Variability of snowmelt over a Rocky Mountains headwater basin

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Background

❖ Most of the water supply to the prairie regions of Canada and the US is derived from rivers that originate in the Rocky Mountains, where snowmelt during the spring represents the most significant portion of the total annual runoff.

❖The distribution of both winter snow accumulation and surface energetics during melt are highly complex in this environment, and such complexities are known to influence the magnitude, timing and duration of the snowmelt contribution to headwater streams.

❖ A detailed understanding of the effects of variable snowmelt rates and melt durations on the spring hydrograph is presently lacking. Further, this variability is likely not well-represented by most hydrological models because much of it occurs at scales smaller than model grid cell resolution.

Research Scope and Objectives

❖ This study examines the variation in snowmelt energy and simulated melt rates in relation to elevation over a Rocky Mountains headwater basin during the spring of 2006.

❖ The objectives of the study are to explore the factors that drive snowmelt over this basin and to relate melt in differing parts of the basin to the spring hydrograph.

Study Site

Marmot Creek, Alberta

Location:
50° 57' N, 115° 10' W

Basin Area:
9.4 km²

Elevation Range:
1585 to 2805 m a.s.l.

Mean Annual Precipitation:
600 to 1140 mm (70% snow)

Mean Temperatures:
14 °C (July); –10 °C (January)

⊕ meteorological station ⊗ gauging station — catchment boundary ▨ clearcut

contour interval = 25 m

Snowmelt Simulation

❖ Snowmelt rates were modeled using the Cold Regions Hydrological Model (CRHM) platform.

❖ CRHM is a modular, object-oriented modeling system that can be used to apply dynamic hydrological process algorithms. Various component modules represent basin descriptions, observations, and physically-based hydrological processes specific to cold regions.

❖ A simplified energy balance snowmelt routine (Minimal Snow Model; MSM, based on Essery and Etchevers (2004)) was used, in which available melt energy (Q_m; W m⁻²) after the snowpack has ripened can be estimated as:

$$Q_m = Q_n + Q_h + Q_e \qquad [1]$$

where Q_n is the net radiation at the surface, Q_h is the sensible heat, and Q_e is the latent heat. Changes in internal snowpack energy, energy input from precipitation, and ground heat fluxes are not considered in this melt routine. All fluxes are defined to the snowpack.

❖ The terms on the right side of [1] were calculated using observations of incoming short and longwave radiation, air temperature, humidity and wind speed in 2006 at meteorological stations 1 (open meadow), 5 (forest clearing), and 9 (alpine ridgetop) to examine the effects of elevation on melt energetics.


❖ Wind speeds at stations 5 and 9 were adjusted based on comparisons with nearby stations (i.e. 6 and 8) in the fall/winter of 2006 to better represent above canopy and less exposed alpine conditions respectively.

❖ Incident longwave ($L\downarrow$) radiation was estimated at stations 5 and 9 by first determining sky emissivity (ε) from measurements of air temperature (T_a; K) and $L\downarrow$ at station 1 as:

$$\varepsilon = \frac{L\downarrow}{\sigma T_a^4}, \qquad [2]$$

where σ is the Stefan-Boltzman constant (5.67 x 10⁻⁸ W m⁻² K⁻⁴), and subsequently applying the calculated ε values to T_a measured at the other stations.

❖ Snow albedo was defined as 0.9 at the onset of melt and set to decline toward 0.85 over the duration of melt to (based on measurements at station 5 in the spring of 2006 and values reported by Pomeroy et al. (1998)), and melt was defined to begin once the snowpack was 'ripe' based on a meteorological and energy balance analysis.
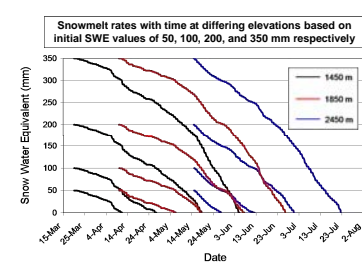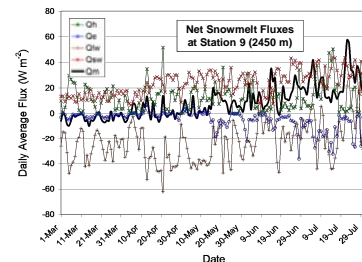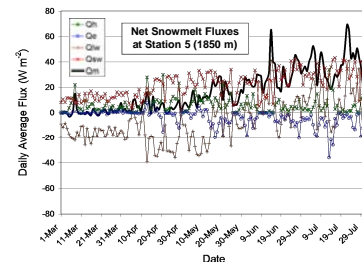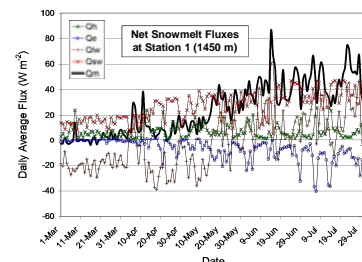
Snowmelt Energetics

➤ At all elevations, the net radiative fluxes, Q_{sw} and Q_{lw}, primarily control the available melt energy, Q_m.

➤ The turbulent fluxes, Q_h and Q_e, appear roughly equal in magnitude and opposite in sign, with the exception of the early-spring conditions at station 9 (2450 m).

➤ At the lowermost two sites, the sudden change in sign of Q_{lw} in mid-May results in a rapid increase in Q_m.

➤ At the uppermost site, Q_{lw} remains predominantly negative and increasing Q_m is driven primarily by increases in Q_{sw}, and to a lesser extent Q_h.

Snowmelt Timing, Rate and Duration

➤ The onset of melting conditions is progressively later at higher elevations, ranging from 20-Mar (1450 m), to 10-Apr (1850 m), to 15-May (2450 m).

➤ Melt duration increases with initial snow water equivalent (SWE) and decreases with elevation (for a given initial SWE).

➤ Average melt rates generally increase with initial SWE and with elevation.

➤ The trend for melt rate to increase with elevation is explained by

i) melt rates increase with time at all elevations,

ii) melt starts later at higher elevations and

iii) SWE increases with elevation causing higher elevation melt to persist later into the season.

Snowmelt rates with time at differing elevations based on initial SWE values of 50, 100, 200, and 350 mm respectively

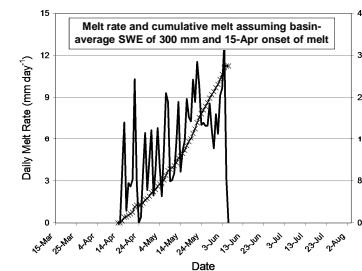| Melt durations and average melt rates for differing elevations and initial SWE values				
	Melt Duration (days)			
Initial SWE (mm)	50	100	200	350
Elevation (m)				
1450	22	39	60	77
1850	26	38	58	78
2450	13	28	47	69
	Average Melt Rate (mm day⁻¹)			
Initial SWE (mm)	50	100	200	350
Elevation (m)				
1450	2.2	2.6	3.4	4.5
1850	1.9	2.6	3.4	4.5
2450	4.0	3.5	4.3	5.1

Melt Rates and Hydrograph Characteristics

❖ At Marmot Creek, end-of-winter SWE generally increases from ~50–100 mm at the lowest elevations to ~350+ mm in sheltered sites at and above the treeline (~2300 m).

Melt rates and cumulative melt based on increasing SWE with elevation
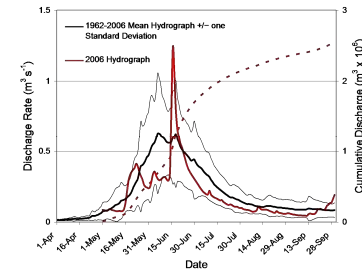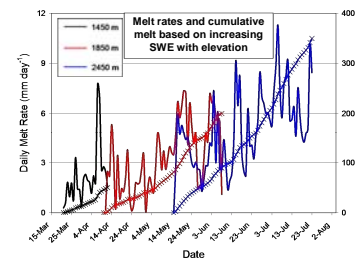
❖ Peak discharge rates occur between late-May and early-July at Marmot Creek, when ~70% of the total annual runoff is generated.

❖ Upper portions of the basin are undergoing active snowmelt during this time whereas lower portions have already become snow-free.

➤ Only a small portion of the total flow is derived from melt at low elevations (delayed flow paths may provide minor peak flow contribution).

➤ The majority of the runoff is derived from deep snowpacks that melt rapidly over long durations in the upper portion of the basin.

➤ Snowmelt ends by mid-July when maximum melt rates deplete the remaining snowpack at high elevations. Very small patches of snow remaining in highly sheltered locations may continue to provide minor and delayed melt contributions to the hydrograph recession.

Snowmelt Modeling Implications

❖ Regional scale hydrological models that treat this basin as a single lumped grid cell and apply basin-wide average parameters (i.e. meteorological forcing; SWE) will likely fail to accurately describe the hydrograph.

Melt rate and cumulative melt assuming basin-average SWE of 300 mm and 15-Apr onset of melt

➤ Based on average data from stations 1, 5, and 9, and assumed basin-average SWE, average melt rates are un-realistically high (5.8 mm day⁻¹), snowmelt completion is too early (6-Jun), and melt duration is too short (51 days).

➤ The resulting hydrograph would display a greater peak flow magnitude with a more compressed shape, and would rise, peak, and decline up to several weeks early.

Conclusions

❖ Spatial associations between elevation, available snowmelt energy (controlling melt timing and rate), and end-of-winter SWE (affecting melt duration) lead to large differences in snow-melt patterns over the basin that strongly influence the spring hydrograph.

❖ Hydrological models must account for such spatial associations in order to properly simulate the hydrograph of Rocky Mountain streams and asses potential impacts of climate change.

Acknowledgements