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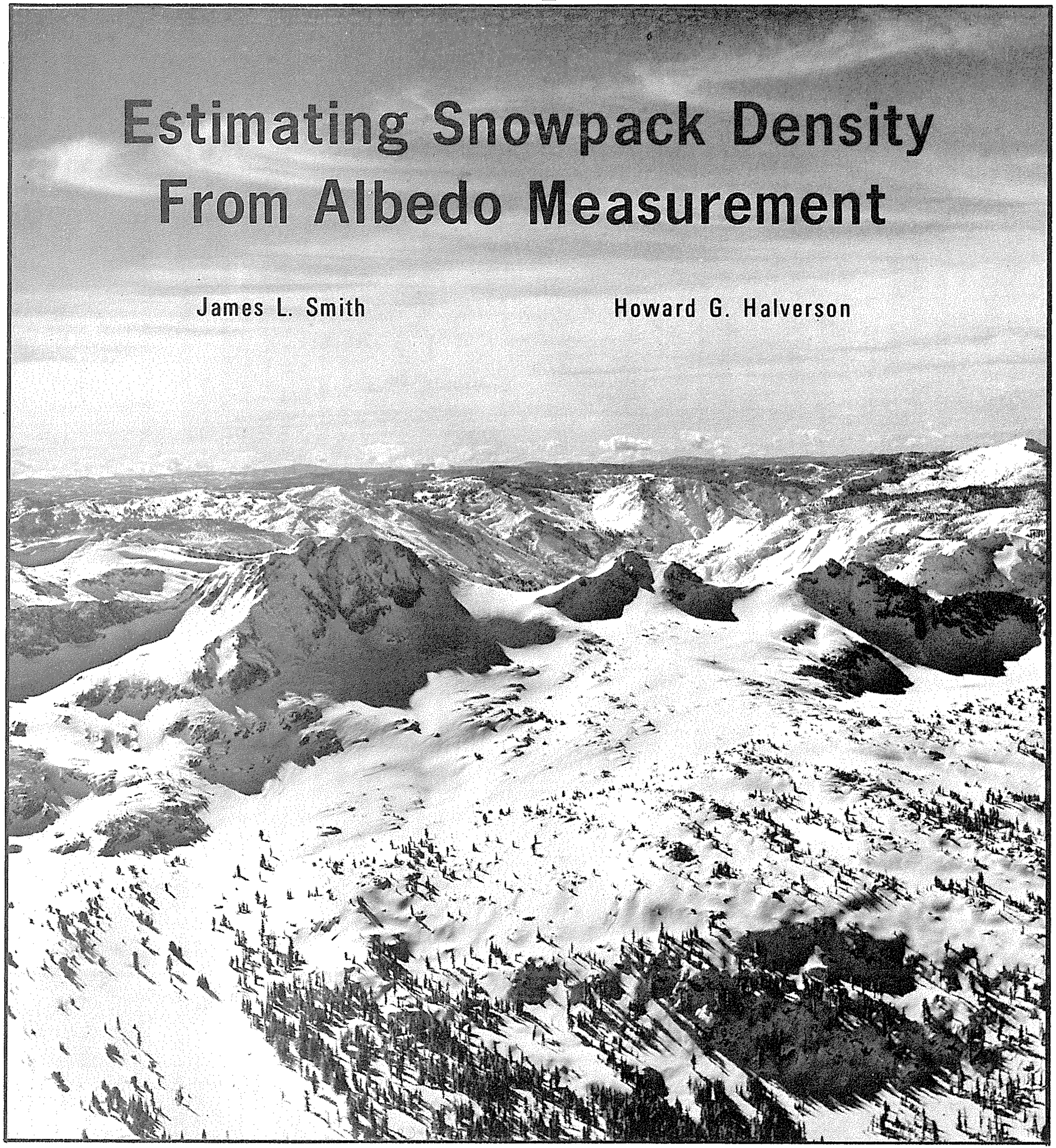
Estimating Snowpack Density From Albedo Measurement

James L. Smith

Howard G. Halverson



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The Authors

JAMES L. SMITH, in charge of the Station's environmental hydrology research unit, joined the Forest Service in 1956, and the Station staff in 1963. He is a graduate of the University of Georgia (B.S. degree in forestry, 1948; B.S., in agriculture, 1949; M.F., 1950) and Michigan State University (Ph.D., in hydrology, 1954). **HOWARD G. HALVERSON** was formerly assigned to the Station's snow hydrology research unit, headquartered in Berkeley, Calif. He is now in charge of research on amenities in municipal watersheds, Northeastern Forest Experiment Station, with headquarters in University Park, Pa. He earned degrees in forestry (B.S., Iowa State University, 1960) and watershed management (M.S., 1962, and Ph. D., 1971—both from the University of Arizona). He assumed his present position in 1975.

Cover: The large open meadow at Tioga Pass in the Sierra Nevada, Northern California, is a typical, high-elevation, remote site ideally suited to the requirements for noncontact remote sensing of snowpack characteristics.

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Pacific Southwest Forest and Range Experiment Station
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IN BRIEF...

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Retrieval Terms: snowpacks; density; depth; water content; measurements; remote sensing; albedo; runoff forecasting.

Snow is a major source of water in the Western United States. Many snowcovered sites are located in relatively inaccessible areas and in Federal wilderness areas. Access is limited to foot travel and remotely operated telemetered snow sensors are not permitted. In such areas it is impossible with the use of conventional methodology to obtain the data necessary for accurately predicting the quantity of available water. A non-contact remote sensing technique is needed to assess snow-water content in such inaccessible areas.

Snow depth can be estimated from aerial snow markers. But measurements of snow density are needed as well for estimating the water content of a snowpack.

A method has been developed for estimating average snowpack density by measuring solar albedo at the survey site when latitude, date, and type of precipitation in the latest storm are known. If the two values—snow depth and snow density—are known, the water content of the pack can be estimated. And the data can be used to forecast water supply.

The method was tested in a study at the U.S. Forest Service's Central Sierra Snow Laboratory, at Soda Springs, California. The Laboratory lies on the west side of the Sierra Nevada, at 2100-m elevation.

Albedo was measured 1 m above the snow and the values were correlated with those of snow density. After five snow seasons, the results showed that 74 percent of the 629 snow density estimates had an accuracy equal to that obtainable by measuring snow density with the conventional gravimetric sampler.

In the study, average snowpack density was correlated with these factors: character of last precipitation event, elapsed time since last precipitation, time of year expressed as solar declination, zenith angle, and the albedo of the snowpack at the time density was measured.

The results were used to develop predictive equations with which density can be estimated from ground-based albedo measurements when it is combined with the factors just listed. The equations can be used to estimate snow density from aircraft-mounted sensors. Although the data reported in this paper were not recorded by aircraft-mounted sensors, other studies suggest that snow albedo measured from an aircraft is closely correlated to that measured by ground-based pyranometers. Measuring albedo by remote sensing techniques makes it possible to estimate snow-water content of inaccessible mountain areas. And it can be done at reasonable cost. Another advantage is that it increases the accuracy of streamflow estimates of water emanating from snowpacks in the areas.

Figure 1—About 75 percent of the currently used snow survey sites above 2750 meters in California are in designated statutory wilderness areas.

The growing need for more water demands more precise techniques of forecasting water yield than can be achieved by using current practices. In the Western United States, snow is a major source of water. Snow courses provide data on snow depth and average snowpack density. These data are used in mathematical models for predicting water supply. Snow data can be collected directly or remotely. They can be obtained by remote sensing techniques—data are telemetered by electronic sensors. To obtain data directly, scientists and technicians travel to the site. Regardless of the method used, data must be obtained from an array of sites covering many different aspects, cover conditions, and elevations. Consequently, the cost of obtaining the data needed for estimating snowpack depth and density is highly prohibitive.

In California, about 75 percent of the snow survey sites above 2750-m elevation now used to collect data are in designated "statutory" wilderness areas *(fig. 1)*. Travel in these areas is restricted to foot transportation in all but the few cases where mechanized vehicles were allowed before a wilderness was designated and usage has been permitted to continue.

What is needed is a method of estimating the water content of a snowpack quickly, accurately, and economically from many points in inaccessible locations. Such a method requires that data be collected by remote means. If we can now measure snow depth remotely and measure snow density as well, we can estimate the water content of a snowpack.

We know of only one non-contact method by which snow density might be remotely estimated from deep snowpacks. And that is by measuring albedo from the air. If albedo measurements can be correlated with snowpack density, then we should be able to estimate density remotely. But a correlation must first be established between albedo and average snowpack density from ground-based observations. If such a correlation can be established, it could then be tested by measuring albedo remotely and comparing measurements with those obtained concurrently on the ground.

Some earlier studies have investigated the relationship between albedo and density. Dunkle and Bevans (1956) reported that solar radiation penetrates the top layer of the snowpack in significant amounts—to a depth of perhaps 15 cm, with maximum penetration of

1 m. Solar reflectivity—albedo—is an integrated measure of grain size and water content in the first several centimeters of the snow cover (Giddings and La Chappele 1961). Dunkle and Bevans (1956) found that reflectance and transmittance of snow could be used to correlate albedo with the physical characteristics of snow. Mellor (1965) studied the extinction coefficients of visible light (0.4 to 0.7 μm) through snow as related to density, grain size, and wavelength and concluded that remote sensing might be used to detect subtle differences within a snowpack since the magnitude and wavelength of reflectances vary with snow type.

Bergen (1970, 1971) found a relationship between the extinction coefficient and snow density and grain size. His results agree with the correlation among snow transparency, air permeability, and density which is suggested in the model of Dunkle and Bevans (1956). Bohren and Barkstrom (1974) found that less than 5 percent reflection takes place at the ice grain interface and that most of the radiation is internally transmitted. Thus, remote observation of the pack is affected by the internal structure of the snowpack. O'Brien and Munis (1975) found that the combination of densification and increased particle size, a result of maturation, reduces the reflectance of snow in relation to the density increase. Mil'kis (1956) published equations and nomograms for estimating snowpack density and albedo for known elevation and date. While density was used merely to characterize the snow, it was possible with his formulae to estimate density if one knew the albedo.

This paper reports a study of albedo measured 1 meter above the snow and the correlation of these measurements with snowpack density. The study was done at the U.S. Forest Service's Central Sierra Snow Laboratory at Soda Springs, California. The findings have application for developing a method for remote sensing of snow density.

SNOW DENSITY AND ALBEDO

Snow Metamorphism

Snow metamorphism in the Pacific Coast Snow Province is largely the result of surface melt percolating through the pack, or rain falling onto the snowpack, or both (Smith 1974). The snowpack matures by layers. Because of this layered maturation, no gradual density increase from the snow-air to snow-ground interface is found as it is in the snowpacks of the midcontinent mountain ranges. In these ranges, there is a general increase in average snowpack density with depth and length of season which is not so evident in the Pacific Coast snowpacks.

Snow density at the Central Sierra Snow Laboratory during the past 24 years has shown these ranges:

	Range of average snowpack density	
	Maximum	*Minimum*
	Gm cm^{-3}	
Month:		
November	0.15 to 0.39	0.07 to 0.26
December	.25 to .47	.09 to .26
January	.31 to .43	.14 to .31
February	.25 to .56	.18 to .38
March	.37 to .50	.10 to .43
April	.31 to .54	.19 to .43
May	.39 to .60	.26 to .49
June	.48 to .65	.41 to .52

Snowpack depths over the same period have shown these ranges:

	Range of snow depth
	Cm
Month:	
November	0 to 38
December	0 to 300
January	8 to 505
February	10 to 566
March	10 to 627
April	0 to 546
May	0 to 432
June	0 to 173

Except for the first major snowfall, melt and water loss from snowpacks we have studied originated at the surface and moved downward through the pack. Sizable quantities of melt water flowed by the end of January in each year between 1966-1967 and 1971-1972 *(table 1)*. During these 6 years, melt water drained from the pack in 21 of the 24 months during the December-March period. More than 2.54 cm of water were released in 18 of these 24 months. And more than 7.62 cm were released in 14 of the 24 months.

The effect of so much snowmelt and water movement through the pack is to "mature" the lower layers of snow early in the season. With maturation, snowpack average density frequently reaches 0.40 gm cm^{-3}. During the years 1966-1967 through 1971-1972, this density was reached as early as January and in each succeeding month through May.

Table 1—*Months in which melt water drained from snowpacks of the Sierra Nevada of California equaled the amounts shown before April 1, during the 6 years, 1966-67 to 1971-72*[1]

Month	Melt water					
	<2.54	2.55 to 5.08	5.09 to 7.62	7.63 to 10.16	10.17 to 12.70	>12.71
	Cm					
December	2	1	0	0	1	0
January	0	1	0	2	0	3
February	1	1	0	1	0	2
March	0	0	1	0	0	5

[1]Excludes drainage induced by rainfall.

The pack does not have to reach an average density of 0.40 gm cm^{-3} for melt to occur. On April 15, 1968, at three study sites in the open and under forest cover, the pack reached average maximum density of 0.322, 0.323, and 0.348 gm cm^{-3}. In January and February, a "mist-type" rain fell on these packs for parts of 3 successive weeks. Maximum air temperatures ranged from 1.10°C to 2.75°C, with minimum temperatures of from -8.35°C to -2.2°C. After the rain, density averaged 0.30 gm cm^{-3}, and the pack had fully matured to a spring-melt condition. Subsequent snowfalls did not materially compress this pack. Sizable amounts of water moved from this pack each month, and the entire pack melted without any layer ever reaching 0.40 gm cm^{-3}. We measured layers within the pack that matured and melted at the end of snow season without exceeding a density of 0.23 gm cm^{-3} (Smith and others 1970).

"Warm snows"—those in which the snow is isothermal all season—increase in density by compression and water absorption *(fig. 2)*. Usually, as each layer of the pack is successively compressed, the proportion of small pores increases and the layer absorbs all the water it can hold. Additional snowfall further increases the small pore content of the snow, thereby increasing its water holding capacity. Finally, strength increase and structural changes related to maturation prevent further compression. Ice lensing, snow bridging, and other formations that produce loadbearing layers protect lower snow layers from further compression.

The rate of density increase appears to depend on temperature and is not linear. The snowpack densifies rapidly just after a storm, then continues to densify at a reduced rate for several days (Bader 1962). Rates of density increase are altered by general weather conditions, precipitation type, aspect, elevation, wind, total snow present, snowmelt, and the time of the snow season. Some elements which affect snow densification, such as air and snow temperature, surface snowmelt, wind, and precipitation type (rain or snow), also alter albedo.

Snow density generally increases with time from the beginning of the snowpack in the dry, light density, "cold" snowpacks of midcontinent. Therefore, reasonably accurate estimates of average density may be made by correlating density with time. This estimate should be more accurate than that for wet snowpacks of the Sierra Nevada. In the Sierra Nevada, where the packs are subject to maturation, melt, and water loss in any month during the snow season and may reach maximum density at any period—even in December—a system of density estimation is needed which avoids many of the shortcomings of the historical time-density relationship system *(fig. 3)*. A density prediction system for use in the Sierra Nevada must be dynamic enough to allow for the variances just enumerated. Such a system would need to incorporate albedo-density changing parameters into its equation. In general, conditions which favor rapidly increasing density reduce albedo. For example, rain-on-snow increases density and decreases albedo. New snow decreases average density and increases albedo. Albedo of new snow in early season will degrade at a slower rate than that falling in May or June.

We reasoned that a correlation might exist between average snowpack density and albedo and other variables. Average snowpack density would be the dependent variable; albedo, type of precipitation in the last storm, date and time of measurement, zenith angle, and number of days since the last storm would be the independent variables. We would test to develop a correlation between average snowpack density and

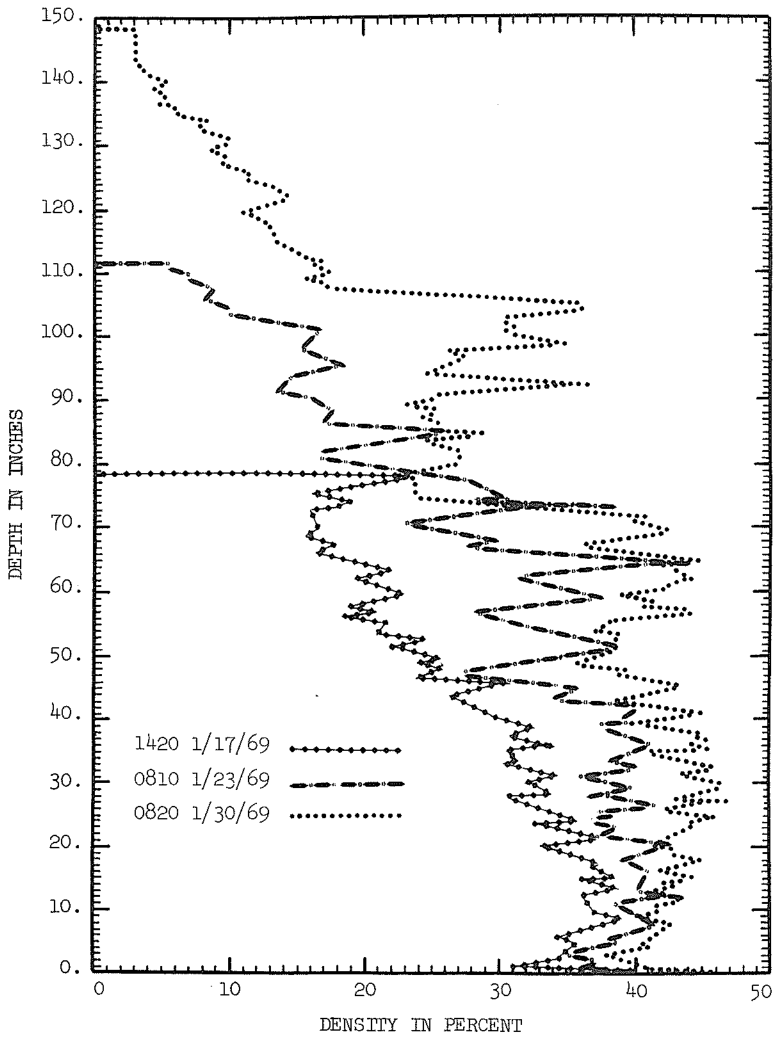

Figure 2—A 7-inch rain, beginning January 17, 1969, fell on a 78-inch deep snowpack. All the rain was absorbed by the pack. The rain and new snowfall between January 17 and January 30 produced density increases ranging from 0.05 gm cm^{-3} to 0.25 gm cm^{-3}.

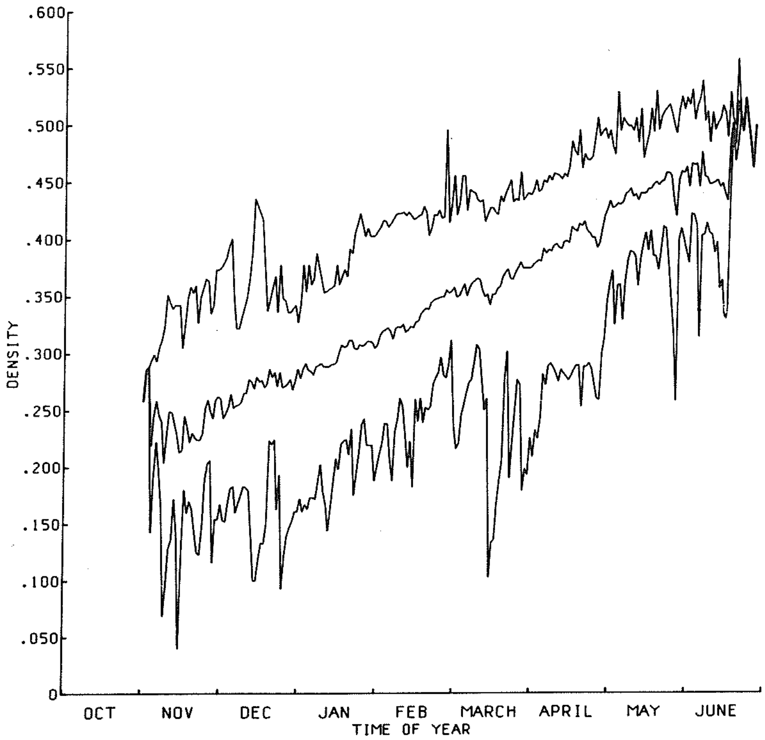

Figure 3—Snow density varies as a result of precipitation, temperature, and snowpack regime for each year. Although density increases in a linear fashion with time, the amount at any particular moment may be either above or below the mean line as a result of new snow, rain, compression, and other variables.

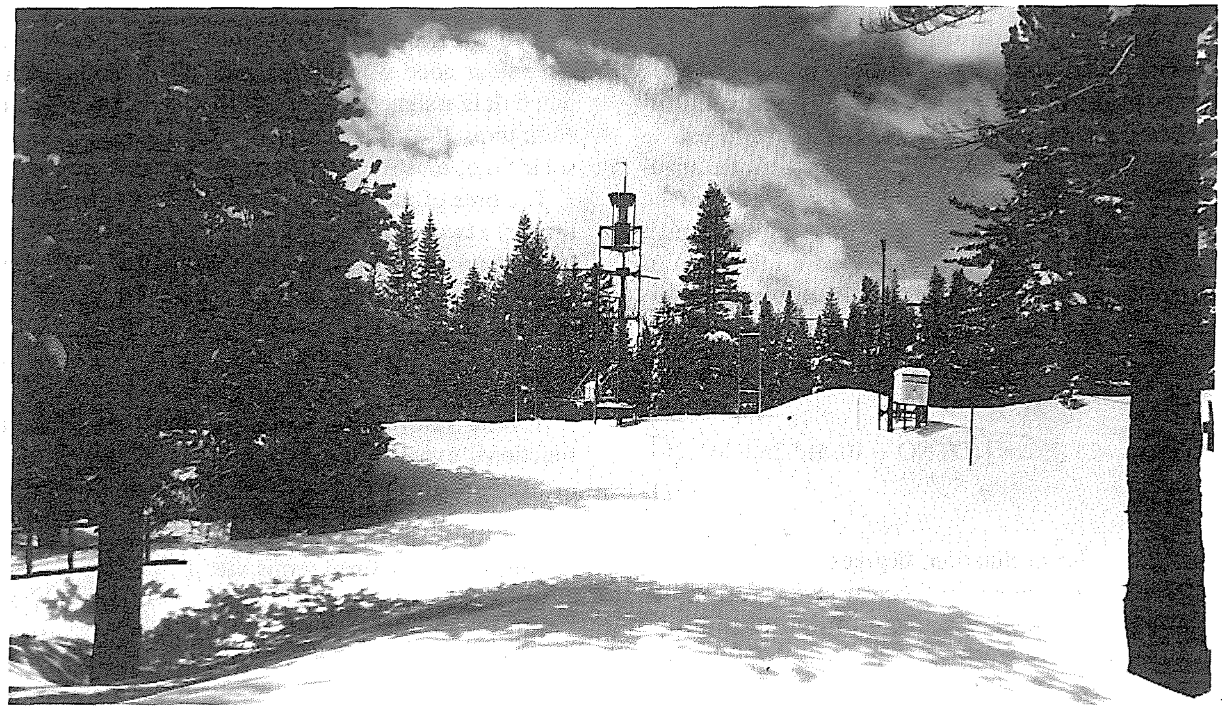

Figure 4—At the Central Sierra Snow Laboratory, Soda Springs, California, daily snow density profiles, precipitation, relative humidity, snow, air, and soil temperatures, dew point, windspeed, direction and amount of air flow, and long-wave and short-wave solar radiation are automatically sensed at predetermined intervals.

each of the independent variables. Correlation data would then be used to derive an equation for predicting snow density.

Developing Density Prediction Equation

Data on albedo and average snowpack density were collected at the Central Sierra Snow Laboratory, at Soda Springs, California *(fig. 4)*. Measurements were recorded for the snow seasons 1967-1968 through 1971-1972. Average snow density and concurrent snow albedo were measured daily for the five seasons. For this study we selected 629 pairs of measurements.

Measurements recorded on some days during each of the five seasons were excluded from the study: days following precipitation of less than 7 mm water equivalent and days when snow density measurements were not recorded. Measurements were begun after the snowpack reached 60-cm depth in early season and were ended when the spring snowpack had melted to this depth, since albedo can be influenced by the character of the underlying soil to a depth of less than 60 cm.

The dependent variable, average snowpack density, was measured with an isotopic profiling snow gage (Smith and others 1972). The gage measures snow density in approximately 1-cm intervals from the soil surface to the air-snow interface. Average snowpack density is the average of all increments in the snowpack. Density determinations by this method have a standard error of about 0.01 gm cm^{-3}.

At one site at Central Sierra Snow Laboratory we periodically measured albedo and snow density at the same time. Type of precipitation was recorded for each storm. To measure albedo we used two Eppley pyranometers[1]—one mounted in the normal position and the second inverted. The plane of the pyranometers was set parallel to the snow surface and 1 m above it. The pyranometers were read sequentially, first the upward-facing instrument followed about 2 seconds later by the inverted. Decimal albedo was measured at 30-minute intervals for 3 hours before and after density determinations, limited by times of sunrise and sunset.

New snow is usually less dense than existing snowpack. The rate of new snow densification and the density of the existing snowpack yield different values, depending on the time of the snow season when measurements are taken. Late season snowpacks are usually

[1] Trade names and commercial enterprises or products are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

more dense than early season packs, and new snow metamorphosis proceeds faster in late season. Because the snow season spans 2 years in the northern hemisphere, calendar date is a difficult variable to use.

Date can be expressed as solar declination, the angular displacement of the sun north (+) or south (-) of the celestial equator. Solar declination reaches a minimum value, -23.45° on December 22, and a maximum of +23.45° on June 22. Solar declination can be determined from an "Ephemeris of the Sun" at 4-day intervals (List 1958), or it can be approximated by the equation:

$$SD = -23.45 \cos\left[(DTNO + 10.5) * 360/365.25\right] \quad (1)$$

in which

SD = solar declination, degrees
DTNO = day number of the year (Julian Date)
recalling that the algebraic signs of cosine are:

0°-90°,	90°-180°,	180°-270°,	270°-360°
+	−	−	+

The type of precipitation affects the average density of the resulting snowpack. Winter precipitation may not be all snow; it may be all rain, or rain and snow mixed. A rain-on-snow event results in rapid declines in albedo and rapid increases in density. Because of different types of precipitation, storms were coded by a classification scheme into three groups: snow only, mixed rain and snow, or rain only and were then assigned the value 0, 0.5, or 1.0, respectively.

The reflectivity of many surfaces is a function of the incident angle of radiation. Snow shows a weak, but significant, albedo change with incident angle (Mellor 1964). New snow reflectivity is more sensitive to the incident angle of radiation; old snow surfaces are less responsive (U.S. Army 1956). With solar radiation, the angle of incidence is described by the zenith angle (Z) of the sun, where Z is the angular displacement of the sun from vertical at the site. The zenith angle changes during the day, reaching 90° at sunrise and sunset over a level surface, and declining to a minimum at solar noon. The minimum is always equal to the algebraic total of latitude minus solar declination. At intermediate times, the zenith angle can be computed by:

$$ZCOS = \sin(L)\sin(SD) + \cos(L)\cos(SD)\cos(h) \quad (2)$$

in which the undefined terms are:

ZCOS = cosine of the solar zenith angle
L = site latitude, degrees
h = hour angle, degrees

The hour angle (h) is the number of hours before or after solar noon when the zenith angle is to be computed. It is assigned a value of 15° per hour because the earth turns 360° in 24 hours, or 15° per hour. Time, as solar time, must be used to compute the hour angle.

The time of measurement is converted to true solar time by a two-step process. First, 4 minutes is added to local standard time for each degree of longitude the snow course is east of the time zone meridian, or 4 minutes is subtracted for each degree west. Second, the equation of time for the measurement date is algebraically added to the result of the first step (List 1958).

Several relevant variables are combined into a functional expression:

$$RHO = f(A, SD, D, R, ZCOS) \quad (3)$$

in which the undefined terms are:

RHO = average snowpack density, decimal
A = albedo, decimal
D = days since cessation of storm, integer
R = proportion of rain to snow in last storm: 0, 0.5, or 1

The final form of the equation was derived by a combination of regression and graphical techniques. Regression techniques are designed to find the mathematical function that best describes the relationship between the dependent and several independent variables. The general linear model for our purposes is:

$$RHO = b_o + b_1A^2 + b_2SD + b_3D + b_4R + b_5ZCOS + E \quad (4)$$

in which the undefined terms are:

E = error, gm cm^{-3}
b_i = the regression coefficients to be estimated.

Initial graphic analysis showed that albedo was, as expected, the best single predictor of average snowpack density, but the relationship was not linear. The square of decimal albedo showed better fit and was adopted for future analyses.

Regression analysis by the least squares technique was done and regression coefficients and their significance tabulated *(table 2)*. The t-test values showed that each variable was significant at the 99 percent level.

The final form of the equation is:

$$RHO = 0.452 - 0.123A^2 + .003(SD) + .002(D) + .027(R) - .039(ZCOS) + E \quad (5)$$

The multiple correlation coefficient (R^2) is 0.68 and the standard error of estimate equals 0.037 gm cm^{-3}.

As with any relationship developed through linear regression techniques, there is an error associated with the predicted variable. The standard error in this work where we used all 629 data points is 0.037 gm cm^{-3}, or 3.7 percent density. According to Work and others (1965), the Federal Slotted Sampler overmeasures water equivalent by from 7 to 12 percent. The Federal Slotted Sampler, which has been used universally in snow surveying for the past 40 to 50 years, extracts gravimetric samples of snow from which density and water content are computed. Because of the influence of depth it is difficult to convert errors in snow-water equivalent to errors in density; however, it appears that snow density measurements are high by about 0.04 gm cm^{-3}.

Factors Affecting Accuracy of Estimate

Classification by Error Class

Because of the low multiple correlation coefficient ($R^2 = 0.68$), we analyzed the 629 pairs of albedo-density measurements used in the study to determine when the density estimation was most accurate and under what conditions it was least accurate. The density error associated with the Federal Slotted Sampler is about 0.04 gm cm^{-3} with an undetermined error distribution. To be useful, any complementary system should at least approach this accuracy. We apportioned the 629 sets of data points into three classes depending upon the difference between measured and estimated density for each point:

Class I Error of estimate <0.04 gm cm^{-3}
Class II Error of estimate ≥ 0.04 to <0.07 gm cm^{-3}
Class III Error of estimate ≥ 0.07 gm cm^{-3}

Four hundred sixty-six (466) of the 629 data points (74.09 percent) fell within Class I accuracy; Class II accuracy contained 110 (17.49 percent); and Class III contained 53 (8.43 percent) of the 629 data points. Because the error of estimate of 25.92 percent of the 629 samples was greater than the average error attainable with the Federal Slotted Sampler, we subdivided the data several ways in an effort to determine the conditions under which errors arose.

Error and Year of Measurement

Analyses were made to determine the relationship between year and error *(table 3)*. A wide range of

Table 2—*Linear regression coefficients and variable ranges used to estimate average density by the equation* $RHO = b_o + b_1A^2 + b_2SD + b_3D + b_4R + b_5ZCOS + E$

Coefficient	Variable	Value	T_b	$T_{\alpha=.05}$	$T_{\alpha=.01}$
b_0	constant	0.452	35.37	1.96	2.58
b_1	A^2	-0.123	-8.62	1.96	2.58
b_2	SD	0.003	17.45	1.96	2.58
b_3	D	0.002	8.44	1.96	2.58
b_4	R	0.027	6.87	1.96	2.58
b_5	ZCOS	-0.039	-3.01	1.96	2.58

and Degrees of freedom = 623
$R^2 = 0.68$
Standard error of estimate = 0.037 gm cm^{-3}

Variable	Maximum	Minimum	Average
RHO	0.466	0.211	0.375
A	1.00	0.314	0.674
SD	20.94	-23.45	-6.53
D	27	0	8
ZCOS	0.948	0.149	0.570

[1]T-test values showed each variable was significant at the 99 percent level.

Table 3—*Sample points by years to determine relationship between error and year of measurement*

Year	Sample points	*Error of measurement (gm cm-3)*		
		Class I <0.04	Class II 0.04 to 0.07	Class III ⩾0.07
1967-68	33	12	12	9
1968-69	24	20	4	0
1969-70	205	128	52	25
1970-71	189	185	3	1
1971-72	178	121	39	18
Total	629	466	110	53

accuracy between years, from almost perfect accuracy (<0.04 gm cm-3) between measured and estimated density in 1968-1969 and 1970-1971, to a lower level of prediction accuracy in other years was evidenced. In 1967-1968, with only 33 sample points, our accuracy was quite poor.

Precipitation Type

To assess the effect of precipitation type upon the accuracy of density estimates, we subdivided the data into the three classes based on the type of precipitation in the last storm before the measurement *(table 4)*.

Greatest accuracy was achieved when we measured albedo after mixed rain-snow or rainstorms. Greatest error occurred when measurements were taken after snowstorms. Ninety to 95 percent of all measurements taken after rain or mixed rain-snow events fell within the <0.04 gm cm-3 density error range, while only 66 percent of those taken after snowstorms fell within this density error class. This is to be expected, since albedo is a surface phenomenon and recent snowstorms will inflate its value.

Elapsed Time Since Last Storm

To test further the effect of new snowfall upon the accuracy of the density estimate obtained, we divided the data into accuracy Classes by years and the number of days elapsing between the storm event and albedo measurement *(table 5)*. Measurements made more than 10 days after the end of a storm were the most accurate.

Month of Measurement

Although late season measurements have an overall improved accuracy over early season measurements, Class II and Class III accuracies can occur in any month *(table 6)*. Errors are not related to time of measurement, but are related to anomalies in albedo resulting largely from recent snowfalls.

Attempts to Increase Accuracy of Estimate

Because of technical problems with the electronic system at the Central Sierra Snow Laboratory in 1967-1968 and 1968-1969, we could use only 33 and 24 data points, respectively, from each of those years. Further, the data from 1967 to 1969 were not evenly distributed through the winter season. These data did not provide us with an adequate array of seasonal conditions; consequently, we decided to delete them from this phase of the analysis.

Available data points for each of the remaining years ranged from 178 to 205. Nineteen of these remaining data points had errors in excess of two standard deviations. We examined these points along with all the others for the years 1969-1970, 1970-1971, and 1971-1972 to determine the reason for the large errors. We found that on all 19 days there was the possibility that the upright Eppley was covered with snow. Light snowfalls were occurring at the time of measurement. The 19 data points were removed from the analysis, along with the 57 points from years 1967-1968 and 1968-1969. In all, 76 data points were removed from the data base of 629 points.

We then analyzed the other data points to determine the effect of cloud cover on albedo correlation (McMillan and Smith 1975). Ambach (1974) pointed out the effect of cloud cover upon the radiation balance over snow. Fritz (1955) noted the uniformity of diffuse radiation over snow cover under overcast skies. Of the original 629 sets of concurrently obtained albedo and snow density measurements, 553 pairs were divided into three sets of data based on cloud cover at the time of measurement.

0.0 to 0.2 cloud cover = clear
0.3 to 0.7 cloud cover = partly cloudy
0.8 to 1.0 cloud cover = overcast

Table 4—*Accuracy classes as opposed to type of precipitation in the last storm before measurement*

Year	Samples	Precipitation type: Snow, Classes I	Snow II	Snow III	Mixed rain and snow, Classes I	Mixed II	Mixed III	Rain, Classes I	Rain II	Rain III
		Number of points by accuracy classes								
1967-68	33	12	12	9						
1968-69	24	14	4	0	6	0	0			
1969-70	205	123	44	25	5	2	0	0	6	0
1970-71	189	80	1	1	13	1	0	92	1	0
1971-72	178	72	39	18	3	0	0	46	0	0
Total	629	301	100	53	27	3	0	138	7	0
Percent of totals for each group		66.3	22.0	11.7	90.0	10.0	0	95.2	4.8	0
Total number for each precipitation type			454			30			145	

Table 5—*Accuracy of estimate classes, by number of days since last storm*

Year	Points	0 to 3 days, Classes I	0 to 3 days II	0 to 3 days III	4 to 9 days, Classes I	4 to 9 days II	4 to 9 days III	10 to 27 days, Classes I	10 to 27 days II	10 to 27 days III
1967-68	33	0	0	2	2	11	7	10	1	0
1968-69	24	14	0	6	6	4	0	0	0	0
1969-70	181	9	27	36	36	20	13	83	5	2
1970-71	189	84	1	43	43	1	0	58	1	0
1971-72	178	28	7	49	49	31	0	44	1	0
Total	629	135	35	136	136	67	20	195	8	2

Table 6—*Effect of time of year upon accuracy of estimate given in percent of total number of points obtained per month, by accuracy classes*

Year	December, Classes I	Dec. II	Dec. III	January, Classes I	Jan. II	Jan. III	February, Classes I	Feb. II	Feb. III	March, Classes I	Mar. II	Mar. III	April, Classes I	Apr. II	Apr. III	May, Classes I	May II	May III
	Percent																	
1967-68	14	79	7	91	9							100						
1968-69				60	40		100									100		
1969-70							9	55	37	4	16	1	98	2				
1970-71	100			100			98	2		100			93	4	4	97	3	
1971-72		76	24	94	6		100			100			8	57	36			
All years	31	56	13	93	7		61	24	15	86	9	5	66	21	13	97	3	

The equation derived with all three cloud conditions with variables listed in their order of significance is:

$$RHO = .00323SD + .00193D + .0279R - .0756A^2 + .412 + \text{error} \quad (6)$$

The multiple correlation coefficient is $R^2 = 0.79$. The standard error of estimate was found to be 0.027 gm cm^{-3}.

When all data were excluded from the analysis except that for overcast conditions, the derived equation was:

$$RHO = .00325SD - .123A^2 + .0334R + .00145D + .436 + \text{error} \quad (7)$$

The multiple correlation coefficient for this equation is $R^2 = 0.79$. The standard error of estimate is 0.031 gm cm^{-3}.

DISCUSSION

An empirical relationship between average snowpack density and albedo, and other site and storm variables exists. Under the conditions of our experiment we found that on-site average snowpack density can be estimated from snow albedo measurements taken 1 meter above the snow when general site and storm information is available.

Many circumstances can affect the accuracy of such an estimate. The pyranometers must not be covered with even a thin film of snow or ice. New snow on the surface of the snowpack will, of course, yield higher values of albedo and in some cases decrease the accuracy of the density estimate. Even with the full data base of 629 points and with the possibility of erroneous pyranometer readings for some of the data, 90 to 95 percent of the estimates of density were within Class I accuracy when measurements were taken after mixed rain and snowstorms, and after rainstorms. Even with the possibility of some portion of the data base having erroneous albedo measurements, 66 percent of the estimates of snow density made after snowstorms were within the minimum error class. And, if density measurements were taken 10 days after a snowstorm, then almost all data fell within the minimum error classification.

This work was designed to devise a method to gather accurate snow survey data by remote means. We know that the average error of Federal Slotted Sampler data and density estimates based on albedo are roughly equal. Except for one study (Work and others 1965), however, we know little about the error distribution of snow densities computed from gravimetrically obtained data—a volumetric sample of snow which is extracted from the snowpack. Work and others (1965) showed that with gravimetrically obtained data, error increased as snow-water equivalent increased. Obviously, some of the data obtained from snow surveys includes errors greater than the mean error of 0.04 gm cm^{-3}. But considering that errors must occur in gravimetric sampling, we can assume that the remote system based on albedo—where most measurements fall within the minimum error class—should yield acceptable estimates.

The albedo method for estimating average snowpack density appears to offer the potential for a method of measuring average density of snowpacks in open areas. Albedo can be measured by aircraft-mounted instrumentation. We suggest that this system of density estimation is useful for increasing accuracy of prediction of streamflow from snowpacks in statutory wilderness and other remote areas.

Snow courses and related instrumentation currently provide the basic snow water equivalent data used in streamflow and flood prediction. Snow survey courses are located in some of the least accessible areas of the western mountains *(fig. 5)*. Traditionally, snow sampling is done on foot or by mechanized travel to the snow course, sampling gravimetrically, and returning. Basic sample information includes snow depth, water equivalent, and core length; average snow density is computed from the depth and water equivalent measurements. Because of cost, only a limited number of samples are now obtainable. The suggested system—albedo measurement of snowpack density—would extend the data base.

Wilderness status has precluded mechanized travel to some established snow survey locations. Many snow courses located in existing or planned wilderness areas are essential—they cannot be relocated or eliminated from the water supply forecast model. These essential snow courses may be difficult or dangerous to reach on foot, especially during winter; but pedestrian oversnow travel is normally the only acceptable means of access under the wilderness statutes. Also, there is an increasing need to gather more data from wilderness sites than are currently being obtained.

The alternative to the traditional sampling scheme is to incorporate automated snow gaging or remote sensing to acquire the necessary information. Several instruments have been proposed to gather snow data. Snow water equivalent can be telemetered from pressure pillows (Beaumont 1965) or from an isotopic snow gage measuring nuclear attenuation by the entire snowpack (Gerdel and others 1950). Depth, density, and water equivalent may be obtained with a profiling nuclear snow gage (Smith and others 1972). In the area of remote sensing, the attenuation of natural radiation has been tested, but its use is limited to about 40 cm water equivalent (Bissell and Peck 1974). Owing to the high cost of installation and operation, only a limited number of automated snow gages can be installed in any area. With the exception of natural radioactivity monitoring, installation in statutory wilderness areas is generally prohibited.

The demand throughout the West for improved snow survey accuracy can best be met by increasing sampling frequency and sampling intensity, but at a more reasonable cost than that associated with remote operation of snow sensors. If snow albedo can be measured from aircraft-borne solar radiometers, these measurements can be related to point estimates from snowpack average density at that site. Snow depth can concurrently be measured from existing aerial snow markers or other systems. Advances in aircraft and satellite remote sensing technology now permit comparisons between ground and remote observations.[2]

Snow albedo has been measured from aircraft (Bauer and Dutton 1962). While results in this report were obtained from pyranometers mounted 1 meter above the snow surface, we believe that albedo measurements taken from aircraft will be essentially the same as those measured from the ground. Studies at the University of Saskatchewan in which ground-based albedo measurements were compared to airborne measurements gave results which were in close agreement[2].

Pyranometers mounted on helicopters may be flown within 100 feet of the snow surface with a forward

[2] Personal communication from D. H. Male, University of Saskatchewan, Saskatoon, Canada, 1975.

Figure 5—This volcano snow course at 3503-m elevation is in the Sierra Nevada, South Fork, San Joaquin River Basin, California.

speed of about 25 miles per hour without affecting the snow cover. At this height the pyranometer reading will not be affected by vegetation alongside the large openings used in snow surveying. The snow surface at the measurement site should be level to prevent differences in albedo caused by slope angle differences or a mathematical adjustment will need to be made.

Operational water supply models of snow survey data are based on empirical relationships. Changing the number and location of snow courses could change the relationship. Measuring a snow course aerially rather than on the ground, however, should have no effect. If extra courses are added, the present proportion of courses in each elevation zone and aspect should be maintained. Unchanged proportion of courses should leave the present water supply model unchanged, but would increase the accuracy of streamflow prediction.

The albedo method is based on an empirical relationship and the several coefficients may need reevaluation if the equation is applied to areas or elevations where the snow maturation process is different from that at the Central Sierra Snow Laboratory.

The correlation established between density and albedo at the Snow Laboratory is most accurate for the type of snow maturation from which the formulas were developed. It should be expected to work in the warm, wet, deep snows of the Pacific Coast Province. In areas subject to depth hoar (temperature gradient metamorphism) this system would be less accurate.

If the density-albedo system is used, aerial surveys would need to be scheduled at times when greatest accuracy of estimate might be attained: after rainstorms, or more than 10 days following snowstorms. But slightly degraded accuracy can be achieved just after a storm stops. The usefulness of the density-albedo system for aerial surveys can only be assessed after the techniques developed from ground-based research are applied to an aerial reconnaissance.

The studies reported in this paper have been used as the foundation for an aerial test of the proposed new system for density estimation from aircraft. In that study, which is currently underway, albedo is measured from a helicopter and snow density is determined with ground measurement using the profiling snow gage.

The research reported here does not include measurements made from aircraft, but only ground-based measurements to indicate the validity of density estimation from albedo measurement.

CONCLUSIONS

We found a positive correlation between snow density, snow albedo, and other parameters in the Sierra Nevada of California. A predictive equation was developed in which average snowpack density could be estimated with an R^2 of 0.68 and a standard error of 0.037 gm cm^{-3}. The only independent variable measured at the site was snow surface albedo. Additional variables used in the equation are date and time of measurement, zenith angle, number of days since last storm, and type of precipitation in the last storm.

The 629 concurrently obtained data points (snow density and snow albedo) used for the formula development were analyzed to determine under what conditions the formula gave the most accurate results. Of the 629 points, 74 percent had errors of less than 0.04 gm cm^{-3}, the approximate average error of the Federal Slotted Sampler. Of all data taken after snowstorms, 66 percent fell within this error classification, while 90 and 95 percent, respectively, fell into this class when data was taken after rain and after mixed rain-snowstorms. If measurements were made as much as 10 days after a storm, 95 percent of the data points had errors of less than 0.04 gm cm^{-3}. The month in which the measurement was taken had little effect upon accuracy.

This study points out the potential for developing a method for aerial estimation of snow density by measuring snow albedo from aircraft.

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1979. **Estimating snowpack density from albedo measurement.** Res. Paper PSW-136, 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Snow is a major source of water in Western United States. Data on snow depth and average snowpack density are used in mathematical models to predict water supply. In California, about 75 percent of the snow survey sites above 2750-meter elevation now used to collect data are in statutory wilderness areas. There is need for a method of estimating the water content of a snowpack in inaccessible locations by remote means. If snow albedo can be measured from aircraft and these measures correlated with snowpack density, we should be able to estimate density remotely. But a correlation must first be established from ground-based observations. This paper reports a study of albedo measured 1 meter above the snow and the correlation of these measurements with snowpack density. The study was done at the Forest Service's Central Sierra Snow Laboratory, Soda Springs, California. The findings have application for developing a method for remote sensing of snow density.

Retrieval Terms: snowpacks; density; depth; water content; measurements; remote sensing; albedo; runoff forecasting.

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