Characterisation of Snowmelt Infiltration Scaling Parameters Within a Mountainous Subarctic Watershed

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ABSTRACT

This study considers the effects of spatial variability of driving variables on upscaling point estimates of snowmelt infiltration to frozen soil to the basin scale. Previous research led to the development of a parametric relationship between infiltration to frozen soil and soil temperature and moisture (water + ice) content at the onset of melt, and infiltration opportunity time (period of application of meltwater to soil). Reasonable success was achieved in field-testing the parametric relationship in forest, shrub and tundra sites in a mountainous, sub-arctic watershed in southern Yukon, Canada. It was determined that the primary governing parameters of snowmelt infiltration into frozen ground in this environment can be represented by late winter snow water equivalent and pre-winter near-surface soil moisture. The spatial variability of these parameters across forest, shrub-tundra and tundra landscapes was examined with respect to topography and vegetation, and reference made to the processes governing snow accumulation and soil moisture storage. The patterns of snow accumulation and soil moisture were found to only be slightly related to vegetation density and topography in forest, subalpine and alpine sites.

Keywords: snowmelt, infiltration, frozen soils, snow water equivalent, soil moisture, scaling

INTRODUCTION

Spring snowmelt is normally the dominant hydrological event of the year in streams draining northern regions. The magnitude and timing of the event is controlled by the distribution of the snowpack over the basin, the rate of snowmelt, and the delivery of the meltwater to the stream channel. In addition to slope and proximity to the channel, the delivery of the meltwater is largely controlled by the infiltrability of the basin, which is in turn a function of the condition of the soil surface. Reliable streamflow estimates are dependent on the suitability of the selected model. Because of the significant variability of climatic and physiographic variables throughout a basin, the accurate parameterisation of this information to represent overall basin conditions is also essential. The application of robust scaling techniques is required to accomplish the necessary parameterisation. At the initiation of snowmelt in the sub-arctic the ground is frozen; this affects 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 coupled heat and mass transfer processes. A comprehensive consideration of the theory is carried out by Engelmark and Svensson (1993); Flerchinger and Saxton (1989); Zhao et

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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 macropores 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 ice content affects hydraulic conductivity through pore constriction by ice blockage.

Subsequent work by Zhao and Gray (1997a; 1997b) and Zhao et al (1997) lead to the development of a parametric relationship based on initial soil surface and matrix saturation, soil temperature and infiltration time. Working with a variety of soils ranging from clay to sandy loam, it was determined that soil texture has a small influence on infiltration rates, and a parametric relationship was developed using data from Saskatchewan boreal forest and prairie sites:

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

in which *INF* is the infiltration in mm, C is a bulk coefficient, S_0 is the soil surface saturation (volumetric soil moisture content / soil porosity) in mm^3/mm^3, S_I is the average soil saturation (water + ice) of the 0 to 40 cm soil layer at the start of infiltration in mm^3/mm^3, T_I is the initial soil temperature in degrees K and t is the cumulative infiltration opportunity time in hours, (Zhao and Gray, 1999). 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 (Janowicz, 2000). The study showed a reasonable trend between observed infiltration and infiltration amounts calculated using the parametric relationship.

Practical use of the point source infiltration model requires estimates of the infiltration opportunity time, which is the length of time that a meltwater flux is applied to the top of the soil. This parameter itself is determined by the snow water equivalent (SWE) and the melt rate. The governing soil parameters include soil surface and initial matrix soil moisture, initial soil temperature and the bulk coefficient "C". The coefficient "C" characterises the differences between estimated and actual infiltration, and can be adjusted to account for a decrease in S_0. For watershed modelling purposes, the spatial variability of these parameters must be accounted for.

Gray et al. (2001) present a conceptual model for scaling frozen soil infiltration during snowmelt events. They suggest that at macro and meso scales infiltration to frozen soils can be estimated based on the spatial distribution of soil moisture and snow water equivalent. Frozen soil temperature can be ignored because infiltration is relatively insensitive to this parameter (as long as soils are frozen), and the remaining terms in the parametric relation are inter-related; therefore, landscape stratification techniques can be used estimate these parameters. Scaling of frozen soil infiltration at the micro-scale is thought to be significantly more complicated and requires the estimation of all process variables.

SPATIAL VARIABILITY OF INFILTRATION PARAMETERS

Snow Water Equivalent (SWE)

Marsh (1999) provides a summary of recent work that characterises the spatial variation of snow cover. Variations in snowcover occur at a range of scales from a micro to a regional scale. Variations in SWE occur because of climatic, topographic and vegetative factors. In a forest environment, the spatial variation in SWE is primarily a result of variations in canopy coverage

and proximity to individual trees (Pomeroy et al., 1998). In open environments, spatial variations in SWE are strongly related to wind exposure and vegetation. Topographic features that produce major divergence in airflow patterns resulting in differential ablation and deposition rates affect snow accumulation patterns. Snow surveys across hillcrests and through the lee side of abrupt slopes indicate the snowpack has greater variability than on flat or gently rolling terrain. Gray et al. (1979) show SWE on brush- covered hillslopes to be 10 times greater than bare slopes. The variability in SWE over landscapes with taller vegetation is generally lower as vegetation tends to dampen the variability.

Bloschl et al. (1991) developed an interpolation procedure for snowpack distribution in the Austrian Alps based on elevation, slope gradient and slope curvature. Shook et al (1993) and Shook (1995) developed an approach for simulating the spatial variation of prairie snowcover using a log-normal probability density function to describe the distribution of snow water equivalent. Pomeroy et al (1997) and Liston and Sturm (1998) used blowing snow models driven by inputs of snowfall, wind speed, temperature and humidity and the spatial distribution of topography and vegetation to calculate and map snowcover distribution in a variety of Arctic terrain types in Canada and Alaska respectively. Using a distributed blowing snow model coupled to a complex terrain wind flow model, Essery et al (1999) were able to simulate coefficients of variation and estimate the log-normal distribution of SWE for terrain types on the arctic treeline. Elder et al (1998) used binary decision trees to interpolate from a detailed snow survey and estimate snow depth and SWE for basins with great extremes of topography, energy balance, elevation and biomes, explaining 60-70% of the observed variance of SWE. Cline et al (1998) used a combination of distributed energy balance model and Landsat images over the melt period to hindcast the spatial variation in SWE over a complex mountainous basin.

Soil Moisture

Pre-melt surface soil saturation (S_0) has been found to be the most significant soil parameter controlling snowmelt infiltration (Zhao and Gray, 1999). Dessication of the surface layer due to strong overwinter temperature gradients or increases in ice content due to mid-winter melts can cause variation in this parameter. Initial matrix soil moisture is also a significant parameter affecting infiltration to frozen soils. This term is an indirect measure of the air filled pore space, and represents the average moisture content in the top 40 cm of mineral soil, at the start of the delivery of meltwater to the mineral soil surface. Numerous studies have observed frozen soil infiltration to vary inversely with soil moisture content (Kane and Stein, 1983; Granger et al., 1984; Burn, 1990). This parameter can effectively be represented by pre-freeze-up soil moisture. Gray et al. (1985) found many examples where over winter soil moisture remained largely unchanged or increased in clay and clay loam Saskatchewan soils. However, many cases were also found with significant moisture losses from the surface soil layer, especially on summer fallow.

Numerous studies have been successful in relating patterns of soil moisture to topographic indices alone. Others have used a combination of topographic indices and geostatistical techniques. High soil moisture levels have been found to be associated with zones of topographic convergence, while low soil moisture is associated with topographic divergence (Beven and Kirkby, 1979; Barling et al, 1994). Aspect has also been found to influence soil moisture (Western et al. (1999), Moore et al., 1993). Relative elevation and slope positions were found to be the most significant variable in several studies (Famiglietti et al., 1998; Crave and Gascuel-Odoux, 1997). Nyberg (1996) found upslope drainage area to produce statistically significant correlation, while Western et al. (1999) found this variable most significant during wet periods and a radiation index best during dry periods. Several researchers have found vegetation to have a significant affect on soil moisture amounts and infiltration rates associated with frozen soils. Infiltration rates beneath shrub mounds were observed to be in the order of twice that of the interspace (Seyfried and Wilcox, 1995; Blackburn et al., 1990; Johnson and Gordon, 1988). Interspace soils were observed to have poorer structure and higher soil moisture than corresponding shrub soils.

STUDY OBJECTIVES

The spatial distribution of soil moisture and snow water equivalent is believed to be largely controlled by topography and vegetation. The objective of this paper is to investigate the variability of soil moisture and snow cover between the three ecosystems making up the Wolf Creek watershed, and, to assess the variability with respect to topographic and vegetative controls. A comparison is made of the aggregate values of soil moisture and snow water equivalent (SWE). The climatic histories of the sampling periods are assessed to determine whether there are anomalous influences on the parameters in question. The spatial distribution of the respective parameters across the grid plots are assessed with respect to topographic and vegetative controls and consideration of the underlying physical processes.

FIELD MEASUREMENTS

Study area

The Wolf Creek basin forms part of the headwaters of the Yukon River drainage and is located 15 km south of Whitehorse, Yukon Territory at approximately 61° N latitude (Figure 1). The sub-arctic continental climate 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 summer and winter monthly ranges of 5°-15°, and -10^0--20° C. respectively. Summer and winter extremes of 25° and -40° C are not uncommon. Mean annual precipitation is 300 to 400 mm per year with approximately 40 percent falling as snow. Basin area is 195 km^2. With a northeasterly aspect, elevations range from 800 to 2250 m with the median elevation at 1325 m.
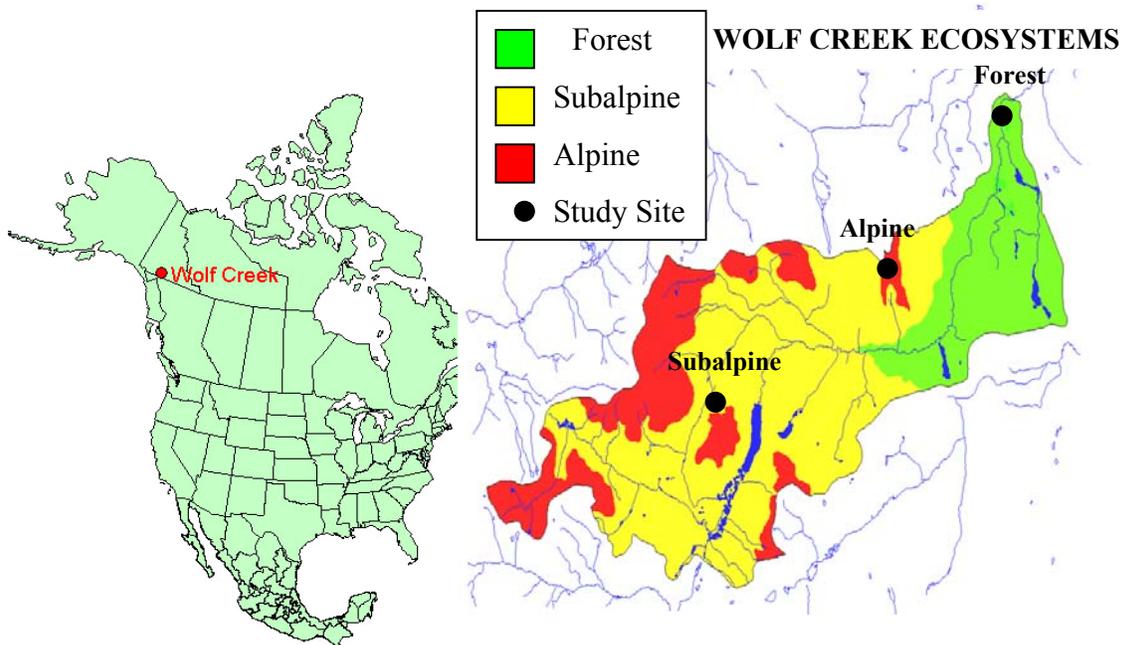

Figure 1. Location plan.

Wolf Creek is situated within the Boreal Cordillera Ecozone (Environment Canada, 1995) and consists of three principle ecosystems, boreal forest, sub-alpine taiga (shrub-tundra) and alpine tundra with proportions of 22, 58 and 20% respectively (Francis, 1997). Permafrost is present in

favourable locations on the north-facing slope and there is sporadic permafrost throughout the basin at these elevations increasing with elevation (Brown, 1977). Study plots are located within each of the ecosystems at elevations of 750, 1250 and 1615 m respectively.

The forest plot is relatively level with gently undulating terrain consisting of an alternating hummock and hollow landscape. The canopy is dense, consisting primarily of white spruce to heights of approximately 20 m, with some poplar trees to approximately 15 m. The understory consists of a wide variety of shrubs with a feather moss mat of approximately 10 to 20 cm., and grasses. The northwest corner of the grid is located on the low-lying Wolf Creek floodplain. Forest soils are coarse, consisting of loamy sand and sandy loam to a depth of 39 cm with an organic layer of about 12 cm. The parent material consists of moderately stony morainal deposits mixed with alluvial and lacustrine material.

The subalpine taiga plot is located on an east facing moderate hillslope of approximately 15 degrees. The hillslope itself consists of undulating terrain with numerous hummocks and depressions. The plot is vegetated with 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. Interspace vegetation consists of a 5 to 20 cm organic mat of grasses and mosses with some lichen. Soils are medium to coarse textured 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 plateau. Approximately 50% of the plot is relatively level, with the balance sloping at approximately 15 degrees to the south. The entire plot also has a gentle (5 percent) slope to the northeast. Vegetation is sparse consisting of mosses, some grasses and lichens with occasional patches of scrub willow no more than 0.2 m high. Soils are primarily silty loam with a 2 cm organic layer. Boulders of up to 1 m are scattered about the landscape.

Field Program

A detailed ground based survey was carried out. Grid surveys centred on the 3 baseline meteorological stations were carried out. A 10,000 m^2 (100 x 100 m) area were partitioned into 5 x 5 m grids at these sites, yielding 441 sampling points (the forest grid is a limited 65 x 65m grid (169 sampling points) – due to inclement weather the grid survey was not completed). Vegetation surveys were carried out where a number of parameters were recorded including species, thickness of the organic mat, canopy coverage, height of canopy, and distance to tree trunk or shrub base. In addition leaf area index (LAI) was measured across the forest site. Fall 2000 soil moisture was sampled to characterise the spatial distribution of pre-melt soil moisture conditions. Pre-freeze-up average soil moisture readings over the upper 15 cm soil profile were obtained at grid intersection points using a portable TDR unit. Pre-melt spring snow surveys were carried out across the grid transects during 2001, with the intention of characterising the spatial distribution of annual maximum snow water equivalent. Snow depth was measured at each grid point, and a density reading was taken at periodic intervals across the grid using the Mount Rose sampler.

CHARACTERISATION OF SOIL MOISTURE AND SNOW WATER EQUIVALENT

2000 Pre-Freeze-up Soil Moisture

The summer and early fall preceding the sampling period was wet with May to October precipitation at the Whitehorse meteorological station totaling 247 mm which represents 135% of normal, though much of the disparity occurred during August when 82 mm or 210% of normal rainfall was observed. The combined September and October precipitation was 55 mm or 95 % of normal. This period was also slightly cooler than normal with a September to October observed mean of 3.4^{o}C as compared to a Whitehorse normal of 4.0^{o}C.The fall soil moisture sampling took place during the periods September 21 to 28, September 28 to October 5, and, October 6 to 10 through the alpine, subalpine and forest ecosystem grids respectively. The objective was to obtain the measurements as close to freeze-up as possible and as such the sampling progressed from the

higher to lower elevation sites. Inspection of grid site meteorological records indicates that precipitation immediately prior and during sampling had minimal effect on the pre-freeze up soil moisture.

2001 Spring Snowpack

Snowfall during the 2000/01 season was 69% of normal. This below normal trend was generally consistent over the season with the exception of February, which had 14 mm or 119 percent of normal precipitation. The period was also considerably warmer than normal, with a mean November to April temperature of –6.0 ^{o}C as compared to a mean of –9.1^{o}C. Two periods of thaw were observed during the winter, occurring during mid-November and mid-March. Coincident rainfall of less than 1 mm was observed during the latter period.

The spring snow surveys were carried out during the periods March 30 to April 6, April 3 to 5, and April 17 through the forest, subalpine and alpine ecosystem grids respectively. As with soil moisture the objective was to obtain the measurements at the time of the maximum snow water equivalent prior to the meltwater leaving the snowpack. Melting and unloading of intercepted snow and snowpack subsidence due to increased density was observed at some of the study sites. The melting may have also contributed to the formation of ice layers within the snowpack; however, meteorological records indicate that the lower snowpack at the three study sites remained frozen until the onset of melt.

Soil moisture and SWE together with background climatological parameters for the grid plots are summarised in Tables 1 and 2.

Table 1: August - October 2000 mean air temperature and wind speed—total precipitation and pre-freeze-up 15 cm soil moisture

	Forest	*Subalpine*	*Alpine*
Air Temp (^{o}C)	5.1	2.3	0.52
Wind Speed (m/s)	1.2	1.8	3.9
Precipitation (mm)	126	131	123
Soil Moisture (%)	12.7	17.9	14.2

Soil Moisture Characterisation

Fall soil moisture increases moving from the forest to the subalpine and than drops off in the alpine. This occurs while fall precipitation is about the same in each of the ecoregions indicating that other processes control the soil moisture regime. The dense evergreen canopy, warmer air temperatures result in higher interception loss and evapotranspiration in the forest than in the shrub and alpine sites (Granger, 1999); this likely contributed to the lower soil moisture found there compared to these sites. Downslope position and poor drainage may have contributed to the shrub site having higher soil moisture than the hilltop, well drained soils of the alpine site.

Forest

Isoline plots illustrating the spatial distribution of soil moisture and SWE are presented in figures 2 and 3. Both canopy density and topography appear to have some control over soil moisture and SWE though the trends are not statistically significant as indicated by the coefficients of determination (r^2) summarised in tables 3 and 4. The parameters, which were assessed included elevation, LAI and distance to the nearest tree, base.

Table 2: October to April 2000 mean air temperature and wind speed - total precipitation and April snow water equivalent

	Forest	Subalpine	Alpine
Air Temp (oC)	-6.5	-7.5	-8.1
Wind Speed (m/s)	1.3	2.1	4.3
Precipitation (mm)	102	55	128
SWE (mm)	32	167	45/59*

* - including "0" values / without "0" values (106)
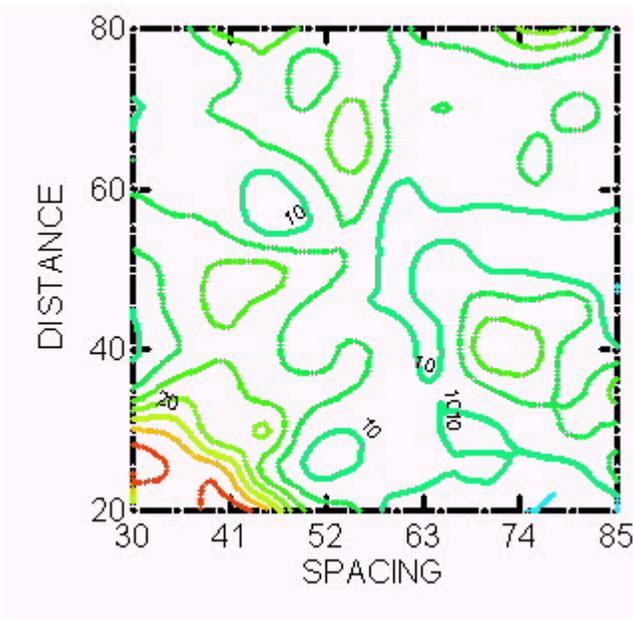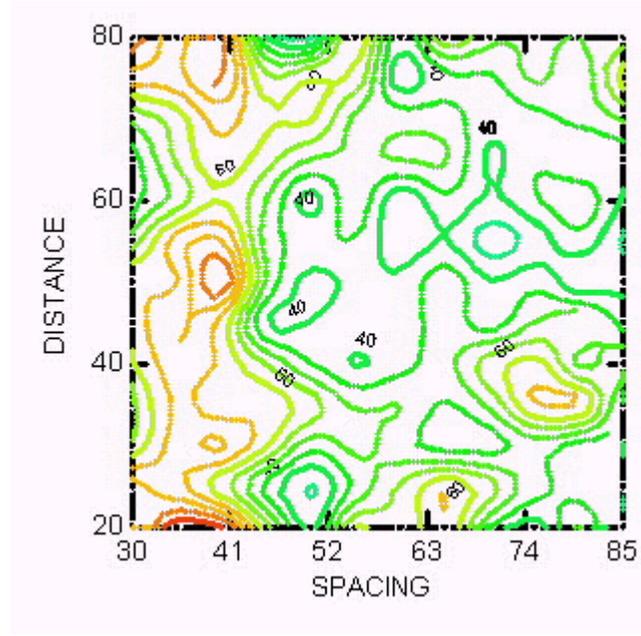

Figure 2. 2000 forest soil moisture.   Figure 3. 2001 forest snow water equivalent.

The highest values of both soil moisture and SWE were observed along the floodplain of Wolf Creek as indicated in figures 2 and 3 near the plot origin (0,0). The floodplain soil moisture data appear to be a separate population in figure 4, which illustrates the poor relationship between soil moisture and elevation. The relationship between these values alone only yielded an r^2 of 0.40. Figures 5 and 6 show that soil moisture decreases with increasing LAI and decreasing distance from the base of the nearest tree respectively. The same parameters were assessed for their influence on SWE; however, the influence on SWE was found to be very small as indicated by the r^2 values summarised in table 4. High values of SWE are observed in the floodplain canopy opening (0,0) as indicated in figure 3. This area is also coincident with an area of low LAI though the relationship between SWE and LAI is poor.

Table 3: Coefficients of Determination for Relationships Between Vegetation and Topographic Parameters and Soil Moisture

Physical Parameters	FOREST		SUBALPINE		ALPINE
Elevation	0.16	[1]0.41	.005	[2]0.17	0.02
LAI	0.17				
Tree / Shrub Dist	0.20		.03		0.09
Canopy Ht			.002		0.08
Canopy Coverage			.01		

[1]Floodplain
[2] Depression
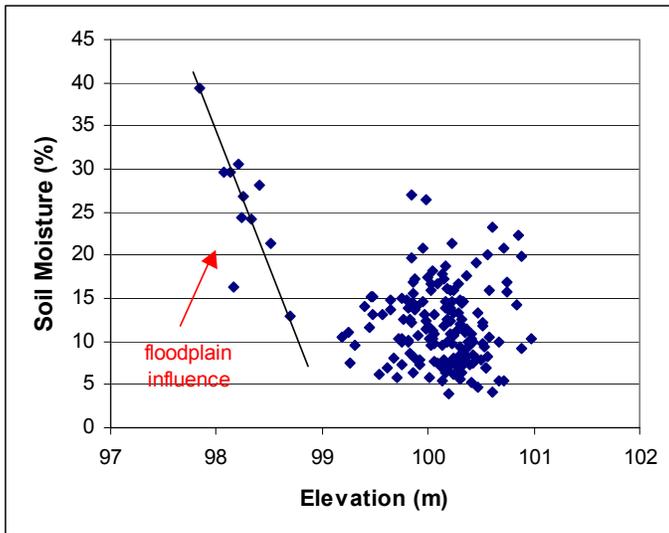
Figure 4. 2000 Forest soil moisture vs. elevation.
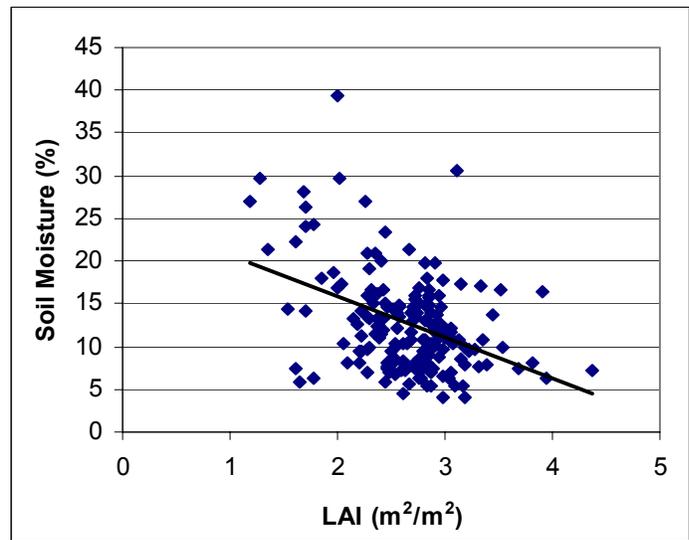
Figure 5. 2001 snow water equivalent vs. LAI.

Subalpine

There appears which to be little relationship between topographic and vegetation parameters and soil moisture and SWE as indicated by the r^2 values summarised in tables 3 and 4. The parameters which were considered included elevation, distance to nearest shrub base, canopy height and estimated canopy coverage. Figures 7 and 8 indicated that an area of both high soil moisture and SWE are coincident with a large depressional area. Such a depression would be expected to be a favourable drainage collection, and snow accumulation area. Values of soil moisture and SWE in the depressional area were thought to represent separate populations, however, the developed relationships between these parameters yields r^2 values of 0.17 and 0.19 respectively (figures 9 and 10).

Table 4: Coefficients of Determination for Relationships Between Vegetation and Topographic Parameters and Soil Moisture

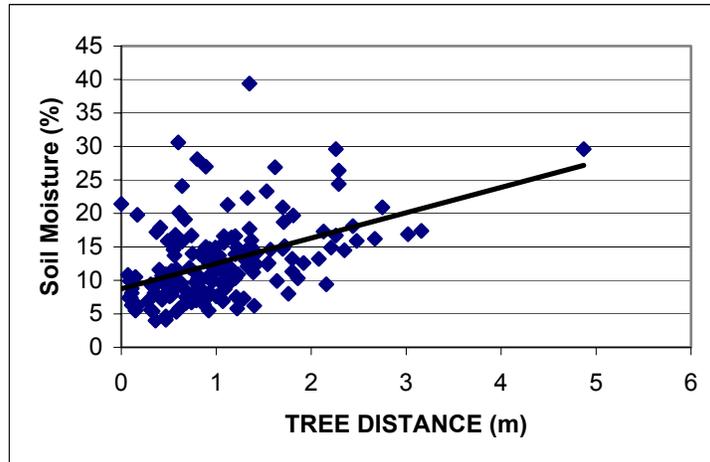| Physical Parameters	FOREST	SUBALPINE		ALPINE
Elevation		.0007	[2]0.19	0.009
LAI	0.08			
Tree / Shrub Dist	0.10	.004		0.04
Canopy Ht		.002		0.26
Canopy Coverage		.003		

Figure 6. 2000 forest soil moisture vs. tree distance.

Alpine

   Vegetation and topography appear to have little effect on soil moisture and SWE as indicated by the r^2 values summarised in tables 3 and 4. The parameters which were considered included elevation, distance to shrub base and canopy height. Figures 11 and 12 indicate that there appears to be little association between soil moisture and SWE. A comparison of figures 11 and 13 indicate that soil moisture is greatest along the entire 40 to 60 spacing range (along the break in slope between the ridge crest and the 15 percent slope along the lower spacing range). This area is relatively flat and contains numerous depressions. This is contrary to what is normally expected; with the possible explanation that the downslope area is a rocky, windward slope with little storage. The higher elevation areas tend to have a relatively shallow slope with numerous depressions and associated storage capabilities. These depressions also tend to be favorable locations for shrubs, which appear to have at least a minimal influence on SWE as indicated by figure 14. Though not statistically significant, figure 14 indicates that there is a trend towards higher SWE with canopy height.
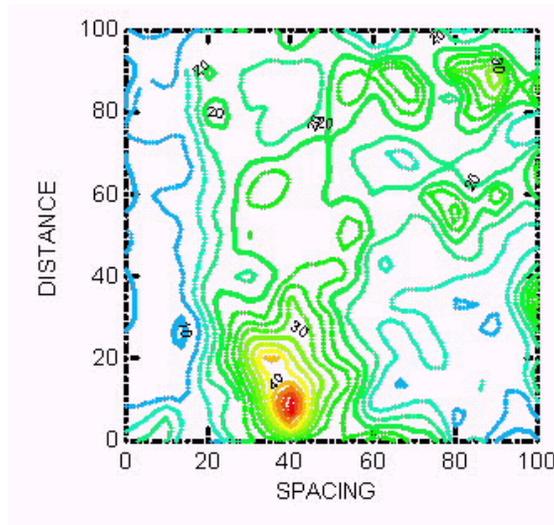

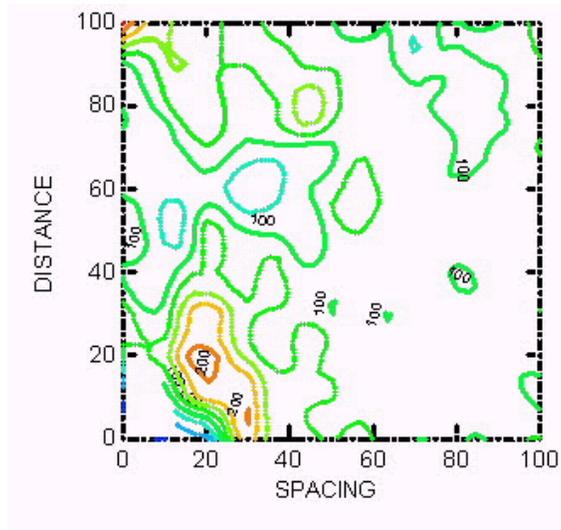
Figure 7. 2000 subalpine soil moisture.

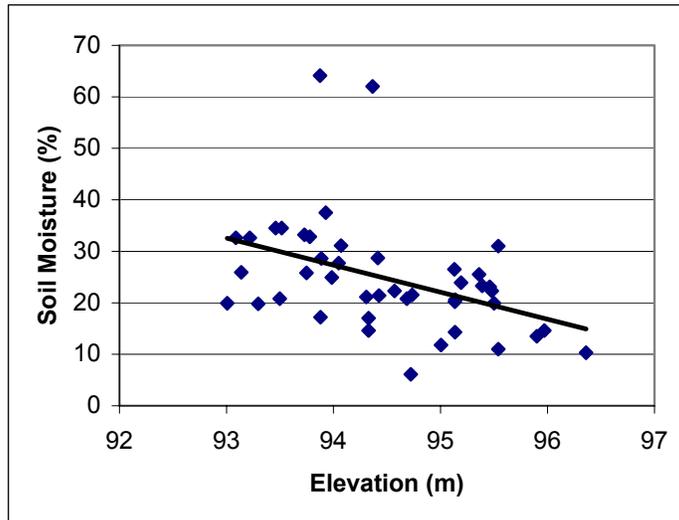Figure 8. 2001 subalpine snow water equivalent.

Figure 9. 2000 subalpine (depression) soil moisture.
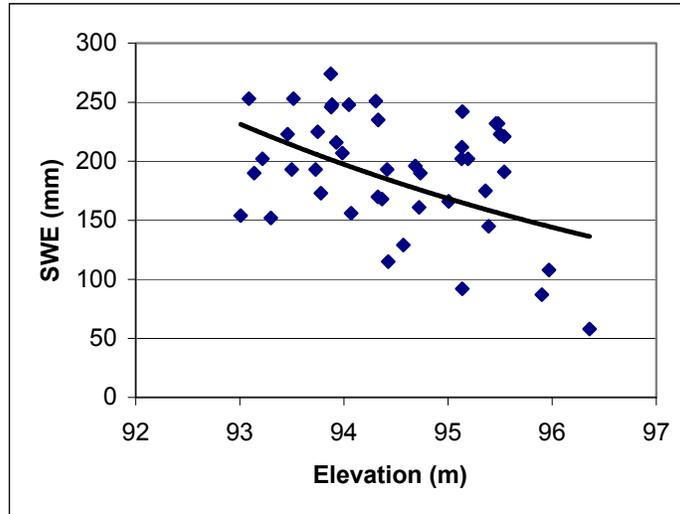
Figure 10. 2001 subalpine (depression) snow water equivalent.
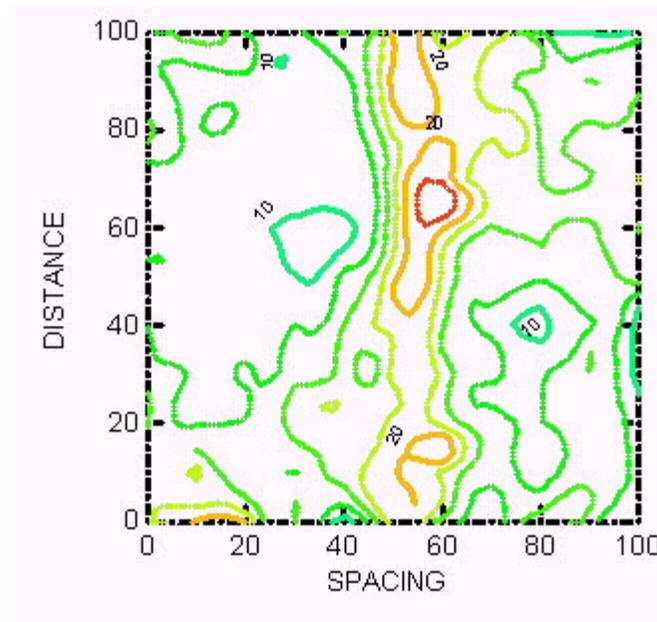
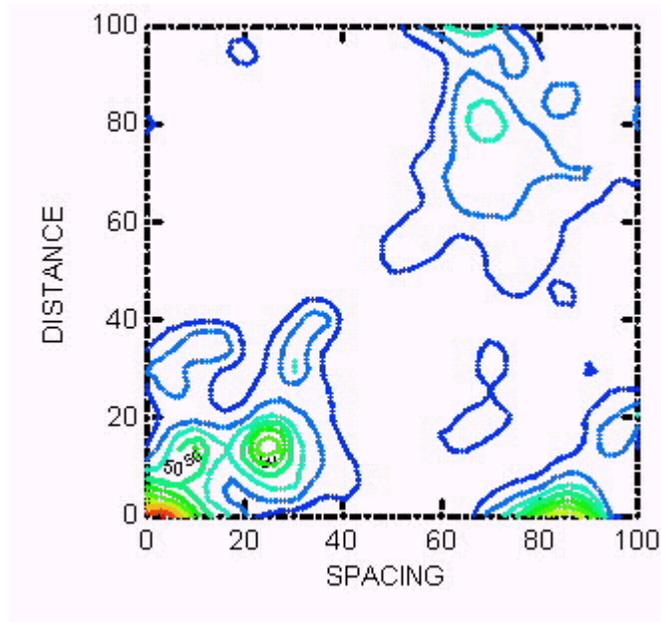

Figure 11. 2000 alpine soil moisture.

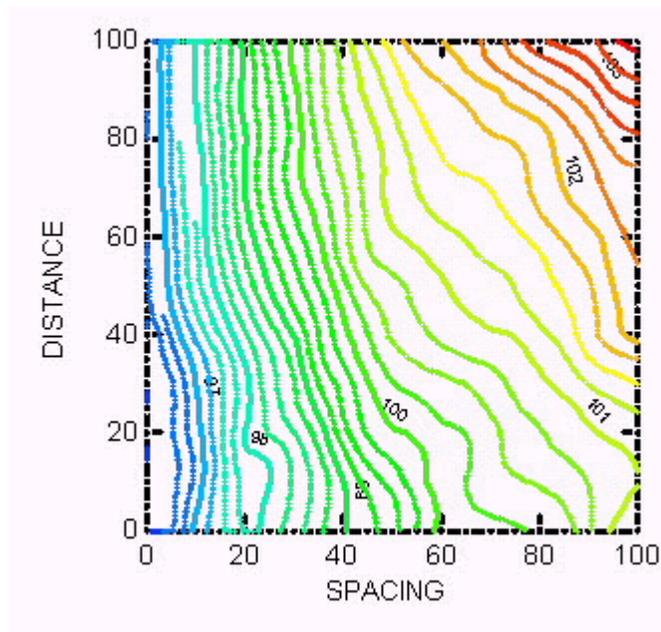Figure 12. 2001 alpine snow water equivalent.
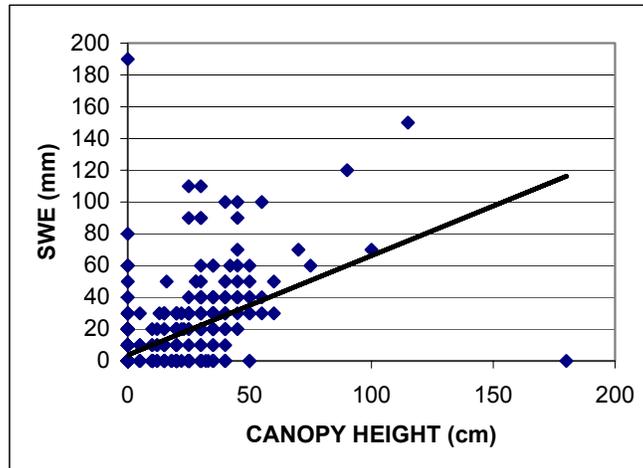

Figure 13. Alpine elevation.

Figure 14. Alpine canopy height vs. snow water equivalent.

DISCUSSION AND CONCLUSIONS

The preliminary results indicate that topographic and vegetative effects are in some cases evident, but these parameters do not significantly influence the spatial distributions of soil moisture and snow water equivalent. Although there are similarities between spatial distribution patterns of snow water equivalent and soil moisture, covariance of point data has not been established. In the absence of rigorous statistical analyses of the data, a descriptive summary of the physical controls exerted at each study site has been provided. Though not strong, the greatest association between canopy density, and, soil moisture and SWE, was observed at the forest site. Increasing canopy coverage promotes interception of both rain and snow, sublimation of intercepted snowfall and evaporation of intercepted rainfall. Previous work has shown that forest interception losses due to sublimation are up to 45 percent of annual snowfall (Pomeroy et al., 1999). In the subalpine, associations between topography and vegetation, at the micro-scale, influence the observed patterns of soil moisture and SWE. A major low lying depressional opening in the shrub canopy tends to trap blowing snow and represents an area of higher soil moisture, however openings on knolls were observed to have lower SWE and soil moisture. Though not statistically significant, topographic effects dominate at the alpine site. Raised sites that are wind-blown and sustain low SWE are also well drained and have relatively low soil moisture. Depressions tend to have higher soil moisture, and subsequently greater shrub productivity, which tends to trap the snow. Further work will examine the association between soil moisture, SWE, vegetation and topography in this exceedingly complex environment.

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