Spatial Variability of Fall Soil Moisture and Spring Snow Water Equivalent Within a Mountainous Sub-Arctic Watershed

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ABSTRACT:

This study considers the spatial variability of soil moisture and snow water equivalent (SWE) within a mountainous sub-arctic watershed. Previous work has determined that the primary parameters governing snowmelt infiltration into frozen ground in this environment are the pre-winter near-surface soil moisture and the late winter snow water equivalent. This suggests that their spatial variability may be used to ‘upscale' estimates of snowmelt infiltration. The variability of soil moisture and SWE between, and within forest, subalpine and alpine ecosystems in the Wolf Creek watershed were investigated. The theoretical lognormal probability distribution was fitted to observed soil moisture and SWE data collected within relatively homogeneous landscape units within the three Wolf Creek ecosystems with good results. Variability within both parameters progressively increased from the forest, to the subalpine, and, to the alpine sites. This increase in variability with progressively higher elevation ecosystems illustrates the ability of vegetation to dampen the variability of both parameters.

Keywords: soil moisture, snow water equivalent, spatial variability, lognormal distribution

INTRODUCTION

Snowmelt is usually the most important annual hydrological event in streams draining northern regions. At the onset of melt, the ground is normally frozen, affecting infiltration to the soil. 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 decreases the hydraulic conductivity through pore constriction and ice blockage and increases the length of flow path. Gray et al. (1985) suggest that snowmelt infiltration to frozen soils is a function of surface conditions, initial soil moisture and snow water equivalent. These researchers suggest that the infiltration potential of frozen soils can be grouped into three functional categories: restricted, limited and unlimited. As the names suggest, infiltration into soils of the restricted class is inhibited because of an impermeable layer, and soils in the unlimited class are able to infiltrate most of the snow water because of preferential flow paths. The focus of their work was on soils in

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the limited class, where infiltration was found to be governed primarily by the ice content within the top 30 cm of soil at the time of melt. A relationship is presented, by these authors, which expresses seasonal infiltration as a function of pre-melt moisture content and snow water equivalent (SWE):

$$\text{INF} = 5(1-\theta_1)\,\text{SWE}^{0.584} \qquad (1)$$

where INF is infiltration in mm, θ_1 is the soil moisture content expressed as a fraction of soil porosity and SWE is in mm.

Subsequent work led to the development of a series of parametric equations based on the moisture content at the surface and the top 30 cm of soil, soil temperature and the infiltration opportunity time, thus providing a means of estimating the variation in cumulative infiltration with time from field obtainable data (Zhao and Gray, 1999). Gray et al. (2001) suggest that the spatial distribution of frozen soil infiltration, can be estimated using the spatial distributions of soil moisture and SWE.

This study examines the spatial variability of the soil moisture content in the fall prior to freeze-up and the maximum accumulation in snow water equivalent prior to snow melt in the spring (SWE) within mountainous forest, subalpine and alpine ecosystems. The spatial characterization of these parameters is an important step leading to the ability to accurately model runoff.

SPATIAL VARIABILITY OF SOIL MOISTURE AND SNOW WATER EQUIVALENT

Soil Moisture

Numerous studies have been successful in relating patterns of soil moisture to topographic and vegetative indices. 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).

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. Janowicz al. (2002) found poor but statistically significant relationships between soil moisture and leaf area index (LAI) and proximity to the nearest tree in a Yukon subalpine forest, and, soil moisture and canopy height in an alpine environment.

Many researchers have studied the frequency distributions of soil moisture parameters. Francis et al. (1986) assessed the relationship between plant cover, incorporated organic matter and soil moisture in a stressed semi-arid Mediterranean environment. They found surface moisture to be normally distributed, stating that transforming (no indication of the nature of transformation was provided) the data did not produce significant improvements in the correlation between observed and theoretical values. Weekly soil moisture samples of the 0-60 cm horizon, taken from the Barapani region of northern India by Sharma and Singh (1987), were found to follow a truncated normal probability distribution. Vachaud et al. (1985) found, as a by product of the study of soil retention curves and the relationship between soil texture and moisture, that the frequency distribution of soil moisture across a cultivated field in Tunisia was approximately lognormal. Li et al. (2001) carried out a soil water balance simulation of a 15 km^2 area of the north China plain near Bejing. They found the simulated and observed soil moisture at the root water uptake level of 1 m, to follow lognormal and normal distributions, respectively.

Snow Water Equivalent (SWE)

Variations in the spatial distribution of SWE occur because of climatic, topographic and vegetative factors. In a forest environment, the spatial variation in SWE is strongly influenced by 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 vegetation is generally less than in open areas as vegetation tends to dampen the variability. Janowicz al., 2002 found poor but statistically significant relationships between SWE and LAI and tree distance in a Yukon subalpine forest, and, SWE and canopy height in an alpine environment.

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.

STUDY OBJECTIVES

The overall objective of this paper is to investigate the variability of soil moisture and snow cover in forest, subalpine and alpine ecosystems in a subarctic, Yukon watershed. Specific objectives include investigating the application of the lognormal probability density function for describing their frequency distributions, and 200investigating the direct association between fall soil moisture and spring SWE.

FIELD MEASUREMENTS

Study Area

The work was carried out in the Wolf Creek watershed, near Whitehorse, Yukon in the subarctic region of northwestern Canada (Figure 1). A comprehensive description of the physiography and climate is provided by Janowicz et al (2002). Wolf Creek 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). 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 mat of feather moss of approximately 10 to 20 cm., and grasses. A portion of the study plot 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.

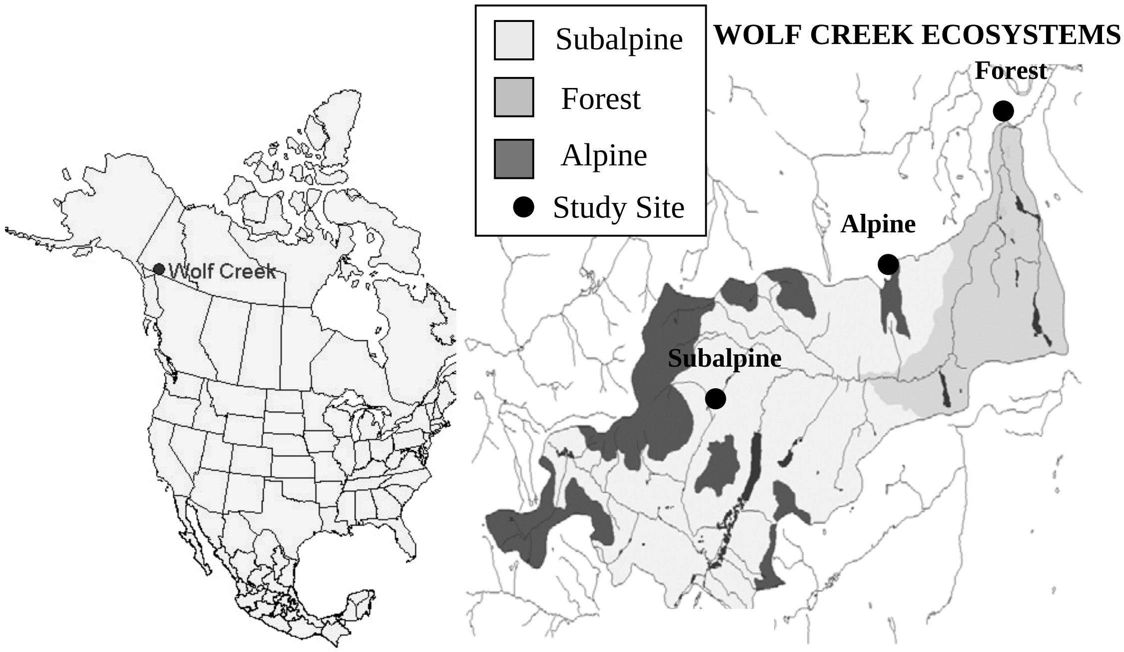

Figure 1: Location Plan.

The subalpine taiga plot is located on a 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. 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 centered 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 characterize the spatial distribution of pre-melt soil moisture conditions. Pre-freeze-up average soil moisture readings over the upper 15-cm profile of mineral soil were obtained at the grid intersection points using a portable TDR unit. Pre-melt spring snow surveys carried out across the grid transects during 2001 were used to characterize the spatial distribution of annual maximum snow water equivalent. Snow depth was measured at each grid point, and a density measurement was taken at approximately every 5th sample across the grid using the Mount Rose sampler.

SPATIAL VARIATION OF FALL SOIL MOISTURE AND SPRING SNOW WATER EQUIVALENT

Soil Moisture Characterization

The sampled grid plot soil moisture data for year 2000 are summarized in Table 1 together with basic statistical properties. Sampled soil moisture represents an integrated mean value over the top 15 cm of mineral soil taken from

Table 1: Integrated 15 Cm Grid Plot Soil Moisture Statistics – 2000

	Forest	*Subalpine*	*Alpine*
Number Of Sample Points	169	441	439
Mean (%)	13.6	17.9	14.2
Standard Deviation (%)	5.8	8.0	4.5
Coefficient Of Variation	0.43	0.45	0.31

below the organic mat. The relatively low values of the forest site, are a result of the coarse texture of the mineral soil, consisting of loamy sand and sandy loam in the forest, silty loam and sandy loam in the subalpine, and silty loam in the alpine, with unrestricted drainage beneath. Mean soil moisture was greater in the forest and alpine ecosystems, and slightly less in the subalpine ecosystem during the study period (Table 1).

Representative seasonal values of key meteorological parameters which affect pre-freeze-up and fall soil moisture are summarized in Table 2.

Table 2. August – October mean monthly air temperature, wind speed and total precipitation – 2000.

	Forest	*Subalpine*	*Alpine*
Air Temp (°C)	*5.1*	*2.3*	*0.52*
Wind Speed (m/s)	*1.2*	*1.8*	*3.9*
Precipitation (mm)	*126*	*131*	*123*

Fall soil moisture is greatest in the subalpine ecosystem and least in the forest ecosystem. Within each year fall precipitation is similar for each of the ecoregions indicating that other processes also affect the soil moisture regime. The dense evergreen canopy and warmer air temperatures result in higher interception and evapotranspiration losses in the forest than in the shrub and alpine sites (Granger, 1999) likely contribute to the lower soil moisture found at the forest site. A relative downslope position and poor drainage may have contributed to the subalpine site having higher soil moisture than the well drained soils of the broad, ridge crest alpine site.

Snow Water Equivalent Characterization

The 2001 spring pre-melt snow cover data for the three Wolf Creek ecosystem grid plots are summarized in Table 3 together with basic statistical properties.

Table 3. Grid plot SWE statistics – 2001.

	Forest	***Subalpine***	***Alpine***
Number of sample points	*156*	*372*	*165**
Mean (mm)	*52*	*111*	*35*
Standard Deviation (mm)	*18*	*40*	*28*
Coefficient of Variation	*0.35*	*0.36*	*0.80*

* without snow – free “0” values (snow free “0” values: 276)

Sampled spring SWE represents the maximum SWE for the accumulation season. The forest SWE sampling program was carried out on a smaller, “limited” grid plot, as compared to the subalpine and alpine plots, due to surveying problems during the grid establishment resulting in fewer sampled values. Mean grid plot SWE and representative seasonal values of key meteorological parameters which affect pre-melt, spring SWE are summarized in Table 4.

Spring pre-melt SWE exhibits a similar trend to that of soil moisture, with the highest values for the subalpine ecosystem, and with the forest and alpine ecosystems 40 % and 45% of subalpine values. The subalpine ecosystem also had the largest amount of precipitation. Likely greater amounts of snowfall are intercepted and sublimated from the forest canopy, which accounts for the low values on the forest floor. Pomeroy et al. (1999) found that the Wolf Creek forest site lost 38 to 45 % of annual snowfall to sublimation from the canopy during the 1993 to 1997 period. Although there is likely some sublimation from the alpine; the dominant process causing depletion of the snowcover is wind ablation. Snow eroded and transported from the alpine and redeposited in the subalpine is a major cause for the relatively high values of SWE in the subalpine. Pomeroy et al. (1999) found the Wolf Creek alpine site to lose 39 to 79 % of annual snowfall to blowing snow transport and sublimation.

Soil Moisture and Snow Water Equivalent Frequency Distributions

In relatively homogeneous landscape classes, where variability in topography and vegetation is slight, total amounts of soil water and precipitation are likely to be fairly consistent. Conversely these parameters may vary between landscape classes, in response to variations in topography and vegetation. In homogeneous landscape settings, the distribution of SWE has been found to be lognormal in character (Donald, 1992; Shook and Gray, 1994). Other researchers have had similar success in describing the frequency distribution of soil moisture parameters using the lognormal probability density function (Vachaud et al., 1985; Li et al., 2001).

Table 4. October to April mean monthly air temperature, wind speed and total precipitation – 2000/01

	Forest	*Subalpine*	*Alpine*
Air Temp (°C)	*-6.4*	*-7.2*	*-8.1*
Wind Speed (m/s)	*1.1*	*1.9*	*3.7*
Precipitation (mm)	*99*	*120*	*M*

M – missing data

Lognormal Probability Density Function

The frequency distributions of most hydrometeorologic parameters do not follow the normal distribution. Often, a log transformation is used to normalise distributions of hydrometeorologic data that are positively skewed. The probability density function, f(y), of the transformed variable:

$$y = \ln (Y) \tag{2}$$

is

$$f(y) = \frac{1}{\sqrt{2\Pi}\, s_y^2} \exp\left(-\frac{\left(y - \bar{y}\right)^2}{2 s_y^2} \right) \tag{3}$$

Where: $\bar{y}$ = mean of the logarithmic values of the variable

s_y = standard deviation of the transformed variable.

The natural values of the observed variable that follow a lognormal distribution can also be linearised as (Chow, 1954):

$$Y = \bar{Y} + Ks; or \tag{4}$$

$$\frac{Y}{\bar{Y}} = 1 + KCV$$

in which $\bar{Y}$, s and CV are the mean, the standard deviation and the coefficient of variation of the natural values the K is the frequency factor K whose value is determined by the exceedance probability.

Soil Moisture Characterization

Figures 2 to 3 are frequency diagrams of soil moisture observations from the forest, subalpine and alpine grids plotted as a lognormal distribution. Review of this information shows that there is close agreement between observed soil moisture and fitted theoretical curves, with r^2 values of 0.99, 0.98 and 1.00 (0.997) for the forest, subalpine and alpine ecosystems, respectively.

Values for the coefficient of variation (CV) for relationships between the observed and theoretical lognormal soil moisture distribution, in forest, subalpine and alpine plots, 0.46, 0.45 and 0.32 respectively. There is no apparent trend for CV to vary with ecoregion The results of the analyses of CV suggest further research is needed to establish whether a common value for CV can be used to describe the frequency distributions of soil moisture in the different ecoregions, i.e., forest, subalpine and alpine.

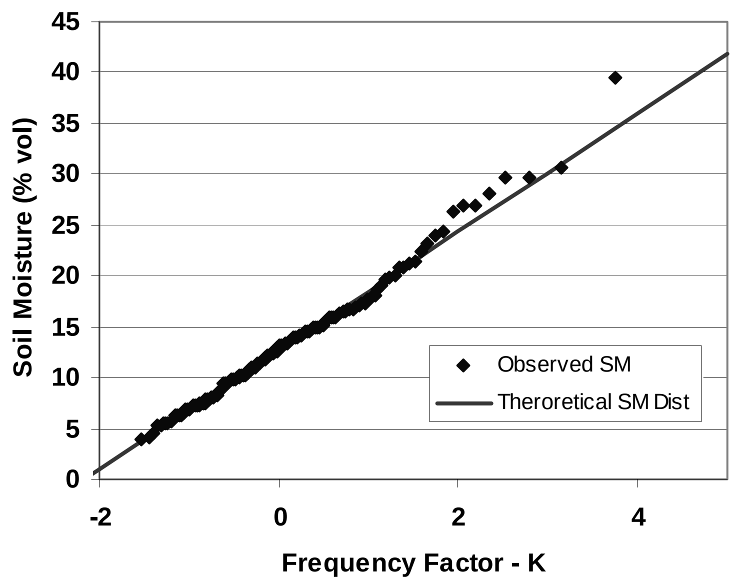

Figure 2: Forest soil moisture and theoretical lognormal distribution – 2000.

Snow Water Equivalent Characterization

Figures 5 to 7 are frequency diagrams of SWE observations from the forest, subalpine and alpine grids plotted as a lognormal distribution. Figures 5 to 7 depict a discrete stepped pattern as a result of the resolution of the snow sampling apparatus and technique for deriving SWE. Due to calibration limitations of the sampling tube and scale, the minimum measurement interval is 10 mm. Generally a close agreement between observed SWE and fitted theoretical curves, with r^2 values of 0.95, 0.91and 0.97 for the forest, subalpine and alpine ecosystems respectively, indicating that the lognormal probability density function can be used to describe the frequency distributions of SWE in these ecosystems.

The weakest agreement was achieved in the subalpine ecosystem, with a r^2 value of 0.91. On this plot the measurements were limited to two adjacent grid lines. These lines partially traversed a prominent ridge crest, which is sparsely vegetated and subject to high wind velocities and subsequent snow ablation. The disproportionate number of samples of smaller depth from the ridge crest resulted in the slightly poorer relationship.

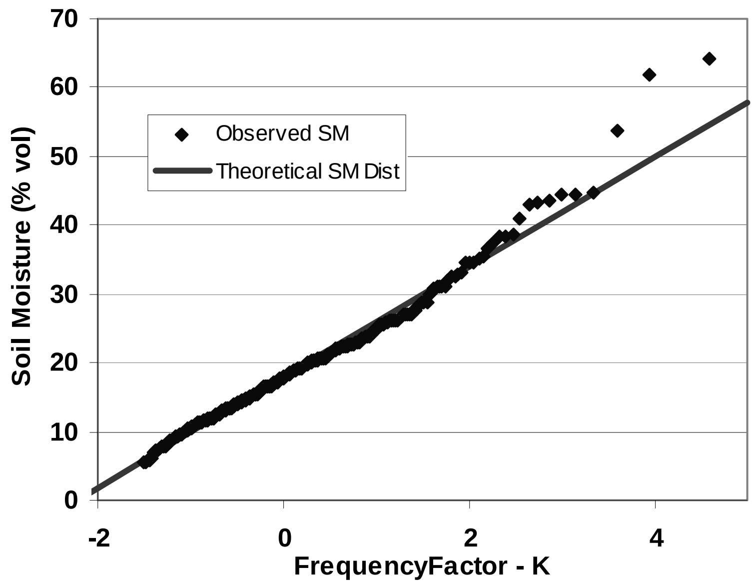

Figure 3: Subalpine soil moisture and theoretical lognormal distribution – 2000.

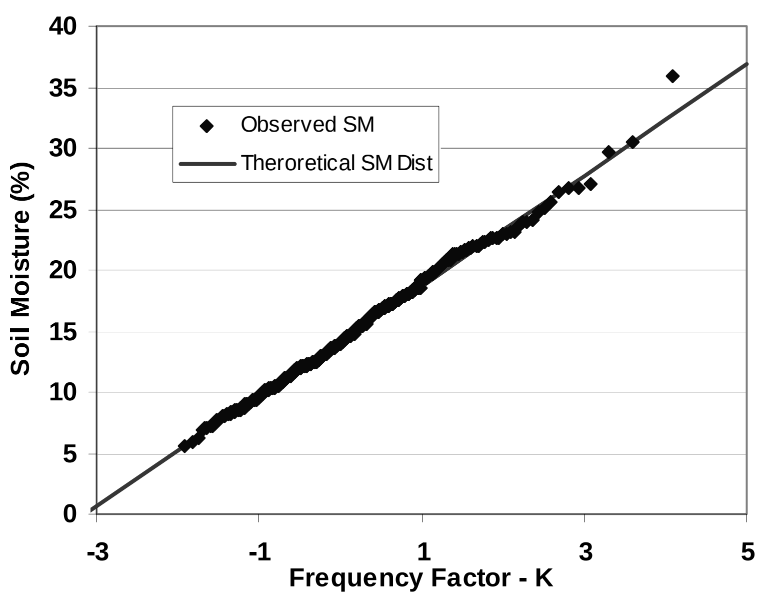

Figure 4: Alpine soil moisture and theoretical lognormal distribution – 2000.

As only 27% of the alpine plot was snow-covered, the results do not accurately reflect the spatial variability of snow over an alpine ecosystem. Values for the CV in forest, subalpine and alpine plots are 0.34, 0.91 and 0.79 respectively. This trend shows the ability of vegetation to reduce variability. The variability in SWE is much greater in the alpine than in forest and subalpine ecosystems because of lower vegetation biomass and higher wind speeds (Table 4).

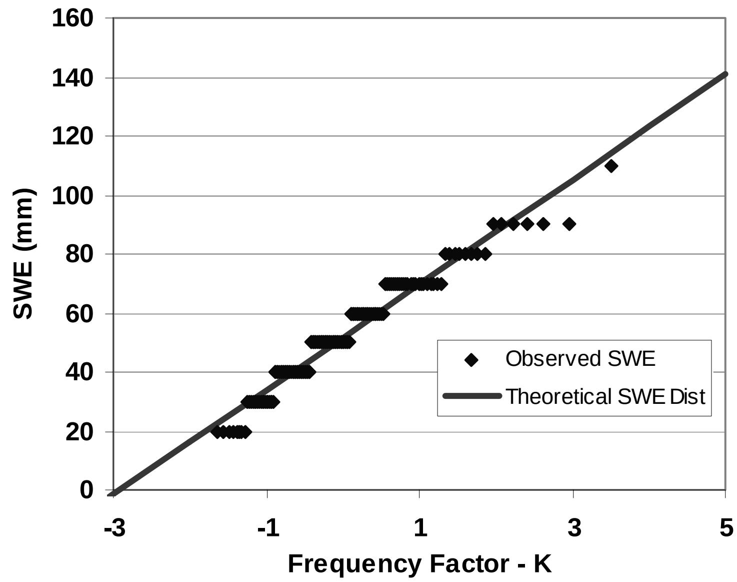

Figure 5: Forest SWE and theoretical lognormal distribution – 2001.

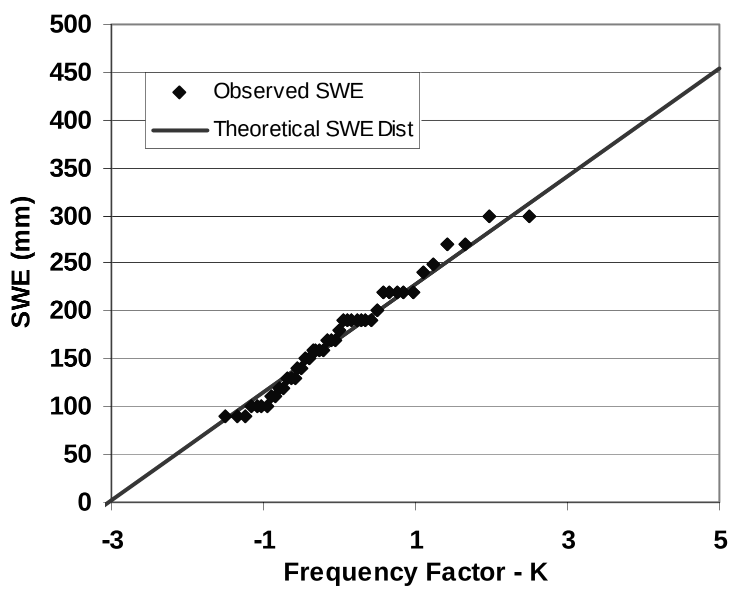

Figure 6: Subalpine SWE and theoretical lognormal distribution – 2001.

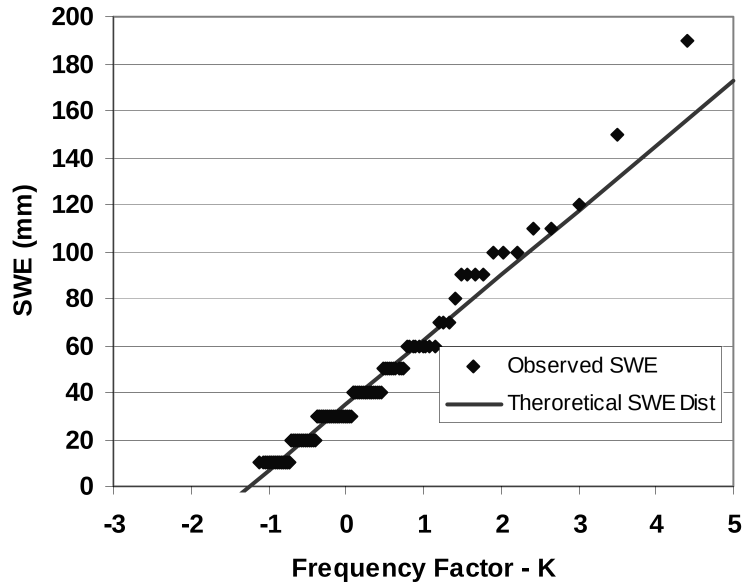

Figure 7: Alpine SWE and theoretical lognormal distribution – 2001.

SUMMARY AND CONCLUSIONS

The theoretical lognormal probability density function was fitted to the observed soil moisture and SWE data with good results. Values of r^2 for the soil moisture and SWE data ranged from 0.92 to 1.00 and 0.91 to 0.98 respectively. Values of CV for soil moisture in the forest, subalpine and alpine ecosystems were 0.41, 0.38 and 0.40 respectively. The consistency in values suggest that the spatial variability in soil water is relatively independent of the ecosystem at the scale of measurement. For SWE, CV values of 0.35, 0.40 and 0.73 in forest, subalpine and alpine ecosystems were calculated. The low values of the CV for forest and subalpine ecosystems, with considerable vegetation, compare to the higher value in the alpine ecosystem, with little vegetation, demonstrates the ability of vegetation to dampen variability.

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