Cold regions hydrology, snow, and PUB

JOHN POMEROY
Centre for Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5C8 Canada and *Institute of Geography & Earth Sciences, University of Wales, Aberystwyth SY23 3DB, Wales, UK*
pomeroy@usask.ca

Abstract Cold regions hydrology has a great demand for improved prediction because most cold regions are notoriously ungauged and because the cold regions hydrological cycle has some uniquely important components related to the solid phase of water. For instance, snow accumulation controls water balance and peak streamflow in many cold region catchments. However, the quantity of snow accumulated in forested catchments is often very uncertain because snow measurements are usually taken in small clearings. Accumulation of snow under forest canopies declines with increasing canopy density and leaf area because of snow interception and sublimation in the canopy. Seasonal snow accumulation measurements collected over a decade from various forest stands in western Canada were used to test and develop methods to relate forest snow accumulation to stand properties and observations of either small clearing seasonal snow accumulation or seasonal snowfall. At the stand-scale, physically-based snow interception equations predicted seasonal snow accumulation from the stand leaf area and the seasonal snow accumulation or snowfall in adjacent clearings. A simple parametric form of these equations showed the sensitivity of seasonal snow accumulation to leaf area at the forest stand scale and suggested a relationship to extrapolate snow accumulation or snowfall measurements from clearings to forests. Leaf area can be easily quantified from remote sensing imagery and so this technique is suited to ungauged basins.

Key words cold regions hydrology; forest snow; interception; PUB; snow accumulation; snow hydrology

INTRODUCTION

The development of scientific hydrology is permitting predictions of water system behaviour that rely to an increasing degree on processes as described by hydrological principles. Predicting land surface processes, streamflow and snow and ice reserves in ungauged areas has particular relevance to the needs of cold regions hydrology and the dynamics of snow and ice systems. Observational networks of snowfall, snow water equivalent, glacier mass balance, ice extent, and streamflow have always been coarse in cold regions, and recently have declined dramatically. For instance, operational monitoring of discharge from the glacial, mountain, boreal, sub-arctic and arctic zones to the Arctic Ocean has declined by at least 40% in the last 15 years; before this decline, 35–50% of discharge to the Arctic Ocean was from ungauged basins. The difficulties of measuring areal snow accumulation, frozen soil moisture content, glacier mass balance and streamflow under ice and during ice break-up mean that even routinely gauged basins represent areas of high uncertainty in hydrological calibration and estimation. Because of a long-standing problem of data availability in cold regions, there is a tradition of applying physically-based predictions based on hydrological processes and remotely sensed data to large-scale systems; the approaches may also have relevance to more temperate hydrological applications. Given current estimates that global warming impacts on hydrology will be most evident in the continental high latitudes, the recognition of the key influence of freshwater on northern ocean circulation and hence global climate, the particularly strong link between cold regions hydrology and ecosystem dynamics and the strong reliance of northern aboriginal peoples on water-based subsistence lifestyles, the neglected "4th world" of the cold regions will be an issue of some importance that PUB should apply a distinctive effort to.

Both water balance and peak runoff in cold regions are strongly influenced by snow accumulation over the catchment. Snow survey networks in "representative" locations have declined dramatically in most countries and forecasters now must often rely on point measurements of snow depth from an automated meteorological station or remote observations of snow water equivalent made from open terrain or gaps in forest canopies. This is particularly serious in the circumpolar boreal forest, which occupies roughly 16% of the continental area of the Earth. A better understanding of the relationship between the snow accumulation observed in small clearings and the accumulation in adjacent forested environments can assist in predicting catchment-wide snow water equivalent. The purpose of this paper is to outline a simple theory for extrapolation of snow accumulation estimates from where they are "gauged" to where they are "ungauged" in a northern forest environment.

THEORY

Presuming horizontal redistribution is negligible, over a snowfall event (period of snowfall) interception, i, is defined as that snowfall which does not reach the ground. If the snowfall, p_c, into a clearing is the same as that to the top of a forest canopy, then:

$$p_c - p_f = i \tag{1}$$

where p_f is the sub-canopy snowfall for some event. The interception term defined in equation (1) was the subject of theoretical and observational study by Hedstrom & Pomeroy (1998). They discussed results in terms of interception efficiency, $i/p_c = e_i$, which was calculated from a physically-based formulation. The snow interception formulation of Hedstrom & Pomeroy (1998) relates interception to leaf area index, tree species, canopy density, air temperature, wind speed and snowfall. For a *single snowfall event into a snow-free canopy*, Hedstrom & Pomeroy's algorithm can be simplified to its primary factors, as:

$$i = 3.94\ LAI' \left(1 - e^{\frac{-C_c p_c}{5.8 LAI'}} \right) \tag{2}$$

where p_c is above-canopy snowfall during the interception event, effective winter leaf area index, LAI', is the total horizontal area of stems, needles and leaves per unit area of ground, C_c is canopy density and the units are mm for the coefficients 3.94 and 5.8,

p_c and *i*. Hedstrom & Pomeroy's interception algorithm tracked snow load in the canopy; however equation (2) is only valid for single snowfall events. For every increment of p_c, equation (2) assumes that *all* intercepted snow is retained as canopy snow load from the previous increment. The assumption that snow load is preserved over the time between snowfall increments is only likely to be valid during individual snowfalls and for short periods afterwards.

Intercepted snow eventually sublimates, unloads or drips to the ground. Over a winter season it may be presumed that this has occurred. Seasonal sublimation *E* may then be found as:

$$P_c - P_f - U - D = E \tag{3}$$

where *P* denotes seasonal snowfall (subscripts *c* and *f* refer, as before, to that of a clearing and sub-canopy, respectively), *U*, unloading and *D*, drip and the seasonal sum of interception, $\sum i = E + U + D$.

Presuming that redistribution, surface melt and surface evaporation are negligible, the mass balance equations for the forest and clearing reduce to $S_c = P_c$ and $S_f = P_f - U - D$, resulting in:

$$S_f = S_c - E \tag{4}$$

The sublimation term *E* was the subject of investigation by Pomeroy *et al.* (1998) and requires the solution of coupled mass and energy balance equations. A sublimation efficiency term, e_s, may be defined as $E/\sum i$. This efficiency is expected to be lower in humid temperate winter environments where in-canopy melt and unloading of wet snow from the canopy are large (e.g. Lundberg *et al.*, 1998; Storck & Lettenmaier, 1999) and higher in cold dry environments where sublimation processes may proceed with relatively little hindrance (Pomeroy *et al.*, 1998; Parviainen & Pomeroy, 2000). It is also expected to vary with several other factors such as snow age, amount of intercepted snow, branch elasticity, wind and radiation penetration into the canopy, and canopy structure.

Using the sublimation and interception efficiencies then equation (5) may be expressed as:

$$S_f = S_c - S_c e_s e_i = S_c(1 - e_s \frac{i}{p_c}) \tag{5}$$

where the efficiencies $e_i = \sum i \,/\, S_c$ or $\sum i = e_i S_c$ and $e_s = E \,/\, \sum i$ or $E = e_s \sum i$, must be evaluated from the same data set and for the same time interval. It is assumed that the seasonal efficiencies can be approximated by the means of the ratios $\sum i \,/\, P_c$ (since $S_c \approx P_c$) and $E \,/\, \sum i$, for shorter time periods for which equation (2) is valid, e.g.:

$$\left(\frac{\sum i}{P_c}\right)_{Seasonal} \cong \left(\overline{\frac{\sum i}{P_c}}\right)_{Monthly} \cong \left(\overline{\frac{\sum i}{P_c}}\right)_{Weekly} \cong etc \tag{6}$$

By summing event-based interception from intervals for which it can be assumed that the canopy has become initially snow-free, equation (2) can be employed. The interception efficiency term may be summed to seasonal terms (the seasonal value being the summation of event interception efficiencies) as $e_i = \sum i/S_c$. With this presumption, equation (2) with its event-based (roughly weekly) time scale can be combined with equation (5) to provide:

$$S_f = S_c\left[1 - e_s\left(\frac{3.94LAI'\left(1 - e^{\frac{-C_c P_{cj}}{5.8LAI'}}\right)}{P_{cj}}\right)\right] \tag{7}$$

where P_{cj} is the snowfall into a clearing over snowfall event time interval j. Equation (7) provides a means of calculating seasonal snow accumulation in a forest, based on accumulation in a clearing, the sublimation efficiency, the magnitude of individual snowfall events, canopy density, and winter leaf area index. It is presumed that the canopy becomes snow-free over time interval j, therefore some estimate of snowfall amount over time interval j must be made.

Field observations

Snow depth and density surveys were conducted during the snow season (usually October to April) in the Canadian boreal forest from 1993 to 2002, on a weekly basis in the Prince Albert Model Forest, Saskatchewan (PAMF) and on a monthly basis at Wolf Creek Research Basin, Yukon. Timing of surveys was sometimes varied slightly to capture a snowfall event or anticipate a melt period, but was constrained by the operational requirements of the study programmes in the respective areas.

RESULTS

Over all stands, seasonal clearing snow accumulation varied from 54 to 124 mm and stand-scale seasonal forest snow accumulation varied from 28 to 110 mm water equivalent with means of 86 and 59 mm for clearing and forested landscapes, respectively. The ratio of forest to clearing snow accumulation S_f/S_c declined from values near 1.0 to near 0.5 as leaf area index, LAI' and canopy density, C_c, rose from 0.2 to 4.1 and 0.95, respectively, as shown in Fig. 1(a),(b). The ratio S_f/S_c was negatively correlated to LAI' and C_c with coefficients of –0.69 and –0.72, respectively.

To implement equation (7) the magnitude of p_c must be found and the behaviour of the sublimation efficiency, e_s, determined. It is proposed that for the boreal forest, the recommendation of Hedstrom (1998) is followed and that weekly snowfall be used to estimate p_c. Over three seasons (1994–1996) at PAMF for which weekly data quality was highest, the mean weekly winter period snowfall into a clearing was 5.1 mm. Mean monthly winter period snowfall at Whitehorse was 20.4 mm over four seasons (1994–1997), providing a weekly mean of 4.8 mm. A value for p_c of 5 mm was therefore adopted for subsequent analysis. Solving for e_s from equation (7) and measurements provided a mean e_s of 0.72 with a standard deviation of 0.32. There were no trends of e_s with leaf area index or clearing snow accumulation.

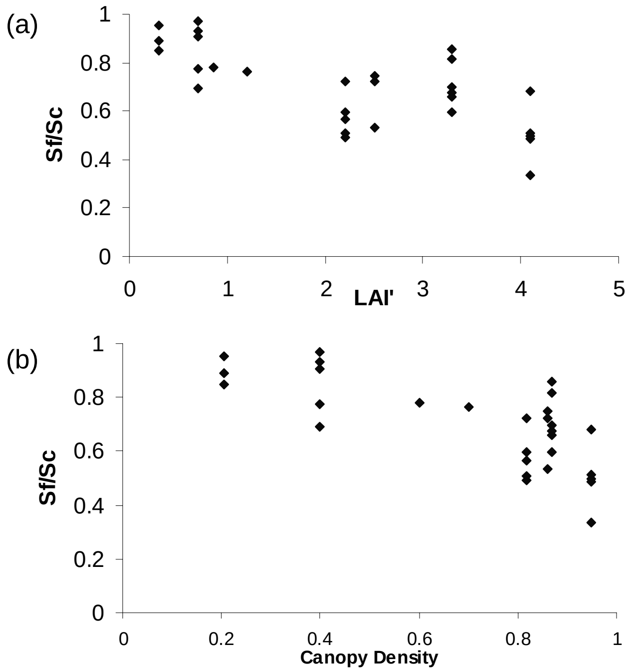

Fig. 1 Ratio of forest to clearing snow accumulation as a function of stand characteristics: (a) leaf area index (effective winter), (b) canopy density (winter).

A comparison of equation (9) using $p_c = 5$ and $e_s = 0.72$ with measurements is given in Fig. 2, with a R^2 of 0.80, mean difference (measured–modelled) of –0.48 mm and a standard deviation of differences of 9.4 mm.

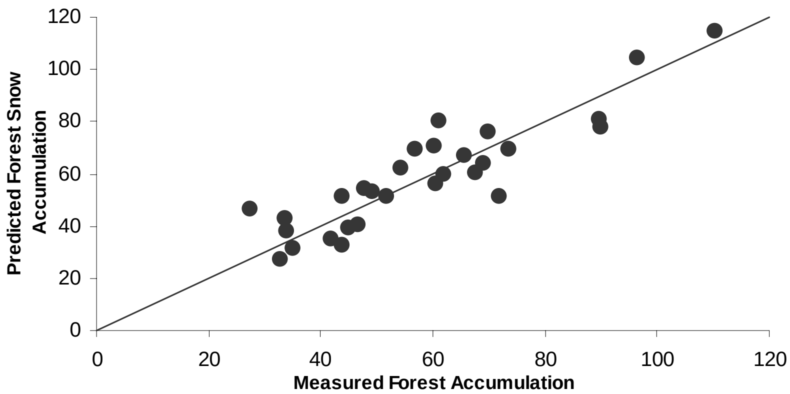

Fig. 2 Points indicating measured seasonal forest snow accumulation (mm) and that predicted using equation (9) using snowfall event size, p_c, of 5 mm and sublimation efficiency, e_s, of 0.72 and a 1:1 line for reference.

DISCUSSION

Equation (7), though linked to interception theory, is relatively complex for prediction and upscaling purposes. An examination of the sensitivity of interception efficiency e_i to LAI' can provide a simpler form. The fitted logarithmic form is:

$$e_i = 0.1984 \ln(LAI') + 0.309 \qquad (8)$$

which has a R^2 of 0.99 when compared to the full physically based equation.

From equations (5) and (8) a parametric equation to predict snow accumulation in forests based on that in clearings and leaf area index is therefore:

$$S_f = S_c(1 - e_s(0.2 \ln(LAI') + 0.31)) \qquad (9)$$

Equation (9) has a mean difference with measurements of –1.24 mm, standard deviation of differences of 9.72 and a R^2 of 0.79 (Fig. 3). Assuming the sublimation efficiency is 0.72, then this equation becomes:

$$S_f = S_c[1 - (0.144 \ln(LAI') + 0.223)] \qquad (10)$$

Equation (10) is recommended for extrapolation of either measurements of snow accumulation on the ground in small clearings or seasonal snowfall, to adjacent forested regions. The degree of uncertainty increases with frequency of mid-winter melt and wind redistribution of snow from the clearing, but the equation appears to work well in the boreal forest of western Canada. Leaf area index can be estimated from remote sensing imagery and converted to the effective leaf area index used in the parametric equation (equation (10)). The other input, S_c, can be derived from snowfall estimates from meteorological models, measurements or snow depth estimates in a small clearing. As standard meteorological stations for weather forecasting, climate monitoring and forest fire prediction are located in small clearings, this permits the use of a wider range of data sets for cold regions forest streamflow prediction and is particularly useful where snow accumulation is not measured.

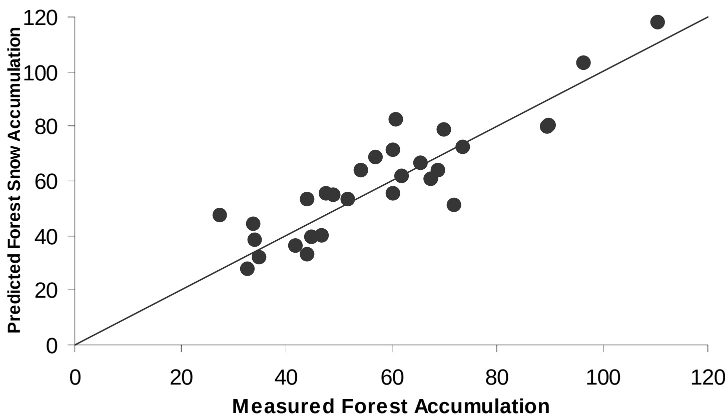

Fig. 3 Performance of the parametric forest snow accumulation equation (equation (9)) presuming that sublimation efficiency is 0.72; measured and modelled accumulation (mm) as points with a 1:1 line for comparison.

CONCLUSIONS

Seasonal snow accumulation in forests at the stand scale is shown to scale with leaf area index following the interception theory of Hedstrom & Pomeroy (1998); the function is one of declining accumulation with increasing leaf area. It is anticipated that the assumptions underlying this relationship are valid where mid-winter melts, wind redistribution and surface evaporation are infrequent or small. Knowledge of snow water equivalent at a point or an estimate of snowfall and the spatial distribution of leaf area index in a catchment can therefore provide the distribution of snow accumulation. This relationship will permit enhanced predictions of the snow reserves available for melt in densely forested areas where they cannot be measured.

REFERENCES

Hedstrom, N. R. (1998) Development and Evaluation of a Cold Regions Snow Interception Model. Master of Science Thesis. Department of Agricultural and Bioresource Engineering, University of Saskatchewan: Saskatoon, Canada.

Hedstrom, N. R. & Pomeroy, J. W. (1998) Measurements and modelling of snow interception in the boreal forest. *Hydrol. Processes* **12**, 1611–1625.

Lundberg, A, Calder, I. & Harding, R. (1998) Evaporation of intercepted snow: measurements and modelling. *J. Hydrol.* **206**, 151–163.

Parviainen, J. & Pomeroy, J. W. (2000) Multiple-scale modelling of forest snow sublimation: initial findings. *Hydrol. Processes* **14**, 2669–2681.

Pomeroy, J. W., Parviainen, J., Hedstrom, N. R. & Gray, D. M. (1998) Coupled modelling of forest snow interception and sublimation. *Hydrol. Processes* **12**, 2317–2337.

Storck, P. & Lettenmaier, D. P. (1999) Predicting the effect of forest canopy on ground snow pack accumulation and ablation in maritime climates. *Proceedings of the Western Snow Conference* **67**, 1–12.