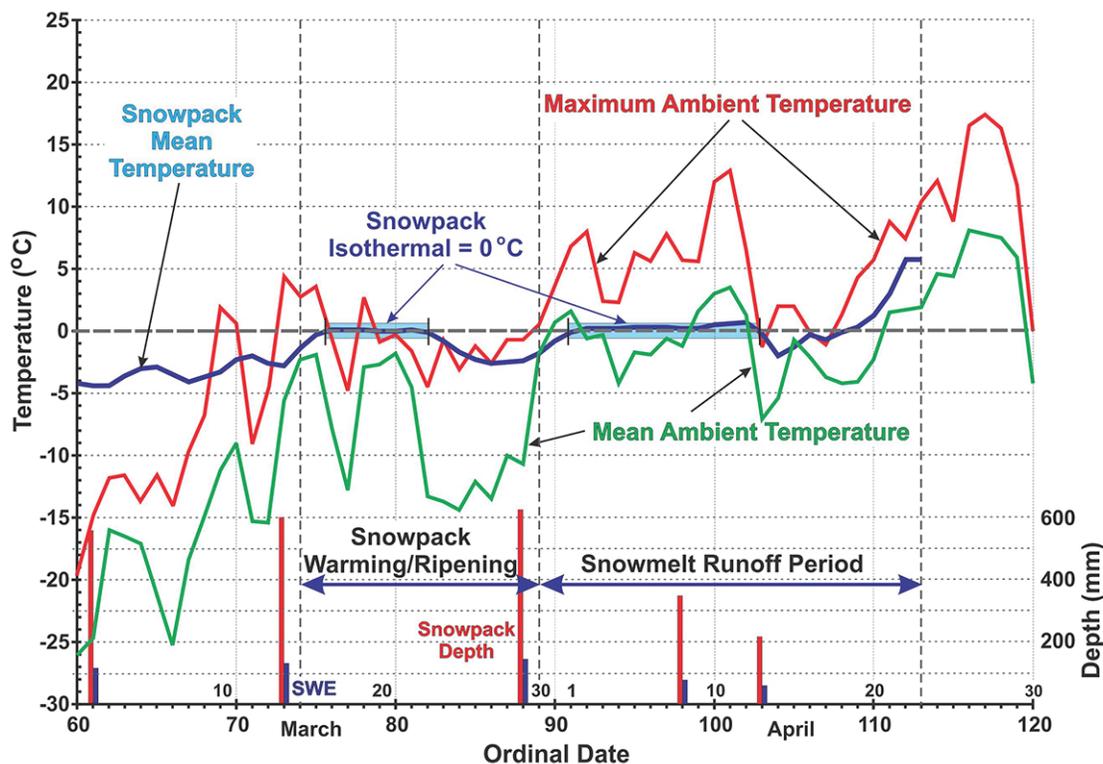


Figure 3: 2011 ambient and snowpack temperatures.

ter equivalent (SWE) depth and snowpack mean density over differing cover types: deciduous, coniferous and mixed forest, open meadows, pastures and cropped fields, aspen woodlots, wetlands and lake ice. Sampling began on November 30, 2010 and continued monthly throughout the winter accumulation period. Final snowpack survey measurements on April 27, 2011, indicated that the snowpack in the Clear Lake watershed had melted in open areas including the research lysimeter site.

The March 29 snowpack represents the maximum measured accumulation of snowfall during the 2010-2011 winter season. Mean snowpack depth in the Clear Lake watershed was 57.1 cm, with a standard deviation of 14.9 cm and a calculated coefficient of variation ( $C = \sigma / \mu$ ) equal to 0.26 (Hofer et al. 2011). The overall mean SWE depth on the Clear Lake watershed was calculated to be 12.6 cm,  $\pm 3.0$  cm. Snowpack densities recorded at the survey sites located in the Clear Lake watershed averaged  $227 \text{ kg m}^{-3} \pm 41 \text{ kg m}^{-3}$  (Hofer et al. 2011). At the snowpack lysimeter site, mean snowpack depth was 61.3 cm, SWE depth 15.0 cm and the snowpack density was calculated to be  $245 \text{ kg m}^{-3}$ , all values within the standard error of the Clear Lake watershed means.

### Snowpack lysimeter results

Table 1 Appendix I summarizes daily temperatures and melt volumes recorded at the research snowpack lysimeter site and the calculated daily snowpack parameters, degree-days, degree-hour-days and degree-day ratios.

Figure 4 illustrates snowpack depth, SWE depth, and the snowpack cold content expressed as a depth measured at the

snowpack lysimeter site for specific snowpack survey dates. Figure 8 also illustrates the recorded daily depth of melt hydrograph and snowpack depletion curves from the snowpack lysimeter site.

During the March 10-15 snowpack warming phase (Figure 4), a total of 41.7 degree-hours generated 1.74 DHDs. Absorbed all-wave radiation reduced snowpack cold content from  $812.2 \text{ kJ m}^{-2}$  calculated for March 9 to  $68.4 \text{ kJ m}^{-2}$ , the thermal quality of 1.02 calculated for March 9 declined to 1.00 on March 16 and 388 grams (0.04 mm SWE depth) of melt were collected.

The snowpack at the lysimeter site was “ripe” from March 16 to March 24 (Figure 4). Thermal quality was at or less than unity (1.00) and  $8589.6 \text{ cm}^3$  of melt drained through the snowpack (0.9 mm SWE depth). A cold snap (March 23-30) cooled the snowpack and cold content increased to  $744.6 \text{ kJ m}^{-2}$  on March 29, was subsequently reduced to  $248.2 \text{ kJ m}^{-2}$  on March 30 and by April 2 snowpack cold content was  $0.0 \text{ kJ m}^{-2}$ . Snowpack thermal quality increased throughout the cold snap to 1.02, declining to unity by March 31. Approximately  $534 \text{ cm}^3$  of residual meltwater drained from the snowpack on March 25. No additional melt was recorded during the March 24-30 cold period.

The snowpack melt over the lysimeter site began on March 31, when the first recorded degree-day (DD) generated a continuous melt. From March 31 to April 23, 1083.8 degree-hours generated 45.2 DHDs, and 21.4 recorded DDs;  $1,247.63 \text{ kg}$  of melt was observed. The 2010-2011 snowpack at the research site was gone by April 24 2011 following 4.2 mm of warm rain between April 21-23.

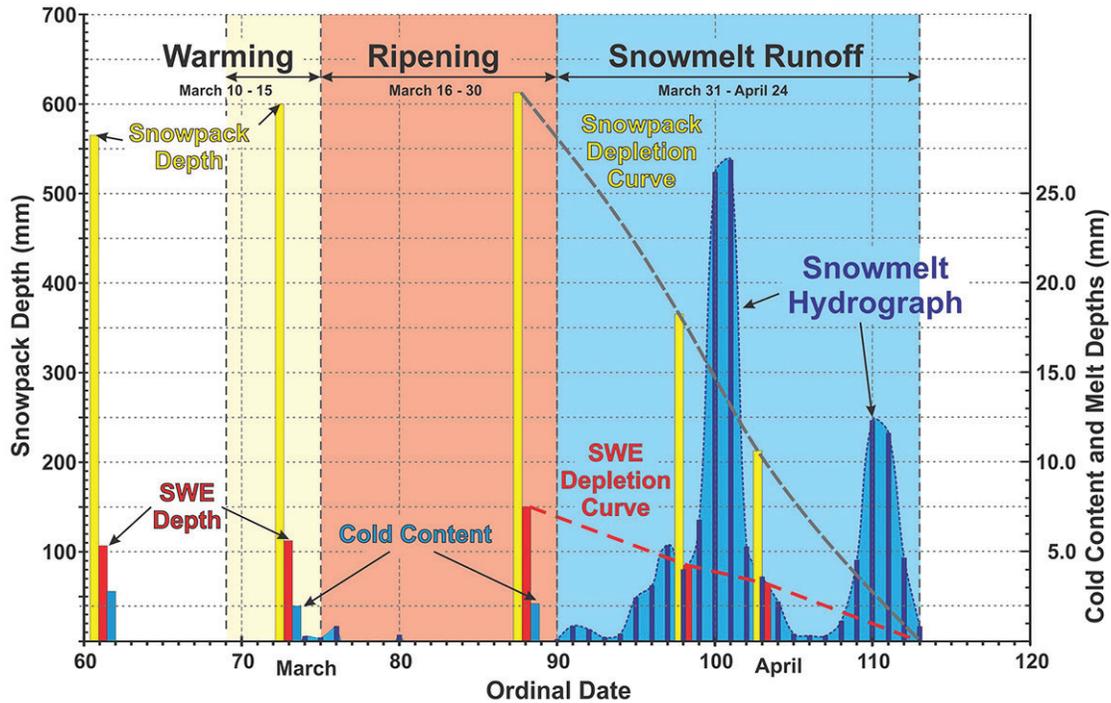


Figure 4: Snowpack, snow water equivalent and melt depths.

Throughout the ablation season (warming, ripening and melting phases) a total of 1028.1 degree-hours generated 42.84 DHDs; 16.8 DDs were recorded and 1,257.44 kg (litres) of melt were measured. That is the SWE of 125.7 mm depth (12.6 cm). Maximum measured SWE depth at the snowpack lysimeter site was 15.0 cm.

### Calculation of the Degree-day Ratios

#### Calculation of degree-day ratios based on empirical data

Table 1 in Appendix 1 includes the calculated daily melt ratios (DD ratios and DHD ratios). The mean DD ratio was 4.02 mm of melt °C<sup>-1</sup> day<sup>-1</sup> for the total ablation season March 10-April 23). The maximum calculated DD value was 8.70 mm °C<sup>-1</sup> day<sup>-1</sup> and zero DDs were recorded for 36 days of the 45-day ablation season. The comparable DHD data registers a mean

DHD ratio of 2.85 mm °C<sup>-1</sup> hour-day<sup>-1</sup>, a maximum calculated DHD ratio of 10.40 mm °C<sup>-1</sup> hour-day<sup>-1</sup> and zero DHDs for 22 days of the 45-day ablation period.

DD melt ratios ( $M_i$ ) vary significantly but generally increase throughout the ablation season (Linsley 1943, Weiss and Wilson 1958, McKay 1968, Grange and Male 1978, Rango and Martinec 1995, Hook 1999). Rango and Martinec (1995) suggested weekly or biweekly means can smooth daily variations, giving a regional  $M_i$  that generates good results. Consequently, DD ratios have been calculated for the warming/ripening phase (March 10-March 30), the early melt March 31- April 8), mid-melt (April 9 – April 14) and the late melt phase (April 15- April 23). These are summarized in Table 2. Melt ratios in Table 2 are based on the total volume of melt per total accumulated DDs or DHDs.

DD melt ratios for early melt, mid-melt, late melt and total melt exceed 7.0 mm °C<sup>-1</sup> day<sup>-1</sup>. DHD ratios range from 1.30 mm °C<sup>-1</sup> hour-day<sup>-1</sup> during early melt to 4.90 mm °C<sup>-1</sup> hour-day<sup>-1</sup> for the mid-melt period (Table 2). The DHD melt ratio for the warming/ripening season was 0.38 mm °C<sup>-1</sup> day<sup>-1</sup>. Mean melt ratios for the ablation season were 7.48

mm °C<sup>-1</sup> day<sup>-1</sup> and 2.93 mm °C<sup>-1</sup> hour-day<sup>-1</sup> (Table 2).

Figure 5 illustrates the diurnal variation in DD ratios. Figure 6 shows the diurnal variation in DHD ratios, calculated for the research snowpack lysimeter site. The graphs indicate periodic variation in the DD and DHD ratios associated with cold periods but show

Table 2: Calculated melt ratios during the 2011 ablation season.

Phase	Date	Melt Volume g & cm <sup>3</sup>	Accumulated Degree-Days	Accumulated Degree-Hour-Days	DD Melt Ratio	DHD Melt Ratio
Warming/Ripening	March 10-30	9814	0	2.56		0.38
Early Melt	March 31 - April 8	173764	2.3	13.40	7.55	1.30
Mid-Melt	April 9 - April 14	712602	9.4	14.53	7.58	4.90
Late Melt	April 15 - April 23	361260	5.1	12.37	7.08	2.92
Total Melt	March 31 - April 23	1247626	16.8	40.30	7.43	3.10
Ablation Season	March 10 - April 23	1257440	16.8	42.86	7.48	2.93

DD Melt Ratio in mm °C<sup>-1</sup> day<sup>-1</sup>

DHD Melt Ratio in mm °C<sup>-1</sup> hour-day<sup>-1</sup>

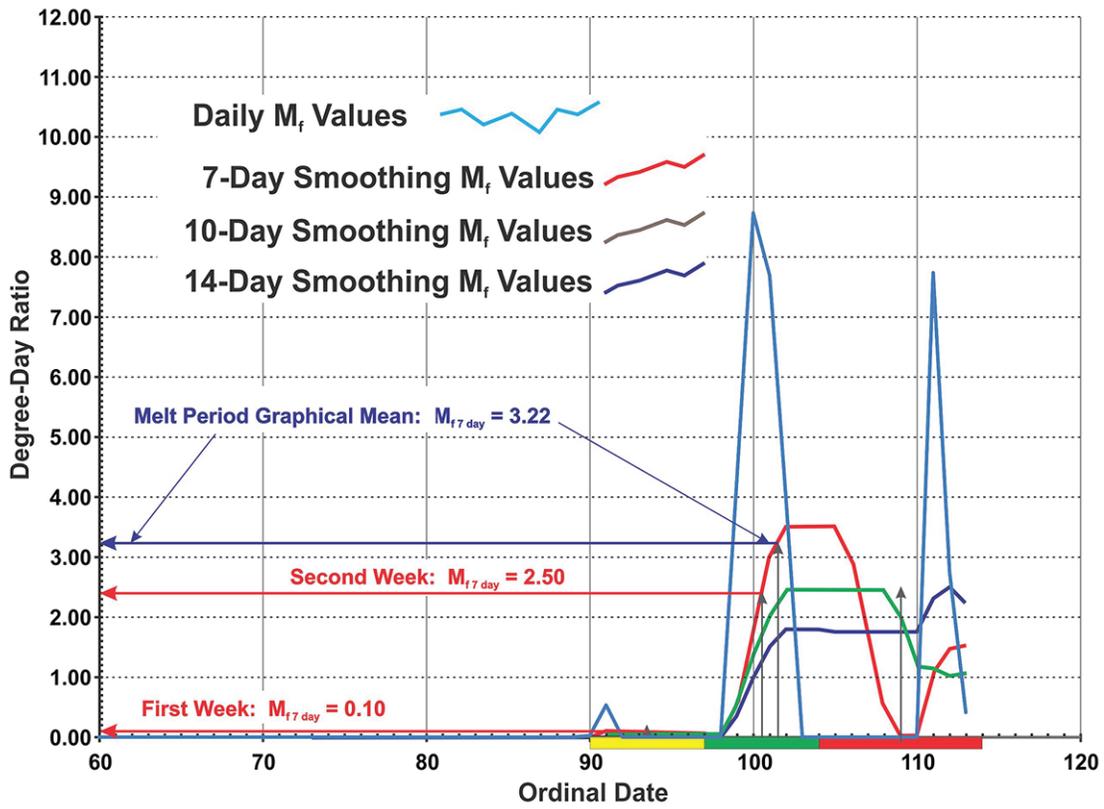


Figure 5: Diurnal variation in degree-day ratios.

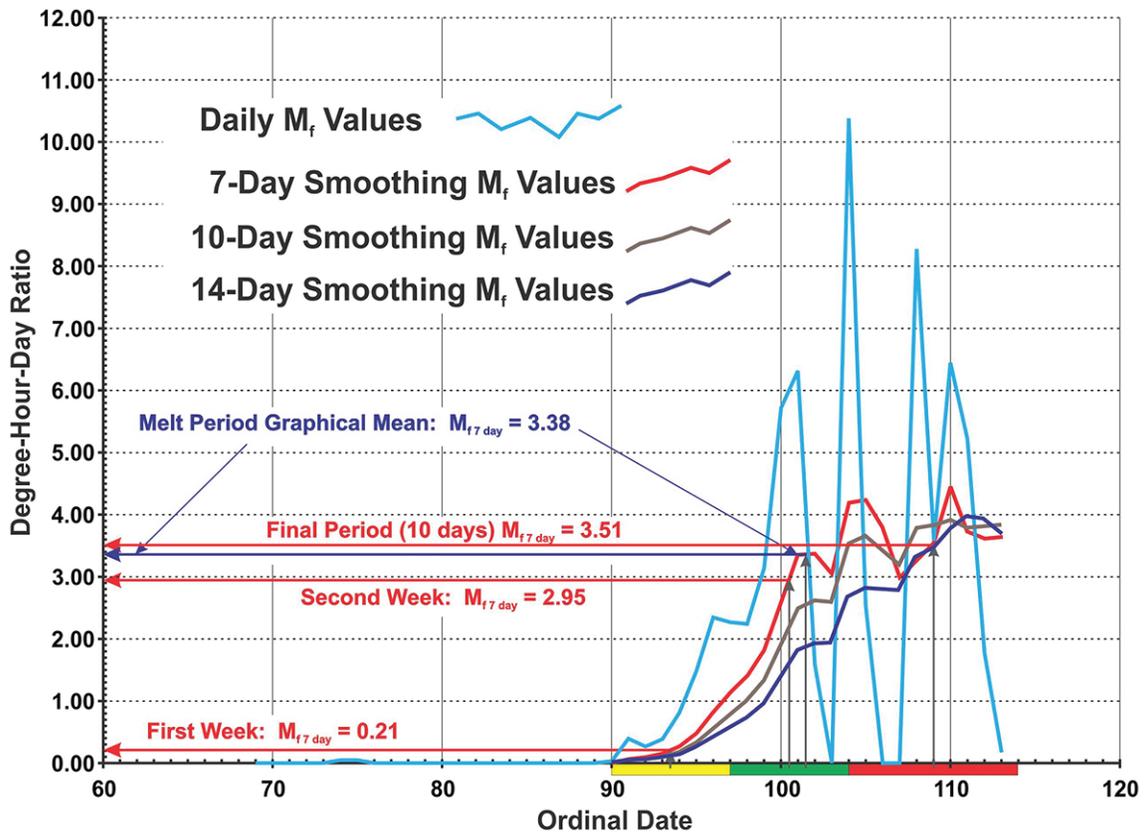


Figure 6: Diurnal variation in degree-hour-day ratios.

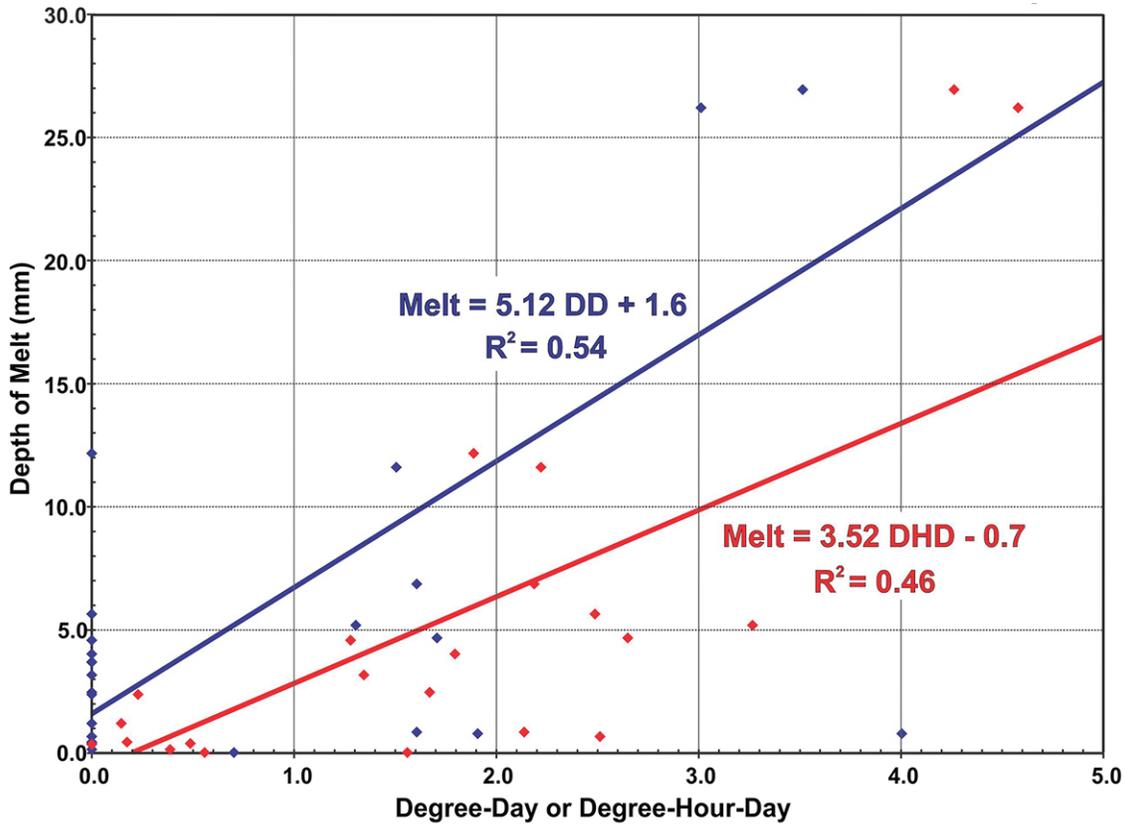


Figure 7: Regression plot for 2011 melt period.

they generally increase through the early and mid-melt periods. A seven-day running mean smoothing function supports this general trend (Figure 5). Weekly means were derived from the plot and are summarized in Table 4. Ten-day and 14-day running mean smoothing functions generate slightly smaller weekly means (Figures 5 and 6). Specific values are included in Table 4 and addressed in the discussion portion of this paper.

**Calculation of degree-day ratios based on regression analysis**

Linear regression analysis has been employed to determine DD melt ratios despite concerns regarding the general assumptions of the linear regression model, specifically the assumptions of linearity, independence, homoscedasticity and normality of errors. For comparative reasons a linear regression analysis was performed on the DD data and DHD data. Graphical results for the melt season data (March 31-April 23) are illustrated in Figure 7.

There is considerable scatter in the data and the respective regression equations can account for approximately 50 percent of the variation; R2 values are not considered useful for this study. The  $M_f$  for DDs was  $5.12 \text{ mm } ^\circ\text{C}^{-1} \text{ day}^{-1}$ ; the DHD  $M_f$  was  $3.52 \text{ mm } ^\circ\text{C}^{-1} \text{ hour-day}^{-1}$ ; both values are comparable to respective empirical mean melt ratio values.

**Calculation of degree-day ratios based on snowpack densities**

Martinec 1960 and Kuusisto 1980 suggest that approximately weekly mean melt ratios are linearly related to snowpack density. Table 3 summarizes snowpack density estimates on various dates and calculated melt ratios based on Martinec (1960) and Kuusisto (1980) functions.

Mean snowpack density in the warming phase (March 10-15) is  $197 \text{ kg m}^{-3}$ ; the Martinec (1960) melt factor  $M_f$  is calculated to be  $2.17 \text{ mm } ^\circ\text{C} \text{ day}^{-1}$ . The Kuusisto (1980) degree-

Table 3: Snowpack density and melt ratios.

Date	2/28/2011	14/03/2011	29/03/2011	8/4/2011	13/04/2011	20/04/2011
Site	<b>Snowpack Density</b>	$\rho_s$	$\rho_s$	$\rho_s$	$\rho_s$	$\rho_s$
Open Meadow	206	204	211	241		
Pasture	210	207	238	296		
Alfalfa	185	190	216	227		
Stubble	197	214	285	293		
Lysimeter Plot	188	180	245	232	307	*307
<b>Mean</b>	<b>197</b>	<b>199</b>	<b>239</b>	<b>258</b>	<b>307</b>	<b>307</b>
<b>Standard Deviation</b>	<b>11</b>	<b>14</b>	<b>29</b>	<b>34</b>		
<b>Melt Ratios</b>	<b>2/28/2011</b>	<b>14/03/2011</b>	<b>29/03/2011</b>	<b>8/4/2011</b>	<b>13/04/2011</b>	<b>20/04/2011</b>
$M_f$ (Martinec 1960)	2.17	2.19	2.63	2.84	3.38	3.38
$M_f$ (Kuusisto 1980)	3.63	3.66	4.45	4.81	5.78	5.78

\* estimate      Snowpack density in  $\text{kg m}^{-3}$       Melt Ratios in  $\text{mm } ^\circ\text{C}^{-1} \text{ day}^{-1}$

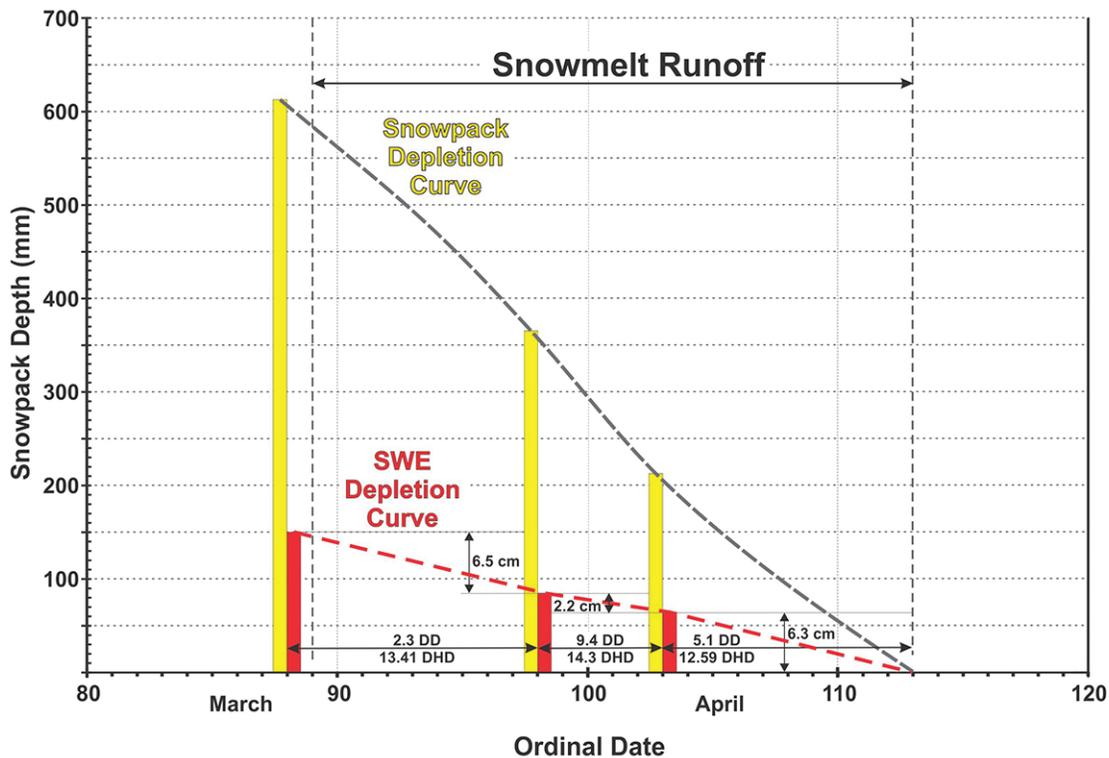


Figure 8: Snowpack and snow water equivalent depletion curves.

day factor  $DD_f$  equals  $3.63 \text{ mm } ^\circ\text{C day}^{-1}$ . During the ripening phase (March 16-24-30) mean snowpack density is estimated to be  $(197+239)/2 = 218 \text{ kg m}^{-3}$ .  $M_f$  is calculated to be  $2.39 \text{ mm } ^\circ\text{C day}^{-1}$ ;  $DD_f = 4.03 \text{ mm } ^\circ\text{C day}^{-1}$ . Mean snowpack density in the early melt phase (March 31-April 14) is estimated to be  $(239+258+307)/3 = 268 \text{ kg m}^{-3}$ .  $M_f = 2.94 \text{ mm } ^\circ\text{C day}^{-1}$ ;  $DD_f = 5.03 \text{ mm } ^\circ\text{C day}^{-1}$ . By the late melt phase (April 15-23) snowpack density had increased to  $307 \text{ kg m}^{-3}$ ;  $M_f = 3.38 \text{ mm } ^\circ\text{C day}^{-1}$ ,  $DD_f = 5.78 \text{ mm } ^\circ\text{C day}^{-1}$ . Assuming the snowpack density remains at least at  $307 \text{ kg m}^{-3}$  from April 14 to April 23, mean snowpack density throughout the total melt season is calculated to be  $278 \text{ kg m}^{-3}$  and respective degree-day melt ratios are  $M_f = 3.06 \text{ mm } ^\circ\text{C day}^{-1}$ ,  $DD_f = 5.44 \text{ mm } ^\circ\text{C day}^{-1}$ . The Martinec 1960 and Kuusito 1980 snowpack density functions appear to provide reasonable estimates of degree-day melt ratios in the Clear Lake watershed.

#### Calculation of degree-day ratios based on snowpack depletion

Melt ratios are frequently derived from the SWE depletion over a given period of time (Martinec 1960, McGuire 1997, Kane et al. 1997 and DeWalle et al. 2002). Figure 8 illustrates the snowpack depth and water equivalent depth depletion from March 29 to April 23, 2011.

From March 31 to April 8 (early melt) a 6.5 cm SWE loss was recorded for 2.3 DDs and 13.41 DHDs. The calculated melt ratios for the early melt are  $28.26 \text{ mm } ^\circ\text{C day}^{-1}$  and  $4.85 \text{ mm } ^\circ\text{C hour-day}^{-1}$ , respectively. For the April 9 to April 14 mid melt period, 2.2 cm SWE melt was recorded during 9.4 DDs and 14.3 DHDs. The calculated melt ratios are  $2.34 \text{ mm } ^\circ\text{C day}^{-1}$  and

$1.54 \text{ mm } ^\circ\text{C hour-day}^{-1}$ , respectively. The remaining late melt of 6.3 cm SWE occurred over 5.1 DDs and 12.59 DHDs. Melt ratios are calculated to be  $12.35 \text{ mm } ^\circ\text{C day}^{-1}$  and  $5.00 \text{ mm } ^\circ\text{C hour-day}^{-1}$ , respectively. The overall melt ratios calculated for the total melt season were 15.0 cm SWE loss in 16.8 DDs and 40.31 DHDs; respectively a  $8.92 \text{ mm } ^\circ\text{C day}^{-1}$  and  $3.72 \text{ mm } ^\circ\text{C hour-day}^{-1}$ .

Short term (approximately weekly) melt ratios derived from snowpack depletion curves are variable and appear to be consistent with DD ratios derived by other methodologies and from empirical data.

## Discussion

Table 4 summarizes  $M_f$  calculated for the open site lysimeter research plot in this study. The active ablation period began on March 10 and concluded on April 23. Snowpack warming and ripening took place between March 10 and March 30. The melting snowpack phase began on March 31 and has been subdivided into three periods; early melt (March 31 to April 8), mid-melt (April 9 to April 14) and late melt (April 15 to April 23).

During the 24-day melt season (March 31 to April 23), there were nine days for which a DD ratio was calculated and recorded. DD ratios were variable throughout the melt phase ranging from  $0.26 \text{ mm } ^\circ\text{C day}^{-1}$  to  $8.73 \text{ mm } ^\circ\text{C day}^{-1}$ . The arithmetic mean DD ratio was calculated to be  $7.43 \text{ mm } ^\circ\text{C day}^{-1}$  for the total melt phase. The early melt mean DD ratio was  $7.55 \text{ mm } ^\circ\text{C day}^{-1}$ , mid-melt,  $7.58 \text{ mm } ^\circ\text{C day}^{-1}$  and late melt,  $7.08 \text{ mm } ^\circ\text{C day}^{-1}$  (Table 4).

**Table 4:** Comparison of melt ratios during the 2011 ablation season.

SNOWPACK PHASE	Warming	Ripening	Early Melt	Mid-Melt	Late Melt	Total Melt
DATES	March 10-15	March 16-30	March 31 - April 8	April 9 - April 14	April 15 - April 23	March 31 - April 23
METHODOLOGY	6 days	15 days	9 days	6 days	9 days	24 days
<b>Empirical Data</b>						
Mean Degree-day	***		7.55	7.58	7.08	7.43
7-Day Smoothing			0.10	2.50	***	3.22
10-Day Smoothing			0.08	1.69	1.19	1.69
14-Day Smoothing			0.05	1.25	1.78	2.00
Mean Degree-hour-day	0.38		1.30	4.90	2.92	3.10
7-Day Smoothing			0.21	2.95	3.51	3.38
10-Day Smoothing			0.15	2.29	3.85	2.54
14-Day Smoothing			0.11	1.60	3.48	1.88
<b>Regression</b>						
Degree-day				6.32	1.08	5.12
Degree-hour-day				4.79	1.28	3.52
<b>Snowpack Density Functions</b>						
Martinec 1960	2.17	3.39		2.94	3.38	3.06
Kuusito 1980	3.63	4.03		5.03	5.78	5.44
<b>Snowpack Depletion Curves</b>						
Degree-day			28.26	2.34	12.35	8.93
Degree-hour-day			4.85	1.54	5.00	3.72

 DD Melt Ratio in  $\text{mm } ^\circ\text{C}^{-1} \text{ day}^{-1}$ 

 DHD Melt Ratio in  $\text{mm } ^\circ\text{C}^{-1} \text{ hour-day}^{-1}$ 

Mean melt ratio = Total melt volume / accumulated Ddor DHD (for the designated period)

Similar to DD ratios, DHD ratios were variable throughout the snowpack melt phase ranging from  $0.32 \text{ mm } ^\circ\text{C hour-day}^{-1}$  to  $10.37 \text{ mm } ^\circ\text{C hour-day}^{-1}$ . The arithmetic mean DHD ratio was calculated to be  $3.10 \text{ } ^\circ\text{C hour-day}^{-1}$  for the total melt phase, a value considerably smaller than the  $7.43 \text{ mm } ^\circ\text{C day}^{-1}$  calculated mean DD ratio for the same period. Likewise, early melt  $1.30 \text{ mm } ^\circ\text{C hour-day}^{-1}$ , mid-melt  $4.90 \text{ mm } ^\circ\text{C hour-day}^{-1}$  and late melt  $2.92 \text{ mm } ^\circ\text{C hour-day}^{-1}$  ratios are less than respective mean DD ratios (Table 4).

Seven-day, 10-day and 14-day running mean smoothing functions have been employed to determine melt ratios for early, mid and late melt periods. Early melt, mid-melt and late melt DD ratios and DHD ratios are summarized in Table 4.

Smoothing results in smaller average melt ratios because below zero temperatures are included in the calculation of running means. Also 14-day smoothing generates smaller means than the 10-day smoothing and both generate smaller mean values than the 7-day running means for respective melt periods (Table 4).

Seven-day smoothing generates a melt season mean DD ratio ( $3.22 \text{ mm } ^\circ\text{C day}^{-1}$ ) similar to the seven-day smoothing melt season mean DHD ratio ( $3.38 \text{ mm } ^\circ\text{C hour-day}^{-1}$ ). The 14-day smoothing functions generate similar DD ( $2.00 \text{ mm } ^\circ\text{C day}^{-1}$ ) and DHD ( $1.88 \text{ mm } ^\circ\text{C hour-day}^{-1}$ ) melt season mean ratios. It should be noted that the 14-day smoothing function melt season ratios are considerably smaller than those generated by seven-day smoothing functions. Ten-day smoothing does not generate a DD ratio similar to the DHD ratio. Considering the overall length of the melt season in the Clear Lake watershed (24 days), seven-day smoothing appears to be the more appropriate averaging procedure. Other snowpack melt ratios have been calculated by least squares regression analysis, the application of the

Martinec 1960 and Kuusito 1980 snowpack density functions and the plotting of a snowpack water equivalent depletion curve (Table 4).

Table 5 summarizes relevant regional  $M_f$  found in the literature. Melt ratios for the Canadian Prairies appear to be consistent, ranging between  $0.6 \text{ mm } ^\circ\text{C day}^{-1}$  and  $2.8 \text{ mm } ^\circ\text{C day}^{-1}$  (Clark 1955, Granger and Male 1978, and McGuire 1997).

The McGuire 1997 DD melt ratio ( $2.78 \text{ mm } ^\circ\text{C day}^{-1}$ ) is a weighted average dependent on cover type and the percentage area of the specific cover type in the Clear Lake watershed. Snowpack ablation over the eight cover types common in the watershed is variable. The Clear Lake watershed is approximately 50 percent forest cover. Snowpack over urban lots, agricultural fields, lake ice, wetlands, and small open meadows melts earlier and depletes faster than snowpack under coniferous, deciduous and mixed forest cover. This implies that DD melt ratios over open areas are greater than average while forest cover melt ratios are less than average.

McGuire's (1997) mean DD ratio has been employed in the annual snowpack survey conducted in the Clear Lake watershed. Following melt, the actual recorded DDs, maximum SWE depth and McGuire's DD ratio is used to calculate the date of complete snowpack ablation. This date is then compared to observed data. Fifteen years of comparative analysis suggests that the  $2.78 \text{ mm } ^\circ\text{C day}^{-1}$  melt ratio can predict the date of total snowpack ablation in the Clear Lake watershed to within one day.

The research lysimeter open site melt ratios were expected to be slightly greater than the McGuire's 1997 weighted mean watershed ratio. The seven-day smoothing generates average melt season ratios that are approximately 19 percent larger than McGuire's 1997 weighted melt ratio. The DD melt ratio of  $3.22$

**Table 5:** Degree-day melt ratios found in the literature.

Clark 1955.	Red River basin, Manitoba	0.9 to 2.7 mm °C <sup>-1</sup> <sub>mean</sub> day <sup>-1</sup>
Clark 1955.	North Branch of Thames River basin, Southwestern Ontario	0.3 mm °C <sup>-1</sup> <sub>mean</sub> day <sup>-1</sup>
Pysklywee <i>et al.</i> 1968.	North Nashwaaksis forested stream basin, St. John River basin, New Brunswick	1.82 mm °C <sup>-1</sup> <sub>mean</sub> day <sup>-1</sup>
Granger and Male 1978.	Canadian Prairies	0.6 to 2.8 mm °C <sup>-1</sup> <sub>mean</sub> day <sup>-1</sup>
Louie and Hogg 1980.	Canadian Climate Stations	0.91 mm °C <sup>-1</sup> <sub>max</sub> day <sup>-1</sup>
McGuire 1997.	Clear Lake Watershed, Manitoba based on snowpack depletion	2.78 mm °C <sup>-1</sup> <sub>mean</sub> day <sup>-1</sup>

mm °C day<sup>-1</sup> is 16% greater and the 3.38 mm °C hour-day<sup>-1</sup> DHD melt ratio is approximately 22% greater than McGuire's 1997 2.78 mm °C day<sup>-1</sup>.

Linear regression (DDs versus melt volume), generates  $M_f$  of 5.12 mm °C day<sup>-1</sup>. The DHD versus melt volume regression results in  $M_f$  of 3.52 mm °C hour-day<sup>-1</sup>. Both values are similar to respective arithmetic mean melt ratios (Table 4).

The Martinec 1960 snowpack density function generates a 2.94 mm °C day<sup>-1</sup> early melt factor, a 3.38 mm °C day<sup>-1</sup> late melt factor and an overall melt factor of 3.06 mm °C day<sup>-1</sup>, values which are similar to the benchmark standards, the arithmetic mean DHD  $M_f$  and the DHD linear regression  $M_f$  (Table 4).

The Kuusito 1980 model however, results in respective melt factors of 5.03 mm °C day<sup>-1</sup>, 5.78 mm °C day<sup>-1</sup> and 5.44 mm °C day<sup>-1</sup>. These values are similar to the arithmetic mean DD  $M_f$  and the DD linear regression  $M_f$  (Table 4).

The calculated DHD depletion curve results in a melt ratio of 3.72 mm °C hour-day<sup>-1</sup>, a value similar to the 7-day smoothing DHD melt ratio (3.38 mm °C hour-day<sup>-1</sup>).

Degree-day methodology rarely provides estimates of runoff for the snowpack warming/ripening phase but the degree-hour-day approach can provide estimates of melt during this pre-melt period.

## Summary and Conclusions

This study empirically determined the melt coefficients throughout the melt-season for a small open grassland site in the Clear Lake watershed, Riding Mountain National Park. A 0.5 ha open relatively flat grassland with full sun exposure was selected for the snowmelt runoff experiments. A 10 m<sup>2</sup> plywood collection platform funneled meltwaters into a collection reservoir. Sample plot runoff was weighed daily. Mean ambient and snowpack temperatures were measured hourly and mean daily values calculated. Degree-days of melt are calculated based on cumulated degree-hours above 0.0 °C for a twenty-four period (degree-hour-days (DHD)).

The 2011 active ablation period began on March 10 and concluded on April 23. Snowpack warming and ripening took place between March 10 and March 30. The melting snowpack phase

began on March 31 and has been subdivided into three periods: early melt (March 31 to April 8), mid-melt (April 9 to April 14) and late melt (April 15 to April 23).

Degree-day and DHD melt ratios were variable throughout the 24-day snowpack melting phase (March 31-April 23). The arithmetic mean DD ratio was calculated to be 7.43 °C day<sup>-1</sup> for the total melt season, a value considerably greater than the 3.10 mm °C hour-day<sup>-1</sup> calculated mean DHD for the same period.

Seven-day smoothing generates a melt season mean DD ratio (3.22 mm °C day<sup>-1</sup>) similar to the seven-day smoothing melt season mean DHD ratio (3.38 mm °C hour-day<sup>-1</sup>). The open site seven-day smoothing  $M_f$  values are approximately 19 percent greater than McGuire's 1997 benchmark forested (50 percent) watershed mean melt ratio of 2.78 mm °C day<sup>-1</sup>. Ten-day and 14-day smoothing functions were not successful in generating melt season  $M_f$  values similar to McGuire's 1997 watershed mean melt ratio.

Other snowpack melt ratios were calculated by least squares regression analysis, the application of snowpack density functions, and the plotting of a snowpack water equivalent depletion curve.

The Martinec 1960 snowpack density function generates a 2.94 mm °C day<sup>-1</sup> early melt factor, a 3.38 mm °C day<sup>-1</sup> late melt factor and an overall melt factor of 3.06 mm °C day<sup>-1</sup>, values that are similar to the McGuire's 1997 benchmark watershed  $M_f$  and the seven-day smoothing  $M_f$  mean values.

Although the DD methodology rarely provides estimates of runoff for the snowpack warming/ripening phase, the DHD approach can provide estimates of melt during this period.

## Conclusions

For shallow ripe snowpacks containing less than 15.0 cm snow water equivalent that melt over a relatively short period (less than one month), a single DD or DHD melt ratio appears to be acceptable for the snowpack melting phase. Melt ratios must be determined for each cover type.

In Riding Mountain National Park, the arithmetic mean degree-day melt ratio tends to overestimate snowpack depletion. Consequently, a seven-day running mean smoothing func-

tion combined with a graphically determined mean for the total melt season is preferred. Alternatively, Martinec's 1960 density function based on a mean of weekly snowpack density estimations can be used to estimate the degree-day melt ratio.

### Acknowledgements

The author wishes to acknowledge the contributions to this research by R. Robinson, for the construction and placing of the snowpack lysimeter; D.B.W. Brown and E. Hofer for their assistance in the collection of the watershed and lysimeter site snowpack data; and R. Robinson, T. Sallows and R. Reside for the twice-daily collection of runoff data.

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