WATER YIELD IMPROVEMENT IN THE SIERRA NEVADA SNOW ZONE: 1912-1982

697-82

by

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INTRODUCTION

Snowpack management is alive and well in California. After decades of intensive study, water yield improvement in the Sierra Nevada faded from view after the mid-1960's. Interest in the subject is now reappearing. The potential for increased runoff is being assessed on each of the 18 National Forests in California. The Pacific Gas and Electric Company manages one of its project reservoir watersheds for increased and delayed water delivery. The State of California is developing a program of watershed management on low-elevation private lands to increase the input to Lake Oroville, in Butte County.

Most of our theories about water yield improvement in the Sierra Nevada Snow Zone come from studies spanning a 50-year period from about 1912 to 1962. The Western Snow Conference was a leading organization bringing together specialists to discuss snowpack management during this period. Its Proceedings reported on some 18 investigations of watershed development from 1933 to 1966. However, few such studies have appeared there since. This paper summarizes watershed management research in the Sierra Nevada since 1912, the constraints on applying management practices, and deficiencies in our present understanding.

Throughout the past 70 years, research in other mountain ranges has contributed enormously to our understanding of snowpack management opportunities in the Sierra. It is the work done "here at home," however, that remains the most directly applicable. Water yield improvement from the Sierra snow zone generally implies an increase and delay in spring runoff. Delayed yield allows greater use of limited reservoir capacity. Although somewhat controversial, a case can be made that our limited knowledge of snow hydrology and forest influences restricts the application of research results from one snow climate to another. Therefore, we will concentrate only on studies in the Sierra. Figure 1 shows several of the main experimental areas in California. Excellent reviews of research throughout the North American snow zone are presented in West (1957), Sopper (1971), Hibbert (1979) and Bosch and Hewlett (1982).

DEVELOPMENT OF PRINCIPLES

1900-1930

Dr. James Church was, of course, the pioneer in this sort of work. Having observed snow cover and snow depth under varying conditions of elevation, exposure, and forest cover, he found it necessary to measure the water equivalent of the snowpack. Consequently, the Mt. Rose Snow Sampler was developed; not for streamflow forecasting originally, but for investigating forest influences on snow (Church, 1912). After applying snow surveying to the famous Lake Tahoe forecasts of 1910 and 1911, Church (1912) wrote, "But the strength of the [Mt. Rose] observatory staff has been employed in determining the principles that underlie the relation of mountains and forests to the conservation of snow. This work should lead ultimately to the improvement of the forests."

In just a few years, Church developed the fundamental principles for maximizing snow accumulation and delaying melt. We have not substantially improved upon his basic concepts. He discovered that openings in a forest collect the most snow, that dense forests lead to the slowest melt rate but accumulate a minimum snowpack, and that solar radiation and wind as modified by trees are the dominant influences on the snowpack. On the basis of these principles, Church (1912) concluded that the ideal forest for water yield would be a network of small shaded openings.

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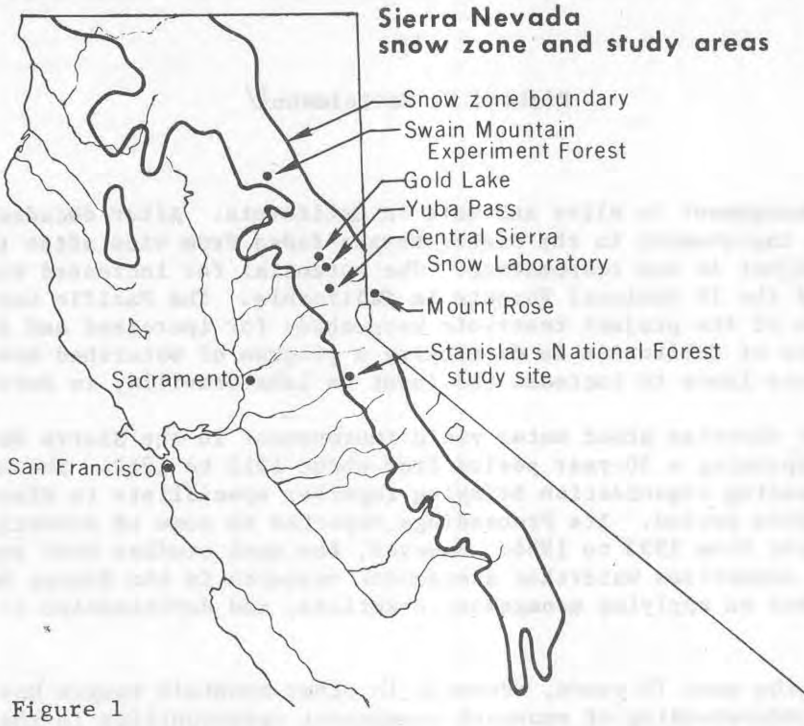

Figure 1

Twenty years later, he republished his findings (Church, 1933) with the classic and oft-quoted statement, "The ideal conservation 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." By then, Church had also recognized the importance of how the melt water is routed to the stream channel and the potential problems of flooding and soil erosion.

1930-1956

In the first Proceedings of the Western Interstate Snow Survey Conference in 1933, Dr. Joseph Kittredge reviewed the interactions of forests and snow (Kittredge, 1933). He agreed with the findings of Church and noted the importance of wind in concentrating snow in small forest openings.

Kittredge began a detailed study of forest influences on snow in 1934 on the Stanislaus National Forest. Although the study was confounded by the effects of terrain variations, it provided many useful results. Maximum seasonal water equivalent in a mixed conifer forest was found in small openings less than twice the height of the surrounding trees (2H) in width (Kittredge, 1953). The values measured in such openings exceeded measurements under adjacent forest cover by 14 to 68 centimeters (cm) (5.6 to 27 in.) with an average of 50 cm (15.7 in.). Kittredge believed that if one-third of a dense mixed conifer forest was cut into small openings, areal snow water storage would be increased by about 13 cm (5 in.). He also found that openings less than 2H wide would only increase the melt rate slightly over the uncut forest.

Kittredge suggested that increased snow accumulation in one area would be offset by a corresponding decrease downwind. He apparently felt that this deficit would occur over a much larger area than current redistribution theory suggests (Gary, 1974; 1980). Kittredge concluded that "Clearcutting in small groups should both yield the most water and prolong the summer flow. Strip cuttings might also give good results if the clearcut strips are narrow, if they follow as far as possible, the contours and are oriented east-west rather than north-south."

During this period, the U.S. Army Corps of Engineers and Weather Bureau Cooperative Snow Investigations produced a wealth of information about snow physics, snow hydrology, and forest micrometeorology (U.S. Army Corps of Engineers, 1956). These studies provided a sound physical basis for methods of forest management for water yield improvement.

1956-1967

In 1956, the Pacific Southwest Forest and Range Experiment Station of the Forest Service, U.S. Department of Agriculture, assumed responsibility for the Central Sierra Snow Laboratory. The Laboratory had been established in 1945, by the U.S. Army Corps of Engineers. Henry Anderson's group contributed much to the understanding of the principles and practices of forest watershed management.

Anderson's first paper on forest-snow relations proposed the concept of the "wall and step" forest (Anderson, 1956). This management system involves a series of narrow east-west oriented strip cuts harvested successively to the south. It provides a wall for shade to the south of a clearcut strip and a regenerating low step of trees to the north which minimize long wave radiation to the snow in the strip. This harvest scheme resulted from an analysis of regression equations relating snow survey data to the effects of trees bordering forest openings. From this analysis, Anderson found that maximum April 1 water equivalent occurs in east-west strips 0.9H wide, maximum late season (June 9) water equivalent occurs in east-west strips 5H wide, and square 1H wide openings would have 8 cm (3 in.) more water on June 9 than the strip treatment. An east-west strip 0.5H wide having 28 cm (11 in.) more water than a dense forest on April 1 would still have 10 cm (4 in.) more water by June 9. It would lose its snow at the same time as the forest on about June 25.

Anderson and Pagenhart (1957) learned that melt rate tended to increase with small amounts of forest cover and then decrease as amounts of shade increased. Anderson, Rice, and West (1958) and West (1961) discovered that cold air drainage seemed to decrease melt in the downslope portion of openings where air may be ponded by the trees. They also noted that only openings less than 1H across on south slopes had melt rates as slow as under south aspect forest. In general, openings 1H to 2H in size had the most water at any time. The statistical analyses appear to have provided good indications of relative amounts and trends. The absolute amounts should be applied with caution.

Working on the Swain Mountain Experimental Forest, Anderson and Gleason (1959) confirmed the ability of small openings to retain maximum amounts of snow. In early June, openings less than 2H wide had 25 cm (10 in.) more water than dense forest or large openings and 10 to 18 cm (4 to 7 in.) more water than stands of lower canopy density. Anderson and Gleason also discovered a major reason for the greater snow catch in the openings and pointed the way for further redistribution studies. They wrote: "Snow immediately to the leeward of the opening is less than snow to the windward of the opening, and less also than the snow further to leeward in the forest. The data suggests that about one-half of the 13 inch [33 cm] greater snow water equivalent in the opening was in effect 'stolen' from the forest to the leeward; the other half represents differences in interception and winter melt." The authors also examined soil moisture losses and reported that strip cuts and block cuts reduced losses by 8 cm (3.2 in.) and 7 cm (2.7 in.), respectively. A water balance analysis determined the potential yield increases from harvesting as 22 cm (8.6 in.) or 51 percent for strip cuts, 16 cm (6.3 in.) or 37 percent for block cuts, and 9 cm (3.4 in.) or 16 percent for selective cuts.

Richards (1959) inventoried the vegetation cover of the west slope of the Sierra Nevada to determine the extent of areas suitable for forest management for water yield. She found that only one-quarter of the area between the 1525 m (5000 ft.) elevation and the crest was covered by forests of greater than 40 percent canopy density. This small proportion of forest, perhaps less than half of which is treatable, limits the water yield potential.

Using principal component analysis of snow survey points, Anderson (1967) compared selection cutting to small block cutting. He concluded that uniform removal of 60 percent of a forest in a selection cut would increase snow accumulation by 4 cm (1.5 in.) or 10 percent. Cutting 60 percent of the forest into small openings would increase total snow storage by 40 percent over the uncut dense forest. Anderson also found that harvesting for maximum water yield would be about twice as effective on north slopes as on south slopes.

1963-1979

Dr. James Smith succeeded Henry Anderson as leader of the Forest Service Snow Hydrology Project in 1963. A decade later, Smith (1974) summarized the project's results from the isotope profiling snow gage and other studies as they applied to water delivery and forest management in the Sierra. Smith discounted aerodynamic placement of snow as a cause of increased snow accumulation in openings. He believed differential melt should account for any differences in observed snowpack water equivalent. As Haupt (1972) had learned in Idaho, Smith found that substantial amounts of melt water dripping from canopy-intercepted snow flow through the pack and do not add to snowpack water. He found this process to be more effective under red fir than lodgepole pine.

Halverson and Smith (1974) developed a technique for controlling forest shade by detailed planning before a timber harvest. They hypothesized that strips oriented north-south would allow less total radiation to be received by a snowpack than in east-west strips of the same width. They believed reradiation from trees north of an east-west strip would cause more melt than a relatively short direct exposure to shortwave radiation in a north-south strip. Their data from Yuba Pass seem to confirm their ideas (Halverson and Smith, 1974; 1979).

Smith (1972; 1975) also pointed out the critical importance of water flow in the soil to its availability for plant use. He stated that plants at the base of a slope have access to more water for longer periods than plants upslope. Therefore, harvesting timber in zones of water accumulation and high water transit should yield more water to streamflow than cutting in other areas.

OPERATIONAL TESTS

Three main tests have been carried out in the Snow Zone since 1912. The Yuba Pass study was the first large-scale test in the Sierra of harvesting designed specifically to increase water yield and delay melt. The study site is south of Yuba Pass on Highway 49 at 2000 to 2130 m (6600 to 7000 ft.). In fall 1962, the Forest Service cut five 40-m (2 chain) wide east-west strips in an old-growth stand of red fir. The 1 km (0.6 mi.) long strips were separated by 120 m (6 chain) of uncut forest. Two 80-m (4-chain) wide strips were cut in 1964 to the west of the narrow strips. Parts of the strips had an extra "lane" partially cut to the north of the strips to simulate a wall and step forest. Slash disposal treatement also varied in parts of the strips.

The first year's results (Anderson, 1963) indicated that the wall and step 40 m- (2 chain-) wide strip increased total areal snow water storage at the end of April by 25 percent over a predicted average of 48 cm (19 in.) had the area not been harvested. Spring snow surveys in 1963 (April 24), 1964 (March 25), and 1965 (March 31) indicated the strips averaged over 40 percent more snow water equivalent than the averaged forest condition (Smith, 1964; 1965). By mid-May in 1965, the strips still contained 25 percent more water than did the forest.

In 1966, two north-south (N-S) natural openings were surveyed to test the hypothesis that melt rates are lower in N-S openings than east-west (E-W) clearings. By early May, more water was found in an 80 m (4 chain) wide N-S opening than in similar width E-W openings. A 40 m (2 chain) wide E-W wall and step cut had the same amount of water as a N-S opening and five times that of a 40 m (2 chain) wide E-W strip with mature timber to the north (Smith, 1966).

The area was not resurveyed until 1981. A "quick and dirty" survey in May of three 80-m (4-chain) wide openings showed the E-W strips with more water than the N-S opening and any of the forest locations. Although this survey was not statistically located or replicated, it is believed to be no less representative than previous surveys in the study area. The 1981 survey also indicated that the positive effects of harvesting on the snowpack have not substantially decreased after almost two decades of tree regeneration. An intensive, statistically based survey is planned for spring 1982.

The principal payoff here is in streamflow, and the lack of such an evaluation is a major deficiency of Sierra water yield research. There has never been a precise evaluation of streamflow response to harvesting in the Sierra Nevada snow zone. Circumstances beyond the control of investigators stymied two earlier attempts at relating streamflow to harvesting. Castle Creek streamflow in two relatively dry years increased by about 4 cm (1.7 in.) over a predicted value after a commercial diameter limit (selection) harvest on one quarter of the 1025 ha (4 mi^2) Central Sierra Snow Laboratory watershed (Anderson, 1963). During the third year after harvest, freeway construction interfered with the monitoring. The proposed control watershed for the Berry Creek drainage containing the

Yuba Pass study area burned at about the same time as the Yuba Pass area was harvested. A less precise analysis of Berry Creek streamflow seems to indicate a significant response to harvesting in the watershed. Unfortunately, poor and incomplete data on timber volume removed, area logged, precipitation, and streamflow prevent any quantitative conclusions. In particular, the dates and amounts of harvest are in doubt.

The Yuba Pass study area represented an area of 24 ha (60 ac) clearcut in strips in 1962 and 1964. Additionally, another 20 ha (50 ac) were clearcut and the canopy was reduced by about 50 percent in selection harvests on approximately 500 ha (1200 ac) of the 1950 ha (7.54 mi^2) basin in the early 1960's. Other selection harvests reduced the canopy by about 25 percent on another 450 ha (1100 ac) between 1967 and 1970.

Streamflow records for Yuba Pass were averaged for three periods: 1955-1962 (before significant harvesting), 1963-1967 (during and after significant harvesting), 1974-1979 (after second period of harvesting) (Fig. 2). Data are not available from 1968-1973 because the gaging station was not operating. Streamflow volumes, April 1 measurements of three nearby snow courses, and annual precipitation from the two closest gage locations were averaged for the three periods (Table 1). Snow storage in the general region as indexed by the April 1 snow course averages was lower in both postharvest periods than in the preharvest period. During and after selection removal of less than one-quarter of the timber volume on the watershed, April to September runoff increased by over 50 percent in a 5-year period. After several years of regeneration and harvesting of another 10 percent of the trees, April and December runoff averaged 30 percent more volume in a relatively dry period than in the preharvest period. Although the available data do not permit any quantitative conclusions, logging appears to have resulted in a substantial increase in streamflow.

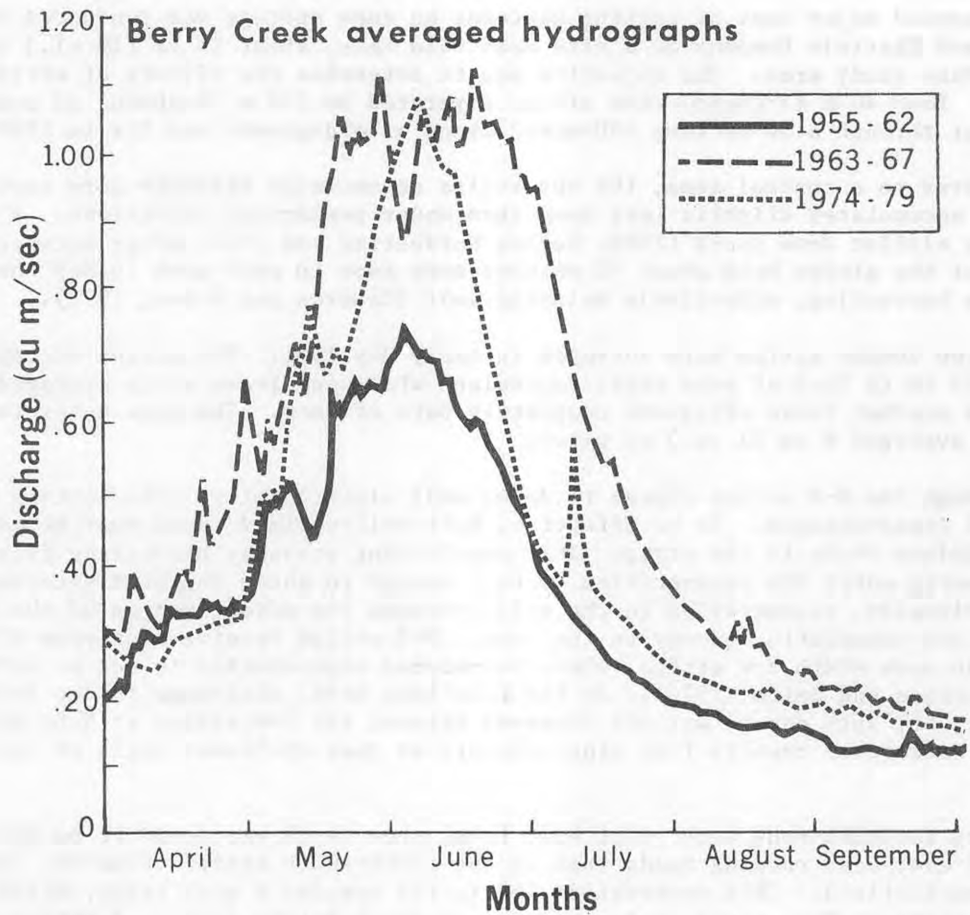

Figure 2

Table 1

Streamflow, snow course, and precipitation averages, at Berry Creek, Sierra Nevada, California

Period	Discharge		April 1 Snow Water Equivalent			Annual Precipitation	
	Annual cm	April-Sept cm	Yuba Pass cm	Webber Peak cm	Webber Lake cm	Sierraville cm	Sagehen Creek cm
1955-1962	42	28	78	113	1/80	65	86
1963-1967	68	45	67	116	72	72	88
1974-1979	51	37	68	97	71	57	71

1/ Estimated

The Yuba Pass strip harvest also provided information on the overall practicality of timber management designed to optimize water yield. Narrow east-west strip cuts appear to be quite desirable for red fir silviculture. The species regenerated readily in the strips and is growing rapidly. A 1981 regeneration survey indicated the strips averaged more than 5,000 trees per hectare (2,000 trees/acre), but the trees occupied only 56 percent of the area. This maldistribution of the stocking was due primarily to overconstructed haul roads and landings and large slash piles.

The second major test of cutting patterns on snow storage was conducted by the Pacific Gas and Electric Company on a site near Gold Lake, about 16 km (10 mi.) northwest of the Yuba Pass study area. The objective was to determine the effects of strips oriented north-south. Four 40 m (2-chain) wide strips separated by 120 m (6-chain) of uncut leave strip were cut through a 30-hectare (80-acre) stand of old-growth red fir in 1968.

Compared to a control area, the cut strips accumulated slightly more snow and the leave strips accumulated slightly less snow than under preharvest conditions. A comparison of relatively similar snow years (1968, before harvesting and 1970, after harvesting) indicated that the strips held about 40 percent more snow in each week in May than did the forest before harvesting, effectively delaying melt (Cameron and Weiss, 1972).

The two longer strips were surveyed in early May 1981. The strips averaged 13 cm (5 in.) and 15 cm (6 in.) of snow water equivalent while one leave strip averaged 5-8 cm (2-3 in.) and another leave strip was completely bare of snow. The snow cover in a nearby large meadow averaged 8 cm (3 in.) of water.

Although the N-S strips appear to delay melt significantly, this cutting technique has practical disadvantages. To be effective, both well-defined edges must be maintained to provide maximum shade to the strip. This requirement prevents harvesting from either side of the strip until the regeneration is tall enough to shade the next successive strip. Additionally, regeneration in the strip reduces the effectiveness of the treatment by absorbing and reradiating energy to the snow. N-S strips receive much more direct solar radiation than same width E-W strips, where sun-warmed regeneration is not as much of a problem (Halverson and Smith, 1979). At the Gold Lake site, windthrow in the leave strips was extensive, but such damage was not observed between the E-W strips at Yuba Pass. Whether this difference results from wind exposure or just shallower soils at Gold Lake is not known.

During the PG&E snow surveys at Gold Lake, snow depth was found to be much greater on the nearby east-west running roads than in the north-south strips (Cameron, 1980, personal communication). This observation led to the company's next trial, which is a test of east-west strips. This study is in progress on North Battle Creek. A series of 3/4H wide east-west strips were cut on a 10 percent south slope in 1978 and 1979. Snow survey results from 1980 indicate that snow storage was about 15 percent greater in the strips than in the forest throughout the melt season.

CONSTRAINTS AND CONCERNS

Operational water yield improvement is subject to a wide variety of management constraints. The goal of improving water yield must be balanced against the goals for other forest resource uses. Timber is generally the principal forest product, and only where techniques for water yield improvement are compatible with timber production will they be used. In fact, the emphasis of watershed management research is shifting from the design of harvests to optimize water yields to evaluating water yield consequences of harvests designed to optimize timber production. One detailed evaluation procedure is that of Troendle and Leaf (1980). In time, we should be able to go back and propose modifications to these harvests to improve water benefits without negatively affecting timber production. The existing stand structure often restricts how the stand can be managed for water or for timber.

Management for increased water quantity may conflict with water quality objectives. More water can often translate into more erosion. A common concern with forest management for increased water yields is that of increasing flood potential. Spring snow melt rarely causes much flood damage in California, and even the most optimistic yield increases resulting from forest manipulation should not add to any hazard. Rain-on-snow events tend to cause the greatest peak flows in Sierra streams. Larger clearcuts may have the potential for greater snowmelt contribution during rains due to the greater turbulent heat exchange (convection/condensation melt) in the windswept clearings. They may also permit rapid routing of water over ice lenses to stream channels. Small openings and strips, on the other hand, may actually reduce rain-on-snow flood peaks by providing greater water holding capacity than the usually saturated-under-canopy snowpack. The smaller openings are not believed to increase windspeeds over those within a forest stand (Bergen, 1976; Swanson, 1980).

RESEARCH NEEDS

In addition to research predicting the effects of, and modifying, timber management harvests, much remains to be learned about the interaction of vegetation management and snow and forest hydrology. We urgently need to conduct a watershed study in the Sierra so that we may add some streamflow numbers to the conjectures. We must increase our understanding of soil water flow and streamflow generation in the forest environment in order to know how increased on-site available water translates into streamflow. We do not know what efficiency losses occur by delaying melt in openings upslope from forests. Similarly, the effectiveness of different spatial relationships between openings and uncut forest, other openings, channels, and the topography of an entire watershed should be studied. The importance and magnitude of snow redistribution, interception loss, and transpiration in the Sierra are not agreed upon, let alone quantified.

Operationally, we still do not really know how to manage a large basin for optimum water flow. Little is known about proper management of the low elevation (900- to 1700-m [3000-5500 ft.]) transient snow zone, the higher unforested ridges or the northern east side of the Sierra. A large-scale test of means and effects of brushfield conversion remains to be done. Weather modification has been suggested as a means of increasing the effectiveness of vegetation manipulation elsewhere (Satterlund, 1969; Leaf, 1975), but the potential has not been studied in the Sierra. The economics of water yield improvement have not been studied to the point of having sound justification for application of the known management techniques.

SUMMARY

So, where does seventy years of research leave us? Apparently, not much beyond Dr. Church's concept of a honeycomb-like forest of small openings. Indeed, openings about an acre (0.4 ha) in size with a solid wall of tall trees to the south and not more than 2H wide from south to north should provide the maximum accumulation and delayed melt benefits of any harvesting method. Such a forest should be compatible with timber management objectives, have few water quality problems, be beneficial to wildlife, and be visually acceptable. It requires detailed full rotation planning, scheduling, and design of all harvests and roads before the initial harvest.

Strip cuts oriented east-west may be thought of as a connected series of small blocks. The lack of edges on the east and west sides permits more energy to reach the snow surface than in small blocks, except for very narrow strips. This potential for greater melt is probably balanced by greater soil moisture savings and lower transmission losses. A forest of strip cuts is easy to regulate and provides the opportunity to minimize longwave back radiation to the snow in the strip by creating a wall and step pattern. North-south strips are effective in delaying melt but represent a one-time treatment. The edges cannot be removed without accelerating melt.

The following are some basic guidelines for increasing and delaying streamflow from the snow zone:

- Open the forest to redistribute snow to the shaded openings where vegetation is not present to deplete soil moisture.
- Shade the snow and the trees to the north of the opening to delay melt.
- Maximize evapotranspiration savings by harvesting in areas with the most soil water in storage or in transit.
- Harvest where channels are present to route the water to streams where water quality considerations permit.
- Concentrate activities on north slopes which allow a wide range of options and are more effective water producers than south slopes.

CONCLUSIONS

Extensive research in the Sierra Nevada snow zone has provided the means of maximizing snow accumulation, delaying snowmelt, and reducing water losses through forest management. Operational tests have shown the methods to be quite effective and persistent in increasing on-site water available for runoff. Observations from an uncontrolled watershed indicate that streamflow does increase dramatically after the least water-yield efficient type of timber harvest. Further work is needed to quantify the potential for improving water yields before the techniques can be broadly applied. If greater water demand should call for improving the quantity and timing of water flow from forests in the Sierra Nevada, the necessary management practices to achieve that end appear to be compatible with other resource values.

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