

## Forest harvest, snowmelt and streamflow in the central Sierra Nevada

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**ABSTRACT** Forest harvest techniques have often been suggested as a means of increasing snow accumulation and beneficially delaying snowmelt in the Northern and Central Sierra Nevada mountains in California. To test the effect of such management practices on streamflow, extended snowmelt was simulated in June 1985 on four 960 m<sup>2</sup> plots in a 50 ha drainage basin. Less than 1% of a bromide tracer in the simulated snowmelt was detected at a downstream weir through the summer and early fall of 1985. Although significant increases in the water table and soil moisture content were found in the treated plots and, in some cases, downslope, the simulated snowmelt apparently did not substantially increase streamflow in 1985. The consistently high concentrations of bromide observed at the weir in 1986 are believed to be a function of basin lithology. The results to date cast doubt on the linkage that can be made between an increase in snow water equivalent on the hillslope and downstream discharge.

### *La coupe, la fonte et les débits dans le centre de la Sierra Nevada*

**RESUME** On a souvent suggéré des techniques de coupe pour accroître l'accumulation de la neige et retarder la fonte dans le nord et le centre de la Sierra Nevada, en Californie. Afin de tester l'effet d'un tel traitement sur les débits, on a simulé une extension de la fonte en juin 1985 sur quatre parcelles de 960 m<sup>2</sup> dans un bassin de 50 ha. Moins de 1% du bromure utilisé comme traceur a été détecté à un seuil en aval au cours de l'été et de l'automne suivant. Malgré une augmentation de la teneur en eau du sol et une élévation de la nappe sur, et parfois en aval des parcelles traitées, la fonte simulée n'a eu aucun effet apparent sur les débits de 1985. Les fortes concentrations de bromures observées de façon constante en 1986 sembleraient être dues à la lithologie du bassin. Les résultats jettent un doute sur la possibilité de relier une augmentation du couvert neigeux à une augmentation des débits.

## INTRODUCTION

The deep winter snowpacks of the Sierra Nevada are of critical importance with regard to both the volume and timing of California's water supply. It has been estimated that 51% of the surface runoff in California is derived from the snow zone (Anderson, 1963). The lag between snowfall and snowmelt helps alleviate the temporal asynchrony between supply and demand. With high-elevation water often valued at over \$0.16 per m<sup>3</sup> (\$200 per acre-foot) (Romm & Ewing, 1987) and excess snowmelt runoff making reservoir spillage a common event for some reservoirs (MacDonald, 1986a), snow management techniques which reduce snowmelt runoff peaks and/or extend snowmelt runoff have long been of interest.

Church (1912) concluded that the ideal forest in the Sierra Nevada would have many small shaded openings which would both accumulate snow and delay melt. Since then numerous forest harvest trials have produced highly variable results (Kattelmann, 1982; McGurk & Berg, 1987). Estimated values for the increase in maximum SWE (snow water equivalent) in cut openings and narrow strips as compared to the uncut forest are 39 cm (Kittredge, 1953), 33 cm (Anderson & Gleason, 1959), and 25 cm (Anderson, 1963).

These values are for maximum SWE, however, and the persistence of this increased SWE during the snowmelt period is much more uncertain. Large clearcuts have been shown to increase the rate of spring snowmelt by up to 50% (to a maximum of 4-5 cm SWE per day) compared to uncut forest, and this shifts the disappearance of snow forward by approximately 16 days (Anderson, 1963). In the case of small patch or narrow strip cuts, melt rates may be slightly higher than melt rates in the uncut forest, so the increased SWE in small openings will postpone the disappearance of the snow by at most a few days (Kattelmann, 1982; McGurk & Berg, 1987).

Cloud-seeding is another means of manipulating the Sierra snowpack, and this is being practiced by several public utilities. The untested assumption is that an increase in maximum SWE will be transformed into a useful increase in streamflow. Early studies claimed a 32% increase in precipitation from cold westerly storms in the Lake Almanor catchment basin (Mooney & Lunn, 1969) and a 6% increase in runoff in the Kings River basin (Henderson, 1966). More intensive studies by the U.S. Bureau of Reclamation suggest an increase in precipitation of closer to 1% (Reynolds & Dennis, 1984), but even small increases in precipitation represent a substantial volume of water if achieved over a large area.

This assumption--that an increase in snow water equivalent or a delay in snowmelt beneficially affects streamflow--is conceptually a question of how additional snowmelt will be partitioned among:

- (a) relatively rapid surface or subsurface flow to the stream channel;
- (b) evapotranspiration; and
- (c) groundwater storage.

Both (a) and (c) should result in the desired increase in water yield, but the timing of this increased yield will be quite different. By definition, (a) will increase streamflow on the recession limb of the snowmelt hydrograph and thus contribute to late spring and early summer streamflow. Water entering groundwater

storage (c) will serve primarily to sustain baseflow and reduce the amount of recharge needed in the autumn, and thereby increase the amount of runoff from storms in the autumn and early winter. This paper presents preliminary results from a field experiment designed to quantitatively assess the linkage between late season snowmelt (due either to cloud-seeding or forest harvest techniques) and streamflow in the Central Sierra Nevada of California. While the results are specific to the study site, they have significant ramifications for other areas, particularly those underlain with fractured or permeable bedrock.

#### SITE DESCRIPTION AND METHODS

The study site was Onion Creek 1, a 50 ha research basin in the Central Sierra Nevada ranging in elevation from 1870 to 2200 m (Fig.1). The vegetation is largely undisturbed old growth forest in the transition zone between Sierran west slope mixed conifer and the higher elevation true fir. Annual precipitation is 1300 mm, with roughly 90% of this amount falling as snow. Eighty-six percent of all precipitation falls between 1 October and 31 March (Smith & Berg, 1982), with almost no precipitation between mid-June and 1 September.

Soils are generally poorly developed and less than 1 m thick. The experimental sites are all underlain by the Valley Springs formation, a nearly horizontal rhyolitic ash. Thick latite deposits, which are less porous and more resistant to weathering, lie both above and below the Valley Springs formation.

Snowmelt was simulated on four 960 m<sup>2</sup> plots by surficially applying approximately 2.5 cm of water per day for 10-12 days in early June 1985 (at the end of the normal snowmelt period). While this rate (2.5 cm/day) of simulated snowmelt is slightly low for forested sites in the Central Sierra Nevada in June, the duration of treatment (10-12 days) represents the difference in the date of snow disappearance between large clearcuts and small strip cuts, as well as the magnitude of increase in SWE which might optimally be expected as a result of cloud-seeding. The treated plots were roughly circular, with the size corresponding to openings 1 H (H=tree height) in diameter.

Since the volume added was small relative to the total flow at the Onion Creek 1 weir, and there was no other catchment which could be paired with Onion Creek 1 to predict untreated flows, a tracer (sodium bromide) was added to the simulated snowmelt applied in the four treated plots. A salt form of bromide (NaBr) was selected as the tracer because the natural concentrations of bromide are extremely low, it is non-toxic and very mobile in aqueous systems, and it is not lost from aqueous systems by phase changes or other transformations (Smith & Davis, 1974; Bowman, 1984). Sodium bromide is also easily dissolved, inexpensive and aqueous systems can be quickly and accurately analyzed for bromide over a wide range of concentrations.

From the amount of tracer applied and the volume of runoff and concentration of tracer at the weir, it was possible to calculate the timing and delivery of the simulated snowmelt to the stream. In

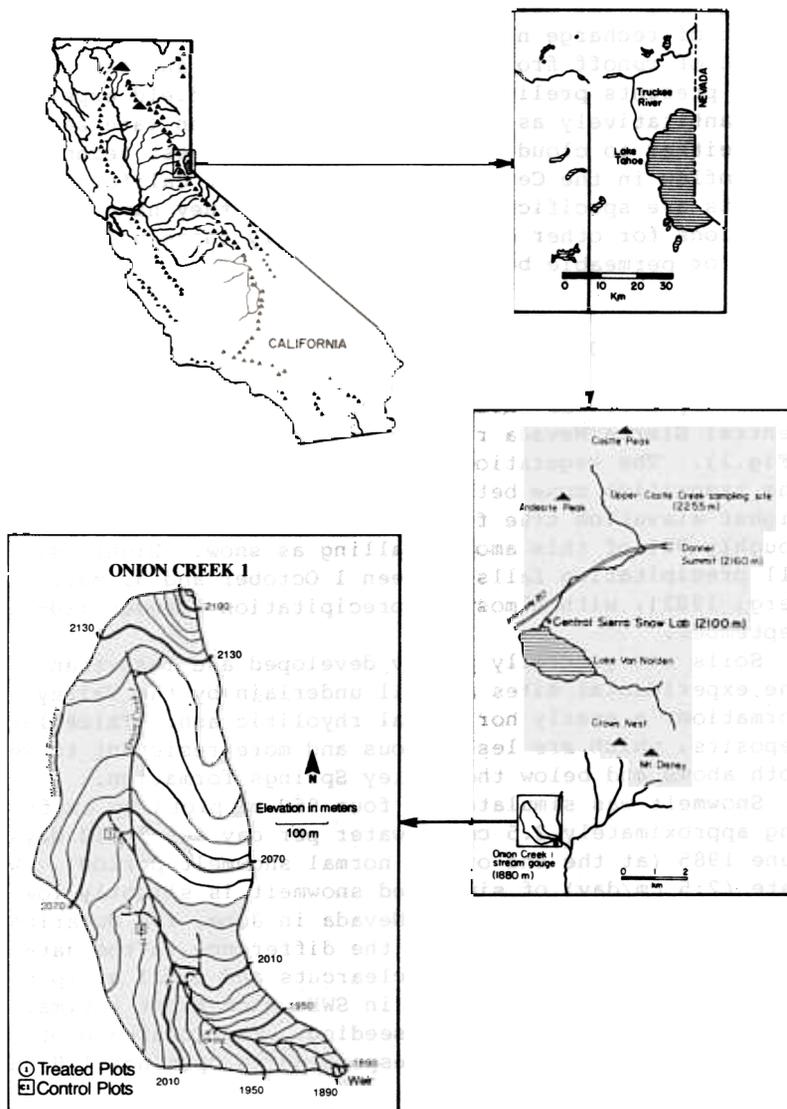


FIG.1 Topographic map of the Onion Creek 1 catchment.

the absence of regular monitoring of bromide concentrations along the stream channel, it was not possible to determine the respective contribution from each treated plot to the tracer concentrations observed at the weir.

Extensive instrumentation was placed in treated plots 1 and 3 (Fig.1) in order to provide an understanding of the runoff processes, and to assist in the interpretation of the downstream tracer data. Similar instrumentation was placed immediately adjacent (upstream) of treated plots 1 and 3 to serve as untreated controls. The layout of the instrumentation in treated plot 3 and its adjacent control area is shown in Fig.2. Treated plot 1 was laid out in a similar manner, but was closer to the stream and on a slope only

half as steep (16% vs. 30%). Typical depths for the nests of tensiometers and soil water samplers in both plots was 30, 70 and 90-120 cm (a more detailed description of instrumentation can be found in MacDonald, 1986b). In 1986 additional tensiometers, piezometers and soil moisture blocks were placed upslope of the treated and control plots in order to clarify the effect of the treatment, and additional piezometers were installed at depths of 1.5-4.5 m to permit monitoring of groundwater levels throughout the summer.

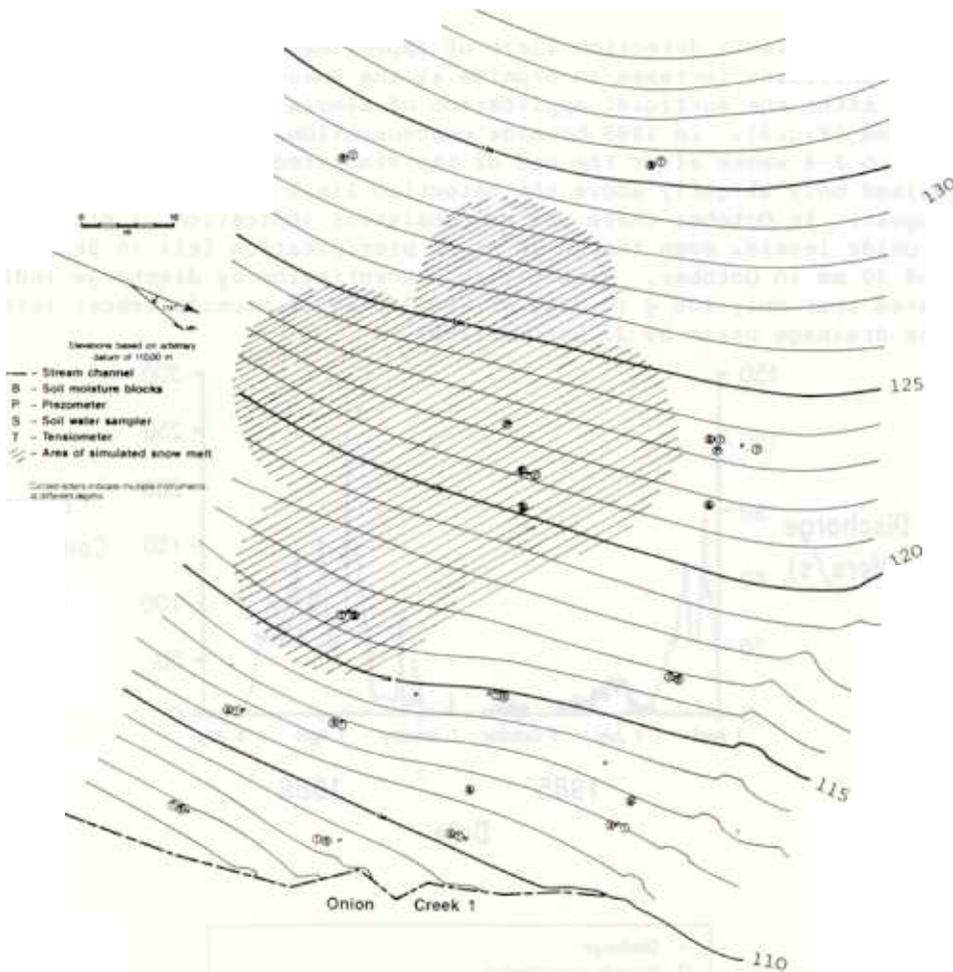


FIG.2 Map of treated plot 3 and control plot 2

In 1985 and 1986 simulated snowmelt began when the snow still covered about 10% of the study area. In order to avoid confounding the bromide results, no tracer was used in 1986. Soil water, litter, soil and foliage samples were collected in both 1985 and 1986.

All the bromide analyses reported here were done with a Dionex<sup>1</sup> ion chromatograph. Aqueous extracts were used to determine the bromide concentrations in the soil, foliage and litter samples (Abdalla & Lear, 1975).

A Guelph permeameter (Soil Moisture Equipment) was used to measure the saturated hydraulic conductivity in the soils and decomposed rhyolite. Constant head tests in each piezometer (U.S. Dept. of Interior, 1980) provided estimates of the hydraulic conductivity below a depth of 1.2 m.

## RESULTS AND DISCUSSION

Given a reliable detection limit of approximately 5 ppb, there was no significant increase in bromide at the Onion Creek 1 weir until a week after the surficial application of simulated snowmelt had ceased (Fig.3). In 1985 bromide concentrations peaked at about 35 ppb 2-4 weeks after the end of the simulated snowmelt, and remained only slightly above the detection limit until the end of August. In October there was no consistent indication of elevated bromide levels, even though 76 mm of precipitation fell in September and 40 mm in October. Multiplying concentration by discharge indicates that only 100 g (0.04%) of the 280 kg of bromide tracer left the drainage basin by 31 October 1985.

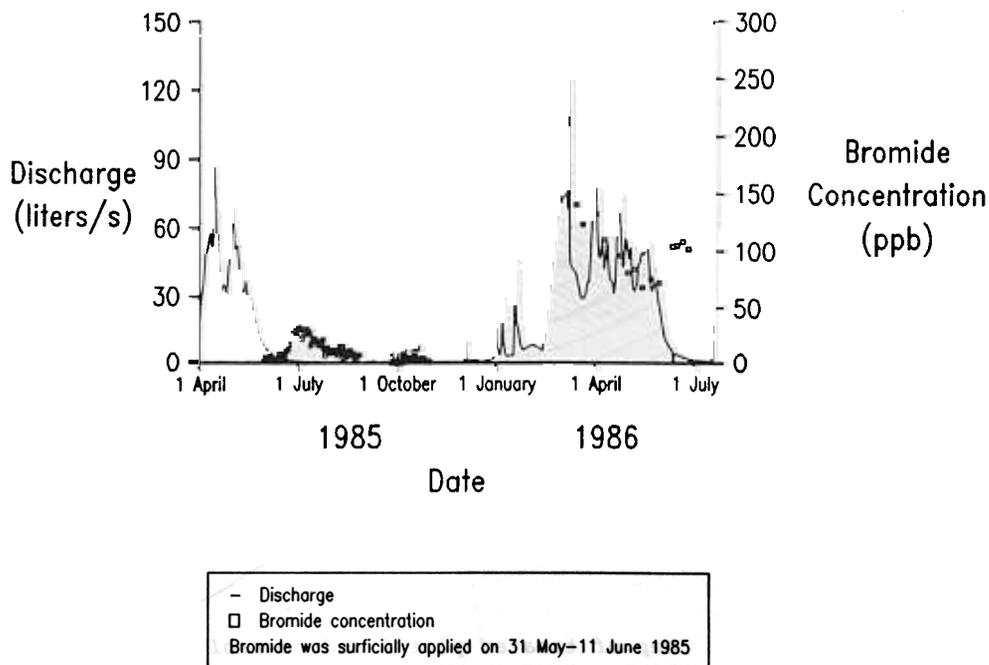


FIG.3 Bromide concentrations and average daily discharge at the Onion Creek 1 weir.

<sup>1</sup>Mention of a specific product does not imply endorsement by the US Forest Service.

Bromide concentrations in late February 1986 at the Onion Creek 1 weir were nearly 10 times greater than in the previous summer. These higher concentrations, combined with high discharges due to a series of rain-on-snow events, resulted in an estimated flux of 33 kg of bromide between 24 February and 21 March 1986. Bromide concentrations were lower but relatively stable throughout the spring melt period, and from 21 March to 17 July approximately 28 kg of bromide passed over the Onion Creek 1 weir. From 17 July to mid-October 1986 there were no major discharge events, and bromide concentrations have remained in the range of 50-70 ppb. For the period 1 November 1985 to 24 February 1986 stream water samples were not available, but average daily discharge exceeded  $20 \text{ l s}^{-1}$  for only two days prior to 11 February. Severe storms from 12-22 February produced high discharges, but in the absence of both streamflow and tracer data the flux of bromide can only be crudely estimated at 20-25 kg. Thus in the fifteen months following the application of the tracer on the sideslopes, approximately 30% (80-86 kg) of the bromide tracer left the Onion Creek 1 catchment as streamflow. This relatively low percentage suggested that bromide might not be a conservative tracer, and for this reason soil, litter and foliage samples were analyzed for their bromide content.

Bromide concentrations in soil samples taken at various depths and locations, when combined with bulk density data and corrected for rock content, indicated that approximately 4 kg of bromide tracer remained in both site 1 and site 2 in the summer of 1986. Similar calculations showed approximately 1 kg of bromide downslope from each of the two plots. Assuming the other two sites are similar, the soils in all the treated plots and downslope areas could be estimated to contain perhaps 20 kg of bromide, or less than 10% of the total applied.

Bromide concentrations in litter samples collected in the summer of 1986 averaged 35 ppm (0.0035%) in the treated plots. Average litter weight is approximately  $5000 \text{ g m}^{-2}$  in the study area, resulting in an estimated 170 g of bromide per treated plot, or 0.7 kg in the study area.

Bromide concentrations in the 1985 and 1986 foliage of small trees in the treated plots was found to be 0.01-0.09% (100-900 ppm) of their dry weight. From Stangenberger's (1979) values for foliage weights in red fir forests and Zinke's (pers. comm.) estimate of the life span of red fir needles, it can be estimated that approximately 1 kg of the bromide tracer has been taken up in the foliage.

The total amount of bromide absorbed or taken up and held within the soil, litter and foliage is estimated to be 22 kg. While there is some uncertainty associated with this estimate, the magnitude of loss tends to confirm the validity of using bromide as a tracer.

If it is assumed that the bromide concentrations at the weir reflect the delivery of the simulated snowmelt to the stream, it appears that delayed melt was not effective in augmenting late spring and early summer streamflow. Even if bromide is not assumed to be a conservative tracer and concentrations at the weir are multiplied by a factor of 4 to correct for known (soil, litter and vegetation) and unknown losses, the amount of tracer delivered to the stream throughout the summer of 1985 is still much less than 1%.

On the other hand, the tensiometer, piezometer and soil moisture block data for 1985 consistently show that the simulated snowmelt had a significant effect within the two intensively-monitored plots (MacDonald, 1986b). The treatment effect also extended to the stream channel in the downslope area of plot 1, but apparently not for treated plot 3 (Fig.2). While the increased height of the water table dissipated rapidly once treatment ceased, the tensiometers and soil moisture blocks indicated that the initial 10-12 day lag in the soil drying curve due to the simulated snowmelt treatment persisted for up to two months (MacDonald, 1986b). Preliminary review of the 1986 data indicates similar trends.

The apparent conflict between the bromide tracer results and the observed changes in groundwater and soil moisture can be reconciled by reference to the hydrologic properties of the Onion Creek 1 soils and substrate. First, however, it should be remembered that the bromide concentrations at the weir did not peak in the summer of 1985 until 2-4 weeks after sprinkling had ceased. This small, delayed peak of bromide suggests that pipe or macropore flow was not transporting significant quantities of the simulated snowmelt to the stream, even though groundwater levels were less than 1 m below the surface (and hence well within the rooting zone) for several sites for some or all of the treatment period.

Measured saturated hydraulic conductivities for the soil at depths of 60 and 90 cm were all in the range of  $2 \times 10^{-4}$  to  $9 \times 10^{-4}$  cm s<sup>-1</sup>. Using the high value of  $9 \times 10^{-4}$  cm s<sup>-1</sup>, a horizontal distance of 20 m to the stream channel for Site 2, and a slope of 32%, it would take 80 days for the tracer to reach the stream. Similar calculations for Site 1 yield a minimum transit time of 100 days. However, in both 1985 and 1986 the water table had dropped to the C horizon no more than 10 days after the cessation of sprinkling. Soil water content remained at or above field capacity for another 4-6 weeks, but hydraulic conductivity declines dramatically with desaturation (Bloemen, 1980). Since the measured hydraulic conductivity of the underlying rhyolite is on the order of  $10^{-5}$  to  $10^{-7}$  cm s<sup>-1</sup>, the transient increase in groundwater levels and soil moisture due to the simulated snowmelt treatment cannot be expected to result in a substantial increase in the delivery of water to the stream channel.

The key factors controlling the delivery of the simulated snowmelt to the stream are the distance to the stream channel, steepness of the slope, flow path to the channel, and effective hydraulic conductivity. Changes in any one of these could substantially alter the transit time of the simulated snowmelt, and hence the likelihood of being lost to evapotranspiration. Assuming "typical" values of 50 m from a stream channel and a slope of 35%, the hydraulic conductivity would have to be  $2 \times 10^{-2}$  cm s<sup>-1</sup> if the simulated snowmelt is to reach the stream within 10 days. This suggests that relatively few sites would be capable of delivering substantial quantities of late season snowmelt to the stream. Alternatively, if one assumes that piston or translatory flow is an effective means of generating runoff, it may be possible to have both the observed pattern of tracer and a significant increase in summer streamflow. These aspects are expected to be further quantified through the use of a

physically-based saturated and unsaturated transient and steady-state porous media flow model.

One of the more surprising results in the study has been the consistently high levels of bromide observed at the Onion Creek 1 weir fifteen months after the tracer was applied on the side slopes. This suggests a large storage capacity and a relatively long retention time, and a variety of evidence indicates that this is a function of the underlying lithology rather than the overlying soils. First, the remarkably stable concentration of the tracer through spring snowmelt and the summer baseflow period (precipitation from mid-May to mid-September 1986 was only 14 mm) suggests that the streamflow was derived primarily from deeper sources. Second, the amount of tracer remaining in the soil is relatively small, and the extreme dryness of the soils in the latter part of the summer precludes any contribution to streamflow. Third, rock samples taken at depths of 1-5 m during spring 1986 have an effective porosity of 15-27%, and since the ash deposit under the study site is on the order of 30 m thick, the potential exists for storing large quantities of water.

#### CONCLUSIONS

The bromide tracer results suggest that much less than 1% of the simulated snowmelt actually contributed to late spring runoff and summer baseflow. While the groundwater and soil moisture data indicate a clear and persistent effect, there was insufficient time for this supplemental input to reach the stream before desaturation occurred and the rate of flow approached zero. That proportion of simulated snowmelt which did not percolate below the rooting zone is assumed to have been used for evapotranspiration over the dry California summer.

If neither translatory flow nor macropore flow are important means for delivering upslope snowmelt to the stream channel, the only means by which the simulated snowmelt could be transformed into useful runoff is if the applied water seeps into a groundwater storage layer which is not available to the vegetation. In this case less recharge would be needed in the following autumn, and the amount of runoff in late fall and early winter would be correspondingly increased. The timing of such an increase is optimal for the generation of hydroelectricity, as reservoirs are typically at their lowest levels in the fall and there is no chance of spillage (MacDonald, 1986a). There are strong indications that most of the tracer in the Onion Creek 1 catchment has entered into deep storage, but whether this has been transformed into the desired beneficial effect on streamflow is a question that cannot yet be fully answered. It is expected that current modelling efforts will help quantify the controlling processes, and assist in extrapolating from these results--which are based on specific plots in a single catchment--to other areas.

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