Snowcover melt and runoff at the forest-tundra transition zone: Mackenzie River basin

P. Marsh[1], W. Quinton, N. Neumann, C. Onclin, S. Pohl, J. Pomeroy, M. Russell and R. Essery

[1] National Water Research Institute
National Hydrology Research Centre
11 Innovation Blvd.
Saskatoon, Saskatchewan, Canada S7N 3H5
philip.marsh@ec.gc.ca

1. INTRODUCTION

Field studies have been conducted at National Water Research Institute (NWRI) research basins in the Inuvik area, located in the forest/tundra transition in the zone of continuous permafrost which is representative of the northern and north-western sections of the Mackenzie Basin. The primary goals of this work are to better understand the processes controlling the hydrologic cycle in this environment, determine the magnitude of the individual components of the mass and energy fluxes, develop appropriate process based algorithms, and incorporate and test these algorithms in distributed models. The following article will provide a brief overview of activities during the last few years.

2. FIELD ACTIVITIES

Over the period 1993 to present, field studies have been carried out in two research basins located in the Inuvik, NWT region (approximately 68°20'N, 133°45'W) (Figure 1). Havikpak Creek (HPC), located near the Inuvik Atmospheric Environment Service upper air station, is dominated by a sparse black spruce forest, while Trail Valley Creek (TVC), located approximately 50 km NW of Inuvik, is dominated by tundra vegetation (Marsh and Pomeroy, 1996).

Detailed process based studies in these basins have included the following: point surface energy balance measurements; hill slope runoff; meltwater percolation into cold snowpacks; basin scale energy balance measurements to consider the role of local advection in surface fluxes; and water storage components. During four water years (1992/93, 1995/6, 1997/8, and 1998/9) effort was expended to collect data on all of the major water balance components. As part of this work, NWRI has maintained a remote weather station at each of the research basins and Water Survey of Canada, with enhanced measurements from NWRI, have collected streamflow measurements for the period 1993 to present. Since the autostations are unmanned for much of the year, some of the data (radiation for example) are unreliable for extended periods. Other parameters (air and ground temperature, soil moisture, snow depth etc.) do not require frequent attention, and therefore are much more reliable over an entire annual cycle. In addition, only during years with enhanced streamflow observations are streamflow estimates during the melt period reliable.

During the Canadian GEWEX Enhanced Study (CAGES) period (1998/99 water year), the standard observations described above were carried out, as well as monthly site visits during the winter to obtain snow cover measurements and check autostation operation. In addition, sensible and latent heat flux measurements were made using eddy correlation during the spring melt and summer periods. These observations were co-ordinated with the National Research Council of Canada aircraft flux measurement program in the Inuvik area during the spring and early summer of 1999.

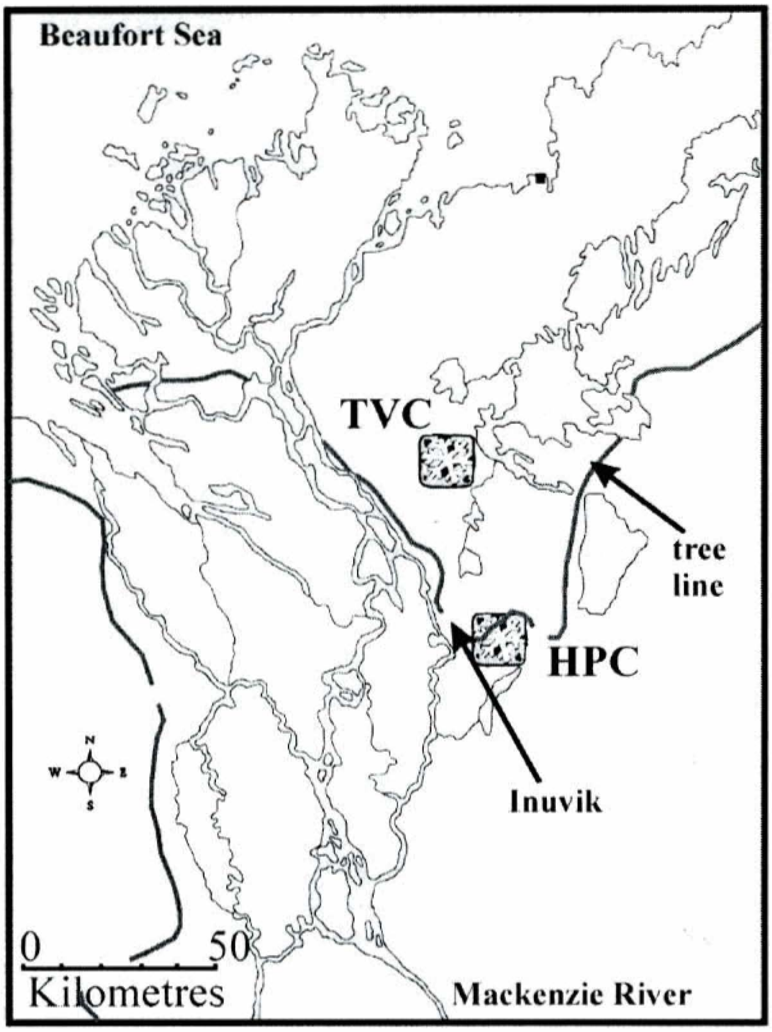

Figure 1: Research basin locations in the Inuvik area. TVC is Trail Valley Creek, and HPC is Havikpak Creek. Also shown is the approximate location of the treeline.

3. SCIENTIFIC RESULTS

(a) Snowmelt, changes in snow covered area during melt, and advection of sensible heat

Spatial variations in snow water equivalent at the end of winter (Marsh and Pomeroy, 1996; Pomeroy et al., 1997) combined with spatial variations in snowmelt result in a patchy snow cover (Marsh and Pomeroy, 1996) during much of the spring melt period. Estimates of the spatial variation in melt energy have been obtained from both changes in wind speed over the basin and estimates of local scale advection.

A wind flow model (Essery et al., 1999), applied for conditions with continuous snowcover, demonstrates spatial variations in wind speed from 0.85 to 1.10 times the mean wind speed over TVC during periods of continuous snowcover. For typical air temperature and wind conditions, such variations in wind speed would result in variations in sensible heat flux from 80 to 125 w/m^2, and therefore significant spatial variations in melt. The combination of variations in radiation due to slope angle and aspect and snowcover depth, results in patchy snowcovers during melt. Basin scale variations in snow patches has been documented using SPOT images (Neumann, 1999).

Once a patchy snowcover forms, the spatial variability in melt is further enhanced by the horizontal transfer of energy at a small scale, a process termed local advection. The magnitude of this process was estimated from both field measurements (Neumann and Marsh, 1998) and using the UK Met Office Boundary Layer Model (BLM). Model results (Marsh et al., 1999) suggest that the efficiency of local scale advection increases with decreasing snow cover, increasing wind speed, and decreasing patch size. Results suggest that average sensible heat flux to a melting snow patch increases substantially as snowcover decreases. A simple parameter relating advection efficiency (F_S) to snow cover area has been developed (Marsh and Pomeroy, 1996), and ongoing work is considering the role of wind speed and snow patch "size and shape" in controlling F_S. F_S may be used to estimate the advection of sensible heat (Q_A) to patchy snowcovers by

$$Q_A = \left[\frac{Q_{H_i} \; P_V}{P_S} \right] F_S$$

where Q_{H_i} is the sensible heat flux to a snow-free patch, P_S is the snow cover fraction, P_V is the snow-free, vegetated fraction, and F_S varies between 0 and 1 (Marsh et al, 1999).

(b) Snowmelt percolation

Due to the initial cold content of the snowcover, soil heat flux, and the requirement to fill liquid storage within the snowcover, there is considerable lag time between the beginning of melt and runoff (Marsh, 1999). Determination of the delay is further complicated by the occurrence of flow fingers at the leading edge of the wetting front. These flow fingers typically carry approximately 20% of the total meltwater over only 10% of the horizontal area (Marsh, 1991). As a result, meltwater in the flow fingers move more quickly through the snowcover, and portions of the meltwater reach the base of the snowcover significantly earlier than would be expected if it is assumed that the flow is homogeneous. When combined with differences in snowcover depth, the timing of initial runoff varies greatly over the study basins. Such variations play a critical role in controlling both the timing and magnitude of runoff since approximately 30% of the total basin snow storage occurs in only 10% of the basin area where large drifts form during most winters (Marsh and Pomeroy, 1996).

A simple model of wetting front advance, and resulting runoff, was presented by Marsh (1991) and Marsh and Pomeroy (1996). This shows that for the Trail Valley Creek area, the availability of water at the base of the snowcover occurs up to 10 days later for the deep drifts than for the shallow tundra snow covers, with a total delay of up to 15 days between the start of melt and runoff. Using mapped snowcover depths, Marsh and Pomeroy (1996) used this information to map spatial variations in runoff. Ongoing work will link this model with the modelled variations in snowcover and melt to better estimate spatial variations in the timing and volume of melt.

(c) Snowmelt runoff pathways

Many tundra soils are heterogeneous in the horizontal direction due to the presence of mineral earth hummocks. On hummock-covered hillslopes in the Arctic-tundra (which are the most extensive landform in permafrost areas), the horizontal hydraulic conductivity integrated over the saturated layer is three orders of magnitude higher in the inter-hummock area than in the hummocks (Quinton and Marsh, 1998a). Consequently, surface runoff is uncommon, and the task of delivering runoff rapidly to the streambank is accomplished by subsurface flow (Quinton and Marsh, 1999a). Such runoff from hummock-covered hillslopes occurs preferentially through the relatively permeable inter-hummock area, which serves as the hillslope drainage network. Tundra soils are also heterogeneous in the vertical direction due to the changes in physical and hydraulic properties of the peat with depth. The rate of flow through the inter-hummock area therefore depends strongly upon the elevation of the saturated layer within the peat profile. When the saturated layer is within the highly conductive peat near the surface, flow can occur at velocities as high as for overland flow (Quinton and Marsh, 1999b). Although flow in the near-surface peats occurs at velocities similar to overland flow, analysis shows that the flow is laminar and that Darcy's Law is applicable.

Using measured water level in the inter-hummock zone, in conjunction with estimates of active layer depth, hydraulic conductivity, the size and frequency of the inter-hummock channels, and melt of the deep drifts within the stream channels, allows an estimate of streamflow (Quinton and Marsh, 1998b). The similarity between predicted and observed streamflow demonstrates that the majority of meltwater is transferred from the uplands and hillslopes to the stream channels as flow through the inter-hummock channels.

Ongoing studies are aimed at developing appropriate, physically based algorithms to predict inter-hummock flow, thus allowing a coupling of the upland and hillslope snowmelt to stream flow (Quinton and Marsh, 1999).

(d) Integrated modelling

Process based algorithms developed from the above studies are being tested for the TVC and HPC study sites in the Inuvik area and compared with observed changes in snowcovered area and observed water balance components, examples of which are shown in Figure 2. Similar water balance data is available for 1992/93, 1995/6, 1997/8, and for the CAGES water year (1998/99).

In addition, WATFLOOD is currently being tested on both TVC and HPC. Initial runs will be compared to estimated water balance components as shown in Figure 2. Once available, WATCLASS will be run for these study basins and predictions compared to observed as well as to the predictions of the detailed process based models. This will lead to recommendations for improving WATFLOOD and WATCLASS for use in these arctic environments.

4. SUMMARY

Ongoing studies are considering the wide range of processes controlling the fluxes of water and energy at the arctic treeline. Field and modelling studies have demonstrated the role of variable wind speed and local scale advection of sensible heat in controlling the spatial variation in melt. When combined with predicted variations in snow cover, this will allow an improved prediction of the change in snow covered area over the melt period, the flux of sensible and latent heat to the atmosphere, albedo, and snow melt runoff. In addition, improved physically based algorithms for routing meltwater through the snow pack and horizontally from the uplands and hillslopes to the stream channel will result in improved runoff simulation. Physically based models of these processes, WATFLOOD and, when available, WATCLASS, will be compared to measured water balance terms for the study areas, leading to suggested improvements for use in these arctic environments.

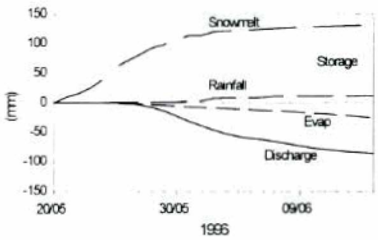

Figure 2a: Cumulative water balance components for Trail Valley Creek for the 1996 snowmelt period.

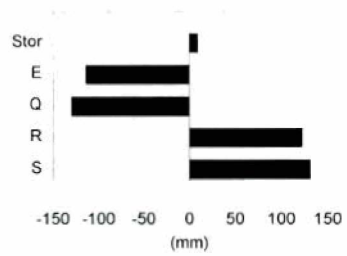

Figure 2b: Annual water balance totals for Trail Valley Creek, 1996. Stor, E, Q, R, and S refer to Storage, evaporation, discharge, rainfall, and snowfall respectively.

5. REFERENCES

Essery, R., L. Li, and J. Pomeroy. 1999. A distributed model of blowing snow over complex terrain. Hydrological Processes, 13, 2423-2438.

Marsh, P. 1991. Water flux in melting snow covers. Corapcioglu, M. Y. (Editor). Advances in Porous Media. Elsevier. Amsterdam. 1. 61-124.

Marsh, P. 1999. Snowcover formation and melt: recent advances and future prospects. Hydrological Processes, 13, 2117-2134.

Marsh, P. and J.W. Pomeroy. 1996. Meltwater fluxes at an arctic forest-tundra site, Hydrological Processes, 10, 1383-1400.

Marsh, P., N. Neumann, J. Pomeroy, and R. Essery. 1999. Comparison of model and field estimates of local scale advection of sensible heat over a patchy Arctic snow cover. Interactions between the cryosphere, climate and greenhouse gases. Tranter, M. (Editor). IAHS, UK. 103-110.

Neumann, N. and P. Marsh. 1998. Local advection in the snowmelt landscape of arctic tundra. *Hydrological Processes*, 12, 1547-1560.

Neumann, N. 1999. Local advection of sensible heat in the arctic snowmelt landscape. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada. 120pp.

Pomeroy, J.W., P. Marsh, and D.M. Gray. 1997. Application of a distributed blowing snow model to the arctic. Hydrological Processes, 11 1451-1464.

Quinton, W. L. and P. Marsh. 1998a. The influence of mineral earth hummocks on subsurface drainage in the continuous permafrost zone. *Permafrost and Periglacial Processes*, 9, 213-228.

Quinton, W. L. and P. Marsh. 1998b. Meltwater fluxes, hillslope runoff and streamflow in an arctic permafrost basin. 7th International Conference on Permafrost. June 1998, Yellowknife, NWT. 921-926.

Quinton, W.L. and P. Marsh. 1999a. A conceptual framework for runoff generation in a permafrost environment. Hydrological Processes, 13, 2563-2581.

Quinton, W.L. and P. Marsh. 1999b. Image analysis and water tracing methods for examining runoff pathway, soil properties and residence times in the continuous permafrost zone. Integrated Methods in Catchment Hydrology - Tracer, Remote Sensing and New Hydrometric Techniques. C. Leibundgut (Editor). IAHS, UK., 257-264.