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Introduction

- Soil filled areas play a key role in controlling hydrological and energy fluxes despite lakes and bedrock covering a large portion of the subarctic Canadian Shield landscape.
- Studies during the International Hydrological Decade (1965-1974) (e.g. Landals and Gill, 1972; Park, 1979) and the Mackenzie GEWEX Study (1993-2005) (e.g. Spence and Woo, 2006) provided many advances in the understanding of runoff generation in the subarctic Canadian Shield.
- Focus to date has been on the hydrological role of individual landscape elements in regulating water flow and storage. Uncertainties remain on how soil filled areas regulate water flow and storage in cold regions.
- This uncertainty is in part caused by the presence of frozen ground that creates a unique dynamic boundary issue for subsurface water movement and storage.

Study Objectives

- Studies have started to link soil moisture with frost table processes, especially at wet locations (e.g. Carey and Woo, 1998 & 2000; Wright et al., 2009). Detailed intra- and inter-site information is lacking in the literature.
- Since both soil moisture and frost table depth have important implications on storage, greater certainty on their spatiotemporal link and controls is needed to improve prediction of catchment storage and runoff in regions with frozen ground.
- To fill these research gaps, the objectives of this project were to:
 - investigate the interaction between spatiotemporal near-surface soil moisture and frost table depth at three typical soil filled areas; and,
 - examine how surface water influences the interaction between near-surface soil moisture and frost table depth.

Methods

Research Sites:

- Baker Creek Basin in the Taiga Shield ecozone, Northwest Territories, Canada
- Subarctic Canadian Precambrian Shield underlain with discontinuous permafrost
- Studied three sites located by Vital Lake at 62°35'N, 114°26'W: peatland site, valley site, and wetland site (Fig. 1a-d) from April 14-July 17, 2008

Near-Surface Soil Moisture (SM) Patterns:

- At each site, surface (top 0.10 m) volumetric water content was surveyed with a portable time domain reflectometry (TDR) unit in a grid fashion: 4 m x 8 m at peatland, 2 m x 2 m at valley and 15 m x 15 m at wetland (Fig. 2)
- 16 surveys at peatland, 14 at valley and 7 at wetland
- TDR was calibrated against gravimetric soil samples

Frost Table (FT) Patterns and Surface Topography:

- At each grid, FT was measured using a steel rod (Fig. 2)
- A total station was used to survey each grid (Fig. 2)

Water Budget and Energy Fluxes:

- Calculated to facilitate explanations of SM and FT patterns
- Modified Péclet number: $mPe = \frac{\text{Heat Advected from Flowing Water}}{\text{Heat Conducted from Surface Soil and Ponded Water}} = \frac{Q_w}{Q_c + Q_p}$

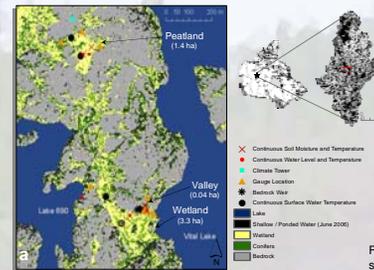


Fig. 1 (a) Instrument locations, land cover classification and total survey area of the three study sites (b-d). The insets show location of the ~165 km² Baker Creek Basin with the solid black indicating lakes. (b) Setting up survey grids. (d) Arrow shows location of climate tower.

Results

Spatiotemporal SM and FT Patterns

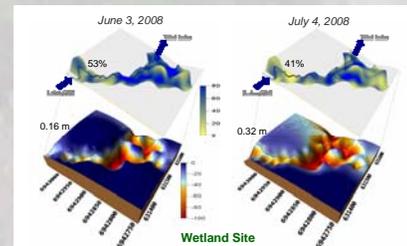
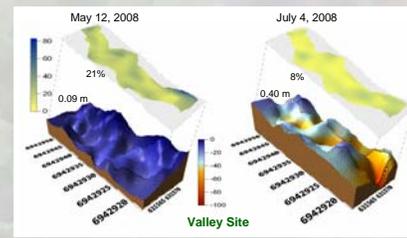
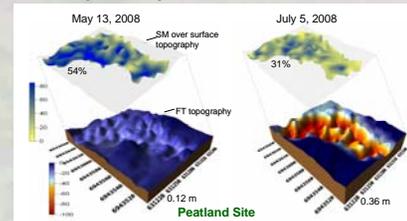


Fig. 2 Top maps are SM layers (m) overlying surface topography layers (m a.s.l.) for selected surveys. Bottom maps are FT topography layers (cm, up to 1 m). The near-surface maximum volumetric water content is 85% at the peatland, 83% at the valley and 80% at the wetland. The stream through the wetland is shown in the site's top maps. Mean SM and FT from the selected survey dates are shown.

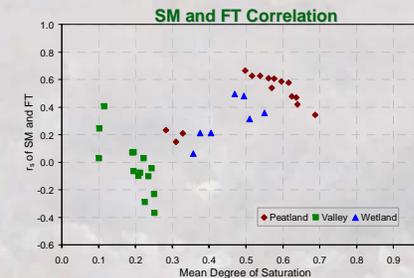


Fig. 3 The Spearman's rank correlation coefficient (r_s) between SM and FT over the sites' average degree of saturation (S). The line of best fit through data from all three sites is $r_s = 1.2S - 0.22$ with $r^2 = 0.57$.

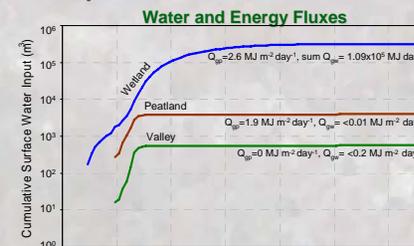


Fig. 4 Surface water input to the sites (snowmelt runoff at all sites and additional lake input at wetland site) and potential amount of energy from water available for ground thaw at each site. Q_w is conductive heat energy from ponded water and Q_p is advective heat energy from surface water inflow. The listed Q_w at the wetland site is not over unit area due to variable area influenced by flowing water over the study period. For example, when 3.3 ha of the 3.3 ha site had flowing water running through, a maximum of 9.5 MJ m² day⁻¹ of Q_w was available for transfer into the frozen ground.

Correlation Spectrum for Variable Site Wetness

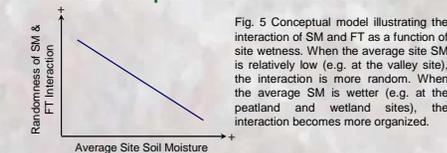


Fig. 5 Conceptual model illustrating the interaction of SM and FT as a function of site wetness. When the average site SM is relatively low (e.g. at the valley site), the interaction is more random. When the average SM is wetter (e.g. at the peatland and wetland sites), the interaction becomes more organized.

Discussion

SM and FT Spatiotemporal Interaction:

- Combined results from all three sites showed SM and FT interacted dynamically and non-linearly.
- The positive SM-FT trend at the landscape scale incorporates more complex patterns within individual soil filled units (Fig. 3)
- High evapotranspiration to precipitation ratios and reduced lateral input led to decreasing SM over the study period
- The degree of organization and hydrological connectivity decreased over time with drying and a deepening FT
- Locations with wetter soils often had deeper ground thaw which revealed preferential surface and subsurface flow routes

Surface Water Influences:

- At wetter survey grids, conductive and advective ground heat energies controlled soil thawing along flow routes and ponded areas (Fig. 4)
- Patterns of linkage between SM and FT were comparable to those observed by Devito et al. (1996) in wetter areas with thick till depth near the southern limit of the Canadian Shield, but due to soil energy budget processes at Baker Creek
- Findings differed from temperate regions with a fixed impermeable boundary and stable active soil column that found SM can be lower in areas with thick soil
- Radiative energy remained important to ground thaw at locations situated outside of flow pathways and without ponded water
- With more thaw, soil hydraulic conductivity and water storage capacity increased and enhanced percolation. These feedbacks resulted in an interactive link between SM and FT

Modified Péclet Number for Northern Wetlands:

- Peatland $mPe = 0.0004$, Valley $mPe = 0.09$ and Wetland $mPe = 1.1$
- Advective energy (Q_w) from lake water input at wetland site overwhelmed other energies

Conclusion

- Results did not show a simple interaction between SM and FT.
- Instead, different hydrological and energy influences dictated largely by site topology, topography and typology created an indirect, diverse and dynamic relationship between SM and FT. The findings support Buttle's (2006) T³ concept.
- Main controls were water and energy influxes from surface inflow and ponding. The water kept SM high and permitted transfer of substantial quantities of latent heat to thaw frozen ground.
- A spectrum of correlations between SM and FT among wet to dry sites exists (Fig. 5).
- The relationship between SM and FT can be quantified using a modified Péclet number.

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