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Avalanche Forecasting Methods Highway 550

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U.S. Department of Transportation
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13. ABSTRACT (Maximum 200 words)
This 33-mile segment of US Highway 550 has a greater avalanche hazard than all other Colorado highways combined. A total of 95 avalanche paths intersect the highway with an avalanche hazard of 443. More than 70 encounters between avalanches and vehicles and six fatalities have occurred since 1950. The objective of this research project is to develop a methodology for calculating the severity of a particular avalanche activity. The project is not intended to develop a "black box" type of computer program for avalanche forecasting. Instead, it is intending to investigate parameters that may be important in forecasting on Highway 550, and to suggest how they may be used to forecast avalanches in the future. Results of the study exhibit a positive correlation between length of centerline covered, volume of avalanche debris and the avalanche activity index. While volume is a better measure of maintenance requirement to keep the road open, the length parameter is a better measure of hazard because it more directly relates the probability of a vehicle being hit by an avalanche. The author recommends continued quantification of avalanche activity data collection after storm events, shear strength tests of snowpack, and establishment of an automated weather station.

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1 INTRODUCTION, OBJECTIVES, AND LIMITATIONS

1.1 INTRODUCTION

The 33–mile long stretch of U.S. Highway 550 from Ouray to Coal Bank Pass (including approaches to Red Mountain, Molas, and Coal Bank Passes) has greater avalanche hazard than all other Colorado highways combined (Mears, 1995) and is one of the most seriously–exposed highways in North America. A total of 95 avalanche paths intersect the highway; many of these produce avalanches that reach the road more than once during a typical winter. The avalanche–hazard index (AHI) for the 33–mile stretch of road from Coal Bank Pass to Ouray is 443.

A "continental" snow climate, characterized by a relatively thin, cold snowpack with numerous weak layers exists throughout the study area. Although annual precipitation is relatively light in comparison to maritime climates of West coastal states (e.g. California, Washington, Alaska), the San Juan Mountains receives occasional high intensity, long duration storms, particularly on southwesterly to westerly wind flows. These storms, which are usually accompanied by strong winds, quickly add destabilizing snow mass to the numerous avalanche starting zones. Because avalanche terrain remains steep to Highway 550 at many avalanche sites, avalanche frequency is high. The net result is high avalanche hazard. More than 70 encounters between avalanches and vehicles and six fatalities have occurred since 1950.

The Colorado Department of Transportation (CDOT) in cooperation with the Colorado Avalanche Information Center (CAIC) has an active avalanche control and hazard reduction program on Highway 550. This program is based, in part, on recommendations of two CAIC forecasters stationed in Silverton. These observers systematically observe weather and snowpack conditions, record avalanche activity, and are available to CDOT for advice and assistance. Their conclusions about snowpack stability on avalanche paths affecting Highway 550 depend, in part, on the availability and interpretation of snowpack and weather data obtained in this area.

1.2 OBJECTIVES AND LIMITATIONS

The objective of this research project is to develop a methodology for calculating the severity of a particular period of avalanche activity. Furthermore, this project suggests if certain readily–available data can be utilized to improve the reliability of avalanche forecasts. The project is not intended to develope a "black box" type of computer model to forecast avalanches. Instead, it is intended to investigate parameters that may be important in forecasting on Highway 550 and to suggest how they may be used to forecast avalanches in the future.

2 CURRENT FORECASTING METHODS ON HIGHWAY 550

2.1 INTRODUCTORY COMMENTS

As defined by LaChapelle (1980), "Conventional avalanche forecasting is practiced as a mix of deterministic treatment for snow and weather parameters and inductive logic to reach actual forecast decisions. Inductive logic of the scientific method dominates, making frequent use of iteration and redundancy to minimize decision uncertainties." This definition generally applies to the methodology applied by skilled avalanche forecasters on Highway 550. The forecast is partially subjective, partially based on data, and strongly based on experience with and observations of avalanche behavior in response to weather and snowpack conditions along the highway.

2.2 FORECAST METHODOLOGY

The following comments result from interviews with Mr. Don Bachman and Mr. Denny Hogan in which their reliance on storm and snowpack parameters was discussed. The forecasters' use of "inductive logic," although this is highly relevant in arriving at forecasts, will not be discussed here.

2.2.1 Use of wind data

Wind data are first used as a "general verification tool" to determine if the forecast weather conditions are correct. Both anemometer sites at Mt. Abrams (11,900 feet) and Red Mountain #3 or "Putney" (12,800 feet) are effective in sensing the velocity and direction of approaching storms, in determining the duration and strength of storms, and in determining wind shifts as low pressure systems rotate through the area. For example, the largest and most energetic San Juan storms usually approach with a wind direction ranging from approximately 180° (south) to 225° (southwest). As wind velocity increases and the storm intensifies, wind direction will not vary significantly for several hours (or days with the largest storms). As the storm center (center of the low–pressure cell) passes to the east of the San Juans, wind direction will usually change to a northwesterly direction (approximately 300–330°). This general wind data will be used by the forecasters, therefore, to verify that the storm has arrived in the area, to check if the strength and size of the storm is as forecast, and to determine if the storm center has passed to the east and the storm, therefore, is nearly over. These are important "semi–quantitative" uses of the wind data which are highly useful in an avalanche forecasting program.

2.2.2 Combination snowfall/wind data

Strong winds without snowfall, especially if new snow has not fallen for several days, will probably not trigger avalanches that fall to the highway in most paths affecting Highway 550. Some avalanches may reach the road during exceptional conditions or in avalanche paths that remain steep to the highway. Wind alone, however, will produce localized "hard slab" conditions. Winds, therefore, often result in a snowpack structure that can be hazardous to backcountry travel, particularly when avalanche starting zones (slopes in excess of 30°) are disturbed.

In contrast, when new snowfall accompanies strong winds, redistribution of snow into starting zones will occur and avalanches are more widespread, larger, and can travel farther in the path. Wind with new snow is more likely to produce avalanches that reach the highway. The combination of persistent wind *and* new snow is considered a critical combination of conditions by the CAIC avalanche forecasters (Bachman & Hogan, pers. comm.). Quantification of the amount of snow or the duration or velocity of wind necessary to produce avalanches has not been made, but will be considered in Section 5 of this report. Experienced forecasters will be aware when critical magnitudes of wind and snowfall occur and are likely to produce avalanches on the highway.

2.2.3 Snowpack tests

The current program regularly samples the snowpack to assess depth, strength, snow surface conditions and presence or absence of weak layers that might serve as avalanche release surfaces. These tests are conducted on a level study plot approximately 1,000 feet (300m) south of Red Mountain Pass at an elevation of 11,100 feet (3,300m). They usually consist of testing the snowpack strength through use of a Swiss "Ram Penetrometer," then excavating the snowpack to the ground, measuring temperatures, densities, and hardness, and identifying and recording the snowpack stratigraphy. The data obtained at the Red Mountain Pass snow study plot does not relate directly to the conditions in avalanche starting zones because these steep slopes are modified by wind and sun exposure. However the study plot data do provide an excellent measure of the snowfall, storm, snowpack, and seasonal "snow climate" at high elevations.

In addition to the detailed snowpit data obtained as discussed above, the forecasters also sample the snowpack at or near the avalanche starting zones when time and accessibility permit.

2.2.4 Other forecasting procedures

The following standard observations are regularly made by avalanche forecasters to assist in arriving at an avalanche stability evaluation and hazard forecast on Highway 550.

a. *Old Snow Depth* fills in the ground-surface irregularities and provides a smooth surface upon which an avalanche can start and flow. The general distribution of snow depth can be estimated from the highway by observing the apparent roughness and amount of ground surface exposed in avalanche starting zones. Experience has shown that a snowcover depth of approximately 30 inches (0.75m) at Red Mountain Pass is required before new snowfall will produce significant avalanche activity that reaches the highway. The old snow depth is likely to be highly variable from one exposure to another. Therefore the potential for avalanching at the highway may be significantly greater or less depending on the avalanche path exposure to sun and wind and the resulting snow cover at each location. During the 1995/96 season, snow depth was shallow in November and December, thus a substantial storm at the end of December did not result in significant avalanche activity. In contrast, an early-winter storm of similar size three years earlier fell on a deep snowpack and produced avalanches that covered more than 2,000 feet of the highway.

b. The *old snow surface* is related to the bonding strength between the new snow and the old snow. Exposure to sun and wind usually strongly affects the character and potential bonding strength at the new snow/old snow interface. For example, "sun crusts" result from repeated melting and re-freezing of the snow surface and is common on steep south-facing slopes all winter long. When this surface is frozen (no free water present), new snow will not bond well to the old snow.

c. *New snow depth* is the single most important cause of avalanches. The weight of new snow induces shear stresses in the snowpack, particularly at the boundary between the old snow and the new snow.

d. *Snowfall/precipitation intensity* is a measure of the rate that snow or mass (and induced stress) is being added to the snowpack. A prolonged storm that deposits 2 or 3 feet (0.3 – 0.6m) of new snow over a period of days may not produce avalanches because the new snow would have sufficient time to densify and gain in strength during this longer time period. In contrast, 2 feet of snow in a 24-hour period (with or without wind) is almost certain to produce some avalanches because the new snow may not have sufficient time to gain strength. Precipitation intensity is a more basic factor for avalanche formation than is snowfall intensity because it directly measures the rate that mass and shear stress is added to the snow. It is measured along Highway 550 by the CAIC forecasters through direct measurements at snow study plots on Coal Bank, Molas, and Red Mountain passes and through interpretation of remote National Resources Conservation Service Snotel stations. These Snotel data are used in Section 3 of this report to contrast the snowfall amounts at three locations along Highway 550 and to compare each of the four snow seasons.

e. *Wind* is the primary agent in rapid slab avalanche formation. Because wind is such an important factor and can be readily measured at remote sites it deserves and receives special attention. Current methods for using wind data have been discussed above in Sections 2.2.1 and 2.2.2 and are discussed further in Section 5.

f. *Avalanche activity* is an obvious indicator of snowpack instability. Avalanches indicate that the various factors producing instability exist.

3 THE FOUR SNOW SEASONS AND 13 STORMS STUDIED

3.1 SNOW SEASONS

As defined in this report, a "snow season" extends from November 1 through May 31. Prior to November 1 the San Juan snowcover is rarely deep or continuous, consequently avalanches that affect Highway 550 are rare. After May 31 the snowpack is usually either thin and discontinuous or has stabilized through numerous melt/freeze cycles and does not produce avalanches that reach the highway, except during unusual conditions.

Millimeters of water in the snowpack (water equivalent) on the ground for each of the four seasons (1992/93, 1993/94, 1994/95, and 1995/96) is shown as a function of "snow season day" in Figures 3-1 through 3-4. November 1 is "day 1;" May 30 is "day 212" on each of the four graphs. Each graph has a resolution of 3 days. Data were taken from National Resources Conservation Service (NRCS) "snotel" sites at Red Mountain Pass, Molas Pass, and Coal Bank Pass. Each site provides a continuous, daily record of water equivalent, precipitation, and temperature for the entire length of each snow season. The snow weight is measured by a snow pillow of several square meters surface area. Figure 3-5 provides the average of the water equivalent at the three sites as a function of day throughout each of the four snow seasons. Figure 3-5 therefore provides an indication of the amount of snow that precipitated within the entire study area during each season.

Steep portions of each precipitation vs. day curve are periods in which the precipitation rate, or "intensity" was large. See Section 2.2.4 (b) for a discussion of this factor. These steep portions of each curve often correspond to times when the snowpack was unstable. Instability results when the rate of shear stress increase resulting from the new snow is rapidly approaching the shear strength of the snow. Avalanches result when stress and strength are equal, therefore they are common during these periods of high precipitation rates. However, avalanches do not occur when the new snow is strongly bonded to the old snow even when precipitation rates are high. Typical periods of rapid shear stress increase when avalanches were widespread occurred during the days 111-116 (February 17-22, 1993) and 103-107 (February 11-15, 1995). A period of rapid shear stress increase when avalanches did *not* occur because of strong bonding between the new and old snow was day 111-114 (February 19-22, 1994).

Figures 3-1 through 3-4 also illustrate the variation in total precipitation and precipitation rate differences between the three sites. Significant differences between the relative amount of snow at each site resulted from storm characteristics in each season.

During the 1992/93 season, the three curves are approximately parallel, however, Coal Bank Pass received 30% to 50% more snow than either Molas or Red Mountain passes. During this winter, most of the major storms approached from the southwest, and were uplifted against the southern side of the San Juans (e.g. Coal Bank Pass). Heaviest precipitation, therefore, occurred on Coal Bank with lesser amounts available when the storms reached Molas and Red Mountain Passes. Four major periods of avalanching occurred from late December through January. One of the three heaviest precipitation periods occurred from February 17–22 (see also 1994/95 for the other two major storms) and caused the most extensive period of avalanching during the entire four-year study period.

During the earlier portion of the 1993/94 season, the precipitation curves are similar at each site. The curves diverge when major southwest storms reached the San Juans in early and mid February. Coal Bank Pass received significantly more snow during these storms which therefore increased the snowpack in the southern end of the study area. This period of relatively heavy February precipitation produce the only major avalanche activity during this season.

During the first half of the 1994/95 avalanche season, the three sites received similar amounts of precipitation as most storms approached the San Juans from the west. However, major storms of mid February and early March flowed into the mountains from the southwest and produced high precipitation rates that favored Coal Bank Pass. Each of these storm periods produced extensive avalanching, however, because the snowpack was strong and much of the new snow was well bonded to the old snow, avalanching was not as widespread as in 1993. Probably the most remarkable aspect of the 1994/95 season was the heavy precipitation in late April and May. Although this continued to increase the snow depth through mid–May (day 200), the snowpack was strong and avalanches did not affect Highway 550.

The 1995/96 season was the only one of the four studied in which precipitation was heaviest on Red Mountain Pass. This fact was not the result of heavy precipitation on Red Mountain Pass, but resulted from light precipitation on the southern side of the San Juans. Due to the light precipitation many avalanche starting zones had discontinuous snowcover through mid winter. Early storms fell on the ground surface or on a thin snowcover with rocks and other roughness protruding through the snow (see discussion of "old snow depth" in Section 2). Avalanche activity was therefore significant only as a result of the late January storm # 96–3 (days 91–93). A steep precipitation curve resulted from a warm, high density storm (#96–4) during February 19–22 (day 112–115), however the new snow bonded well with the old snow and avalanches did not affect the highway.

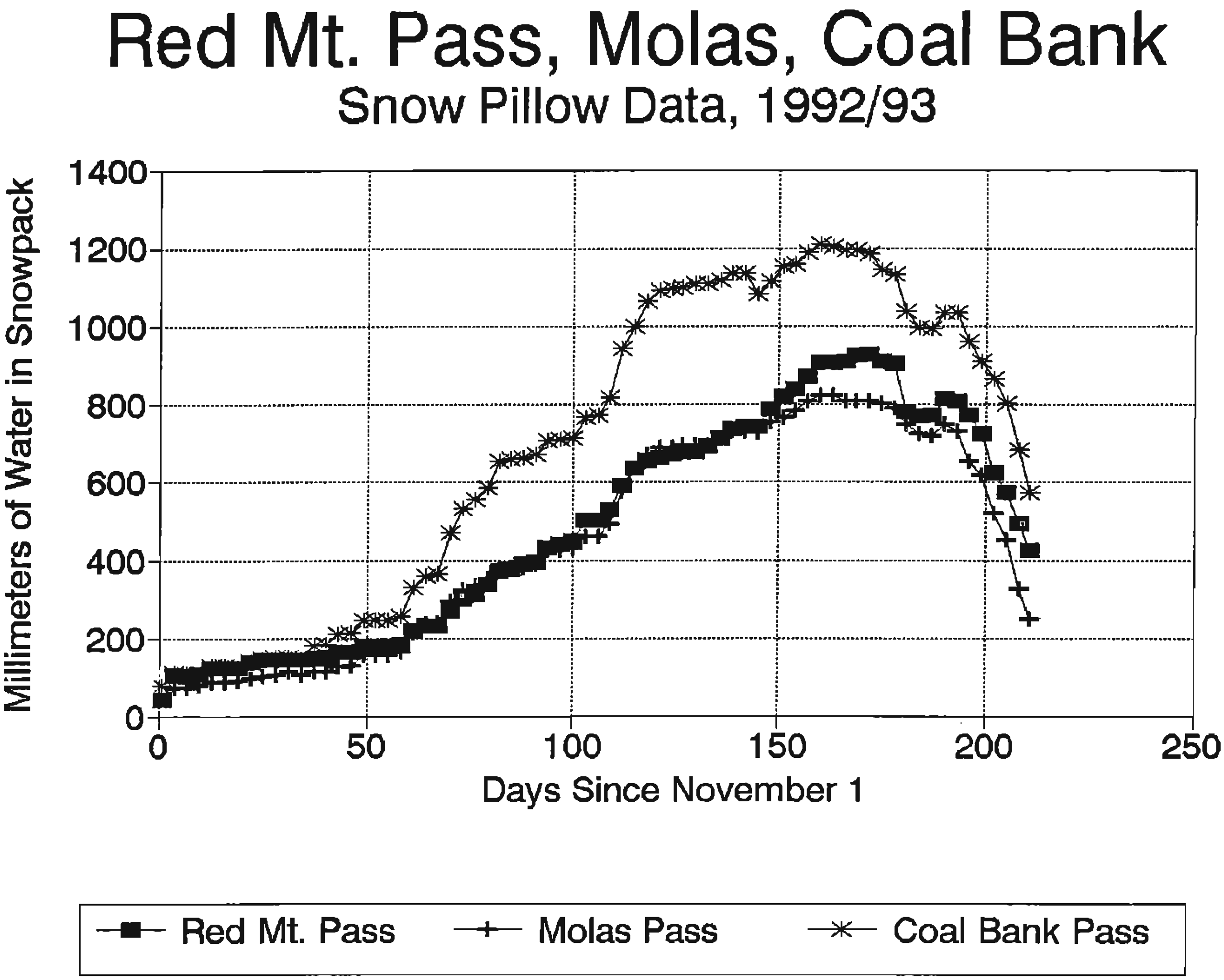

Figure 3-1. Water equivalent on the ground during the 1992/93 snow season. Data was obtained from the National Resources Conservation Service (NRCS) Snotel site as measured by a standard snow pillow. Steep portions of the curves are times when the rate of precipitation was large. Day 1 is November 1, Day 212 is May 31. During this avalanche season the major storms approached from a southerly direction, consequently, the heaviest precipitation occurred on Coal Bank Pass. The largest storm of the four-year study began on day 109. As a result of this storm, more than 22,000 feet (6,700m) of highway was covered by avalanche debris.

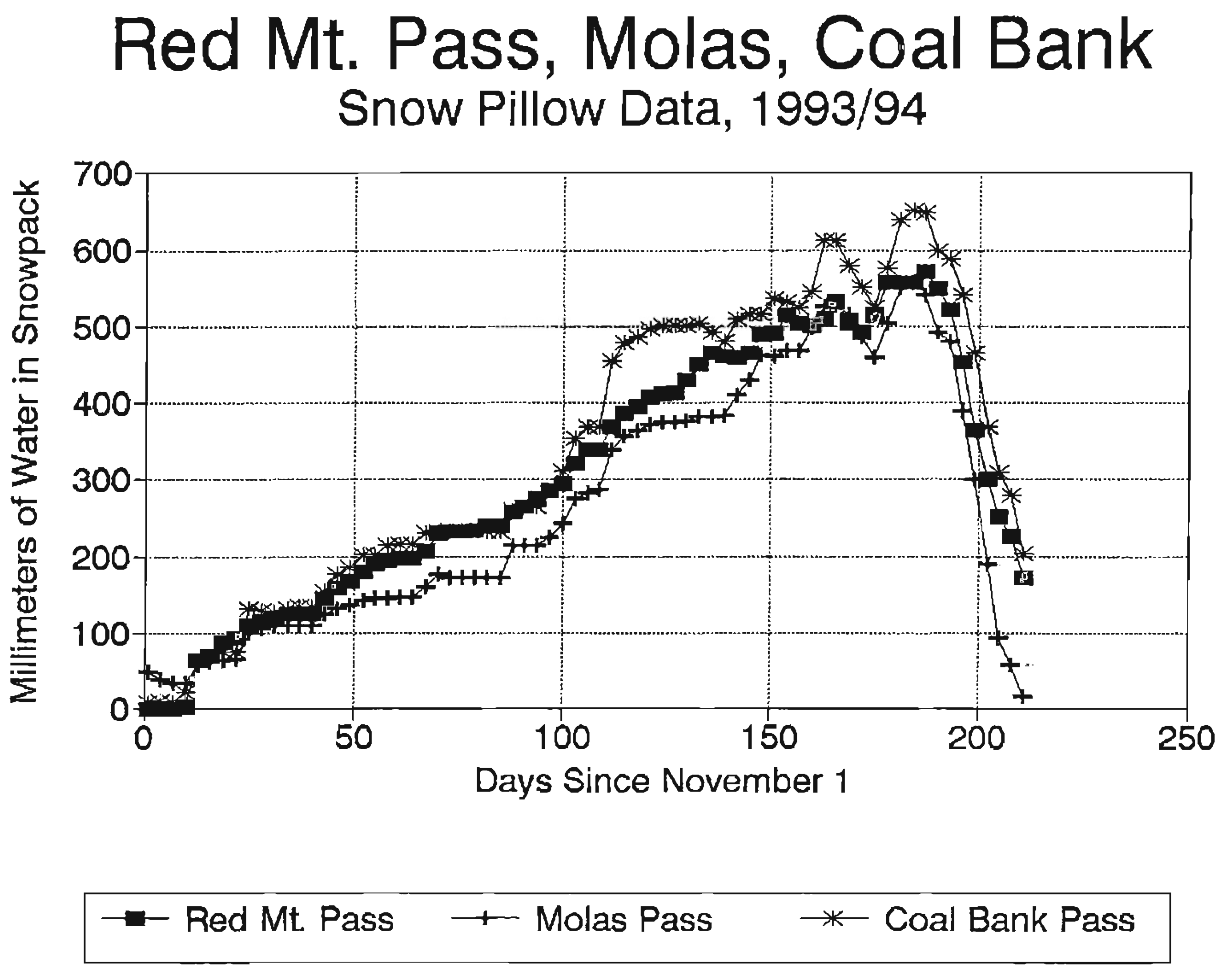

Figure 3-2. Water equivalent on the ground during the 1993/94 snow season. Data was obtained from the National Resources Conservation Service (NRCS) Snotel site as measured by a standard snow pillow. Steep portions of the curves are times when the rate of precipitation was large. Day 1 is November 1, Day 212 is May 31. Relatively light snows characterized the first half of this season, resulting in a thin, structurally weak snowpack. A period of relatively high precipitation rate (day 100–103) produced extensive avalanching in which approximately 6,300 feet (1,900m) of avalanche debris covered the highway.

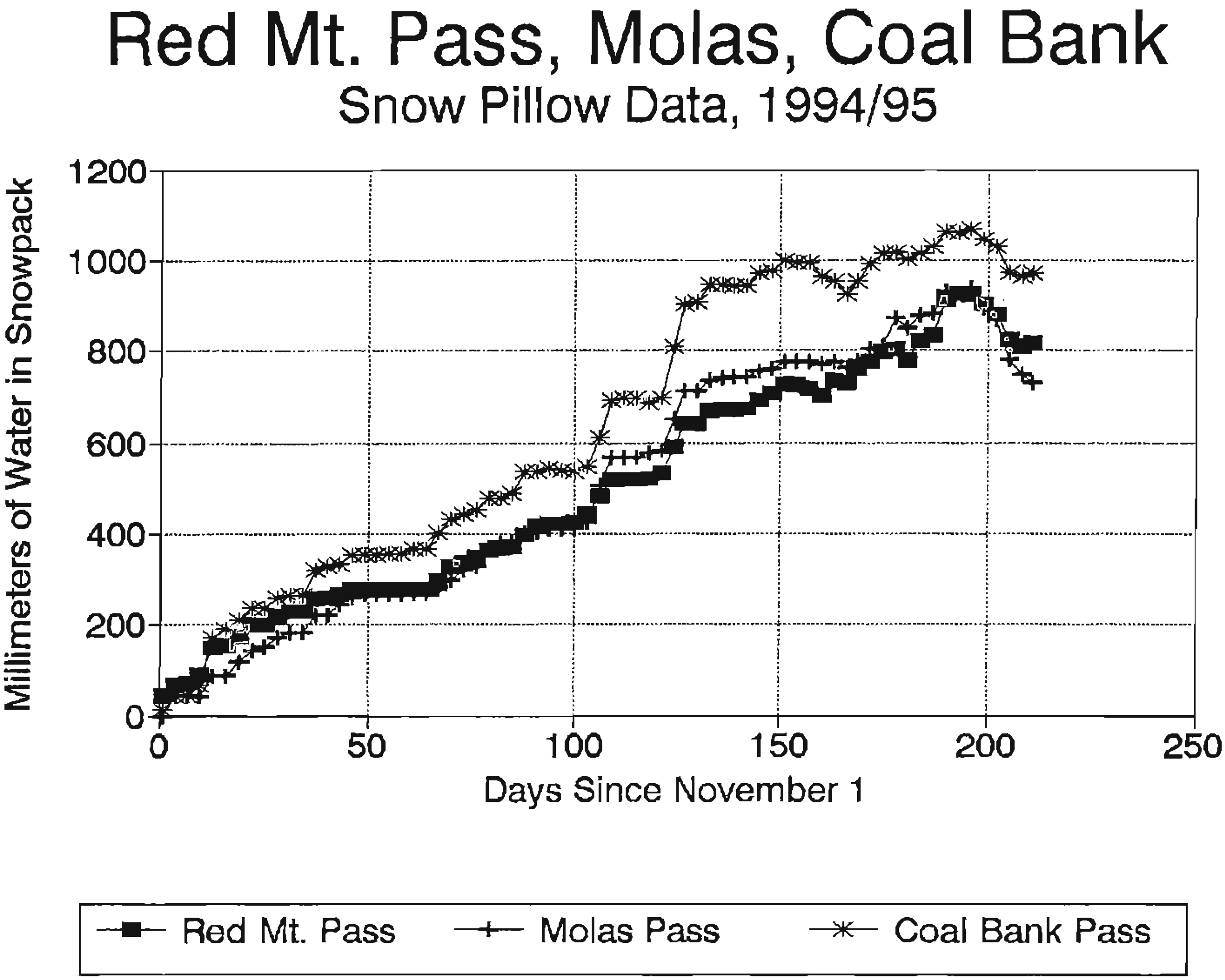

Figure 3–3. Water equivalent on the ground during the 1994/95 snow season. Data was obtained from the National Resources Conservation Service (NRCS) Snotel site as measured by a standard snow pillow. Steep portions of the curves are times when the rate of precipitation was large. Day 1 is November 1, Day 212 is May 31. Steady snows fell during the first half of the snow season, producing a relatively strong snowpack. Heavy precipitation periods of mid–February (beginning on day 103) and early March (day 120) produced extensive avalanching, however it was not as extensive as during the storm of February, 1993.

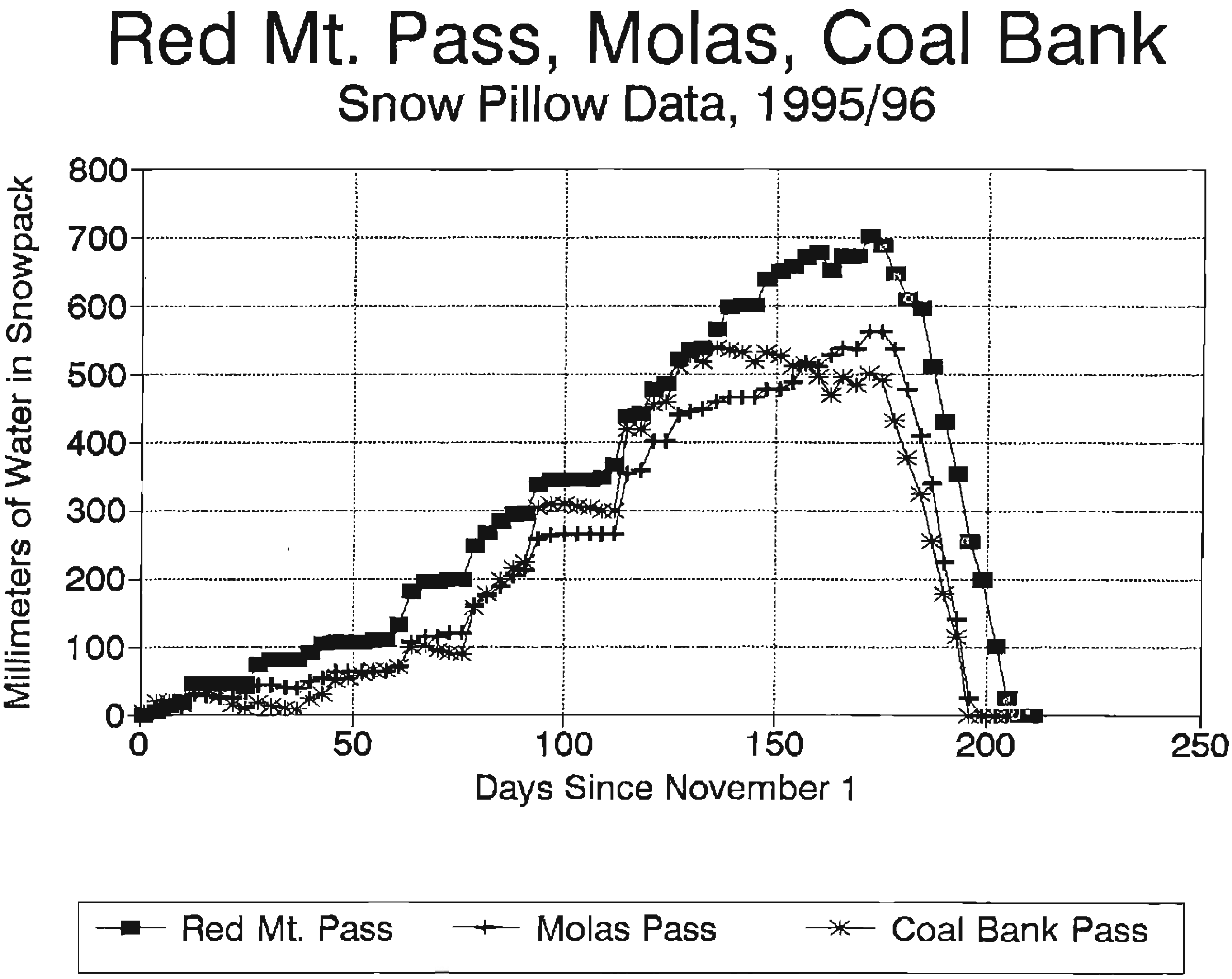

Figure 3–4. Water equivalent on the ground during the 1995/96 snow season. Data was obtained from the National Resources Conservation Service (NRCS) Snotel site as measured by a standard snow pillow. Steep portions of the curves are times when the rate of precipitation was large. Day 1 is November 1, Day 212 is May 31. This was the only year in which snowfall was heaviest on Red Mountain Pass, as most storms approached from the west or northwest. The only period of extensive avalanching occurred on January 30 – February 2 (days 90 – 93).

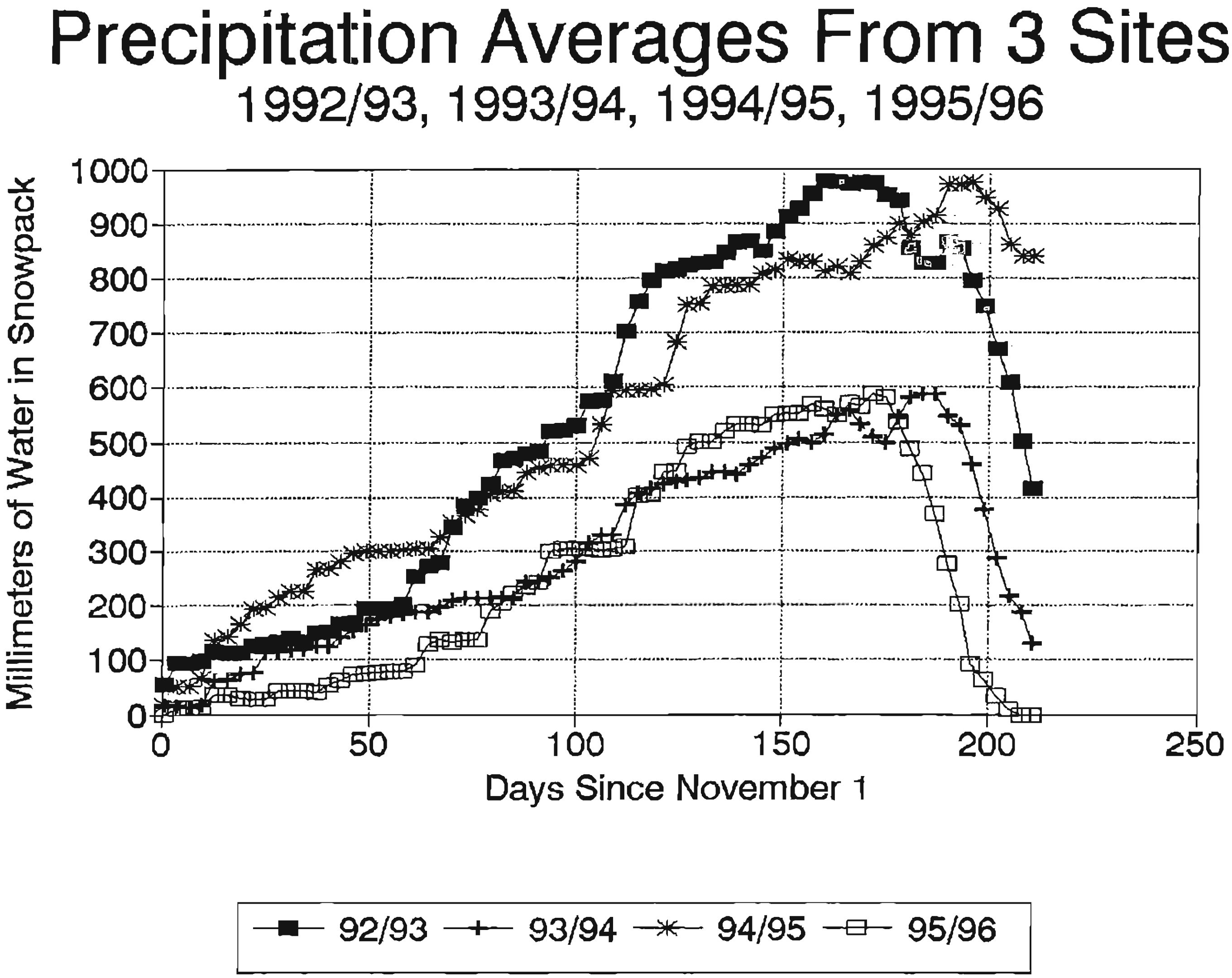

Figure 3–5. Comparison of the four snow seasons, as measured by the NRCS snow pillow data. Two seasons (1992/93 and 1994/95) had relatively deep, strong snowpacks; two seasons had relatively thin, weak snowpacks.

3.2 STORMS

Tables 3–1, 3–2, and 3–3 provide details about each of the 13 storms studied during the four years of this project at each site. Table 3–4 averages the precipitation and temperatures over the four sites. Column labels are as follows:

Storm:	Designation of storm during that season
Day 0:	Beginning of precipitation
End Day:	Day storm ended
Length:	Duration of storm (nearest day)
Precip:	Total storm precipitation in mm
Mean T:	Average of all high and low temperatures on all days

Table 3–1. Storms Producing Avalanches on Red Mountain Pass During 1992/93, 1993/94, 1994/95, and 1995/96

Storm	Day 0	End Day	Length	Precip. (mm)	Mean T.(°C)
93–1	12/28	12/30	2 days	36	–6.2
93–2	1/6	1/9	3 days	38	–5.8
93–3	1/10	1/12	2 days	25	–9.2
93–4	1/18	1/20	2 days	33	–6.2
93–5	2/17	2/22	5 days	104	–8.3
94–1	2/7	2/9	2 days	23	–8.5
94–2	2/17	2/19	2 days	25	–5.5
95–1	2/11	2/15	4 days	76	–6.9
95–2	3/1	3/6	5 days	91	–3.4
96–1	12/30	1/1	2 days	53	–8.8
96–2	1/15	1/18	2 days	51	–5.5
96–3	1/30	2/2	3 days	43	–6.0
96–4	2/19	2/22	3 days	76	–3.4

Table 3–2. Storms Producing Avalanches on Molas Pass
During 1992/93, 1993/94, 1994,95, and 1995/96

Storm	Day 0	End Day	Length	Precip. (mm)	Mean T.(°C)
93–1	12/28	12/30	2 Days	41	–5.8
93–2	1/6	1/9	3 Days	53	–6.8
93–3	1/10	1/12	2 Days	25	–9.3
93–4	1/18	1/20	2 Days	25	–4.7
93–5	2/17	2/22	5 Days	145	–5.2
94–1	2/7	2/9	2 Days	43	–7.7
94–2	2/17	2/19	2 Days	43	–3.5
95–1	2/11	2/15	4 Days	145	–5.9
95–2	3/1	3/6	5 Days	117	–2.3
96–1	12/30	1/1	2 Days	36	–7.3
96–2	1/16	1/18	2 Days	41	–5.0
96–3	1/30	2/2	3 Days	48	–6.0
96–4	2/19	2/22	3 Days	71	–2.3

Table 3–3. Storms Producing Avalanches on Coal Bank Pass
During 1992/93, 1993/94, 1994,95, and 1995/96

Storm	Day 0	End Day	Length	Precip. (mm)	Mean T.(°C)
93–1	12/28	12/30	2 Days	71	–5.7
93–2	1/6	1/9	3 Days	104	–8.1
93–3	1/10	1/12	2 Days	56	–10.0
93–4	1/18	1/20	2 Days	64	–6.0
93–5	2/17	2/22	5 Days	180	–7.2
94–1	2/7	2/9	2 Days	66	–7.2
94–2	2/17	2/19	2 Days	71	–4.7
95–1	2/11	2/15	4 Days	145	–6.8

Storm	Day 0	End Day	Length	Precip. (mm)	Mean T.(°C)
95–2	3/1	3/6	5 Days	188	–3.9
96–1	12/30	1/1	2 Days	28	–6.3
96–2	1/16	1/18	2 Days	69	–4.0
96–3	1/30	2/2	3 Days	79	–6.8
96–4	2/19	2/22	3 Days	109	–2.9

Table 3–4. Average of storms from 3 Sites
During 1992/93, 1993/94, 1994,95, and 1995/96

Storm	Day 0	End Day	Length	Precip. (mm)	Mean T. (°C)
93–1	12/28	12/30	2 Days	49	–5.9
93–2	1/6	1/9	3 Days	65	–6.9
93–3	1/10	1/12	2 Days	35	–8.7
93–4	1/18	1/20	2 Days	41	–5.6
93–5	2/17	2/22	5 Days	143	–6.9
94–1	2/7	2/9	2 Days	44	–7.8
94–2	2/17	2/19	2 Days	46	–4.6
95–1	2/11	2/15	4 Days	122	–6.5
95–2	3/1	3/6	5 Days	132	–3.2
96–1	12/30	1/1	2 Days	39	–7.5
96–2	1/16	1/18	2 Days	54	–4.8
96–3	1/30	2/2	3 Days	57	–6.3
96–4	2/19	2/22	3 Days	85	–2.9

As discussed in Section 2, wind is an important factor in avalanche formation. Wind data have not been included in the above tables because 1) it has was not available during the 1992/93 season (which produced the most avalanche activity), and 2) wind data are taken from mountain ridge and summit sites north of Red Mountain Pass, thus may not apply directly to data taken from the Coal Bank Pass and Molas Pass Snotel sites. The use of wind data in avalanche forecasting is discussed in subsequent sections of this report.

4 DEFINITION OF PARAMETERS USED IN THIS STUDY

Because an objective of this project is to find correlations between weather, snowpack, and avalanche-activity on Highway 550, several additional parameters were defined. These are described below and are tabulated in Section 5.

4.1 AVALANCHE PARAMETERS

Although Highway 550 is well known for frequent and severe avalanche problems, objective methods have not been derived to evaluate the severity of any particular avalanche period. A first step in this study, therefore, was to develop objective and repeatable methods through which the severity of avalanche activity during any period could be quantified. One period could, therefore, be compared with others and related to factors the cause avalanches. The parameters derived are discussed below.

4.1.1 Avalanche Activity Index (AAI)

The AAI defines a numerical ratio of current avalanche activity during a particular storm or period of avalanching to the maximum activity possible:

$$AAI = (\Sigma\ [\text{Observed classes}])/(\Sigma\ [\text{Potential classes}]) \quad (1)$$

Following the U.S. Forest Service standard classification of relative avalanche size, each avalanche is classified "2" through "5" with larger numbers representing larger avalanches *in each path.* A class 2 avalanche is a relatively small event (usually less than 5% of the total avalanche path area) while a class 5 avalanche is a very large event involving most of the snow in the path. Class 1 avalanches are small, loose sluffs and are ignored. Because the classification is relative to the potential in the particular path, a class 3 avalanche in a large path can be larger than a class 4 or 5 avalanche in a much smaller path. We have considered a 133 avalanche-path data set along Highway 550. Several of these paths cannot reach the highway but are easily observed and are used by observers and forecasters to assess avalanche hazard (see Section 2.2.4[f]). During some avalanche periods certain paths will avalanche more than once. Each additional avalanche event in a path is therefore counted as a separate path in calculating the AAI (the storm data set is therefore increased to more than 133 paths). An AAI-value of 1.000 would mean that all avalanche paths in the data set produced a class 5 avalanche. However, avalanche paths affecting Highway 550 have widely varying exposures to sun and wind, therefore a single storm will usually not induce avalanche conditions in most paths. The range in AAI-values for the nine avalanche periods on Highway 550 was 0.056 to 0.283. In contrast AAI-values > 0.400 were common during the same period on the road to the Yule Creek marble quarry where most of the avalanches have similar orientations. Because the size classification is non-linear (e.g., a class 4 may involve 10-30 times the mass of a class 2 in a given path), the AAI is also a non-linear measure of avalanche activity.

4.1.2 Length of highway centerline covered

This parameter is simply a measure of the total length of highway centerline covered by avalanche debris (in feet) during a particular episode of avalanching. This numerical value is based on data reported by the Colorado Avalanche Information Center or the Colorado Department of Transportation. The length parameter is only a crude measure of the avalanche hazard that existed during the storm because avalanche depth or volume is not considered. It does relate to the amount of effort and cost expended in reopening the highway.

4.1.3 Volume of avalanche debris removed

Debris volume on the highway was calculated in yd^3 assuming a 45 foot roadway width (including shoulders which are normally cleared), and a parabolic debris depth distribution along the centerline. Avalanche debris is usually reported as a maximum depth and length (in feet) of centerline covered. Assuming a rectangular debris cross section tends to exaggerate the actual debris volume, hence the parabolic adjustment factor is applied. Debris volume is therefore calculated

$$\text{Volume} = [(\text{Length})*(\text{Depth})*45*2/3]/27, \qquad (2)$$

where 27 is the number of cubic feet in one cubic yard. The volume parameter defined in this section may be more accurate than length (Section 4.1.2) in estimating the time, effort, and money involved in clearing the highway.

4.2 WEATHER PARAMETERS

4.2.1 Snowfall

Snowfall is measured at Red Mountain Pass, Molas Pass, and Coal Bank Pass sites by the Colorado Avalanche Information Center. Generally data are collected each day during storm periods unless the highway is closed by avalanches or avalanche hazard. When the measuring site cannot be reached for more than one day and snowfall continues, the new snow will compress under its own weight and the measured snowfall amount will not be as large as it would be if it were measured each day. The amount and rate of snowfall is an important indicator of avalanche potential (Section 2). It provides a measure of the increase of new snowslab thickness above some weak layer in the snowcover. Because of the above difficulties in obtaining accurate snowfall data, they have not been used in this study. Recommendations about obtaining more accurate snowfall data are made in the final section of this report.

4.2.2 Water Equivalent

Water equivalent is measured at Red Mountain Pass, Molas Pass, and Coal Bank Pass sites by the Colorado Avalanche Information Center. Generally data are collected each day during storm periods unless the highway is closed by avalanches or avalanche hazard and the measuring site cannot be reached. Unlike the snowfall data (Section 4.2.1), a delay in measuring water equivalent will not produce an inaccurate number unless snow melts or is somehow removed from the site. Additional data on water equivalent are obtained by NRCS Snotel remote telemetry sites near each of the three passes. These Snotel data are obtained continuously and are available each day. Because they are thought to be reliable and consistent, they were used in tabulation of snow season and storm parameters in Section 3 and have been analyzed in more detail in Section 5.

4.2.3 Wind

Wind velocity and direction are measured at anemometer sites located at the summit of Red Mountain #3 (12,800 feet elevation) and on the south ridge of Mt. Abrams (East Riverside at 11,900 feet elevation). Although wind velocity and direction are important parameters in avalanche forecasting, the wind data collection systems were not installed during the 1992/93 winter. This was the first season of the CDOT avalanche–hazard reduction program and also produced the largest storms and most extensive avalanching during this study. Only the East Riverside was operational continuously during the 1993/94 season. Both sites were operational during the 1994/95 and 1995/96 seasons although data were not obtained during storm 96–2.

The importance of wind during a storm has been quantified in terms of "miles of wind > 20mph (8m/s) *during a precipitation episode*. Wind during non–precipitation periods did not produce significant avalanche activity on the highway. For example, an hourly wind velocity of 32 mph followed by an hour with an average velocity of 29 mph is (32 – 20)*1+(29 – 20)*1 = 21 "miles of wind." The required threshold of 20 mph is based on observer's observations that a velocity of roughly 15 mph (at the snow surface) will transport snow. The anemometer sensors are located above the snow surface, where velocity will be larger than at the surface, hence the 20 mph threshold was adopted.

4.3 SNOWPACK PARAMETERS

4.3.1 Relative Shear Strength

Relative shear strength is measured by the "Rutschblock" (shearblock) test from sites that represent avalanche starting zones on east, west, and north exposures. Southern exposures often have well–developed surface and internal melt–freeze crusts in this snow climate and do not produce reliable Rutschblock scores. The typically thin, early season snowpack in the San Juans will typically contain significant amounts of faceted snow grains (depth hoar) that are weak in shear and contribute to avalanche realease. Surface hoar (frost deposited on the snow surface during clear weather) also occurs and is known to be a factor in avalanche release.

In accordance with Swiss and Canadian standard procedures (Fohn, 1987; Jameison and Johnson, 1992) Rutschblock scores are rated 1 (very weak in shear) to 7 (very strong in shear). This test is performed by excavating a snowblock 1.5m (5 feet) by 2.0m (6.5 feet) to the ground on slopes of 30° or more and subjecting the block to increasingly larger stresses (by standing or jumping on the surface of the block with skis on) until failure occurs on some shear plane parallel to the snow surface. Certain specific procedures with respect to weighting, jumping and stressing the block and attempting to induce shear are used. Rutschblock scores of "1" and "2" are conditionally unstable (Rutschblock class "A" in Table 5–1); avalanches are likely with little additional load. Scores of "3," "4," and "5" are conditionally stable (Rutschblock class "B" in Table 5–1); substantial loading will be required for avalanching. Scores of "6" and "7" are stable (Rutschblock class "C"); avalanches are not likely within snow as represented by the excavated block. The Rutschblock tests are performed between storms to attempt to predict in advance the likelihood of snowpack failure *below the base of the new snow* as the result of new snow loading. Prolonged, high intensity storms (e.g. storms 93–5, 95–1, and 95–2) may produce extensive avalanching within the new snow regardless of Rutschblock scores.

The tests were conducted on various exposures near Red Mountain Pass and Molas Pass. Care was taken to select slopes that represented starting zones of different exposures, all slopes selected had gradients in excess of 30°, and Rutschblock boundaries were fully excavated or cut as recommended in the Swiss and Canadian procedures.

Several difficulties are associated with using the Rutschblock test in an operational avalanche forecast program. First, the tests must be made in areas representative of avalanche starting zones where releases might reach the highway. Proper representation requires accessing starting zones (usually by skis) in several locations, a time–consuming process. Second, access may be dangerous because of residual avalanche hazard. Third, the Rutschblock test requires roughly 30 minutes to complete. Fourth, the results may not be repeatable from one observer to the next. Finally, the Rutschblock may not be reliable in the thin, weak snowcover that often characterizes the San Juan snowpack in early winter. The skier should not penetrate sufficiently deep in the snowpack to disturb the potential shear layers. In spite of these problems, we have found this test to be the most reliable indicator of snow shear strength.

5 ANALYSIS OF AVALANCHE, WEATHER, SNOWPACK DATA

5.1 DATA

Data obtained during the four winters are summarized in Tables 5-1 and 5-2. Wind data have only been obtained, as discussed, during the past three winters. Snowpack strength data were not obtained during the storm of February 17-22, 1993 or February 11-15, and March 1-6, 1995 because extensive avalanche debris on Highway 550 did not allow collection of data for several consecutive days.

Table 5-1. Avalanche, Precipitation, Wind, and Snowpack Data
1992/93, 1993/94, and 1994/95 Avalanche Seasons, Highway 550

Storm Dates	AAI	Length (ft)	Volume (yd^3)	Precip.* (mm/days)	Wind (Miles)	RB-Class
Dec 28-30, 1992	0.159	3,710	30,900	49mm/2	------	B
Jan 6-9, 1993	0.102	2,390	26,300	65mm/3	------	B
Jan 10-12, 1993	0.174	2,150	26,800	35mm/2	------	B
Jan 18-20, 1993	0.175	2,675	50,400	41mm/2	------	B
Feb 17-22, 1993	0.283	22,552	241,277	143mm/5	------	----
Feb 7-9, 1994	0.189	6,300	48,917	44mm/2	340/58	A
Feb 17-19, 1994	0.056	1,330	9,900	46mm/2	844/54	A
Feb 11-15, 1995	0.184	3,640	46,225	122mm/4	891/115	B
Mar 1-6, 1995	0.158	2,010	13,967	132mm/5	243/120	B
Jan 16-18, 1996	0.069	325	802	54mm/2	No Data	A
1/30-2/2, 1996	0.168	2,420	28,078	57mm/3	271/72	A

AAI: Avalanche Activity Index (defined in Section 3)
Length: Length of centerline covered (discussed in Section 3)
Volume: Volume of debris on highway (discussed in Section 3)
Precip.: Snotel data (discussed below); average value at the 3 passes
Wind: "Miles of wind" in excess of 20 mph during storm period (hours)
RB-Class: A = Score of 1 or 2; B = score of 3, 4, or 5; C = score of 6 or 7

Precipitation data were obtained from three automated National Resources Service "Snotel" stations at Coal Bank, Molas, and Red Mountain Passes. These data are downloaded every 24 hours, thus resolution is one day. Column 5 of Table 5-1 averages the total precipitation over the segment of Highway 550 affected by avalanches (similar to data of Table 3–4) and indicates the number of days over which the precipitation occurred. Calculation of precipitation per day results in the precipitation intensity rating (column 6 of Table 5–2).

Wind data are obtained from East Riverside or Red Mountain #3 anemometer sites. Average wind velocities were summed for all hours during each storm period in which the average hourly velocities exceeded 20 mph.

Because only 11 avalanche periods were available for study during the four winters (two of the 13 storms listed on Tables 3–1 through 3–4 did not produce avalanches), and only five of these 11 storms had any wind data associated with them, a non-parametric test of correlation significance was used, the Spearman's Rank coefficient, R_S. Table 5–2 ranks the parameters listed in Table 1, with 1 being the largest and 11 being the smallest. The five storms that included wind data are given an overall rank and a rank during the last five storms.

Table 5–2. Ranks of the Avalanche Activity and Storm Parameters

Storm Dates	AAI	L	Vol	Prec.	Prec. Inten.	Tot Wind	Wind Inten.	RB	T.
Dec 28–30, 1992	7	3	5	7	5	----	----	B	7
Jan 6 – 9, 1993	9	7	8	4	8	----	----	B	3.5
Jan 10–12, 1993	5	8	7	11	11	----	----	B	1
Jan 18–20, 1993	4	5	2	10	9	----	----	B	8
Feb 17 – 22, 1993	1	1	1	1	2	----	----	--	3.5
Feb 7 – 9, 1994	2(1)	2(1)	3(1)	9(5)	7(4)	(3)	(3)	A	2
Feb 17 – 19, 1994	11(5)	10(5)	10(5)	8(4)	6(3)	(2)	(1)	A	10
Feb 11–15, 1995	3(2)	4(2)	4(2)	3(2)	1(1)	(1)	(2)	B	5
Mar 1 – 6, 1995	8(4)	9(4)	9(4)	2(1)	4(2)	(5)	(5)	B	11
Jan 16–18, 1996	10	11	11	6	3	----	----	A	9
Jan 30–Feb 2, 96	6(3)	6(3)	6(3)	5(3)	10(5)	(4)	(4)	A	6

5.2 RANK CORRELATIONS

Table 5–3 is a matrix of the dependent and independent variables (with the exception of the Rutschblock shear strength test) used in this study. The dependent variables avalanche–activity index "AAI," length of highway covered L, and volume covered

"Vol." are all measures of avalanche severity on Highway 550. The only independent variables available for analysis are total precipitation "Prec." and precipitation intensity "P.I." Mean temperature data are also available, Tables 3-1 through 3-4, but all storms were below freezing and ranges over only 5.8°C (-2.9° maximum to -8.7° minimum).

Table 5-3. Spearman's Rank Coefficients R_s
Between Avalanche Activity Variables

	A.A.I.	L	Vol.	Prec.	P.I.	Temp.
A.A.I.	1.000	**0.845**	**0.918**	0.055	0.082	**0.621**
L	**0.845**	1.000	**0.927**	0.145	0.155	0.539
Vol.	**0.918**	**0.927**	1.000	0.018	0.036	0.489
Prec.	0.055	0.145	0.018	1.000	**0.673**	-0.175
P.I.	0.082	0.155	0.036	**0.673**	1.000	-0.297
Temp.	**0.621**	0.539	0.489	-0.175	-0.297	1.000

Correlation coefficients that proved significant at the 5% level are those exceeding a critical $R_s = 0.618$. These correlations are shown in bold. The table is redundant because values above and below the diagonal represent identical correlations (e.g. L correlates with Vol. as well as vol. correlates with L).

6 DISCUSSION

6.1 POSITIVE CORRELATIONS

Both length of centerline covered (L) and volume of avalanche debris (Vol.) correlate well with the avalanche-activity index. Therefore all three measure the severity of a period of avalanching on Highway 550. However, the length and volume parameters both vary by roughly two orders of magnitude ($2.512 < \log L < 4.353$; $2.904 < \log Vol. < 5.383$) and therefore are better measures of the maintenance problem and the hazard on the highway. Volume covered is probably a better measure of the severity of an avalanche period because it more directly measures the amount of work (hence time and money) required to reopen the highway. Length is probably a better measure of hazard because it more directly relates to the probability of a vehicle being hit be an avalanche.

Length of centerline covered, (L) and volume of debris, (Vol.) also correlate strongly with one another. This is true simply because the larger avalanches are deeper and involve more mass.

Mean storm temperature, T, is the only independent variable that correlates with any of the dependent variables. The correlation coefficient $R_s = 0.621$ (5% level significance) between T and A.A.I, $R_s = 0.539$ between T and L, and $R_s = 0.489$ between T and Vol. The ranking of temperature assigned a rank of "1" to the coldest mean storm temperature (–8.7°C) and a rank of "11" to the warmest mean temperature (–3.2°C). This means that the colder mean storm temperatures correlated positively with the overall extent of avalanche activity on Highway 550. Interestingly, the warmest of all the storms (storm 96–4) which produced the fourth largest precipitation (85mm) and third largest precipitation rate over the storm (28mm/day), produced no avalanches that reached the highway. The positive correlations between cold storms and more extensive activity may mean that new snow was not able to bond as readily to the old snow during colder temperatures.

6.2 LACK OF CORRELATION

The parameters in Table 5–3 that are not significant should also be discussed. Total storm precipitation (Prec.) does not correlate with A.A.I., L, or Vol. With one exception (storm 93–5 in February, 1993), storms with the larger amounts of new snow did not produce the most widespread avalanche activity.

6.3 PARAMETERS NOT ANALYZED

The lack of correlation between most of the independent and dependent variables suggests other factors controlled the amount of avalanche activity at the highway. Three other factors are probably important but have not been included in the Spearman's rank correlation analysis of Section 4:

a. *Avalanche-control activity* (use of explosives delivered by helicopter or guns) strongly affects the snowpack depth and may also affect the surface condition of the new snow. When a moderate-sized storm follows control activity after a few days or less the amount and size of avalanche activity is usually reduced as a result of the control. Major storms (e.g. storms 93-5 and 95-1) are probably not strongly affected by previous avalanche control activity. These storms produce such deep and widespread new snow accumulations that the new snow slab may behave independently of the old snow surface. Explosive control of avalanches on Highway 550, when combined with a comprehensive forecasting program is, of course, vital to the safe operation of the highway.

b. *Wind speed and direction* strongly control the location of unstable avalanche starting zones, as discussed in Section 2 of this report. However, wind alone is rarely an important factor in producing widespread avalanche activity (large values of A.A.I., L, and Vol.), unless it is accompanied by new snowfall. Furthermore, substantial new snow rarely occurs without wind. Unfortunately, because data on only five wind storms were available, an insufficient data base exists upon which to base any conclusions.

c. Finally *snow shear strength* must be an important controlling factor in the amount and distribution of avalanche activity. Qualitatively, at least, this appears to have been the case in the four winters of this study. Rutschblock scores of "B," (moderate strength of 3, 4, or 5) prevailed during storms 93-1 through 93-4; these storms produced substantial avalanche activity. Storm 93-5 was so large and produced so much avalanche activity that the highway was blocked and Rutschblock tests were not possible. A weak snowpack Rutschblock category "A" (weak strengths of 1 or 2) prevailed in February, 1994 and a moderate sized storm (94-1) produced extensive avalanche activity (6,300 feet of highway covered). Neither of the large storms of the next season (storms 95-1 and 95-2), which fell on a snowpack with a strength category "B," produced as much activity on the highway as the smaller storm of the previous season. A weak or extremely thin snowpack prevailed through early February of 1995/96 and the first storm that fell after the snowpack was continuous (96-2) produced fairly extensive activity even though it was only a moderate-sized storm. The first storm of that year (96-1) did not produce avalanches because it fell on a discontinuous snowpack with much exposed bare ground. The last storm, (96-4) even though it was the fourth largest of the study period, fell on a strong snowpack (category "C") and produced no avalanches.

Although shear strength appears, qualitatively, to be an important variable, and the Rutschblock is one effective method for evaluating shear strength, this study has not found a method for integrating it into a forecast scheme.

7 RECOMMENDATIONS

The following recommendations result from the findings of this study.

7.1 QUANTITATIVE AVALANCHE ACTIVITY DATA

Quantification of the severity of all avalanche periods should be continued after the storm has ended. Quantification procedures derived for this study should be continued. Total length of highway (L) covered is readily available after each storm or can easily be measured after the storm and avalanche period is over. Volume of debris on the highway (Vol.) can be calculated as shown in this study. Both length and volume relate directly to the severity of avalanche hazard or potential hazard and the effort involved in reopening the highway. Both parameters may relate to independent variables used to forecast avalanches. The avalanche–activity index (A.A.I.) can also easily be computed after each storm period and may be useful for future comparisons between episodes of avalanching on Highway 550.

7.2 SHEAR STRENGTH TESTS

Forecasters should continue to test the snowpack strength through use of various shear strength tests. These tests should be conducted on north, east, and west exposures at elevations representative of avalanche starting zones. Crude, qualitative correlations between the values of shear strength obtained in the field, and the extent of avalanche activity, measured as discussed above, justify the continued use of shear strength tests.

Use of the Rutschblock test, because it is becoming an international standard, is useful in testing shear strength near Highway 550 when the snowpack has become deeper than 30 to 40 inches (0.75 to 1.00m). Because of difficulties in achieving repeatable measures of shear strength, it may not be useful to define more than three–to–five strength categories. Only three categories of Rutschblock strength (based on seven strength intervals) were used in this study. An extension to five categories may be justified. The Rutschblock test should not, however, be modified, as in sometimes done, in conducting the test. The dimensions of the block should remain at $3m^2$ surface area (1.5m downslope; 2.0m across the slope), and all lateral boundaries must be cut. Tests must be conducted on slopes of 30° or more.

Additional methods of measuring or estimating shear strength should be experimented with to determine if good correlations with the extent of avalanche activity are obtained. The results of any additional methods should be compared with results obtained with the Rutschblock.

Finally, these strength tests should be conducted in as many locations as possible. Some of the areas should be revisited for additional tests as often as possible throughout the avalanche season. This will provide both areal and temporal distributions of shear strength changes throughout the snow season.

7.3 WEATHER DATA

This study was seriously limited by the lack of good weather records. It is strongly recommended that additional weather stations be established as follows.

7.3.1 RED MOUNTAIN PASS. **An automated weather station should be established at the INSTAAR snow study plot, at an elevation of approximately 11,100 (3,300m) immediately south of the Pass.** This site should collect the following data which should be available to the CDOT/CAIC avalanche forecasters continuously during the November – May period.

a. *Water equivalent* should be measured by a precipitation gauge. A gauge that has proven reliable to Yule Creek Avalanche Services (Chris Landry) for the past four seasons is a Noah II, alcohol-based gauge manufactured by ETI, Fort Collins, Colorado. Data from this gauge should be available hourly (or at any specified interval).

b. *Snow depth* should be measured by a sonar system located adjacent to the precipitation gauge. A sonar system that has proven reliable in numerous applications is manufactured by Judd Communications in Salt Lake City. Snow depth data should also be available hourly to the forecasters.

c. *Air temperature* must also be measured and available hourly.

The approximate density of the new snow can be estimated by computing the ratio of water equivalent to new snow depth, obtained as suggested above. To obtain the density in kg/m^3 the following formula should be used: Density = (W/D)*1000, where W is the water equivalent (in mm) and D is the new snow depth (also in mm). This calculation will overestimate the density (perhaps by 5% to 10%) during major storms because the weight of new snow will compress the old snow. This compression will cause an underestimation of the new snow depth and an overestimation of the density. The error is estimating density will probably be small (probably 2% to 5%) when the water equivalent of the new snow is less than 20mm.

Use of this recommended system will be a significant improvement over the current method in which precipitation is obtained by NRCS Snotel data (downloaded each morning to a central station in Portland, OR), and available to the forecasters at a resolution of 0.1 inch (2.54mm) on a daily basis. Snow depth data (obtained by sonar, as suggested) would be far more reliable than the current measurements. At present, the forecaster must drive to Red Mountain Pass to measure the snow. During major storms the snow depth data may not be available when it is most needed for forecasts because travel to the pass may be hazardous or impossible and skiing to the study plot would be too time consuming and also hazardous.

If the data are collected as suggested, far more accurate correlations between the most important weather variables and avalanche activity would be possible. The data must, however, be stored for analysis after the storm and avalanche period is over.

7.3.2 COAL BANK PASS. **An automated weather station should be also be established near the summit of Coal Bank Pass at approximately 10,600 feet elevation.** This site should collect exactly the data recommended for Red Mountain Pass (Section 6.3.1) and must also be available continuously during the November – May period to the CDOT/CAIC avalanche forecasters.

7.3.3 MOTHER CLINE. **Temperature and precipitation data should be recorded at the summit of Mother Cline. In addition, thick steel snow stakes should be drilled and grouted into the rock slab starting zones to estimate snow depth.** All of this data must be available through remote telemetry to the forecasters in Silverton. Temperature data will be essential in estimating the onset of wet slab releases in the Mother Cline; snow depth measurements on the rock slabs will enable estimates of the potential size of avalanches. The snow depth estimates are important in determining if the larger "plunging" avalanches are likely.

7.3.4 SUMMIT OF EAGLE/TELESCOPE. Although wind data are already available at the summit of Red Mountain #3, and on the south ridge of the East Riverside avalanche path, **additional wind data should be obtained at the summit ridge of Eagle/Telescope avalanche paths.** This group of paths are some of the most hazardous on the highway and are highly susceptible to wind loading from either west winds or north winds. Wind velocity and direction should be measured and transmitted to the forecasters in Silverton on an hourly basis (or as needed). The Campbell station on the summit or Red Mountain #3 should be duplicated at the summit of Eagle/Telescope.

The above recommendations about the type and location of data collection result from discussions with the two Silverton–based forecasters (D. Bachman and D. Hogan) during late winter 1994 and on my personal opinions about the need for additional data. Since that time experience has been gained during the 1994/95 and 1995/96 winters. I recommend that the current forecasters also be asked their opinions about the need and locations of additional weather sensors.

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