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SPATIAL VARIABILITY OF SNOWMELT INFILTRATION TO FROZEN SOIL WITHIN THE YUKON BOREAL FOREST

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ABSTRACT: This paper presents the results of field studies, which were initiated to study the variability of snowmelt infiltration to frozen soil. The overall objective of the study is to develop a practical method of transferring point source infiltration to a hillslope scale. Previous work has led to the development of a parametric relationship which provides a means of estimating point source infiltration rates to frozen soil using field obtainable data (Zhao and Gray, 1999). Preliminary work has been carried to field test the developed relationship within variable settings in the boreal forest ecoregion of southern Yukon, Canada. Tested sites include a variety of vegetation types and associated canopy coverages. Hydrometeorological inputs at each site are monitored at multiple levels in and above the canopy and within the soil cross section to provide a vertical structure to conditions at each site. Frozen soil infiltration was determined using twin probe gamma attenuation techniques and volumetric water content was measured by time domain reflectometry. Thermal and soil moisture characteristics vary considerably at each site during the melt period because of variable snowpack accumulation and melt associated with vegetation and terrain affects on snowfall and energy distribution. Because of these environmental differences, infiltration at each site is subsequently variable. Comparisons between frozen soil infiltration at several sites have been made comparing the 1998 and 1999 snowmelt seasons. Reasonable preliminary comparative trends between observed and calculated infiltration amounts were observed.
KEY TERMS: frozen soil; infiltration; parametric relationship; snowmelt; subarctic

INTRODUCTION

Spring snowmelt infiltration is an important hydrological process which controls streamflow, soil moisture recharge, solute leaching and surface erosion. During the time of snowmelt the ground is usually frozen affecting the initial surface entry conditions as well as transmission conditions within the soil. The theory underlying the movement of water into frozen ground is complex and requires a sound understanding of heat and mass transfer processes. A comprehensive consideration of the theory is carried out by others (Engelmark and Svensson (1993); Flerchinger and Saxton (1989); Zhao et al (1997)). Consideration of the process involves many components including the thermal and hydrophysical characteristics of the soil, the soil moisture and temperature regimes, the rate of supply of snowmelt water and the energy content of the infiltrating water (Granger et al, 1984).

Infiltration studies into frozen soils have provided an understanding of the mechanics of the process (Kane and Stein, 1983, Granger et al., 1984, Stahli et al., 1997). In the absence of cracks or other micropores which promote preferential flow, soil moisture in the upper soil horizon, is thought to be the most significant parameter governing infiltration into frozen soil (Gray et al., 1970; Kane and Stein, 1983; Granger et al., 1984). It is generally accepted that there is an inverse relationship between frozen soil moisture and infiltration. Soil moisture content affects hydraulic conductivity through pore constriction by ice blockage.

The role of soil temperature is less clear than that of soil moisture but is generally thought to be less significant (Steenhuis et al. (1977),Tao and Gray (1994), Granger et al. (1984)). Upon entering a soil with a temperature below 0° C, water will freeze. The amount which freezes is a function of the amount of free water available, the energy status of both the soil and water, and the energy exchange between the two media. Freezing of infiltrating water acts to raise the temperature of the soil matrix through the release of its latent heat of fusion which is than transported downward by conduction together with of sensible heat from the snowpack. Though refreezing can occur at any time, the process tends to follow a diurnal cycle with infiltration occurring during the day when the melt rate is high and dropping off at night as solar radiation decreases. The depth of freezing also has a significant affect on infiltration. When depth of freezing is shallow, the heat contained in the infiltrating water will quickly thaw the soil, returning infiltration characteristics to those of an unfrozen state. A depth of 15

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cm was observed to be the critical depth in which the soil acts as if it were unfrozen, while freezing depths beyond 60 cm were found to have no further effect on infiltration(Komarov and Makarova,1973).

Using infiltrability to classify soils for forecasting snowmelt runoff in Russia, Popov (1972) developed a two class scheme in which a soil had an unlimited infiltration capacity or was impermeable, or secondly, runoff was produced subsequent to a limited infiltration abstraction. As a component of a modified streamflow forecasting model, Gray et al (1985) used a similar approach in developing a snowmelt infiltration algorithm for frozen soils. The researchers suggested that the infiltration potential of frozen soils could be grouped into three functional categories which consisted of restricted, limited and unlimited classes. Within the restricted class, infiltration is impeded by an impermeable layer such as an ice lens at or near the surface resulting in negligible infiltration. Such a condition may develop with the freezing of a late season rain event, or the refreezing of meltwater resulting in a basal ice layer. In the unlimited class, supplied water is quickly accommodated by the soil in question due to a high proportion of large, air filled non-capillary pores. In the limited class, infiltration was found to be governed primarily by ice content within the top 30 cm of soil at the time of melt. A relation was presented with infiltration a function of premelt moisture content and snow water equivalent.

Subsequent work by Zhao and Gray (1997a; 1997b) and Zhao et al (1997) and lead to the development of a parametric relationship based on initial soil surface and matrix saturation, soil temperature, saturated hydraulic conductivity and infiltration time. Working with a variety of soils ranging from clay to sandy loam, it was determined that soil texture had little influence on infiltration rates, and parametric relationships without the hydraulic conductivity term were developed using data from Saskatchewan boreal forest and prairie sites:

$$INF = CS_0^{2.92}\left(1 - S_I\right)^{1.64}\left(\frac{273.15 - T_I}{273.15}\right)^{-0.45} t^{0.44} \qquad (1)$$

in which *INF* is the infiltration in cm, C is a bulk coefficient, S_0 is the surface saturation, S_I is the initial soil saturation, t is time in hours, and T_I is the initial soil temperature in degrees K (Zhao and Gray, 1999).

Practical use of the point source infiltration model requires estimates of initial surface and matrix soil moisture, initial soil temperature and infiltration opportunity time. Preliminary work has been carried out to assess the variability of snowmelt infiltration to frozen soil at the Wolf Creek Research Basin, and, to assess the applicability of the parametric relationship to southern Yukon Boreal forest conditions. In terms of model application, potentially significant differences between Saskatchewan and Yukon fields sites include generally coarser and drier soils with significantly greater organic material.

STUDY AREA

The Wolf Creek basin is located 15 km south of Whitehorse, Yukon Territory at approximately 61 degrees north latitude (Figure 1). The basin occupies a 195 km² area in the southern Yukon headwater region of the Yukon River. With a northeasterly aspect, elevations range from 800 to 2250 m with the median elevation at 1325 m. It is situated within the Boreal Cordillera Ecozone straddling the Southern Yukon Lakes and Yukon-Stikine Highlands Ecoregions (Environment Canada, 1995). The geological makeup is primarily sedimentary in nature comprised mainly of limestone, sandstone, siltstone and conglomerate. Some volcanic materials consisting of andesite and basalt are present with some intrusions of granite. The basin is overlain with a mantle of glacial till ranging from a thin veneer to depths of one to two m. The deposits consist of glacial, glaciofluvial and glaciolacustrine origins. Fine textured alluvium covers most of the valley floors adjacent to drainages. Upper elevations have shallow deposits of colluvial material with frequent bedrock outcrops present. Valleys are extensively scoured. (Mougeot and Smith, 1994).

The Wolf Creek watershed consists of three principle ecosystems the boreal forest, subalpine taiga and alpine tundra with proportions of 22, 58 and 20 percent respectively (Francis, 1997). Study plots are located within each of the ecosystems at elevations of 750, 1250 and 1615 m respectively. The forest ecosystem consists of mixed spruce, pine and popular tree to heights of approximately 20 m. The understory consists of a wide variety of shrubs with feather moss and grasses. Treeline is located roughly at 1300 m. Soils are comprised primarily of gleyed cumulic regosol with coarse textures (loamy sand and sandy loam) to a depth of 39 cm with an organic layer of 12 cm. The parent material is mixed alluvial, lacustrine and morainal material. The subalpine taiga site is characterised by shrub alder and willow to heights of approximately 2 m. Interspace vegetation consists of a 5 to 20 cm organic mat of grasses and mosses with some lichen. The soil is an orthic eutric brunisols with some volcanic ash and reworked hillslope materials. Textures are medium to coarse consisting of silty loam in the upper horizons (0 to 18 cm) with sandy loam in the lower horizons and a 5 cm organic layer. The alpine tundra site occupies a windswept ridge top. Vegetation is sparse consisting of mosses, some grasses and lichens with occasional patches of scrub willow no more than 0.2 m high. Boulders of up to 1 m are scattered about the landscape. The alpine site is comprised primarily of orthic eutric brunisols with a primarily silty loam texture and a 2 cm organic layer. The parent

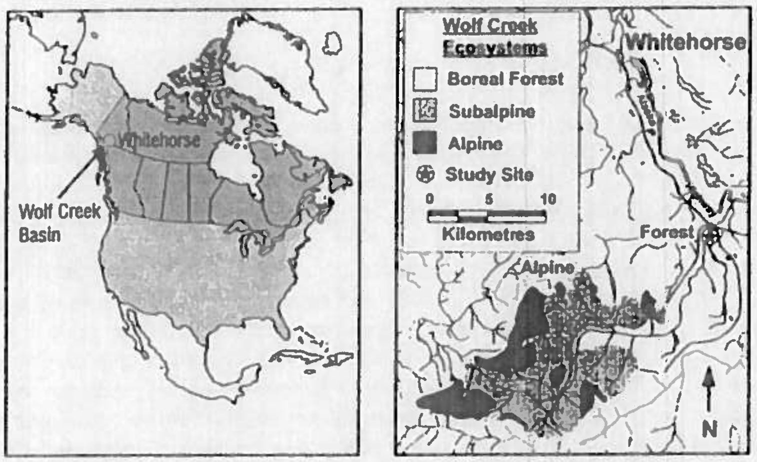


Figure 1. Location Map

material consists of moderately stony morainal deposits. The basin in underlain with a 2 cm volcanic ash layer approximately 10 cm below the surface (Rostad et al., 1977). The basin is within the discontinuous/scattered permafrost zone with sporadic permafrost at higher elevations (Brown, 1977).

The basin has a sub-Arctic continental climate which is characterised by a large variation in temperature, low relative humidity and relatively low precipitation (Wahl et al., 1987). Mean annual temperature is in the order of -3°C. with a summer and winter monthly range of 5° to 15°, and -10° to -20° C. respectively. Summer and winter extremes of 25° and -40° C are not uncommon. An Arctic inversion develops during the winter months when air temperatures increases with elevation. Mean annual precipitation is 300 to 400 mm per year with approximately 40 percent falling as snow.

FIELD MEASUREMENT PROGRAM

Snowpack ablation was monitored continuously using ultrasonic depth sensors (Campbell UDG01/SR10) which was mounted on the meteorological station towers. The towers are located approximately ten m from the infiltration plots. Snow depth on the study plots was measured during each visit. Measurements of snow water equivalent and corresponding depth were obtained periodically through the study period using a Mount Rose sampler. This information was used to develop a record of available snow water for the infiltration process. Data was recorded at 30 minute intervals by Campbell Scientific 21x data loggers.

Soil temperature was obtained using YSI 40328 thermistors which were inserted horizontally within soil pit walls at the study plots. Unfrozen soil moisture was obtained using Campbell Scientific CS615 time domain refractomatry (TDR) probes which were likewise inserted within the soil pit walls adjacent the thermisors. The thermistors and TDR were located at depths of 5, 15, 30 and 80 cm at the forest site and 5 and 15 cm at the alpine site. Soil temperature and moisture were recorded at 10 minute intervals.

Total soil moisture (frozen and unfrozen) was obtained by monitoring soil density using a twin probe density gauge. This method utilizes 50 mm diameter plastic access tubes spaced 304 mm apart. The tubes are placed vertically in the soil to depths of 140 and 80 cm within the forest and alpine study plots respectively. A radioactive gamma source and a detector are placed simultaneously in the adjacent tubes at common depths and the number of attenuated photons travelling between the two during a one minute interval is recorded. Soil density is calculated using the obtained reading, initial moisture content, the unattenuated intensity of the radioactive source and the attenuation coefficients for soil and water. Soil samples taken at the time the access tubes were installed were used to determine the initial dry soil density and moisture content. Assuming the soil mass remains constant, any changes in density from one sample to the next can be attributed to changes in soil moisture content. Reading are taken at 2 cm intervals within the top 40 cm of the soil profile, and at 4 cm intervals within the remainder of the profile. Soil profile moisture measurements were taken on a daily basis at the forest plot during the snowmelt period. Due to access limitations the subalpine and alpine plots were sampled every one or two days.

DETERMINATION OF INFILTRATION PARAMETERS

Initial soil matrix saturation (S_I) was represented by the average total soil moisture, within the upper 30 cm of the soil profile prior to the beginning of snowmelt. The term ($1-S_I$) represents the air filled pore space of the soil column. This data was obtained using the twin probe gamma attenuation technique. Initial surface soil moisture represents the head imposed on the soil surface during the infiltration event. Zhao and Gray (1999) used the average soil moisture in the top 1 cm of the ground surface during the period when meltwater is being supplied to the surface. Surface soil moisture data was no available In the present study so it was necessary to estimate this parameter using other data. A correlation was develope between Saskatchewan boreal forest and prairie matrix and surface soil moisture. Initial soil matrix temperature wa represented by the average of the 15 and 30 cm depth temperature values immediately prior to a significant increase in soi liquid soil moisture. Snowpack temperature was used to estimate the infiltration opportunity time, the period which the snowpack is isothermal and in theory capable of releasing meltwater to the soil surface. Air temperature was used to supplement this information since the infiltration plots generally continued to have a snowcover after the snow temperatur sensors became exposed. Infiltration opportunity time was taken to be the total time, during which a snow cover wa present, that the air temperature was positive and the snow temperature was greater than –0.1 °C. The coefficient "C represents the characterisation of infiltration differences between the model and natural processes. Zhao and Gray (1999 found values of 1.14 and 2.05 to provide the best fits for forest and prairie conditions respectively. Soils at Wolf Creek wer similar in texture to the Saskatchewan forest calibration sites. A preliminary calibration using Wolf Creek data indicate that at value of 0.3 would be more appropriate for the present study.

RESULTS AND DISCUSSION

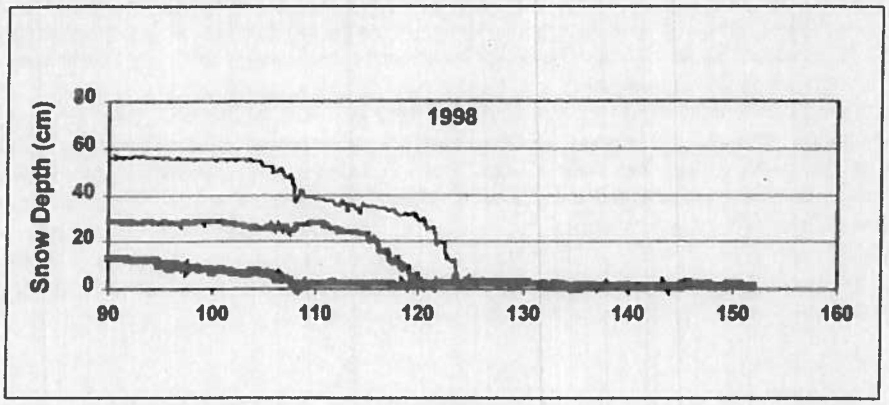
Due to the variable snowpack accumulation, pre-melt soil moisture regime and snowmelt process, associated wit vegetation and terrain affects on snowfall and energy distribution, the melt and subsequent infiltration characteristics varie considerably between the three sites, as well as across the individual sites. In addition the snowmelt regimes between th two years were also significantly different. The 1999 mean snowpack was approximately 180 percent of the 1998 event an the snowmelt period was approximately twice as long at the subalpine and alpine sites due to a cooling and sno accumulation period which occurred midway through the event (Figure 2). The snowpack at the forest site was effectivel ablated prior to the commencement of the cooling trend. Values of available snow water equivalent are presented in Table The 1998 snowmelt ablation process as monitored by the respective snow depth sensors commenced on April 2, 12 and with durations of 15, 20 and 21 days at the forest, taiga and alpine sites respectively. The 1999 snowpack ablation proce commenced on April 5, 6, and 10, with durations of 21, 44, and 47 days at the forest, taiga and alpine sites respectively. Th snowmelt period was interrupted by a 11 day cooling period with low radiation and air temperature levels during which tin a net accumulation of the snowpack occurred at the subalpine and alpine sites commencing April 24.

Soil temperature between the two years was fairly similar at the respective sites. During 1998 the 15 cm temperatu gradually increased from approximately –2, -1 and –6 °C on April 1, to 0 °C on April 16 at the forest and subalpine sites, a May 6 at the alpine site, and were maintained at this temperature while a snow cover persisted. These isothermal conditio are produced in part by infiltrating water refreezing thus releasing latent heat and warming the surrounding soil. Under the conditions liquid water and ice will coexist in equilibrium. The 1999 pattern was similar though temperatures were slight lower. The 15 cm temperature gradually increased from approximately -4, -2 and -8 °C on April 1 to 0 °C on April 11 a 16 at the forest and taiga sites, and May 27 at the Alpine site. The effect of snow cover on soil temperatues is evident comparing respective conditions at the forest and taiga sites. Though winter air temperature is greater at the forest site, s temperatures are lower due the significantly shallower snowpack.

Pre-melt total soil mositure was generally greater in 1999 than 1998 due to a significant fall rain event. Mean saturati fraction values of .09 and .11 were observed for at the forest and subalpine locations respectively during 1998, as compar to .17 and .16 in 1999. Pre-melt soil mositure values for the individual infiltration plots are provided in Table 1.

Observed Infiltration

Cumulative bulk infiltration amounts for the snowmelt season were measured using the twin probe gamma attenuati method for 1998 and 1999. Though the access tubes extend to depths of 140 cm at the forest and subalpine sites, and 80 at the alpine site, little infiltration was observed at lower levels. Accordingly the comparison of infiltration amounts in present analysis was limited to the upper profile, with specific depths varying with location and year, ranging from 22 to cm. Observed seasonal infiltration values are presented in Table 1. Infiltration amounts are assumed to be the change total soil moisture (liquid and frozen) occurring in the soil profile from one measurement to the next. Given changes in soil moisture within the study plots can be attributed to infiltration, phase change associated with the melting of pore ice, lateral moisture movement or combination of these processes. In situations where observed infiltration rates exceed observed snow water equivalent, other processes in addition to infiltration are involved. In these situations, additional work is required to



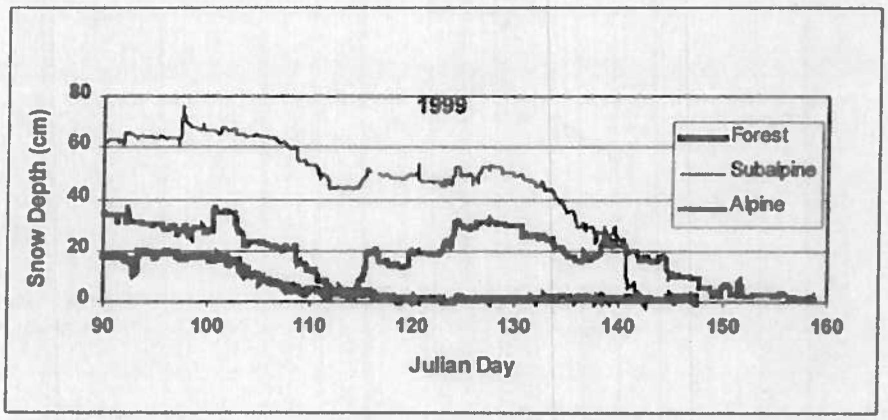


Figure 2. Wolf Creek Snowpack Ablation

Table 1. Infiltration and Snowpack Parameter Data

Site	Year	S_0	S_I	T_I °C	Time hrs	SWE mm	Ablt Rate mm/h	INF obs mm	INF obs mm/h	INF calc mm
F2	1998	0.46	0.08	-1.8	207	20	0.10	69	0.33	25
F3		0.55	0.11	-1.8	159	12	0.07	20	0.13	36
A		0.76	0.22	-3.8	52	43	0.82	50	0.95	33
S6		0.56	0.16	-0.5	183	83	0.45	52	0.28	65
S7		0.38	0.07	-0.5	270	83	0.31	29	0.11	30
F2	1999	0.43	0.16	-0.3	287	67	0.23	37	0.13	48
F3		0.59	0.17	-0.3	165	47	0.28	81	0.49	93
S6		0.64	0.24	-0.4	165	128	0.77	90	0.54	91
S7		0.31	0.08	-0.4	339	128	0.38	41	0.12	20

F2, F3 – Forest ; A – Alpine; S6, S7 - Subalpine

quantify the respective contributions. Observed infiltration amounts were generally greater in 1999 than in 1998 following a similar trend for snow water equivalent. The overall ablation rate followed a similar pattern with observed rates greater in

1999. The ablation rate was calculated by dividing snow water equivalent by infiltration opportunity time. Infiltratio was calculated in a similar fashion and is shown in Figure 3 plotted against the ablation rate. Though there are insuff data to achieve statistical significance, there is a reasonable trend between the two parameters similar to the findings of and Gray (1999). The comparison indicates that the infiltration rate closely approximates the ablation rate, and as su estimate of the ablation rate could be used to estimate infiltration at locations with similair in character to those of the p study. It is interesting to note that Wolf Creek rates are approximately thirty percent of those observed in Saskatch likely due to differences in melt rate.

A similarly reasonable trend was observed by plotting observed infiltration against infiltration amounts calculated the parametric relationship (Figure 4). The results are better than expected since there exist potentially significant diffe between Saskatchewan and Yukon fields sites. These include generally coarser and drier soils with a greater organic The differences are greatest at the forest location where soils are most coarse, driest and have the thickest organic Because of the relatively low snowpack and significant storage, an unlimited infiltration capacity would be expected. applicability would be expected at the subalpine and alpine sites where the snowpack is significantly greater, and so finer, wetter and have a smaller organic layer. The reasonable observed trend indicates that it may be possible to ca the parametric relationship for use in various in Yukon ecozones.

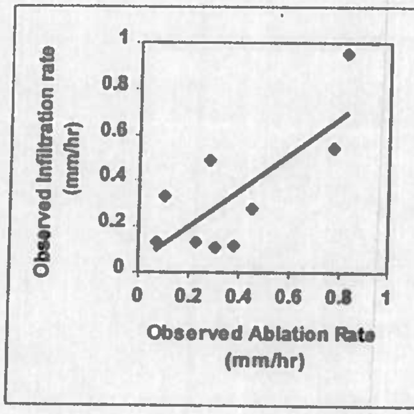


Figure 3. Observed Infiltration rate compared to snow ablation rate

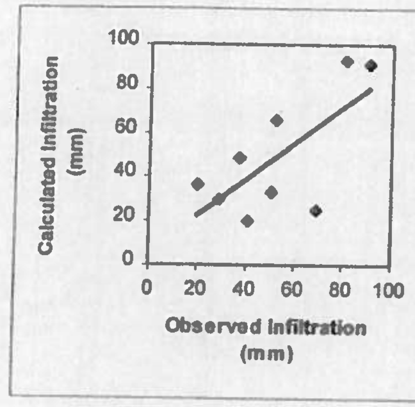


Figure 4. Observed Infiltration compared to calculated infiltration

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