Progress in Canadian Snow and Frozen Ground Hydrology, 2003-2007

Sean K. Carey and John W. Pomeroy

Abstract: This paper reviews advances made in Canadian snow and frozen ground hydrology between 2003 and 2006, and follows the 1999 to 2002 review of Woo and Marsh (2005). In this assessment, frozen ground hydrology encompasses the influence of both seasonally and perennially frozen ground (permafrost) on hydrology. In reviewing snow hydrology, we exclude processes associated with precipitation, glaciers and snow avalanches. With respect to frozen ground, its influence on infiltration, percolation and runoff in both permafrost and more temperate environments continues to be an active area of research. The role of permafrost at the landscape scale, and its interaction with soil properties in controlling runoff, has received particular attention. In snow hydrology, knowledge on physical processes of accumulation, redistribution and melt continue to advance through both field experiments and numerical modelling in both natural and urban settings. There also continues to be research on snow chemistry.

Résumé : La présente communication passe en revue les progrès accomplis au Canada en matière d'hydrologie de la neige et du gélisol entre 2003 et 2006 et se penche sur l'étude menée de 1999 à 2002 par Woo et Marsh (2005). Dans cette évaluation, l'hydrologie du gélisol englobe l'influence à la fois du gélisol saisonnier et du pergélisol (permagel) sur l'hydrologie. Dans l'examen de l'hydrologie de la neige, nous excluons les processus associés aux précipitations, aux glaciers et aux avalanches. En ce qui concerne le gélisol, son influence sur l'infiltration, la percolation et l'écoulement dans les milieux à pergélisol et dans les milieux plus tempérés continue de constituer un domaine de recherche actif. Le rôle du pergélisol à l'échelle du paysage, ainsi que son interaction avec les propriétés du sol pour ce qui est du contrôle du ruissellement, ont fait l'objet d'une attention particulière. En matière d'hydrologie de la neige, la connaissance des processus physiques de l'accumulation, de la redistribution et de la fonte continue de progresser grâce aux expériences sur le terrain et à la modélisation numérique dans les milieux à la fois naturels et urbains. Des recherches continuent également d'être menées sur la composition chimique de la neige.

Sean K. Carey[1] and John W. Pomeroy[2]

[1] Department of Geography and Environmental Studies, Carleton University, Ottawa, ON K1S 5B6
[2] Centre for Hydrology, University of Saskatchewan, Saskatoon, SK S7N 5C8

Submitted September 2007; accepted February 2008. Written comments on this paper will be accepted until December 2009.

Frozen Ground Hydrology

Frozen ground behaves as transient subsurface layer with reduced permeability. The magnitude of this reduced permeability varies widely, and is dependent upon the volume and disposition of ice within the pore spaces and the soil temperature. Whereas seasonal frost affects snowmelt infiltration and redistribution of water within soils during certain periods of the year, permafrost, by its nature, acts as a semi-permanent aquitard, although it is subject to melt over longer time scales.

The accurate prediction of the ground thermal regime is of central importance to frozen ground hydrology. Between 2003 and 2006 there have been a number of papers detailing improved methods to predict frost table in both permafrost and seasonally frozen environments (Woo *et al*., 2004; Carey and Woo, 2005; Yi *et al*., 2006) using different numerical schemes. Quinton *et al*. (2005) examined the effect of thaw status and liquid water content on the annual subsurface energy balance of a permafrost slope demonstrating that most energy exchange on an annual basis was associated with latent heat.

Seasonally Frozen Soils

Research examining the role of seasonally frozen soils on hydrology has been geographically concentrated in prairie and forested (typically managed) watersheds. Hayashi *et al*. (2003) observed depression-focused infiltration of snowmelt water in the prairies and demonstrated that frozen soil, owing to its low infiltration capacity, retained snowmelt water and allowed it to infiltrate rapidly upon the complete thawing. This process plays an important role in groundwater recharge in the prairies, where numerous depressions collectively retain a large fraction of snowmelt runoff water. Also in the prairie, van der Kamp *et al*. (2003) linked land-use changes with the sustainability of wetlands, finding that the infiltration into frozen soils of former agricultural fields converted to grasslands was high enough to absorb most or all snowmelt, reducing the sustainability of wetlands that previously existed under cultivation.

In central Ontario, Murray and Buttle (2005) examined snowmelt infiltration and soil water mixing on forested and harvested slopes. Greater soil wetness in the harvested area restricted mixing between inputs of pre-melt soil water, leading to longer water residence times at depth in the ablation till. They suggested harvesting may promote increased subsurface flow above the basal till contact and saturation overland flow during spring melt. Monteith *et al.* (2006a; 2006b) used Cl^- as a conservative tracer along with concomitant hydrometric and hydrochemical data to study snowmelt pathways of water between paired harvested and forested catchments. A short-circuiting mechanism was observed in the harvested watershed, whereby wetter soils and higher water table levels restricted infiltration inputs and allowed a portion of incoming event water to be delivered laterally via surface and near-surface pathways. However, no significant differences in mean residence times were found between the catchments during snowmelt.

Permafrost Hydrology

The influence of permafrost on hydrology is largely dependent upon its continuity in space. In continuous permafrost environments, deep drainage is largely restricted, whereas in discontinuous permafrost environments, taliks and areas of perennially frozen ground link deeper subsurface aquifers with surface recharge. Canadian research in the zone of continuous permafrost has predominantly been confined to the Queen Elizabeth Islands. Young and Woo (2003a) reported how frost table development beneath patchy wetlands facilitates wetness through limiting percolation. Shallow frost tables are maintained by ground ice, which allows energy to be largely consumed by the latent heat in the soils. In addition, the high air content of organic soils delays ground thaw. Young and Woo (2003b) detailed the thermo-hydrological responses of a high arctic environment to the extremely warm summer of 1998, documenting a deepening active layer, alteration in the evapotranspiration regime, and adjustment of the water table and runoff. Semi-permanent snowpacks and patchy wetlands buffer some local sites from drying. Similarly, Woo and Young (2006) reviewed the occurrence, characteristics and sustainability of wetlands in the high Arctic. Reliable water supply during the thaw season is critical for wetland sustainability, whose sources often include late-lying snowbanks, groundwater discharge, streamflow and inundation, and for some ice-wedge wetlands, ground ice melt. Organic layers play a critical role, insulating soils and encouraging permafrost aggradation and hence a thinner, more easily saturated active layer. In a study of tundra ponds, Woo and Guan (2006) showed that the dominance of overland flow in the spring is their principal agent of recharge. Freshet gives rise to extensive flow connectivity sustained for only a brief two week period. Following this, lateral drainage declines as the active layer thaws, although some subsurface drainage among ponds was documented.

Recent work links catchment hydrological processes in permafrost regions with sediment records. Forbes and Lamoureux (2005) presented a two-year study in the high Arctic that demonstrated the clear hydrological controls over sediment delivery contrasting earlier studies that emphasized temperature controls over sediment transport. Sediment erosion increases disproportionately with increasing spring snow water equivalent (SWE), suggesting a strong sensitivity of erosion to snow availability. Lamoureux *et al*. (2006) reported a hydrological reconstruction in the Canadian Arctic and showed with annually-resolved sedimentary records that spring discharge had declined substantially since the early 1800s, and is substantially higher during the 1600-1800 period. The explanation for this decline is difficult to discern, but may represent shifts in the spring water balance due to increased ablation and soil storage (degrading permafrost), effectively reducing peak discharge.

Discontinuous Permafrost Hydrology

Discontinuous permafrost environments are hydrologically complex. The presence or absence of permafrost affects soil storage and drainage along with vegetation and soil properties. Between 2003 and 2006, research has advanced upon previous work by improving conceptual and numerical models of the hydrological systems and by increasing the scale of investigation from more traditional plot/slope studies to the headwater and larger catchments.

In the Subarctic Canadian Shield near Yellowknife, NWT, Spence and Woo (2003) demonstrated that soil filled valleys in the Canadian Shield perform three functions: (i) they receive inflows from upslope bedrock outcrops, (ii) retain it as storage and (iii) transfer it downslope to lakes or other water courses. The mechanism by which soil filled areas conduct the water is the "fill and spill" runoff mechanism. Valley physiography results in a series of storages, each of which must be filled before either subsurface or surface flows are conducted downslope. The threshold in each store varies spatially with soil depth, type and thermal state. Although not stated explicitly in the paper, the "fill and spill" mechanism is broadly applicable to soil filled areas in other terrains. Spence and Woo (2006) expanded on this work by conceptualizing runoff generation processes across a heterogeneous headwater catchment. Basins can be conceptualized as a number of hydrological elements, whose storage are defined by the processes acting within them as well as inputs from adjacent elements. Runoff is only generated when saturation thresholds are exceeded. The importance of inputs from adjacent elements causes landscape geometry and topology to control where, when and how runoff is generated across a catchment. Also in the Subarctic Canadian Shield, Mielko and Woo (2006) studied snowmelt runoff processes in a headwater lake and its catchment. Time lags ranging from days to a week exist between the commencement of snowmelt and the arrival of water to the lake due to the heterogeneous nature of runoff pathways. Water is delivered quickly from uplands and more slowly from bottom lands, where frost table development controls subsurface storage, flow and groundwater recharge. As with the work of Spence and Woo (2003; 2006), this paper highlighted the importance of catchment topology in the generation of runoff from Subarctic Canadian Shield basins.

Several hundred kilometres west in the Mackenzie Valley near Fort Simpson, NWT, Quinton *et al*. (2003) and Hayashi *et al*. (2004) examined the hydrologic functions of unique peatland types in a lowland discontinuous permafrost environment; including channel fens, flat bogs, and peat plateaus. Using isotopic and chemical signatures of surface and subsurface water, as well as hydrometric measurements, they found that peat plateaus were important runoff producers, flat bogs stored most of the water they receive, and channel fens conveyed water to the basin outlet. Tracer-based hydrograph separation showed that direct snowmelt contribution to spring runoff was less than half of total discharge, stressing an importance of the water stored over winter in lakes and wetlands.

In the mountainous western subarctic near Whitehorse, YT, the Wolf Creek Research Basin continues to be a location of active research (Janowicz *et al.*, 2004). Janowicz *et al.* (2003) considered the spatial variability of the two major parameters controlling snowmelt infiltration to frozen soils; soil moisture and snow water equivalent. Variability was considered between, and within forest, subalpine and alpine ecosystems in the Wolf Creek basin. A lognormal probability distribution was fitted to observed soil moisture and SWE data collected within these relatively homogeneous ecosystems. Variability progressively increased from the forest, to the subalpine, and, to the alpine sites. This increase in variability with progressively higher elevation ecosystems illustrates the ability of vegetation to dampen the variability of infiltration to frozen soils. Carey and Quinton (2004; 2005) used hydrometric and hydrochemical data in an 8 km^2 alpine sub-basin of Wolf Creek to determine the sources and pathways of water for the melt and summer seasons. Stable isotope and hydrochemical parameters suggest that, at the beginning of the melt period, meltwater infiltrates soil pores and resides in temporary storage. As melt progresses and bare ground appears, thawing of soils and continued meltwater delivery to the slopes allows rapid drainage through surface organic layers. As melt continues, soil thawing progresses and pre-event water mixes with melt water to impart streamflow with a gradually decreasing meltwater contribution. For the melt period, it was calculated that 21% of freshet was supplied by the snowpack, and the remaining majority was pre-melt water stored in the catchment slopes over-winter and displaced during melt. For summer rainstorms, Carey and Quinton (2005) employed three-component hydrograph separation to distinguish the streamflow contribution of rainfall, water in mineral soils and water in the organic layer. Results suggested that water from the mineral soil dominated the stormflow hydrograph, yet there were equivocal results based on tracer selection. In the same sub-basin, McCartney *et al*. (2006) segmented the catchment into Hydrological Response Units (HRUs) with distinct soil, vegetation and hydrological regimes and examined snowmelt water balances. Areas with greater snow accumulation were associated with taller shrub vegetation, lee slopes and to a lesser extent, elevation. The timing of snowmelt among HRUs was controlled by available energy and runoff was enhanced from HRUs with (i) high SWE, (ii) rapid melt rates, (iii) thin or no organic soil covers, (iv) high antecedent moisture, and (v) cold soil temperatures. For the catchment, tall shrub and tundra HRUs accounted for 81% of the calculated runoff while accounting for 50% of the total area.

Results from hydrometric and hydrochemical work in both subarctic and arctic environments continues to guide the development of process-based models. For organic-covered permafrost slopes, Quinton *et al*. (2004) presented a hillslope runoff model that couples snowmelt with heat and liquid water transfer within the soils. The model was able to produce the general characteristics of slope drainage, yet it was suggested that incorporation of spatial variability in thaw across the slope and preferential flow pathways would improve simulation.

Snow Hydrology

Snow hydrology continues to be a major focus of Canadian research. While this review excludes precipitation, remote sensing, glaciers and snow avalanches, there is considerable Canadian snow research in each of these areas. With regards to snow processes, advances continue in areas of snow accumulation, redistribution, melt and chemistry along with improved methodologies for sampling and representing snow in hydrological and land-surface models.

The Effect of Shrubs on Accumulation and Melt

There has been an increase in the distribution of shrubs in the circumpolar north (Sturm *et al*., 2001), which has provided impetus to investigate the role of low vegetation on snow accumulation and melt. Essery and Pomeroy (2004a) applied a fine-scale model of blowing snow redistribution in the low Arctic to investigate the influence of changing shrub coverage and height. Increasing shrub height increased the snow depth within the shrub-covered area, up to a limit determined by the snowfall amount plus blowing snow inputs. However, increasing shrub coverage decreased snow depth within shrubs as the supply of blowing snow imported from open areas was reduced. Simulations without any shrub cover gave much greater accumulations of snow on lee slopes of the prevailing winds than on windward slopes than if shrubs had been present. Marsh *et al*. (2003) carried out a study of snow accumulation and melt at a large shrub area in the same region. End of winter snow surveys showed that the SWE varied from 98 mm for tundra sites, to 141 mm for shrub sites, 499 mm for drift locations, and 155 mm at forested sites, with a basin average of 142 mm; largely confirming the model results of Essery and Pomeroy.

Bewley *et al*. (2004a) and Pomeroy *et al*. (2006) presented results from a study of the effect of shrub tundra on snow accumulation, radiation transfer, turbulent transfer and melt rates. They found that snow accumulation in shrubs is higher than in open tundra due to retention of snow by short shrubs and redistribution of blowing snow to tall shrubs. They also found that the emergence of shrubs during melt dramatically decreases surface albedo, increases surface temperature and sensible heat flux to the atmosphere, reduces transmissivity and turbulent transfer to underlying snow, has little effect on evaporation rates from snow and has little effect on net radiation to the snow surface. As a result of this combination of effects, snowmelt rates are generally, but not always, enhanced under shrub canopies in comparison to open snowfields. The results on snow accumulation and melt are largely consistent with observations noted by Marsh *et al.* (2003), who showed that at a low tundra site, although a shrub site had an end of winter SWE approximately 40% higher than an open tundra site, the mean SWE at the shrub site deceased faster than at the tundra site.

Snowmelt Variability

Pomeroy *et al.* (2003) showed that in areas of high relief the turbulent and radiative fluxes to melting snow in the Arctic not only differ in magnitude, but in direction. This is partly due to feedback between incoming solar radiation, inception of melt and resulting shrub vegetation exposure and subsequent effects on surface temperature on north and south aspect slopes. A 25% difference in insolation between slopes resulted in sensible heat fluxes and net radiation of differing directions and vastly different magnitudes after a few days of melt. These differences create complications for aggregated representation of these fluxes and snowmelt in large scale models (Dornes *et al*., 2006). In an area of low relief, Pohl *et al.* (2005a) demonstrated that spatial variability in incident solar radiation is also important in controlling Arctic snowmelt. Accumulated net solar radiation varied widely, with important effects on snowmelt. Pohl *et al.* (2006) addressed the issue of small-scale variability in sensible and latent energy fluxes related to topographically induced wind speed variations. They implemented and tested a simple wind model to simulate topographic effects on the surface wind field at a scale of 40 m. Hourly wind observations were distributed by the model and used to calculate spatially variable sensible and latent turbulent heat fluxes.

Pohl and Marsh (2006) combined model results of spatial variability in incident solar radiation (Pohl *et al.*, 2005b) and turbulent fluxes (Pohl *et al.*, 2006), with estimates of local scale sensible heat advection and a spatially variable end of winter snow cover, to demonstrate the relative importance of each. This study also illustrated appropriate methods to model snow cover melt, depletion and runoff at a variety of scales.

Turbulent transfer was considered from both vertical sensible and latent heat exchange and for horizontal advection to snow from bare ground. Helgason *et al.* (2005) examined problems with turbulent exchange calculations to an open melting snowfield in a mountain valley bottom in the Rocky Mountains. The momentum roughness length values, z_{0m} derived from the eddy covariance measurements were at least an order of magnitude larger than typical values over snow. Accordingly, the measured wind profile did not match to the expected wind profile using Monin-Obukhov similarity theory and first-order closure methods. The failure of Monin-Obukhov similarity theory at this site suggests that the application of flux estimation techniques that are based on flux-profile relationships would predict smaller heat flux values than those that were measured. The advection of energy from bare ground to melting snow patches was studied by Granger *et al.* (2006) and Essery *et al.* (2006) in northern Canada. A model was developed using boundary layer principles that showed remarkably good results in estimating the additional sensible heat flux to melting snow patches and in reproducing temperature profiles over melting snow patches. The model is very sensitive to snow and bare ground patch size and to atmospheric stability. This shows that advection of energy from bare ground must be considered when calculating the energy budget to melting snow in high latitude areas where melt occurs over long periods and insolation is high but air temperatures are often cool during melt.

For the high Arctic, Woo and Young (2004) presented a model of late-winter snow cover and the ensuing snowmelt at a 1 km scale. Indexing was used to spread the snow data over a 16×13 km area and meteorological variables measured at a base station were spatially extended for the computation of melt at various terrain units using the energy balance method. The simulated snow pattern compared favourably with the snow cover imaged by LANDSAT. However, the authors pointed to several assumptions that should be scrutinized in sub-grid parameterization of snow distribution.

In a review article, Young *et al.* (2006) assessed methodologies for measuring snow and rain in northern basins; and examined the temporal and spatial patterns of snow accumulation, ablation, and extreme events. Results indicated that northern hydrologists continue to employ a variety of gauges and approaches that hinder inter-comparison, and that countries should seek a harmonized approach for snow research.

Forest Snow Hydrology

Snow hydrology in managed forested catchments continues to be an active area of investigation. The effect of evergreen forest canopies on short and longwave radiation to snow was examined by Sicart *et al.* (2003, 2004). They showed the effect of canopy density was most commonly to decrease the net radiation to snow, but also outlined the conditions under which the 'radiative paradox' develops, where increasing canopy density increases net radiation to snow because of enhanced longwave radiation from the canopy to snow — this is favoured in clear sky, high altitude, low solar angle and high snow albedo conditions. In Murray and Buttle (2003), accumulation and melt on north- and south-facing slopes were compared for a mature hardwood maple stand and an adjacent clearcut at the Turkey Lakes watershed in central Ontario. Snow accumulation in the clearcut exceeded that in the forest, although the degree of difference varied with slope, aspect and year. Melt was significantly faster in the south-facing clearcut and forest relative to corresponding north-facing sites. Daily melt in the clearcut was slightly greater and more spatially variable than in the adjacent forest, with the exception of the south-facing slope in 2000. Nevertheless, the effect of aspect on spatial variations in melt was larger than that due to clearcutting. There was a slight increase in melt rate with decreased canopy density in the south-facing clearcut and forest; however, variations in canopy density did not explain inter-point differences in daily melt within either the north-facing clearcut or the forest. The hydrological consequences of greater pre-melt snow water equivalent and larger daily melt in clearcuts include quicker delivery of meltwater to the soil surface and promotion of rapid near-surface runoff to receiving waters relative to undisturbed forest stands. Winkler *et al.* (2005) and Winkler and Moore (2006) looked at snow accumulation and melt rates at sites selected to represent a chronosequence associated with forest harvesting, including old (unlogged) forest, recent clearcut, and 15-year-old stands (unthinned and thinned) in British Columbia. Winkler *et al*. (2005) focussed on mean values for each stand whereas Winkler and Moore (2006) looked at within-stand and among-year variability in 1 April snow accumulation. There was no evidence of spatial correlation for point separations 15 m or greater, likely due to the minimal possibility for wind transport within the stands and in the relatively small cutblocks studied. Point-scale stand measures alone did not adequately predict the variation in snow accumulation across small spatial scales, e.g., of less than a hectare. They are therefore not able to assist as surrogate variables for parameterizing sub-grid-scale variability in snow accumulation. It is likely that interannual differences in snowfall patterns, particularly in relation to variability in wind speed and direction above the canopy, are a more important control on SWE.

Talbot *et al*. (2006) measured SWE during three springs on north- and south-exposed sites representing a range of stand structure and development stages of Quebec's balsam fir forest. Maximum SWE of the season, mean seasonal snowmelt rate, snowmelt season duration and total snowmelt season degree-day factor were related to canopy height, canopy density, light interception fraction and basal area of the stands using random coefficient models. Seasonal mean snowmelt rate was better explained by stand characteristics (R^2 from 0.41 to 0.61) than was maximum snow water equivalent (R^2 from 0.08 to 0.23). The best relationship was found with light interception, which explained 61% of snowmelt rate variability between stands. These relationships were not significantly affected by stand aspect, as snow dynamics seemed less dependent on aspect than on stand characteristics. Snowmelt recovery rates could be used by forest planners to establish an acceptable time step for the harvesting of different parts of a watershed in order to prevent peak flow augmentations.

Urban Snow Hydrology

Studies modelling snowmelt in urban areas are scarce in Canada. Valeo and Ho (2004) examine the problems with current urban snow models and proposed a new model, the Urban Snow Model (USM), with parameters developed from field studies focussing exclusively on urban snow. The USM was compared with a popular model for urban hydrology, Storm Water Management Model (SWMM). Results indicated that the manner in which urban snow is redistributed, including piling snow into piles and along the side of the road, can have a significant impact on the timing and value of peak flow rates and must be appropriately parameterized for accurate prediction. The full energy budget version of USM outperformed other models in terms of time to peak, peak flow rate and model efficiency; however, the modified version of USM using just net radiation performed well and is recommended for limited data situations. The degree day method and SWMM performed poorly. In a subsequent paper, Ho and Valeo (2005) investigated the characteristics of urban snow that differentiate it from rural snow, and made recommendations for incorporating these characteristics into an urban snow model.

Snow Cover Depletion

Snow covered area depletion from measurements and models were investigated in a pair of papers by Pomeroy *et al.* (2004) and Essery and Pomeroy (2004b). Pomeroy *et al.* (2004) showed that the variability of the initial SWE in a complex basin could be related to its vegetation cover and wind exposure. The variance of SWE was preserved during melt until the last few days of melt. Covariance between SWE and melt energy strongly biased snow cover depletion curves and hence snowmelt duration and rate. However, the covariance changed direction with scale. At Granger basin in the Wolf Creek watershed, a negative covariance was evident at all scales (higher SWE associated with lower melt rates) because of drifts on north-facing slopes and deeper snow near shrubs. At the Wolf Creek basin scale, a positive covariance developed with higher SWE associated with higher melt rates because of lower melt energy under forests and at high elevations where SWE was also lower. Essery and Pomeroy (2004b) modelled this effect by proposing a simple snow covered area depletion curve formulation based on the variance of SWE, and then showing how to account for the additional effects due to covariance between SWE and melt energy. Such a modelling approach is felt to be necessary to obtain good performance from land surface schemes and hydrological models applied in areas of complex terrain.

Pohl *et al.* (2005b) utilized the fully distributed hydrology land-surface scheme WATCLASS, to model changes in snow covered area and spring snowmelt runoff in an Arctic basin. WATCLASS was able to predict runoff volumes (on average within 15% over five years of modelling) and mean SWE, as well as the timing of snowmelt and meltwater runoff for open tundra fairly accurately. However, the model underestimated melt in the energetically more complex shrub tundra areas of the basin. Furthermore, the observed high spatial variability of the snow covered area at a 1-km resolution was not captured well by the model. Davison *et al.* (2006) attempted to improve the sub-grid variability of the snow cover and the subsequent melt by including wind-swept tundra and drift classes based on topography rather than the traditionally used vegetation land classes. This approach improved the ability of WATCLASS to better simulate the variability in snow covered area during the melt period. Dornes *et al.* (2006) modelled the snowmelt hydrology of Granger basin using the Cold Regions Hydrological Model using both a lumped and distributed approach. Results showed that it was necessary to subdivide the basin into HRUs based on accumulation, slope and aspect to successfully model both snow depletion and runoff.

Snow Chemistry

Snow chemistry was reviewed in a chapter for the Encyclopaedia of Hydrological Sciences by Pomeroy *et al.* (2005b) which showed that previously broadly based research on this topic has diminished greatly in recent years with only two exceptions. Lalonde *et al.* (2003) examined photo-induced transfer of Hg from snow to air in northern Ontario. More than 40% of Hg was lost to air within 24 hours of its deposition. It was hypothesized that the loss of Hg was caused by a sunlight-initiate reduction in snow and subsequent transfer of Hg to the atmosphere. This has important implications for interpretation of ice core records of Hg that might be biased by this process. Quinton and Pomeroy (2006) showed the effect on flow through macropores in frozen organic soils on snowmelt chemistry. The principle effects were rapid uptake of inorganic N when meltwater entered the frozen soil macropores and release of soil chemical components such as K, Ca and Mg, likely due to mixing and solution of soil materials.

Meetings and Networks

For snow and ice hydrology in Canada, meetings and networks play an important role in fostering research and integration. In March 2004, the Water Survey of Canada and the Canadian Society of Hydrological Sciences co-hosted a workshop entitled "Predicting Streamflow in the Mackenzie Valley: Today's Techniques and Tomorrow's Solutions". The objectives were to: 1) provide practitioners with the results of recent cold regions hydrology research in the context of predicting streamflow; 2) assess "state of the art" techniques to predict streamflow in ungauged basins in northern landscapes; and 3) define technical needs and recommend a research agenda that can be delivered over the next ten years. The workshop was attended by 53 international participants and produced a book entitled "Prediction in Ungauged Basins: Approaches for Canada's Cold Regions" (Spence *et al.*, 2005). The IAHS Decade for Prediction in Ungauged Basins (PUB) had a cold regions hydrology component (Pomeroy, 2007). Pertinent papers on snow and frozen ground hydrology were given by Quinton and Hayashi (2005) who summarized important cold region runoff generation processes for the wetland dominated Fort Simpson area and Pomeroy *et al.* (2005b) who described the fundamental behaviour of land-surface hydrological process, parameters and algorithms for physically based hydrological modelling in cold regions.

In 2005, the Mackenzie GEWEX Study (MAGS) issued its final report as the study came to a close after 12 years (di Cenzo, 2006). The MAGS program greatly improved understanding of the fundamental processes on atmospheric and hydrological sciences of cold regions and gained world recognition in hydrometeorological sciences. MAGS fostered integration of atmospheric and hydrological sciences in Canada and produced a substantial collection of publications in refereed journals and conference proceedings along with producing synthesis articles (Rouse *et al.*, 2003). Most notably, under MAGS, a new generation of atmospheric and hydrologic scientists, engineers and technical personnel were trained.

Two new research networks supported by the Canadian Foundation for Climate and Atmospheric Science were initiated in 2006 that relate to snow and frozen ground processes. The first entitled Western Canadian Cryospheric Network (WC2N) [http://wc2n.unbc.ca/] is a research team studying western Canadian glaciers, to improve understanding of the influence of the North Pacific climate system on glacier mass balance in the mountain ranges of British Columbia and Alberta. The second is entitled, Improved Processes and Parameterization for Prediction in Cold Regions (IP3) [http://www.usask.ca/ip3] whose purpose is to gain a better understanding of the key climate processes affecting the hydrometeorology of cold regions. Researchers will gather data from research sites in the Rocky Mountains and northern territories along a transect of high latitude and high altitude locations. The work will help improve and validate weather, water and climate models and result in better predictions of atmospheric impacts on water resources and surface climates.

References

Bewley, D., J. W. Pomeroy, and R. Essery. 2004a. Processes of solar radiation transfer through a sub-arctic shrub canopy. *Proceedings of the Eastern Snow Conference*, 62: 109-128.

Carey, S. K. and W. L. Quinton. 2004. Evaluating snowmelt runoff generation in a discontinuous permafrost catchment using stable isotope, hydrochemical and hydrometric data. *Nordic Hydrology*, 35: 309-324.

Carey, S. K. and W. L. Quinton. 2005. Evaluation of runoff generation during summer using hydrometric, stable isotope and hydrochemical methods in a discontinuous permafrost environment. *Hydrological Processes*, 19: 95-114.

Carey, S. K. and M. K. Woo. 2005. Freezing of subarctic hillslopes, Wolf Creek basin, Yukon, Canada. *Arctic, Antarctic and Alpine Research*, 37: 1-20.

di Cenzo, P. 2006. *Final Report of the Mackenzie GEWEX Study (MAGS): Proceedings of the Final (11th) Annual Scientific Meeting*.

Davison, B., S. Pohl, P. Dornes, P. Marsh, A. Pietroniro, and M. Mackay. 2006. Characterizing snowmelt variability in a land-surface hydrologic model WATCLASS. *Atmosphere-Ocean,* 44: 271-287.

Dornes, P. F., J. W. Pomeroy, A. Pietroniro, S. K. Carey, and W. L. Quinton. 2006. The use of inductive and deductive reasoning to model snowmelt runoff from northern mountain catchments. In Voinov, A., A. J. Jakeman, and A. E. Rizzoli (Eds). *Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software"*. International Environmental Modelling and Software Society, Burlington, USA, July 2006. CD ROM. Internet: http://www.iemss.org/iemss2006/sessions/all.html.

Essery, R. L. H. and J. W. Pomeroy. 2004a. Vegetation and topographic control of wind-blown snow distributions in distributed and aggregated simulations for an Arctic tundra basin. *Journal of Hydrometeorology*, 5: 734-744.

Essery, R.L.H. and J.W. Pomeroy. 2004b. Implications of spatial distributions of snow mass and melt rate on snowcover depletion: theoretical considerations. *Annals of Glaciology*, 38: 261-265.

Essery, R.L.H., R.J. Granger and J.W. Pomeroy. 2006. Boundary layer growth and advection of heat over snow and soil patches: Modelling and parameterization. *Hydrological Processes*, 20: 953-967.

Forbes, A. C. and S. F. Lamoureux. 2005. Climatic controls on streamflow and suspended sediment transport in three large middle arctic catchments, Boothia Peninsula, Nunavut, Canada. *Arctic, Antarctic and Alpine Research*, 37: 305-315.

Granger, R. J., J. W. Pomeroy, and R. L. H Essery. 2006. Boundary layer growth over snow and soil patches. *Hydrological Processes*, 20: 943-951.

Hayashi, M., G. van der Kamp, and R. Schmidt. 2003. Focused infiltration of snowmelt water in partially frozen soil under small depressions. *Journal of Hydrology*, 270: 214-229.

Hayashi, M., W. L. Quinton, A. Pietroniro, and J. J. Gibson. 2004. Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. *Journal of Hydrology*, 296: 81-97.

Helgason, W. D. and J. W. Pomeroy. 2005. Uncertainties in estimating turbulent fluxes to melting snow in a mountain clearing. *Proceedings of the Eastern Snow Conference*, 62: 129-138.

Ho, C. L. I. and C. Valeo. 2005. Observations of urban snow processes. *Hydrological Processes,* 19: 459-473.

Janowicz, R. J, D. M. Gray, and J.W. Pomeroy. 2003. Spatial variability of fall soil moisture and spring snow water equivalent within a mountainous sub-arctic watershed. *Proceedings of the Eastern Snow Conference*, 60: 127-139.

Janowicz, J. R., N. Hedstrom, J. W. Pomeroy, R. Granger, and S. K. Carey 2004. Wolf Creek Research basin water balance studies. In Kane, D.L. and D. Yang (Eds.) *Northern Research Basins Water Balance*, IAHS Publ. No. 290, IAHS Press, Wallingford: 195-204.

Lalonde, J. D., M. Amyot, M.-R. Doyon, and J.-C. Auclair. 2003. Photo-induced Hg(II) reduction in snow from the remote and temperate Experimental Lakes Area (Ontario, Canada). *Journal of Geophysical Research*, 108, D6, 4200, doi:10.1029/2001JD001534.

Lamoureux, S. F., K. A. Stewart, A. C. Forbes, and D. Fortin. 2006. Multidecadal variations and decline in spring discharge in the Canadian middle Arctic since 1550 AD. *Geophysical Research Letters*, 33, L02403, doi 10.1029/2005GL024942.

Marsh, P., C. Onclin, M. Russell, and S. Pohl. 2003. Effects of shrubs on snow processes in the vicinity of the Arctic treeline in NW Canada. Northern Research Basins 14th International Symposium and Workshop, Kangerlussuaq/Sdr. Strømfjord, Greenland. August 25-29, 2003: 113-118.

McCartney, S. E., S. K. Carey, and J. W. Pomeroy. 2006. Intra-basin variability of snowmelt water balance calculations in a subarctic catchment. *Hydrological Processes*, 20: 1001-10016.

Mielko, C. and M. K. Woo. 2006. Snowmelt runoff processes in a headwater lake and its catchment, subarctic Canadian Shield. *Hydrological Processes*, 20: 987-1000.

Monteith, S. S., J. M. Buttle, P. W. Hazlett, F. D. Beall, R. G. Semkin, and D. S. Jeffries. 2006a. Paired-basin comparison of hydrological response in harvested and undisturbed hardwood forests during snowmelt in central Ontario: I. Streamflow, groundwater and flowpath behaviour. *Hydrological Processes*, 20: 1095-1116.

Monteith, S. S., J. M. Buttle, P. W. Hazlett, F. D. Beall, R. G. Semkin, and D. S. Jeffries. 2006b. Paired-basin comparison of hydrological response in harvested and undisturbed hardwood forests during snowmelt in central Ontario: II. Streamflow sources and groundwater residence times. *Hydrological Processes*, 20: 1117-1136.

Murray, C. D. and J. M. Buttle. 2003. Impacts of clearcut harvesting on snow accumulation and melt in a northern hardwood forest. *Journal of Hydrology,* 271: 197-212.

Murray, C. D. and J. M. Buttle. 2005. Infiltration and soil water mixing on forested and harvested slopes during spring snowmelt, Turkey Lakes watershed, central Ontario. *Journal of Hydrology,* 306: 1-20.

Pohl, S. and P. Marsh. 2006. Modelling the spatial-temporal variability of spring snowmelt in an arctic catchment. *Hydrological Processes*, 20: 1773-1792.

Pohl, S., B. Davison, P. Marsh, and A. Pietroniro. 2005a. Modelling spatially distributed snowmelt and meltwater runoff in a small arctic catchment with a hydrology land-surface scheme (WATCLASS). *Atmosphere-Ocean*, 43: 193-211.

Pohl, S., P. Marsh, and A. Pietroniro. 2005b. Spatial-temporal variability in solar radiation during spring snowmelt. *Nordic Hydrology*, 37: 1-19.

Pohl, S., P. Marsh, and G. Liston. 2006. Spatial-temporal variability in turbulent fluxes during spring snowmelt. *Arctic, Antarctic, and Alpine Research*, 38: 136-146.

Pomeroy, J.W. 2007. Cold regions hydrology, snow and PUB. In *Predictions in Ungauged Basins: PUB Kick-off*. IAHS Publ. No. 309. IAHS Press, Wallingford, UK.

Pomeroy, J. W., B. Toth, R. J. Granger, N. R. Hedstrom, and R. L. H. Essery. 2003. Variation in surface energetics during snowmelt in complex terrain. *Journal of Hydrometeorology*, 4(4): 702-716.

Pomeroy, J. W., R. L. H. Essery, and B. Toth. 2004. Implications of spatial distributions of snow mass and melt rate on snow-cover depletion: observations in a subarctic mountain catchment. *Annals of Glaciology*, 38: 195-201.

Pomeroy, J. W., H. G. Jones, M. Tranter, and G. Lilbæk. 2005a. Hydrochemical processes in snow covered basins. In M. Anderson (Ed.), *Encyclopaedia of the Hydrological Sciences*. John Wiley and Co., London, Vol. 4, Chapter 163, 2525-2538.

Pomeroy, J. W., R. J. Granger, N. R. Hedstrom, D. M. Gray, J. Elliott, A. Pietroniro, and J. R. Janowicz. 2005b. The process hydrology approach to improving prediction to ungauged basins in Canada. In Spence, C., J. Pomeroy, and A. Pietroniro (Eds.). *Prediction in Ungauged Basins, Approaches for Canada's Cold Regions*. Canadian Water Resources Association, Cambridge, ON: 67-95.

Pomeroy, J. W., D. S. Bewley, R. L. H. Essery, N. R. Hedstrom, T. Link, R. J. Granger, J. E. Sicart, C. R. Ellis, and J. R. Janowicz. 2006. Shrub tundra snowmelt. *Hydrological Processes*, 20: 923-941.

Quinton, W. L. and M. Hayashi. 2005. The flow and storage of water in the wetland-dominated Central Mackenzie River basin: Recent advances and future directions. In Spence, C., J. Pomeroy, and A. Pietroniro (Eds.). *Prediction in Ungauged Basins, Approaches for Canada's Cold Regions*. Canadian Water Resources Association, Cambridge, ON: 45-56.

Quinton, W. L. and J. W. Pomeroy. 2006. Transformations of runoff chemistry in an Arctic tundra catchment. *Hydrological Processes*, 20: 2901-2919.

Quinton, W. L., M. Hayashi, and A. Pietroniro. 2003. Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrological Processes*, 17: 3665-3684.

Quinton, W. L., S. K. Carey, and N. T. Goeller. 2004. Snowmelt runoff from northern alpine tundra hillslopes: Major processes and methods of simulation. *Hydrology and Earth System Sciences*, 8: 877-890.

Quinton, W. L., T. Sharizi, S. K. Carey, and J. W. Pomeroy. 2005. Soil water storage and active layer development in a sub alpine tundra hillslope, southern Yukon Territory, Canada. *Permafrost and Periglacial Processes*, 16: 369-382.

Rouse, W. R., E. M. Blyth, R. W. Crawford, J. R. Gyakum, J. R., Janowicz, B. Kochtubajda, H. G. Leighton, P. Marsh, L. Martz, A. Pietroniro, H. Ritchie, W. M. Schertzer, E. D. Soulis, R. E. Stewart, G. S. Strong, and M. K. Woo. 2003. Energy and water cycles in a high-latitude, north-flowing river system. *Bulletin, American Meteorological Society,* 84: 73-87.

Sicart, J. E., J. W. Pomeroy, R. L. H. Essery, J. E. Hardy, T. Link, and D. Marks. 2004. A sensitivity study of daytime net radiation during snowmelt to forest canopy and atmospheric conditions. *Journal of Hydrometeorology*, 5: 774-784.

Sicart, J. E., J. W. Pomeroy, R. L. H. Essery, and J. Hardy. 2003. Snowmelt in a Canadian spruce forest: A sensitivity study to canopy cover. *Proceedings of the Eastern Snow Conference*, 60: 99-110.

Spence, C. and M. K. Woo. 2003. Hydrology of subarctic Canadian Shield: Soil-filled valleys. *Journal of Hydrology,* 279: 151-166.

Spence, C., J. W. Pomeroy, and A. Pietroniro (Eds). 2005. *Prediction in Ungauged Basins, Approaches for Canada's Cold Regions*. Canadian Water Resources Association.

Spence, C. and M. K. Woo. 2006. Hydrology of subarctic Canadian Shield: Heterogeneous headwater basins. *Journal of Hydrology,* 317: 138-154.

Sturm, M., C. Racine, and K. Tape. 2001. Increasing shrub abundance in the arctic. *Nature,* 411: 546-547.

Talbot, J, A. P. Plamondon, D. Lévesque, D. Aubé, M. Prévos, F. Chazalmartin, and M. Gnocchini. 2006. Relating snow dynamics and balsam fir stand characteristics, Montmorency Forest, Quebec. *Hydrological Processes*, 20: 1187-1199.

Van der Kamp, G., M. Hayashi, and D. Gallen. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. *Hydrological Processes*, 17: 559–575.

Valeo, C. and C. L. I. Ho. 2004. Modelling urban snowmelt runoff. *Journal of Hydrology,* 299: 237-251.

Winkler, R., D. L. Spittlehouse, and D. L. Golding. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. *Hydrological Processes,* 19: 51–62.

Winkler, R. D. and R. D. Moore. 2006. Variability in snow accumulation patterns within forest stands on the interior plateau of British Columbia, Canada. *Hydrological Processes,* 20: 3683-3695.

Woo, M. K. and P. Marsh. 2005. Snow, frozen soils and permafrost hydrology in Canada, 1999-2002. *Hydrological Processes,* 19: 215-229.

Woo, M. K. and X. J. Guan. 2006. Hydrological connectivity and seasonal storage change of tundra ponds in a polar oasis environment, Canadian High Arctic. *Permafrost and Periglacial Processes,* 17: 309-323.

Woo, M. K. and K. L. Young. 2004. Modeling arctic snow distribution and melt at the 1 km grid scale. *Nordic Hydrology,* 35: 295-307.

Woo, M. K. and K. L. Young. 2006. High Arctic wetlands: their occurrence, hydrological characteristics, and sustainability. *Journal of Hydrology,* 320: 432-450.

Woo, M. K., A. Arain, M. Mollinga, and S. Yi. 2004. A two-directional freeze and thaw algorithm for hydrologic and land surface modelling. *Geophysical Research Letters*, 31: L12501, doi:10.1029/2004GL019475.

Yi, S., A. Arain, and M. K. Woo. 2006. Modifications of a land surface scheme for improved simulation of ground freeze-thaw in northern environments. *Geophysical Research Letters*, 33, L13501, doi:10.1029/2006GL026340.

Young, K. L. and M. K. Woo. 2003a. Frost table development beneath patchy wetlands in a continuous permafrost, High Arctic setting. *Proceedings, Eighth International Conference on Permafrost*, Zurich, Switzerland: 1265-1270.

Young, K. L. and M. K. Woo. 2003b. Thermo-hydrological responses to an exceptionally warm, dry summer in a high Arctic environment. *Nordic Hydrology,* 34: 51-70.

Young, K. L., W. L. Bolton, A. Killingtveit, and D. Yang. 2006. Assessment of precipitation and snowcover in northern research basins. *Nordic Hydrology,* 37: 377-391.