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Use of a GIS to Develop a Stratified Snow Survey in A Mountainous Agricultural Landscape

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Abstract

A stratified snow survey was designed with the aid of a GIS and applied to the Cannonsville Reservoir Watershed (1177 km^2) which supplies drinking water to New York City, and is located in the Catskill Mountains of Eastern New York State. Snow accumulation in the watershed can show a large degree of annual and spatial variability. Within the watershed, the snow cover is affected by orographic effects and a mixed landscape of agricultural fields and forest. The watershed was divided based on three classes of physiographic variables: land use (forest and field), three elevation ranges, and four aspect ranges. During 1994, a 12 point peak snow survey was made within all of the combined categories that represented a greater than 5% portion of the watershed. Estimates of snow depth and snow water equivalent (SWE) were calculated by extrapolating the data, which were stratified by the above physiographic factors, over the area of the entire watershed. Land use and aspect were of primary importance in affecting properties of the snow cover. Forested areas had significantly greater depths and SWE compared to agricultural areas. These differences were most distinct for depth since snow density was significantly greater in agricultural areas, and this tended to reduce land use specific differences in SWE. The affect of aspect is apparently related to turbulent effects which influence levels of snow deposition. Significantly greater depths and SWE were found on eastern slopes which are leeward of the prevailing westerly winds.

Key words: Snow survey, GIS, snow sampling New York state.

Introduction

The New York City Department of Environmental Protection (NYC DEP) manages an extensive network of drinking water reservoirs located within the Catskill Mountain region of Eastern New York State (Fig 1).

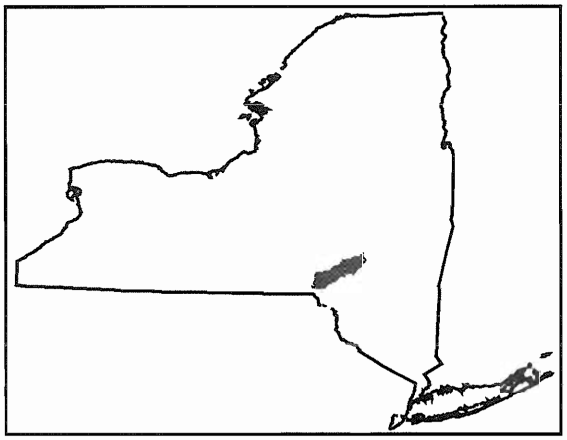

Figure 1. Cannonsville Reservoir Watershed is located in the southeastern part of New York State.

This region receives some of the highest levels of annual precipitation within the State (Lumia 1991) and can receive relatively large and variable amounts of snowfall. Based on 55 years of data collected at the National Climate Data Center Station in Delhi, N.Y. (Fig 2), we estimate that the peak snow pack water equivalent (SWE), varies from between 1.2% and 18% of the annual precipitation, which ranged between 750 mm - 1410 mm. The winter of 93-94 was one of unusually high snow accumulation for Catskill Mountain region. Measurements of snow on the ground at Delhi, NY suggest that the snow depth

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during this study was well above average, and would be exceeded only 13% of the time or approximately once every eight years. Estimates of SWE based on a 25 point snow course in the Cannonsville Watershed (Fig 2), are available from NYC DEP beginning in 1970. These data show that the SWE during the winter of 93-94 was greater than any previously measured, and suggest that the eight year return period based on peak snow depth at Delhi is probably a conservative estimate. In any case, it is clear that the winter of 93-94 had unusually high snow accumulation, and this was an important motivation for undertaking the research described here. Given the potential importance of snow as a source of water to the reservoirs, and the potential role that snow melt can play in influencing runoff and water quality, we investigated the potential to improve estimates of SWE based on a physiographically stratified sampling method that was designed using a GIS system developed by NYC DEP. The project was undertaken in the hope that this approach would provide a middle road between the extreme effort associated with large random samples (e.g. Adams 1976, Elder et al. 1991) and the limited 25 point snow course presently employed by NYC DEP.

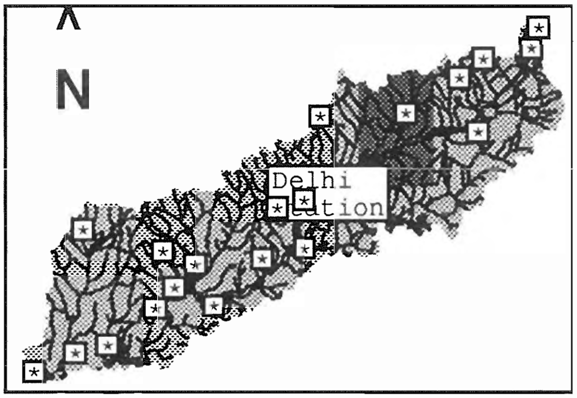

Figure 2. The location of Delhi Station, 25 point snow course (*), the Wright Brook area (darker shaded area) and the road system in Cannonsville Watershed.

Study Area

The Cannonsville watershed is a forested agricultural watershed, where approximately 30% of the watershed area is under agricultural land use. Almost all of the agricultural lands are dairy farms which on average are 16% cultivated for corn and 84% hay and pasture. Of the remaining 70% of the watershed roughly 2% is urbanised and the rest is forested. The West branch of the Delaware River flows from the eastern watershed divide (elevation 1019 m) to the west until entering the Cannonsville Reservoir (elevation 341 m). Tributaries enter the river from both north and south directions, and the morphometry of the basin is strongly influenced by the north - south running valleys associated with these tributaries (Fig 3-4). Slopes in the tributary valleys typically range between 5 - 20 degrees.

Methods

The Geographic Resources Analysis Support System (GRASS) GIS was used to identify sampling sites and later extrapolate our measurements over the watershed area. Snow sampling sites were chosen according to 3 criteria : land use, elevation, and aspect. The watershed was divided into three elevation ranges based on the distribution of elevations within the watershed, four aspect classes (+/- 15 degrees from N, S, E, and W) and the two predominate land use classes (agricultural fields and forest). We chose to sample a phyiographic class only if it represented at least 5% of the land area of the Cannonsville watershed. Of the 24 possible classes, 14 which in total represented 80% of the watershed area were actually sampled (Table 1). The final criteria for choosing a site was its proximity to a road, which was easily calculated using the GIS. For logistical purposes, most sampling was carried out within or in the vicinity of the Wright Brook Watershed (Fig. 2-3) This is a site of stream monitoring by NYC DEP, and due to co-operative programs we had greater access to the private lands in this area. At each site 12 samples were collected at approximately 15 m intervals along a straight line running in the direction of the aspect class and perpendicular to the predominate slope. Samples were collected, with a NYC DEP constructed snow sampler, that was 3 inches (7.62 cm) in diameter and had a nonserated cutting edge. While there is undoubtedly some bias associated with this sampler (Goodison et al. 1981), we used it to maintain consistency with past NYC DEP sampling. The samples were placed in plastic bags, and later weighed using an analytical laboratory scale.

Sampling was carried out during peak snow conditions on 8, 9 ,and 11 March 1994. Unfortunately, there was a significant rain storm on March 10. This storm was a mixture of rain and snow and the distribution of the precipitation was spatially variable. The climate stations in the area of our sampling reported total precipitation ranging between 12 mm and 31 mm. Some of this was snow, but a significant

Depth, Density and SWE are all Different at a Probability Level of 0.0001

Table 1 Snow Measurement Grouped by Sample Site

Site Code	Land use	Elev. Class	Slope Class	Aspect	No. of Sampls	Depth (mm)	CV Depth	Density (Kgm^{-3})	Density	SWE (mm)	CV SWE
ALF	Ag	Low	Low	Flat	12	360	0.13	374.0	0.12	136	0.21
ALN	Ag	Low	Med	N	12	449	0.19	286.8	0.16	128	0.22
AMW	Ag	Med	Med	W	12	345	0.36	319.1	0.17	107	0.35
AMS	Ag	Med	Low	S	12	339	0.30	286.9	0.14	96	0.30
AME	Ag	Med	Low	E	12	564	0.17	358.0	0.14	200	0.17
AHS	Ag	High	Low	S	12	432	0.24	360.1	0.20	152	0.22
AHE	Ag	High	Med	E	12	490	0.30	332.4	0.11	161	0.27
FLN	Forest	Low	High	N	12	581	0.10	285.5	0.07	166	0.10
FMW	Forest	Med	High	W	12	490	0.09	303.0	0.15	148	0.17
FMS	Forest	Med	Low	S	12	587	0.09	284.2	0.10	167	0.14
FME	Forest	Med	Low	E	12	533	0.10	312.2	0.07	166	0.11
FHW	Forest	High	High	W	12	550	0.10	283.6	0.11	156	0.14
FHS	Forest	High	Med	S	12	557	0.12	313.1	0.07	174	0.14
FHE	Forest	High	Med	E	12	760	0.08	203.7	0.26	156	0.29
Overall						503	0.27	307.3	0.19	151	0.26

Key Site Codes A= Agricultural F=Forest L M H = Low, Medium and High Elevation Classes
N S E W F = North, South, East, West and Flat Aspect Classes

Table 2 Snow Measurements Grouped by Physiographic Characteristics

Variable	Mean Elevatin	Mean Slope	No. of Samples	Depth (mm)	CV Depth	p>F Depth	Density (Kgm^{-3})	CV Density	p>F Density	SWE (mm)	CV SWE	p>F SWE
AG	599.9	9.7	84	425	0.30	0.0001	331.0	0.18	0.0001	140	0.33	0.0002
Forest	652.0	15.6	84	580	0.17		283.6	0.17		162	0.17	
East	659.1	10.1	48	587	0.24	0.0001	301.6	0.24	0.0004	171	0.23	0.0001
North	527.9	19.5	24	515	0.19		286.1	0.12		147	0.20	
South	687.8	11.8	60	493	0.25		305.6	0.17		149	0.25	
West	593.8	17.4	24	418	0.28		311.0	0.16		128	0.30	
Flat	444.0	3.9	12	360	0.13		374.0	0.12		136	0.21	

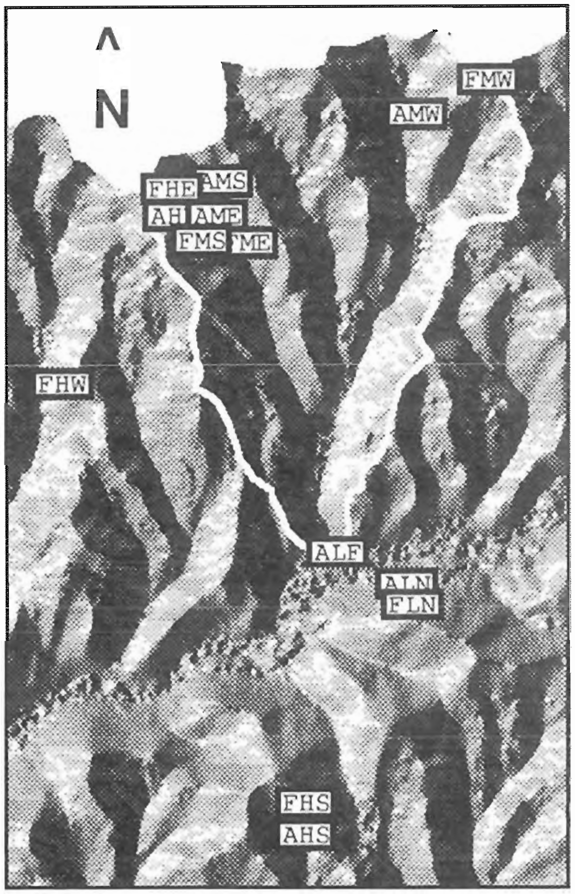

Figure 3. The location of the sampling sites in the Wright Brook Watershed area.

portion was rain. We re-sampled site AME (Table 1) on March 11 and found that neither the SWE, depth or density had changed significantly. The relatively small effect of the storm on the snow cover is possibly the result of: 1) the precipitation being relatively low in the general vicinity of Wright Brook; 2) the fact that stored SWE was much greater than the precipitation from the storm; and 3) the fact that a number of winter melt and rain events had already increased the density of the snow pack. The four sites sampled on March 11 were FHS, FMW, AHS and ALF (Table 1).

There are a number of possible methods of extrapolating snow measurements over the total area of a watershed (Trivett & Waterman 1980). Our sampling was limited to the vicinity of the Wright Brook Watershed and was not evenly spaced throughout the entire Cannonsville Watershed. This, while necessary for logistical reasons, limited us to extrapolating our measurements by physiographic categories with unique snow cover characteristics. These categories were identified by Analysis of Variance using the SAS statistical package. When a significant difference was found between 3 or more groups, the source of the difference was identified by a Duncans multiple range test (SAS 1987).

Stream discharge was calculated from continuous measurements of stage made at the outlet of Wright Brook, and a rating curve developed by the NYC DEP hydrology group. Snow melt occurred during March and April in conjunction with a number of large rain storms. Since stream discharges could not be clearly related to only snow melt, SWE in the Wright Brook basin was estimated as the difference between the rain inputs to the basin and the total runoff leaving the basin between 12 March and 30 April. There were no significant rain storms during the last two weeks of April.

Results and Discussion

Comparison of Data by Sample Site

ANOVA (Table 1) found highly significant differences in snow depth, density and SWE between the sites. The fact that clear differences do exist suggest that improved estimates of the snow cover can be obtained by stratified sampling. The Duncans grouping of the sites show a number of distinct groups. For both depth and SWE the forested sites tended to group separately from the agricultural sites, with greater values measured in the forested locations. East facing slopes also seemed to preferentially accumulate snow. While these comparisons suggest that stratified sampling by physiographic parameters is warranted, the relative importance of the different physiographic parameters is not resolved by the analysis. The data were therefore re-analysed by ANOVA after regrouping the data by single physiographic characteristics.

Effect of Land use

There is an obvious and unavoidable covariation among a number of the physiographic parameters associated with each sample site largely due to cultural influences. This was examined by a two step process. First a correlation analysis was used to examine the relationships between slope, elevation, and aspect. The results showed only weak relationships between slope and elevation ($r = -0.208$ $p < 0.01$), and aspect and elevation ($r = 0.207$ $p < 0.01$). No significant relationship was found between aspect and slope. Second, ANOVA was used to examine the

Table 3 Snow Measurements Grouped by Landuse and Aspect

Varialbe	Mean Elevatin	Mean Slope	No. of Samples	Deph (mm)	CV Depth	p>F Depth	Density (Kgm3)	CV Density	p>F Density	SWE (mm)	CV SWE	p>F SWE
Agricultural												
East	675.5	9.1	24	527	0.24	0.0001	345.2	0.13	0.0022	180	0.24	0.0001
North	500.0	16.2	12	449	0.19		286.8	0.16		128	0.22	
South	659.6	8.0	24	385	0.29		323.5	0.21		124	0.34	
West	584.5	13.6	12	345	0.36		319.1	0.17		107	0.35	
Flat	444.3	3.9	12	360	0.13		374.0	0.12		136	0.21	
Forest												
East	642.7	11.1	24	647	0.20	0.0001	257.9	0.26	0.0122	161	0.21	NSD
North	555.8	22.8	12	581	0.10		285.5	0.07		166	0.10	
South	706.5	14.4	36	565	0.10		293.6	0.10		166	0.14	
West	603.2	21.3	12	490	0.09		303.0	0.15		148	0.17	

Table 4 Physiographic Groupings Used to Estimate Basin Wide Snow Depth and SWE

Parameter	Physiographic Group	No. of Samples	Mean (mm)	CV	Percent Area Wright Brook	Percent Area Cannonsville
Depth	AG - East	24	527	0.24	11.22	8.06
	AG - N & S	36	406	0.26	10.85	15.09
	AG - Flat & W	24	352	0.26	17.21	10.52
	Forest - East	24	647	0.20	27.90	17.88
	Forest - N & S	48	569	0.10	16.05	26.88
	Forest - West	12	490	0.09	15.77	18.56
SWE	AG - East	24	180	0.24	11.22	8.06
	All Other AG	60	124	0.30	28.06	25.62
	All Forest	84	162	0.17	59.71	63.32
Final Results					Wright Brook(mm)	Cannonsville (mm)
	Area Weighted Depth				518	516
	Area Weighted SWE				153	153
	SWE Estimated from Wright Brook Discharge				162	N/A
	SWE Estimated from DEP 25 Point Snow Course				N/A	141

physiographic differences between the two classes of land use. ANOVA showed highly significant differences in slope and elevation between land use catagories ($P < 0.0001$ in both cases) with agricultural lands having lower average elevations and slopes (Table 2). We conclude from these analyses that the major cause for covariation among the physiographic parameters is due to the fact that agricultural lands tend to be developed at lower slopes and elevations. There does not appear to be a strong correlation between slope and elevation purely due to geomorphologic effects. The effect of land use on the snow cover is therefore, a result of both direct influences due to differences in vegetation and indirect effects related to the covariation of elevation and slope with land use.

There was a highly significant difference in all snow cover parameters between the two land use categories that dominate in the Cannonsville Watershed. Greater snow depth and greater SWE were found in the forested area of the basin. The affect on depth was most pronounced with 36% deeper depths in the forested areas. SWE was greater in the forested area, but by only 16%, since snow density was significantly greater in the agricultural areas. These differences in the snow cover of forested and agricultural areas results from three factors. First, increased sublimation and melt in the open areas due to greater levels of solar radiation striking the snow cover (Elder et al. 1991), and possibly greater winds which increase sublimation by snow movement and snow pack ventilation (McKay & Gray 1981). Second, wind mediated transport of the snow from the fields to adjacent forested areas. The role of wind transport and drifting is suggested by the greater snow cover variability (CV values Table 2) in the open agricultural areas. Third, a greater elevation of the forested sites would also be expected to increase snow depth and SWE.

Effect of Aspect

Significant differences in all snow cover parameters were also found between aspect classes (Table 2). However, the Duncan test shows the difference in density to be entirely the result of greater densities in the flat aspect class (site ALF n=12) The other four aspects classes group together, and therefore density showed little variation with aspect. Differences in snow depth were the result of greater depths on the eastern slopes and lower depths on the western slopes. Three significantly different groupings were obtained from the Duncan test: E, N & S, and W & flat. SWE is ranked in a similar manner, but the Duncan test showed only the eastern aspect to be a separate and distinct group.

The affect of aspect on snow cover parameters is commonly attributed to differences in incident solar radiation, with greater densities and lower SWE on southern slopes (Elder et al. 1991, Troendle et al. 1993). This effect was not apparent here, although it obviously must have occurred to some extent. We hypothesise that the greater snow accumulation on eastern slopes and the lower accumulations on western slopes is the result of turbulence associated with the prevailing winds. Wind measurements are sparse in the area of the snow sampling; however, daily wind observations (measured once a day over a several minute period) were available from the State University of New York at Oneonta (25 km NW of Wright Brook). Vector averaging of these data over the snow accumulation period (Dec - Mar) results in an average wind speed of 1.2 m s^{-1} blowing from 292 degrees. The standard deviation of the wind direction was only 87 degrees showing that winds did not deviate greatly from the prevailing direction. These prevailing westerly winds apparently resulted in greater snow deposition on the eastern downwind slopes which are common in the watershed due to the north - south orientation of the tributary valleys (Figs 3 and 4).

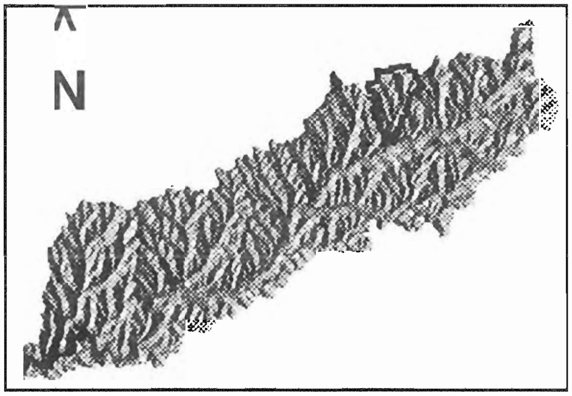

Figure 4. Aspect map of Cannonsville Watershed.

Final Classification by Physiographic Factors.

The results of the above analyses suggest that land use and aspect were the two major factors that influenced the snow cover in this study. In order to derive a classification scheme based on these factors two sets of ANOVA analyses were performed. The data were first sorted by land use, the factor felt to be

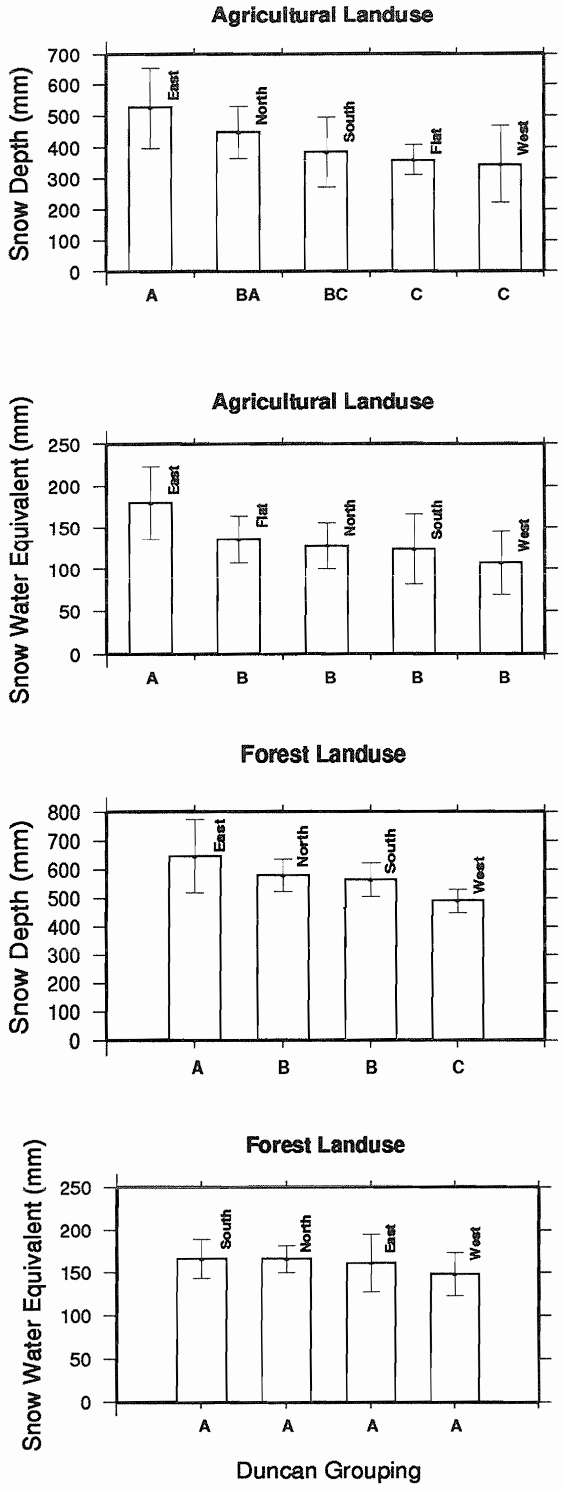

Figure 5. Results of landuse specific ANOVAS which used aspect as the independent variable. The final physiographic classification (Table 4) is based on the Duncan groupings shown here.

of primary importance, and then ANOVA was performed separately on the data from each land use using aspect class as the independent variable. The results of these analyses are given in Table 3, and the Duncan groupings are shown in Fig 5. Based on Fig 5, six physiographic classes were derived for snow depth and three physiographic classes were derived for SWE (Table 4). The reduced resolution of the SWE classification is the result of a weak inverse relationship between snow density and depth (Fig 6).

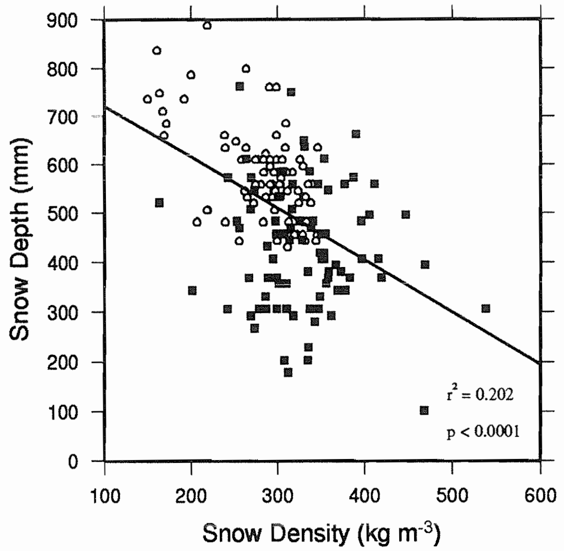

Figure 6. Regression of snow depth vs snow density; solid squares are samples from agricultural sites open circles symbols are samples from forested sites.

Areas of lower depth had higher densities, indicating that a portion of the differences in depth were due to snow pack metamorphosis, rather than snow deposition.

Basin Wide Estimates of Snow Depth and SWE

The spatial distributions of the estimated snow depths and SWE based on the classification in Table 4 are shown in Fig 7 and 8. The snow distribution largely reflects the distribution of land use within the watershed. In general, lower SWE values are found in the agricultural fields which are adjacent to most of the perennial streams in the watershed. The effect of aspect is most clearly seen by the greater SWE values on eastern agricultural slopes. While eastern

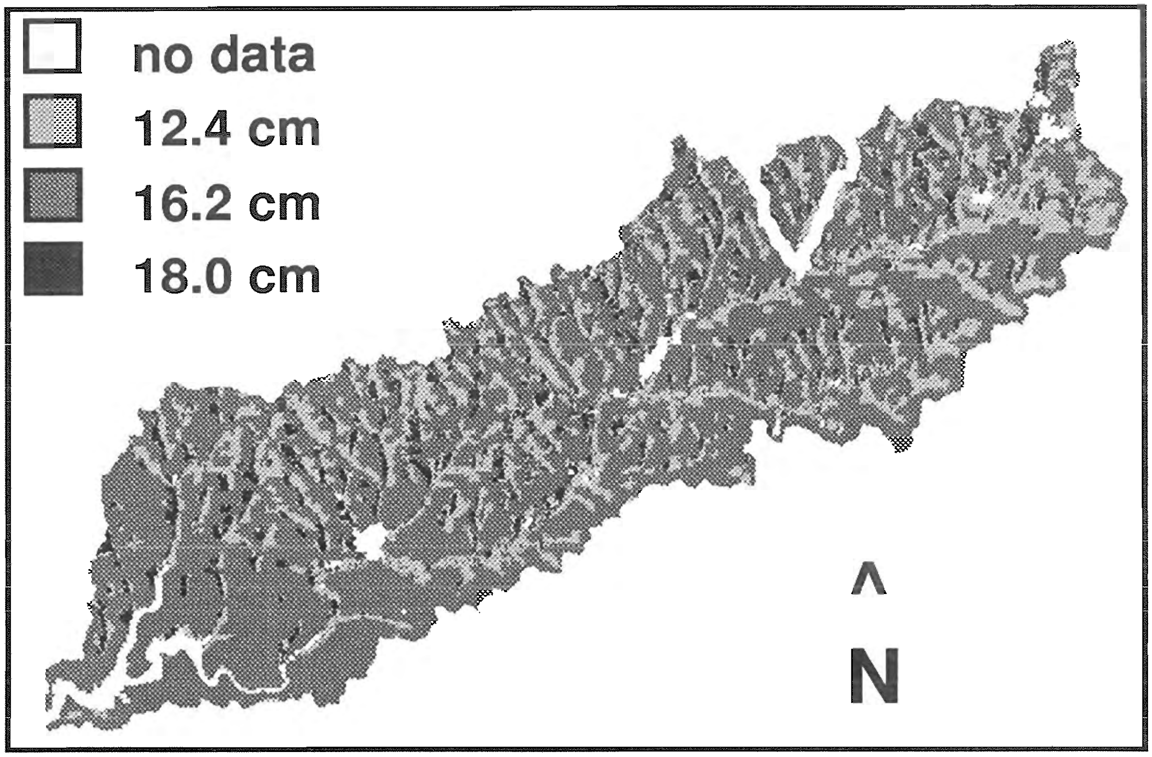

Figure 7. Calculated spatial distribution of SWE for the Cannonsville Watershed.

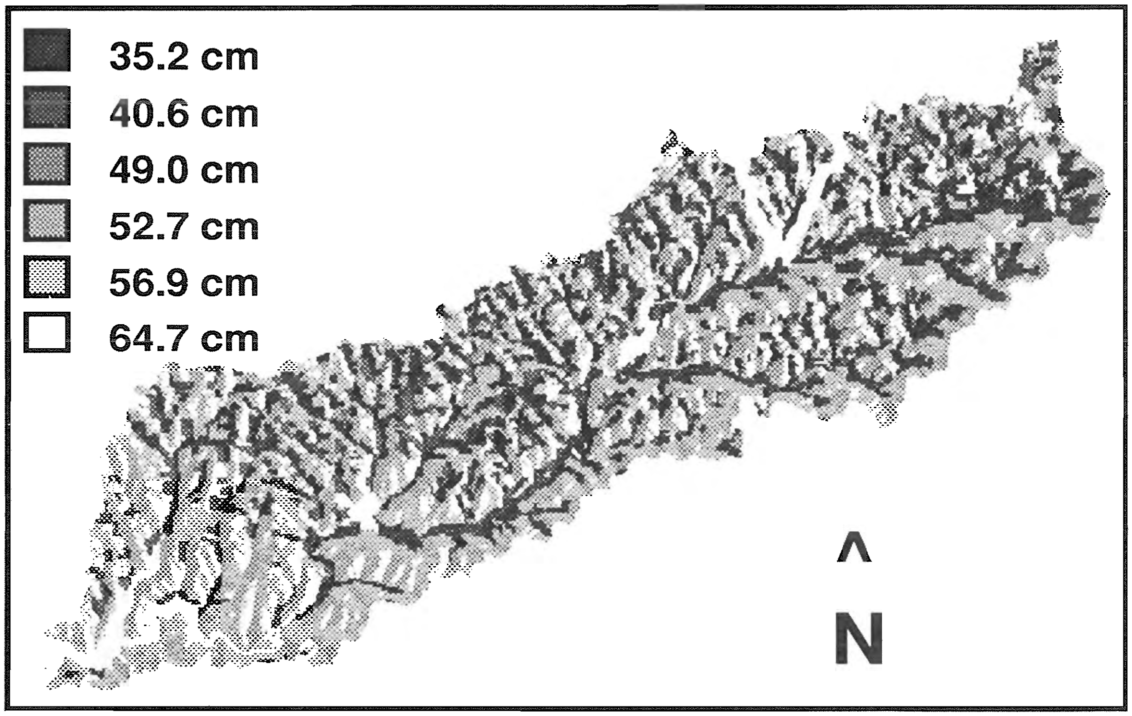

Figure 8. Calculated spatial distribution of snow depth for the Cannonsville Watershed.

agricultural slopes only account for 8% of the Cannonsville Watershed (Table 4), agricultural areas can potentially contribute greater nutrient inputs to the nearby streams. The map of snow depth is more complex than SWE due to the greater number of depth classes (Table 4), The overall pattern is however, similar to that of SWE.

In Table 4 the final Basin wide estimates of Snow depth and SWE are given for both the Cannonsville and Wright Brook Watersheds. The values of these two parameters were essentially the same for both watersheds, which suggests that the snow cover of Wright Brook is representative of the Cannonsville Watershed as a whole. An independent estimate of the SWE of Wright Brook was obtained from stream discharge measurements (Table 4). This value is only 6% greater than our estimate and therefore confirms the accuracy of the methods described here. The comparison with the standard DEP based estimate of Cannonsville SWE was also favourable. The DEP estimate was 8% lower than the GIS calculated estimate, probably as a result of an over-sampling of open areas by the 25 point snow course. The 12.2 mm difference is of minor significance considering that the total precipitation input to the basin during the 93-94 hydrologic year was approximately 1250 mm.

Conclusions

It appears that under the climatic conditions of this region two factors act to influence the spatial variability of deep snow packs. On the one hand, deep snow packs tend to retain a certain degree of spatial variability, since a large accumulated SWE can buffer the short term effects of melt and rain, and this tends to maintain spatial differences that may be related to physiographic parameters such as land use. On the other hand, for deep snow packs melt and rain will be more likely to increases snow pack densities to greater and more spatially uniform levels, and decrease the spatial variability of depth.

The data presented here suggest that both of the above mechanisms influenced the spatial variability of the measured snow pack. The coefficients of variation associated with our sampling sites (Table 1) are much less than those found by Adams (1976) in a similar climatic region, but for a much shallower snow pack. Furthermore, both Adams (1976) data and NYC DEP's long term snow course data show an inverse relationship between the magnitude of SWE and the variability in this parameter. Thus, evidence exists which suggests that deep snow packs, including the one in this study, are spatially less variable. At the same time, even though climate effects apparently reduced the spatial variability of the snow cover, there were distinct and statistically significant differences in the snow cover which could be related to different physiographic parameters.

This investigation was a pilot study to test the possibilities of developing an improved snow sampling method, and to obtain measurements of the snowcover during a year with unusually large snow accumulation. The study was conceived during the winter as the importance of the snow cover became clear, and there are obviously a number of limitations associated with it. The greatest limitation is the fact that, as a pilot study, it was carried out during only one winter. It is not possible to generalise these results to other years with different levels of snow accumulation and different climatic histories. The results do, however, illustrate a method of designing a stratified snow sample with the aid of a GIS. Furthermore, the results show that differences in snow cover can be related to physiography, and that these methods are worth pursuing. We predict that the value of the sampling strategy we employed will increase when snow accumulation is less and the spatial variability of the snow cover would be greater. A major factor affecting snow accumulation in the Cannonsville Watershed is land use, and the snow cover is more variable in agricultural areas. This suggests that in the future a greater emphasis should be placed on sampling the agricultural areas, particularly in regard to the relationship between aspect and the direction of the prevailing winds. Our results confirm the observations of others (Dickinson & Whiteley 1972) that snow depth is more variable than snow density, particularly when sampling is stratified by land use. This suggests that increasing measurements of depth relative to density would improve the speed and ease of sampling and allow more sites to be sampled and a more detailed coverage of the physiographic classes to be obtained.

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