A HISTORY OF RAIN-ON-SNOW FLOODS IN THE SIERRA NEVADA

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The most damaging floods in Sierra Nevada rivers have resulted from rainfall extending into the snowpack zone. The largest floods in the major tributaries to the Sacramento and San Joaquin rivers have inundated farmland and communities in the Central Valley. Smaller events have also caused considerable damage, particularly to roads and bridges, at higher elevations. Although most of the runoff is generated from the rainfall itself, the presence of snow cover influences the timing and magnitude of the flood peaks. In maritime snow climates, rain-on-snow tends to produce greater peak flows than either rain alone or snowmelt alone (Harr 1988). Basic information about the magnitude, frequency, and time of occurrence of rain-on-snow floods in the Sierra Nevada has not been available. This paper discusses major rain-on-snow floods of the past two centuries in California.

STUDY APPROACH

Streamflow records from several snow-zone watersheds with no or minimal regulation or diversion were examined. Unfortunately, only about three dozen streams with unimpaired flow have been gaged in the Sierra Nevada snow zone for more than 40 years. Information from books, reports, and newspapers describing historic floods prior to systematic measurement was sought to frame the short records in a longer-term perspective. Although such information is not quantitative and is limited to the Central Valley, it is critical to understanding the hydrologic context of the recent streamflow data.

Peak flows throughout the period of continuous measurements for each basin were tabulated. Corresponding meteorological records were examined to determine which floods involved rain-on-snow. The ten largest floods of each river were examined to describe the magnitude and frequency of the floods of greatest concern. Rivers were selected in three hydrologic regions of California: Sacramento (4 rivers), San Joaquin (8), and Lahontan (6) (Table 1). In addition, six rivers with large drainage areas (>1550 km^2) and long records (U.S. Geological Survey) and four rivers below the snow zone were also studied for comparative purposes. The large rivers no longer have unimpaired flow conditions, but were used to take advantage of their long period of record.

HISTORICAL FLOODS

Historical accounts of floods in the Sacramento and San Joaquin valleys allow qualitative evaluation of the frequency of the largest floods from the Sierra Nevada over a longer time period than the relatively short record of measured streamflows. Most of the rivers used in this study have only been gaged since the 1930's, but a few records began just after the turn of the century (e.g., Feather at Oroville, American at Fair Oaks, and West Fork Carson). Direct observations of floods published in newspapers and books began to appear in the 1850's during the California Gold Rush. Three major floods were also documented between 1800 and 1850 by historians from Indian traditions, Mission records, and accounts of trappers, explorers, and the military. Although we can only speculate on the magnitude and source area of the 19th century floods, the historical accounts provide some information about the relative sizes of these floods.

The flood of Jan. 9-12, 1862 is generally regarded as the largest in California history (Williams 1986). Precipitation was very large in the two months preceding this storm as well as during it--1800 mm of rain was recorded at Sonora between Nov. 11, 1861 and Jan. 14, 1862 (Alta California, Jan. 18, 1862). During the storm, 250 to 400 mm of rainfall was measured in the Sacramento Valley. Newspapers also reported that snow covered both the Sierra foothills and Coast Range to low elevation in January prior to the storm. Twenty cm of snow was reported in Red Bluff and 30 cm accumulated in Yolo County below the foothills (Sacramento Union, Jan. 7, 1862). This extensive snow cover undoubtedly contributed a substantial amount of water to the flood. High water marks were 3.5 m above those observed

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in 1907 on the American River near Folsom. The peak discharge of the 1862 flood on the lower American River has been estimated as 7,900 m^3s^{-1} (Williams 1986). The 1907 flood produced the third largest peak on record for the American River at Fair Oaks at 4,400 m^3s^{-1}, which was 10% less than the largest **recorded** peak in November 1950.

Table 1

Largest Recorded Floods in the Sierra Nevada

REGION/ RIVER	Area (km^2)	Annual Mean Flood (m^3s^{-1})	Number Peaks > 2x Mean	Largest ROS Flood (m^3s^{-1})	Specific Discharge Largest ROS ($m^3s^{-1}km^{-2}$)	Date Largest ROS Flood	Largest Snowmelt Flood (m^3s^{-1})	Rank Largest Snowmelt Flood
NORTH								
Butt	179	38	4	110	0.6	2-86	47	13
Spanish	477	178	5	555	1.2	2-86	68	42
N. Yuba	648	282	8	1133	1.7	2-63	180	30
S. Yuba	135	111	7	521	3.9	1-63	95	17
SOUTH								
Bear	137	25	3	none	-	-	48	5
Pitman	60	21	5	104	1.7	12-55	36	7
San Joaq	645	146	2	470	0.7	12-55	238	5
Merced	469	88	4	279	0.6	12-55	154	5
Tenaya	122	38	3	193	1.6	12-37	54	4
Falls	119	46	6	189	1.6	12-55	55	11
Clark	176	38	3	123	0.7	11-50	57	5
Cole	54	45	7	174	3.2	12-64	64	11
EAST								
L Walker	163	12	3	43	0.3	1-63	22	3
W Walker	466	55	2	184	0.4	12-37	118	2
W Carson	168	31	6	138	0.8	2-63	65	6
U Truckee	85	24	2	72	0.8	2-63	33	7
Blackwood	28	19	6	59	2.1	12-64	19	9
Sagehen	28	5	5	22	0.8	2-63	8	8

Although the 1862 flood was the largest in California history, it appears to have been exceeded by a flood in California's recent pre-history. High water marks observed in the San Joaquin Valley were some 1.8 m higher than those from the flood of 1862 (Ellis 1939:141). Mission records mention 1805 as a year of heavy flooding in southern California and Indian stories tell of a great flood at about that time (Ellis 1939:139, Taylor 1913:60). Many other floods have been documented before streamflow records became continuous (Table 2). Descriptions of these floods relative to those of 1907 and 1909, which were measured in a few rivers, permit a crude ranking and estimate of the frequency of large magnitude floods over the past two centuries.

Table 2

Central Valley Floods from Earliest Anecdotal Information until 1937

Date	Comments	Source
1805	high water marks > 1862	Taylor 1913:60, Ellis 1939:139,140
1825-26		Ellis 1939:140
1841-42		Ellis 1939:220
1850 1/17	Sacramento flooded	Taylor 1913:60
1851		McClure 1925
1852 3/7	Sacramento levees failed	Taylor 1913:60
1852 12/19		McClure 1925
1852 12/31	Sac. flooded; little damage	McClure 1925, Taylor 1913
1861 3/28	flood on American	Taylor 1913
1861 12/9	rains melted snow	Ellis 1939:145
1862 1/12	largest historic flood	Ellis 1939, Taylor 1913, Williams 1986
1878 2/1	American just less than 1907	Taylor 1913:62
1907 3/20	severe floods throughout valley	Ellis 1939, Taylor 1913,
1909 1/14-25	series of widespread floods	Taylor 1913:80
1909 2/1-10	continued flooding	Taylor 1913:70
1911 2/1	worst in south San Joaquin	Taylor 1913
1928 3/27	second highest measured peak on American River	Ellis 1939:158
1937 12/11	little snow at low elev.	Kelly 1938, McGlashan & Briggs 1939

For example, nine floods on the American River at Fair Oaks have exceeded 2,800 m^3s^{-1} (100,000 ft^3s^{-1}) since gaging began in 1905. Other floods in recent years might have exceeded this threshold if not for flood control storage. Another seven floods appear to have exceeded this arbitrary threshold in the century prior to measurement. If we assume that floods in 1805 and 1862 exceeded the highest flood of record in 1950, then the estimated recurrence interval ([number of years + 1] / rank) of the 1950 flood on the American decreases somewhat from about 85 years (based on the measurement period) to about 65 years (third largest flood in 200 years). Estimated recurrence intervals for other floods of record change only by a few years when incorporating the 19th century information. The recurrence interval of the threshold level of 2,800 m^3s^{-1} also remains about the same -- 12 versus 9 years. Unfortunately, the historical information available so far does not appear to be useful in the rapidly-emerging techniques for employing historical data in flood frequency analyses (e.g., Hosking and Wallis 1986).

The historical accounts also help document the importance of snowpack contributions to flooding. For example, in both 1907 and 1909, snowmelt was mentioned in descriptions of the floods (Taylor 1913:68,80). Prior to the March 1907 flood, snow covered the entire Sacramento Valley (Ellis 1939:152). In contrast, the December 1937 flood apparently involved little snowpack contribution from low elevation portions of the basins. Prior to this storm, only 25 cm of snow covered the ground at Donner Summit, but rainfall during the storm was particularly intense: in just two days, 275 mm was reported at Soda Springs and 345 mm fell at Lake Spaulding (McGlashan and Briggs 1939). More than 25 cm of snow was reported at Lake Alpine, Kaiser Pass, and Twin Lakes. Snow was 244 cm deep at Helen Lake on Mt. Lassen. Additionally, McGlashan and Briggs (1939) estimated that snowmelt contributed 5 to 8 cm of water to the American River flood from the elevation band between 2000 and 2300 m. Therefore, the December 1937 flood can be considered a rain-on-snow event in basins with portions above 2000 m even though the role of the snowpack was not as great as in other large-magnitude floods.

LARGEST RECORDED FLOODS

The ten largest floods recorded on each river were tabulated and examined to estimate the frequency and geographic distribution of rain-on-snow floods. Although the variable record lengths prevent ideal comparisons within and between the three regions, the same set of storms generally produced the highest flows in most of the rivers. However, the rank of these floods is not consistent between rivers. Peak flows exceeding twice the mean annual flood were defined to be "large-magnitude floods". On the average, less than five floods were greater than this index among the principal study rivers (Table 1).

The floods that consistently appeared on almost all lists of the ten greatest floods were December 1955, November 1950, December 1964, February 1963, and December 1937. These five floods met the "large-magnitude flood" criteria in at least half of the study basins. This index was also exceeded by at least one of the following three floods of January 1980, February 1986 or March 1986 in at least half of the rivers studied. Using this criterion, six large-magnitude floods occurred in the past 60 years in the larger Sierran rivers such as the Feather, American, and Tuolumne. The rank of these events varied between the study basins depending on storm characteristics and the area-elevation distribution of each basin. None of these floods was dramatically larger than the others in a majority of rivers. Therefore, we infer that major floods occurred (and may be expected to occur) about once per decade, on the average, throughout the western slope and northern part of the eastern slope.

The January 1980 storm had regional impact, generating floods ranked in the top ten in 13 rivers. However, these floods exceeded the "large-magnitude" index in only 5 cases. The two storms in 1986 produced varying results in different basins. The February 1986 storm generated the highest flows on record in three northern basins, but failed to make the top-ten list in any of the southern basins and ranked behind the March 1986 storm (ranked 7) in a fourth northern basin that has a high proportion of its area at higher elevations. This March storm generated considerable streamflow at the higher altitudes but was not a particularly strong flood-producer downslope. Similarly, neither of the large storms in 1982 produced top-ten floods in the northern west slope of the Sierra, but the February storm was ranked in the top six in five rivers in the Truckee and San Joaquin basins and the April 1982 flood was ranked 3, 5, 5, and 8 in four other rivers.

The largest floods on record were generated by rain-on-snow events in all study rivers except for Bear Creek (Table 1). The maximum floods in the study rivers tended to be three to five times greater than the mean annual flood. The specific discharge of the maximum floods ranged from 0.2 to 4 $m^3 s^{-1} km^{-2}$. This specific discharge was highest in the South Yuba River, Cole Creek, and Blackwood Creek. Even these values are not particularly high compared to maximum floods produced by thunderstorms in other parts of California.

TEMPORAL DISTRIBUTION

The seasonal distribution of rain-on-snow floods in California has not been well-established, although a few memorable events have generated a variety of assumptions. Dates of floods from a sample of rivers were used to examine the relative likelihood of occurrence at different times of the year. Flood peaks determined to have been caused by rain-on-snow events were selected from the partial duration series of eight rivers. These flood peaks were tabulated by week of occurrence and magnitude. The short period of record limits the number of events in the higher elevation basins where rain-on-snow is infrequent. These data demonstrate that 60 percent or more of the rain-on-snow floods exceeding the USGS base level occur in December, January, and February. An additional 10 percent of the peak flows occur in each of November and March. Another 5-10 percent of these floods occur in April and less than 5 percent occur in May, on most rivers.

The distribution of the largest rain-on-snow floods over the past two centuries has, of course, been far from uniform. For example, in the past sixty years, two of the ten largest floods occurred within two years (Feb. 1 1963 and Dec. 24 1964), and 17 years elapsed before the next large, regional flood (Jan. 13 1980). This flood was followed by another in February 1986, which was then followed by an even larger flood at upper elevations within one month (Mar. 8 1986). Several large, though independent, floods can also occur within a single snow season. For example, four of the twenty highest peak flows on record in the South Yuba River occurred in water year 1982: Nov. 23 1981 (#8), Dec. 20 1981 (#6), Feb. 16 1982 (#9), and Apr. 11 1982 (#20). There were no obvious trends in flood magnitude or frequency over the historical period.

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