SNOWMELT IN A FOREST AND CLEARCUT

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ABSTRACT

Methods for obtaining daily snowmelt rates in forest and clearcut environments were evaluated at high elevation sites in the southern interior of British Columbia, Canada (Upper Penticton Creek Watershed Experiment). Snowmelt was measured during spring 1998 to 2002 in a clearcut with snowmelt lysimeters and calculated for the clearcut and a forest from the daily snow pack depth and snow density. Daily melt rate was calculated in the forest and clearcut from weather station data using an air temperature index method and with the energy balance. Measurements were used to calibrate clearcut and forest snow albedo models, to determine solar radiation transmission through the forest canopy and to calculate the canopy view factor for longwave radiation in the forest. Snow temperature measurements were used to define the beginning and end of the melt season when modelling snowmelt. Lysimeter and snow depth and density based measurements of snowmelt agreed quite well. The air temperature index method gave acceptable estimates of melt but tended to overestimate melt in the forest. The energy balance calculations slightly overestimated melt in the clearcut and slightly underestimated melt in the forest. Net radiation provides almost all the energy for melt in the forest and about 75% of the energy in the clearcut. Snowmelt rates of over 40 mm d^{-1} were measured in the clearcut and up to two thirds of this in the forest under the same weather condition

INTRODUCTION

Assessing the effects of forest harvesting on water quantity and quality requires the quantification of snowmelt at remote sites. This can be achieved through measurements such as snow surveys, snow pillows and lysimeters (Gray and Male 1981, Prévost et al. 1991, Anderton et al. 2004,Winkler et al. 2004). Snowmelt can be calculated with air temperature index equations or from the snowpack energy balance (Prévost et al. 1991, Link and Marks 1999, Kongoli and Band 2000, Thyer et al. 2004). Each of these techniques has limitations such as measurement resolution, ability to work in remote areas with limited maintenance, information requirements, and location specific calibration. This paper evaluates the ability of snowmelt lysimeters, snow depth plus density measurements, an air temperature index method and energy balance calculations to determine daily snowmelt in forests and clearcuts. The research was part of a project calibrating a watershed model for evaluating the affect of forest harvesting on stream flow in the southern interior of British Columbia (Thyer et al. 2004). We evaluate what is necessary to extrapolate site specific daily snowmelt within a watershed without resorting to the large amount of data and technical resources necessary to run watershed models.

METHODS

Site Description

The research was done in the 240 Creek watershed (49° 39’ 25”N, 119° 24’ 10”W) of the Upper Penticton Creek Watershed Experiment (Winkler et al. 2003). The watershed is typical of headwater streams in the drier Engelmann Spruce – Subalpine Fir Zone (Lloyd et al. 1990) on the Okanagan Plateau, southern interior of British Columbia. The snow pack starts to develop between mid October and early November and disappears between mid May and early June depending on the elevation and year. Peak snow pack water equivalent ranges from 250 to 450 mm. The forest consists of 125-year-old lodgepole pine with dominant and co-dominant trees 15 to 20 m tall at a stand density of 2000 stems ha^{-1} and canopy cover of 40%. The forest floor is partially covered with a layer of lichens, moss, grouseberry and woody debris that is less than 0.2 high. The forest site is at 1650 m elevation and the clearcut is about 0.5 km south at 1620 m on gently rolling topography. The clearcut had a partial cover of lodgepole pine seedlings and pinegrass.

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Weather Data

Measurements of solar radiation, air temperature and humidity, wind speed, snow temperature (soil/snow interface and 0.2 and 0.5 m into the pack), and precipitation were made in the clearcut. Hourly and daily averages, totals and maximum and minimum values were recorded on a data logger (Campbell Sci. Inc CR10) from 1998 to 2003. Snow albedo was measured in the clearcut during spring 2001 to 2003 using an Epply black and white pyranometer. Downward longwave radiation was measured during spring and summer 2003 with an Epply pyrgeometer. These radiation instruments and the weather station solarimeter were inter-compared during early summer 2003 with a Kipp and Zonen CNR1. This instrument separately measures the incident and reflected solar radiation and the longwave radiation from the sky and the surface. Hourly measurements of air temperature and humidity, snow temperature and snow depth were made in the forest using the same methods as in the clearcut. Epply pyranometers were used to measure snow albedo and shortwave radiation transmission in spring 2002 and the CNR1 was used for all radiation streams during 2003 in the forest. These are single location measurements and only daily averages and totals were used.

Snowmelt Measurement

Outflow from two snowmelt lysimeters was measured at the clearcut weather station. A lysimeter consists of a 2.4x1.2x0.1-m shallow open-topped box at the base of the pack draining into a buried tipping bucket (Winkler et al. 2004). The lysimeter box was slightly sloped to facilitate drainage. Daily melt, resolution of ±0.17 mm of melt, was obtained by summing output between 0500 and 0500 on consecutive days because the pack continues to drain after midnight.

Snow depth was measured at midnight with a sonar ranging sensor (Campbell Scientific Inc., UDG01). Depth was converted to snow water equivalent using the mean snow density obtained from biweekly 32-point snow survey made with a Federal snow tube over 0.5 ha adjacent to the forest and clearcut weather stations (Spittlehouse and Winkler 1996). Density was interpolated between measurement periods using snow temperature and air temperature to indicate the likelihood of the density changing. The manufacturer suggests an accuracy of ±10 mm for the depth measurement. Our experience with the sensor suggests that during the melt season we get better than this and have an uncertainty of ±2.5 mm in daily melt at peak densities. An error of 0.01 Mg m^{-3} in snow density results in an uncertainty of 2.5% in snow water equivalent, less than ±1 mm on the daily melt rate at peak melt. Combined measurement errors in depth and density likely result in an uncertainty of ±3 mm d^{-1} in melt.

Snowmelt Calculation

Snowmelt is calculated in two ways. The first approach uses a temperature index method where daily mean air temperature in the clearcut is regressed against snowmelt measured in the clearcut or forest. The method was calibrated with data for 1999 and is applied when the snow temperature is greater than -0.1°C and air temperature greater than –0.5°C.

The second approach uses the energy balance of a melting snow pack, i.e.,

$$Q_M = Q_{Rn} + Q_H + Q_E + Q_G + Q_P + Q_S \qquad [1]$$

where Q_M is the energy available to melt the snow (MJ m^{-2} d^{-1}). The other subscripts indicate the source of energy used for snowmelt, i.e., energy from net radiation (Rn), sensible heat (H), latent heat (E), soil heat (G) and rain (P), and change in heat storage in the pack (S). Q_G is neglected because it small (Adams *et al.* 1998). During melt Q_S is negligible because the snow pack is close to 0°C (Male and Gray 1981). Q_P depends on the temperature difference between the rain and the snow. Snow temperature data are used to indicate when the snow pack is ready to melt. The surface of a melting snow pack is assumed to be at 0°C and saturated. If mean daily air temperature is less than zero then the snow surface temperature is assumed equal to the air temperature. This equation can be applied on an hourly or daily basis (Anderson 1976, Pomeroy and Goodison 1998) and is applied on a daily basis in this paper.

Daily net radiation (Rn, MJ m^{-2} d^{-1}) to the snow pack is calculated from measured solar radiation and calculated albedo and longwave radiation, i.e.,

$$Rn = S_g - a_f S_g + L_d - L_u \qquad [2]$$

where S_g is the solar radiation received at the pack (MJ m^{-2} d^{-1}), a_f is the albedo of the snow, L_d is the downward longwave radiation (MJ m^{-2} d^{-1}), and L_u is the upward longwave radiation from the snow surface (MJ m^{-2} d^{-1}). Snow albedo is calculated using c0.85^N^b (Thyer et al. 2004), where c is a base albedo value, b is a decay coefficient and both depend on snow temperature and whether the snow is in the forest or clearcut. N is the number of days since the last snowfall up to a maximum value of 5. The longwave radiation depends on the temperature of the surface emitting the radiation, i.e., $\varepsilon\sigma T^4$, where ε is the emissivity, σ is the Stefan-Boltzman constant (4.9×10^{-9} MJ m^{-2} d^{-1} K^{-1}) and T is the surface temperature (K). Snow temperature is assumed to be 0°C for a melting snow pack (Bohren and Thorud 1973, Male and Gray 1981). The emissivity of the snow is 0.98. In the open, L_d is from the sky. The emissivity of the sky is $(1-0.84n)\varepsilon_{clear}+0.84n$, where n is the fraction of cloud cover $(1-S_{go}/S_{gclear})$, S_{go} is solar radiation above the canopy, S_{gclear} is the maximum clear-sky radiation at the ground for the day and ε_{clear} is the clear-sky emissivity (Spittlehouse 1989, Monteith and Unsworth 1990). At Upper Penticton Creek, $S_{gclear} = 18.9+12.7(\sin[0.0172(DoY-81)])$, where DoY is the day of the year and the sine is in radians. ε_{clear} is calculated using the Brunt formula $(0.53+0.206e_a^{0.5})$, where e_a is the mean daily vapour pressure.

Below a forest canopy, the solar and downward longwave radiation must be adjusted to allow for shading by the trees. Solar radiation below the canopy (S_{gc}) is τS_{go} where τ is the transmissivity and depends on canopy cover, fraction of diffuse radiation in S_{gc} and the time of year (Black et al. 1991, Pomeroy and Dion 1996). The downward longwave is a combination of radiation from the sky and from the trunks and foliage, i.e., $L_{dc} = fL_{dcanopy} + (1-f) L_d$, where f is the forest canopy view factor (Reifsnyder and Lull 1965, Black et al. 1991). $L_{dcanopy}$ is calculated assuming the foliage and trunks are at air temperature and an emissivity of 0.98. Multiple reflection of short or longwave radiation is not included.

Bulk transfer or exchange coefficients are used to calculate sensible and latent heat fluxes on hourly and daily time steps (Moore 1983, Prévost et al. 1991). A limitation with the daily time step approach is the assumption that a mean value of wind speed or the scalar gradient can represent a range of conditions through the day when relationships may be non-linear. Sensible heat flux (H, MJ m^{-2} d^{-1}) and latent heat flux (E, MJ m^{-2} d^{-1}) are given by

$$H = \rho_a c_{pa} D_H F(T_a - T_s), \quad E = \rho_a \lambda D_E\, F(0.622/p_a)(e_a - e_s) \qquad [3]$$

where ρ_a is air density (1.292 kg m^{-3} at sea level and 0°C), c_{pa} is specific heat of air at constant pressure (1.01×10^3 J kg^{-1} K^{-1}), λ latent heat of vapourization (2.5×10^6 J kg^{-1} at 0°C), D_H and D_E are the exchange coefficients (m s^{-1}), p_a is air pressure (kPa), T_a is the daily average air temperature (K), T_s is the daily average snow surface temperature (K), e_a is daily average vapour pressure of the air (kPa) and e_s is the vapour pressure at the snow surface (kPa). For a melting snow pack T_s is assumed to be 273.1 K (0°C), e_s is the saturated vapour pressure at this temperature and F is a unit conversion factor (86400 s d^{-1}/1000000 J MJ^{-1}). ρ_a is temperature and pressure (elevation) dependent, p_a is elevation dependent and λ varies with temperature. The exchange coefficients are assumed equal to the stability corrected (D_s, m s^{-1}) exchange coefficient for momentum (D_m, m s^{-1}) (Moore 1983). Thus, $D_m = k^2u_z[\ln(z/z_0)]^{-2}$, $D_s = D_m/(1 + 10R_b)$ for $R_b > 0$, $R_b = [g(T_a - T_s)z]/[T_a u_z^2]$, where $D_s=D_H=D_E$, k is von Karman's constant (0.41), u_z is the daily average wind speed (m s^{-1}) at the measurement height z (m), z_0 is the roughness length (0.004 m for a relatively smooth snow surface), R_b is the bulk Richardson number, and g is the gravitational constant (9.81 m s^{-2}). T_a and e_a should be measured at the same height as u. Generally, the atmosphere is stable during snowmelt. For neutral conditions ($R_b = 0$) $D_s = D_m$, and for unstable conditions ($R_b < 0$) $D_s = D_m (1 - 10R_b)$. Bulk transfer coefficients are presented in various forms in the literature. In some cases, the wind speed is not included in the coefficient and is explicit in the equations for H and E (Male and Gray 1981). The sensible and latent heat flux equations are applied below the canopy with wind speed reduced to 30% of that in the open. This will only approximate the fluxes because these equations simplify the flow process below the canopy. However, because these fluxes are small under the canopy and the atmosphere is stable, there should be only a minor error in the melt calculation.

Melt energy from rain percolating through the snow pack is $Q_P = \rho_w c_{pw} (T_P-T_s)P10^{-6}$, where ρ_w is the density of water (1000 kg m^{-3}), c_{pw} is the specific heat of water (4.18 kJ kg^{-1} K^{-1}), T_P is the temperature of the rain (K) assumed to be at air temperature, and P is the daily rainfall (mm d^{-1}).

The daily energy in Q_{Rn}, Q_H, Q_E and Q_P are converted to millimetres of melt water by multiplying by $(1000/[\rho_w\lambda_f B])$ where λ_f is the latent heat of fusion (0.333 MJ kg^{-1}) and B is the thermal quality of the snow (0.96) (Male and Gray 1981).

RESULTS

Lysimeter Outflow

At least one of the lysimeters worked each year. The usual reason for failure was a blockage of the drain by ice. Lysimeter outflow was correlated with the snow and air temperature. Outflow occurs when the snow pack is close to 0°C and the mean daily air temperature above 0°C (Figure 1). As expected warmer days tended to have greater outflow. Maximum daily outflow in the clearcut over the six years varied from 20 to 50 mm d^{-1}. Similar results were reported by Winkler et al. (2004) for a site about 200 km north. Total outflow from the lysimeters average 92% of the precipitation accumulated during the period of snow cover (R^2=0.82, n=6). This is excellent agreement allowing that some of the snow pack would be lost to sublimation and evaporation during the winter.

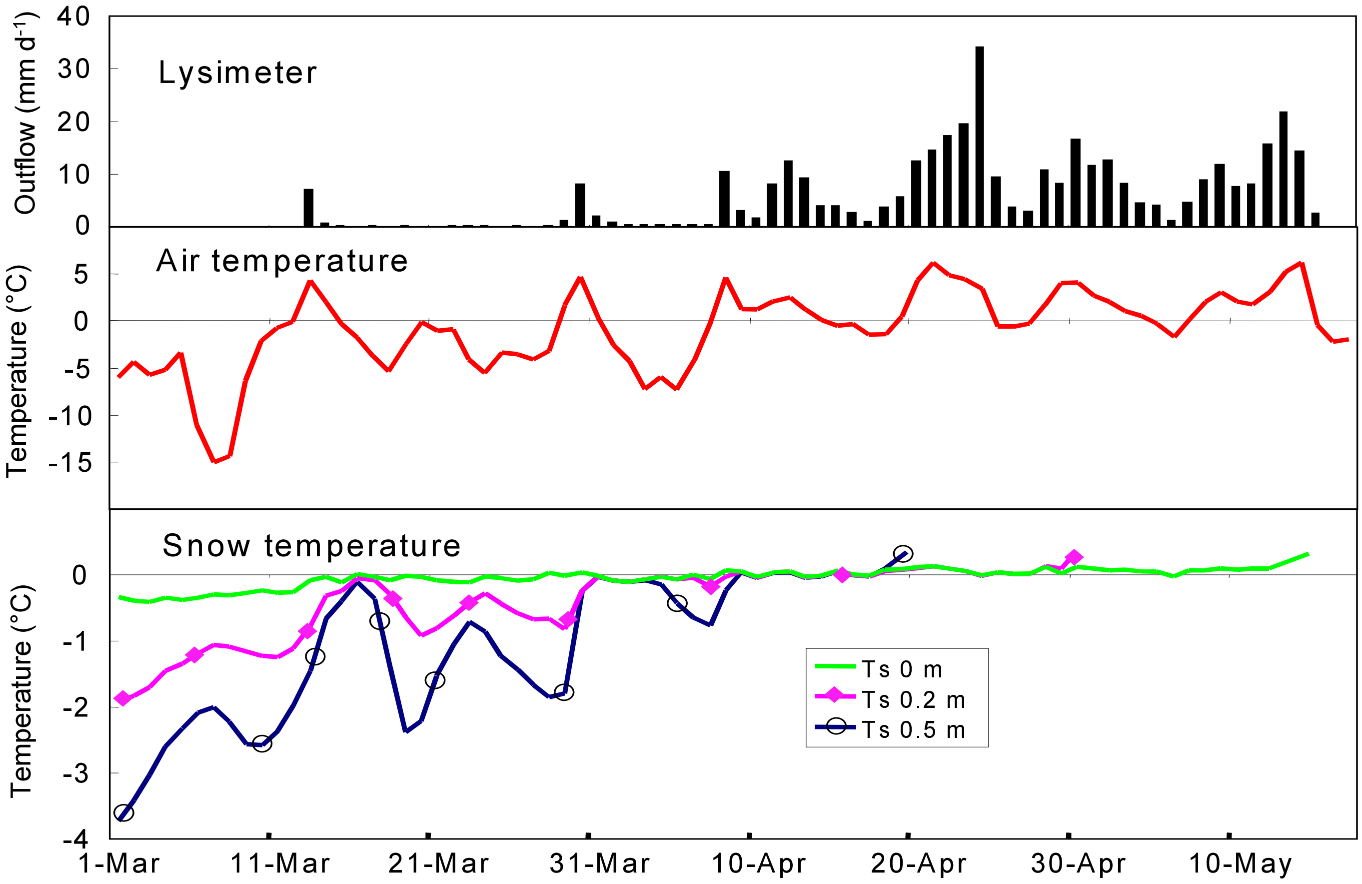

Figure 1. Daily lysimeter outflow, air temperature and snowpack temperature at 0.5, 0.2 and 0 m above the soil surface in the clearcut from March to May 2003.

Snowmelt from the Snow Depth and Density

The calculated snowmelt followed the trend in lysimeter outflow but there were discrepancies in daily flows. The sunny and warm 1998 melt season shows excellent agreement while the variability for the cooler 2002 melt season is typical of most years (Figure 2). A rainstorm interrupted the 1998 season where rain percolating through the pack probably enhanced outflow (indicated by the arrow in Figure 2). The snowmelt calculation is not particularly sensitive to the value of snow density. For example, in 1999 a density of 0.36 Mg m^{-3} used over the whole melt season gave 412 mm of melt, 0.4 Mg m^{-3} gave 434 mm and changing from 0.36 to 0.43 Mg m^{-3} to match measured values gave 426 mm melt. Consequently, error in this method (about ±3 mm d^{-1}) is mainly due to the accuracy of the change in depth measurement. Averaging over two days greatly reduces the variability between this approach and the other methods. The comparison with the lysimeters indicates that the depth and density technique is suitable as the reference value for evaluating the calculations of snowmelt in the forest where there are no lysimeter measurements, though measurement error is a larger percentage of the lower forest snowmelt rates.

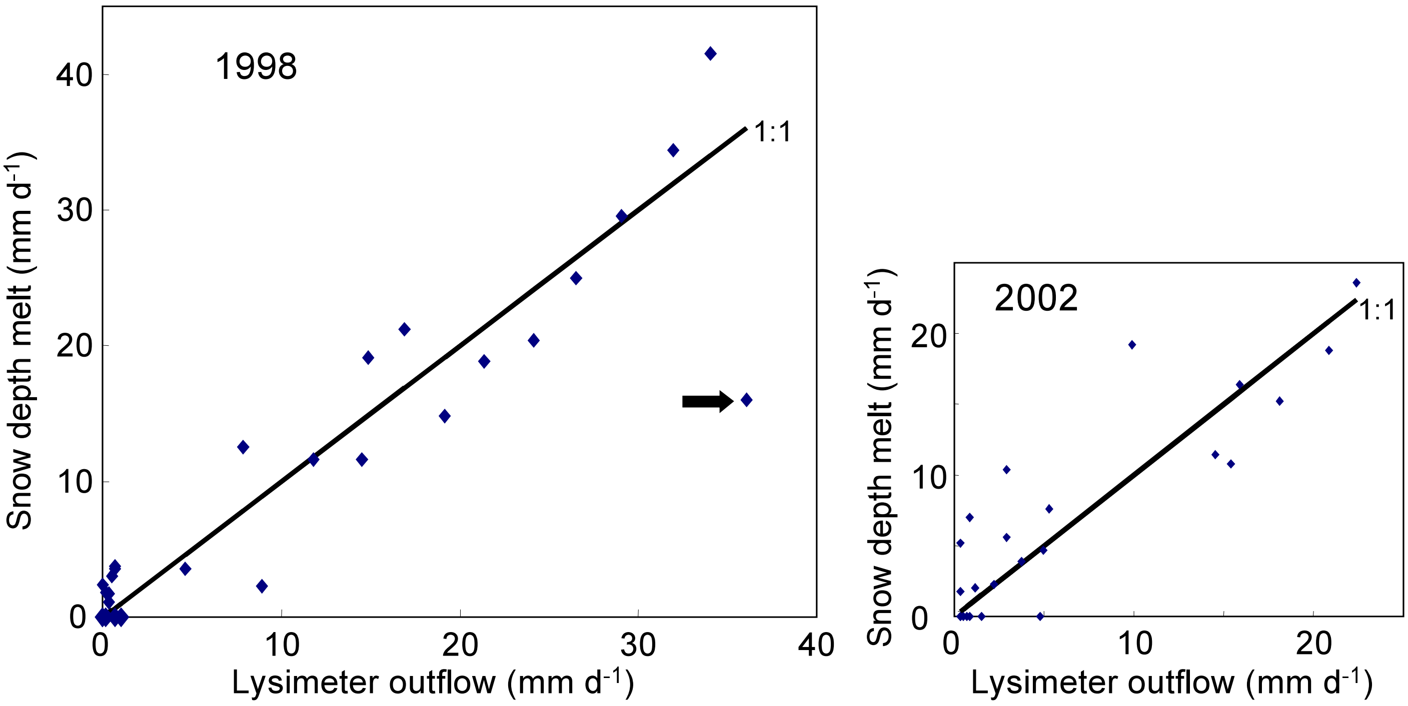

Figure 2. Daily snowmelt calculated from changes in snow depth and density and daily lysimeter outflow for 1998 and 2002. The arrow in the 1998 panel indicates a day with 19 mm of rain on a 0.5-m-deep snow pack. The R^2 values are 0.853 and 0.788 for 1998 and 2002, respectively.

Air Temperature Index Method

Figure 3 shows the data for 1999 used to determine the melt factors for the forest and clearcut based on clearcut air temperature. Lysimeter outflow provided the melt data for the clearcut and melt from the depth and density measurements provided that for the forest. For the clearcut, daily melt = 2.6+2.9Ta, (R^2=0.751, intercept ±1.4 mm d^{-1}, slope ±0.31 mm d^{-1} $°C^{-1}$, s.e. ±5.3 mm d^{-1}, n=31). For the forest daily melt = 2.7+2.0Ta (R^2=0.655, intercept ±1.2 mm d^{-1}, slope ±0.26 mm d^{-1} $°C^{-1}$, s.e ±4.5 mm d^{-1}, n=40). Melt is calculated only when the daily average snow temperature is greater than –0.1°C and air temperature greater than –0.5°C.

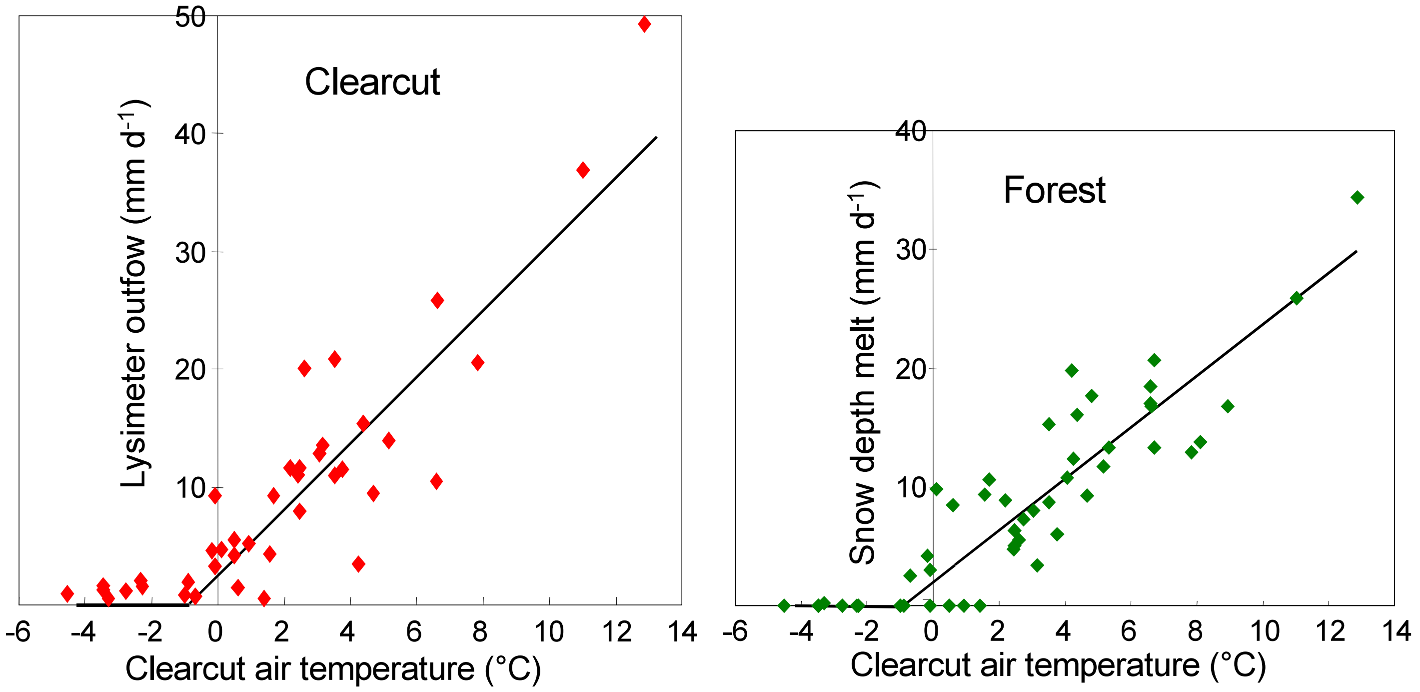

Figure 3. Data for 1999 melt season used to determine the melt factors for the air temperature index method in the clearcut and forest. The lines indicate the equations given in the text.

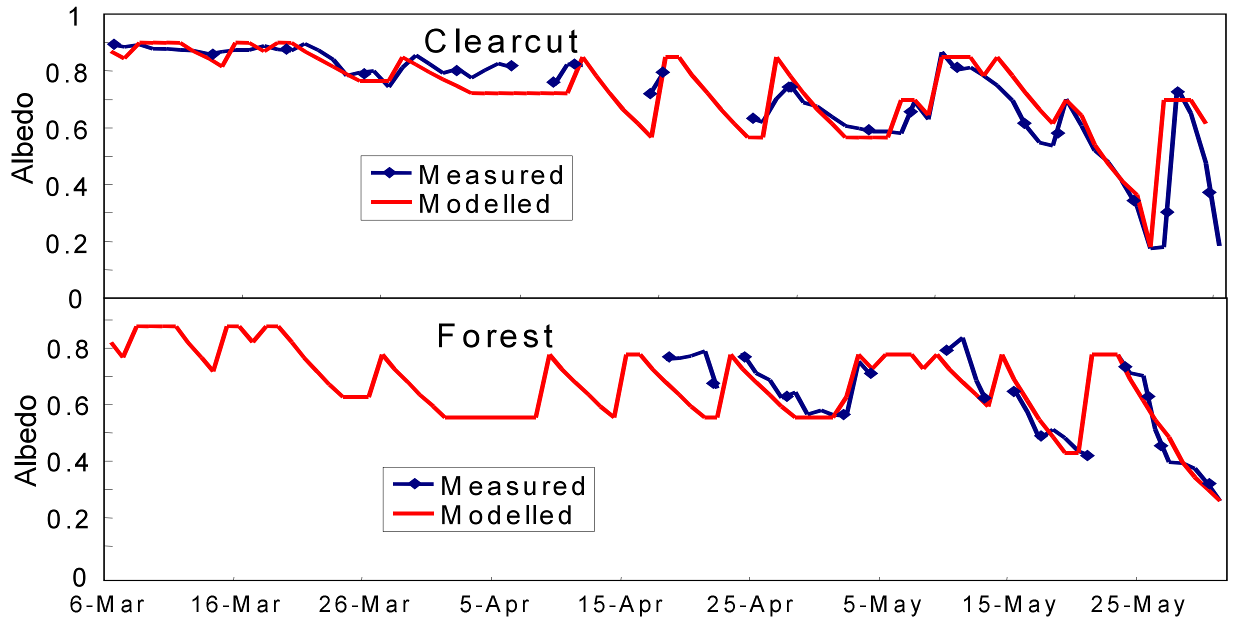

Figure 4. Measured (line with diamonds) and modelled snow albedo in the clearcut and forest from March to May 2002. The gaps in the measurements are due to snow on the upward facing sensors.

Energy Balance Melt

The coefficients for the snow albedo equation were determined using data for 2003 and tested with data for 2002 (Figure 4). The values of c and b are set after each snowfall using the following algorithms. In the clearcut c=0.9 if T_s<-1°C, 0.7 if T_s>-0.2°C, else 0.85, and b=0.8 if snow depth<0.2 m, 0.5 if T_s>-0.2°C, else 0.2. In the forest, the respective values for c are 0.9, 0.65 and 0.8 and for b are 0.8, 0.7 and 0.4. The greater decay rate and lower base values in the forest reflect the influence of forest litter on the snow surface creating a slightly lower forest albedo (Melloh et al. 2001). Days when the sky was clear or overcast all day and there was no snow on the solarimeters were used to determine solar transmissivity for the forest, i.e., $\tau = 0.2+0.07(\sin[0.0172(\mathrm{DoY}-81)])$. Daily measurements of downward longwave radiation in the open and in the forest and forest air temperature for days when there was no snow, rain or dew on the longwave sensors gave a view factor of 0.81±0.01 (n=21).

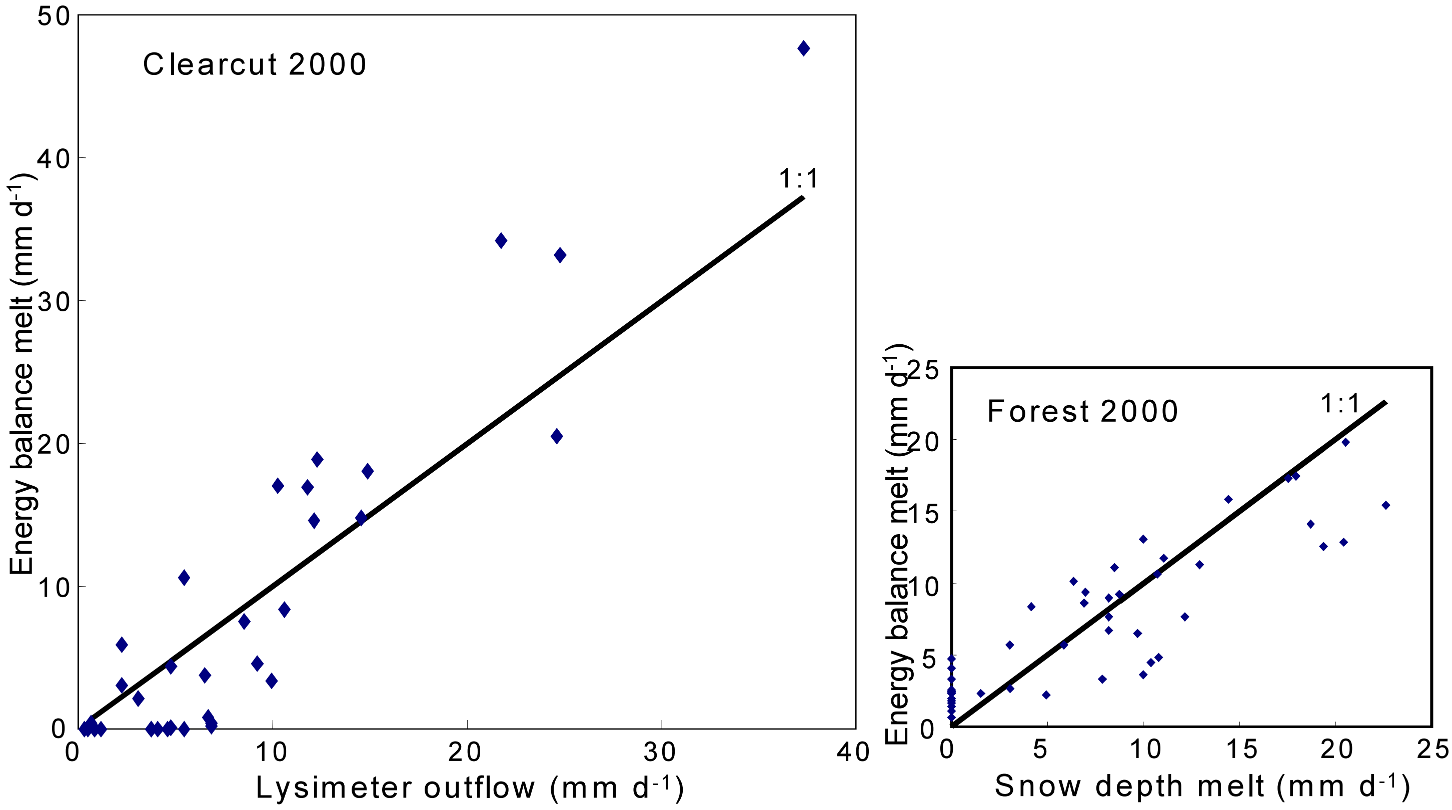

Figure 5. Daily clearcut energy balance melt and lysimeter outflow, and daily forest energy balance melt and melt from the snow depth and density measurements in 2000. The R^2 is 0.870 for the clearcut and 0.756 for the forest.

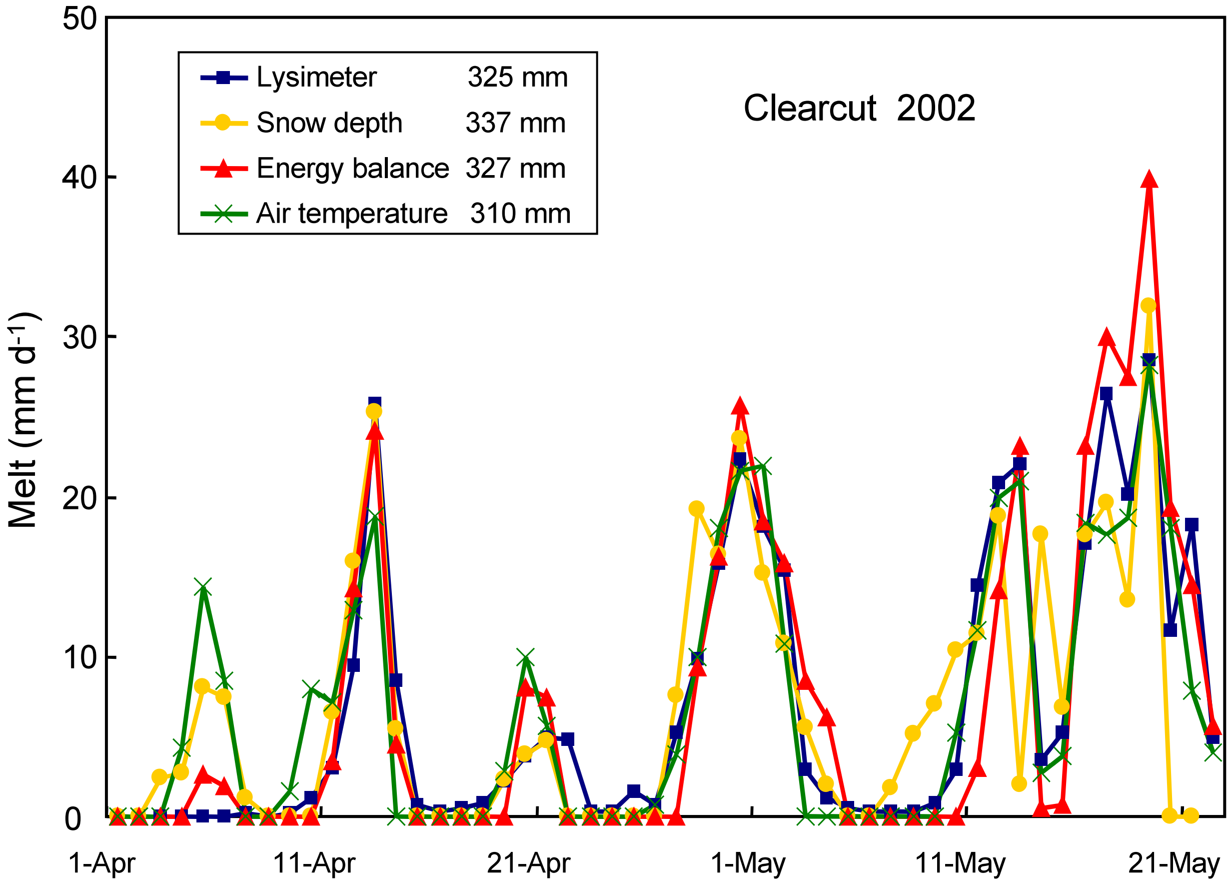

Figure 6. Daily melt rate from the lysimeter outflow, snow depth and density measurements, energy balance calculation and air temperature index method for the clearcut in 2002. The legend gives the accumulated melt.

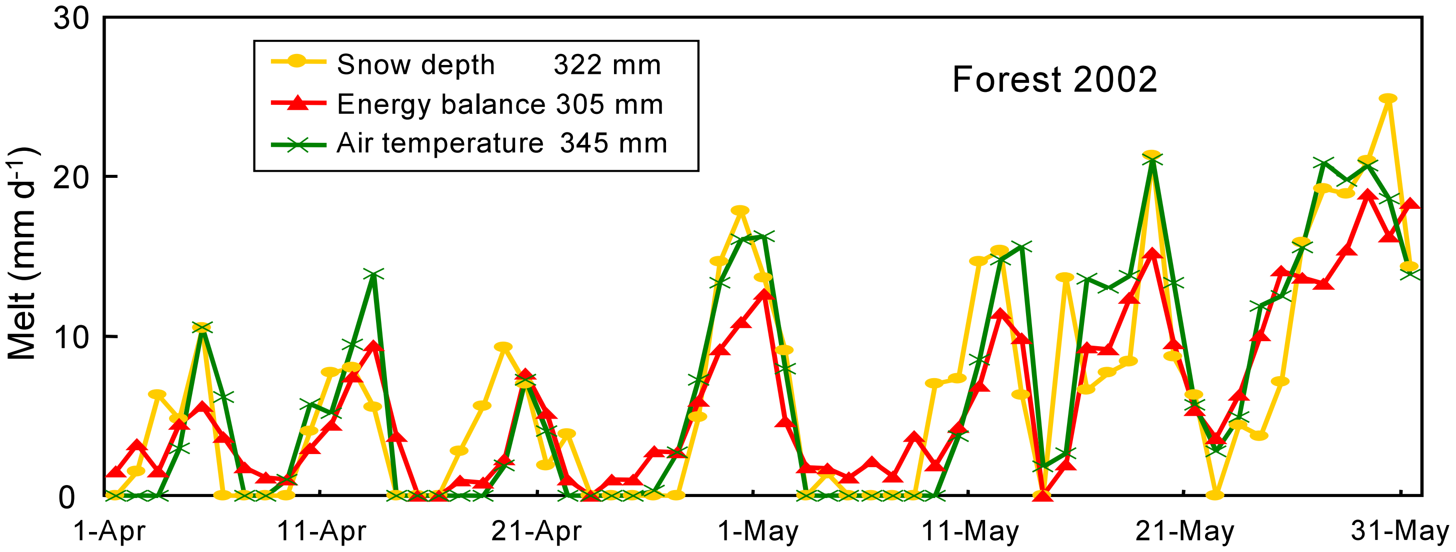

Figure 7. Daily melt rate from the snow depth and density measurements, energy balance calculation and air temperature index method for the forest in 2002. The legend gives the accumulated melt.

Daily energy melt in the clearcut was in good agreement with the lysimeter outflow (Figure 5 and 6), though there was a tendency for the calculated values to be higher at higher rates. In the forest, the energy balance tended to give slightly lower values than the snow depth and density melt estimates (Figure 5 and 7). However, the energy balance well simulated the trends and magnitude of melt including cool periods with no melting that occurred during the main melt season. Net radiation is the major source of energy for melt. On windy days in the clearcut up to 25% of the melt energy comes from the sensible and latent heat fluxes. Warm, windy and low humidity days were the only ones that resulted in evaporation and usually there was a minor downward flux of latent heat. Almost all of the energy for melt in the forest comes from the net radiation because the sensible and latent heat fluxes are small due to the low wind speeds, consistent with Prévost et al. (1991) and Adams et al.

(1996). Air temperature is well correlated with the solar radiation during the melt period and the downward long wave flux from the canopy in the forest. Consequently, the trend of the air temperature-based melt agrees with that from the energy balance (Figures 6 and 7).

In the clearcut, season's total snowmelt from the energy balance tended to be slightly great than from the lysimeter over the 6 years of measurement (Table 1). However, the energy balance was much better correlated with lysimeter outflow than the other two methods. In the forest, the energy balance approach gave totals lower than the other two methods (Table 2). The poorer correlation of the air temperature index method with clearcut lysimeter melt was the result on one year with a much higher value for the index method.

Table 1. Mean annual melt and mean peak melt rate in the clearcut for 1998 to 2003 from the lysimeter outflow, energy balance calculation, snow depth and density measurements and the air temperature index calculation. R^2 is the correlation of seasonal totals with the lysimeter outflow. Std is one standard deviation about the mean.

	Melt (mm)			
	Lysimeter outflow	Energy balance	Snow depth and density	Air temperature
Maximum	381	393	398	397
Minimum	244	299	266	234
Mean	319	340	310	322
Std.	47	33	50	53
R^2	----	0.90	0.53	0.41
	Mean peak melt rate (mm d^{-1})			
	28	34	30	25

Table 2. Mean annual melt and mean peak melt rate in the forest for 1998 to 2003 from the energy balance calculation, snow depth and density measurements and the air temperature index calculation. R^2 is the correlation of seasonal totals with melt from the snow depth and density measurements. Std is one standard deviation about the mean.

	Melt (mm)		
	Energy balance	Snow depth and density	Air temperature
Maximum	347	429	426
Minimum	235	242	300
Mean	305	321	363
Std.	48	73	46
R^2	0.48	----	0.45
	Mean peak melt rate (mm d^{-1})		
	17	20	20

DISCUSSION

There is generally excellent agreement between all of the approaches to determining snowmelt in the clearcut. They all follow the same trend through a year (Figures 6) and have similar peak melt rates (Table 1). The agreement is not quite as good in the forest (Figure 7 and Table 2). Prévost et al. (1991) obtained similar agreement between an air temperature index method, the energy balance and lysimeter measurements in a balsam fir forest in eastern Canada. Lysimeters are suitable for measuring snowmelt in the open provided they are cleaned prior to the start of the snow season. Work needs to be done reduce the risk of ice blockage in the drains and to get them to work reliably in our forest.

The snow depth and density measurement method provided reasonable estimates of melt. It requires snow density measurements that would not always be available for remote locations. However, once the snow pack was close to 0°C and the melt season underway, the density was usually at its maximum value (between 0.41±0.02 Mg m^{-3} for our pack depending on the year and whether forest or clearcut) and a constant value could be assumed. Changing the density during the transition period from snow pack that has just reached 0°C (0.31±0.01 Mg m^{-3}) to maximum density can be done using the air temperature to indicate ripening conditions. This method obviously includes some degree of subjectivity but knowing the snow depth and limits to snow density for the pack constrains the estimate of melt. As noted earlier, melt is relatively insensitive to the density assuming a reasonable value is used. Averaging snowmelt over two or three days reduces the uncertainty.

The air temperature index method gave reasonable values and seasonal totals for the clearcut though sometimes it tended to overestimate early season melt. This method tended to give the highest seasonal totals in the forest. Using more years of data to determine the melt factor may improve its accuracy. Calibration will be site specific (climate, vegetation cover). The melt factors obtained here (2.9 and 2.0 mm $°C^{-1}$) are similar to the value of 2.6 mm $°C^{-1}$ obtained by Prévost et al. (1991).

The energy balance method appears to slightly overestimate melt in the open. Snow albedo (Figure 4) is consistent with data reported in the literature (Pomeroy and Dion 1996, Melloh et al. 2001). Using the measured albedo and downward longwave radiation for 2002 and 2003 does not improve the estimate. The sight upward bias may be a result of using daily data rather than a simulation through the day on an hourly basis. This could be done with the weather data but errors in simulating downward longwave radiation, snow albedo and snow surface temperature through the day probably would offset any gains in accuracy from increasing the time resolution. The energy balance calculations tended to underestimate melt in the forest by 5 to 10% relative to the snow depth and density method. Values for the transmission of radiation through the forest canopy consistent with data in Reifsnyder and Lull (1965) and Pomeroy and Dion (1996). The forest view factor is also of the magnitude expected. For example Black et al. (1991) obtained a canopy view factor of 0.95 for a forest with a solar transmission of about 5%. Using measured radiation data for 2002 and 2003 did not change the estimates significantly. It is possible that the contributions of sensible and latent heat are underestimated because equation 3 is not appropriate below canopies. However, considering the coefficients were derived from a single point, the energy balance calculations from weather station data can be considered to have done extremely well in estimating clearcut and forest snowmelt. Discrepancies between energy balance melt and the lysimeter or depth based melt are within the measurement errors of the methods.

All the methods have strengths and weaknesses that will influence how they can be used in an operational setting. Direct measurements of melt should be done where possible. However, the lysimeter and snow depth and density methods require equipment at each location of interest. The air temperature index method requires site specific calibration. The energy balance method offers the capability to estimate melt rates in other points in of a watershed. However, this requires the ability to extrapolate weather data, e.g., temperature lapse rates, and to take account of the affect of topography on solar radiation and long wave radiation. Information on how solar transmission and canopy view factors may vary with canopy cover is necessary. Where possible, more than one approach should be used to determine snowmelt.

CONCLUSIONS

There was good agreement between snowmelt measured as lysimeter outflow and calculated from the snow depth density and density measurements. Snowmelt calculated with air temperature index and energy balance methods followed the course and magnitude of measured snowmelt exceptionally well. Discrepancies between the approaches to measuring or calculating melt are within the measurement errors of the methods. The energy balance method provides a relatively easy way to estimate snowmelt from weather data. A basic set of measurements should include solar radiation, air temperature and humidity, wind speed and snow temperature. Net radiation provides almost all the energy for melt in the forest and about 75% of the energy in the clearcut. Snowmelt rates of over 40 mm d^{-1} were measured in the clearcut and up to two thirds of this in the forest under the same weather conditions.

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