HYDROLOGIC RESPONSE OF CENTRAL SIERRA NEVADA SNOWPACKS TO RAINFALL

by

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INTRODUCTION AND BACKGROUND

The hydrologic response of a Sierra Nevada snowpack to rainfall has always been of great concern because this frozen reservoir is a major hydroelectric power source and supplies over half of California's total water supply.

In the Sierra Nevada snow zone, there is a high potential for mid-winter rains, which may cause local and widespread Central Valley flooding. Because snowpack response to rainfall varies, predicting snowpack response is risky, especially due to spatiotemporal variations in snow depth, density, lens and layer development, and other snow properties that affect water retention and transmission. But measuring and analyzing rain-on-snow events may provide the knowledge necessary to mitigate the effects of potentially excessive snowpack outflow.

Considerable gaps exist in knowledge relating snowpack response to natural rainfall. During the early 1950's, research at the Central Sierra Snow Laboratory (CSSL) indicated that little rainfall runoff was stored or delayed in either shallow or deep snowpacks (Corps of Engineers, 1956). In a study of one artificial and two natural rain-on-snow events using the newly developed isotope profiling snow gage at CSSL, Smith and Halverson (1969) reported an 80% increase in snow water-equivalent (SWE) after applying 27 cm of water to a 180 cm "dry" snowpack, and that a mature "ripe" snowpack was unable to retain additional water. However, these studies provided insufficient data for the analysis of rain-on-snow events and suggested the need for further research into the nature of a snowpack's response to rainfall.

This paper reports an analysis of the seven natural rain-on-snow events of more than 4.5 cm that have occurred at CSSL since 1969 (February and December 1972, January 1974, 1979, 1980, and February 1981 and 1982), to determine if a pattern of snowpack response exists.

METHODS

Located near Soda Springs, California, in the central Sierra Nevada at an elevation of 2100 m, CSSL is influenced by maritime air masses which cause frequent large snow storms and some mid-winter rains. Average peak snow depth reaches about 4 m.

Depth and density variations, at about 1-cm vertical intervals throughout the snowpack, were recorded by an isotope profiling snow gage. Precipitation was measured by a shielded standard weighing bucket recording gage and snow temperature was monitored by a vertical array of copper/constantan thermocouples, spaced at 30.5-cm intervals from the soil surface up to 3.35 m. Nonquantifiable documented visual observations augmented the numerical data base.

The isotope profiling snow gage is accurate to ±1.5% of SWE but directly measures only a 2 cm^2 by 67 cm cylindrical volume of snow (Smith et al., 1970). The presence of snow gage probe tubes in the snowpack may have slightly influenced the development of the measured section of snow. However, in this study, data from the snow gage are presumed to represent the snowpack in the immediate area. The weighing recording precipitation gage is accurate to ±0.1 cm and the thermocouples are accurate to $\pm 0.5^{\circ}C$.

To illustrate high, intermediate and low rainfall intensities over similar time periods, the rain-on-snow episodes in January 1980, February 1982, and January 1974 were selected. The 1982 episode also illustrates the effect of new snow midway through a storm. Storm characteristics and snowpack response were similar for all seven events.

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During each event snow gage measurements were frequent (about every 4 to 6 hours) depending on rainfall intensity. From the profile data, snow depth, density, and SWE were obtained. If ice lens and density layering were evident, they were identified and their development followed throughout the storm. Density change was used to best illustrate the effect of rain on snow. Density values at all depths in the snowpack profile were subtracted from density values at the same depths in a prestorm reference profile. In the density change graphs the vertical dashed line represents the prestorm profile subtracted from itself, thus yielding a zero change line. Each succeeding profile is subtracted from the prestorm profile to show cumulative density changes over the course of the storm.

Precipitation during a storm was determined for the periods between snow gage measurements and was visually classified as rain, snow, or a mixture of both. This amount was compared with the change in SWE to determine whether the snowpack retained any rainfall.

Snow temperatures were recorded before, during, and after each storm with the intent of tracking temperature profile changes throughout each episode.

RESULTS AND DISCUSSION

The three rain-on-snow events selected represent the typical response of snowpacks to rainfall at CSSL (Table 1): overall snow depth decreased, average density increased, and SWE remained the same or decreased slightly. Before rainfall the snowpack was "dry" and anisothermal below $0^{o}C$. After rain occurred it had warmed to near $0^{o}C$. The decrease in SWE was minimal indicating that rain-caused melt contributed only a small amount to snowpack outflow. Apparently the snowpack was not at its water-holding capacity.

Table 1. Hydrologic Characteristics of Three Rain-on-Snow Events at Central Sierra Snow Laboratory, Soda Springs, CA

Date	Time (PST)	Snow Depth (CM)	Average Density (%)	Snow Water Equivalent (CM)	Precipitation Between Meas. (CM)	New Snow (CM)	Snow Temperature (^{o}C) at Height (cm) Above Soil							
							0.0	30.5	61.0	91.5	122.0	152.5	183.0	213.5
1/11/80	0856	177.7	28.2	50.2	1.27 SNOW	16.5	-0.3	-0.3	-0.3	-0.3	-0.8	-2.5		
1/11/80	1517	170.4	30.0	51.1	1.22	0	*	*	*	*	*	*		
1/12/80	1026	149.1	35.5	52.9	12.60	0	-0.3	-0.3	-0.3	0	0			
1/12/80	1848	144.2	36.0	51.9	2.82	0	*	*	*	*	*			
1/13/80	0956	131.1	38.1	50.0	7.14	0	-0.3	-0.3	-0.3	0	*			
1/13/80	1230	124.1	38.6	47.9	1.60	0	*	*	*	*	*			
1/13/80	1625	124.1	39.0	48.3	3.07	0	*	*	*	*	*			
1/13/80	2035	124.1	39.6	49.2	1.73	0	*	*	*	*	*			
1/14/80	0018	122.5	39.1	48.0	0.18	0	*	*	*	*	*			
1/14/80	0415	124.7	48.6	48.6	0.51	0	*	*	*	*	*			
1/14/80	0800	127.1	38.4	48.8	0.56 SNOW	3.8	-0.3	-0.3	-0.3	0	0			
2/12/82	0823	222.3	31.7	70.6	0	0	-0.3	-0.6	-0.8	-1.4	-1.9	-3.1	-5.6	-9.4
2/13/82	1215	217.2	32.0	69.6	0.93	0	-0.3	-0.6	-0.8	-1.4	-1.9	-3.1	-2.8	-0.8
2/13/82	1805	216.3	32.1	69.5	1.38	0	*	*	*	*	*	*	*	*
2/13/82	2225	213.9	32.4	69.2	1.68	0	*	*	*	*	*	*	*	*
2/14/82	0320	212.1	32.5	68.9	1.60	0	*	*	*	*	*	*	*	
2/14/82	0730	212.4	32.8	69.7	0.83	0	-0.3	-0.6	-0.6	-0.8	-1.4	-1.1	-0.3	
2/14/82	1150	210.6	33.0	69.4	0.40	0	*	*	*	*	*	*	*	
2/14/82	2250	218.7	32.8	71.8	3.03	0	*	*	*	*	*	*	*	*
				OF WHICH SNOW WAS	2.40	12.5								
2/15/82	0540	216.3	33.1	71.5	1.05	0	-0.3	-0.3	-0.6	-0.6	-0.8	-0.3	0	0
2/15/82	1130	211.2	33.6	71.0	2.85	0	*	*	*	*	*	*	*	
2/15/82	1730	206.4	34.1	70.4	2.90	0	*	*	*	*	*	*	*	
2/15/82	2300	200.7	34.6	69.4	4.05	0	*	*	*	*	*	*	*	
2/16/82	0730	199.4	34.2	68.1	0.93	0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	0	
2/18/82	0807	195.9	34.9	68.4	0.05 SNOW	T	-0.3	-0.3	-0.3	-0.3	-0.3	0	-3.3	
1/14/74	0750	182.7	33.5	61.3	0.05 SNOW	T	0	0	-0.8	-2.2	-1.9	-1.9	-0.6**	
1/14/74	1815	181.2	35.0	63.4	1.88	0	*	*	*	*	*	*		
1/14/74	2250	177.6	35.8	63.5	1.80	0	*	*	*	*	*	*		
1/15/74	0745	171.3	35.7	61.1	1.13	0	0	0	-0.8	-1.1	0	0		
1/15/74	1450	168.0	36.1	60.7	0.05	0	0	0	*	*	*	*		
1/16/74	0805	164.1	36.6	60.0	0	0	0	0	-0.6	0	0	0		
1/21/74	0820	166.2	39.3	65.3	13.35	0	0	0	0	0	0	-1.9		
				OF WHICH SNOW WAS	5.35	21.3								

* Denotes lack of temperature data; ** Snow surface

During a 31-cm high intensity rainfall in January, 1980, the snowpack retained no additional water and lost a small amount possibly due to rain-caused melt (Figure 1). At the height of the storm, 12.6 cm of rain fell during a 19-hour period. Rain was so intense that about 5 cm of water was observed flowing over the snow in small drainage channels. Over-snow flow ceased when rainfall intensity decreased. A visual increase in flow in a nearby stream was apparent about 12 hours after rain began and seemed to peak when water flowed over snow. Two closely spaced layers at 60 and 70 cm increased substantially in density while portions of the pack above and below them altered only slightly (Figure 2). These two high density lenses may have delayed downward flow, directing water laterally into drainage channels.

Figure 1. Snow depth, density, snow water equivalent (SWE), and precipitation during a rain-on-snow event, January 11-14, 1980.

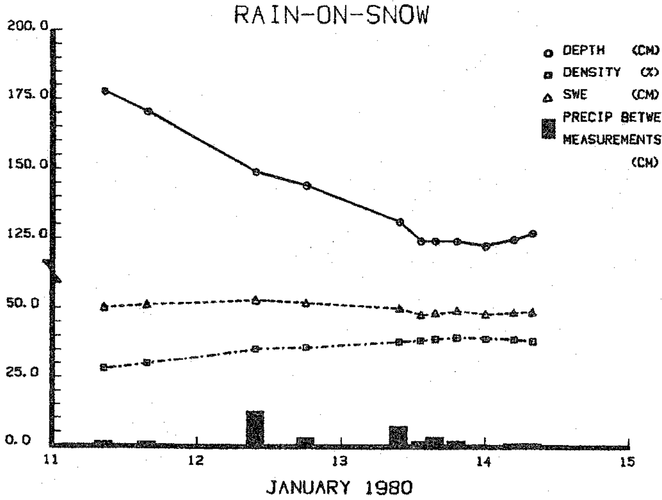
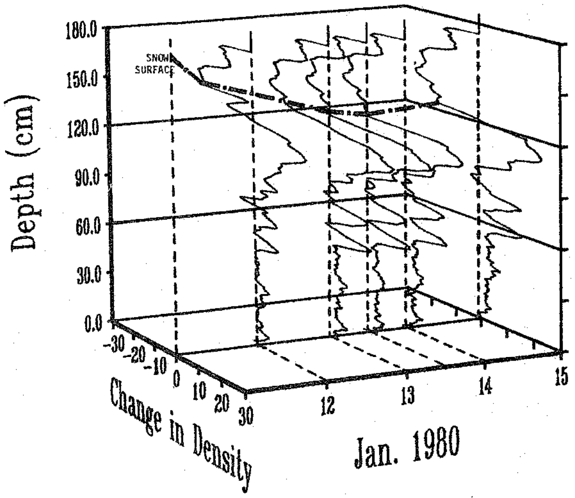


Figure 2. Snow density change profiles during a rain-on-snow event, January 11-14, 1980.

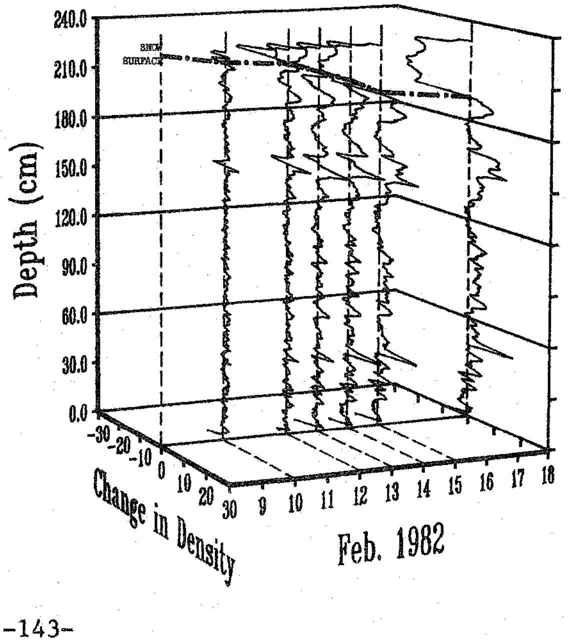


The February 1982 event was more intensely monitored. Besides profiling snow gage data, data was obtained from two melt pans, soil moisture was measured, and a dye experiment was performed before the storm.

Data from this medium intensity storm indicates that little or no rainfall runoff was stored or delayed in this subfreezing "dry" snowpack (Table 1, Figure 3). Snowpack outflow, as measured by the melt pans, increased tenfold 5 to 7 hours after rain began. A simultaneous increase in flow was observed in nearby Castle Creek, and soil moisture at three sites increased by 3 to 7% over the course of the storm.

In a prestorm dye experiment, dyed water at 3°C was sprayed on 1.5 m^2 of snow at 38 cm/hour for 20 minutes. After 45 minutes a snow pit was excavated immediately adjacent to the application area. Dye was found extensively in vertical channels between major lenses (> 0.5 cm) and had spread laterally 4.5 m from the application point indicating overlens flow on the thicker lenses (> 1.5 cm). Poststorm snow pits revealed drainage

Figure 3. Snow density change profiles during a rain-on-snow event, February 8-18, 1982.



patterns that were similar to the flow patterns found during the prestorm dye experiment. Large irregularly spaced vertical flow channels, about 12 cm in diameter, formed between the major horizontal lenses. The channels consisted of very large round grains while adjacent snow was still fine grained and dry. When an ice lens was encountered, water apparently flowed over it until penetration occurred, creating a new drainage channel.

The January 1974 low intensity event appears to support the hypothesis that an "immature" snowpack will not retain additional water from rain on snow. Measured SWE increased only slightly after rain began then decreased several hours later (Table 1). High density lenses and layers developed during the course of the storm (Figure 4). Density above and below these lenses changed slightly while SWE increased only after rain turned to snow.

Contrary to conclusions obtained from the study of one artificial and two natural rain-on-snow events (Smith and Halverson, 1969), the results obtained from the events analyzed in this paper refute the theory that rain water may percolate evenly through the snowpack with drainage occurring only after its storage potential is satisfied. During all seven episodes snowpack outflow equaled or exceeded rainfall, and SWE stayed the same or decreased slightly.

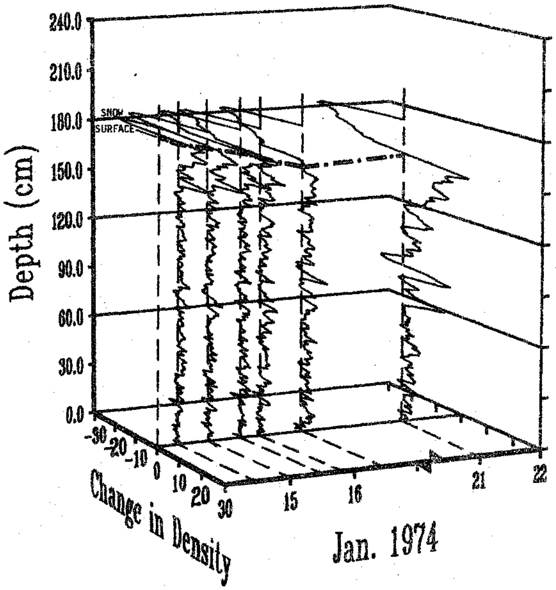


Figure 4. Snow density change profiles during a rain-on-snow event, January 14-21, 1974.

CONCLUSIONS

Visual observations of streamflow increases, dyed water flow within the snowpack, and over-snow runoff substantiate snow density measurements of seven rain-on-snow events at CSSL and suggest the following: (1) a snowpack in a "dry," subfreezing, anisothermal state does not retain additional water from rainfall, (2) ice lenses and high density layers restrict downward movement of rain water and direct it laterally, thereby delaying snowpack outflow by 5 to 12 hours, (3) warm rains falling on a subfreezing snowpack create vertical flow routes through the snow which eventually lead to snowpack outflow, and (4) rain-caused melt does not significantly contribute to snowpack outflow.

LITERATURE CITED

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