1.2 Snow cover melt and runoff in boreal and tundra ecosystems: Final MAGS-1 Report

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Introduction

The long term goal of this project was to develop improved predictive algorithms of the energy and water fluxes during the spring melt and summer periods, and to compare them to results from distributed-hydrologic models/land surface schemes applicable to forested and tundra areas in the zone of continuous permafrost. Work towards the attainment of these goals has included the consideration of: the distribution of snow at the end of winter; the role of blowing snow in controlling the distribution and volume of snow through processes of transport and sublimation; the surface energy balance during the snow melt period and the role of the local advection of sensible heat from snow-free areas to snow patches; the percolation of meltwater through the snow cover and the resulting delay in runoff, and the spatial variability in the timing of runoff; the role of hummocky terrain and peat in controlling hillslope runoff; and the relative magnitude of water balance components both annually and daily during the runoff period. For many of the process noted above, improved model components have been developed and tested. In addition, this study has begun preliminary work in the comparison of hydrologic and atmospheric models with the detailed data sets developed for the study basins in the Inuvik area. Such comparison and the testing of improved model components in these models will continue during the second phase of MAGS.

Methodology

Building on ongoing studies conducted by the National Water Research Institute, this study utilized field data collected at two research basins located in the boreal forest/tundra transition zone near Inuvik, NWT. These two river basins have been the focus of hydrological research since 1992. Trail Valley Creek (TVC) located approximately 50 km northeast of Inuvik, is 68 km^2 in area and dominated by tundra vegetation (Marsh and Pomeroy 1996). Havikpak Creek (HPC), located a few km north of the Inuvik airport, is 17 km^2 in area and is predominantly covered by northern boreal forest. This contrasting vegetation results in differing snow cover distribution and melt. For example, blowing snow occurs more frequently at the tundra site, resulting in a greater spatial variability in the end of winter snow cover than that at the forest site. In addition, the snowmelt rates are different at both sites due to differences in net radiation and local scale advection of sensible heat. This last difference is related to variations in snow cover patch distribution, a factor that is associated to the spatial distribution of the end of winter snow cover. A Meteorological Service of Canada (MSC) upper air station is located in the HPC basin. The National Water Research Institute (NWRI) has operated meteorological stations since 1992 in both research basins. Measured parameters include air temperature, rainfall, snowfall, net radiation, incoming and outgoing solar radiation, sensible heat flux and latent heat flux for example. Detailed observations of discharge by NWRI during the spring melt assist in reducing the large errors typical of discharge estimates in snow/ice clogged channels. Snow surveys, stratified by terrain type, were also conducted at both TVC and HPC by NWRI. Routine meteorological and hydrological measurements by the MSC and Water Survey of Canada (WSC) can be used to place the short-term research basin measurements into a longer-term perspective. WSC discharge is available for TVC since 1979 and at HPC since 1994.

Results

A brief overview of the key scientific results stemming from work conducted as part of the Mackenzie GEWEX Study (MAGS) are presented below. Instead of a detailed description of each, only an overview is presented here, along with references to the original, published source of these results.

Snow cover distribution

Marsh and Pomeroy (1996) demonstrated the importance of vegetation and terrain in controlling the distribution of the snow cover at the end of winter. For example they provide an example where snow water equivalent varied from 68 mm for upland tundra, to 252 mm for shrub tundra, and 617 mm for drifts. When weighted by the area of each landscape type, they reported that 31% of the total snow cover was contained in the tundra areas (which cover 70% of the basin), 35% occurs in the shrub areas (covering 22% of the basin), and the remaining 35% of the total snow cover is contained in the drift area, which only covers some 8% of the basin area. Such a large portion of the total snow cover occurring over such a small area has implications for runoff modelling (with delayed runoff due to percolation through the deep snow) and for remote sensing (for example, this has possible implications for using microwave remote sensing methods to estimate snow water equivalent. Marsh et al. 1997 found that microwave estimates of snow water equivalent best matched the snow cover on the extensive upland tundra areas, not the average basin snow water equivalent). The impact of blowing snow on both the re-distribution of snow and modification of the snow available for runoff due to between basin transport of snow and removal of snow due to sublimation have been demonstrated by Pomeroy et al. (1997) for example. This work has also demonstrated the ability to predict the snow cover water equivalent within each terrain type, an important ability required for snow cover runoff modelling.

Snow cover melt and runoff

Marsh and Pomeroy (1996) demonstrated the utility of models of surface energy balance and snow metamorphism for predicting the temporal and spatial variability in meltwater fluxes. Calculated melt was routed through the snow cover in each landscape type using a variable flow path, meltwater percolation model. Model results indicate that the initial release of meltwater first occurred from the shallow upland tundra snow packs, and that meltwater release did not occur until nearly two weeks later from the deep drift snow covers. During the early periods of melt, not all meltwater was available for runoff. Instead, there is a period when some snow packs are only partially contributing to runoff (the remainder of the surface melt is freezing within the snow cover, releasing latent heat, and therefore warming the snow cover to 0C, or is being stored in the snow pack as liquid water). This work has clearly demonstrated the importance of considering the delay in runoff due to the percolation of meltwater into cold dry snow covers, and presented an appropriate model for calculating this delay. In addition, this work has demonstrated the large spatial variability in the timing and magnitude of runoff. Factors which are critical in predicting snowmelt runoff from northern regions.

Advection of sensible heat from snow-free patches to snow patches

Field measurements demonstrated that the local scale advection of sensible heat from snow-free patches to snow patches was significant. Results from field and modelling studies were reported by Marsh and Pomeroy (1996), Marsh et al. (1997), Neumann and Marsh (1997), Neumann and Marsh (1998), and Marsh et al. (1999). This advection of sensible heat results in significant increases in sensible heat flux to the snow patches, and therefore melt, at the leading edge of the snow patch throughout the melt period, and increased average sensible heat flux and melt once the snow pack becomes sufficiently patchy. For example, Marsh et al. (1999) showed that average sensible heat flux to snow patches increased four-fold due to local scale advection (for a terrain that was 50% snow covered with 20 m snow patches). This increase in sensible heat flux has a significant impact on melt rates. In addition to field and modelling results, these studies presented a simple method to parameterize local scale advection through an “advection efficiency” term, which represents the fraction of the sensible heat from snow-free patches that is advected to snow patches. This advection efficiency term was found to decrease exponentially from over 0.8 with a snow-free area of less than 10% to a value of 0.1 with a snow-free area of over 80%. This work provides a simple method to estimate the effect of local advection of sensible heat to snow patches and the average flux from a composite surface, using only fluxes calculated independently for 0% snow cover and 100% snow cover and an estimate of the advection efficiency term.

Runoff from hummock and moss covered hillslopes

The role of hummock covered hillslopes on slope runoff were outlined in a number of papers including Quinton et al. (2000), Quinton and Marsh (1998), and Quinton and Marsh (1999). These studies clearly demonstrated that subsurface drainage dominates and that it occurs predominantly through the saturated zone within the layer of peat. The hydraulic conductivity of the peat varies with depth, with the upper profile having significantly higher values. As a result, runoff response is much more rapid when the water table is near the surface. A conceptual model of runoff from this terrain was developed and published.

Water balance

Marsh et al. (1994) and Marsh et al. (in press) have provided estimates of the annual water balance and the daily water balance during the runoff period. This work has demonstrated that snowfall is the largest input of water to these basins, totaling some 60% of the annual total. Sublimation of snow during blowing events may remove on the order of 10% of total inputs. Although the majority of annual precipitation is released over a brief period in the spring, the initiation of runoff is delayed by the processes of vertical percolation of meltwater into the snow and frozen soil. As a result, basin water storage increases dramatically during the early melt period, with approximately 150 mm of melt occurring before streamflow begins. Of these water inputs, approximately 40% is removed by runoff and 60% by evaporation. Ongoing work is considering the annual variability in the water balance components through the analysis of 8 years of record.

Hydrologic and atmospheric model comparison

Ongoing studies have considered the utility of the WATFLOOD hydrologic model for the boreal forest/tundra transition zone. This work has allowed us to become familiar with the model, and to be prepared to fully test the WATCLASS model as it becomes available. In addition, we have compared field observations with model output from the GEM weather model. These results have shown reasonable agreement between temperature and air pressure for example, and with precipitation for much of the year. However, there are apparent problems with convective precipitation events. Other problems with radiation and fluxes of sensible and latent heat flux are apparent in the data set. These analyses are ongoing and will be submitted for publication when completed.

Estimates of sensible, latent and radiative fluxes

During the CAGES period, the National Research Council of Canada Twin Otter flux aircraft operated in the Inuvik area. Preliminary comparison of the tower based, and aircraft based, observations of sensible, latent, and radiative fluxes have been promising. The tower and aircraft measurements are similar, providing confidence in both measurements. The combination of aircraft and tower data, therefore provides an excellent data set on both the temporal and spatial variability of fluxes during both the spring melt and summer periods. In addition, it allows comparison of changes in fluxes along a transect crossing the “arctic treeline”. Analysis of these data sets is ongoing, and will be submitted for publication.

Discussion, Conclusions, Recommendations

Studies during the first phase of MAGS have concentrated on the physical processes controlling the hydrology of the boreal forest/tundra transition zone typical of the northern Mackenzie Basin. These have included the effect of blowing snow processes on snow distribution at the end of winter, snow cover melt and percolation, advection of sensible heat from snow-free patches to snow patches, the role of hummocky peat terrain on hillslope runoff, and the turbulent fluxes of heat and water. For each of these, consideration has been given to temporal and spatial variability, scaling, and the development and testing of simple models. Ongoing work is concentrating on the comparison of existing hydrologic and atmospheric models, and the testing of appropriate physically based algorithms in these models.

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Data inventory available for future research.

A two volume Report/CD-ROM set had been provided to the MAGS Data Archive, entitled:

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hese reports/CD contain the following information: snow surveys, surface energy fluxes, water balance, satellite images showing snow cover depletion, and standard micro-meteorological information including air temperature, relative humidity, wind, soil temperature and moisture, precipitation, and radiation. Most of these data are for the CAGES 1998/99 water year. In addition, water balance data is provided for the 1994/95 water year.

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