# Rain-on-snow avalanches: forecasting the return to stability

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ABSTRACT: Mid-winter rain-on-snow often results in avalanches that threaten the Milford Road between TeAnau and Milford Sound on the southwest coast of new Zealand. Avalanche activity is typically widespread minutes after the onset of rain; the timing of these immediate avalanches can be predicted with accuracy better than an hour from meteorological forecasts of the transition from snow to rain. The avalanche potential can remain high for several hours after rain starts. Accurate prediction of these delayed avalanches is complicated by difficulties defining how the stress and strength of the snowpack evolves during infiltration of liquid water. During continued rainfall, avalanche activity usually decreases after 24 hours; at Milford we have not observed avalanches more than 36 hours after the onset of rain. The return to stability occurs when drainage through the snowpack has been established; the evolution of snow stability can be tracked by monitoring outflow from the snowpack. Observations of waterfall activity provide information about the state of the snowpack: lack of waterfalls during rain events indicates drainage is not yet established, while active waterfalls implies that drainage is established. Measurements of outflow from an array of spatially distributed lysimeters located near the start zones provides additional information. The time between the onset of rain and first outflow varies depending on the rate of rainfall as well as the stratigraphy and temperature of the snowpack. A large flux of water infiltrates through isothermal, homogeneous snow faster than a small flux through cold, layered snow.

KEYWORDS: Rain-on-snow, avalanches, forecasting.

## 1 INTRODUCTION

Three evolutionary stages of snow stability have been identified following the onset of rain on new snow (*Conway and Raymond,* 1993). Figure 1 shows a conceptual picture of conditions during infiltration of water: (1) Observations indicate that avalanche activity often increases immediately (within a few minutes) after the onset of rain. At this time, water is usually retained within the upper few centimeters of the snow pack; apparently redistribution of stresses caused by alteration of the rheology of the near-surface snow can cause failures at depth (*Conway*, 1997). The timing of these immediate avalanches can be predicted with an accuracy of an hour or better by high-resolution forecasting the transition from snow to rain; (2) before drainage has been fully established, additional rain or melt-water is retained in the snow pack. Slopes remain potentially unstable because stresses from the overburden are increasing and because the liquid water might weaken subsurface layers in the snowpack; (3) stresses from the overburden will decrease as water drains out of the snowpack. Although full-depth avalanches might release if liquid water weakens the basal interface, in our experience the snowpack is stable once drainage is established.

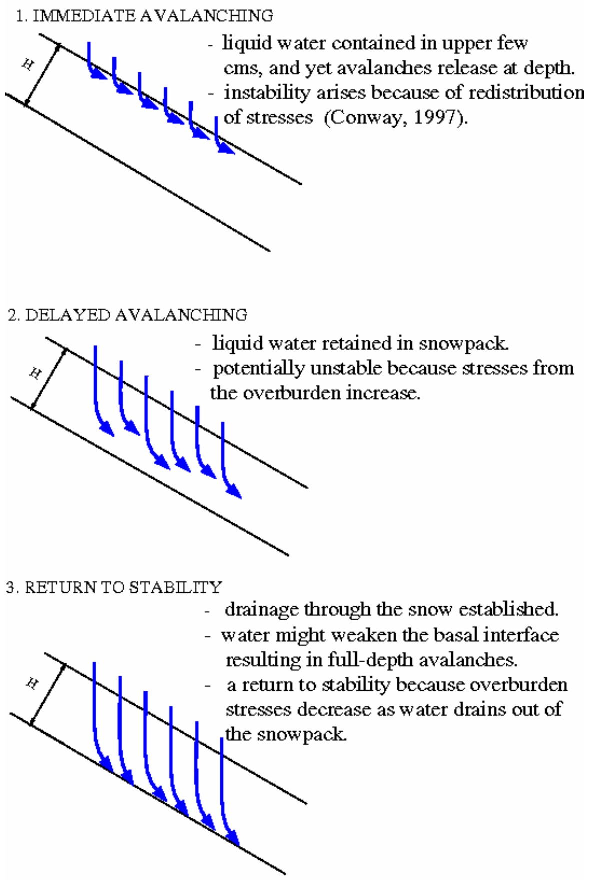


**Figure 1:** Conceptual picture of the evolution of stability during rain-on-snow.

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Following this view, we hypothesize that the return to stability can be forecast by comparing the outflow from the base of the snowpack with the influx of rain or meltwater at the surface. The idea is that the onset of stability occurs when the magnitude and timing of outflow is similar to the influx of water at the surface.

## 2 THEORY

First rain falling on sub-freezing dry snow will freeze, and the latent heat released during the phase change warms the snow to 0°C. The energy balance and the liquid water mass balance are coupled. The one-dimensional energy balance is:

$$\rho_s C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[k \frac{\partial T}{\partial z}\right] + \frac{\partial Q}{\partial t} \quad (1)$$

where $\rho_s$ is the bulk density and $C_s$ is the heat capacity of the snow, $t$ is time and $z$ is the vertical coordinate, positive down from the surface. $k\,\partial T/\partial z$ is the downward conductive flux, and $\partial Q/\partial T$ accounts for nonconductive processes. When liquid water makes contact with subfreezing snow, the nonconductive term is dominated by the latent heat released during freezing $\frac{\partial Q_f}{\partial t} = L_f \frac{\partial m_f}{\partial t}$, where $L_f$ is the latent heat of fusion, and $\partial m_f/\partial t$ is the mass rate of freezing. The volume loss of liquid water due to freeze-on $\partial F_f = \frac{1}{\rho_w}\frac{\partial m_f}{\partial t}$, where $\rho_w$ is the density of water.

Freezing of liquid water and the release of latent heat rapidly warms the snow; the amount of freezing required to warm maritime snowpacks to 0°C is usually a small fraction of the total rainfall (*Conway and Benedict*, 1994).

From continuity, one-dimensional infiltration of water is:

$$\frac{\partial \theta_s}{\partial t} = -\frac{\partial q_w}{\partial z} + \partial F_f \quad (2)$$

where $q_w$ is the water flux, $\theta_s$ is the volumetric water content; $\theta_s = \phi_{eff} \times S_{eff}$, where $\phi_{eff}$ is the effective porosity and $S_{eff}$ is the effective water saturation. In the case of mature snowpacks (homogeneous, coarse-grains), pressure gradients are small and Darcy's law describing unsaturated flow through a porous medium is well approximated by (*Colbeck*, 1974):

$$q_w = \alpha k S_{eff}^3 \quad (3)$$

where $\alpha$ is a constant, $k$ is the permeability. This power-law dependence on the saturation implies that other things being equal, a large flux of water will infiltrate faster than a small flux.

Combining eqns (2) and (3) yields the rate of infiltration:

$$\frac{\partial z}{\partial t} = 3\alpha^{1/3} k^{1/3} \phi_{eff}^{-1} q_w^{2/3} \quad (4)$$

These basic equations for flow through homogeneous snow can be adapted for heterogeneous snow by including terms for pressure gradients (*Colbeck,* 1974; 1977; 1979), which disperse the flow and reduce the shock front at the leading edge of the propagating wave. Stratigraphic boundaries in heterogeneous snow serve to impede infiltration.

## 3 MONITORING THE WATER FLUXES

### *3.1 Influx of water*

We have found that scaling measurements of precipitation from a heated tipping bucket gauge at road level yields the most reliable measure of accumulation in the start zones. Precipitation at elevation $z$ is assumed to fall as rain when $T_z > 0$°C, and snow otherwise. $T_z$ is calculated by interpolating between measurements of air temperature from the network of remote weather stations in the region. When visibility allows, we also monitor the rain/snow transition during storms through road-level observations.

### *3.2 Outflux – waterfall activity*

Waterfalls on the Milford Road are spectacular (Fig. 2). Avalanche forecasters have long recognized that waterfall activity during rain events provides important clues about the state of the snowpack.


**Figure 3:** Active waterfalls during rain-on-snow provide an indication that drainage through the snowpack has been established.

A lack of waterfalls during rain events implies that drainage is not yet established. In this case, loading is increasing and the avalanche potential is considered high. In contrast, observations of active waterfalls are a signal that drainage has been established; water is routed away from potential weak layers and out of the snowpack. In our experience at Milford, waterfalls usually start flowing after 24 hours of continued rain. Avalanche activity bas usually decreased by that time; we have not observed avalanches after continued rain for more than 36 hours.

*3.3 Outflux - lysimeters*

During summer 1998 we installed a lysimeter (Fig.3) at 1600m between the East Homer and Raspberry avalanche paths.

**Figure 3:** Summer pictures of the lysimeter at Belle (1600m). Upper picture shows the catchment tray. Lower picture shows the housing for the tipping bucket gauge. During winter the lysimeter is typically covered by 3-4m of snow.

It is well known that water penetrates snow through channels that occupy only a fraction of the total snow volume (*Colbeck,* 1979; *Conway and Benedict,* 1994; *Gerdel*, 1954; *Kattelmann and Dozier*, 1999). Local infiltration through the snowpack is much faster than the average rate. The spacing between drain channels is typically 2m or less. In order to capture flow from at least one channel, we constructed the catchment tray with dimensions 2m x 2m. A tipping bucket gauge installed beneath an orifice at the edge of the tray is used to measure the outflow. Antifreeze is pumped into the orifice to prevent freezing; the antifreeze contributes 0.03mm every 3 hours to the outflow.

Measurements of outflow, together with additional snow and weather measurements from the adjacent weather station are telemetered hourly back to the base station in TeAnau. Fig. 4 shows measurements of precipitation at 900m, air temperature and outflow at 1600m. The lysimeter measurements show the first major outflow (more than 115mm) peaked at 0200 on August 31 (243.08). The outflow was probably a combination of melt and rain water (less than 40mm precipitation was recorded at East Homer, and air temperatures indicate that at least some of this would have fallen as snow at 1600m). The snowpack remained stable and the avalanche hazard was low during this period.

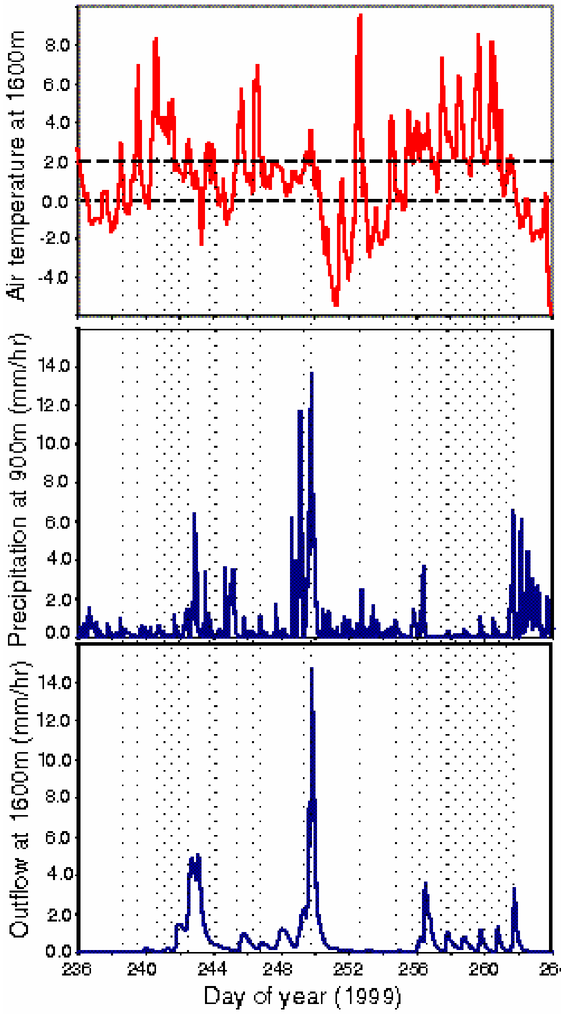


**Figure 4:** Air temperature at 1600m, precipitation at 900m, and outflow from the snow pack at 1600m. Measurements start August 24 (236) and end September 21 (264), 1999. Shaded regions indicate times when the air temperature at 1600m was greater that 2°C; we assume that precipitation falls as rain when $T_Z$>2°C.

One week later the thickness of snow above the lysimeter was 1.7m. The peak outflow (14.6mm/hr on day 249.79) lagged the peak rainfall by less than an hour (Fig. 5). Both the timing and magnitude of the outflow closely resembled the rainfall. Drainage was very well established, and again the snowpack was stable and avalanche hazard was low.

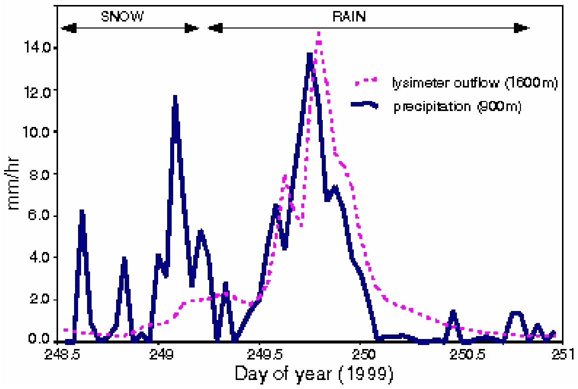


**Figure 5:** Precipitation at 900m, and outflow from the snow pack at 1600m. Measurements start at 1200 September 5 (248.5) and end September 8 (251), 1999. Snow depth at the start of the period was 1.7m.

### *3.4 Outflux - a spatial array of lysimeters*

Crucial for forecasting the hazard during rain events is to determine the time when drainage is established at all elevations. Recognizing this, and motivated by results from the Belle lysimeter, we installed a second lysimeter at the Cleddau weather station (1740m) in 2005. Compared to conditions at Belle (1600m), we expect that colder temperatures at higher elevations will reduce the rain-fraction of the precipitation; other things being equal, we expect the timing of outflow at Cleddau will lag that at Belle.

We found that some modifications were needed. Specifically, freezing of the outflow orifice was much more problematic than at Belle, likely because of the colder temperatures. To get around this problem., we recently increased the number of de-icing jets and we now pump a larger volume of antifreeze. We anticipate that these modifications will improve the reliability and quality of the data from Cleddau.

## 4 SUMMARY

Observations and measurements during rain-on-snow events support the hypothesis that the avalanche potential remains high until drainage through the snowpack has been established. The return to stability after drainage is established can be monitored through road-level observations of waterfall activity, and through measurements of outflow from an array of spatially distributed lysimeters located near the start zones.

The time between the onset of rain and first outflow varies depending on the rate of rainfall as well as the stratigraphy and temperature of the snowpack. Thermal conditions generally play a relatively minor role in maritime snowpacks; most of the rainwater is available to wet and then infiltrate the snowpack.

Other things being equal, infiltration will be slower in cases of small surface fluxes through layered snowpacks that have not been previously wetted. Infiltration is faster through homogeneous snow during high intensity rainfall. In our experiences at Milford, drainage is usually established after 24 hours of continued rain, after which avalanche activity decreases. We have not observed avalanches after continued rainfall for more than 36 hours.

## 6 ACKNOWLEDGEMENTS

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