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Peak flows from snowmelt runoff in the Sierra Nevada, USA

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ABSTRACT Snowmelt runoff in the Sierra Nevada of California fills rivers with vast quantities of water over several weeks, although it does not cause the highest flood peaks. Snowmelt flood peaks are limited by the radiant energy available for melt, shading by terrain and forest canopies, proportion of the catchment contributing snowmelt, and synchronization of flows in tributaries. The volume, duration, timing and peak of snowmelt floods may change systematically with a warmer climate and reductions in forest density and area.

INTRODUCTION

Snowmelt floods are the main hydrologic event in the rivers of the Sierra Nevada. Each spring, the precipitation of winter is released from its storage as the snow cover of the Sierra Nevada to become streamflow. The snowmelt runoff provides sustained high water in the rivers for a two or three month-long period. In most years, the spring snowmelt flood is readily managed by California's network of reservoirs and aqueducts to deliver water for irrigation and urban use throughout the state. However, in some years, the seasonal volume of runoff exceeds the artificial storage capacity and riparian areas and low-lying parts of the San Joaquin Valley are flooded. Although engineering aspects of these largest snowmelt floods have received considerable attention, there has been little study of their basic characteristics.

Some concern exists that the general nature of snowmelt floods in the Sierra Nevada may change in the next few decades if the climate and vegetation change. A series of four relatively dry years and continuing discussion of global warming have made Californians aware of the potential for climatic change. If winter temperatures increase and precipitation becomes more variable from year to year, the snow hydrology of the Sierra Nevada can also be expected to change (Lettenmaier & Gan, 1990; Tsuang, 1990). Vegetation cover and, consequently, snow storage, evapotranspiration, and soil moisture storage may be altered in the next 50 years. The 1987-1990 drought has left forests susceptible to insects, disease, and fire. Harvesting and conversion to other uses are changing the composition of Sierra Nevada forests. Air pollution and acidic deposition have also damaged Sierran forests (Olson & Lefohn, 1989). If large-scale alterations in vegetation occur over the Sierra Nevada, the pattern of spring floods may also change (e.g., Anderson, 1963; Kattelmann et al., 1983). This paper discusses the characteristics of snowmelt floods in the Sierra Nevada during the past century.

Sierra Nevada Geography

The Sierra Nevada forms the drainage divide between the Pacific slope and the Great Basin in eastern California and western Nevada. The range trends northwest-southeast for more than 600 km and averages about 100 km in width. Snow dominates the hydrology of the Sierra Nevada, accumulating from November through March or April and then melting from April through June or July. At higher elevations, the snow-free part of the year lasts only from mid-July through mid-October. The alpine zone begins above 2800-3000 m in the northern Sierra Nevada and above 3000-3300 m in the south (Storer & Usinger, 1963). The subalpine forest zone is found below the alpine zone and extends down to about 2100-2400 m in the north and 2500-2900 m in the southern part of the range. Few stream gages or climate stations exist above 2000 m, but more than 100 snow courses and snow sensors are used to monitor the snow cover. Discharge in a few major rivers at lower elevations began to be measured in the 1890s. Streamflow records for about two dozen streams and rivers in the Sierra Nevada with unimpaired flow began sporadically after 1915.

CHARACTERISTICS OF SNOWMELT FLOODS IN THE SIERRA NEVADA

In the Sierra Nevada, snowmelt floods become hazards because of their long duration and total volume rather than their peak discharges, which are considerably lower than those caused by other flood-generating processes such as rain-on-snow (Kattelmann, 1990b). In a major snowmelt flood, water levels can remain high for several weeks. For example, during the flood of 1983, daily mean discharge of Sagehen Creek near Lake Tahoe exceeded bankfull stage for 45 days and exceeded 230 percent of bankfull discharge for 14 days (Andrews & Erman, 1986). Discharge at this level of 230 percent of bankfull had been equalled or exceeded on only 16 days in 29 years of record before 1983. Snowmelt runoff during June 1983 ranged from 400 to almost 900 mm in various rivers of the Sierra Nevada (Table 1). Peak flows from snowmelt can sometimes be significant in mountain rivers by effectively entraining and transporting bedload (Andrews & Erman, 1986). Specific peak discharges during the 1983 snowmelt flood ranged from 0.2 to 0.8 $m^3 s^{-1} km^{-2}$ in a sample of Sierra Nevada rivers with natural flow conditions (Table 1). Consistent relationships between peak specific discharge and geographic attributes of these basins could not be identified.

The sustained input of water into reservoirs and canals can overwhelm storage and conveyance capabilities and can cause substantial leakage through levees (Dean, 1975). Inundation of agricultural land by spring snowmelt floods occurs during the growing season and can lead to greater financial losses than higher water levels in mid-winter. The San Joaquin Valley tends to be more susceptible to damage from snowmelt floods than the Sacramento Valley because a greater proportion of its contributing area is in the deep snowpack zone at higher altitude, this high-elevation snow cover of the southern Sierra Nevada persists later into the spring, and there is less available reservoir storage on rivers in the southern part of the range than in the northern part.

TABLE 1 Snowmelt floods during 1983 in mountain rivers (north to south).

River	Gage Elevation (m)	Drainage Area (km^2)	June Runoff (mm)	Peak Flow ($m^3s^{-1}km^{-2}$)
North Yuba	748	647	412	0.28
South Yuba	1682	135	873	0.66
Sagehen	1927	28	372	0.27
Blackwood	1902	28	839	0.70
Upper Truckee	1928	85	504	0.39
West Fork Carson	1755	168	435	0.39
Cole	1799	54	767	0.79
Clark/Stanislaus	1679	176	555	0.33
Falls	1634	119	706	0.44
Merced	1225	469	519	0.33
San Joaquin	1393	645	560	0.34
Bear	2246	136	400	0.29
Pitman	2136	59	806	0.61

Five large-magnitude snowmelt floods affecting most of the Sierra Nevada have occurred in this century: 1906, 1938, 1952, 1969, and 1983. These events were notable for their extensive flooding in the San Joaquin Valley. Although their peak discharges were generally less than twice the mean annual snowmelt flood and only one-tenth to one-half as great as the largest rain-on-snow floods, their total volumes were two to four times larger than average. In the floods of 1952 and 1969, more than 80 000 ha of "reclaimed" agricultural land in Buena Vista Lake, Tulare Lake, and along the San Joaquin river were flooded (Stafford, 1956; Dean, 1975). In 1952, 1969, and 1983, extensive snow surveys indicated that the snowpack water equivalence in early April and early May was two to three times greater than average values over the period of record (Department of Water Resources, 1969; 1970; and 1983). These years were also characterized by above-average snowfall and below-average energy input (as indicated by low air temperatures) during April. Temperatures remained low throughout the spring of 1952 and, thereby, moderated the rate of snowmelt (Stafford, 1956). However, in 1969, clear skies prevailed in May and temperatures were high; snowmelt was correspondingly high (Dean, 1975). Peak discharges at high altitude where most of each basin was snow covered and contributing runoff were greater than previous snowmelt peaks. Dean (1975) provides the example of Golden Trout Creek (gage elevation of 2700 m) where the 1969 snowmelt peak was more than twice as large as the previous maximum snowmelt peak. High radiation input and high temperatures in late May 1983, combined with nearly continuous snow cover at high altitude, led to peak flows comparable to or exceeding those in 1969 in most streams and rivers of the Sierra Nevada (Department of Water Resources, 1983). Unusually deep snowpacks were also present in 1986 at high altitude. However, the near-absence of snow below 2000-2500 m in May limited the size of the spring flood that year.

FLOODS FROM THE FOREST ZONE

Most studies of snow hydrology in the Sierra Nevada have been conducted in the forest zone, primarily at the Central Sierra Snow Laboratory near Lake Tahoe (e.g., Miller, 1955; U.S. Army Corps of Engineers, 1956; McGurk, 1985). The catchments of the major rivers of the Sierra Nevada are largely forested, with proportion of the basin covered by forest generally declining from north to south. Rain-on-snow events typically generate the annual flood in the forest belt, although this area also maintains a deep snowpack until spring. Snowmelt maintains streamflow above 0.05 $m^3 s^{-1} km^{-2}$ for several weeks in most years. However, melt rates of the forest snowpack are constrained by the reduction in energy input provided by shading from the tree canopies. Drainage basins of moderate size (20 to 200 km^2) are still capable of producing large snowmelt floods. For example, the South Yuba river near Cisco collects snowmelt runoff from a well-forested area of 135 km^2 between 1700 and 2500 m. The specific discharges of the three highest snowmelt floods in this basin were between 0.5 and 0.7 $m^3 s^{-1} km^{-2}$, which are much greater than the values for most of the rivers in Table 1. Specific discharge was above 0.3 $m^3 s^{-1} km^{-2}$ in one-quarter of the years of record in this catchment and in an adjoining one of 9 km^2. Specific discharges during spring snowmelt in tributaries to the South Yuba have also been high in years of above-average, though not extreme, runoff: 0.5 $m^3 s^{-1} km^{-2}$ in a catchment of 10 km^2 and 0.74 $m^3 s^{-1} km^{-2}$ in a basin of 2.4 km^2.

Small research catchments provide examples of peak flows generated by snowmelt runoff in the forest zone. The Pacific Southwest Forest and Range Experiment Station of the USDA-Forest Service maintained stream gages on catchments of 0.5 to 2 km^2 at an experimental forest in the northern Sierra Nevada and another in the southern part of the range. The average and maximum snowmelt peaks were compared for these nine catchments (Table 2). The specific discharges of the mean and maximum snowmelt peaks were almost twice as large in the northern forest (Onion Creek) than in the southern forest (Teakettle). Although both experimental forests have a generally southern exposure, the denser canopy and assumed-greater groundwater storage capacity at Teakettle limit the generation of peak flows. At each forest, the maximum snowmelt peak was almost twice the average peak flow. For comparison, maximum peak flows from rain-on-snow events at Teakettle ranged from 1 to 2 $m^3 s^{-1} km^{-2}$. The maximum snowmelt peaks in Table 2 occurred in 1967 for Onion Creek and in 1983 for Teakettle.

Snow accumulation and ablation under forest cover and in an adjacent clearing have been compared at the Central Sierra Snow Lab over the period from 1974 to 1983 (Bergman, 1985; Kattelmann, 1990a). When the snowpack was at a maximum, the snowpack water equivalence in the open exceeded that in the forest by an average of 200 mm (980 mm vs. 780 mm). In two years of unusually large snowfall (1982 and 1983), the difference exceeded 300 mm. The rate of snowmelt averaged over the entire melt season was 75 percent greater in the clearing than in the forest (20 vs. 12 mm per day) (Bergman, 1985). In years with a long-lasting snowpack at this site, the average melt rate after May 1 was 25 mm per day in the open versus 15 mm per day in the forest (Kattelmann, 1990a). The slower rate of snowmelt under the trees resulted in the forest site remaining snow covered for an average of 18 days after loss of snow cover in the clearing. Because of their greater initial store of snow, faster melt rate, and minimal evapotranspiration losses, snowpacks in open areas provide a greater contribution to snowmelt floods than those under forest cover (Anderson, 1963).

TABLE 2 Snowmelt runoff maxima at experimental forests.

Location		Drainage Area (km^2)	Period of Record	Mean Snowmelt Peak ($m^3 s^{-1} km^{-2}$)	Maximum Snowmelt Peak ($m^3 s^{-1} km^{-2}$)
Onion Creek	1	0.5	58-67	0.21	0.43
	2	1.2	59-67	0.27	0.48
	3	1.7	59-67	0.18	0.39
	5A	1.0	59-66	0.18	-
	7	2.1	59-64	0.16	-
Teakettle	1	2.0	60-69, 78-83	0.12	0.28
	2	2.2	"	0.12	0.30
	2A	0.7	"	0.13	0.36
	3	2.2	"	0.13	0.28

FLOODS FROM THE ALPINE ZONE

Contributions to snowmelt floods from the area of the Sierra Nevada near and above timberline add to those from the forest zone but differ in their intensity and timing because of differences in the energy balance at high altitude. Snow cover in the alpine zone represents another large reservoir of potential runoff. At elevations above 2500 m, the long-term average snowpack water equivalence from snow survey records is about 750 to 850 mm (Kattelmann & Berg, 1987). Water equivalence in the alpine snowpack can exceed 2000 mm in wet years such as 1983 and 1986.

Because the hydrology of the Sierra Nevada alpine zone has received little attention and long-term stream gages have not been maintained at these high elevations, most of our information about snowmelt-flood processes comes from a recently completed study of a small basin in Sequoia National Park (Dozier et al., 1989; Tonnessen, in press). This Emerald Lake basin is a 1.2 km^2 cirque with northern exposure and elevations between 2800 and 3400 m. Snowmelt runoff in this basin was at a maximum when high snowmelt rates coincided with a high proportion of snow covered area. Peak runoff occurred in mid- to late May in three of the five years of the study and was delayed until the end of May or early June in the other two years. Snow covered area declined at the rate of approximately one percent per day between 60 and 20 percent coverage of the basin. More than half of the annual runoff volume occurred in May and June in each of the five years. Streamflow averaged over the basin area exceeded 7.5 mm per day on 71, 32, 26, 24, and 20 days in the five seasons. Streamflow exceeded 15 mm per day on 44 days in one of the years. The highest daily equivalent depth on record was about 30 mm. Instantaneous flows rarely exceeded 0.5 $m^3 s^{-1} km^{-2}$ during snowmelt runoff. Under combinations of conditions favoring high rates of snowmelt, peak discharges approached 1 $m^3 s^{-1} km^{-2}$ during 3 days over the study period. However, such conditions were rare, and peak flows in the other four snowmelt seasons were barely half of those maxima observed in 1986.

LIMITS ON THE PRODUCTION OF SNOWMELT RUNOFF

Although the seasonal volume of snowmelt runoff is determined largely by the amount of water stored as snow cover, the daily and seasonal peaks in streamflow depend on the amount of energy available for melt and the combination of tributary contributions. A variety of approaches for estimating snowmelt runoff have been developed in the past three decades (e.g., WMO, 1986; Leavesley, 1989). Field observations of high melt rates and associated conditions may help to refine some of these methods.

The energy available for snowmelt from a variety of sources constrains the overall melt rate. Upper bounds on daily snowmelt can be estimated by calculating the energy available from potential net radiation at any latitude. The British Flood Studies Report (Natural Environment Research Council, 1975) uses an estimate of 42 mm per day as probable maximum snowmelt. Church (1988) calculated maximum snowmelt to be less than 43 mm per day at the summer solstice and about 38 to 40 mm per day for most of May, June, and July at latitudes of 30 to 50^{o}N. Furthermore, there is little change in the maximum potential melt rate after early May in the northern hemisphere (Church, 1988). At the Central Sierra Snow Lab, the radiation balance of the snowpack during May 1983 was not substantially different from that during other years when the bulk of snowmelt occurred earlier (Aguado, 1985). Energy loss from upwelling longwave radiation under the typical cloud-free and low humidity conditions in the Sierra Nevada partially compensate for the high solar radiation in spring.

The highest value of daily snowmelt found in the literature was 60 mm at Knob Lake in the Canadian Subarctic (Price et al., 1979). At the Central Sierra Snow Lab, maximum changes in snowpack water equivalence measured with an isotopic profiling snow gage and maximum amounts of snowpack outflow from snowmelt lysimeters have been about 40 mm per day. When the contributing areas of the snowmelt lysimeters were greater than the area of the collector itself, apparent depths of snowpack outflow were much higher. At Emerald Lake, the highest daily amounts of snowmelt averaged over three or four days from ablation stake data were about 30 mm in June and July.

Maximum hourly melt rates may be useful for estimating design floods for road drainage structures and erosion control projects at mountain developments such as ski areas. The highest hourly rate of snowmelt found in the literature was 9 mm per hour (Kuzmin, 1961). Most reported extremes were about 1 to 3 mm per hour. A 6-hour 100-year maximum snowmelt rate of 7 mm per hour +/- 0.6 mm per hour at the 68% confidence level was estimated for the Colorado alpine zone (Payton & Brendecke, 1985). Outflow from snowmelt lysimeters at the Central Sierra Snow Lab has been observed to occasionally exceed 10 mm per hour when the surface contributing area is larger than the collection area. However, some areas of the soil receive these locally-high rates of snowpack outflow.

The generation of snowmelt floods in all but the smallest headwater basins depends on the spatial distribution of snow available to melt and the rates at which different slopes and tributaries deliver meltwater. Local daily rates of snowmelt tend to be highest when several conditions coincide: solar radiation, wind speed, and atmospheric humidity are high; snow albedo and nighttime radiation cooling of the snowpack are low; and the snow cover is thin enough to permit radiation penetration to the ground. The highest daily amounts of melt often occur during the occasion of clear days and cloudy nights. At Emerald Lake, snowmelt was particularly rapid once rocks began to be exposed because the longwave radiation from the sun-warmed rocks was more effective at melting snow than direct solar radiation. These high rates of snowmelt are obviously self-limiting because of the disappearance of the snow. In the 1.2 km^2 Emerald Lake basin, peak snowmelt runoff in the different years occurred when 50 to 75 percent of the basin was snow covered. Local melt rates in this north-facing basin that increased with seasonally-higher sun angles were offset with respect to streamflow by declining snow covered area. In larger catchments, peak snowmelt generally occurs at lower elevations a few weeks before that at higher elevations. The size of the snowmelt flood is also limited by disappearance of snow from south-facing slopes before melt rates peak on north-facing slopes.

Widespread reductions in forest density and/or forested area would tend to increase the local rate of snowmelt and advance the local timing of snowmelt runoff. The effect of such changes on spring peaks in streamflow would depend on the relative timing and synchronization of tributary peaks under present conditions (Anderson, 1963). In smaller basins within the forested zone, the current slow rate of snowmelt runoff from forested areas tends to spread the seasonal hydrograph over several weeks. Conversion of more forest to clearings would compress the snowmelt season, and flood peaks could be expected to increase. In larger basins, the earlier melting of snow in the former forest might lower water levels during late spring when the alpine-snowmelt contributions would be at a maximum.

Assuming precipitation amounts remain in the current range, warmer temperatures throughout the Sierra Nevada may also reduce the size of snowmelt peaks in large basins. Regional snowlines would probably be found at higher elevations, and snowmelt would occur earlier at lower elevations (Lettenmaier & Gan, 1990). However, snowmelt rates in the alpine zone may not be affected significantly by warmer air temperatures alone because of the overriding importance of net radiation in the snowpack energy balance. The snowmelt-runoff regime of the Sierra Nevada could be further affected by interactions of changes in both vegetation and climate.

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