Snow distribution pattern and its influencing factors in a small watershed in Atlantic Canada

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Abstract—**Snowmelt events contribute significantly to surface runoff and sediment and nutrient loadings in cold climate regions such as in most part of Canada. To better understand the snowmelt hydrology, a snow survey was carried out in a small watershed in New Brunswick, Canada in March, 2012. Snow cores were sampled from 33 predetermined locations, covering different land uses and slope positions. The snow depth ranged from 0.17 m to 0.74 m and averaged at 0.36 m. The water equivalent depth of the snow ranged from 0.06 m to 0.23 m and averaged at 0.10 m. Forested area had significantly deeper snow than cropped area. Points on the edge of the forested area had the deepest snow. The variability of snow depth was high and the variation did not correlated well with terrain attributes extracted from a 30 m grid DEM. A Ground Penetrating Radar (GPR) was used to measure the snow depth along transects. The GPR was effective in detecting the soil surface under the snow. The GPR data also demonstrated the strong effect of local topography on snow depth. Future studies are required to examine the use of these data for snow depth predictions.**

INTRODUCTION (HEADING 1)

Studies on watershed hydrology and water quality have focused on rainfall events and rainfall induced runoff. In cold climate regions, such as in most of Canada, a large portion of the annual precipitation is in the form of snow fall. As a result, snowmelt runoff has reported to consist more than 30% of the total runoff at some water monitoring stations in this region (Chow and Rees, 2002) as well as in several other sites in Canada (e.g., Li et al., 2011). However, our knowledge on snowmelt hydrology is limited, which has been identified as a major restriction on the modeling and interpretation of water quality at the watershed scale. One of the limitations is due to the lack of input information on snow distribution, which is normally not uniform in a watershed and is affected by many factors such as climate, topography and land use. The objectives of this study are to measure snow distribution pattern and to determine dominant factors for snow distribution in a small watershed in cold climate region.

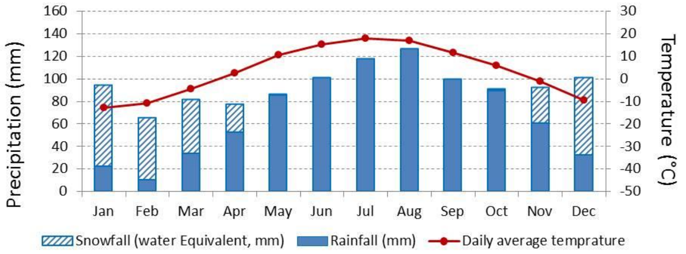

Figure 1. Long-term normal precipitation and mean air temperature at a climate station in Grand Falls, New Brunswick, Canada (data source: Environment Canada website).

MATERIALS AND METHODS

Study site

The study was carried out in the Black Brook Watershed (BBW) in the province of New Brunswick, Canada. The area of BBW is approximately 1,450 ha. The climate in this region is moderately cool boreal, with an average annual temperature of 3.2°C and approximately 120 frost-free days (Fig. 1). Annual rainfall, snowfall and total precipitation averaged at 769 mm, 354 mm and 1,092 mm, respectively. Elevations in BBW range from 150 to 241 m above sea level (Fig. 2). Most of the area in BBW is undulating to gently rolling with slopes of 1–6% in the upper portion, 4–9% in the central part and 5–16% in the lower part of the watershed. Soils were predominantly moderately well drained Orthic Humo-Ferric Podzols, developed on coarse-textured till. The major land-use within the watershed is agriculture, which accounts for 65% of the total watershed area (Fig. 2). The major crops are potato and barley, followed by other crops in rotation. Approximately 25% of the watershed is forested. Roads, urban areas and streams cover the remaining 10% of the watershed.

Snowmelt discharge and snowmelt erosion play an important role in the BBW. Chow and Rees (2002) reported that approximately 36% of discharge and 39% of sediment loadings measured at the watershed outlet occurred during the snowmelting period in April. The source of runoff and sediment load coming from snowmelt strongly relies on the spatial distribution of snow cover and watershed characteristics. Therefore, examining the spatial and temporal variations of snow cover over the watershed has both practical and scientific significance in understanding snow hydrology and in particular the management of BMPs related to snowmelt runoff, sediment loading, and water quality.

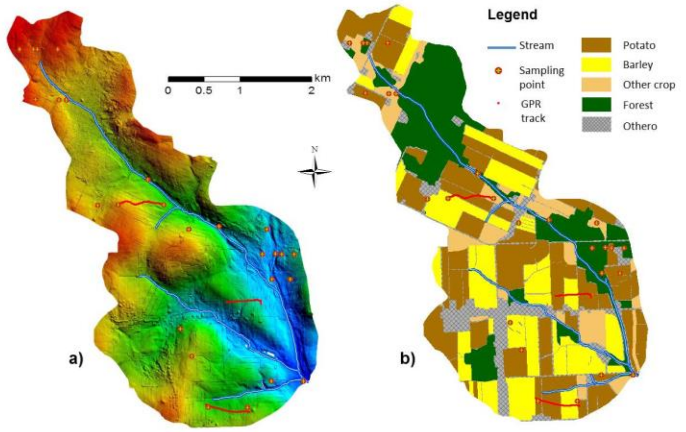

Figure 2. Maps of a) topography; and b) land use in 2002 for the Black Brook Watershed. Manual snow sampling locations and three example Ground Penetrating Radar (GPR) survey tracks were shown in both maps.

Field snow sampling and survey

A field snow sampling and survey campaign was carried out on March 21st and 22nd, 2012. Snow depth (SnD) and weight-based snow water equivalent depth (WED) were measured using a snow sampling kit at 33 predetermined locations (Fig. 2). A snow redistribution model developed by Guelph Watershed Evaluation Group (2010) was used to estimate the general pattern of snow depth as a result of variations in land use and terrain attributes. The terrain attributes were calculated based on a 30 m grid Digital Elevation Model (DEM), which is derived from the lidar data collected in 2007 (approximately 1 – 2 m^2 per point, error at the level of 0.3 m horizontally). The selected 33 locations represented the major variations of these variables across the landscape. The coordinates of these locations were recorded using a Trimble GeoXH GPS system with a theoretical real-time accuracy at the level of 10 cm.

For detailed in-field snow depth variation, a total of 18 transects were surveyed using a Ground Penetrating Radar (GPR) system (pulseEKKO Pro, Sensors and Software) with a 500 MHz antenna. The GPR unit sends out radio waves and detects the return waves reflected from the snow and ground interface. The time takes for the radio wave to return is converted to the depth of the snow (from snow surface to the snow and ground interface). During the survey, the GPR was secured in a toboggan sled, which is attached to a snowmobile. The snowmobile was moving at a speed of ~10 km hr^{-1} and point interval for the measurement was approximately 0.2 m. A handheld Garmin GPS with an accuracy of ~5-10 m was connected to the GPR unit to record the coordinates and elevation of each measuring point. The GPR survey tracks were designed to go through some of the manually measured sampling points so that the GPR data can be calibrated against the manual measurements.

Statistical analyses

The manual sampling points were categorized into three general land use types (i.e., forest, pasture and cropped). Analysis of Variance (ANOVA) was conducted for the snow depth and snow water equivalent depth data to examine the effect of land use. The effect of topography was considered as random noise and was not considered specifically in the ANOVA. A Tukey's test was used for paired comparisons between the means of different land uses. For each sampling point, a set of terrain attributes—including elevation, aspect and slope gradient and slope curvature along the predominant wind direction (north-west) —were extracted from the 30 DEM derived from the lidar data. The effects of these terrain attributes on SnD and WED were examined using simple linear correlation analyses. The correlation analyses were conducted for all data and also for each sub-dataset for individual land use type. A t-test was used to determine the significance of the correlation coefficients.

RESULTS

Snow depth and snow water equivalent depth both were highly variable across the landscape (Table 1). With all sampling points considered, the coefficients of variation (CVs) for SnD and WED were 41% and 34%, respectively. Within the same land use types, the CV values ranged from 20% to 36%, which were still very high. Despite the high level of variability of the data, the ANOVA tests indicated that for SnD and WED, the effect of land use was significant (P = 0.001 and P = 0.03 for SnD and WED, respectively). The mean SnD and WED both followed the order of Forest > Pasture > Cropped. The Tukey's test suggested that mean SnD in forest fields was significantly higher than that in Cropped fields, whereas the mean SnD in pasture fields were in between those of the Forest and Cropped fields, but the differences were not statistically significant (Fig. 3). The mean WED values for forest and pasture fields were the same and were significantly higher than that of the cropped field.

TABLE I. SIMPLE STATISTICS FOR THE SNOW DEPTH AND SNOW WATER EQUIVALENT DEPTH DATA MEASURED MANUALLY AT THE SAMPLING POINTS (SD = STANDARD DEVIATION; AND CV = COEFFICIENT OF VARIATION)

	Forest	Pasture	Cropped	All
n	13	6	14	33
Snow Depth				
Mean (cm)	45	38	26	36
SD (cm)	15	13	7	15
CV (%)	34	35	26	41
Water Equivalent Depth				
Mean (cm)	12	12	9	10
SD (cm)	4	3	2	3
CV (%)	36	29	21	34

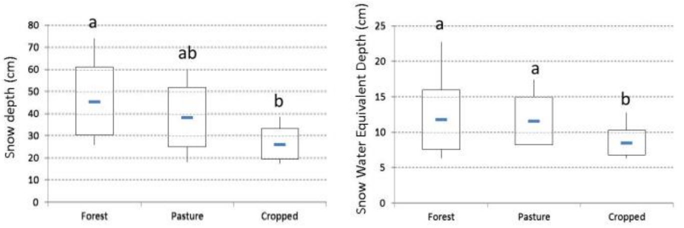

Figure 3. Summary of the snow depth and snow water equivalent depth data and the multiple comparison results based on the Tukey's test. The blue bar indicates the mean value; the upper and lower bounds of the box indicated the values of mean ± standard deviation, respectively; and the upper and lower ends of the whisker indicate the maximum and minimum values, respectively.

Correlation coefficients between SnD/WED and all four terrain attributes examined in this study were all non-significant at P = 0.10 (Table 2). Only a few correlation coefficients were significant even when the significant level was lowered to P = 0.20. However, with only one exception, there appeared to be a consistent trend of negative correlations between SnD/WED and slope gradient and between SnD/WED and slope curvature. This suggests that topography may have some profound impact on snow distribution.

TABLE II. CORRELATION COEFFICIENTS (R-VALUES) BETWEEN SNOW DEPTH/SNOW WATER EQUIVALENT DEPTH AND TERRAIN ATTRIBUTES EXTRACTED FROM A 30 M GRID DEM. NO R-VALUE WAS SIGNIFICANT AT P = 0.10. BOLD FACED R-VALUES WERE SIGNIFICANT AT P = 0.20.

	n	Elevation	Aspect	Slope Gradient§	Slope Curvature§
Snow Depth					
Forest	13	-0.35	0.04	-0.22	0.20
Pasture	6	**0.65**	**0.65**	-0.22	-0.13
Cropped	14	-0.03	-0.37	**-0.38**	-0.06
All	33	**-0.27**	0.10	-0.13	**0.26**
Water Equivalent Depth					
Forest	13	-0.19	0.04	-0.30	-0.16
Pasture	6	**0.70**	0.15	-0.33	-0.02
Cropped	14	-0.13	-0.14	**-0.43**	**-0.40**
All	33	-0.15	0.05	**-0.25**	-0.03

§. Terrain attributes along the predominant wind direction, i.e. north-west direction

The GPR data provided further evidence of the effects of topography on snow distribution. It appeared that local variations in snow depth is strongly affected by small scale topographic features, in particular some manmade linear features. An example was shown in Fig. 4. The shallow snow depths at location b and e were likely due to the fact that these two locations are on the top of knolls. In contrast, a deep snow depth at location c may be a reflection of the local depression at this location. The effect of man-made linear features are most visible at location a and d, located near an in-field trench-like feature and a field boundary, respectively. In both cases, there were high peaks of snow depth observed.

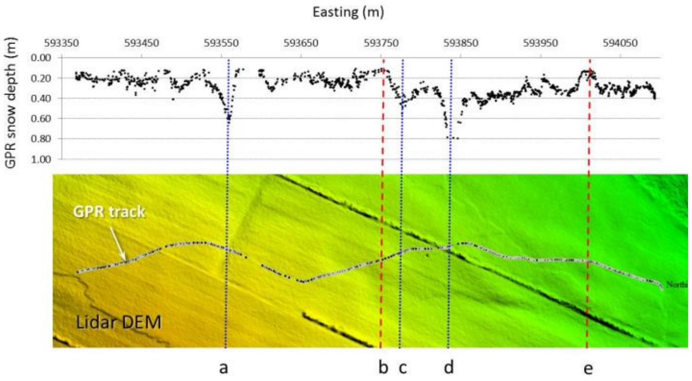

Figure 4. Upper: Snow depth along one of the 18 tracks, determined using a Ground Penetrating Radar unit the Black Brook Watershed; and Bottom: colored shaded relief map showing the topography and the position of the GPR survey track on the ground.

DISCUSSION

The effect of land use on snow distribution was expected. On forest and pasture lands, living plants serve as snow traps and prevent the redistribution of snow by wind. On cropped fields, the ground was mostly bare in the winter and fallen snow can be reactivated and redistributed by wind. The windblown snow can be deposited along field boundaries, roads or forest edges, creating large snow banks along these linear features (e.g., Fig. 4). On the other hand, additional surface roughness created by the living plants on forest and pasture lands may have contributed to the high variations in snow depth (Table 1). It should be noted that the snow survey was carried out in the transition period from winter to spring in BBW, when the snow cover is normally the deepest. However, the temperature rose earlier than normal in 2012 and snowmelt has started before the survey dates. As a result, the measured snow depth was not at its highest level. Also, the snow has high water content, especially towards the bottom of the snow profile, due to the high air temperature. This is evidenced in the high density of the snow (the ratio of WED over SnD is much higher than 0.1, which is the most common factor used to convert SnD to WED). To better understand the dynamic nature of snow redistribution snowmelt, future research is suggested to carry out multiple snow survey campaigns over the period of the snow coverage in the winter.

The non-significant correlations found between SnD/WED and terrain attributes could be due to several reasons. One possible reason is that the random variations of snow depth were too high to detect, with the limited sampling points we had. Another reason could be that there are strong interactions between different terrain attributes such that the effect of any individual terrain attribute was non-linear. Consequently, the simple linear correlation was not suited for the analysis and the coefficients were all non-significant. Lastly, the effect of topography may be scale dependent, as evidenced in the GPR data, which showing the effects of small scale topographic features and man-made linear features on local snow depth variations (Fig. 4). Future study is suggested to consider the use of multivariate models for statistical analysis to account for the interactions among variables and to examine the effects of the same set of terrain attributes at different scales, extracted from DEMs of different grid sizes.

This study also tested the applicability of GPR on snow depth survey. The 500 MHz antenna appeared to work well with the snow depth range of 0.2 – 1.0 m. Due to the direct reflection of the device, snow depth within 0.1 m is nearly impossible to detect (reflection cannot be separated from the direct reflection from the unit itself). Beyond 2.0 m, return radio signals are mostly being absorbed by the snow and, therefore, are hard to detect. Nevertheless, the GPR did provide detailed snow depth information and can be very useful in future studies of snow depth survey.

CONCLUSIONS

Our field survey data suggested that land use had significant effect on snow distribution. Terrain attributes extracted from a 30 m DEM did not show significant correlations with snow depth but slope gradient and slope curvature did show consistent, although non-significant, negative correlations with snow depth, indicating possible effects of topography on snow distribution. GPR data further proves the strong effect of small scale topography and man-made features on snow distribution pattern.

ACKNOWLEDGMENT

This study is funded by the Watershed Evaluation of Best Management Practices (WEBs) project under the Agriculture and Agri-Food Canada. The authors would like to thank Dr. Wanhong Yang W. from U of Guelph for his valuable inputs, Mr. Andrew Ringeri and Hangyong Zhu from U of New Brunswick and John Monteith, Lionel Stevens and Sylvie Lavoie from the AAFC-PRC for assisting with field work. The author would also like to express their appreciations to the WEBs manage team, particularly Brook Harker, Terrie Hoppe, Irene Hanuta and Terra Jamieson for their continuous support.

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