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# Flooding from rain-on-snow events in the Sierra Nevada

**RICHARD KATTELMANN**

*Sierra Nevada Aquatic Research Laboratory, Star Route 1, Box 198, Mammoth Lakes, California 93546, USA*

**Abstract** The most damaging floods in rivers of the Sierra Nevada of California have occurred during warm storms when rain fell in snow covered catchments. These large floods have inundated communities and farms in California's prime agricultural region. Forecasting of runoff from rain-on-snow events has been difficult for managers of dams and power plants within the Sierra Nevada and for downstream flood control agencies because of uncertainties about runoff production at high altitudes and snowmelt contributions at low altitudes. The high potential for flood generation from rain-on-snow events is related to their large contributing area, intensity and duration of rainfall, opportunity for snowmelt contributions, and the timing of water release from the snowpack.

## INTRODUCTION

Rivers of the Sierra Nevada tend to have their highest flows when warm winter storms (those with an unusually high rain–snow elevation) interact with extensive snow cover. Although storm rainfall is the overwhelming source of runoff, the contribution of snowmelt can significantly increase flooding and associated damage. The greatest historic floods in the major rivers of the mountain range have occurred under rain-on-snow conditions (Kattelmann *et al.*, 1991). In maritime snow climates of the Pacific Coast of North America, the most intense rainstorms of long duration tend to occur during midwinter when snow is likely to cover at least part of the larger river basins (Harr, 1981; Brunengo, 1990; McGurk *et al.*, 1992). The warmest storms can bring rain to the highest divides and enough energy to the snowpack to produce substantial augmentation of the rainfall–runoff. Perhaps because of difficulties experienced in forecasting flood flows during warm storms, rain-on-snow events seem to have been regarded as somewhat mysterious and have generated considerable folklore. During a recent assessment of the hydrology of the mountain range for the Sierra Nevada Ecosystem Project (Kattelmann, 1996), the author had the opportunity to examine hundreds of reports on local water development activities. Relatively few of these documents showed much appreciation of how water gets to the project site. That review of water resources development suggested that project planning and operation could often benefit from more attention to physical processes that influence the basic resource. This paper attempts to provide an overview of some aspects of rain-on-snow flooding in the Sierra Nevada.

The Sierra Nevada extends roughly northwest–southeast for more than 600 km along the eastern edge of California and is about 100 km wide, on the average. The Mediterranean climate of the area results in a strongly seasonal precipitation pattern with about half of the average annual precipitation occurring in winter and another third in late autumn. Streamflow generated below about 1500 m is usually directly associated with storms, while streamflow above 2500 m is almost entirely a product of spring snowmelt. Between these approximate bounds, streamflow is generated both by warmer storms and by snowmelt during April–July. Peak flows in different parts of the Sierra Nevada result from snowmelt, warm winter storms, summer and early autumn convective storms, and outbursts from storage (Kattelmann, 1990). In river basins extending into the snowpack zone, snowmelt floods occur each spring as events of sustained high flow, long duration, and large volume. However, they rarely produce the highest instantaneous peaks. Even in basins that are largely above 2000 m, the highest peaks tend to be caused by rain-on-snow events. For example, in the Merced River in Yosemite National Park, the four highest floods of record were caused by rain-on-snow, with peak discharges 50–80% greater than the largest snowmelt peak of record.

The largest rain-on-snow floods, such as the severe events of February 1996 in Oregon and Washington (Taylor, 1996), cause widespread and significant damage in the lowlands. Sacramento, the capital of California, has been inundated numerous times in its history when rainfall was augmented by snowmelt. Other cities in the Central Valley as well as extensive areas of agricultural fields have been flooded under rain-on-snow conditions throughout California's history (e.g. Taylor, 1913; McClure, 1925; Ellis, 1939; McGlashan & Briggs, 1939). Towns within the mountains, such as Downieville, Truckee, Reno and Bishop, have also been damaged by rain-on-snow flooding (Waananen, 1971; US Army Corps of Engineers, 1974, 1975; Kattelmann, 1992). Smaller events often cause considerable damage to roads and bridges within the forest zone. Channel erosion and mass movement are other common results from rain-on-snow events in the Sierra Nevada (Bergman, 1987; McCaffrey & DeGraff, 1983). Extensive damage to roads and culverts was observed following warm storms in 1982, 1983, 1986 and 1995. The impact of rain-on-snow floods on fluvial processes may be enhanced by the confining effect of snow along streambanks. When deep snowpacks are present along streams, the snow may limit overbank spreading of flood water and increase flow depth and bed shear stress for discharges above bankfull (Erman *et al.*, 1988).

## THE GREAT FLOODS IN SIERRA NEVADA RIVERS

The streams and rivers of the Sierra Nevada have relatively short and inconsistent flow records. Routine gauging did not begin until the 1930s and has usually been associated with water projects and diversions. Extensive development of water resources in the Sierra Nevada has resulted in few gauge sites with unimpaired flow. Analyses of the flood series have to rely on records from a few rivers where gauges were established just after the turn of the century but were later dammed, where gauging started later and still have natural flows, and various sources of historical information. Observations of floods and associated weather and snow conditions began to be published in newspapers and books during the California Gold Rush of the 1850s.

The flood that is generally considered the largest in the history of the Central Valley occurred 9–12 January 1862 when an intense storm followed antecedent precipitation that was more than usually falls in an average year. Flows in the

American River were far beyond channel capacity and inundated much of Sacramento (Williams, 1986). High water marks believed to be from the 1862 flood were found near Folsom that were 3.5 m above the crest level of the 1907 flood, which was the third largest peak flow in the gauged record for the American River at Fair Oaks (Taylor, 1913). Historical accounts also help document the importance of snowpack contributions to flooding in 1862. Twenty cm of snow was reported in the northern Sacramento Valley and 30 cm covered areas at elevations less than 500 m (*Sacramento Union* 7 January 1862). The extensive snow cover in the Sierra Nevada foothills suggested by such observations must have contributed vast amounts of water to the flood. Although the flood of 1862 was the greatest event with extensive documentation in California's history, it may have been exceeded by a flood in 1805 suggested by Mission records and Indian legends.

Flooding in the Central Valley after 1862 was exacerbated by the channel aggradation caused by immense amounts of mining debris flushed out of the Sierra Nevada hydraulic mines. After the turn of the century, significant floods were noted in March 1907, January 1909, February 1911 and March 1928 (Taylor, 1913; McClure, 1925; Ellis, 1939). Snowmelt was mentioned in descriptions of both the 1907 and 1909 floods (Taylor, 1913). Before the March 1907 flood, snow was observed to have covered the entire Sacramento Valley (Ellis, 1939).

Better documentation of streamflow and weather conditions has been available since the 1930s. Since that time, about six floods have exceeded twice the mean annual flood in each of the major rivers of the Sierra Nevada. The dates of floods exceeding this arbitrary criterion were not consistent among all rivers, but were included among the following events: December 1937, November 1950, December 1955, February 1963, December 1964, January 1980, February 1986 and March 1986. Weather and snowpack records indicated that snowmelt contributed to each of these floods (Kattelmann *et al.*, 1991). The flood of December 1937 apparently involved little contribution from snowmelt at lower elevations, although records from a single site suggest that there was about 25 cm of snow on the ground above 2100 m. Snowmelt from the elevation band between 2000 and 2500 m was estimated to add about 5–8 cm of water to upper tributaries of the American River during the 1937 flood (McGlashan & Briggs, 1939). Snow was also less important in the 1950 and 1963 events than in others.

During the historic period, rainfall above 2000 m has been rare during spring in the Sierra Nevada. The one large flood of this type occurred in April 1982 and ranks in the top ten floods in the annual flood series in many headwater streams. Another significant event occurred in May 1995, although flow records were not available in time for this paper. Otherwise, there are only a few moderate rain-on-snow events superimposed on spring snowmelt floods in the streamflow record.

## THE ROLE OF SNOW COVER IN FLOOD GENERATION

The high potential for flood generation from rain-on-snow events is related to their large contributing area, intensity and duration of rainfall, opportunity for snowmelt contributions, and, sometimes, the timing of release of water from the snowpack. The primary factor is simply the increase in contributing area with rainfall–runoff production from the higher elevation portions of river basins that typically receive snow during other winter storms. Rainfall has occurred up to the highest elevations of the Sierra Nevada during winter, but the freezing level of winter storms generally fluctuates between about 1000 m and 2500 m. During the warmest storms, the effective area of some drainage basins may become several times larger than during more typical storms that deposit snow over most of the area.

Some of the storms affecting the Sierra Nevada that have the highest rain–snow lines also tend to have relatively intense precipitation and last for several days (McGurk *et al.*, 1992). Storms that develop at low latitudes (i.e. near the Hawaiian Islands) often deliver greater amounts of precipitable water to the Sierra Nevada than colder storms tracking more directly from the Gulf of Alaska. Rainfall can be relatively intense for long periods during some of these warm storms. For example, upto 180 mm of rainfall has been recorded in 24 h at the Central Sierra Snow Laboratory near Soda Springs at 2100 m (Azuma & Berg, 1990). More than 200 mm of rainfall has been recorded in 24 h on seven occasions since 1948 at Blue Canyon at 1600 m (McGurk *et al.*, 1992).

The presence of snow during warm storms provides the opportunity to augment rainfall–runoff with snowmelt. Snow melts from convective heat exchange and condensation when temperatures are high and winds are strong. This potential is greatest when snow occurs at very low elevations. Snow falls at elevations below 300 m a few times per decade and occurs below 1000 m a couple of times in most years. Although snow at these low elevations usually melts within a few days of its deposition, it is temporarily available for melt and runoff. Snowmelt during rain storms is most important in the low elevation, transient snowpack zone where sufficient energy is available to melt substantial amounts of snow (Harr, 1981). This condition was readily met at the onset of the warm storm that led to record flooding in parts of the Pacific Northwest in February 1996. Melt of more than 25 cm of snow water equivalence was observed at some monitoring sites during that period. Snowmelt at low elevations where air temperatures are warmer than 10°C or even 15°C can exceed 50 mm in 24 h under severe convection/condensation conditions during warm, windy storms. A detailed analysis of three rain-on-snow events (1963, 1964, 1982) in the American River basin indicated that snowmelt added more than 50 mm of water at lower elevations and could have been greater if more snow was present (Hall & Hannaford, 1983). Such amounts can augment rainfall–runoff by 10–30%. At Blue Canyon, one of the few monitoring sites in the intermittent snowpack zone of the Sierra Nevada, complete disappearance of snow cover was often a limiting factor in the generation of runoff during warm storms (Kattelmann & McGurk, 1989). Seasonal peak water equivalence at this site varied from 9 cm to 70 cm between 1960 and 1980, inclusive. With increasing elevation, less snow melts because less energy is available. In most years, relatively little snowmelt occurs at elevations above 2000 m during rain-on-snow events in the Sierra Nevada (Bergman, 1983).

The deep snow cover found at higher elevations is potentially important in regulating the supply of water to streams during rain-on-snow events. The extent to which such regulation occurs depends on the storage and transmission properties of the snowpack. During rain storms, the presence of a snowpack causes an initial delay in streamflow response compared to bare ground. Depending on snowpack structure and storm characteristics, hydrologists have hypothesized that water may be released to streams at rates less than, equal to, or greater than rainfall intensity, with consequent effects on downstream flooding. Early estimation methods that have limited physical basis (e.g. Bertle, 1965) are still used in recent flood assessments (e.g. US Army Corps of Engineers, 1991).

The role of snow cover in regulating release of water to soil and streams is poorly understood. A data set of 42 rain-on-snow events with adequate records of rainfall and outflow timing was recently compiled from records at the Central Sierra Snow Laboratory near Soda Springs (Kattelmann & Dozier, 1996). The observed snowpacks stored little water before the first outflow and imposed only a few hours of delay on its timing. For the entire data set, lag times between the onset of rainfall and the onset of snowpack outflow averaged about 4 h when snow was less than 1 m deep and about 6 h when depth exceeded 2 m. Rainfall intensity was an important influence on the delay to water release from the snowpack. Rain that fell at rates greater than 2 mm $h^{-1}$ was observed to take between 1 to 8 h to flow through a wide range of snowpacks. The quantity of water detained in transit through the snowpack before the onset of outflow was greatest ($>10$ mm) under both the lowest rainfall intensities (when flow was quite slow) and at the highest intensities (when water accumulated at rates faster than it moved through). Calculated storage was less than 2% by volume. These small values are much less than commonly assumed in runoff forecasting models.

Influences of forest cover on rain-on-snow flooding are a major concern throughout the forests of the Pacific Coast (e.g. Berris & Harr, 1987; Brunengo, 1990). Because turbulent exchange processes account for most of the snowmelt during rainfall, forests would tend to reduce melt by limiting wind speed. Creation of large openings in forests should increase snowmelt relative to the forest and could increase water input to soils by 10–25% (Harr, 1981). Plot studies in Oregon and British Columbia further suggested that interception and melt of snowfall in the forest canopy both greatly reduce the amount of snow in the forest relative to clearings and alter the timing of water release to the soil (Beaudry & Golding, 1983; Berris & Harr, 1987). Comparison of changes in snowpack water equivalence during rainfall between a forest and a clearing at the Central Sierra Snow Laboratory showed that snow in the clearing lost twice the water equivalence of the forest site on the average but quantities were small (generally 10–30 mm of loss in a storm) (Kattelmann, 1987). That study and a subsequent one (Berg *et al.*, 1991) did not find any significant differences in characteristics of outflow between forested and open snowpacks greater than 0.5 m deep.

## IMPROVEMENTS IN FORECASTING

The greatest uncertainties in operational flood forecasting particular to rain-on-snow events are the availability of snow for melt and the position of the rain/snow boundary. Unfortunately, there are few snow monitoring sites in the intermittent snow zone of the Sierra Nevada. Better knowledge about the amount of snow at low elevations would be helpful in estimating potential runoff augmentation during warm storms. Similarly, knowledge of how much of a river basin is receiving rainfall and contributing runoff in near-real time would provide a much better basis for forecasts. Estimates of the rain–snow line from temperature data are accurate only within a few hundred metres elevation, which can cover 10–20% of some catchments. Instrumentation for operational discrimination between rain and snow is yet to be developed. Detailed studies at the small basin scale would be helpful for quantifying lag times and influences of forest management.

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