DETERMINATION OF SNOW DEPTH AND WATER EQUIVALENT BY REMOTE SENSING

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ABSTRACT

This exploratory study was designed to investigate the possibilities of using inexpensive aerial remote sensing methods to measure the snowpack and its water content.

The relation of snow depth and elevation on the same aspect (north or south) was definitely linear but the slopes of the regression lines varied between months and between years. Thus no uniform prediction was possible of snow depth over an entire watershed from a single measurement at one point. Example: The regression equation for March 4, 1972 on the north aspect was $Y_{SNOW\ DEPTH(dm)} = -24.5 + (1.10 \pm 0.51)X_{ELEV(100m)}$. Snow depth and water equivalent were consistently related to melt date, sometimes quite strongly. The addition of vegetation density to the equation significantly increased the proportion of variability of snow depth which is accounted for. Little strength was added by including the other environmental factors, - aspect, elevation, and slope degree. However, elevation was more strongly related to snow depth early in the spring and aspect was more strongly related later. Prediction of water equivalent was improved by including degree of slope early in the season, and by including aspect and then slope later in the season. An example of multiple regression equation with a multiple R^2 of 0.81 is $Y_{SNMAR} = -14.0 + 0.081X_{MELTDA} + 0.095X_{VEGDEN} + 0.004X_{ELEV} - 0.021X_{FROMN} - 0.053X_{SLOPE}$ where subscripts mean SNow depth (dm) in MARch, MELT DAte (year-day), VEGetation DENsity (100-foot candles), ELEVation (meters), azimuth FROM due North less than 180^{o} (degrees), and degree of SLOPE (Percent). Therefore by measuring the melt date and environmental variables one could predict snow depth and water equivalent, once these equations were established for a given area. Melt date can be measured by observation from two aerial flights at three-day intervals in early spring.

The relationship between the elevation of the snow-melt line and time was determined to be linear for each of the three years observed. The average slope of the linear regression was 19.64 meters per day (0.82 meters per hour) during the snow melt period. This rate of recedence was consistent during the three-year period of observation. The variation in date over the three-year period for the snow-melt line to be at a given elevation, was approximately equivalent to the time period for the snow-melt line to raise 600 meters.

The photogrammetric determination of snow depths over the area was restricted by the limited number of ground control targets. The measurement and computational procedures for the photographic imagery were adequate for the intended purpose. The determination of the location of additional visible ground control in the available photography would permit more definitive results.

The point measurement of the elevation of snow fields can be accomplished if there are sufficient shadows due to vegetation or image texture due to dirt or surface irregularities.

Our conclusion is that determination of snow depth and water equivalent by remote sensing from aircraft is possible. We have uncovered the basic principles but further work is needed to develop the method.

INTRODUCTION

Prediction of spring runoff of water from Colorado mountains increases in importance each year as human populations grow and the demand for food and energy accelerates. Present methods of prediction have been reasonably satisfactory, but they are expensive and they sample only very small portions of the mountain snowpack. The recent rapid development of the technology of remote sensing from aircraft offers new possibilities for more rapid and efficient measurement of the snowpack over large areas. The combination of these two thoughts led to the questions which became the objective of this study. First, how precisely can snowdepth and water equivalent be estimated from snow cover and snow melt pattern as detected from the air in a mountain watershed? And second, how feasible is the photogrammetric determination of snow depth. The first named author of this report investigated the first question, and the second author investigated the second.

The study area was a portion of Missionary RIdge 20 miles northwest of Durango, Colorado. Elevations range from 2300 m to 3500 m. Vegetative types grade from oakbrush (*Quercus gambellii*) and aspen (*Populus tremuloides*) at lower elevations to Thurber fescue (*Festuca thurberi*) and spruce-fir (*Picea engelmannii*-*Abies lasiocarpa*) at the higher ones. Degree of slope varies from level to as much as 80 percent. This site was chosen because of the amount of basic climatic and ecologic data already available there from the San Juan Ecology Project. Field data were produced during the summers and following winters of 1972, 1973, and 1974. Original plans to duplicate this procedure at Wolf Creek Pass were changed because a related cooperating research project was unable to provide ground data there.

DETERMINATION OF SNOW DEPTH FROM SNOW MELT PATTERNS

METHODS

Thirty-one snow stake sites were established with characteristics indicated in Table 1. Two sites were chosen to represent each of four elevation levels, each vegetative type, and the two major aspects, north and south. The stakes were nominal 2 x 2 lumber, 1.2 or 2.4 m long, painted with alternating yellow and blue bands 1 decimeter wide. They were installed with either five stakes in a cross pattern 10 m square, or nine stakes arranged equidistant to the corners, side,and center of a 10 m square.

Sites were visited on approximately the first of each month. Snow depth of each stake was recorded to the nearest decimeter. During the spring melt period more frequent visits were necessary to observe the melt date, i.e., the date on which the site was completely clear of snow. Water equivalent was measured at each site on approximately March 1 and April 1 by the use of snow-tubes.

RESULTS

Rationale

If depth of snow is related to elevation in some predictable way, and if depth and water equivalent of the snow pack at several points in certain key vegetative types is predictable from the melt date, then the snow pack and water equivalent of an entire watershed can be predicted by measuring melt date. Melt date over a large area can be observed very quickly from the air, by carefully timed flights two or three days apart. To test this system and to devise a specific method if it were valid, we subjected the snow-stake data to a series of analyses, as follows.

Table 1. Location and characteristics of snow stakes on Missionary Ridge.

Location	Site Code 1/	Elevation (meters)	Aspect (degree)	Slope (percent)	Vegetative Type	Vegetative Density (100 ft. candles)	No. of Stakes
Top Park (TP)	5-SU-S-1	3500	215	35	Spruce	10	9
TP	5-SU-S-2	3500	200	32	Spruce	8	5
TP	5-F-S-2	3500	195	22	Fescue	40	5
TP	5-SC-N-2	3490	0	80	Spruce-cut	35	5
TP	5-SU-N-2	3475	290	36	Spruce	10	5
Between Top Park & Little Bear Park (TP & LBP)	2-SU-N-1	3315	335	42	Spruce	10	5
Big Bear Ridge (BBR)	5-F-S-1	3270	190	10	Fescue	10	5
BBR	5-F-N-S	3265	340	14	Fescue	40	1
BBR	5-SU-N-1	3260	295	53	Spruce	5	5
BBR	5-SC-N-1	3245	305	30	Spruce-cut	40	5
BBR	5-A-S-1	3225	155	44	Aspen	15	5
Little Bear Park (LBP)	2-SU-S-1	3210	230	23	Spruce	8	9
LBP	2-SC-N-1	3195	300	24	Spruce-cut	35	5
LBP	2-F-N-S	3180	280	18	Fescue	40	1
LBP	2-A-S-1	3160	195	28	Aspen	20	9
LBP	2-F-S-S	3140	175	19	Fescue	40	1
LBP	2-F-N-1	3135	310	27	Fescue	30	5
LBP	2-F-S-1	3135	180	31	Fescue	40	5
Between LBP and Elk Spur LBP& ES	2-A-S-2	3170	190	53	Aspen	20	5
LBP & ES	2-SC-N-2	3170	5	25	Spruce-cut	40	5
LBP & ES	2-SU-N-2	3165	340	51	Spruce	10	5
LBP & ES	2-SU-S-2	3150	235	51	Spruce	5	5
Elk Spur (ES)	2-F-S-2	3145	240	22	Fescue	40	5
Middle Fork, Coon Creek (MFCC)	9-A-S-1	2895	160	10	Aspen	20	9
MFCC	9-O-S-1	2865	155	28	Oak	30	5
MFCC	9-F-N-S	2830	325	55	Fescue	30	1
MFCC	9-F-S-S	2830	180	33	Fescue	40	1
Pretty Creek	6-A-N	2610	350	30	Aspen	30	5
Switchbacks	6-O-N	2465	295	24	Oak	30	5
Switchbacks	4-O-N	2310	325	55	Oak	30	5
Switchbacks	4-O-S	2310	155	22	Oak	30	5

1/ First symbol, approximate elevation 3500, 3200, 2900, 2600 or 2400 m.
Second symbol, vegetative type.
Third symbol, aspect. North or South.
Fourth symbol, replication. Number 1 or 2.

Data Analysis

- Relationships of snow depth to elevation. Snow depth data in relation to elevation were analyzed separately for north and south aspects. Through experimentation with a series of computer programs it was found that of all regression equations attempted, the straight-line equation $Y = b_o + b_1X$ fit the data best. The north aspect stations in 1972 gave the most uniform slope of regression lines throughout the year (Figure 1) and the south aspect stations in 1973 gave the most heterogeneous slopes (Figure 2). The simplest and most accurate prediction for all years and months would result if the slopes of the linear regression of snow depth on elevation were the same all through the winter in all years. However, Figure 3 shows this is not the case. Slopes of regression varied as much as from 0.03 in January 1974 to 3.00 in late April 1973. Considerable variation both throughout the winter and between years is evident in Figure 3. Thus no general prediction equation is possible. Nevertheless the strong linearity of the depth-elevation relationship means that if two points can be measured on the curve, prediction still may be possible.

- Indirect measurement of snow depth and water equivalent. If snow depth can be measured photogrammetrically, then the depths over an entire watershed can be reconstructed. The question of whether or not this can be done is discussed later in this report. But another possibility exists for estimating snow depth and water equivalent, through their relationship to melt date. Snow station data were subjected to stepwise multiple regression analysis and the results are shown in Table 2. Snow depth and water equivalent are consistently related to melt date, sometimes quite strongly. The addition of vegetation density to the equation significantly increases the proportion of variability of snow depth which is accounted for, as shown by the multiple R^2. Little strength is added by including the other environmental factors. Note in Table 2 that elevation is more strongly related to snow depth early in the season and aspect is more strongly related later. This corresponds well with general observations in the field.

Prediction of water equivalent was improved by including degree of slope early in the season and by including aspect and then slope later in the season. Water equivalent can be predicted more accurately and more easily late in the spring.

By measuring the melt date and environmental variables one could predict snow depth and water equivalent, then, once these equations were established for a given area. Melt date can be measured by observation from two aerial flights at two or three-day intervals. The environmental variables are fixed ones such as elevation, aspect, and slope so they need be measured only once for the area.

Potential prediction system

Predictions are most useful if they can be made no later than May 1. Melt dates at the lower elevations (2400 to 2900 m) of the study area varied from February 5 (year day 36) to May 19 (year day 139). At intermediate elevations (3200 m) they varied from April 1 (year day 91) to July 4 (year day 184). Thus measurements of melt date must be made only at lower to intermediate elevations in most years, and perhaps only at lower elevations in heavy snow years,in order to be most practical. This restricts even the two-point prediction basis for the depth-elevation curve, because the two points should really be measured at the extremes of the elevational range.

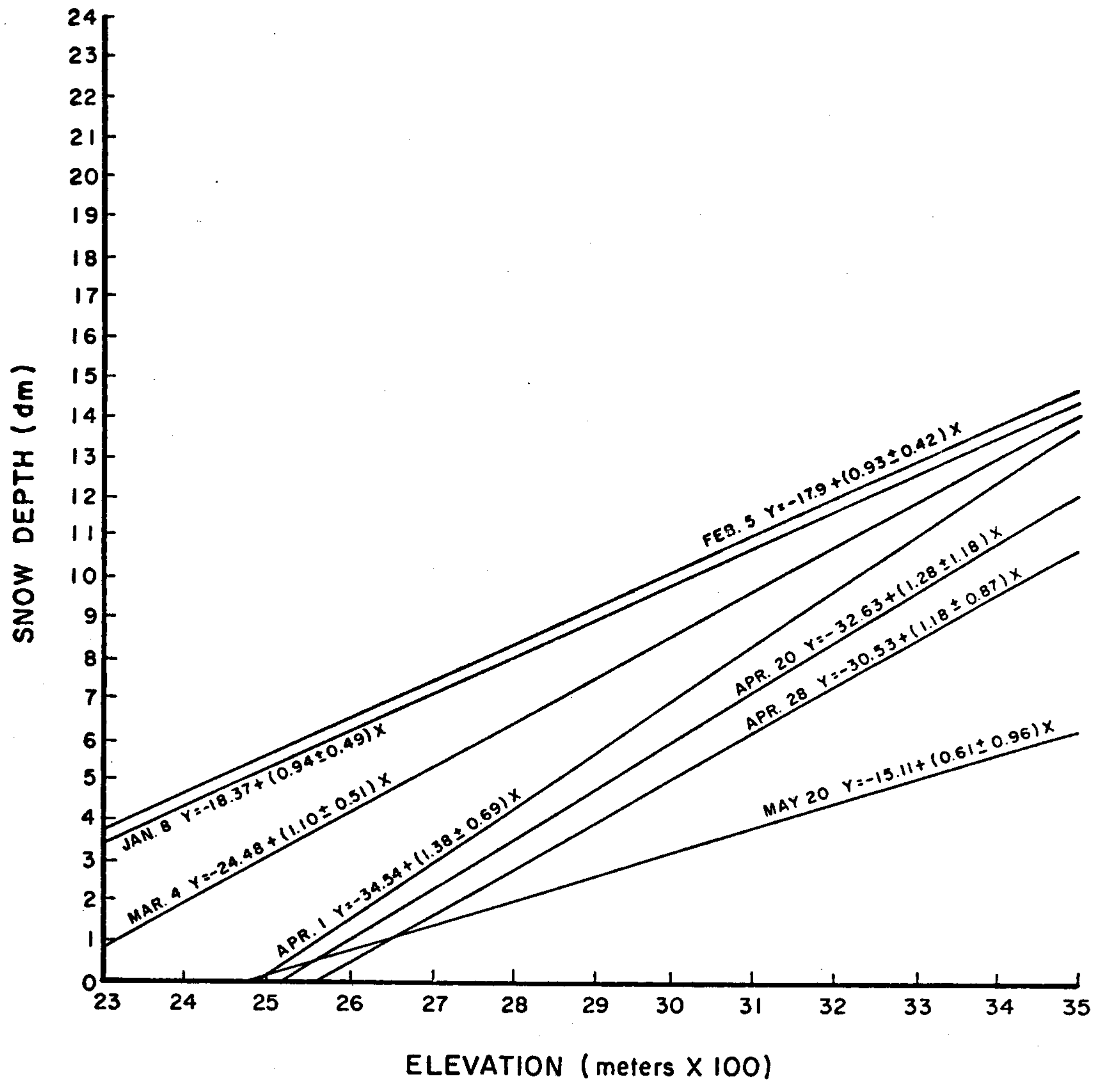

Figure 1. Regression lines for snow depth vs. elevation for north station group, 1972.

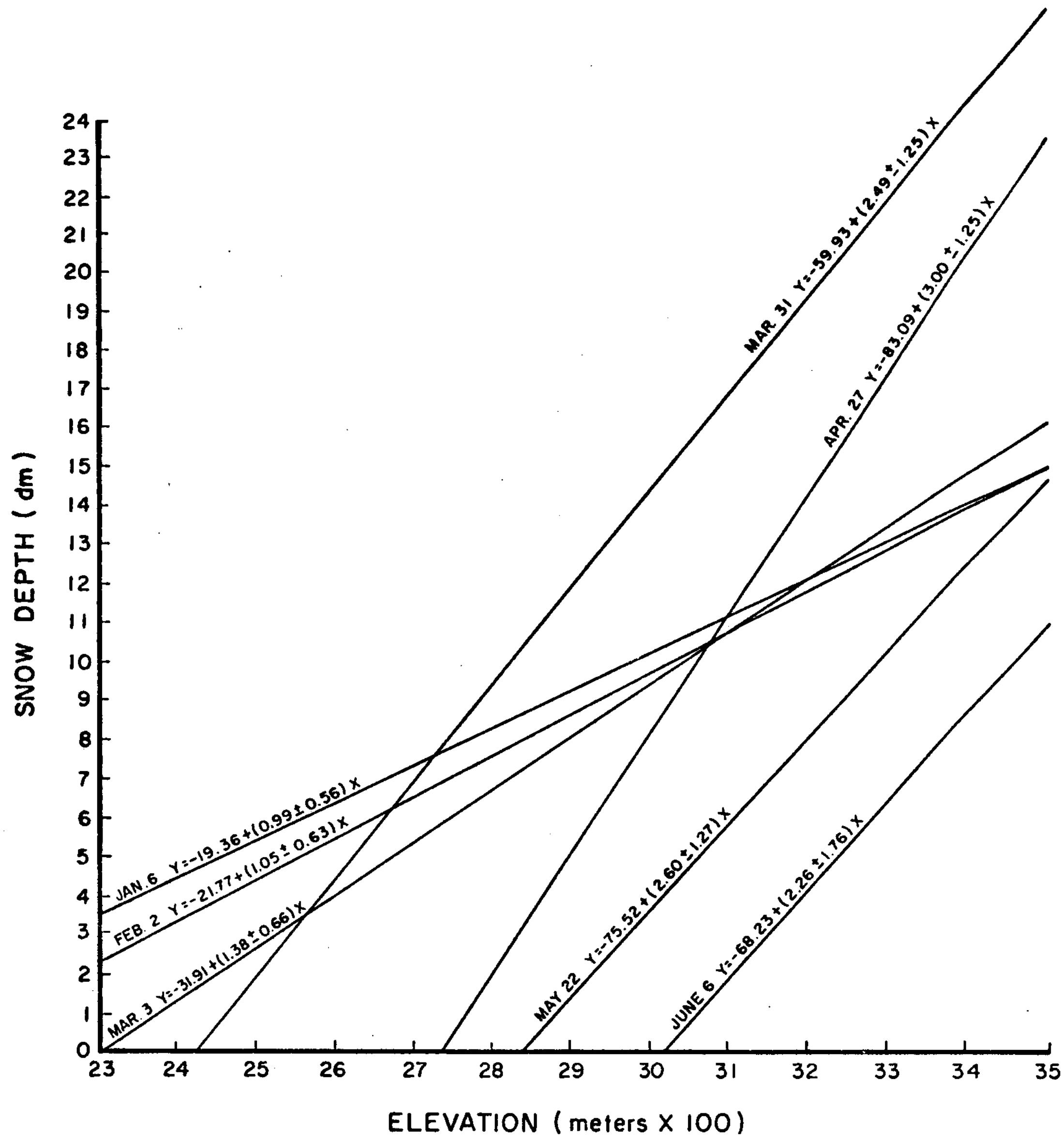

Figure 2. Regression lines for snow depth vs. elevation for south station group, 1973.

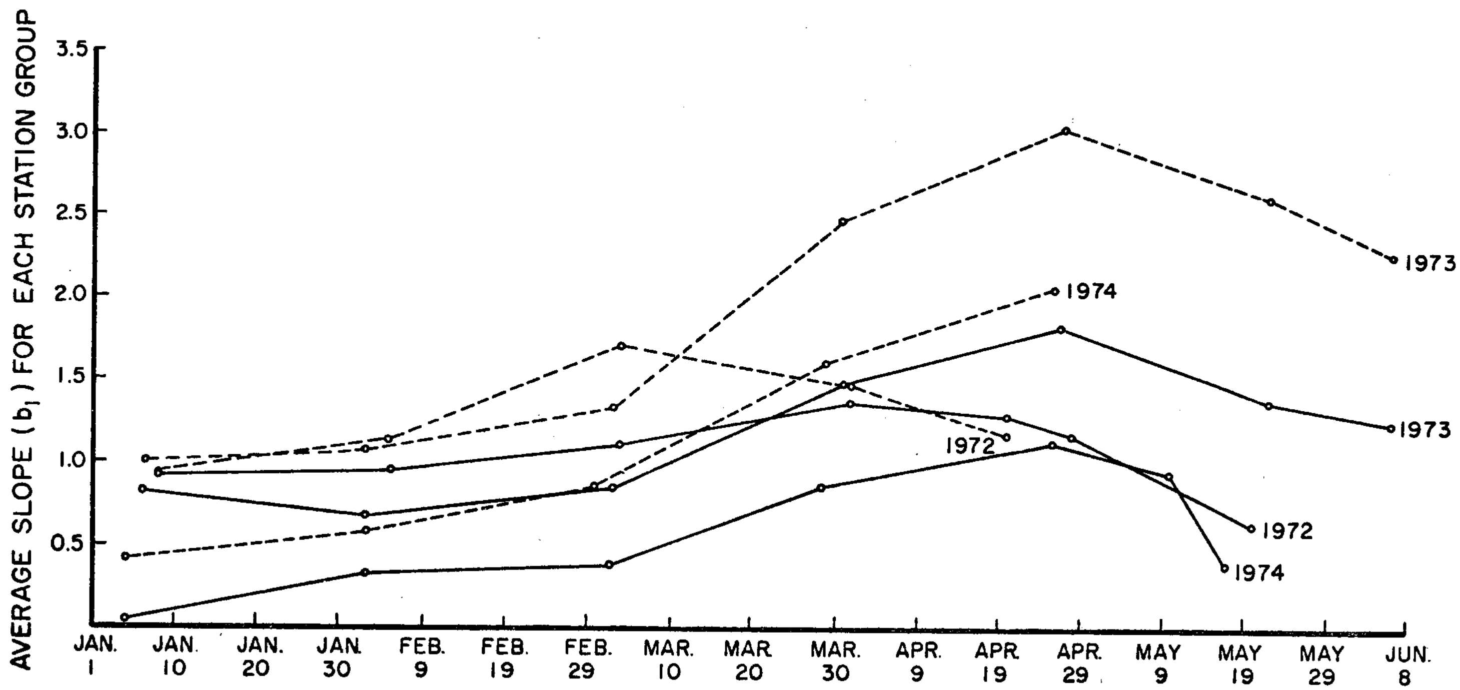

Figure 3. Average slope of regressions for each station group vs. time for each time measurements were taken each year. Solid line indicates north station group, broken line indicates south station group.

Table 2. Relationship of snow depth and water equivalent to melt date and environmental variables.

		Mult R^2
Y_{SNMAR}	$= -5.4 + 0.105X_{MELTDA}$	0.64
	$= -8.7 + 0.109X_{MELTDA} + 0.108X_{VEGDEN}$	0.73
	$= -16.1 + 0.095X_{MELTDA} + 0.117X_{VEGDEN} + 0.003X_{ELEV}$	0.75
	$= -16.0 + 0.085X_{MELTDA} + 0.113X_{VEGDEN} + 0.004X_{ELEV} - 0.015X_{FROMN}$	0.79
	$= -14.0 + 0.081X_{MELTDA} + 0.095X_{VEGDEN} + 0.004X_{ELEV} - 0.021X_{FROMN} - 0.053X_{SLOPE}$	0.81
Y_{SNAPR}	$= -11.5 + 0.147X_{MELTDA}$	0.62
	$= -15.3 + 0.152X_{MELTDA} + 0.22X_{VEGDEN}$	0.68
	$= -14.2 + 0.149X_{MELTDA} + 0.120X_{VEGDEN} - 0.006X_{FROMN}$	0.69
	$= -11.7 + 0.148X_{MELTDA} + 0.104X_{VEGDEN} - 0.011X_{FROMN} - 0.045X_{SLOPE}$	0.70
	$= -13.6 + 0.143X_{MELTDA} + 0.106X_{VEGDEN} - 0.011X_{FROMN} - 0.048X_{SLOPE} + 0.001X_{ELEV}$	0.70
Y_{SNMAY}	$= -13.6 + 0.151X_{MELTDA}$	0.63
	$= -16.0 + 0.155X_{MELTDA} + 0.075X_{VEGDEN}$	0.65
	$= -14.2 + 0.151X_{MELTDA} + 0.069X_{VEGDEN} - 0.010X_{FROMN}$	0.66
	$= -19.2 + 0.140X_{MELTDA} + 0.075X_{VEGDEN} - 0.012X_{FROMN} + 0.002X_{ELEV}$	0.67
Y_{WTRMAR}	$= - 3.9 + 0.095X_{MELTDA}$	0.39
	$= - 1.7 + 0.105X_{MELTDA} - 0.125X_{SLOPE}$	0.54
	$= - 6.1 + 0.116X_{MELTDA} - 0.106X_{SLOPE} + 0.102X_{VEGDEN}$	0.63
	$= -10.6 + 0.098X_{MELTDA} - 0.098X_{SLOPE} + 0.105X_{VEGDEN} + 0.002X_{ELEV}$	0.64
	$= -10.2 + 0.095X_{MELTDA} - 0.111X_{SLOPE} + 0.101X_{VEGDEN} + 0.001X_{ELEV} - 0.005X_{FROMN}$	0.65
Y_{WTRAPR}	$= - 13.7 + 0.149X_{MELTDA}$	0.58
	$= - 9.9 + 0.137X_{MELTDA} - 0.015X_{FROMN}$	0.61
	$= - 1.4 + 0.129X_{MELTDA} - 0.042X_{FROMN} - 0.125X_{SLOPE}$	0.69
	$= 6.2 + 0.131X_{MELTDA} - 0.043X_{FROMN} - 0.134X_{SLOPE} - 0.002X_{ELEV}$	0.72

Data from 31 snow stake sites in 3 years (1972-1974), n = 89.
Y = snow depth (decimeters) or water equivalent (inches) on March 1, April 1, or May 1.
X_{MELTDA} melt date, year day
X_{VEGDEN} vegetation density, hundred foot candles.
X_{ELEV} elevation, meters
X_{FROMN} azimuth from due north, clockwise or counterclockwise, less than 180°, in degrees.
X_{SLOPE} slope, in percent.

Another difficulty is that the two points on the depth-elevation curve should be measured on the same date for a valid estimation of the slope coefficient. Since the melt dates are consistently significantly later as elevation increases, this would seem an impossible qualification to meet. Only if a pattern of variation of the slope of linear regression were discovered, could these melt dates, which are measured at two different times, be used. There is some hope of this, because in a light snow year (Figure 1) the slopes of the regression were quite similar, while in a heavy snow year (Figure 2) they consistently increased in steepness late in the winter. Also the annual pattern of change (Figure 3) is quite consistent, as shown by the similarity of the annual curves.

An alternative would be simply to relate total snowpack to key measurements on carefully selected sites at lower elevations in the watershed. This is roughly similar to the present system used to predict runoff. The snow depth and water equivalent at these selected sites, at their maximum accummulations, would be predicted by a measurement of melt date as described above. Of course the basic prediction equations, similar to Table 2, would be derived from field studies.

PHOTOGRAMMETRIC OBSERVATIONS

SNOW MELT LINE

Another useable predicator for the dynamics of snow melt is the elevation of the edge of the receding snow field. This will be referred to in the following as the snow-melt line. The time rate of change of this measurable quantity was a consistent value over the three-year period of observation.

Data

The photographic coverage of the Missionary Ridge Site during the spring of 1973, 1974 and 1975 provided the data for this study.

A photograph was selected which displayed the snow-melt line. The location of the photograph on a U.S.G.S. 7½-minute quadrangle map was determined by relating roads, drainages or other prominent topographic features. The elevation of the snow-melt line was determined by scaling of approximate distances on the photograph to the map and reading off the corresponding contour elevation. No attempt was made to preselect the topographic location of the snow-melt line. A representative elevation was observed, recorded and plotted versus the date for that particular year.

The number of photographic coverages for each year were: 1973 - five, 1974 - four, 1975 - four. Some of the flights were made early in the spring before the snow-melt line was evident or late in the spring when it was questionable whether there was a snow line or merely protected residual snow.

Thus only three observed elevations for each year were used. The data are presented in the following table:

Year	Month	Date	Elevation of snow-melt line - meters MSL
1973	May	3	2,408
1973	May	17	2,860
1973	June	8	3,230
1974	March	12	2,250
1974	April	5	2,620
1974	April	27	3,080
1975	April	20	2,320
1975	May	18	2,990
1975	June	3	3,170

A linear regression of these data for the corresponding years yield the following results:

Year	a_o	a_1	r^2	S_1
1973	1076	22.1	0.93	6.25
1974	1995	19.1	0.98	2.39
1975	1331	19.9	0.97	3.26

in which:

a_o = y- intercept in meters of elevation

a_1 = slope of the regression in meters of elevation per day

r^2 = coefficient of determination - dimensionless

S_1 = standard error of the slope (a_1) in meters of elevation per day.

The weighted mean slope of the regression lines is 19.64 meters per day. The weighted mean standard deviation of the slope is plus or minus 4.30 meters per day. Thus, the coefficient of variation of the weighted mean slope of the regression line is approximately 22 percent.

Discussion

The results presented above are subject to several possible discrepancies mostly random in nature. These random influences may include the following:

a. Natural variability from year to year due to net energy input to region.
b. Variability of the topography both aspect and orientation to the solar energy input.
c. Variability of the surface soil and vegetation.
d. Estimation of the elevation of the snow-melt line from the photographs and topographic maps.
e. The limited number of data points during each year tend to exaggerate the effects listed above.

In spite of the random influences mentioned above and others not specifically identified, it is surprising that the agreement between the slopes of the regressions were as consistent as they were. Based on this consistency, an estimate of the time between the same elevation of the snow-melt line for different years was made. The same regression was used as determined above. Two different elevations were considered; namely, 2,600 and 3,200 meters. The results are presented in the following table:

Year	Delay between 2,600 meters and 3,200 meters elev. for same year	Delay between 1974* and given year	Days	Weeks
1973	27.15 days	2,600 m elev.	37.3	5.3
	3.88 weeks	3,200 m elev.	33.0	4.7
1974	31.41 days	2,600 m elev.	0	0
	4.49 weeks	3,200 m elev.	0	0
1975	30.15 days	2,600 m elev.	32.1	4.6
	4.31 weeks	3,200 m elev.	30.8	4.4

* 1974 was used as the base year since the snow melted earlier than the other years observed.

These results indicate that both 1973 and 1975 were approximately the same, in time of the snow-melt line at the same elevation. Furthermore, this delay from the year 1974, was approximately the same as the time for the snow-melt line to raise from 2,600 meters to the 3,200 meters level.

One could conclude from these results that the difference between the years 1973 and 1975, and the year 1974 was roughly equivalent to a 600 meter (3,200 minus 2,600) difference in elevation. Thus, during any thirty day period during the snow-melt period there will be a probability of at least a 600 meter difference in snow line elevation.

SNOW DEPTH COMPUTATIONS

Concept

The attempt to determine the depth of snow by measurements from aerial photography was based on the following concept:

The difference in elevation of the snow surface and the bare ground is the desired depth. The elevation of the ground surface could be determined from photography taken before the first snow (or after the spring melt). The elevation of the snow surface was to be measured photogrammetrically from photography taken periodically during the spring melt season.

For optimum depth-measurement accuracy, elevation determination should be made at the same horizontal positions on both the with, and without snow photographs.

A more representative depth would be the average depth along a given line, vertical section, profile or transect. This profile must be along the same line in both the with, and without snow photographs.

Procedure

In order to determine surface elevations from aerial stereophotography, the following information is desirable and, in part, necessary: camera focal distance and location of the principal point; cameraposition (horizontal and vertical) at the time of the exposure, and its orientation (rotation angles). The camera position and orientation can be computed from the measured photographic images and known ground locations of at least three visible targets.

Targets

Ground targets were established in the field. Their relative locations were determined by conventional survey techniques to accuracies commensurate with their intended use. The targets were approximately 5-feet by 5-feet square platforms made of plaster-lathes on edge. They were supported approximately 5 feet above the ground in order to be visible with snow on the ground. They were discernible on the low altitude (12,500 feet) photography but not on the high altitude (18,000 feet).

Measurements & Analysis

Stereo-pairs of photography were selected which imaged as many targets as possible. The "no snow" photography had three targets. The after-snow had only one target for the stereo-pair of the same area covered by the "no snow" photographs. This was due to an unavoidable flight line location and altitude.

The target image positions on the "no snow" stereo-pair were measured on a stereocomparator. From the coordinate values and parallax between the stereo-pairs, the altitude and aerial base (distance between exposures) was computed. The agreement between three computed values was excellent even assuming that the exposures were vertical.

Measurements were then made of the profiles along the lines between targeted control points. Measurement points from a straight horizontal line were made as close to the straight line as possible. Some deviation was unavoidable due in part to relief displacement.

The "with-Snow" photographs were analyzed in a similar manner except as follows. Since only one control target was visible, it was necessary to compute the aerial base from the parallax of the principal points. The altitude of the camera was then determined from this aerial base and the parallax of the known elevation of the targeted control point.

Snow surface profiles were measured along lines from the one visible ground target toward the other targets. These lines followed as closely as possible the same lines measured with no snow. The elevations and coordinates were computed using the computed camera altitude and aerial base. The profile was then plotted and compared with the no-snow profile.

The discrepancies between the with, and without snow were greater than the expected snow depths. These differences were possibly due in large measure to (a) uncertainty of the camera altitude, (b) uncertainty in the aerial base and (c) the measured points not being at the same horizontal location for the with, and without snow. These differences could be overcome with additional and sufficient ground control. The measurement of the snow surface elevation itself was possible in regions where there was sufficient image contrast. This contrast was due to tree shadows, old snow with ridges, melt patterns and dirt residues. In areas of new clean snow, the surface is too uniform to be seen stereoscopically. This condition is analagous to a "white out" for a person at ground level.

CONCLUSIONS

SNOW DEPTH PATTERNS

At present

It is concluded that with present knowledge we could predict snow depth, water equivalent, snow pack, and runoff from Missionary Ridge, but somewhat crudely. The method could be extended to other areas a bit more accurately using experience gained in this study. Insufficient time and resources remained in this project to test the system, and further study is needed.

Future

A testing and refinement of the system developed in this study should be conducted on Missionary Ridge. If successful, it would then be ready for application in other areas. Special attention should be given to (1) estimation of statistical error, (2) verification of consistency of the prediction equations, and (3) selection of key areas. From present experience the key areas would be in an open vegetative type, at elevations between 2600 and 3200 meters, on a north aspect.

SNOW-MELT LINE

For the geographical location and elevation of the Missionary Ridge Site, these data indicate that the rise of the snow-melt line is at the rate of 19.64 meters per day (0.82 meters per hour).

The rate of rise is consistent from year to year during the period of observation with a coefficient of variation of 22 percent.

The variation in date for the snow-melt line at a particular elevation, during the observation period, was approximately equivalent to the time for the snow melt line to rise 60 meters.

SNOW DEPTH COMPUTATIONS

The comparison of profiles along prescribed lines before and after the snow cover did not produce differences in elevations which could be interpreted as snow depth.

Photographic image measurements of position and parallax were sufficiently accurate to predict elevation of the measured surface.

The accuracy of the results was limited by the available ground control appearing in a given stereo-pair.

The measurement of parallax of a snow surface is possible if the snow field is "old" enough to show texture, shadows or dirt accumulations.

APPLICATION OF FINDINGS

If this technique were successfully developed through further testing, one would simply fly over the area twice, at three-day intervals on some carefully chosen dates, say April 1 and 4. Records would be made visually or photographically of key areas which become bare of snow during the period. From this the snow depth and water equivalent (at maximum accumulation) would be estimated from the regression formulas previously devised for the area. From this the total snowpack and consequent runoff would be predicted by current regression technique.

Results could be checked by photogrammetric measurements of snow depth.

The runoff estimate would permit prediction of reservoir and ditch regimes, availability of irrigation water for crops, availability of domestic water for towns and cities, and a prediction of flooding probabilities.

Future efforts to measure snow depths by the photogrammetric procedure should provide for a denser pattern of known ground control targets.