Managing California's Snow Zone Lands for Water

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Foreword

Since 1956, the Pacific Southwest Forest and Range Experiment Station and the California Department of Water Resources have conducted the California cooperative snow management research program. Other organizations cooperating in the project include the University of California, U. S. Geological Survey, U. S. Weather Bureau, Fiberboard Corporation, and Pacific Gas and Electric Company.

This report summarizes the results of basic studies of snow zone hydrology completed during the first seven years of this joint program. It describes the results of the first application of management tests for improved water yield in the California snow zone.

We hope soon to have more elaborate techniques to meet the specific problems of increasing the amount of water yield, improving the timing of water yield, and preventing floods and sedimentation.

We do not yet know all there is to know about managing high elevation forest lands for improved water yield. But the information now available may help those who must decide about water resources management and plan for the future.

The Author

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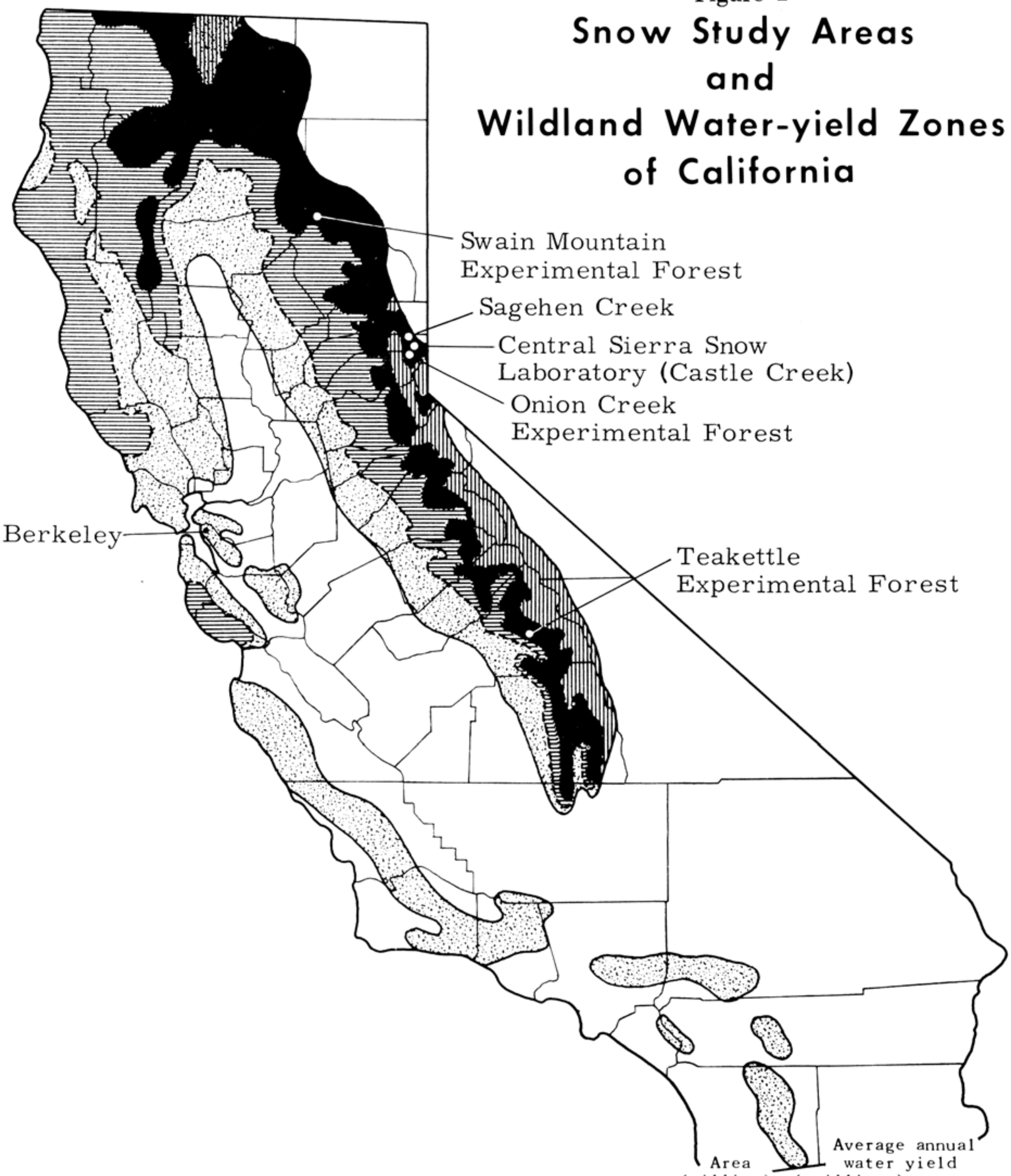


WILDLAND ZONES	Area (million acres)	Average annual water yield (million acre feet)	Average annual water yield (percent)
Woodland-brush-grass zone	18	9	12
Lower conifer zone	12	23	32
Snow zone: Commercial forest	9	27	38
Alpine	3	9	13
WILDLAND TOTAL	42	68	95
ENTIRE STATE	101	71	100

No single method of managing forested watersheds will provide improvement in all aspects of water yield. Consequently, some objectives of water resources managers are contradictory. If we want more water, it is likely to come sometimes when we do not want it, and we may have to make special provisions to keep that extra water from doing damage. If we want delayed water yield for summer irrigation, we may sometimes adversely delay the yield for winter power production. The purest water of the forest comes from the least use of the forest. Objectives of flood control are not likely to be compatible with those of greatest water yield. In some places the conflict over objectives will be critical; in other places, trivial.

Those who must produce timber for the mill and water for use want answers to such questions as: What difference does it make when logging is done in this way or that? At this place or that? On the north side of Granite Peak and in Holcomb Valley? In thin stands and dense stands? How does a particular logging practice affect-water yield?

This report includes information which, when combined with what the water resources manager knows about his particular watershed and its behavior, may allow him to make critical management decisions. But only he can decide whether the differences are likely to be worthwhile to him and the water users.

Water Yield and Water Sources

Before we consider water management, perhaps we should look at "inventory sheets" of our water supply: What do we have, when do we get it, where is it coming from, how variable is it, and why does it vary? Answers to such questions will indicate the areas where management for water is likely to be the most effective.

Water Yield by California *Streams*

Water yield by California streams comes largely from four zones: (a) the high elevation alpine snowpack zone; (b) the commercial timber snowpack zone; (c) the lower conifer zone; (d) the woodland, brush, and grass zone at lower elevations (fig. 1). Together these four zones yield 95 percent of California's streamflow (Colman 1955). The two snowpack zones combined yield 51 percent, the lower conifer "rain zone" 32 percent, and the foothill woodland zone about 12 percent. The average annual yield of water from the four zones is 71 million acre-feet (California Department of Water Resources 1957). This amount would be enough to meet California's foreseeable needs if water was delivered where needed, and in an orderly manner each year. But much of today's water is produced far from the point of need, flood flows are far from orderly, and water yield varies widely from year to year.

In an average year, we have enough water to fill most of our reservoirs and to refill them after the first early summer irrigation use. If we always had the average water yield, we would have no problems, but we do not. Some years are dry and we thirst for water; other years are wet and we lose our water in flood runoff.

Variability of Annual Streamflow

How does annual streamflow vary in the elevation and geographic zones of California? It is least variable from the high elevation snow zone, highly variable from the foothill watersheds of the south part of the Sierra Nevada, and most variable from areas adjacent to the southern San Joaquin Valley and coastal areas south of San Luis Obispo (Corps of Engineers 1958).

How often do we get dry years in the different zones? "Dry years" can be defined as those in which a zone yields less than half the normal streamflow. The snow zone along the Sierra Nevada crest and whole north end of California are high water-producing sources and the most consistent producers. Less than 1 year in 10 is a "dry year" in these zones. In the southern Sierra Nevada's lower conifer zone, 2 to 3 years in 10 are dry. And, as we go lower in the Sierra Nevada to the foothill woodlands zone, not only do we get less water annually, but. it is more variable: 3 to 5 years in 10 are dry years.

Why this variability in annual streamflow? We might possibly look further into the causes, because they have implications in forest management for water yield. Certainly in comparing the variability of streamflow in northern California and the southern Sierra Nevada, the number of winter storms which cross the northern part is not only greater, but less variable from year to year. But if we consider the variability in the southern Sierra Nevada as a unit, the remarkably low variability at high elevations deserves explanation.

Let us consider differences in precipitation and winter losses of water. Most water stored in the Sierra Nevada snowpack is nearly immune from evaporation losses, flash flood runoff, and rapid melt. Water loss by evaporation from the snowpack is small: 4.5 inches on exposed ridges, 2 inches in large open area, and less than 1 inch under forest stands (Anderson 1958; Kittredge 1953; West 1959; West and Knoerr 1959). Snow held until late spring gains water by condensation rather than losing it by evaporation. The surface of the snow reflects most of the heat from the sun: 90 percent reflected from new snow, and 60 percent as the surface ages (Miller 1955). Small snowstorms are hydrologically important in the Sierra Nevada snowpack zone, restoring the high reflectivity of the snow surface. The snow and snowmelt water cools the soil, tending to minimize transpiration losses by the trees over long periods. As a result of the short, fairly cool summer and occasional .summer and fall rainstorms, water in smile years may remain unused in the soil at the end of the summer and thus contribute to next year's streamflow (Anderson and Gleason 1959).

In contrast, let us examine the hydrology of the lower elevation forests and woodland brush and grass zones. Precipitation is mostly in the form of rain or light snowfall that melts after a few hours or days. Part of the rain of every storm is caught by the forest trees, evaporates rapidly during breaks in the storm and between storms, and is thus lost. Whenever water is stored in the soil, transpiration by the trees is likely to be active. Between every storm, the vegetation, litter, and soil surface dry by evaporation (Rowe 1955; Rowe and Colman 1951). Small storms contribute little except to replenish and keep active these evaporative losses. Only in large storms does significant water penetrate the soil mantle and add to streamflow. Large storms in these lower zones are almost always rainstorms which in some places may produce floods and erosion problems rather than usable water. Clearly, the variability in annual streamflow from the rain zone and the woodland brush, and grass zone is associated with the size and number of storms and the opportunity for evaporative losses. The number, size, and distribution of these storms vary widely from year to year and bring about the wide difference in streamflow for the foothill woodland zones and to a lesser degree for the forest zones immediately above.

Seasonal Distribution of Streamflow

The interplay of winter rains and summer droughts, high elevation snowpack storage and fall rains, and runoff in dry and wet years all contribute to wide variability in the seasonal distribution of streamflow. Natural seasonal variability in streamflow may influence the objectives of our management for water. Let us consider briefly this variability as expressed by monthly streamflow in a snow zone watershed.

Monthly streamflow distribution even in snow zone watersheds differs widely between average dry and wet years (table 1). If we look at the critical period from June to September, we find in the average year that we get 24 percent of our water during that period. But in the driest of 10 years not only is the flow low for the year, but we get only 7 percent of our water during this important June to September period. Analyses of other snow zone watersheds in this area show similar results—flows come earlier in the dry years (Court 1961). Management that would pro-

Table 1. Streamflow distribution, in inches, in a watershed whose yield is chiefly from snowmelt (North Fork of Kings River at Cliff Camp, elevation 6,144 to 12,595 feet)

Month	Streamflow		
	Medium	10-year minimum[1]	10-year maximum [1]
Oct.	0.5	0.04	0.03
Nov.	.12	.05	1.00
Dec.	.30	.06	.98
Jan.	.39	.08	.82
Feb.	.53	.14	1.06
Mar.	1.33	.36	1.97
Apr.	4.72	2.24	7.29
May	10.52	3.20	17.20
June	6.00	.73	17.37
July	.81	.12	4.55
Aug.	.11 24%	.04 7%	.46 42%
Sept.	.04	.02	.14
Year	29	12	53

[1] *10-year minimums and maximums are flows expected to be not exceeded and exceeded, respectively, in 10 percent of all years.*

Figure 2.—Towers support meterological instruments which help evaluate moisture losses in summer and winter, snowmelt in winter, and the effects of wind, humidity, and temperature on water losses and snowmelt.

long water yield in these dry years would be most beneficial.

But we do not really manage whole watersheds; we manage individual forest sites on watersheds, each of which may require its own prescription. Knowledge of how snow accumulates and melts at different elevations and on different aspects and slopes, and of how forest cover plays its role will prescribe management of high elevation, forests for water yield.

Accumulation and Melt of the Snowpack

Let us concern ourselves first with two important characteristics of the Sierra Nevada snowpack: (a) maximum accumulation of snow, which is usually taken as the April 1 snowpack expressed as depth of water (inches) in the pack, and (b) ablation of the pack, or the rate of melt of snow water from the pack after April 1.[1] This first characteristic of the snowpack—the maximum accumulation—is a good indicator of total water yield[2] after April 1 each year; the second characteristic—melt rate—determines when that water is delivered.

Effects of Topography

Studies have shown wide differences in maximum snow accumulation and snowmelt under natural conditions differing in topography, includeing elevation, slope, aspect, exposure (narrow canyons v. broad valleys), curvature (ridge v. slope v. valley bottom), and forest characteristics that affect interception, shading, shelter from the wind, and cold air drainage (fig. 2).

Elevation Effects

The effect of elevation on snow accumulation and melt is shown by averages for the Yuba River Basin of the north central Sierra Nevada. Maximum snow accumulation there increases by 1.2 to 2.2 inches per 100 feet (Anderson and Pagenhart 1957; Anderson and Richards 1960, 1961; Mixsell et al. 1951); the long term average increase in the south fork of the Yuba River Basin is about 2 inches per 100 feet (Hannaford, Wolfe, and Miller 1958).

The spring melt rate of the snowpack tends to decrease with greater elevation. Re-analysis of the data of Mixsell et al. (1951) showed that between elevations of 6,800 and 8,600 feet, melt in April and May 1950, was greater by 0.4 inches of water per month for each drop of 100 feet in elevation, (Anderson and Pagenhart 1957). By combining these results with the long term average progresssion of melt with season (Anderson 1956), we get the general picture of change in snow and snowmelt with elevation (fig. 3). These relations of snowmelt to elevation apply to average slope exposure, curvature, and forest.

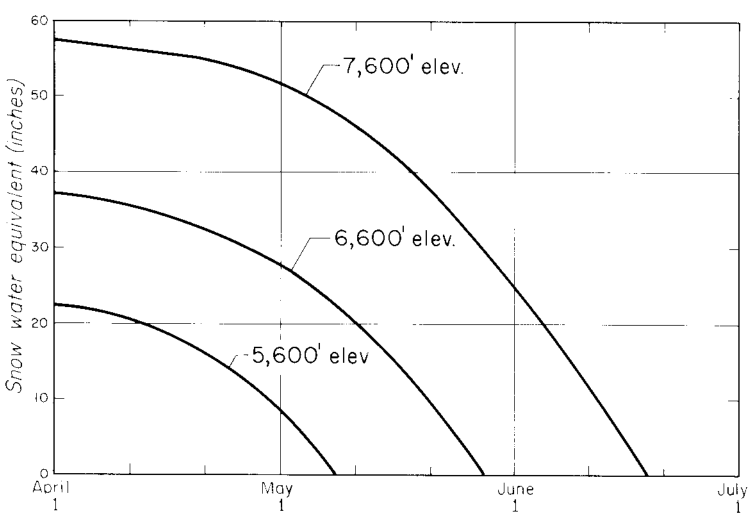


Figure 3.—Snow water in pack at average site and year, for three elevations, Yuba River Basin, California.

[1]Ablation consists mostly of snowmelt, but small amounts of gains by condensation or less by evaporation usually occur. It probably can be safely said that 95 percent of the ablation produces melt water in the Sierra Nevada.

[2]The maximum snowpack serves as a good indicator of the subsequent water yield because by April 1 the soil is nearly everywhere fully wet by winter snowmelt and fall and winter rains (Anderson 1960).

Slope and Aspect Effects

Slope and aspect effects on snow accumulation and melt rank next in importance to elevation (Anderson and Pagenhart 1957). Slope effects on maximum snow accumulation were best measured when slope was expressed in terms of the energy received on its surface. In winter the south slopes of 25 percent gradient received three times as much solar radiation as a north slope of 25 percent gradient. This fact principally explains why the north slope had 21 inches more water in the pack than did the south slope at the time of maximum snow accumulation. (South slopes also are exposed to the prevailing south and southwest winds. But these separate effects need more study, because trees can modify energy and wind effects in different ways.)

In the spring snowmelt, energy received on various slopes was also the most important single factor (Anderson and Pagenhart 1957). Mid-April melt of snow was 70 percent greater on the south slopes of 25 percent gradient than on the north slopes of 25 percent gradient. Thus, south slopes had less snow water stored at the time of maximum pack and then more rapid melt.

Curvature and Exposure Effects

The effects of curvature and exposure on snow accumulation and melt are only about one-fourth as great as those of elevation and solar energy differences. Snow accumulation and melt are different on ridges than on valley bottoms. These differences have been evaluated by classification of position on slope or shape of the terrain in terms of curvature: (1) Highly concave at the bottom of the slope, (2) moderately concave, (3) neutral in midslope or level, (4) moderately convex, and (5) highly convex at the ridge (Anderson and Pagenhart 1957; Mixsell et al. 1951).

At the time of maximum snow accumulation, ridge tops had 5.6 inches less water than did valley bottoms, according to an analysis of data from the Central Sierra Snow Laboratory (Anderson and Pagenhart 1957). Why? On exposed ridges loss of snow water by evaporation is twice that in a flat valley bottom (West 1959). Wind tends to blow drifting snow from exposed ridges. At a snow course on Boreal Ridge on April 22, 1958, we found only 1 to 6 inches of snow water on an exposed ridge, 180 to 200 inches in the drifted cornice, and 76 inches average in sheltered forest opening. Spring snowmelt also was about 20 percent faster on the ridges than in valley bottoms (Anderson and Pagenhart 1957; Mixsell et al. 1951).

Exposure also affects snow accumulation and melt. Snow accumulation tended to be less and melt faster in open exposed sites than in narrow canyons, even after considering the amount of direct solar radiation received. Open sites had 4 inches less water at the time of maximum accumulation, and the early spring melt rate was some 50 percent greater in the exposed sites than in the narrow canyons. The bottom of narrow draws, which have the least curvature and exposure, have maximum snow accumulation. Minimum melt rates also are found there, making them a good place to store snow. These results suggest the possibility of creating snow "ponds" to act as snow catchment and retention areas.

Heat Equivalent of Terrain

The relative effects of slope, elevation, and other topographic variables on maximum snow accumulation and on snowmelt can be compared by converting their effects into heat equivalents (Miller 1955). By using the results of multiple regression analyses of Mixsell et al. (1951) and Anderson and Pagenhart (1957), we get:

	Average difference in heat equivalent	
	Dec.-March	April-May
Range of topographic variable:	*(Calories per day)*	
Slope and aspect (25 percent N to 35 percent S)	+35	+41
Elevation (100 feet decrease)	+20	+37
Curvature (concave to convex)	+23	+23
Exposure (open to closed)	+ 5	+ 9
Forest (none to dense)	+20	–72

To convert melting snow to 1 inch of water requires 200 calories per square centimeter of area. We get, for example, 41/200 or about 0.2 inch per day more snowmelt in spring on a 25 percent south slope than on a 25 percent north slope. The maximum contrasts are between elevation zones and between forest and open areas; the forest prevented rapid snowmelt in the spring, but supplied heat in winter to evaporate or melt intercepted snow and snow near tree trunks.

In the above reported terrain effects on snow accumulation and melt, each effect was a partial one. That is, each was the independent effect of that terrain condition for average conditions of forest cover. Now let us consider some of that complexity known as "the forest effects on snow accumulation and melt."

Effects of Forests

Nearly 50 years ago, Church (1914) started making observations of snow in forests and openings. He advocated the use of timber screens instead of solid forests to create snow drifting and to delay snowmelt. From observation and measurement of snow in many sites, Church (1933, p. 538) concluded: "The ideal forest is one honeycombed 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 effect of sun and wind."

Kittredge (1953) made studies in the central Sierra Nevada mixed conifer belt at elevations between 5,200 and 6,200 feet, where snow accumulation ranged from 3 to 30 inches. He sought to find out what kinds of forests and what densities and sizes of openings in forests were most effective in promoting snow accumulation and melt. He concluded that openings with a width about 1 to 2 times the tree height had the most snow. The effects of species and densities were so tied in with topographic variation as to make impossible direct comparisons of their effects on snow accumulation. Kittredge further 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."

Studies of the California cooperative snow management research program in recent years have elaborated on the suggestions of Church and Kittredge and tested the effects of different methods of management. These studies add to our knowledge of how forests influence snow accumulation and melt and how cutting a forest may be done so as to maximize water yield, delay snowmelt runoff, or minimize local flood runoff and sedimentation.

How a forest affects snow accumulation and melt depends on its density, the height of its trees, and the position of the trees with regard to their neighbors and to the topography associated with the forest site. The specific role of a forest is determined by its effects on wind, shade, radiation, and pondage of cold air.

Wind

The wind affects the location of snow, its method of drifting, and its melting rate. Holes in the forest canopy, whether natural or made when forests are cut in blocks or strips, act as traps for snow during snowfall. Falling snow is trapped in the opening and then deposited by back eddy into the forest on the windward side of the opening. This excess of snow results in some deficit of snow in the forest to the leeward (Anderson and Gleason 1959, 1960; Anderson, Rice, and West 1958). Almost all wind during storms in the Sierra Nevada blows from the southwest or south (Court 1957). The most snow in openings is deposited where it can be best protected from the sun, that is, in the shade of the trees. Wind also affects evaporation of the snowpack (West 1959).

Shade

Shade effects on snowmelt are such that the maximum shade results in the least melt. But about 85 percent shade is nearly as effective as 100 percent shade (Anderson 1956). The effects of shade, for canopy densities greater than 85 percent, are partly negated by winter melt and interception. Trees to the south of a snowpack have a marked influence on snowmelt, but trees to the north are only about 12 percent as effective in preventing melt. The trees to the north do intercept sky radiation, but they also heat up from the direct sun rays and radiate back longwave radiation to the snowpack.

Longwave Radiation

Longwave radiation effects on snowmelt are influenced by the forest in several ways. The forest reflects longwave radiation better than does the snowpack, but it prevents longwave radiation at night upon the snowpack. In open areas, heat loss by longwave radiation at night causes snow to form a crust; whereas in a forest, longwave radiation is intercepted by the trees and back radiated to the snow, and less crust forms.

The familiar melt cone around tree trunks and depressions of snow under tree canopies is in part the radiation phenomenon and, of course, part interception. The cone may be of little quantitative importance. A study of snow accumulation around 111 trees (Anderson, Rice, and West 1958) showed that in forest stands averaging 50 percent canopy cover, only one-half inch less water in the snowpack within forest stands was attributable to the cone around the trees.

Cold Air

Cold air drainage effects of trees at the downhill border of openings are quite striking. Maximum snow accumulation in a study was always found in the downhill side of forest openings, no matter whether the opening was on a north, south, east, or west slope (Anderson, Rice, and West 1958). We inferred that cold air draining downhill during the long winter accumulation period was repeatedly trapped against the trees on the downhill side. This cold air cooled the snow and effectively prevented winter melt of the pack. In selected individual forest openings, West (1961) found that the lower side of the opening on a north slope had 3 inches more snow and on a south slope 13 inches more than the uphill side of the opening.

The processes are operating in forests and when forests are cut, we change in some degree each process. The result is an increase or decrease in snow accumulation and melt. Let us combine what we know of these processes and estimate how cutting the forest in different ways and patterns will affect water yield.

Forest Cutting in the Snow Zone

Does it make any difference to water yield how forests in the snow zone are cut? To water yield? To the time of delivery of water yield? To water quality? To flood discharge and sedimentation discharges? How much difference if forests are clear cut? If cut in strips of various widths and orienttation? If block cut in various sizes? If selectively cut? Or if cut in designs calculated to give maximum snow accumulation?

Clear Cutting

Clear cutting may be defined as cutting blocks of more than 20 acres or strips wider than four times the tree heights. Such a cutting has its own special influence on snow accumulation and melt. Maximum accumulation of snow is greater in the cut than in the uncut forest. For example, it was 14 inches greater at the Central Sierra Snow Laboratory in 1950 (Mixsell et al. 1951) and 12 inches greater as a long term average (Anderson 1956).

Snowmelt is rapid in open areas. Data from Mixsell et al. (1951) showed 22 inches greater melt from April 1 to June 1, 1950 for the open areas than for a dense forest. Anderson (1956) estimated a long term average of 16 inches of snow water left in the forest at 7,600 feet elevation on June 9 when all snow had melted in the large open areas. Clear cuts that create large open areas do store more snow than does a forest, but they have much more rapid melt (fig. 4).

Block Cutting

If block cutting of the forest is silviculturally desirable and economic, consider the shape and size of block on snow accumulation and melt. Research results so far suggest that if a square block were cut in the forest with each side about one tree height across, the water equivalent in late spring (June 9) would be about 3 inches more than that of a cut strip one tree height across (Anderson 1956). This arrangement would produce the "honeycomb" forest proposed by Church (1933). In a rectangular block five tree heights long by one tree height wide, with the long dimensions oriented east and west, snow water in early summer would be only about one-half inch greater than in the strip.

Studies by Anderson, Rice, and West (1958) have suggested that an L-shaped block cut on east and west slopes may be the most effective in achieving maximum snow accumulation and delaying melt. On west slopes, the arms of the "L" extend along the slope to the north and uphill to the east; on east slopes the "L" is reversed, one arm extending uphill to the west.[3] This shape of opening permits cold air drainage down the downslope arm of the "L" and pondage of that cold air in the arm along the slope. Differences of 2 inches in maximum snow accumulation and as much as 6 inches more snow left in early summer as compared to strip cuts are indicated for these "L" shaped blocks.

Selective Cutting

Selective cutting of forests may increase the maximum snow accumulation by 5 inches of water if the average crown cover is reduced from 90 percent to 50 percent. If the cover was further reduced to 35 percent, the snowpack would be an-

[3]An inverted "T" would probably be a satisfactory alternative to the "L", with the bottom of the inverted "T" extending along the contour, or along the bottom of the slope.

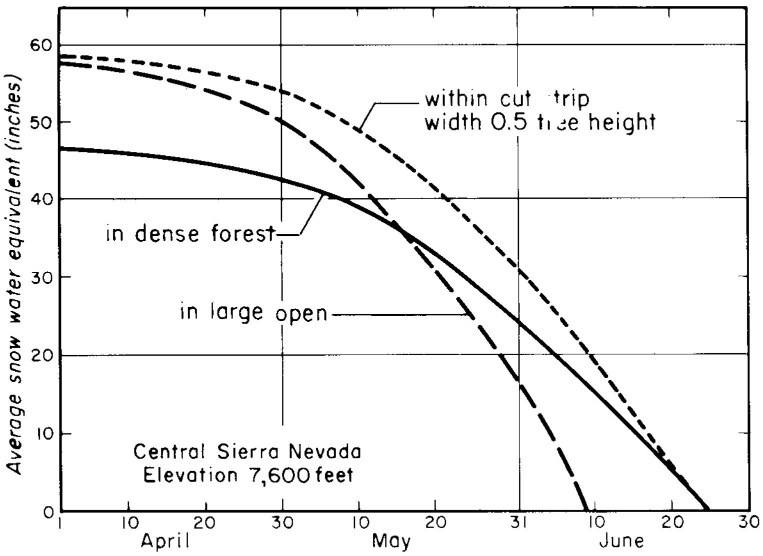


Figure 4. — Snowpack water equivalent at various dates in an average year for two forest conditions and in the open.

other 4 inches greater (Anderson, Rice, and West 1958). In another study in 1958, we found 7 inches more water in a commercial selection cut than in the uncut forest, and 6 inches more a year later (Anderson and Gleason 1959, 1960).

For late spring yield, we found that the advantage of the 35 percent density over the 50 percent density had disappeared, but stands with both of these lower densities had about 4 inches more water in late spring (June 1, 1958) than did the stand of 90 percent density (Anderson, Rice, and West 1958).

Strip Cutting

Strip cutting has some advantages over clear cutting. Maximum snowpack in cut strips occurs when strip widths are approximately one times the height of the surrounding trees (Anderson 1956; Anderson, Rice, and West 1958; Church 1914; Kittredge 1953). Melt of the pack is more rapid in wide strips than in narrow; as the spring season progresses, the maximum unmelted snow is found in narrower and narrower strips. For example, by June 9 in the average year, the maximum snow water equivalent was found in strips only one-half as wide as the trees were tall (Anderson 1956).

How much difference in maximum snow water equivalent would strip cuttings make? We found 12 inches more water in the snowpack at time of maximum accumulation (April 1) in the cut strip than in the uncut forest (fig. 4) (Anderson 1956). Strips cut in the forest had about 1 inch more water than did large unshaded areas. In late spring (June 9), when all snow was gone from large unshaded areas, 16 inches of water remained in the dense forest and 20 inches in the cut strips. The last snow disappeared from the dense forest and the cut strip at about the same time—16 days later.

What portion of the increased snow found in openings is a true increase rather than mere redistribution of the total snow supply? Data from 58 to 66 snow courses (Anderson, Rice, and West 1958; Anderson and Richards 1960) provide some answers. We can compare the average of snow courses within forests with snow courses having openings as part of the site:

	Snow at maximum pack	
	1958	1959
Snow courses:	*(inches of water)*	
In forest near opening (area 1½ times area of opening)	56.0	22.6
In opening (average all sizes)	63.2	26.3
Within forests, 35 percent density	57.0	23.2
Within forests, 50 percent density	53.4	21.5
Within forests, 90 percent density	48.1	15.8
Opening associated snow (opening plus extra snow surrounding)	67.1	29.0

Only about half the difference between forest and cut opening (that is, 67.1 —53.4= 13.7) was found when comparing openings and adjacent forest (63.2-56.0=7.2). This is contrary to some interpretations that openings exaggerate the difference between cut and uncut areas. The effect of openings on snow is not fully indicated by differences in snow within and adjacent to openings.

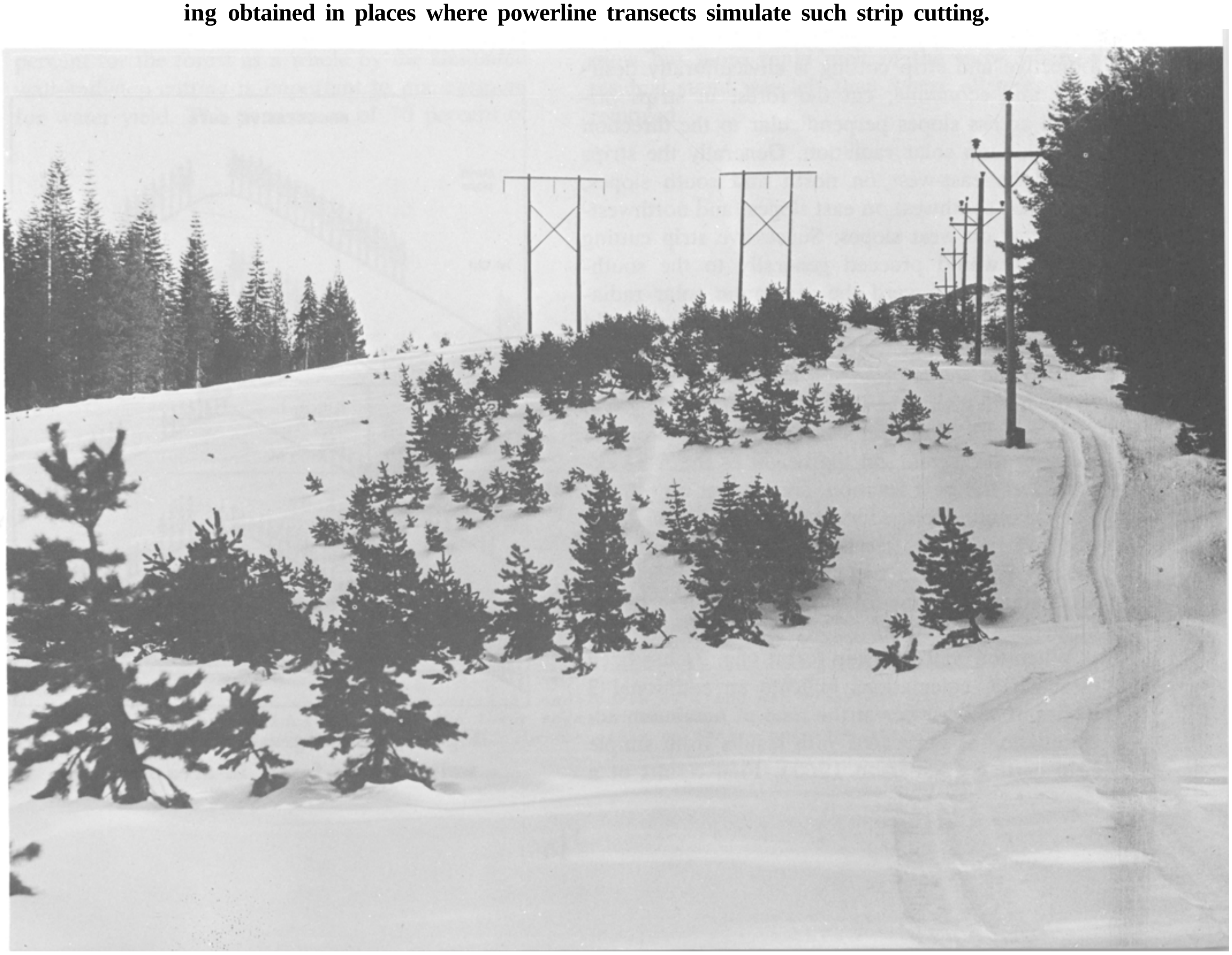
The effects of management in drought years may be interpreted from the above data. Cutting openings increased snow storage by 35 percent in the drought year of 1959 as contrasted with 26 percent in the near maximum year of 1958 (both compared to a 50 percent forest). In contrast, if by selection cutting we reduced a 90 percent dense forest to one of 35 percent density, we would get nearly as great an effect in the drought year-34 percent increase—but only a 17 percent increase in the year 1958. The effectiveness of selection cut in drought years applies only to the spring snowmelt runoff; soil moisture deficits would deplete total yield. In years of heavy runoff, the snowmelt flood runoff is considerably reduced, so that where forest control of flood runoff is required, selective cutting promises less snowmelt floods than does strip cutting.

For how many years does the excess of snow in cut strips persist? We have measured snow accumulation in a strip made by a powerline clearing made 10 years ago and also in an area of that clearing widened 5 years ago (fig. 5). The excess of snow in the 5-year-old cut area was the same as that expected the first year after the cut—13 inches; the excess in the 10-year-old cut area—where the red fir reproduction is 7 feet tall—was still 10 inches. In the Fraser study in Colorado, remeasurement of the cuttings 13 years after the logging showed no apparent decrease in the excess of snow in the cuttings (Rocky Mountain Forest and Range Experiment Station 1956).

Wall-and-Step Cutting

A special sequence of strip cutting called a wall-and-step cutting has been designed as an "ideal forest" (fig. 4) for maximizing snow accumulation

Figure 5.—How long will cutting of successive strips in the forest affect snow accumulation and melt and water losses? Advance information is being obtained in places where powerline transects simulate such strip cutting.



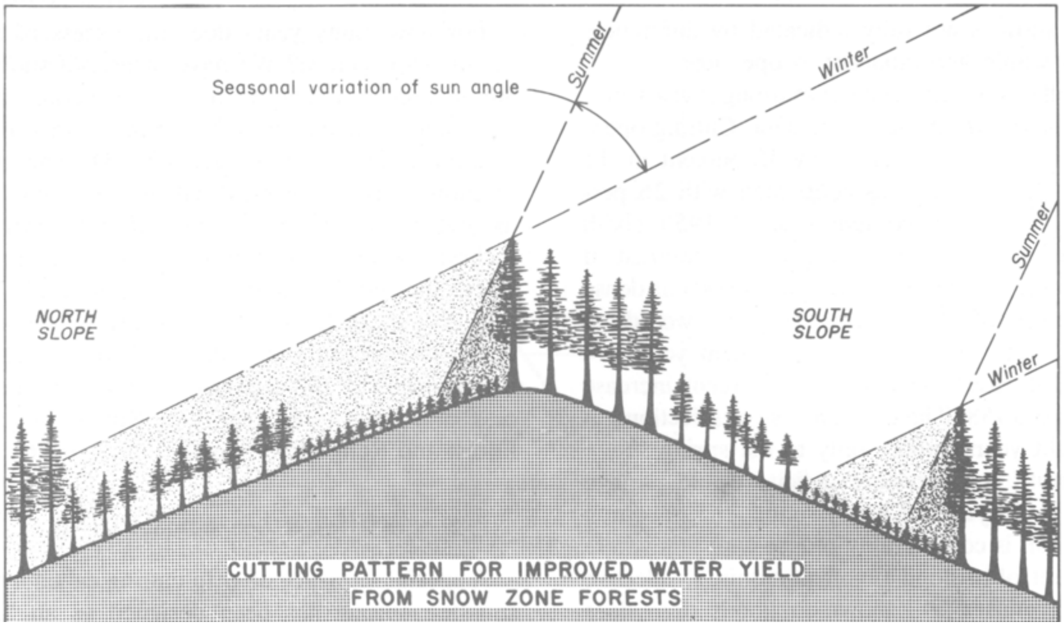


Figure 7.—Wall-and-step forest for maximum snow accumulation and delaying melt.

and delaying melt (Anderson 1956). If maximum accumulation of the snow pack is the management objective and strip cutting is silviculturally desirable and economic, cut the forest in strips oriented across slopes perpendicular to the direction of maximum solar radiation. Generally the strips would be east-west on north and south slopes, northeast-southwest on east slopes, and northwest-southeast on west slopes. Successive strip cutting (fig. 6) would proceed generally to the southward, that is, toward the maximum solar radiation. Once through a cutting rotation, we would have established a wall-and-step forest, with the wall to the south providing shade, and the steps to the north giving the least back radiation (fig. 7).

The width of the cut strip would depend on the slope of the terrain, on the height of the trees expected at the next rotation, and on our objectives. For maximum delayed snowmelt, we suggest strips one-half times the tree height on steep south and west slopes, one to two times the tree height on level areas, and one to four times the tree height on steep north slopes.

When the wall-and-step forest (fig. 7) has been established, calculations indicate an additional 3 inches of snow water at the time of maximum accumulation as compared with results from simple strip cutting (Anderson 1960). First results of a recent test confirm an increase, but suggest more increase than predicted.

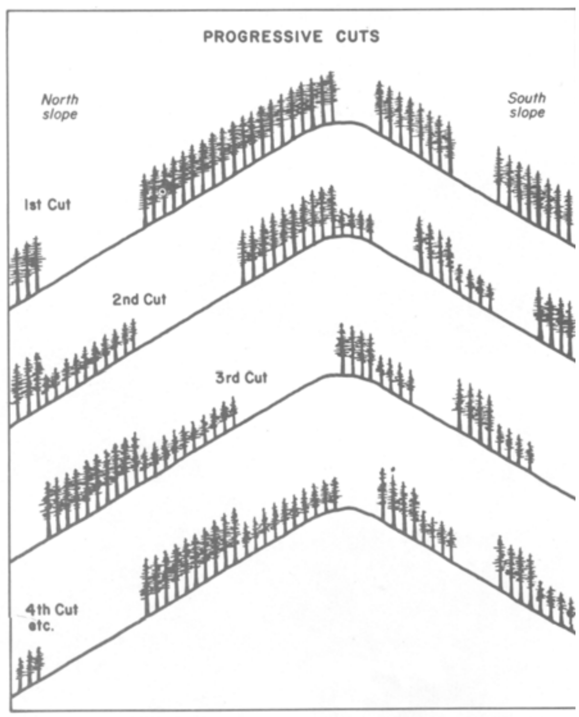


Figure 6.—Progressive cuts establish wall-and-step forest in area rotation.

The recent test included a simulation of a wall-and-step cutting and strip cuts. The tests also included variation in residual stand treatment and slash disposal (Anderson 1961; West and Adams 1963). Five east-west strips (0.6 miles long, 135 feet wide, 400 feet apart) were cut in th e fall of 1962. The cutting was in an old-growth red fir stand on a 15 percent north slope at elevation of 6,700 feet in the Tahoe National Forest near Yuba Pass, California.

First results were from measurements of the snowpack at some 400 points on April 24, 1963—about the time of the maximum pack—and again on May 21—when about 60 percent of the pack had melted. Snow in the center of uncut forests averaged 19 inches on April 24 and 7.7 inches on May 21 (table 2).

Slightly more than half the increase in snow accumulation in the wall-and-step cutting was found within the cut strip. The distribution of the increase for the wall-and-step and the simple strip cut (both with slash bulldozed downhill) is shown in figure 8. The wall-and-step treatment with slash lopped and scattered gave 0.2 inches less snow and with slash piled gave 0.4 inches less snow than where the slash was pushed downhill.

The increase in total snow accumulation of 25 percent for the forest as a whole by the simulated wall-and-step cutting is important to management for water yield. The persistence of 70 percent of the increase (3.3 inches) as delayed melt is also encouraging. The concomitant reported benefits of "little or no blowdown in the severe October storm" and "an economical logging show" suggest that the treatment method is feasible.

Differences in snow accumulation and melt result not only from the pattern of cutting but from the slash and residual stand treatment after logging (fig. 9).

Slash left on the ground affects shallow snowpacks—speeding melt when the slash is in the sun, slowing melt when it is shaded. In the 2-chain wide strips at Yuba Pass, burning and piling the slash versus lopping and scattering the slash made little difference. In contrast, the wide 5-chain strips at Swain Mountain showed that the piled and burned area had 4 inches more snow than did the area with slash (Anderson and Gleason 1960). There, when snow accumulated slowly in the fall or when shallow packs occurred late in spring, sunshine penetrated the pack, heated the slash, and speeded snowmelt.

If a residual stand of small trees is left in cut strips, the effectiveness of the cut is reduced, with the reduction depending on width of cut area and shading of the small trees. In the Yuba Pass test, first results show intermediate amount of early snow but more rapid melt of the snow where a residual stand was left than where all trees were removed.

Table 2. Excesses of snow water equivalent, in inches, associated with cutting compared with uncut forests

Date and area considered	Excess of snow associated with treatment--				
	Slash piled	Slash lopped	Small trees left	Slash dozed downhill	Wall-and-step[1]
April 24, 1963:					
Cut strip only	4.4	6.4	8.0	14.4	18.9
Whole forest	1.1	1.6	2.0	3.6	4.7
May 21, 1963:					
Cut strip only	7.2	7.2	-5.2	1.2	13.2
Whole forest	1.8	1.8	-1.3	-0.3	3.3

[1] *In wall-and-step cutting, one-fourth of stand was clear-cut with slash bulldozed down to the lower edge; in an equal width to the north, the taller trees were removed. In the other cuttings, only the strip was cut.*

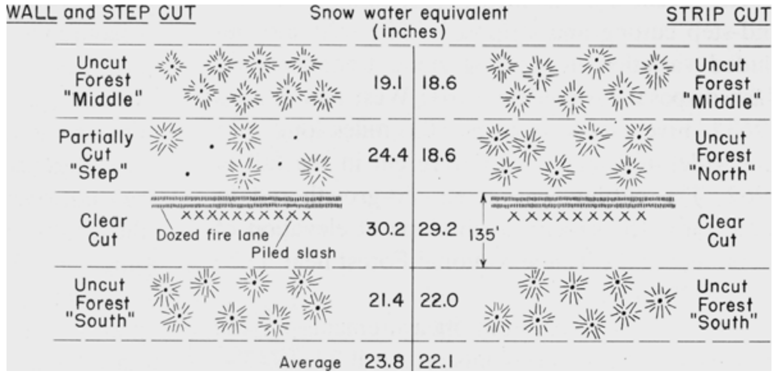


Figure 8.—Snow in cut strip and in simulated wall-and-step test, Yuba Pass, California, elevation 6,900 feet, April 24, 1963.

Figure 9.—Slash disposal has an important role in snow accumulation. Slash being windrowed downhill with a bulldozer traps cold air, preventing snow melt in winter.

Effects of Logging on Water Yield

Experiments in Fraser, Colorado, started in 1943, have contributed to our knowledge of the effects of logging on water yield. The studies of Wilm and Neiderhoff (1941) and Wilm and Dunford (1948) on the effects of forest cuttings on snow accumulation and melt, snow evaporation, and soil moisture losses have lead to predictions of increases of "water available for streamtlow."

These predictions have been tested on whole watersheds and the data analyzed by Goodell (1958). Cutting of 39 percent of a lodgepole-spruce-fir forest in strips of 1, 2, 3, and 6 chains was begun in 1954 and completed in 1956. Associated with the logging was an average of 4.03 area-inches of streamflow from the watershed in 1956 and 1957. Peak discharges from the logged watershed was 50 and 45 percent greater in two years (1956 and 1958) and 23 percent less in one year (1957) after logging. Similar effects were found in a Sierra Nevada watershed under quite different conditions.

The effect of management on total water yield is largely through change in the water loss by evapotranspiration. We may say, "Snow management will control delivery of water from the snowpack; loss management will control total water yielded as streamflow." Logging effects and duration of these effects on loss differ widely between winter and summer.

Water Losses in Winter and Spring

Winter and spring water losses occur when most of the ground is snow covered. During that period, the losses consist chiefly of interception of snow and winter rain by the trees, evaporation from the snow surfaces, and transpiration by the trees or other vegetation. First, we must admit that we have not found a way of measuring the winter transpiration loss by trees when the ground is snow covered. Estimates of these losses range from 2½ 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 forest.

Interception loss is the water lost by evaporation from the wet 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 1951). 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. In a selectively cut mixed forest, Kittredge (1953) found that interception decreased by 50 percent when 50 percent of the tree canopy was removed. Anderson and Gleason (1959) have estimated reductions in interception loss due to logging 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 have been found to be small in the Sierra Nevada, except in 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, exaporation from a large open area was 1.7 times that from the small opening, and evaporation from exposed ridges was three 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 ½ to 1 inch per year. Clear cutting of large areas might increase losses by 1½ inches year year, on exposed ridges by 3½ inches.

We have concluded that logging reduces 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).

Water Losses in Summer and Fall

Water lost from the soil during summer and fall must be replaced by fall precipitation or by winter snowmelt before streams will start to rise. Summer and fall storms may lose much of their effectiveness because of interception by the forest trees and other vegetation. How forests are logged can affect these losses. We have studied the amount of water losses under various types of timber harvest and the duration of the logging effects.

Summer and fall soil moisture losses were taken as a 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 by a nuclear soil moisture probe. Summer and fall precipitation was added to the soil moisture losses to give total summer water losses. In natural forest sites near the Central Sierra Snow Laboratory, soil moisture deficits ranged from only 3 inches on bare soil sites to as much as 17 inches in heavily forested sites with deep soils.

Logging effects on summer water losses were evaluated by measurements taken under three types of logging and under adjacent unlogged forest stands. Differences in summer water losses between forest cut in strips, in blocks, and by commercial selection cut were compared (Anderson and Gleason 1960). In each case, logging saved water.

Strip cutting saved water by reducing the summer and fall soil moisture losses. Savings for the first 3 years after logging differed with soil depth (table 3), averaging 2.2, 4.0, and 4.6 inches for the 3-, 4- and 5-foot soil depths, respectively.

Duration of summer savings resulting from cutting of strips is important to any evaluation. Savings were greatest the first years after the cutting and in the deepest soils (table 2). For 4-foot soil, the saving was 4.9 inches the first two years, but decreased to 3.4 inches the fourth year after the logging.

Ziemer[4] traced the long-term effects of logging by measuring soil moisture losses in forests logged at times ranging to 12 years before. He found that the logging effect averaged 6.9-inch increase the first year after logging and this diminished to zero by the sixteenth year. Total savings in the cut strip for the 16-year period were estimated as 34 inches.

Other data are consistent with the above. For example, a power line cleared 10 years ago, then widened 5 years ago, showed savings of 1 inch and 3 inches, respectively. It must be pointed out that savings other than summer soil moisture diminish much more slowly with time, interception taking perhaps 35 years to "recover" and evapotranspiration during the spring, fall, and winter somewhat less. These slower diminutions are suggested by the slow decrease in snowpack differences—only 23 percent in 10 years.

Block cutting effects on summer water losses were dependent on the size of the block and the residual trees left in the cutting or the regeneration coming into the stand. A large open block with some residual stand had one-half inch less saving than did the cut strip of table 2. Similarly, the data of Ziemer can be interpreted to show one-half inch less saving in a circular opening (one tree-height across) than in a cut strip. Thus, some of the advantage of small openings in snow accumulation is offset by additional summer water loss by root penetration from the trees at the cut margin.

Selection cutting has a small effect on soil moisture losses. Saving was nearly 2 inches the first two years after the logging and diminished to about 0.8 inch the fourth and fifth years after the logging. Data for a 4-foot soil were:

	Soil Moisture Storage at End of Summer				
	11/2/58	9/2/59	9/15/60	9/8/61	8/16/62
Treatment:			*(inches)*		
Logged (A)	8.25	7.34	6.60	6.86	8.96
Unlogged (B)	6.33	6.12	5.56	6.12	8.11
Saving	1.92	1.22	1.04	0.74	0.85

The trend indicates a zero saving by about the twelfth year, with a total soil moisture saving over the 12-year period of 7.5 inches.

We see that in the area cut the summer soil moisture savings resulting from strip cutting is more than six times that of selection cutting.

Commercial selection cutting.—Basic studies and plot tests can give us first clues to differences which management alternatives may be expected to produce, but measured streamflow is the final check. The effects on streamflow of a commercial selection logging were evaluated at the 4-square-mile Castle Creek watershed near Donner Summit

[4]Ziemer, Robert R. Summer evapotranspiration trends as related to time following logging of high elevation forest stands in Sierra Nevada. 1963. (Unpublished master's thesis on file School of Forestry, University of California, Berkeley.)

in the Sierra Nevada. Most trees exceeding 20 inches in diameter in a 1-square mile area were cut, leaving a good stand of pole-sized trees and reproduction.[5] We found that water yield as streamfiow apparently increased by the equivalent of 7 inches deep (in the area logged) for at least 2 years after logging (Anderson and Richards 1960, 1961; Rice and Wallis 1962). These increases were brought about in the two subnormal runoff years of 1959 and 1960. About half the increase came in June. How long the logging effect persisted after 2 years is not known, because a freeway was built on the watershed.

Three cuttings compared.—In another test, we compared water available for streamflow under logged and unlogged conditions for commercial selection cutting, strip cutting, and block cutting for the year starting April 15, 1958 (Anderson and Gleason 1959). The results were obtained from the standard water balance equation: yield equals precipitation minus interception, winter evapotranspiration, summer evapotranspiration, and fall evaporative losses. The method is useful in comparing relative effectiveness of different treatments, but does not give exact values of yield. In making estimates of the water yield, we supplemented our soil moisture loss measurements with snow evaporation data from Kittredge (1953) and West and Knoerr (1959), and with snow interception measurements of Rowe and Hendrix (1951) and West and Knoerr (1959).

Precipitation for the year at the three sites was similar—46 to 47 inches—so that differences in water yield attributable to the logging methods can be compared:

Forest condition:	Water loss	Water saved
	(inches)	
Unlogged	21	–
Strip cut	12	9
Block cut	15	6
Selection cut	18	3

Water yield increased under each logging method, ranging from 3 to almost 9 inches. The strip cut as the most effective in saving water, the block cutting next, and the commercial selection cut least.

About half the differences between the comercial cut savings and the strip and block cut savings were in soil moisture losses—water that is held over at the end of fall. That water will be yielded with the first winter melt, or sometimes with late fall floods.

Slash disposal.—The method of slash disposal may affect water losses in summer. Losses of water from the soil during the first three summers after logging at the Swain Mountain Experimental Forest were somewhat different within cut strips under two slash disposal methods:

	Summer soil moisture loss		
	1959	1960	1961
Slash treatment:		*(inches)*	
Piled and burned	3.2	3.7	3.1
Left where it fell	3.8	4.0	3.8

Summer water losses were nearly the same in both treatments. Combined losses from interception and evaporation from the soil were slightly less in the bare soil area in each year. The magnitude of summer losses depended upon the amounts and time of occurrence of the summer precipitation, and upon the evaporation rate.

Brushland Conversion to Forest

High elevation brushlands may be converted to forest, with benefits to water supply. During the conversion period, interception and transpiration losses will be reduced. After the forests arc established, snowmelt may be delayed with resultant benefits in delayed water yield in late spring and summer.

[5]The 2.8 million board feet removed was 30 percent of the volume in the logged area and 12 percent of the total volume in the 4-square-mile watershed.

Water Savings in Summer

A test in the fall of 1957 showed that soil moisture was saved in a brushfield cleared by bulldozing manzanita-whitethorn brush and windrowing the brush (Anderson and Gleason 1960). Initial field capacity storage was 18.5 inches of water. Final water storage in the cleared and uncleared areas and water savings for soil 4 feet deep in each of 4 years after clearing were:

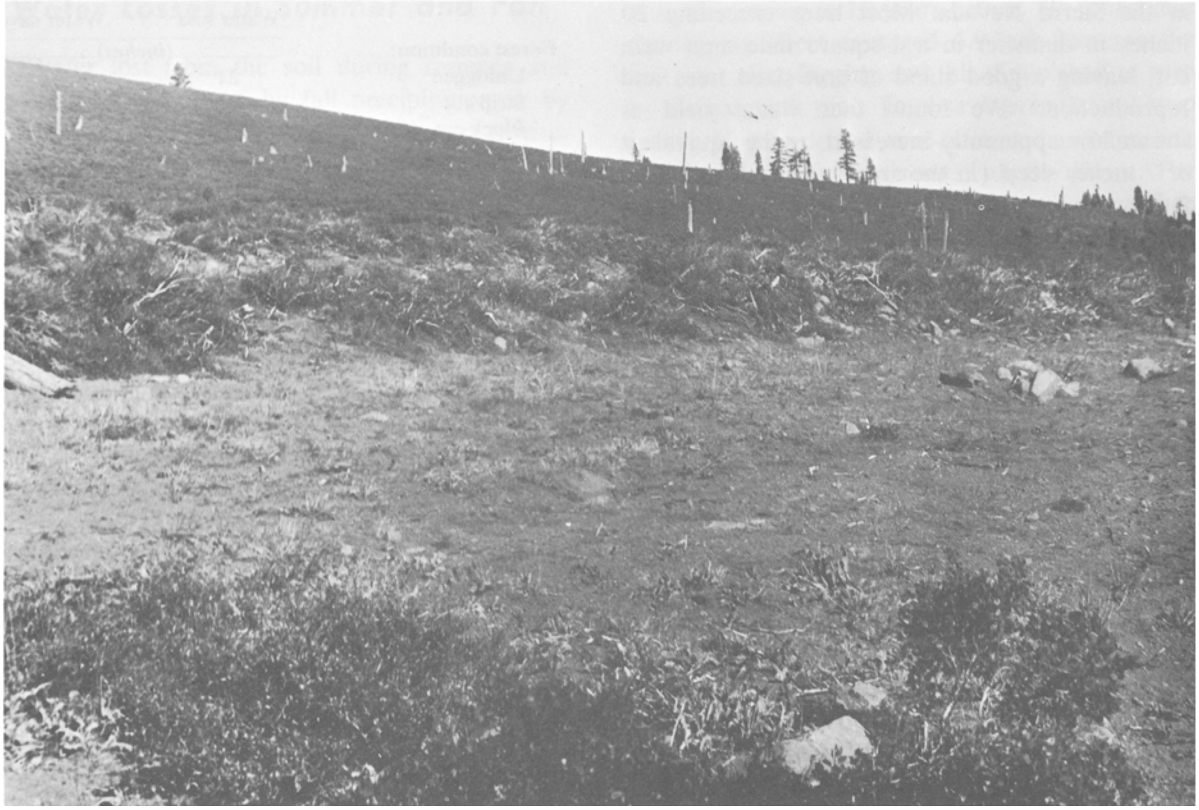


Figure 10.—Clearing of brushfields pays double dividend: Water is saved for a number of years after the clearing, and planted trees in the strips may later yield timber products and help slow the snowmelt.

Figure 11.—Sedimentation, a possible conesquence of any watershed treatment, is being measured here with a depth-integrating sampler.

Treatment:	Final summer soil moisture 1958	1959	1960	1961
	(inches)			
Brush cleared	15.9	15.0	13.7	11.9
Natural brush	11.6	11.4	11.0	11.6
Saving	4.3	3.6	2.7	0.3

The savings in summer water losses were greater in deeper soils, less in shallower soils; in both soils the saving had diminished to zero by the fifth year

Water Losses in Winter and Early Spring

Additional savings in winter and early spring snow and rain interception would approximate 6 percent of the precipitation when the brush was not snow-covered (Hamilton and Rowe 1949). This saving was estimated at about 0.5 inches. Early winter and early spring transpiration savings would be about 0.01 inches per day in early winter and 0.02 inches per day in early spring in clear weather days when the brush is not completely snow covered. The resultant saving in the conversion period is 0.8 inches of water. The estimated total savings the first 3 years of the conversion period was about 4 to 5 inches of water per year for soils 4 feet deep.

The saving diminished as brush sprouts occupied the site. By the fifth year after the bulldozing, soil moisture was as low as before the treatment. Even though interception would be expected to be somewhat lower, total saving would be about 1 inch, even for those soils 5 feet deep.

Delayed Yield of Water

Benefits in delayed snowmelt can be expected as trees mature. Delay in snowmelt would exceed that indicated in figure 4 for the cut strip versus the large opening. In 1959, at elevation 6,800 near the Central Sierra Snow Laboratory, melt in brushfields was 3 inches greater than in a comparable large open area hare of brush:

Area:	Snow water 4/1	5/10	Melt
	(inches)		
Large grassy open area	23.4	5.9	17.5
Brushfield	23.0	2.4	20.6
Forested (50 percent density)	21.4	8.7	12.7

The above melt rates suggest that when all snow is gone from a brushfield, we would have about 7 inches more snow water in the converted forest in that year of slight snowpack.

Temporary benefits in total water yield and long term benefits in delayed yield, as well as timber values, may he expected from brushland conversion. Such combined water and timber benefits may justify conversion of brushfields which was not justified by either single benefit.

Sedimentation in High Elevation Forests

Sedimentation includes erosion, sediment transport, and sediment deposition. It is thought to be less of a problem in high elevation forests than in any other zone. Precipitation falls mostly as snow or rain, and snowmelt or rain penetrating the deep snowpack causes little soil erosion. Transport of stream sediments is generally low because peak flows, which carry most of the sediment, are dampened by the snowpack. However, this lower meteorological potential, may be offset by greater soil erodibility. Willen[6] found high elevation soils 2.7 times as erodible as low elevation soils of the same geologic parent rock. If the bare areas are large and continuous, rilling may occur, and soil from such rills and surface wash reach minor channels. Once sediment reaches a channel, it can cause damage by restricting channel capacities, affecting water quality, and depositing sediment in culverts, reservoirs, and percolation basins.

The principal sources of sediment subject to management include roads, land slips, logging, skid trails, and land clearings. Often roads are the principal offender (Anderson 1954). Methods of prevention are well known (Haupt 1959; Meadowcroft et al. 1954). Not so well known is the economics of various levels of prevention.

Land slippage may follow logging, land clearing, and road cutting. It may occur soon after

[6]Willen Donald W. Erodibility indexes and surface soil characteristics of some southern Sierra Nevada forest soils as related to parent rock, topography, and vegetation type. 1963. (Unpublished master's thesis on file at School of Forestry, Univ. Calif., Berkeley.)

treatment owing to excess water storage, or occur years later when the binding roots have decayed. Logging, with its accompanying roads and skid trails, can be expected to increase sediment. The clear cutting of lands subject to slipping into stream channels must be questioned, if sedimenttation is any problem. Studies of some method of harvest which will not cause major land slips seem indicated.

Effects of Commercial Selection Cutting

At Castle Creek, near Donner Summit, discharge of suspended sediment for an average year before logging, totaled 900 tons from the 4-square-mile watershed (table 3). The first year after logging one-fourth of the watershed, sediment discharge soared to 4,600 tons a year; the second year after logging, it dropped to 1,800 tons a year. If we consider only the logged area, sediment production was increased by 17 times the first year and by 5 times the second year.

Increases in sediment concentration were associated mostly with the highest discharge classes. For example, the highest 7 percent of the streamflow carried more than 50 percent of the sediment (table 4).

Deposition of coarse sediment in the small debris basin in Castle Creek totaled only 50 tons per year. This amount was 1 to 5 percent of the sediment discharge in the two low-flow years after logging. Part of the coarse eroded material remains upstream of the basin. It may be discharged in later years when the streamflow becomes higher.

Erosion from roads and landings which formed part of the logging operation provided most of the sediment. Minor rivulets were often diverted down logging roads, causing the erosion of all fine material. Landings made by building deep fills across stream channels now have deep V-notched gullies across them (Rice and Wallis 1962). These landings have been an obvious source of increased sedimentation. Rice and Wallis concluded that "even though a total disturbance of the Castle Creek watershed was not great, the location of roads and landings created a large sediment source. More attention to water values could have eliminated much of this source."

Effects of Forest Fire

The effects of forest fire on sediment discharge from snow zone watersheds depend largely on the kinds of runoff events that follow (Anderson 1962). In the area of the Donner Ridge burn (north of Truckee) where only snowmelt runoff

Table 3. Differences in summer soil moisture depletion between logged strips and adjacent forest, Swain Mountain Experimental Forest, 1959-1961

Year, condition, and saving	Soil moisture storage (inches) for soil depths of--		
	(3 feet)	*(4 feet)*	*(5 feet)*
1959:			
Strip	10.7	15.3	19.9
Forest	8.2	10.4	14.8
Saving	2.5	4.9	5.1
1960:			
Strip	10.2	15.0	19.5
Forest	8.1	11.4	15.0
Saving	2.1	3.6	4.5
1961:			
Strip	9.6	14.2	19.3
Forest	7.7	10.8	15.0
Saving	1.9	3.4	4.3

Table 4. Average annual suspended sediment discharge from sediment sampling and streamflow duration before and after logging of 1-square-mile of the 4-square-mile Castle Creek, Yuba River headwaters, California, 1958 and 1959

Discharge class	Mean discharge	Streamflow frequency	Relative volume	Sediment samples	Streamflow in various sediment concentration classes, p.p.m.						Average sediment concentration
					<12.5	13-27	28-72	73-142	143-400	>400	
BEFORE LOGGING, 1958											
	C. f .s.	*Percent*	*Number*		- - - - - - -*Percent* - - - - - -						*P.p.m.*
<1	0.2	44.0	.006	2	44.0	--	--	--	--	--	7
1- 10	4.1	30.0	.089	15	26.0	4.0	--	--	--	--	9
11- 40	20.2	14.0	.200	14	7.0	6.0	--	--	1.0	--	36
41-100	60.0	8.8	.380	6	--	7.3	1.5	--	--	--	25
101-200	125	2.8	.258	15	0.2	0.4	0.6	1.4	0.2	--	104
201-250	210	0.25	.038	0	--	--	--	--	0.25	--	[1](190)
>250	270	0.15	.029	6	--	--	--	--	--	0.15	(430)
Totals		100.00	1.000	58							
Average	14.7				7	20	50	108	270	430	[2]64
AFTER LOGGING, 1959											
<1	0.2	44.0	.006	11	36.0	4.0	4.0	--	--	--	12
1- 10	1	30.0	.089	13	23.1	--	--	4.6	2.3	--	43
11- 40	21.0	14.0	.200	18	7.8	4.7	1.5	--	--	--	16
41-100	63	8.8	.380	12	2.2	2.2	0.7	2.2	1.5	--	83
101-200	130	2.8	.258	3	--	--	--	--	1.9	0.9	413
201-250	216	0.25	.038	--	--	--	--	--	--	0.25	(1,700)
>250	280	0.15	.029	--	--	--	--	--	--	0.15	(3,200)
Totals		100.00	1.000	57							
Averages	15.3				7	20	50	108	210	980	[3]303

[1]*Values in parentheses were taken from sediment concentration-discharge curve.*
[2]*Total sediment discharge for 1958: 935 tons.*
[3]*Total sediment discharge for 1959: 4,600 tons.*

Figure 12.—Contour trenches at the Tahoe National Forest are being tested in research on runoff and erosion prevention. Studies are being made on the effects of forest fires and the effectiveness of four alternative treatments on flood peaks, sedimentation, snow storage, and soil moisture loss.

in less than normal amounts occurred in 1961, sediment production was small—a maximum of 78 p.p.m. in runoff water. In the area a few miles to the east where a high intensity summer storm struck the burned area, sediment production was high (Copeland and Croft 1962). Sediment production was 1.5 acre-feet per square mile on untreated areas when rain fell at the rate of 9 inches per hour for a 5-minute period. Where the Forest Service had installed emergency contour trenches, the runoff was contained and little flood flow or sediment discharge occurred. Thus, poor vegetation cover and high intensity rainfall can combine to produce high yields of sedimentation in the snow zone.

Effects of Grazing

No experiments on the effects of grazing on sedimentation in snow zone watersheds have been conducted, but evidence indicates small amounts of sediment production are associated with heavily grazed watersheds under usual snowmelt runoff conditions:

	Area intensively grazed	Annual streamflow	Sediment production
	(percent)	*(inches)*	*(acre feet/ sq. mi./yr.)*
Experimental forest:			
Castle Creek	10	50	[1]0.14
Onion Creek	10	38	0.05
Teakettle	8	21	0.02
Sagehen Creek	10	14	0.004

[1]Before logging in watershed.

The effects of heavy grazing on sedimentation under high intensity rainfall conditions in the Sierra Nevada are still unevaluated. Under major storm conditions, sediment production can be high—15 inches of rain in 3 days in January 1962 produced 0.6 acre feet of sediment per square mile in the Onion Creek watersheds.

Management Effects on Floods

Flood frequencies from snow zone watersheds may change as management changes. We expect changes in each of these basic hydrologic processes: (a) The supply processes—precipitation, rainfall amounts and intensities, snowfall, distribution of snow on the ground, and snowmelt; (b) the storage and detention processes at the surface, in soil, and in channels; and (c) the loss processes—interception, evaporation, transpiration, and, in some places, groundwater “losses” or deep seepage (Anderson 1962). These processes operate differently for snowmelt floods than for rain or rain-on-snow floods. Management effects on floods may be different depending on the kind of flood, the kind of management, and the time of yield of water resulting from management. In one year, a management practice may increase floods, in another decrease the flood.

Snowmelt Floods

Snowmelt floods periodically produce some inundation in the great valleys, usually in June. The amount of the snowpack and its rate of melt are the primary cause variables. Figure 4 illustrates the effect that alternative methods of forest management will have on snowmelt contribution at a specific site to floods. In general, a dense uncut forest has about 11 inches less runoff and much slower melt; selection cutting has some advantages over strip cutting. The synchronization of snowmelt from the many part of watersheds will determine the flood size from large watersheds. Different management practices in various parts of watersheds may augment or destroy such synchronization and so affect floods.

Rain and Rain-on-Snow Floods

Rain and rain-on-snow historically have produced the large floods in California (Hall 1943). In contrast to snowmelt floods, these are complex events—a dozen or more hydrologic processes combine to determine flood size (Anderson 1962). The effect of management on floods depends on the effects on each of these processes.

Let us consider one source of variation in floods —fall soil moisture deficit. This deficit must be replenished before major floods occur. In natural forest site, soil moisture deficits range from 3 to 17 inches.[7] When vegetation was removed by logging or brush removal, soil moisture deficits were 1 to 8½ inches less (Anderson and Gleason 1960; Anderson and Richards 1961).

Soil moisture deficits differ not only between local sites and with vegetative treatment, but for whole watersheds. Conditions and flood results during the December 1937 flood illustrate these differences for whole large watersheds on the west side of the Sierra Nevada. Pre-flood retention in the September to December period reached a maximum in the Feather River Basin—about 20 inches of the 30 inches of precipitation never appeared as runoff (data from McGlashan and Briggs 1939). Runoff in the flood was high—6 to 10 inches. In contrast, the total September through December retention in the Kings River Basin was about 10 inches. But only 1½ inches of this shortage was depleted before the 1937 flood, so that over 8 inches of the precipitation during the flood was stored in the watershed. As a result, the Kings River had a rather low flood runoff of only 1½ inches.

Combinations of shallow or absent snowpacks, frozen ground, and torrential rain occasionally occur, even in the snow zone. Shallow snow or absence of snow occurs about four times for every 50 years.[8] Under such conditions, cold weather, common in the late fall, persists into mid-winter and the ground freezes. Such was the early winter of 1963. The soil had been wetted by a heavy October storm; soil in open areas near the Central Sierra Snow Laboratory was frozen to a depth of 18 inches, and under forests to a depth of 9 inches. Then another heavy rain storm hit—20 inches in 3 days. High unit discharges and large quantities of debris came even from unlogged watersheds. A thousand acres of floating debris were carried into Folsom Reservoir. Peak flows in several central California watersheds approximated the record peak of 1907 (Rantz and Harris 1963).

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[7]Knoerr, Kenneth R. Exponential depletion of soil moisture by evapotranspiration at forest sites in the Sierra Nevada, as related to available soil moisture and vapor pressure deficit, 1960. (Unpublished Ph.D. thesis on file at School of Forestry, Yale Univ., New Haven, Conn.)

[8]U.S. Weather Bureau. Climatological records, Norden. Calif.

Retention differed widely between adjacent watersheds. Of the 21 inches of rainfall in the January 1963 storm, 19 inches ran off in the North Fork of the American River (at French Meadows), only 6.5 inches in the South Fork of the Yuba (near Washington). Thus retention was 2 inches and 14 inches, respectively.

How did cut areas contribute to the peak discharges? The contribution may be appraised in three ways: (a) The frozen soil being deeper has already been mentioned; (b) the soil moisture was greater in the cut areas, as high as 40 percent, as contrasted with 28 in the forest; and (c) bulking of flows with sediment would be expected to be greater from disturbed areas. Thus, the flood consequences of cutting to increase water yield also must be evaluated.

We see that the effects of management practices on floods are not simply related to the single variable of fall soil moisture deficit; other variables may augment or lessen the management effects on floods (Anderson 1962).

Areas Subject to Watershed Management

Opportunities for managing for water yield may be appraised from the amount and kind of vegetation in a watershed.

Vegetation subject to management on the west side of the Sierra Nevada may be extracted from an inventory by Richards (1961). If forest stands exceed 40 percent density and if brushfields are contiguous and greater than 132 feet across, these might be the first area considered for management for improved water yield.

What specific areas of dense timber and large brushfields might be subject to management? For the snow zone of major river basins west of the Sierra Nevada crest, these data are summarized in table 5 and for the Cascades and North Coast watersheds in table 6. We see then that 42 percent of the high elevation Sierra Nevada has vegetative cover which might be subjected to management for improved water yield. In the Sierra Nevada, brushlands subject to management are greatest in the northern river basin, and forests in the southern basins. In the northern watersheds, forest covers about 57 percent of the area and brushland about 20 percent.

Table 5. High elevation areas of major drainage basins, west of the Sierra Nevada crest, subject to management for improved water yield

Drainage basins	Forested[1,2]	Large brushfields[2,3]
	Percent	*Percent*
American River	21	24
Feather River	24	27
Kaweah & Tule Rivers	45	13
Kern River	39	9
Kings River	26	12
Merced River	23	16
Mokelumne River	23	17
San Joaquin River	28	15
Stanislaus River	26	17
Tuolumne River	16	16
Yuba River	22	39
Average	25	17

[1] Forests of greater than 40 percent canopy cover.

[2] West of Sierra Nevada crest, above 5,000 feet latitudes 35° 57½' north to 39° 57½' north.

[3] Brushfields more than 132 feet across their narrowest part.

The benefits of management for water yield depend on when and how the forests are cut and the brushlands, if present, are removed.

Benefits in terms of increased water yield may result from harvesting forest timber crops; benefits in brushland conversions may help pay for such conversion. Land managers may wish to defer cutting or brush removal until some critical period of drought or need occurs. Today's prescription of how to manage for water is summarized in the appendix.

Further study is needed in this broad field of resources management. Can other logging methods, ones designed specifically to give greater yield or delay yield longer, improve on these results? Other studies are now under way to develop, test, and evaluate "better" methods.

Summary

Research results have suggested how high elevation snowpack forests can be managed for water production—that is, for such objectives as increaseing water yield, delaying yield, and maintaining water quality. Logging forests and clearing brushfields can result in water benefits, yet may have adverse consequences in the form of floods and sedimentation.

Snow accumulation and total water yield can be increased by cutting forests. Interception and transpiration losses can be reduced without corresponding increases in evaporation from the snow and soil. Water yield can be delayed by cutting forests in patterns designed to slow snowmelt—retaining the shade of trees and minimizing back radiation of trees to the snowpack. Both streamflow and sedimentation have increased after commercial timber harvesting.

Clearing brushland in converting to forest will increase water yield during the conversion period by reducing interception and transpiration losses. The pattern of the new forest can be designed and managed to give delayed water yield as compared to yield from natural brushlands.

Specific suggestions for management are given in an appendix.

Table 6. Forest and other land types of some major river basins, Cascades and north coastal California[1]

River basin	Drainage area	Forest	Brush	Grass	Urban and agric.	Barren
	Sq. miles	- - - - - -	-	*Percent*	- - - - - -	
Eel (below Van Arsdale)	2,766	61	10	22	4	3
Klamath (below Copco)	7,611	57	21	8	4	10
Mad	485	64	14	21	0	1
McCloud	606	58	31	2	--	9
Sacramento	427	51	40	0	0	9
Scott	662	41	22	11	12	12
Shasta (below Dwinoll)	657	20	34	31	12	2
Smith	613	51	32	0	0	17
Trinity	2,846	66	17	1	1	15
Van Dusen	214	64	4	26	0	6
Average		57	20	10	4	9

[1] Compiled by James R. Wallis from timber stand maps, dated 1947 to 1958, published by the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley California.

Figure 13.—Water yield resulting from application of alternative management techniques will be tested on a dozen small watersheds with weirs.

Figure 14.—Measurement of snow water at 100 special snow courses permits evaluation of management effects on water yield.

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Appendix

Logging for Water

In forest stands of uniform size and condition:

1. Log in east-west strips (figs. 6, 7).
   a. Make strips about one-half tree height (rotation height) wide on south slopes steeper than 20 percent.
   b. Make strips about one tree height wide on all east and west slopes and on north and south slopes of less than 20 percent gradient.
   c. Make strip widths one to four tree heights across on north slopes steeper than 20 percent.

Space the first cut strips three to four strip-widths apart depending on whether you plan for three or four cutting cycles in a rotation.

2. Bulldoze or pile slash near the downhill edge of your cut strip, on all except north slopes. This arrangement will pond cold air to retain snow longer. For fire protection, make windrowed slash discontinuous at ridges and minor rises to minimize fire hazard and bulldoze a lane between the slash and the forest margin. On north slopes doze slash only to the shade line for maximum delayed water yield.

3. If you cut strips up and downhill, as on east or west slopes, "cross your T" at the bottom of the strip by having strip run along contour so as to trap the cold air drainage.

4. In subsequent cuts, cut the strips parallel to the original cut, progressing generally to the south. Thus, a wall of mature trees will always be shading the most recent cut (fig. 6).

If stands have more than 50 percent mature and over-mature trees and are a high risk, "pre-logging" will save some of the values; then:

1. Cut out the patches of decadent trees in this "pre-logging" cut, and

2. In the next cut, connect up these openings so as to make east-west strips:
   a. Make strips about one-half as wide as the rotation tree height on steep (greater than 20 percent slope) south slopes.
   b. Make strips about one tree height wide on gentle north and south slopes and on all east and west slopes.
   c. Make strip widths one to four tree heights across on north slopes steeper than 20 percent, depending on desire for delayed yield versus greater total yield.

In subsequent cuts, cut strips progressing generally southward so as to create a wall-and-step forest with the wall of mature trees facing the south and the steps toward the north.

3. On east and west slopes, connect up the openings, so as to make an uphill strip, and at the bottom of this strip "cross the T" with a strip on contour. The cutting will provide cold air drainage from the uphill cut. This cold air, caught in the contour cut, will result in maximum delay of snowmelt in the contour strip.

If individual high value or high risk trees occur scattered in the stand, take up to 25 percent of the stand volume.

Disposing Slash

Slash may be piled and burned, windrowed, lopped and scattered, or left as it falls, with different results on water yield:

1. Pile and burn slash for delayed snowmelt in spring. Unless shaded, slash if left as it falls causes melting of snow in winter and spring when the snow thinly covers the slash. Slash removal results in 3 to 4 inches more snow water in late spring, when sun reaches the snowpack.

2. Windrowing slash near the downhill wall of trees in cut strips is another way of delaying snowmelt (except on wide strips on north slopes). The slash so placed will help pond cold air near the snow and prevent snowmelt. Windrows should be discontinuous at each ridge and minor rise to reduce fire hazard. A bulldozed strip between the slash and the forest margin helps reduce fire hazard further.

3. Lop and scatter slash or chip slash for immediate soil protection on highly erodible soils and sites, where skid trails run up and downhill, where large areas are clear cut so needle fall will not protect the soil, and where steep slopes and shallow soils combine to make a runoff and erosion hazard.

Converting Brushlands for Water

To convert high elevation brushland to forest in order to achieve temporary increases in water yield and long term improvement in delayed snowmelt yield:

1. Bulldoze brush in strips approximately on contour:
   a. Make the strip width about one-half tree height across (expected height of trees at rotation age) on steep south slopes of greater than 20 percent gradient.
   b. Make the strip widths about one tree height across on north and south slopes of less than 20 percent gradient and all east and west slopes.
   c. Make strip widths one to four tree heights across on north slopes of greater than 20 percent gradient.

2. Windrow the brush on the downhill side of the cleared strips to trap cold air and intercept eroded soil. Make windrows discontinuous at ridges and minor rises to reduce fire hazard.

3. Plan cut strips in time and space for the desired cutting cycles and rotation of the forests being established. For example, space the first strips three strip widths apart for three cutting cycles in the rotation. Clear successive strips progressing generally toward the maximum solar radiation, that is, southward. This clearing and planting plan will result in a wall-and-step forest (fig. 6). Once established, management can perpetuate the forest pattern.

Preventing Floods

For prevention of rain-caused floods or rain-on-snow floods, use selection cutting or cutting in narrow strips (one-half tree height across). Strips should be on contour; selection cutting should leave trees with high vigor. For snowmelt flood prevention, cut narrow strips, which (for the amount of cut) are more effective than selection cutting. To prevent flood synchronization, cut low elevation south slopes so as to speed winter and early spring melt, such as by using wide strips, and leave high elevation north slopes uncut or cut in narrow strips. Convert brush fields to forests to slow snowmelt and hence reduce snowmelt floods.

The above suggestions are interim answers to the questions on how to log forests and convert brushlands to forests for improved water yield. They are based on research studies still in progress. The suggestions are as yet untested on whole watersheds, but they are based on sound physical principles of the disposition of heat and water on forest slopes. First results of tests indicate that the methods are performing well.

We do not expect radical changes in these suggestions because they are largely elaborations of recommendations made 40 years ago by Church, and later elaborated upon by Kittredge. Refinements and specific modifications of the methods now proposed can be expected as well as information on how the patterns can be developed to meet special requirements for controlling the timing of water yield or preventing flood and sedimentation on some watersheds.

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