RAIN-ON-SNOW ON DONNER SUMMIT, CALIFORNIA

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ABSTRACT

Rain-on-snow events occur regularly during winter in the Donner Pass area of California, and their frequency is increasing. These storms have the potential to dramatically alter the stratigraphy of the snowpack, initiate rapid streamflow response, and cause local and downstream flooding. This paper reviews rain-on-snow events on Donner Summit, California at 2098 m elevation. Examined are case studies, rain-on-snow event size, duration, frequency, timing, anecdotal field observations, and supporting hydrometeorological data and snowpack response. Since the mid-1970s, personnel at the UC Berkeley Central Sierra Snow Laboratory have collected detailed information on precipitation type, highlighting the frequency and increasing trend of liquid precipitation during the (historic) snow season. (KEYWORDS: rain-on-snow, rainfall, snowpack outflow, flood)

INTRODUCTION

Winter rainfall on the Donner Pass region of the Sierra Nevada is a regular occurrence during the snow season. Figure 1 shows the historic rain storm distribution across the four core winter months. Personnel at the UC Berkeley's Central Sierra Snow Laboratory (CSSL, 39.326° N, -120.368° W, 2098 m elevation) have collected data and made observations on winter rain for decades. In addition to standard meteorological instrumentation, CSSL operates a 36 m^2 lysimeter array to measure the amount and timing of snowpack outflow, and the CSSL study site is bordered by Upper Castle Creek, which drains a 1300-hectare snow-dominated watershed with elevations up to 2775 m. Lysimeter outflow and changes in Upper Castle Creek stage height have been key in determining streamflow response to rain-on-snow. CSSL personnel make direct observations and/or use cameras to determine precipitation type. Determining precipitation type remotely has not been successfully modelled, but has shown to be a complex function of surface air temperature, humidity, and upper atmosphere temperature, among others. At the CSSL, the relationship of precipitation type and air temperature has run the gamut from pouring rain at 0° C, to high-intensity accumulating snowfall at 4° C. Only rarely has liquid precipitation been observed at air temperatures below 0° C, tied mostly to freezing clouds and fogs that contribute insignificant precipitation amounts.

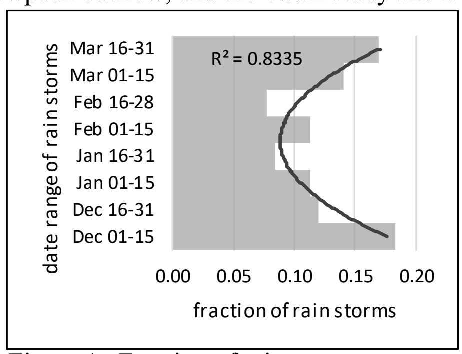

Figure 1. Fraction of rain storms across the winter months.

The CSSL averages 1.5 m of precipitation and 11 m of snowfall per year. The average maximum height of snowpack (HS) is 3.6 m. While analyses point to little change (but much variation) in average annual precipitation at the CSSL, the fraction of liquid precipitation is increasing both annually and during the core winter months (Figure 2). Other research has shown that the average storm rain/snow line (the elevation above which is snowfall, below rain) has risen as much a 37 m per year in the Sierra Nevada in the last decade. The siting of the CSSL (in 1946) was determined by access, climatology, and position in the watershed, but this author is unaware that an anticipated change in rain/snow line climate variables was any consideration. If snow lines continue to rise, the CSSL is well sited to monitor and record those changes.

Rain-on-snow storms are important hydrometeorological events. Over the decades, mid-winter rain storms have produced significant flooding both locally and far downstream. Flood flows in channels of all sizes have the ability to significantly change channel morphology. And, as a watershed's precipitation regime changes from snow to rain, so will the shape (magnitude and timing) of its hydrograph. California, with its Mediterranean climate and reliance on the Sierra Nevadan snowpack for water supply, is vulnerable to changes in runoff magnitude and timing.

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The rain storms considered here are from 68 different winters (since 1946), occurred between December 1 and March 31, and precipitated 1 cm rain or more.

OBSERVATIONS

On average, 3 to 4 rain storms occur each winter. Interestingly, Winter 1986 had the most (9), while the winters before and after (1985 and 1987) had no rain storms exceeding 1 cm. The largest event occurred December 1965 and dropped 858 mm of rain. For rain event frequency, 3-4 storms/year is a minimum. Rain events that dropped less than 1 cm (which are not analyzed here) still have the potential to significantly change snowpack structure (forming occlusive rain crusts, for instance) and may therefore play an important role in a snowpack's response to future and/or larger events. The mean annual maximum rain event drops 151 mm and lasts 92 hours. This storm has a recurrence interval of 2.6 years. The 2x mean annual maximum event recurs on average every 6.2 years. The magnitude, duration, and intensity of the mean storm have all increased in the past 20 years. As of 1998, the mean event dropped 57 mm, lasted 32 hours, and rained at an average intensity of 1.6 mm/hr. Today, the mean event is 65 mm, lasts 42 hours, and has an average intensity of 1.8 mm/hr. Storm duration and amount are positively correlated.

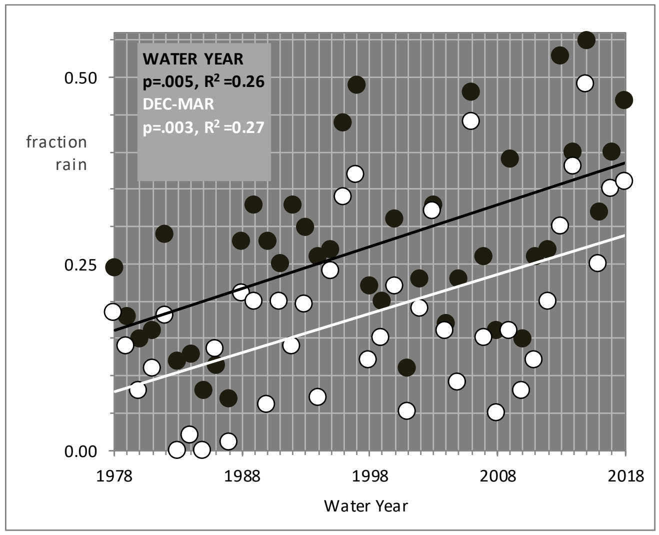

Figure 2. The increase in rain fraction during the winter and the water year.

Avalanche Response

When rainfall follows closely behind significant snowfall, avalanche response can be rapid. Both in the backcountry and within ski areas, large (size 3) avalanches have been observed when rainfall closely follows snowfall (Figure 3). Avalanche response seems most likely when rain falls onto new snow no more than three days old; observations suggest the newer the snow the more rapid the response. Therefore, abrupt rises in snow line during heavy precipitation is an important observation in managing risk in or around avalanche terrain. The mechanics of these releases are not fully understood, but differential loading caused by rain infiltration fits our understanding of initial wetting fronts, preferential flow, and lateral flow, which will be discussed further.

Figure 3. Avalanche above Lake Tahoe's west shore following rain on new snow, March 2018.

Infiltration and Outflow

Significant free water moving through a snowpack—whether the result of rain and/or melt—eventually establishes defined flow channels (Figure 4), the final structure commonly referred to as macropores. But an initial wetting front must proceed background wetting which in turn forms macropores. How initial wetting fronts establish flow channels through snow has not been well modelled, and presents a real challenge in field data collection across many variables. Once preferential flow channels are formed, precipitation to snowpack outflow time is reduced significantly. Macropores can be viewed by excavating the snow profile, and reveal themselves during the melt season within receding snowpacks. The final termini of macropores around Donner Summit commonly have a diameter of 5-10 cm, and display a smooth finish on their interior. That they melt at slower rates than the surrounding snowpack reveals their structure in bas-relief and suggests a higher density than coincident snows. Flow channels have been observed forming and routing free water in close proximity (less than 30 cm) to cold, dry snow, resulting in a small percentage of the snow volume conducting water. Until some network of flow channels is formed, initial wetting fronts do not appear to move water efficiently. This differential dispersion of free water by initial wetting fronts may be responsible for the uneven distribution of new load on a snow slab, causing avalanche response during rain on new snow. During prolonged rain storms, as flow channels get established, storm slab avalanche activity has been observed to end abruptly even as heavy rainfall continues. If migrating free water encounters occlusive or near occlusive snowpack layering, lateral flow will develop. This can easily be observed by applying dyed water to the snow surface, waiting a few minutes, then digging into the snow profile. (Cold coffee works well for this too.) Lateral flow can move free water directly toward stream channels without traversing the entire height of the snow profile, and has the potential to undercut overlaying snow slabs producing wet slab avalanches. Since most Sierran snowpacks consist of many layers of various densities and hardnesses, the potential for at least a limited amount of lateral flow is ever-present.

Figure 4. Infiltration channels on the Snow Lab study site after 100 hours of rainfall, January 2016.

The amount of snowpack outflow, as measured by lysimeters, is correlated (+/-) with rainfall amount, rain duration and rate, HS, the snowpack's cold content (Q_{cc}, the amount of energy required to bring a volume of snow to its melt point), and whether flow channels were preexisting. Outflow lag correlates to HS and Q_{cc}. Separate research has shown the efficiency capture of lysimeters is proportional to the ratio of HS to lysimeter area. Hence, as HS increases the efficiency of lysimeter capture decreases with a higher probability of lateral flow beyond the lysimeter boundary. This rests on the assumption that water distribution is not homogenous through the snow volume. Local streamflow response remains a key observation when assessing flood potential from rain-on-snow. Increase in near-surface soil moisture may also be an indicator.

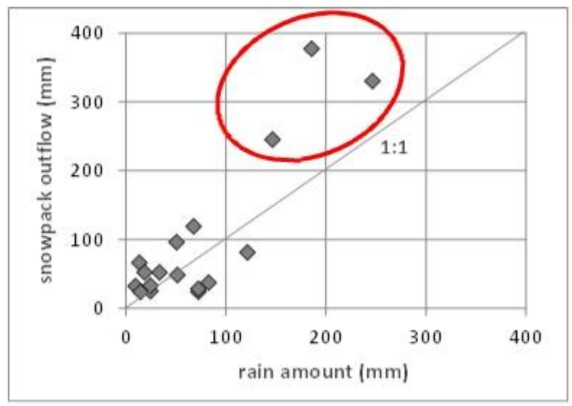

Figure 5. Snowpack outflow can exceed input, especially during the larger rain storms.

If rain water moving through a snowpack mobilizes preexisting free water, and/or induces snowmelt by conduction, turbulent exchange, and latent heat release, snowpack outflow can exceed input (Figure 5). This has been observed during large rain events with high precipitation intensities. If this hyperproduction of free water continues, snow can reach its water holding capacity (often 10-11 percent/volume) and become super-saturated. Free water will then start pooling and running on surface channels, the bed and banks of which are snow (Figure 6). Rapid streamflow response follows.

DISCUSSION AND THOUGHTS

While we have much understanding of the processes that can occur as a result of rain-on-snow, predicting when and where these will happen remains problematic. Our observation network throughout the snow zone of the Sierra is not especially robust with respect to precipitation, precipitation type, snowpack outflow, streamflow, and snowpack cold content. Some lines of inquiry…

Where is it raining? Not only at what elevation, but at what elevation as a function of longitude. Storm fronts can behave very differently on the windward and lee sides of the range, and very different snow lines have been observed during storms east and west of the Sierra crest. Cameras, in general an underused resource at instrumented tower sites, may be a good first step.

Figure 6. Water pooling on the snowpack surface.

Stream stage increase. Stream gauges, as well as many other instruments, are difficult to maintain at high elevation. However, gauges higher in the watershed may provide a unique look at stream response through the elevational profile of a watershed, especially with very warm rain storms. A Sierran rain storm in early April 2018 had snow lines above 4000 m elevation.

If the frequency and/or magnitude of rain storms continues to increase, at what rate? How will the shape of annual hydrographs change?

What's the Q_{cc} distribution, especially in March? March, historically one of the wettest and snowiest months, can also be spring-like. Wide variations in snow temperature and metamorphism are often observed during late winter. Mid-March 2019 was a good example: 0° C snowpacks dominated the south aspects while -9° C snows existed across the northerly aspects. These unique snow profiles will react very differently to rain.

How high has it previously rained? Are there established flow channels in mid- to upper-elevation (2500-3000 m) snowpacks? Repeated rain storms at high elevation may result in snowpacks that are very efficient at moving their free water into stream channels.

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The poster version of this paper as presented at the 2019 Western Snow Conference, April 2019, Reno, Nevada can be viewed here