Snowpack accumulation in relation to terrain and meteorological factors in southwestern Montana

by John Thomas McPartland

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Science (Geology)
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Abstract:
The relationships between mountain snowpack accumulation and terrain and meteorologic parameters were investigated in three separate mountain areas in Southwestern Montana.

Parameters of elevation, aspect, slope, geographic location, and degree of potential windiness were determined for each sampling site in the three study areas. These were used as terrain/meteorologic parameters in the data analysis. Snowpack variables measured were snow depth and water equivalent.

Statistical treatment of the data was performed through use of simple correlation and multiple linear regression analyses, and by principal component analysis. Snow depth was used as the snowpack variable throughout all analyses. However, a very high simple linear correlation consistently existed between the snow depth and water equivalent, and it is concluded that results of the statistical analyses apply equally to water equivalents.

In the Bangtail area of the Bridger Range, elevation was generally the most important variable in explaining variance in snowpack depth.

The potential windiness parameters used were usually second in importance in explaining the depth variance. Southwest winds are known to dominate in the area, and exposure to the southwest quadrant was the most significant of all the potential wind variables. Aspect, slope, and location parameters were generally not effective in explaining the variance in snowpack depth.

Variations in snowpack depth at the Carrot Basin area of the Madison Range, and the Cooke City area of the Beartooth Range were largely explained by the elevation parameter. Wind effects in both areas were unimportant. Lack of wind effects is attributed to effective blocking by upwind ranges, and by location of sampling sites in sheltered valley floor positions.

Comparisons between the individual study areas revealed that total snow amounts received were quite comparable. Differences in snow on the ground at 8000 feet MSL in late March and early April were less than the annual variations experienced by the areas. However, comparison of snow depth gradients from 7000 to 8000 feet MSL revealed a high degree of variability in both space and time.

Due to the high correlation coefficients between snow depth and water equivalent it is suggested that networks of aerial snow depth markers could provide accurate water content estimates in any of the three mountain ranges, if index density values were available.

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ABSTRACT

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I. INTRODUCTION

General

This study presents an analysis of mountain snowpack accumulation in relation to terrain and meteorological variables. The field investigations were conducted in three mountainous areas of differing morphology in southwestern Montana. Terrain and meteorologic parameters include: elevation, aspect, degree of slope, location with respect to upwind mountain barriers, and degree of exposure to wind. Snowpack accumulation was measured in terms of snow depth and water equivalent. Sampling sites in each of the three study areas were established to encompass as wide a range of these variables as practical.

Need for Investigation

Present knowledge of the interrelationships between snowpack and terrain is limited. Review of the literature supports the conclusions of Cooper and Jolly (1969) who stated, "Little is known about the spatial distribution of mountain snowpacks in relation to topography, exposure, wind, and total snow amount, except that the distribution is markedly non-uniform." Several prior studies have utilized data from the Federal-State-Private Cooperative Snow Survey network, which is comprised of some 1400 snowcourses in the Western United States and Canada. These data are routinely collected by the various cooperating agencies to provide predictive indexes for runoff and flood forecasts.

These snow sampling sites are not entirely representative of conditions in the typical high mountain environment. A very limited number of sites, generally around the perimeter of major mountain masses, may be used to index a large accumulation area and, with the exception of elevation, the sites are selected to be as uniform as possible. Sharp declivities, heavily forested areas where significant interception losses may occur, and areas likely to be subject to wind redistribution of snow are generally avoided.

An improved understanding of the distribution of the seasonal mountain snowpack with respect to terrain and meteorological variables could have important applications in future water resources management and recreational planning efforts.

The importance of maximizing use of available water resources is rapidly increasing in this country and elsewhere. Rapid population growth, particularly in urban areas, and associated industrial and agricultural expansion have already depleted available water supplies in certain areas of the United States. It is estimated (Holburt, 1970) that major water shortages will develop over the entire Colorado River before the turn of the century. Water supply deficiencies in the near future have also been forecast for the Upper Missouri, Great Basin, and South Pacific watersheds (Plan to Develop Technology for Increasing Water Yield from Atmospheric Sources, 1966). All of these areas have a common dependence on melt runoff from high mountain snowpacks for a major portion of their water supply. For example, an appraisal of the Missouri River near Sioux City, Iowa (Missouri: Land and Water, 1953), indicated that approximately 50% of the water flowing past that point had its origin in the mountainous areas of southwestern Montana and northeastern Wyoming.

Weather modification programs aimed at increasing the high elevation snowpack will probably soon be operational in many areas of the western United States. Ability to accurately predict the final distribution of resulting additional snowfall would be of benefit in water resources management programs. Increased knowledge of the development patterns of various types of snow accumulation zones as related to increased snowfall is necessary in predicting possible ecological effects which may result from widespread winter orographic weather modification programs.

Development of improved forestry practices to increase snow storage and runoff from timbered areas could also benefit from additional information on the relationships between topography, forest cover, and wind effects. Knowledge of natural variability of snow distribution could be applied in selecting a timber management program most suitable for a particular area in terms of both water resources and sustained yield of forest products.

The advent of reliable remote sensing and telemetry equipment capable of long period unattended operation has made it possible to obtain hydrologic data from areas which are inaccessible during the winter months. High unit costs for equipment of this type make it imperative that each remote station be located in as representative a site as possible. Improved understanding of terrain-snowpack relationships would aid in selection of the minimum number of sites which would most accurately index the snowpack distribution in all reaches of a mountain watershed. The resulting data would allow more accurate prediction of volume and rate of Spring runoff and subsequent improvement in operation of flood control and water storage impoundments.

Winter recreation has become an important economic aspect of the mountainous areas of the West. Selection of potential recreation sites and construction of ski lifts and access roads demand more adequate knowledge of snow distribution in relation to terrain and meteorologic variables.

Scope of the Study

This study was undertaken to investigate the distribution of the mountain snowpack during the winter accumulation season, and to relate this distribution to the parameters of elevation, aspect, degree of slope, location in relation to upwind ranges, and degree of exposure to prevailing winds.

Investigations were conducted at sites selected in the Bridger, Beartooth, and Madison Ranges of southwestern Montana to determine if consistent relationships between snowpack accumulation and terrain and meteorological variables could be developed using data from areas differing in geographic location and physiography. Field data were obtained during three winter seasons to test the consistency of these relationships from year to year.

II. REVIEW OF THE LITERATURE

Relationships between the snowpack and terrain variables have been a subject of continuing scientific interest in the United States since early in the Twentieth century. Demands for improved predictors of streamflow resulting from snowmelt, and increased awareness that forestry practices can alter watershed runoff characteristics have stimulated much of the research into snowpack-terrain relationships in the western states.

Snow surveys in the United States were first initiated in the Sierra Nevada region of California following the development of the Mount Rose snow sampler by J.E. Church in 1904 (Church, 1933). The development of this instrument allowed field personnel to make rapid, accurate measurements of the water content of the snowpack for the first time. From his early pioneering work, Church concluded that the snow water content increased with elevation on the windward side of the Sierras. He attributed this to the effects of increased wind action at higher elevations packing the snow into high density drifts above the tree line (Church, 1933). Church was also the first to postulate that the "ideal" forest from the standpoint of water storage was one which contained a large number of open glades which would reduce interception and serve to trap snow (Church, 1912).

Comparative studies by Bates and Henry (1928) of two small watersheds near Wagon Wheel Gap, Colorado, established that a clear-cut watershed generated a larger volume of runoff than one which remained in its natural state. Runoff was observed to be generated earlier in the melt season in the denuded watershed, and the rate of erosion was greatly accelerated in comparison to the uncut watershed.

Connaughton (1935) compared runoff produced from five study areas in the Boise River watershed in central Idaho. All study plots were in mature stands of ponderosa pine and were similar in terrain characteristics except for degree of forest cover. Maximum water yields were consistently obtained from a clear-cut area. The snow catch in timbered areas was observed to be less than in open areas, and this difference was attributed to interception losses. Although timbered areas stored less snow than open areas, they retained snow longer into the melt period.

A graphical correlation technique for estimating missing precipitation data in western Colorado was developed by Spreen (1947). Using eleven years of historical data for 32 precipitation stations, winter precipitation was graphically related to topographic parameters of elevation, slope, exposure, and orientation of the greatest exposure. A linear correlation of .86 was obtained from a comparison of actual to estimated precipitation using the four variables. No attempt was made to evaluate the magnitude of the contributions of individual parameters.

Wilm (1948) presented results from several plot studies conducted in the Fraser Experimental Forest in Colorado. Twenty plots having an area of five acres each were subjected to varying degrees of thinning after several years of control observations. Open areas were found to accumulate more snow than heavily forested plots. However, all plots reached the end of the melt season at approximately the same time and no retention of snow in the forested areas was observed. Exposure of plots to radiation was important during the melt period, but had no discernable effect during the accumulation season.

Haupt (1951) made a three year study of 256 sampling points in uneven-aged virgin ponderosa pine in the Boise Basin Experimental Forest in Idaho. Sampling locations covered a wide range of slope aspects and tree cover, but were limited to an elevation range of 4000 to 5000 feet MSL. Openings in the timber on north facing slopes having a diameter greater than 60 feet were found to be most effective in accumulating and retaining snow.

Two thinning treatments in young lodgepole pine stands in the Fraser Experimental Forest of Colorado were studied by Goodell (1951). They produced significant increases in snowfall accumulation and volume of spring melt. During the three years after thinning treatments were performed, a snowpack increase averaging 20% was observed in the thinned areas. The eighteen experimental plots were selected to obtain a wide distribution of slope, aspect, and stand density, but none of these factors apparently produced any noticable effect during the accumulation season.

The Corps of Engineers (1951, 1953, 1956) carried out experiments at the Central Sierra Snow Laboratory (CSSL) in California, and at the Upper Columbia Snow Laboratory (USCL) in Montana for a period of several years. These were analyzed to determine the effects of terrain characteristics on snow accumulation. Terrain parameters considered were: (1) elevation, (2) slope, (3) aspect, (4) curvature of the slope in the vicinity of the site, (5) exposure, and (6) canopy cover within a radius of approximately 400 feet of the site. Multiple linear regression analysis of data from the CSSL study area showed that 58% of the snowpack water equivalent variance could be explained using all variables. However, in general only elevation, aspect, and exposure were statistically significant. Of these, elevation produced the largest effect with an increase of approximately 1 to 2.5 inches of water equivalent per 100 foot increase in elevation. It should be pointed out that these studies were carried out over a relatively narrow range of terrain conditions, and that variables were not always adequately sampled due to the physical characteristics of the study areas. For example, the majority of the steep slopes at CSSL had only southerly exposures. Also the CSSL portion of the study utilized data from only 21 to 36 individual snowcourses depending on the year of the study, while the snow sampling network in the USCL contained only 17 snowcourses. Due to the lack of comprehensive data it was concluded that it was probably not valid to apply the quantitative relationships developed to other areas.

Anderson and Pagenhart (1957) used water equivalent data from the 32 CSSL snowcourses of 1950-1951 to investigate the effects of terrain and forest characteristics on snow accumulation. Terrain variables utilized were: (1) elevation, (2) curvature, (3) exposure, (4) average incoming shortwave radiation, (5) slope, and (6) aspect. Forest characteristics considered were: (1) shade, (2) shelter from wind by adjacent trees to the south, and (3) shelter from wind by trees within one-quarter mile south of the sites. Multiple regression analysis showed that 62% of the April 10 variance in water equivalent values could be explained using all variables. The solar radiation term was more effective in explaining variance than the inclusion of both slope and aspect, and a 24% increase in explained variation was attributed to the inclusion of the forest characteristic terms. The snowpack water equivalent was found to increase with elevation and with protection by heavy cover some distance to the south. Decreases were observed in areas having large amounts of incoming solar radiation, and in locations having tree cover immediately adjacent to the site.

Leaf (1962) investigated the characteristics of reliable snowfall sampling sites in the vicinity of Climax, Colorado. Snowboard, snowcourse, and precipitation gage data were analyzed using double mass plots and multiple regression techniques. The most favorable sites for obtaining representative snowfall data along the 33 snowboard network were protected from storm winds by trees, with an angle from the sampling point to the treeline of approximately 30 degrees. An almost linear relationship between elevation and snowpack water equivalent was observed.

An intensive investigation of the relationships between snowpack water equivalents and terrain variables of elevation, aspect, and canopy cover was conducted by Packer (1962) in the Priest River Experimental Forest of northern Idaho. Water equivalent measurements during the accumulation season were made at approximately 10 day intervals at 273 stations in 1949, 408 stations in 1950, 370 stations in 1951, and 191 sites in 1952. Curvilinear multiple regression analysis indicated that elevation had the greatest effect on the water content of the snowpack. The water equivalent consistently increased with elevation in a curvilinear manner. Sites with northerly aspects accumulated more snow than did those on south facing slopes; however, the differences may have been largely due to melt effects. Canopy cover had the least effect, and differences were felt to be largely due to interception losses, as larger openings accumulated more snow than small ones.

Anderson and West (1965) made a detailed study of data from 163 snowcourses in the central Sierra Nevada region of California using both factor analysis with varimax rotation and principal components analysis. Terrain variables were considered on both a meso and micro scale. Meso-terrain variables measured included parameters of:

(1) topographic shade, (2) forest density within one mile of the site, and (3) position of the site with respect to surrounding topography. Micro features at the sites included: (1) elevation, (2) slope, (3) aspect, (4) canopy cover, (5) tree height, and (6) location of the snowcourse within a forest or clearing. Three years of data were used in the analysis and the following general conclusions were reached:

(1) Water equivalent of the snowpack increased with elevation.

(2) Snowcourses with mid-slope positions accumulated more water than ridge or valley bottom locations.

(3) Large openings contained more snow than smaller ones, particularly at high elevations in heavy snow years.

(4) Immature tree stands had more snow trapped under them than did mature stands, particularly in low snowfall years.

(5) Tree species had a definite effect. Red fir stands consistently accumulated more snow than lodgepole or ponderosa pine stands.

Snow accumulation in clear-cut blocks ranging from 5 to 20 acres in size were studied in the Big Horn Mountains of Wyoming by Berndt (1965). Maximum water equivalent of the clear-cut blocks was observed to be 40% greater than the uncut blocks. Snow which accumulated in the clear-cut areas melted sooner than that in the undisturbed forest, and it was concluded that clear-cut blocks smaller than five acres would be necessary to provide both increased accumulation and delayed melt.

Stanton (1966) investigated differences in accumulation in forested and clear-cut areas of the Crowsnest Forest of western Alberta, Canada. Clear-cut areas were found to have 3 to 36% more snow than forested control areas. Melt was observed to take place more rapidly on the clear-cut blocks. Accumulation patterns on north facing slopes showed an increase in water content of 1.5 inches per 100 feet of elevation.

An interesting study on interception losses in Colorado was conducted by Hoover and Leaf (1966) in the Fraser Experimental Forest. Observations made during the winters of 1963-64 and 1964-65 indicated that mechanical processes may dominate over vaporization in removal of intercepted snow. It was found that in the absence of riming, intercepted snow was not firmly attached to vegetative surfaces, but instead, merely rested gently upon them. Any mechanical disturbance of the trees through wind action tended to remove the intercepted snow from the branches and redistribute it through the forest. Reevaluation of data from the Wagon Wheel Gap and Fool Creek Watershed studies indicated that strip or clear-cutting practices had not increased the total snow storage on the watersheds. Instead, the distribution of the snowpack was altered, while the total amount remained approximately the same. It was concluded that losses through sublimation or evaporation of intercepted snow were insignificant. Hoover and Leaf attributed the differences in snow accumulation in forested and open areas to the effectiveness of open strips in trapping snow transported from forested areas. They theorized that before cutting, wind action tended to distribute intercepted snow quite uniformly throughout the forest, but opening of strips or clear-cut blocks created effective snow traps.

Observations were made in the Beaver Creek watershed in north-central Arizona by Ffolliott and Hansen (1968) to determine how snowpack accumulation was affected by elevation, timber stocking, and potential insolation. As in other studies, snow accumulation was found to increase with: (1) elevation, (2) open rather than dense stands, and (3) sites with low potential insolation.

Meiman (1969) summarized a considerable number of prior investigations in his review of the relationships between snow accumulation and elevation, aspect, and forest canopy. He concludes that elevation is the most important factor in explaining snowpack accumulation differences, although great variability between individual study areas is noted. Effects of aspect seemed to be confined to influencing melt, and timber management practices which reduced canopy cover consistently produced increases in snowpack accumulation.

Summary

The literature surveyed suggests that the following generalized conclusions can be made regarding the interrelationships between the snowpack and terrain factors:

(1) The snowpack increases with elevation in a linear or curvilinear manner depending on the particular study

area. Elevation is the single most important terrain factor in explaining variation in mountain snowpack distribution.

(2) Openings in forests, whether natural or the result of timber harvesting practices, contain more snow than the forest proper. The majority of authors attribute this difference to losses by sublimation or evaporation of intercepted snow on the forest canopy. The study by Hoover and Leaf, however, strongly suggests that wind redistribution is largely responsible for the observed distribution, and that losses by vaporization are of minor importance. Studies which indicate that protection from storm winds is an important factor in explaining snow accumulation tend to support Hoover and Leaf's conclusions.

(3) Open, or sparsely stocked forest areas, generate a greater volume of melt per unit area and do so earlier in the year than heavily forested tracts. This is apparently due to several separate factors including: (a) the increased amounts of direct solar radiation reaching the snowpack in open areas, (b) the smaller water deficit in soils underlying clear areas, and (c) the fact that evaporative losses are reduced when the rate of melt is accelerated.

(4) Sloping areas with northerly aspects tend to accumulate more snow and retain this snow longer into the melt season than do

south-facing slopes. These differences are largely attributable to the amounts of solar radiation received. In some studies melt on south-facing slopes may have occurred at intervals during the accumulation season.

III. DESCRIPTION OF STUDY AREAS AND SAMPLING PROGRAM

General

Three areas were selected for study to determine if the interrelationships between the snowpack and other measured variables were consistent over mountain ranges differing in location and terrain features. Locations were selected in the Bridger, Madison, and Beartooth Ranges of southwestern Montana (Figure 1) during the fall of 1967. Each of the areas was within reasonable traveling distance of Bozeman, and offered a sufficient diversity of terrain to allow selection of a wide sample of terrain parameters for study.

Bangtail Area of the Bridger Range

Location and general description. The Bangtail area of the Bridger Range (Figure 2) is a secondary range lying approximately six to eight miles east of the main ridge crest of the Bridger Mountains. The study area lies 12 to 18 miles north and east of Bozeman, and is bounded on the north and east by latitude 45° 53', longitude 110° 45', and on the south and west by latitude 45° 41', longitude 110° 53'. Maximum relief within the area is 2600 feet, and local relief is moderate allowing reasonable summer travel throughout the area by truck or trail cycle, and winter travel by snowmobile. A curving ridge which dominates the area extends southeast from Grassy Mountain to the Bangtail Ranger Station, then turns south to Angel benchmark and west towards School