VERY WARM STORMS AND SIERRA NEVADA SNOWPACKS

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ABSTRACT

Winter storms in the Sierra Nevada typically have rain/snow levels between 1200 and 2000 m. Warm storms with higher rain/snow levels of up to 2500 m occur a couple of times in most winters and generate rain-on-snow floods. However, in the past two years, very warm storms with rain/snow levels up to 3500 m have generated serious flooding. These very warm storms provided an opportunity to examine snowpack response to rainfall at high elevations where such warm temperatures during storms have rarely been observed. At our snow-research station at 2930 m on Mammoth Mountain in the eastern Sierra Nevada, air temperatures exceeded 4°C during both storms. Rainfall was about 140 mm in the 1996 event and 220 mm in 1997 at this site. The snowpack had just begun to melt and produce outflow a few days before the warm storm in May 1996. The event in 1997 occurred in mid-winter on cold and dry snow cover. The spring snowpack delivered water to the soil within two hours of the onset of rain, but the winter snowpack delayed release of water by 9 to 23 hours. The winter snowpack developed a highly variable and complex stratigraphy with dozens of alternating wet and dry layers.

INTRODUCTION

The highest flows in rivers of the Sierra Nevada tend to occur when warm winter storms (those with an unusually high rain-snow elevation) coincide with extensive snow cover. During the warmer storms, the effective contributing area of some drainage basins may become several times larger than during more typical storms that deposit snow over most of the area. Although most of the runoff is generated from storm rainfall, the contribution of snowmelt can substantially increase flooding and associated damage. The largest floods on record in the major rivers of the mountain range have occurred under rain-on-snow conditions (Kattelmann et al., 1991). In the Cascades and Sierra Nevada, the most intense rain-storms of long duration tend to occur when snow is likely to cover at least part of the larger river basins (Harr, 1981; Brunengo, 1990; McGurk et al., 1992). The availability of snow for potential melt and the availability of energy interact with the amounts and distribution of rainfall to determine the runoff response.

The largest rain-on-snow floods, such as the severe events of February 1996 in Oregon and Washington (Taylor, 1996; Marks, 1997-in press), cause widespread and significant damage in the lowlands. Sacramento and 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 and Briggs, 1939). Towns within the mountains, such as Downieville, Truckee, Reno, and Bishop, have also been damaged by rain-on-snow flooding (Waananen, 1971; U. S. Army Corps of Engineers, 1974 1975; Kattelmann, 1992). In the forest zone of the west slope of the Sierra Nevada, channel erosion and mass movement resulting from rain-on-snow events have caused much damage to roads and bridges (Bergman, 1983; McCaffrey and DeGraff, 1983).

Rain-on-snow floods have been documented throughout the past century and half in California. The event that is generally considered the largest flood observed in the Central Valley occurred January 9-12, 1862 when a warm storm followed unusually high antecedent precipitation. Flows in the American River were far beyond channel capacity and inundated much of Sacramento (Williams, 1986). Twenty cm of snow was reported in the northern Sacramento Valley and 30 cm covered areas at elevations less than 500 m (Sacramento Union Jan. 7, 1862). These observations suggest that extensive snow cover in the Sierra Nevada foothills must have contributed vast amounts of water to the flood. During the early part of this century, significant floods were noted in Mar. 1907, Jan. 1909, Feb. 1911, and Mar. 1928 (Taylor, 1913; McClure, 1925; Ellis, 1939). More systematic records of streamflow and weather conditions have 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

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among the following events: Dec. 1937, Nov. 1950, Dec. 1955, Feb. 1963, Dec. 1964, Jan. 1980, Feb. 1986, Mar. 1986. Weather and snowpack records indicated that snowmelt contributed to each of these floods.

The potential for flood generation in rivers of the Sierra Nevada is obviously dependent on the climate of the mountain range. 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. Winter storms in the Sierra Nevada typically have rain/snow levels between 1200 and 2000 m and lead to the development of semi-continuous seasonal snow cover above about 1500 m. Snow cover below this approximate elevation tends to be intermittent and is usually present for short periods following colder storms. 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 during winter and by snowmelt during April to July. Most of the warm storms observed in this century have had rain/snow levels of up to 2500 m. Rain/snow levels of such elevation have been sufficient to produce dramatic runoff volumes when rainfall is intense and/or snow is available for melt at lower elevations. However, in the past two years, very warm storms with rain/snow levels up to 3500 m have generated serious flooding and provided an opportunity to examine snowpack response to rainfall at high elevations where such warm temperatures during storms have rarely been observed.

STORM OF MAY 1996

In the past few decades, warm storms during the snowmelt season of April, May, and June have been rare in the Sierra Nevada. Typical weather conditions in spring in the Sierra Nevada have been characterized by high pressure and mostly clear skies. The occasional storms of spring have usually come from high latitudes, incorporating relatively cool air masses and consequently have had rain/snow levels below 2000 m or often 1500 m. A notable exception to this generalization was a warm storm that occurred April 9-11, 1982. This storm closely followed a major snowfall event and therefore did not occur during active snowmelt. However, this occurrence of rainfall at elevations above 3000 m on relatively fresh snow initiated a widespread wet avalanche cycle and generated high flows in some streams. Peak flows generated by this event rank in the top ten floods in the annual flood series in many headwater streams. Otherwise, there are only a few moderate rain-on-snow events superimposed on spring snowmelt floods in the streamflow record.

The warm storm of May 15-16, 1997 occurred when spring snowmelt was well underway. Heavy cloud cover in advance of the weather system suppressed snowmelt at high elevations on May 14. However, the clouds also reduced nighttime heat loss from the snowpack, and convection-condensation melt occurred during the night of May 14 where winds, humidity, and temperatures were high. A brief period of light rain occurred on the morning of May 15. Continuous rainfall started that afternoon at Mammoth Mountain. I observed rainfall above 3600 m on Pinchot Pass in the southern part of the range late in the day. Although air temperatures at the micrometeorological station at 2930 m on Mammoth Mountain were more than 4°C for the first few hours of the storm, they decreased to 1-2°C by nightfall. Rain turned to snow at this elevation by dawn on the 16th. This lowering of the rain/snow level early in the storm reduced the contributing area of rainfall-runoff in most basins of the central Sierra Nevada. Otherwise, flood levels could have been considerably higher.

The initial pulse of rainfall on the afternoon of May 15 took 1-1.5 hours to flow through the 2 m of snow covering the snowmelt lysimeters at the Mammoth Mountain snow study plot. The delay in water release from the snowpack was so short because water was already flowing through the snowpack at the beginning of the rainfall. The rainfall did not cause any obvious changes to the structure of the snowpack.

Approximately 7-8 cm of precipitation occurred as rain at the Mammoth Mountain site. Stations in the foothills at about 1000 m elevation received 10-12 cm of rain during the storm. Snowmelt at the 2930 m snow study plot was estimated to be less than 2 cm from May 15 0600 to May 16 0600. Clear weather melt at the study plot at that time of year is typically about 2 cm. At lower elevations, convection-condensation melt during the storm probably exceeded the usual amount of snowmelt that would occur in mid-May under clear skies. The combined rainfall and snowmelt was several times greater than typical amounts of radiation-induced melt.

The large inputs of water led to much greater runoff than usually occurs on a typical spring day, and streams responded accordingly. Peak flows were quite high for spring but did not compare to the large mid-winter floods caused by sustained warm storms. Nevertheless, this storm raised water levels in the Merced River to more than one meter above bankfull in portions of Yosemite Valley. The flooding led to the evacuation and closure of all seven campgrounds in Yosemite Valley and closure of the three highways accessing the Park. Bridges were washed out on some smaller streams in Tuolumne County.

STORM OF JANUARY 1997

The New Years storm of 1997 was more typical of rain-on-snow events in the Sierra Nevada than the May 1996 event because it occurred during winter rather than spring. However, the very warm temperatures and intense rainfall clearly put it in the category of extreme events for this century in the Sierra Nevada. Even though rainfall totals were greater during the last major flood, which occurred in February 1986, other factors led to comparable or greater runoff during the 1997 flood in many rivers. The New Years storm produced the highest flows of record in many streams and even in some major rivers with decades of data, such as the Cosumnes, Merced, and Tuolumne Rivers. Damage was extensive in both upland communities, such as Truckee, Quincy, Walker, Gardnerville, and Reno, and in the Central Valley, where levee failures contributed to the inundation of many towns and vast tracts of farm land. More than 120,000 people were evacuated from low-lying areas. Parts of Olivehurst, Linda, Wilton, Arboga, Manteca, and Modesto were submerged. Estimates of financial damage totaled about $1.8 billion in California and $200 million in Nevada. The National Park Service estimated that $178 million would be needed to repair and relocate facilities affected by flooding in Yosemite National Park. Major repairs were needed on US highways 50, 70, and 395 and California state highways 89 and 140. Damage to other roads and bridges can only be described as extensive.

The snowpack began to accumulate with a storm on November 21-22, 1996 that deposited more than 90 cm of snow at Mammoth Mountain. More than a meter of snow fell at this same site between December 9 and 11. Two additional large storms near the end of the month each deposited more than a meter of snow at Mammoth Mountain. Lower-elevation parts of the Sierra Nevada snow zone received a mixture of rain and snow during these storms. For example, the Central Sierra Snow Lab at 2100 m on Donner Summit received some rain during three of the four major storms in December. Nevertheless, this site still had a two-meter deep snowpack at the end of 1996. Precipitation for December was more than twice the average at almost all recording sites throughout the Sierra Nevada and was 3-4 times average at several stations. Rainfall and snowmelt from some of the milder storms of December recharged soil moisture at lower elevations and generated moderate runoff in many streams.

The storms of December left the Sierra Nevada with nearly ideal antecedent conditions for major flooding: soil moisture was near capacity in many low-elevation areas, streams were already conveying substantial runoff, flood-storage capacity in most reservoirs was already partially used, and there was snow cover as low as 1200 m. A couple of snow sensors operated by the California Department of Water Resources indicated there were 15-20 cm of snow water equivalence at 1500-1600 m in the northern Sierra Nevada on December 26.

The flood-producing series of storms began on December 26 with fluctuating rain/snow levels averaging around 2000 m. Warmer air began entering the Sierra Nevada on December 29, and rain fell at higher elevations. Temperatures continued to rise and precipitation intensified for the following four days. Average air temperatures were +4°C on December 31 and +6°C on January 1 at the Central Sierra Snow Lab at 2100 m, which higher during the New Year 1997 event than during the February 1986 storm. On January 1 and 2 at the Mammoth Mountain snow study plot (2930 m), air temperatures ranged from +2-4°C Precipitation totals for the period December 26 through January 3 included the following: Bucks Lake 107 cm, Four Trees 105 cm, Blue Canyon 76 cm, Central Sierra Snow Lab 45 cm, Calaveras Big Trees 39 cm, and Giant Forest 32 cm. The greatest 24-hour amounts occurred on January 1-2 when 24 cm was measured at Blue Canyon and 35 cm was collected at the Four Trees station. The high air temperatures suggest that rain was falling above 3000 m for at least 36 hours and up to 3500 m for perhaps 12 hours. Therefore, only small high-elevation fractions of the major river basins were not receiving rainfall and generating runoff.

Although the huge rainfall amounts and large contributing areas ensured that rainfall-runoff would be dramatic, snowmelt at lower elevations added even more water to the streams. With air temperatures exceeding 10°C at the lower extent of snow cover, 3-5 cm of water equivalence could be melted each day. Up to 20 cm of melt was recorded by snow sensors at 1500-1600 m over the course of the storm, and this amount was limited by disappearance of snow cover. Records from most snow sensors at higher elevations show relatively constant water equivalence during the storm period. However, the availability of so much energy suggests that 1-3 cm of melt occurred during each of the warmest three days of the storm at elevations up to about 2500 m. In the Truckee River basin on the eastern slope of the Sierra Nevada, rainfall during this event was only about one-third of that recorded during the February 1986 flood. However, the presence of high antecedent soil moisture, high streamflows, snow cover down to low elevations, and very warm temperatures combined to produce much higher flood levels this time than in 1986.

In the higher elevation areas of the Sierra Nevada, substantial amounts of mid-winter rainfall have been rare during the few decades of observation. One of the few well-documented events occurred in January 1980 when rain was recorded for five days at the Mammoth Mountain snow study plot (2930 m) (Davis and Marks, 1980). A few millimeters of rainfall were observed at this research site during both the 1995 and 1996 winters. The 1997 event provided an opportunity to observe rainfall interactions with a high-elevation snowpack in the Sierra Nevada. At the research station on Mammoth Mountain, steady rain began shortly after midnight on January 1. There may have been minor amounts of rain mixed in with the predominantly solid precipitation as much as six hours earlier. Rainfall intensities varied between 1 and 6 mm per hour on January 1 and increased on January 2 with a few periods of more than 10 mm per hour. About 22 cm of rainfall was measured at the site during the storm. A similar amount was recorded at Mammoth Pass on the south of Mammoth Mountain. Air temperatures ranged from +2 to +4°C during most of the storm. Wind speeds averaged over 15-minute intervals varied from 4 to 13 m/s. Before the rain started, the snowpack was about 2.5 m deep with an average density of about 300 kg m^{-3} and temperatures of -1 to -5°C. The first water that percolated through the snowpack and was captured by one of nine snowmelt lysimeters took about 9 hours. Snowpack outflow began to be recorded by other snowmelt lysimeters over the following 14 hours. Four of the collectors gathered water from several times their surface area of 1 m^2. Peaks in rainfall produced peaks in outflow after 3 to 8 hours, but the response was highly variable between snowmelt lysimeters. Outflow declined rapidly after the rain turned to snow about 1900 on January 2. Water continued to drain from the snowpack at very low rates for several weeks without any further input of water.

Snowpits were excavated at several sites on and near Mammoth Mountain following the storm. The rainfall produced a very complex layer structure in the top 30 cm in all sites. In this near-surface region, wet zones alternated with ice lenses and dry zones. Thickness of the different zones varied across pit profiles and between pits. Some of the wet zones and ice lenses appeared to be only a millimeter or two in thickness. Other ice lenses and complexes of ice lenses were up to 50 mm thick. On flat ground, the intricate stratigraphy continued throughout the profiles to the soil surface. However, there were a few dry zones of up to 12 cm thick. Snow temperatures were 0°C on level ground. Below the near-surface region, snowpits examined on sloping ground differed markedly with their level counterparts. Evidence of water flow below the top 30 cm was either lacking altogether or present in bands of 5-10 cm thickness at the presumed interfaces between snow layers deposited by different storms. A few irregular ice blobs were found in the otherwise dry layers. Temperatures of these layers remained below -3°C. Although these snowpits only provide a very limited sample of snowpack response to rain during this one event, they suggest that water largely bypassed much of the snowpack on sloping terrain as it flowed down slope in the near-surface region. Most slopes in the region were covered with surface expressions of a trellis-pattern rill network after the storm.

SUMMARY

Most rain-on-snow events in the Sierra Nevada have had rain/snow levels of about 2500 m or less. Extraordinary storms incorporate warmer air masses and may deposit rain up to the highest drainage divides. Two recent storms provided examples of these very warm conditions and snowpack response. The event that occurred in May 1996 added rain to a melting snowpack and produced unusually high peak-flows for the spring snowmelt season. Snowmelt augmented the rainfall-runoff and added little delay to the runoff. The New Years storm of 1997 produced the highest flows of record in several major rivers and caused extensive damage in the mountains and lowlands. The very warm nature of this storm expanded the contributing area of most river basins to or near their full extent and provided enough energy to melt substantial amounts of snow at low elevations. Consequently, this storm generated higher flows in some river basins than other storms of the past that had greater precipitation but cooler temperatures.

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LITERATURE CITED

Bergman, J. A. 1983. Hydrologic response of central Sierra Nevada snowpacks to rainfall. Proceedings of the Western Snow Conference 51: 141-144.

Brunengo, M. J. 1990. A method of modeling the frequency characteristics of daily snow amount, for stochastic simulation of rain-on-snowmelt events. Proceedings of the Western Snow Conference 58: 141-144.

Davis, R. and D. Marks. 1980. Undisturbed measurement of the energy and mass balance of a deep alpine snowcover. Proceedings of the Western Snow Conference 48: 62-67.

Ellis, W. T. 1939. Memories: My Seventy-Two Years in the Romantic County of Yuba, California. University of Oregon, Eugene.

Harr, R. D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. Journal of Hydrology 53: 277-304.

Kattelmann, R. 1992. Historical floods in the eastern Sierra Nevada. In: The History of Water in the Eastern Sierra Nevada, Owens Valley and White Mountains, ed. by C. A. Hall, V. Doyle-Jones, and B. Widawski. pp. 74-86. University of California Press. Los Angeles, California.

Kattelmann, R., Berg, N., and B. McGurk. 1991. A history of rain-on-snow floods in the Sierra Nevada. Proceedings of the Western Snow Conference 59: 138-141.

Kattelmann, R. and Dozier, J. 1997 (in review). Water release from snowpacks during rain in the Sierra Nevada. manuscript on file at Sierra Nevada Aquatic Research Lab

Marks, D. 1997 (in press). The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A study of the February, 1996 Pacific Northwest flood. Proceedings of the Western Snow Conference

McCaffrey, W. F. and DeGraff, J. V. 1983. Observations on a debris avalanche triggered by a rain-on-snow event, Sierra Nevada, California. Geological Society of America Abstracts with Program 15: 387.

McClure, W. F. 1925. Sacramento flood control project. State Department of Public Works, Sacramento.

McGlashan, H. D. and R. C. Briggs. 1939. Floods of December 1937 in northern California. Water-Supply Paper 843, U. S. Geological Survey, Washington, D.C.

McGurk, B., Berg, N., Azuma, D., Kattelmann, R., and T. Edens. 1992. Monthly recurrence intervals of rain-on-snow events in California's forested areas. Report to Pacific Gas and Electric Company and Southern California Edison Company. USDA-Forest Service, Pacific Southwest Research Station, Berkeley.

Taylor, N. R. 1913. The rivers and floods of the Sacramento and San Joaquin watersheds. Bulletin 43, Weather Bureau, Washington, D.C., 92 pp.

Taylor, G. 1996 (unpublished). 1996 flooding in the Pacific Northwest. paper presented at the Western Snow Conference, Bend, OR.

U.S. Army Corps of Engineers 1974. Flood plain information, Truckee River and Martis Creek, Truckee, California. Sacramento District, Sacramento, California.

U.S. Army Corps of Engineers 1975. Flood plain information, North Yuba and Downie Rivers, Downieville, California. Sacramento District, Sacramento, California.

Waananen, A. O. (1971) Floods of December in central and southern California. In: Summary of Floods in the United States during 1966, ed. by J. O. Rostvedt. Water Supply Paper 1870-D, D78-D89. U. S. Geological Survey, Reston, Virginia.

Williams, P. B. 1986. Analysis of the February 1986 flood on the lower American River. Report by Philip Williams and Associates, San Francisco.