Preliminary findings on snow accumulation in the Niaqunguk River watershed near Iqaluit, Baffin Island, Nunavut

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This work is part of the Carleton University–led Partnership for Integrated Hydrological and Water Quality Monitoring, Research and Training in the Niaqunguk River Watershed, Iqaluit, Nunavut, a Polar Knowledge Canada–supported integrated collaboration with Nunavut Research Institute, Université du Québec à Montréal, Queen's University and Nunavut Arctic College. The research is also supported through an ArcticNet initiative, Water Security and Quality in a Changing Arctic. The shared objective of these programs is to improve knowledge in the area of arctic snow hydrology and its cascading influences on freshwater resource supply and aquatic ecosystems in the Niaqunguk River watershed, and is being developed for long-term sustainability and capacity building with local residents.


Abstract

Snow is the predominant input to arctic hydrological systems, and the spring melt is the most hydrologically important time of the year. Predicting timing and volume of meltwater arrival is therefore of great importance to hydrological modelling and water management and requires the estimation of the snow water equivalent storage in the landscape at the time of melt. Estimation is complicated by redistribution of snow by wind and by a lack of spatially distributed measurements. In this study, extensive field surveys of snow water equivalent were conducted to characterize the snow distribution in the Niaqunguk River (commonly known as Apex river) watershed, near Iqaluit, Nunavut. The mean snow water equivalent storage was 24 ±3 cm (number of samples = 193) for the whole watershed in 2016. Segmenting this sample by terrain type showed shallow accumulation on the ridges and broad valley floors, which form most of the landscape, and deep drifts on mainly steep slopes. As part of this project, a meteorological tower was established north of Iqaluit to monitor basic weather variables through the winter. In 2017, this tower will be equipped with an open-path eddy covariance system for direct measurement of the latent heat flux. This work contributes to the hydrological characterization of the Niaqunguk River, identified by the City of Iqaluit as a secondary water supply. Ongoing work will focus on incorporation of micrometeorological observations for full water balance accounting within the watershed, including sublimation and evaporation rates over the spring snowmelt period. This will make fundamental contributions to the understanding of snow and landscape hydrology in southern Baffin Island.

Résumé

La neige est la composante prédominante des systèmes hydrologiques de l’Arctique et la fonte au moment du dégel printanier, la période la plus importante de l’année au sens hydrologique. Il est donc très important de pouvoir prévoir aussi bien le volume que le moment où l’eau de fonte se manifestera aux fins de modélisation hydrologique et de gestion des ressources hydriques; pour ce faire, il s’agit d’estimer la capacité de stockage d’équivalent eau-neige du paysage au moment de la fonte. Cette évaluation est rendue d’autant plus difficile que la neige est remaniée par le vent et que trop peu de mesures réparties spatialement sont disponibles. Dans le cadre de la présente étude, des levés de grande envergure ont été réalisés dans le bassin hydrographique de la rivière Niaqunguk (communément appelée Apex), près d’Iqaluit, au Nunavut, afin d’y caractériser la répartition de la neige. La moyenne de stockage d’équivalent eau-neige pour l’ensemble du bassin hydrographique était de 24 ±3 cm (nombre d’échantillons = 193) en 2016. En segmentant l’échantillon en fonction du type de terrain, il est possible de voir de faibles accumulations de neige sur les crêtes et les fonds de vallée plus larges, ce qui constitue la majorité du paysage, mais aussi d’épaisses congères sur les pentes escarpées. Une étape du projet a vu l’installation d’une tour météorologique au nord d’Iqaluit, laquelle a pour fonction de suivre les variables climatiques au cours de l’hiver. Cette tour sera équipée en 2017 d’un système de covariance des turbulences en circuit ouvert permettant la mesure directe du flux de chaleur latente. Ces travaux contribuent ainsi à la caractérisation hydrologique de la rivière Niaqunguk, que la ville d’Iqaluit a désigné à titre de source d’eau complémentaire. Des travaux en cours verront à incorpor-
er les observations de nature micrométéorologiques de façon à obtenir un portrait exact du bilan hydrique au sein du bassin hydrographique, tenant compte des taux d’évaporation et de sublimation au cours de la période de fonte lors du dégel printanier. Il s’agit d’une contribution fondamentale à l’état des connaissances portant sur l’interaction de la neige et de l’hydrologie du paysage dans le sud de l’île de Baffin.

**Introduction**

### Arctic hydrology in brief

Arctic rivers show extreme seasonality in their flow behaviour, relative to similar watercourses in the south, and exhibit strongly nival (snowmelt-dominated) flow regimes, with peak discharges during snowmelt and reduced summer/autumn base flows. Smaller rivers may dry up or freeze-up completely in winter, whereas large rivers (e.g., Sylvia Grinnell River on southern Baffin Island) flow under the ice through the winter (Williams and Smith, 1989). This strong seasonality is coupled to arctic atmospheric conditions—water is stored as ice and snow for months during the long, cold winters and the prolonged cold leads to the formation of permafrost in the subsurface.

The presence of permafrost gives arctic rivers their ‘flashy’ characteristics, as permafrost acts as a largely impermeable aquitard, preventing connection of surface water to deep groundwater. The top of the permafrost table also presents a limit to infiltrating water. Since the active layer thickens through the summer, infiltration capacity increases as the warm season continues, and percolation to an increasingly lower water table reduces the responsiveness of rivers to inputs (Dingman, 1973; Church, 1974). Rivers underlain by continuous permafrost show higher peaks and lower base flows relative to those underlain by discontinuous or sporadic permafrost (Newbury, 1974).

The active layer is still frozen at the time of snowmelt, preventing infiltration of meltwater. This causes a rapid initial response in streamflow. As snowmelt continues and patches of bare ground open, active layer thaw begins, allowing some infiltration and gently moderating the streamflow response. However, this also decreases ground albedo, increasing absorbance of shortwave radiation and resulting in increased melt energy (Woo, 2012). Thus, predicting the quantity and timing of peak discharge in an arctic river is a complex function of the meteorological variables affecting the melt rate, the responsiveness of the watershed to meltwater inputs and, most importantly, the antecedent water storage in snow at the end of winter. Unfortunately, snow water storage in the landscape is a difficult variable to quantify because of the spatial variability resulting from redistribution by wind, and the inability of standard measuring techniques to accurately represent it.

### Snow distribution

Snow’s low density and high aerodynamic resistance allow it to be entrained by wind during snowfall events, so snow distribution on the ground is initially determined by differential accumulation at snowfall. McKay and Gray (1981) observed that this process is determined by terrain characteristics and vegetation at 0.1–10 km scales, and by obstructions on the ground at smaller scales. Although this is generally true, open landscapes with limited vegetation, such as the Canadian Prairies or eastern Arctic, tend to be more strongly affected by redistribution of snow after falling (Pomeroy et al., 2002), with either interception at the surface or sublimation being the ultimate fate of entrained particles.

Snow transport by wind is described in detail by Pomeroy and Gray (1995). Three mechanisms prevail: creep, saltation and turbulent suspension. Creep is the movement of particles, which are too heavy to be lifted en masse, by rolling action—commonly seen in the Arctic as advancing snow dunes. Creep typically occurs over poorly consolidated snow cover during periods of light winds, but is not typically the dominant transport mechanism.

When wind speeds exceed a threshold velocity (which varies, dependent mainly on the roughness of the snow surface and the strength of bonds between surface snow particles), saltation begins; particles are dislodged from the snow surface and move abruptly upward, then they are carried a distance downwind and re-impact the surface, dislodging other particles. Saltation is the dominant mode of transport in many cases, with most mass moving within a few centimetres of the snow surface.

If saltation can continue long enough, small particles may move from the upper saltating layer into turbulent suspension, moving at a horizontal velocity approximating that of the air. Due to their large exposed surface area, suspended particles are prone to an extremely high rate of sublimation during periods of available energy, for example, on clear sunny days (Pomeroy, 1988). This sublimation returns their water equivalent to the atmosphere. In the western Arctic, wind transport has been found to result in snow accumulations ranging from 54 to 419% of measured snowfall (Pomeroy et al., 1999).

A variety of measurement techniques exist for monitoring snow (Pomeroy and Gray, 1995; Lundberg et al., 2008), with point measurements ranging in simplicity from moni-
The base-flow period through summer and fall is generally nival, with a significant discharge peak during spring melt. The river’s flow regime is Iqaluit and draining into Frobisher Bay at the nearby neighborhood of Apex (Figure 1). The river’s flow regime is estimated by budget, labor-intensive and repeatability of measurement.

Environment and Climate Change Canada monitors weather variables at the climate station situated at Iqaluit International Airport. At this location, point-based measurements are made of snow depth on the ground and a snowfall gauge is used to make point-based measurements of precipitation. Snow accumulation measurements are only representative of the terrain type that they are situated in, with exposed sites potentially losing upward of 50% of snow to wind action (Pomeroy and Li, 2000). Similarly, snowfall gauges require careful shielding and wind-bias compensation to reduce the effect of wind, as wind undercatch rates as high as 75% have been reported for arctic tundra by Liston and Sturm (2004). Both snow measurements are conducted in a wind-exposed valley at Iqaluit airport, where the problems associated with their measurements are greatest.

Ground-based, spatially extensive field measurements may comprise one of the best estimates for end-of-winter snow accumulation and are commonly used for ground-truthing remote-sensing data during short-term research projects (e.g., Rees et al., 2013). In long-term monitoring, they have typically been avoided because they are very labor intensive. Their use in this project is made possible through the partnership between Carleton University (CU), Nunavut Research Institute (NRI) and Nunavut Arctic College (NAC). The college provided local student support and other logistical resources allowing the study area to be covered at a reasonably dense sample spacing over a relatively short period. One anticipated outcome of this work is an efficient sampling approach that will minimize the fieldwork required for future surveys.

**Regional setting**

This study is being carried out in the Niaqunguk River (commonly known as Apex river) watershed (NRW), a small (58 km²) watershed, originating in the hills north of Iqaluit and draining into Frobisher Bay at the nearby neighborhood of Apex (Figure 1). The river’s flow regime is nival, with a significant discharge peak during spring melt. The base-flow period through summer and fall is generally low flow, but exhibits occasional large rainfall peaks (such as the late July 2016 rainfall and flooding event [Zerehi, 2016]). There is no flow during the winter (Environment and Climate Change Canada, 2016a).

The watershed is situated in the continuous permafrost zone, on the Precambrian shield. The topography ranges from rugged to rolling hills arranged in parallel ridges running to the northwest. The surficial material is primarily thin glacial till with granite/granitoid rock outcrops (Blackadar, 1967; St-Onge et al., 1999; Hodgson, 2005; Allard et al., 2012; Tremblay et al., 2015). Frequent boulder fields and isolated glacioluvial or lacustrine deposits (Squires, 1984) are also evident. Vegetation is extremely low lying and consists of tundra grasses, dwarf shrubs and forbs, considered typical for the region. This low vegetation provides very little interception to blowing snow, unlike arctic shrub tundra or taiga landscapes.

Annual precipitation is 404 mm, with 57% received as snow, mostly from October to May (though precipitation type has not been reported at the Iqaluit airport climate station since 1997), with 97% of daily snow accumulation rates below 9.5 mm, though extreme daily snowfalls up to 32 cm have been recorded in the 1981–2010 climate normals (Environment and Climate Change Canada, 2016a). Rainfall predominates from June to September, when average daily air temperatures rise above 0°C.

Prevailing winds are funneled northwest or southeast between the mountainous areas of the Hall and Meta Incognita peninsulas (to the north and south, respectively), which is channeled in the NRW by the northwest-trending ridges that dominate the topography. Average annual wind speeds are 15.7 km·h⁻¹, though winter storms can bring gusts well over 100 km·h⁻¹ (Environment and Climate Change Canada, 2016a). These storms originate primarily over Hudson Bay to the south, over the Arctic Ocean to the northwest, or from the eastern seaboard of North America (Gascon et al., 2010). Frequent blowing snow events during these storms pose considerable logistical challenges and hazards for eastern Arctic communities (Gordon et al., 2010), and redistribute snow from exposed to sheltered areas. This results in substantial snow depth variability before spring melt (Figure 2a), which contributes to the development of a patchy snow cover during melt (Figure 2b).

**Review of Niaqunguk River hydrological studies**

Past scientific interest in the NRW has been limited. A Water Survey of Canada gauge has been recording stage (water level) near the river’s mouth at Apex since 1973 (Environment and Climate Change Canada, 2016b, record gap from 1997 to 2006), and a geochemical characterization of the watershed was conducted by Obradovic and Sklash (1986) and repeated by Kjikjerkovska (2016), but little other hydrological information is available. In recent years, there...
Figure 1: Locations of snow survey points from the spring of 2015 and 2016 and the Carleton University/Nunavut Research Institute meteorological tower, Niaqunguk River watershed, southern Baffin Island, Nunavut. Snow water equivalent (SWE) measured in the field in 2015 and 2016 corresponds to the maximum snow accumulation on the ground for that snow year, just before the onset of spring melt. The digital elevation model (derived from WorldView-1 stereo optical data) for this map was provided by Canada Centre for Remote Sensing, Natural Resources Canada (NRCan). Shoreline and watercourse shapefiles were drawn from NRCan’s CanVec dataset (Natural Resources Canada, 2015). Map created using ArcGIS 10.4 (Esri, 2016).
has been renewed interest in the Niaqunguk River as a secondary water supply for the rapidly growing City of Iqaluit (Sims and Allard, 2014) to augment the current supply from Lake Geraldine (Golder and Associates Ltd., 2014). The City of Iqaluit classified the watershed as a protected area (FoTenn Consultants Inc., 2010), and several subsequent studies on the hydrology of the NRW have been conducted to support source water planning efforts.

Snowmelt is the largest contributor to the annual streamflow of the Niaqunguk River, delivered in a short-lived pulse during spring melt. The continuous permafrost underlying the NRW prevents significant annual infiltration, and the shallow frost table in the active layer during spring melt further limits snowmelt infiltration. Recent work by Thiel (2016) identified partial overland flow along the soil–vegetation interface during snowmelt, determined using the concentration and composition of dissolved organic carbon (DOC). The DOC concentration decreased after peak discharge, simultaneous with a compositional change away from a dominance of humic compounds derived from vegetative material. The associated increasing dominance of protein-like molecules, typically generated in the water by microbial action, suggests a switch from surface to subsurface pathways after peak discharge, and an increasing importance of lake water or groundwater to the total stream discharge.

During the summer base-flow period, an increase in specific conductance (Obradovic and Sklash, 1986; Chiasson-Poirier, 2016) and total dissolved solids (Rusk, 2016) indicate increased groundwater contributions. Since the isotopic signals of lake water and groundwater were not well resolved in the two isotope studies conducted in NRW to date (Obradovic and Sklash, 1986; Kjikjerkovska, 2016), the exact contribution of lake water to annual streamflow is not known. Richardson and Shirley (in press) determined that thorough mixing of snowmelt and soil water occurred before streams entered lakes in the NRW, but the mixing between this streamflow and the lake water column was limited. This suggests that stored lake water does not become an important component of river flow until after snowmelt has concluded.

Despite the recognition by past researchers of the importance of snowmelt for providing peak discharge and comprising the largest overall source of water to the NRW annually, there have been no systematic snow cover observations reported, and no effort to quantify the end-of-winter snow water storage at a landscape scale. Improvements to precipitation measurement by Environment and Climate Change Canada at the Iqaluit airport ‘supersite’ (Mariani et al., 2016) will allow for increased confidence in estimates of snowfall depths, but must be matched by field data, due to the strong wind-driven redistribution typical to arctic tundra. This redistribution results in a spatially heterogeneous snow cover, complicating prediction of water storage and melt dynamics from point measurements.

The work described here partners researchers from Carleton University with staff and students from the NRI and NAC Environmental Technology Program (ETP) to fill this gap in hydrological knowledge. A community-based water quality monitoring campaign has been conducted by the NRI in the NRW since 2009 (Shirley, 2014) and long-term monitoring work at Tasiluk Lake (commonly known as Crazy lake) has been conducted by ETP students for over a decade (Dyck, 2007). During the project described in this paper, the ETP students learned snow hydrology monitoring techniques and applied them while working in the field with the author. The students are exceptionally knowledgeable of the complex terrain in the NRW, well trained in environmental science, with particular focus on local conditions, and skilled snowmobile operators; these attributes make them an essential part of data collection for this project, especially in more remote areas of the watershed. A sustainable program of annual snow surveying is in development, which will engage future cohorts of ETP students.
and enhance capacity for field data collection to monitor trends in the end-of-winter snowpack.

**Methodology**

**Snow surveying**

Extensive snow surveys were conducted in the NRW in April–May of 2015 and 2016 (see Figure 1 for sampling locations) by CU researchers, NRI staff and ETP students (Figure 3). Travel in the field was by snowmobile, with sampling stops at predetermined locations. At each location, a SWE sample was taken using a Geo Scientific Ltd. Federal snow sampler and weighed on a sling scale, providing a measurement of snow depth and density. When the cores were weighed, they were sheltered from the wind as much as possible to prevent jittering of the scale, which could cause erroneous readings. Calibration of the snow scale in the NRI lab at the end of the 2016 season confirmed that the scale’s readings were linear along its measurement range ($R^2 = 0.999$). Several supporting depth measurements were taken at random locations within 2–3 m of each core using a Snowmetrics depth probe, to characterize the site-scale variability in snow depth. This variability was expressed in terms of both a standard deviation (SD) and a coefficient of variation (CV, a unitless standardization of SD divided by mean).

The sampling strategy differed between the two years. Since 2015 was an exploratory analysis, locations were visited systematically (every 1 km) along seven transects running northwest-southeast in the NRW. Two additional areas were surveyed at a much closer spacing (30–100 m), with a SWE core being measured at approximately one out of five sampling sites; only depth was measured at the remainder of the sites to save time. These areas were lake catchments, one situated to the north of the NRW and the other in the southern end of the NRW (see Figure 1). Variography of the closely spaced samples indicated an autocorrelation range of approximately 80 m, giving a minimum range between future samples (Figure 4; variography was performed using the R spatial statistics package geoR [Ribeiro and Diggle, 2001]).

The 2016 sampling strategy was modified accordingly. A terrain-based model predicting snow accumulation was created in

![Figure 3](image-url): Nunavut Arctic College Environmental Technology Program student S. Noble-Nowdluk weighs a snow water equivalent (SWE) core during the 2016 snow survey, Niaqunguk River watershed, southern Baffin Island, Nunavut.

![Figure 4](image-url): Variogram from the 2015 data, indicating the 80 m autocorrelation range identified in the snow surveying work, Niaqunguk River watershed, southern Baffin Island, Nunavut.
2015–2016, and used to stratify the NRW by terrain unit. Six transects were planned, again running northwest-southeast to take advantage of faster travel time along river valley floors. Points were then randomly generated along these transects, with a minimum spacing of 100 m, stratified by the terrain units identified in the model. Opportunistic random sampling, stratified by terrain unit, was conducted during the last days of surveying, to maximize survey coverage before the melt.

*Carleton University/Nunavut Research Institute meteorological tower*

To facilitate measurement and modelling of the snowpack energy balance, and to provide local weather monitoring data for the lower Niaqunguk River watershed, an automated meteorological tower was set up with the help of ETP students (Figure 5) at latitude 63.752°N, longitude 68.437°W, in April 2015 (see Figure 1 for location).

The meteorological tower was augmented in October 2015 with the addition of automated melt collectors (Figure 6a, b), and in spring 2016 with solar panels, additional sensors and communication devices (Figure 7a, b). In its present configuration, the tower averages meteorological data on 15 min intervals, takes a high-resolution photograph of the nearby valley daily, and transmits all data and photographs via cellular modem weekly.

The tower will provide winter wind data to drive blowing snow models, and to drive energy balance models by collecting air temperature, humidity, wind speed (and direction) and net radiative data through the year. Rainfall data is also collected from May through October. In 2017, the tower will be upgraded with an open-path eddy covariance system to measure the latent heat fluxes of snow sublimation and water evaporation. A summary of the measurements currently taken at the tower, including the sensors used, their instrumental accuracies and the measurement periods throughout the year, are presented in Table 1.

Aside from installation and maintenance of the meteorological equipment, the author also monitored melt in snow pits during the spring of both 2015 and 2016. These data will be used to validate the snow ablation model being developed. During this work in May 2016, two new snowfalls occurred, allowing density sampling of the newly fallen snow.

*Figure 5: Nunavut Arctic College Environmental Technology Program students A. Pedersen and P. Aqqqaq taking measurements at the Carleton University/Nunavut Research Institute meteorological tower in April 2015, Niaqunguk River watershed, southern Baffin Island, Nunavut.*

*Figure 6: Carleton University/Nunavut Research Institute automated snowmelt collector, Niaqunguk River watershed, southern Baffin Island, Nunavut: a) schematic view of collector and b) photo of collector, taken in October 2016. Instruments are 1) basal thermocouples, 2) ablation stake with mounted thermocouple array and 3) drain heater with control system.*
Snow distribution: spatial and statistical analysis

Terrain analysis was conducted in System for Automated Geoscientific Analyses (SAGA), an open-source, cross-platform GIS application designed for geoscientific analyses (Conrad et al., 2015). A variety of terrain variables were computed from a digital elevation model (DEM; derived from WorldView-1 stereo optical data and provided by the Canada Centre for Remote Sensing, Natural Resources Canada) in an effort to determine which terrain variables were correlated to snow accumulation. Due to the complex interplay of terrain and wind in determining snow distribution, no single variable provided a relationship robust enough for reliable prediction of snow accumulation.

An alternative approach was tested using k-means clustering (Forgy, 1965; MacQueen, 1967) to delineate terrain units. The technique of k-means clustering is one of the fundamental methods of data classification by automated machine learning, where a multivariate dataset is divided into unique, definitive groupings (called clusters) based on similar values in the independent variables. Terrain clusters were defined based on hillslope gradient, aspect, curvature, a topographic openness index and a normalized height index. The initial result was four terrain clusters, which corresponded roughly to hilltops/ridges, valley floors, hill mid-slopes and hill toe-slopes.

The SWE data was then segmented by terrain cluster and differences between clusters were tested using a one-way analysis of variance (ANOVA), which indicated that the two slope classes were sufficiently similar to warrant merging them into a single class. The distribution of the resulting three terrain classes in the NRW is shown in Figure 8. The ANOVA tests for difference in means between multiple groups using an F-test, and as such is an extension of the classic two-group t-test (Fisher, 1970). Even though the test indicates whether a difference exists, a post-hoc test is required to determine the statistical nature of each difference. A Tukey test allows for pairwise comparison of group means, with an associated confidence (Tukey, 1949). Statistical analyses were performed using the R statistical programming language (R Development Core Team, 2013).

Results

Snow accumulation differed substantially between the two years (Table 2). The full-survey mean watershed SWE for 2015 was 14 ±1 cm (number of samples \( n = 152 \)), with a mean watershed snow density of 330 ±14 kg m\(^{-3}\) \((n = 152)\), and mean watershed snow depth of 39 ±4 cm \((n = 392)\). The full-survey mean watershed SWE for 2016 was 24 ±3 cm \((n = 193)\), with a mean watershed snow...
density of $460 \pm 16$ kg m$^{-3}$ ($n = 193$), and mean watershed snow depth of $57 \pm 8$ cm ($n = 193$). The supporting site depth measurements also differed substantially; the 2015 data had a mean site SD of 20 cm, whereas the mean site CV was 0.46. In comparison, 2016 showed less site-scale variability, with a mean site SD of 11 cm and a mean site CV of 0.35. New snowfalls observed in May 2016 had densities of 174 kg m$^{-3}$ on May 21 and 67 kg m$^{-3}$ on May 22.

The terrain model applied to the 2016 data showed clear differences between the snow accumulations within the three terrain units identified (Figure 9; Table 3). The sample populations of SWE on each terrain unit were found to be significantly different by one-way ANOVA (F-test score = 25.21, significance value $[p] = 1.9 \times 10^{-10}$) with a subsequent Tukey post-hoc multiple comparisons test, which confirmed that each of the three clusters was distinct (all $p$ values < 0.005). Ridges accumulated the least, with a mean SWE storage of $11 \pm 3$ cm, whereas valley floors stored $27 \pm 5$ cm mean SWE on average, which is similar to the overall mean value. Each of these terrain units comprises approximately 40% of the landscape. Drifts mainly occurred on slopes, with a mean SWE of $39 \pm 8$ cm, though this unit occupied only approximately 20% of the landscape. With landscape weighting, it was determined that concentrated sampling in drift zones on slopes and on valley floors would help reduce the overall error in the SWE estimate derived from the 2016 survey.

**Discussion**

The 2016 survey showed a near-doubling of snow water storage relative to 2015, despite snow accumulation only
increasing by 50% on average. Observations by the author were that windswept areas appeared similar in the two years, but that drift areas in 2016 were deeper and denser due to increased wind compaction and ice layer presence. This was exemplified particularly well in gullies, where similar depositional patterns were apparent between both years, but larger drift features were found in 2016 (Figure 10a, b).

Consultation with community members made it clear that 2016 was a deep snow year, with an uncharacteristically high frequency of late-season blizzards. These blizzards are clearly evident in the Iqaluit airport weather record and caused almost half of the end-of-winter snow accumulation (Figure 11). These blizzards led to the formation of multiple ice layers in the snowpack in 2016, which increased the overall density and hardness of the pack. Unfortunately, this created challenges for sampling in some locations as the Federal snow sampler could only be pushed into the snowpack if significant force was used. This is undesirable for several reasons: 1) it is labour intensive, 2) it puts high stress on the sampling equipment, risking damage, and 3) it reduces accuracy by compacting snow inside the core barrel. At several locations, multiple cores were taken until one was acquired without applying large amounts of force, whereas some locations were abandoned entirely due to heavy ice layer formation. Because such ice layers were most often encountered at deep drift sites, this introduces bias to any unstratified SWE estimates, favouring shallower locations. This provides further justification for the stratification approach taken here, though it also

Table 2: Summary statistics for the 2015 and 2016 snow surveys, Niaqunguk River watershed, southern Baffin Island, Nunavut. Site depth refers to the supporting depth measurements taken within 2–3 m of each snow water equivalent (SWE) core.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean SWE (cm)</th>
<th>Mean density (kg·m⁻³)</th>
<th>Mean depth (cm)</th>
<th>Site depth SD (cm)</th>
<th>Site depth CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 (SWE n=152, depth n=392)</td>
<td>14 ±1</td>
<td>330 ±14</td>
<td>39 ±4</td>
<td>20</td>
<td>0.46</td>
</tr>
<tr>
<td>2016 (n=193)</td>
<td>24 ±3</td>
<td>460 ±16</td>
<td>57 ±8</td>
<td>11</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Abbreviations: CV, coefficient of variation; n, number of samples; SD, standard deviation.
 underscores the importance of operator experience and training in performing snow surveys.

The supporting measurements suggested that site-scale (<2–3 m) variability in snow depth was higher in 2015 than 2016. This may be due to the smoothing effect of a deeper snowfall, which has the potential to overcome small-scale accumulation forms that occur in rough terrain (Figure 12). These forms were commonly observed during the 2015 surveys, but were generally less prevalent in 2016. This may also be a sampling artefact, however, as the sampling protocol was less strict regarding the distance for support measurements in 2015. A larger footprint has greater potential to pick up on terrain-driven mesoscale variability, rather than the intended roughness-driven microscale variability (McKay and Gray, 1981). For example, supporting depth measurements taken within 2 m of a ridge peak will likely show similar shallow depths, whereas measurements taken within 5 m of the same point could capture both the shallow ridgetop accumulation and the edge of the deep lee slope accumulation.

Terrain clustering showed intuitive, physically oriented relationships to snow accumulation. Higher exposed areas on ridges and hilltops accumulated the least snow, as these areas are prone to scouring by wind. Steeper slopes accumulated the greatest amount of snow, which is commonly observed in arctic landscapes. This may correspond to deposition on lee slopes of hills or on the sides of narrow gullies and stream valleys, which tend to accumulate large drifts (Figure 10a, b). Further work will be needed to refine these relationships and apply them to additional years of snow survey data.

The snowfall densities observed in May 2016 differed from one snowfall event to another, likely resulting from different meteorological conditions, which altered crystal morphologies and liquid water content. Typical densities for North American winter snowfall range from 50–100 kg·m⁻³ (Pomeroy and Gray, 1995). On May 21, 2016, the measured snowfall density of 174 kg·m⁻³ was surprisingly high. It was associated with a mean air temperature of −0.6°C (close to the freezing point) suggesting a potential for high liquid content, resulting in an increased overall density. Crystal morphology consisted mainly of plates and needles, forms which have few delicate processes and thus settle quickly on the ground (McClung and Schaerer, 2006). Comparatively, on May 22, 2016, a density measurement of 67 kg·m⁻³ corresponds more closely to the range reported by Pomeroy and Gray (1995). The snow that day was composed mainly of stellar dendrites and plates (low density crystals corresponding to the classic snowflake). This snow compacts over a longer period on the ground as delicate processes are broken during settling. Mean temperature on that day was −1.8°C, suggesting a moderate liquid water content in the snow. Anecdotally, the snowfall felt drier on the skin that day.

**Further work**

Work is ongoing to fine-tune the terrain-based snow accumulation model, and to compare those results to results from a blowing snow model driven by data from Iqaluit airport and the CU/NRI meteorological tower. Improved models will help to develop more accurate sampling schemes, to maximize accuracy and efficiency in the field. Efforts continue through this partnership project to build the capacity at NRI and NAC to monitor snow hydrology, with sustained interest in the project from a number of students and recent ETP graduates. Training students in sampling techniques can benefit other research projects, both in

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**Table 3:** Summary statistics for the 2016 clustered data, indicating the snow storage depth and areal coverage of each terrain unit identified within the Niaqunguk River watershed, southern Baffin Island, Nunavut. Compare the cluster results to the full-survey mean in Table 2.

<table>
<thead>
<tr>
<th>Terrain unit</th>
<th>Mean SWE (cm)</th>
<th>Landscape area (%)</th>
<th>Contribution to overall error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridges</td>
<td>11 ±3</td>
<td>41.4</td>
<td>27</td>
</tr>
<tr>
<td>Valley floors</td>
<td>27 ±5</td>
<td>39.2</td>
<td>41</td>
</tr>
<tr>
<td>Slopes</td>
<td>39 ±8</td>
<td>19.4</td>
<td>32</td>
</tr>
<tr>
<td>Overall</td>
<td>23 ±5</td>
<td>100</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviation: SWE, snow water equivalent

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**Figure 9:** Boxplots showing the 2016 clustered data for the Niaqunguk River watershed, southern Baffin Island, Nunavut. Notches indicate the 95% confidence interval around the median value.
the NRW (e.g., NRI microbial monitoring campaign [Shirley, 2014]) and further afield in the territory.

Work is also being conducted to prepare a snow ablation model to quantify spring sublimation and evaporative loss. This will be enhanced by the addition of an open-path eddy covariance system to the CU/NRI meteorological tower in 2017. This sophisticated equipment allows for direct measurement of the movements of water vapour in the near-surface boundary layer at high frequency, and should significantly improve the understanding of surface-atmospheric exchanges during snowmelt. This, in turn, will improve modelling of fluxes of water and atmospheric contaminants in the arctic environment (Richardson and Shirley, in press).

**Economic considerations**

This joint work between Carleton University, Nunavut Research Institute and the Nunavut Arctic College Environmental Technology Program has generated useful knowledge on spatial distribution of snow water equivalent, as well as an ongoing meteorological record, within the Niaqunguk River watershed. The results can be employed in hydrological analyses and modelling, supporting hydrological and geochemical studies in the area. As the Niaqunguk River has been identified as a secondary water supply for the City of Iqaluit, municipal engineers have an interest in continuing field research efforts to monitor and predict annual water resource availability. The results of this study can inform the planning of such efforts. As baseline data on snow distribution and hydrology are limited in the eastern Arctic, this work represents an important

![Figure 11: Snowfall water equivalent (measured as total precipitation, dark grey bars) and snow accumulation depth on the ground (blue area) measured at Iqaluit International Airport (southern Baffin Island, Nunavut) for the 2015–2016 snow year. Note the large number of precipitation events in March and April 2016, with a near-doubling of snow accumulation in April. High storm-wind speeds may have prevented accumulation during many of the events in March, and these winds, together with rapid densification of snow crystals through settling, likely account for the rapid drop in snow depth on the ground after each accumulation event.](image)

![Figure 10: The same location in the Niaqunguk River watershed (southern Baffin Island, Nunavut) in a) April 2015 and b) April 2016 (taken at different angles). Note the large drift blocking the entrance to the gully in 2016, which was not present to a significant extent in 2015.](image)
Figure 12: Snow features, called sastrugi or uqalurait (in Inuktitut), form from snow accumulation and erosion downwind of sharp surface nonconformities (in this case, boulders at a rough site in a valley bottom, near Iqaluit, southern Baffin Island, Nunavut). These forms can strongly influence site-scale snow depth variability, but can be smoothed out by deeper snow accumulations. Because they indicate the direction of the prevailing wind, uqalurait are traditionally used as navigation aids on the land (R. Qitsualik, pers. comm., 2016).

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