PROSPECTS FOR AFFECTING THE QUANTITY AND TIMING OF WATER YIELD THROUGH SNOWPACK MANAGEMENT IN CALIFORNIA

By

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We might as well face up to it right at the start--no single way of managing land in the snow zone is going to give pur unqualified improvement in all aspects of water yield: more water, better timing of water yield, better quality of water, and reduced floods and sedimentation. If we apply management that will give us more water, we are likely to get more water sometimes when we don't want it. If we apply management that will give delayed water yield for summer irrigation, we may sometimes adversely delay the yield of water for winter power production. If we apply management to get the purest water, the greatest flood prevention, and the least sedimentation we may find it necessary to cover the land with water-hungry plants and we cannot expect the greatest water yield. In some places the conflicts will be critical; in other places trivial. Research results may allow us to resolve some of the conflicts and in any event point out the prospect for affecting the quality, quantity, and timing of water yield for various forest land and topographic sites.

THE SNOWPACK ZONE IN CALIFORNIA

The snowpack zone in California is nearly perfect hydrologically; we will have to watch our step in trying to improve it. California's snow zone is that area where more than half of the streamflow comes from a melting snowpack in the average year. It occupies about twelve million acres in the Sierra and northern California mountainous areas, lying above 5,000 feet elevation in the west side of the Sierra at the southern extremity and above 3,500 feet elevation in the Northern Sierra, Cascade, and Klamouth mountains (Colman, 1955).

Snow Zone Streamflow is Greatest and Least Variable

The zone yields about half of California's streamflow in the average year: 36 million acre-feet per year or 3 acre-feet per acre. Streamflow from the zone is not only the greatest from any zone in the state but is the least variable from year to year; there are fewer dry years than in the lower elevation zones.

How often do we get dry years in this snow zone? If we define dry years as those in which we get less than one-half normal streamflow, only one year in ten is a "dry year" in the snow zone (Corps of Engineers, 1958). By way of contrast, below the snow zone in the commercial timber belt two or three years in ten are "dry," and in the lower Sierra foothills not only do we get less water annually but it is more variable--three to five years in ten are "dry years."

Snow Zone Meteorology

California's snow zone is warm (Miller, 1955), so snow melts on most slopes and streams flow even in winter. Only on north slopes steeper than 15 percent and northeast and northwest slopes steeper than 25 percent is winter melt so small as not to satisfy the soil moisture deficit of 6-1/2 to 8 inches. So streams rise in early winter in most years: In 6 years out of 7, the flow of Castle Creek at the Central Sierra Snow Laboratory rose in January to March. This means that by April 1, in most years, soil moisture deficit is charged, and the April 1 snowpack is a good indicator of the amount of streamflow to follow.

Most of the water stored in the Sierra snowpack is nearly immune from evaporation losses, flood runoff, and rapid melt, despite the warm climate. The surface of the snow reflects most of the heat from the sun, 60 to 90 percent (Miller, 1955). Frequent small snow storms are hydrologically important in the Sierra snowpack zone because they restore the high reflectivity of the snow surface. The cold snow and snowmelt water cool the soil, tending to minimize transpiration losses by trees over long periods of the year. As a result of the short fairly cool summer and occasional summer and fall rainstorms, water may be left in the soil unused at the end of summer, thus contributing to next year's streamflow (Anderson and Gleason, 1959). We may take advantage of some of these characteristics of the hydrology of the snow zone in our management of forest and other lands for improved water yield.

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Snow Zone Terrain

Don't picture the snow zone as mile after mile of unbroken forest; studies by Lucille Richards (1959) have shown that the snow zone is made up mostly of large open areas—either bare or brush-covered--and forests of intermediate densities. Results for the Sierra-Nevada mountains, westside above 5,000 feet elevation, latitudes 37° 57½' to 39° 57½' were:

CONDITION	AREA PERCENT
Forest 15- 39 percent density	17
40- 69 percent density	20
70-100 percent density	5
Rock, bare ground	29
Brush	17
Grass-herb	7
Other	5
Total	100

Richards also found that 81 percent of the Sierra is of less than 40 percent slope, the most common slope being in the 11 to 20 percent class. All slope directions are well represented; the north and east slopes each include about 20 percent of the area, south slopes 26 percent, and west slopes 32 percent. Two percent of the area was level—mostly lakes. These results indicate the need for studying land conditions other than forest—to develop snowpack management for bare ground and rocky areas and, particularly, brushland areas. Management may well differ depending on the topographic site.

Snow accumulation and melt differ widely under natural conditions differing in topography and forest cover: elevation, slope and aspect, exposure (narrow canyons vs. broad valleys), curvature (ridge vs. slope vs. valley bottoms), and forest characteristics that affect interception, shading, shelter from wind, cold air drainage, etc. The effects on snow accumulation and melt of a range of terrain differences under natural conditions at the Central Sierra Snow Laboratory are generalized in the following tabulation (Mixsell et al, 1951), for the year 1950 when the maximum pack averaged 51 inches and the April 1 to June 1 melt averaged 40 inches:

Terrain variable and range	Effect on Maximum snow water	Effect on Apr. 1—June 1 melt water
	Inches	
Slope (5-50 percent)	-25	+ 0.9
Aspect (South to North)	+15	- 4.6
Elevation (6,900 - 8,300 ft.)	+14	-11.1
Curvature (Concave to Convex)	-14	+ 6.9
Exposure (Closed to Open)	- 4	+ 2.6
Forest (None to Dense)	-13	-21.7

Such wide differences of snow accumulation and melt on natural sites suggest that, on the different sites, management for increasing the quantity or improving the timing of water yield may be quite different and certainly differentially effective.

RESEARCH--PAST AND CURRENT

Research in snow management in California is of four vintages—The Tahoe studies of Church in 1910-43, the Stanislaus studies of Kittredge in 1933-39, the Teakettle studies of 1939-1941, and the Cooperative Snow Management Research Program of 1956 to date.

Several other studies have contributed basic information. Notable are the snow hydrology studies of the Cooperative Snow Investigations in the period 1946-52 (Corps of Engineers, 1956), and the snowmelt runoff and flood control studies of various water and power companies and state and federal agencies. These all form a framework in which snow management research operates.

Church's Studies

Nearly 50 years ago, Church (1914) was making observations of the effects of forests and openings in forests on snow. He advocated the use of timber screens instead of solid forests to create snow drifting and delay snowmelt. From observation and measurement of snow in many sites, Church (1933) concluded; "The ideal conservation forest is one honey-combed with glades whose extent is so related to the height of the trees that the sun cannot reach the surface of the snow. Such a forest will permit far more snow to reach the ground than will a forest of great and uniform density and yet will amply protect the snow from the effects of sun and wind."

Teakettle Studies

The studies at the Teakettle Experimental Forest were briefly reported by Connaughton (1940): "Very recently a study of three major watersheds of about 500 acres each has been started in California. These watersheds are on the headwaters of the Kings River in the high Sierra Nevada and support a dense stand of pine and fir. During the winter of 1939 and 1940 water yields from these areas were measured; semi-monthly snow surveys on 2 courses and monthly surveys on 14 courses were made; and records were kept of ground and snow temperatures, and rainfall and snowfall in both shielded and unshielded gages." In 1956, these watersheds were incorporated in the new California Snow Management Studies.

Kittredge's Studies

Kittredge (1953) summarized his studies for the years 1934 to 1941. These were conducted in the Central Sierra mixed-conifer belt at elevations between 5,200 and 6,200 feet, where snow accumulation ranged from 3 to 30 inches. The studies were undertaken to find out what kinds of forests, that is, what densities and sizes of openings in forests, are most effective in promoting snow accumulation and melt. Kittredge found that openings with a width about one to two times the tree height had the most snow. He found also that evaporation from snow was small--seasonal losses averaged only 0.42 inches for all types. Unfortunately in these study sites species and densities were so tied in with topographic variations as to make impossible direct comparisons of their effects on snow accumulation. Kittredge concluded that "clear cutting in small groups should both yield the most water and prolong the summer flow. Strip cutting might also give results if the clear cut strips are narrow, if they follow, as far as possible, the contours, and are oriented east and west rather than north and south."

COOPERATIVE SNOW MANAGEMENT STUDIES

In July 1956, the Forest Service, in cooperation with the State of California, started research aimed at improving California's water yield through management of land in the snowpack zone.1/ Studies are of four general kinds: Inventory of present condition of water yield, land condition, and soil; basic studies of forest hydrology, meteorology, and snow; plot test of the effects of land management methods on snow accumulation and water losses, and preparation for pilot testing of land management of experimental watersheds for their effects on streamflow and sedimentation.

Some of the results of the inventory of forest and land conditions in the snow zone have been summarized above; some of the results of the other studies will be briefly highlighted, some management implications of the research will be discussed, and some major questions and problems still remaining will be outlined.

RESULTS TO DATE

Logging in strips, in blocks, and by selection cutting, the way slash is treated, and brush removal--all have been found to effect snow accumulation, snowmelt, and water yield (Anderson and Gleason, 1959, 1960). The forest effects on snow accumulation and melt have been found to vary widely on various typographic sites (Anderson, Rice, and West, 1958b). Our ability to predict the forest effects on snow accumulation and melt has improved as we have learned to index the separate effects of forests on interception of snow, on solar- and long-wave radiation received at the snow surface, and on heat received by conduction and convection (Anderson, 1956; Anderson, Rice, and West, 1958 a).

Studies of Snow Accumulation and Melt

In the current cooperative snow management research program, 83 snow courses were selected at elevations ranging from 6,000 to 7,800 feet to permit study of snow accumulation and melt in a wide span of combinations of elevation, slope steepness, slope direction, forest densities, opening size, and ground cover conditions. Snow has been measured at about monthly intervals throughout the winters of 1957-58 and 1958-59, and are continuing in 1959-60. In the 1946-52 Snow Investigations at Soda Springs, snow accumulation and melt was measured at 31 snow courses for periods of 1-5 years. These data have been analyzed and published results of studies using these data will be cited in succeeding paragraphs. Effects of four types of logging and brush removal on snow accumulation and melt will be

1/ The studies are being conducted by the Pacific Southwest Forest and Range Experiment Station, with the State Department of Water Resources lending financial and other aid. Other agencies are giving a hand: the Pacific Gas and Electric Company, the Weather Bureau, and the Department of Zoology of the University of California. Currently, eighteen separate studies are under way. A staff of ten technicians-meteorologists, soil scientists, and foresters--are conducting the studies.

discussed: clear cutting, strip cutting, block cutting, and selection cutting of forests.

Effects of Clear Cutting on Snow Accumulation and Melt

Clear cutting[2/] increases the amount of snow water stored in the pack and increases the melt rate in these high elevation forests. Open areas had 12.7 inches more than than dense forests in 1950 at the Central Sierra Snow Laboratory (Mixsell et al, 1951). The estimated long-term average difference between large open areas and dense forest was 11 inches of water (Anderson, 1956). Spring melt of the snowpack was found to be much faster in the large open areas than in the dense forest. April 1 to June 1 melt in 1950 at the Central Sierra Snow Laboratory was 22 inches of water greater in the large clear area than in dense forest. (Mixsell et al, 1951). Long term average April 1 to June 1 melt was estimated to be 41 inches in the large open areas and 23 inches in the dense forest, or 18 inches greater melt in the large open areas (Anderson, 1956). When all the snow was gone from the large open areas, 16 inches of water remained in the dense forest. We conclude that clear cutting of forest areas will increase the total amount of snowpack and also increase the melt rate of the pack.

Strip Cutting Effects on Snow Accumulation and Melt

Strip cutting of forests has been found to have some of the benefits of clear cutting in increasing the maximum snowpack but without increasing the melt to the extent that clear cutting does. Most studies have shown that maximum snow accumulation occurs in strips cut about one times tree height in width (Church, 1933; Kittredge, 1953; Anderson, 1956). However, snowmelt after April 1, or after the time of the maximum pack, is more rapid in wide than in narrow strips; as the spring season progresses, the maximum unmelted snow is found in narrower and narrower strips. The last snow is found in strips about one-half tree height across and in the uncut forest (Anderson, 1956). For east-west oriented strips, in the average year at the Central Sierra Snow Laboratory about 13 inches more water is found in strips one tree height across and about 11 to 12 inches in strips about one-half tree height across. On June 1 in the average year, it was computed that a strip one-half tree height across would have about 6 inches more than the dense forest and about 15 inches more water than the large open areas. Dense forest cut in strips would have an advantage over the uncut forest in snow accumulation and an advantage over clear cut forests in delaying of some of the snowmelt.

Block Cutting Effect on Snow Accumulation and Melt

Forests cut in blocks of small size and of particular shape and orientation may have some advantages over strip cut forests. An analysis showed that a square block one tree height across would have 3 inches more water in late spring than in a cut strip one tree height across (Anderson, 1956). This would be the "honey-comb" forest proposed by Church (1941). For a rectangular block 5 tree heights long by 1 tree height wide, with the long dimension oriented east and west, snow in late spring would be only slightly greater than in the strip—about one-half inch greater.

Some recent analyses (Anderson, Rice, West, 1958) have indicated that L-shaped openings cut in forests on east and west facing slopes may have some advantage over openings that are circular or square in shape. On west-facing slopes we can cut L-shape openings with one arm of the L extending to the north and the other uphill to the east; on east slopes the L is reversed, one arm extending uphill to the west. Snow in L-shaped openings will be cooled by radiation, the air in contact with the snow is then cooled from the uphill arm into the other arm, where it will be trapped. About 2 inches more water at maximum snow accumulation might be achieved by cutting L-shaped openings rather than circular ones.

Selective Cutting Effects on Snow Accumulation and Melt

Selective cutting of forests increases the maximum accumulation of snow and also speeds the melt of the snow, according to recent studies (Anderson, Rice, West, 1958; Anderson and Gleason, 1959). When forests of various average densities, simulating various degrees of selective cutting, are compared, we find that at the time of maximum pack the forest of 20-50 percent density has some 2 inches more water than the forest of 50-80 percent and some 9 inches more than in the forest of 80-100 percent density. These differences were found in a year in which the range of snowpack water was from 48-57 inches; a similar difference, 7 inches as compared with 9 inches, was found in a year with 17 to 24 inches of snowpack water. In another study (Anderson and Gleason, 1959), a commercial selection cut producted 7 inches more water in the snowpack in a year of high snowfall and 6 inches more water in a light snowfall year that followed.

2/ Cutting of block of greater than 20 acres or in strips greater than 4 tree heights in width are here considered as clear-cuttings.

Spring melt of the snow was faster in the forests cut selectively than in the uncut forests--the result was that small amounts of snow water were left in the uncut forest when snow was gone in the selectively cut forest (Anderson and Gleason, 1959). If a 50 percent selection cut and a 50 percent strip cut are compared, we find 7 inches more water in the strip cut forest than in the 50 percent selection cut at the time of maximum accumulation, and 1 inch more in the late spring on June 1, 1958. Hence, we conclude there are some advantages of the strip cut over the selection cut in both snow accumulation and melt.

Water Yield from Strip, Block, and Selection Cuttings

Winter water losses.--How much are the winter water losses--interception, evaporation of snow, and transpiration by the trees? First, let us admit that we have found no way of measuring the winter transpiration loss by trees when the ground is snow covered. Estimates of these losses range from about 2-1/2 inches to 9 inches (Anderson and Gleason, 1959); Miller, 1955). We do have, however, good estimates of interception loss and evaporation from snow under various conditions of logged and unlogged forests.

Interception loss.--This is the water lost by evaporation from the wetted tree parts or from the snow clinging to the trees. Interception loss from a dense lodgepole pine stand at the Central Sierra Snow Laboratory in April, 1958 was 8 percent of the precipitation (West and Knoerr, 1958). Interception during snow storms in an 80-year old ponderosa pine stand at Bass Lake, California was 10 percent of the precipitation (Rowe and Hendrix, 1950). Kittredge (1953) gives similar data for other forest types. Interception losses for an average size snow storm of 2 inches of precipitation, assuming stemflow amounting to 3 percent of the precipitation, were: 11 percent of the precipitation for stands of mature ponderosa pine, 15 percent for stands of mixed conifers, and 16 percent for dense stands of mature red or white fir. The effect of cutting the forests on interception loss is about proportional to the amount of the cut. Kittredge (1953) found, for a selectively cut mixed forest, a 50 percent decrease in interception for a 50 percent removal of the tree canopy. Reductions in interception loss due to logging were estimated by Anderson and Gleason (1959) when winter precipitation was 38 to 41 inches. The saving was 3.4 inches for a strip-cut area, 2.3 inches for a block-cut area, and 1.6 inches for a selection cut area.

Evaporation losses from snow.--Evaporation has been found to be small in the Sierra except at wide open areas and on exposed ridges. During the winters of 1958 and 1959, at 7,000 feet elevation near the Central Sierra Snow Laboratory, West (1959) found that annual snow evaporation losses under forest stands were 0.4 and 0.9 inches; in small forest openings losses were 1.1 and 1.7 inches. In a 10-day study in April 1959, evaporation from a large open area was 1.7 times that from the small opening, and evaporation from exposed ridges was 3 times that from the small opening. These results indicate that cutting of areas in strips and blocks can be expected to increase evaporative losses by 1/2 to 1 inch per year. Clear cutting of large areas, especially on exposed ridges, might increase losses by 1-1/2 to 3-1/2 inches per year.

Logging reduced the total winter water loss. Combined interception, snow evaporation and winter transpiration have been estimated to be 5.4 inches less in a cut strip, 3.6 inches less in a cut block, and 2.5 inches less in commercial selection cutting than in an uncut forest (Anderson and Gleason, 1959).

Summer soil moisture losses.--Water lost from the soil during summer must be replaced by fall precipitation or by winter snowmelt before streams will start to rise. How the forests are logged affects soil moisture losses as well as losses of precipitation during summer, and hence affects the amount of water yielded as streamflow.

Summer soil moisture losses were taken as the difference in stored moisture in the soil at the end of the snowmelt in the spring and at the beginning of the next winter storms. Soil moisture was measured with the nuclear soil moisture probe. Summer and fall precipitation was added to the soil moisture losses to give total summer water losses. Differences in losses between unlogged forests and forests cut in strips, in blocks, and by commercial selection cut were compared (Anderson and Gleason, 1960). In each case logging saved water. Savings for soil 48 inches deep for the 2 years of study were:

Logging Method	Water Saved 1958	Water Saved 1959
	- Inches -	
Strip cut	3.2	4.1
Block cut	2.7	3.4
Commercial selection cut	0.9	0.8

We see that the greatest reduction in summer water losses was on the strip cut area; slightly less saving was realized on the block cut, and only small savings on the commercial selection cut.

Increases in water yield after logging.—Expected differences in water yield resulting from logging can be estimated by putting together these and other data available on snow accumulation, snowmelt, interception loss, and summer water losses. The method is the usual water balance method, similar to that of Wilm and Dunford (1948). For the year April 15, 1958, to April 14, 1959, total water losses in unlogged forests and savings in forests logged in 3 different ways have been estimated by Anderson and Gleason (1959):

Total water losses (inches)	—	21.0
Savings in cut strip (inches)	—	8.6
Savings in cut block (inches	—	6.3
Savings in commercial selection cut (inches)	—	3.4

The strip cut was most effective in saving water, the block cutting next, and the commercial selection cutting least.

Savings in Water Losses by Brush Removal

Appreciable savings in water losses have been measured following brush removal (Anderson and Gleason, 1960). For a 4-foot soil depth, these savings were 2.6 inches in 1958 and 3.2 inches in 1959; for 7-foot soil depth, the saving was about 8 inches per year. By using interception in equations found by Hamilton and Rowe (1948), and snow evaporation data from Kittredge (1953) and West (1959) we may estimate the total savings in water—summer savings in soil moisture, saving of interception in fall and spring, and savings in evapotranspiration losses during early winter and early spring:

Soil water losses	3.0
Fall and spring interception	1.0
Fall and spring transpiration	1.5
Snow evaporation	-0.5
	5.0

These savings would be for the first two years after brush removal; if the brush is replaced by trees or grass, then we would expect these savings to diminish with time.

It can be concluded that cutting of forests and removal of brush can be expected to save water by reduction in the transpiration and interception losses. Reduced soil moisture losses account for roughly half of the savings in the commercial selection cut, strip cut, and the block cut, and where brush was removed. The increase in soil moisture carry-over results in greater water yield with heavy fall rains or winter melt. This soil moisture can contribute to late fall floods because less soil moisture storage capacity is available. When we cut timber or remove brush to get more water, we may get some of the water when we don't want it.

PROBLEMS REMAINING

1. Can certain treatments of forest and brushlands, designed specifically to give greater water yield or delay yield longer, improve on these results?

A method of cutting forests so as to produce a wall-and-step forest, with the wall to the south and the steps to the north has been proposed (Anderson, 1956). This proposal is an elaboration of those of Church (1933) and Kittredge (1953). How much better, if any, is this than the formal strip or block cut or selection cut forest? Equations indicate an average of 3.3 inches more water after April 1 can be delivered from the wall-and-step forest than from a simple cut strip.

2. When forests are logged, does the way that the slash is disposed of affect the timing and amount of water yield?

First results (Anderson and Gleason, 1960) indicate that removal of the slash may increase snow storage by as much as 4 inches—hence water is yielded later in the spring. Little difference in summer water losses was measured between the different slash treatments. Would other benefits arise if slash were chipped into small pieces and distributed over the ground? Would benefits in snow accumulation and melt result if slash were piled on the downhill sides of openings so as to trap cold air? Studies of these treatments are needed.

3. Are permanent screens of trees needed at the "lips of canyons" as suggested by Church (1941), and on ridges?

We need to know much more about the inter-relationship of forest stands and topography affecting snow accumulation and melt and water yield.

4. We need to have a much more thorough understanding of the effects of topography and forests on the heat and moisture balance and its components.

What is the effect of advective melting of the snow versus melting by radiation, especially on slopes exposed to the prevailing winds? Under conditions of condensation of moisture on snow, what happens to the heat of fusion--does it all melt snow, does some of it warm the air, or is some of it lost by radiation? How does it affect albedo? These things will all have an important part in the design of forests of the future or treatment of forests in ways that will increase the quantity of and improve the timing of water yield.

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