AVALANCHE DYNAMICS MODEL RAMMS APPLIED IN TWO NORTH AMERICAN CLIMATES

Chris Wilbur[1] Art Mears[2] Stefan Margreth[3] Sue Burak[4]

[1]Wilbur Engineering, Inc., Durango, Colorado, USA
[2]Arthur I. Mears, PE, Inc., Gunnison, Colorado, USA
[3]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[4]Snow Survey Associates, Mammoth Lakes, California, USA

ABSTRACT: Recent advances in computational methods and availability of digital terrain models allow for improvements in avalanche dynamics models. Such models have been used and calibrated primarily in Europe, but are likely to see increased applications worldwide. This paper describes applications of the Swiss model RAMMS for long-return period avalanches in two distinct North American climates.

A mid-latitude continental snow climate avalanche in the Elk Mountains near Aspen, Colorado occurred in March 1965. This large avalanche left distinct trim lines in the forest along the track and runout boundaries. The track has complex geometry that includes two sharp turns where the flow climbs due to momentum.

A large avalanche occurred in February, 1986 in an unpopulated area of the Eastern Sierra Nevada range near Bridgeport, California. This mid-latitude maritime climate example was unique due to its long runout zone (1,030m) on a 4.6° slope through a mature forest and large-volume release. RAMMS simulations produced a runout approximately 300m short of that observed.

In each case, release volumes and friction parameters are described along with adjustments made to account for local climate and to improve model calibration.

KEYWORDS: avalanche dynamics model, RAMMS, long return period avalanche

1. INTRODUCTION

Avalanche dynamics models have become increasingly useful in recent years due to improvements in computational methods, better calibrations and increased availability of three-dimensional terrain models. Simple fluid frictional models based on the Voellmy equations (Voellmy, 1955) allow the use of a reasonable number of input parameters to be practical for mapping and engineering design purposes. Development and calibration of numerical models has occurred primarily in Europe. As a result, limited model calibrations are available for climates and mountain ranges outside of Europe (e.g. Margreth and Mattice, 2012). This paper describes two cases from different North American climates and mountain ranges.

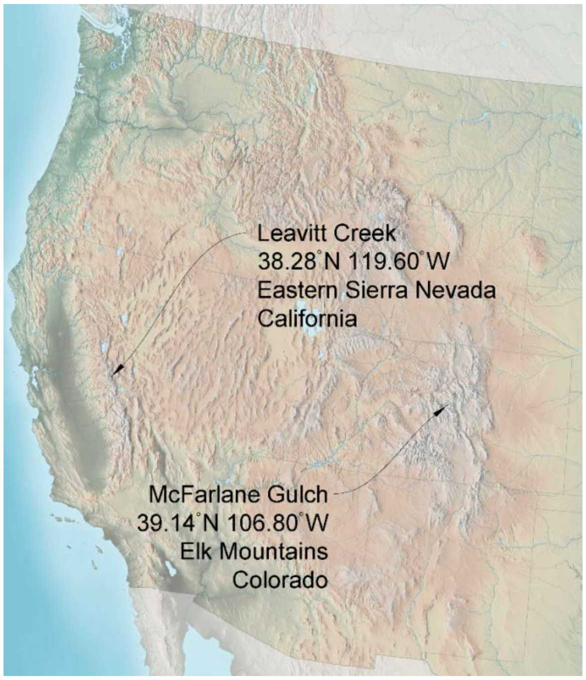

Fig. 1: Site Locations

---

* *Corresponding author address:*
Art Mears
Arthur I. Mears, P.E., Inc.
555 County Road 16
Gunnison, CO 81230
email: art@mearsandwilbur.com

Numerous programs have been developed for calculating avalanche dynamics parameters. Early programs calculated avalanche parameters for two-dimensional profiles without addressing lateral variations in terrain. More recently, models have been developed that allow three-dimensional terrain to be used. (Jamieson, et.al. 2008)

This study used RAMMS (Christen et al., 2010), developed by the WSL-SLF of Davos. The two-parameter Voellmy-based fluid friction model uses depth averaged flow and conservation of mass and momentum. Frictional parameters include Coulomb friction (μ) and a drag coefficient (ξ). They are typically in the range μ=0.15–0.40 and ξ=1000–2500 m/s. They have been calibrated using elevation, avalanche size, terrain shape and return period. Entrainment is not modeled in the applied RAMMS version 1.6.20.

2. CASE 1 – ELK MOUNTAINS, COLORADO

2.1 Snow Climate

The McFarlane Gulch avalanche site is located 5km SSE of Aspen, Colorado in the Elk Mountains. Weather data have been collected intermittently at several locations in the Aspen valley (elev. 2410 meters) since 1899. The average annual snowfall is 350 cm at Aspen. Average annual snowfall increases to 760 cm at Aspen Mountain Ski Resort (elev. 3400 meters).

The starting zone (elev. 3300m) is in a continental snow climate characterized by light-to-moderate snow (300-400mm mean annual SWE and 500-700cm average snowfall.), cold temperatures and moderate winds. Heavy and persistent winter storms occur some years, particularly during the January-March period. These storms with durations of 5-10 days have produced 150-300mm SWE that overstress an existing structurally-weak snowpack and produce large avalanches. Such a storm occurred in the March 23-28, 1965 period.

2.2 March 1965 Snow and Weather

In March 1965, more than 96 cm of new snow fell in 2 days in Aspen and the week total for new snow was over 165 cm. March 24, 1965 remains the 24-hour snowfall record in Aspen at 63.5 cm. The storm caused one roof to collapse in downtown and closed the only highway leading into Aspen. The height of snow at the top of Aspen Mountain was greater than 250 cm at the end of the storm.

The 1965 McFarlane Gulch avalanche occurred about the same time as a long return period avalanche on the south side of the Elk Mountains at Gothic, Colorado. These two events indicate a SW storm flow, based on aspect and wind fetch areas for their starting zones.

Table 1: Aspen Daily Weather Data for 1965 Avalanche (elev. 2410m)

Date	*Tmax (C)*	*Tmin (C)*	*HN (mm)*	*SWE (mm)*	*HS (cm)*
23-Mar	2.2	-2.8	330	23	99
24-Mar	-1.7	-5.0	635	44	140
25-Mar	-3.3	-11.1	127	10	142
26-Mar	0.0	-10.6	38	4	132
27-Mar	6.7	-3.3	89	6	122
28-Mar	2.8	-1.1	305	25	132

2.3 McFarlane Gulch Path Description

Figure 2 shows the McFarlane Gulch avalanche path. The northeast-facing 7-hectare starting-zone consists of two bowls located between elevations of 3,350m and 3200m. The track is channelized with a typical width of 50 m and an average slope of about 19 degrees. The α angle, defined as the slope angle from the top of the starting zone to the farthest runout limit, for the 1965 avalanche was 18.5° The β angle, defined as the angle from the top of the starting zone to the point at which the slope is 10°, is 20.0°. The ten oldest broken trees sampled in the 1965 debris had a mean age of 129 years. Trees older than 80 years were common in the avalanche debris. Snow accumulations were enhanced by southwesterly wind transport into the McFarlane Gulch starting zones. Release details and slab dimensions are not known; however boundaries of the avalanche track and runout zone of this 1965 avalanche are clearly defined on aerial photographs.

The 1965 avalanche destroyed mature timber and left a distinct trimline to the valley bottom. The channelized avalanche track includes two mid-track bends. The first bend is north-facing and supports a forest with three distinct trimlines that can be used to calibrate the model at this location. The outmost trimline corresponds to the 1965 avalanche. Based on tree ages, we estimate that the return period of the 1965 avalanche was 100 years or greater. The two inner trimlines record post-1965 avalanches with estimated return periods on the order of 10 and 30 years.

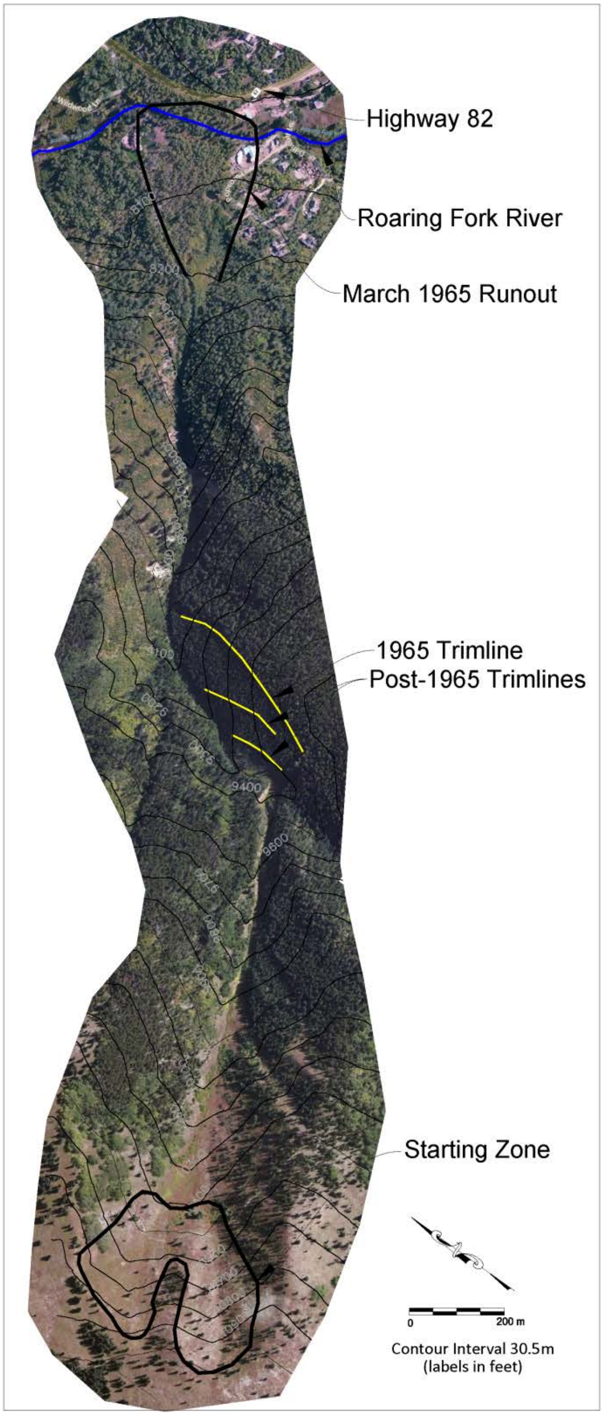

Fig. 2: McFarlane Gulch Avalanche Map

2.4 *Model Description*

The Digital Elevation Model (DEM) has a 3.0m resolution from Aspen-Pitkin County GIS Department derived from photogrammetric methods in 2009. RAMMS simulations of 3m and 10m grid were applied and results were very similar. Based on the weather data, we estimated 2.0m to 2.5m of new unsettled snow in the starting zone. Accounting for settlement and wind-loading, we estimated an avalanche release heights of 1.1 to 1.8 meters with a mean slab thickness of about 1.5m and a corresponding release volume of about 134,000 m3.

We applied RAMMS version 1.6.2 with recommended friction parameters for a large 100-year return period avalanche above elevation 1500m. Terrain curvature effects on friction were applied using the RAMMS automated friction calculating option. Forest friction was applied at the bend. Figures 3 and 4 show the predicted maximum flow heights and velocities, respectively.

We also varied release volume and friction parameters to evaluate sensitivity. Simulations both smaller and larger than the March 1965 event were evaluated. The smaller release volume was 48,000 m^3 with default friction for a medium-size 100-year return period. The larger release volume was 180,000m^3 with large avalanche 300-year return period friction.

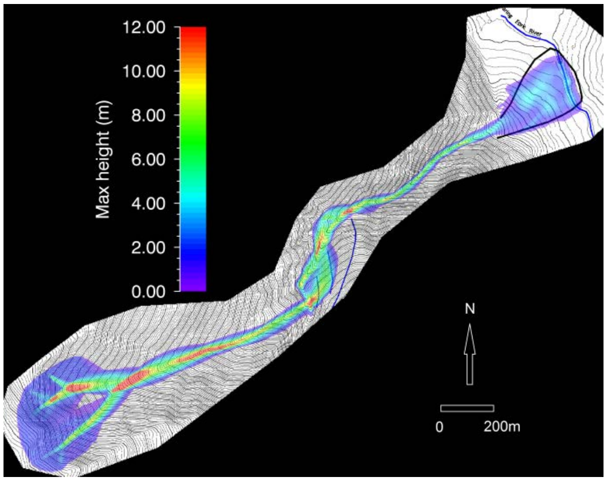

Fig. 3: McFarlane Gulch maximum flow height RAMMS predictions with 1965 trimline and debris limits outlined

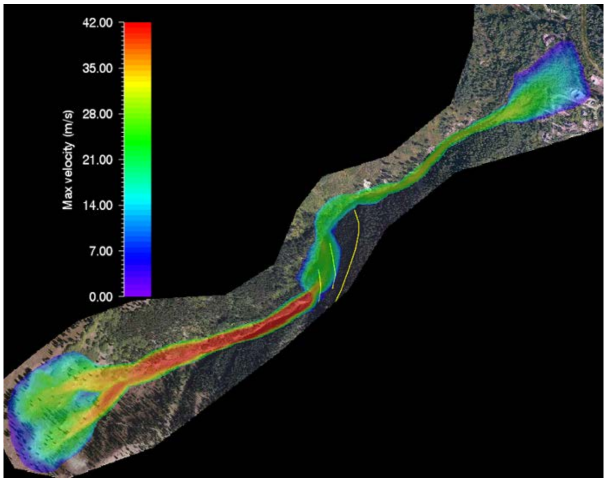

Fig. 4: McFarlane Gulch predicted maximum velocities with three forest trimlines at first track bend

2.5 *Discussion*

Applying our estimate of release volume for the March 1965 (134,000m^3) and high elevation 100-year friction parameters resulted in an underestimate of the climbing height for the mid-track bend (Figures 3 and 4). This discrepancy could be attributed to the high speed fluidized powder component of the avalanche that arrived before the dense flow.

The debris limits for the March 1965 runout match the RAMMS prediction very well (Figure 3).

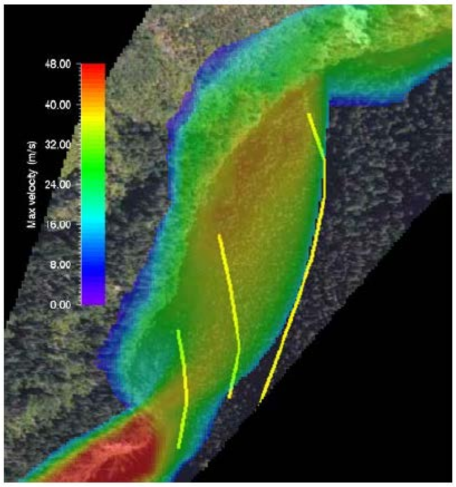

Fig. 5: McFarlane 180,000m3 w/ forest 300-year friction parameters

A better match to the 1965 trimline was achieved by increasing release volume to 180,000m^3 and applying 300-year friction parameters (Figure 5).

However, as described above, the powder avalanche might have caused this trimline.

A smaller release volume of 48,000m^3 with increased friction provided an excellent match to the lowest forest trimline at the sharp bend (Figure 6).

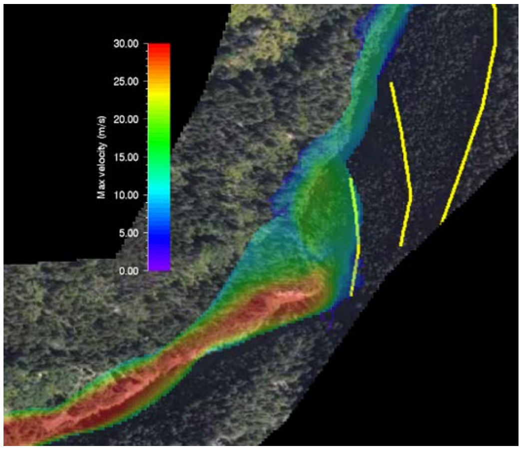

Fig. 6: McFarlane Maximum velocity for 48,000m^3

3. CASE 2 – EASTERN SIERRA, CALIFORNIA

3.1 *Snow Climate*

The Sierra Nevada is generally considered a coastal snow climate with mild mean daily winter temperatures (<-3.5C), deep seasonal snowpacks and frequent and widespread avalanche activity during storms that occur on nonpersistent snow crystals (Bair, 2011). Both locations retain snowpacks until late in the spring and often into June and July. Long term snowpack records and climate data from stations on the eastern slope of the Sierra Nevada suggest the orientation of synoptic scale circulation interacts with the Sierra Crest and the diverse topographic relief to produce considerable variation in snow climates at the watershed scale (Burak and Walker, 2006).

The Leavitt Lake avalanche site is about 85 km NW of Mammoth Mountain Ski Resort where snowfall data are available for the February 1986 storms. A SNOTEL site at Leavitt Lake was installed in 1988. The Leavitt Lake area often has colder average winter temperatures (>-3.5C) and deeper snowpacks than Mammoth Mountain. The long-term average April 1st SWE (1988-2014), is 128 cm at the Leavitt Lake SNOTEL station (2926m). In contrast, April 1st SWE on Mammoth Mountain is 96 cm. Both Mammoth Mountain and

Leavitt Lake experience strong southwest and westerly winds during major Pacific storms. However, despite Leavitt's position east of the Sierra Crest, it receives more snow than Mammoth Mountain, and as expected, generally colder temperatures. This local climate phenomenon is attributed to terrain and its influence on atmospheric circulation.

Based on the available data, it is likely that the starting zone at Leavitt Lake received 20-30% more snow and SWE than the measured amounts at Mammoth Lakes during the Feb 1986 storm. Snow course measurements at Leavitt Lake recorded total snow depth of 178 cm at the end of January and 427 cm at the end of February. The February 1986 storm ended about 11 days prior to the 427 cm measurement.

3.2 *February 1986 snow and weather conditions*

The 1986 winter started off with below average snowfall and mild air temperatures. Mammoth Mountain recorded 64 to 70 percent of average snowfall and precipitation in December and January.

A back-to-back series of Pacific storms originating in the subtropics near Hawaii impacted the Sierra Nevada Mountains of California and Nevada in the middle of February 1986. The storms impacted much of the mountain west, but California was hit especially hard (Birkeland and Mock, 2001). Heavy precipitation and moderately-high snow levels for 8 to 10 days brought catastrophic flooding to much of northern California and also into western Nevada.

Snow began to fall on Mammoth Mountain on February 12; ten days later, 400 cm of snow and 73.6 cm of precipitation had fallen. The change in HS was 282cm. The heaviest snowfall occurred from February 15 to February 19 when 262 cm of snow fell with 51 cm of precipitation. The storm accounted for 45% of the winter's precipitation. A large avalanche triggered by an avalauncher near the summit ridge on Mammoth Mountain ran 500 m, destroying a chair lift near the bottom of the ski area. The crown was up to 655 cm. (Frutiger, 1990).

3.3 *Leavitt Creek, CA Path Description*

The Leavitt Creek avalanche path begins in a 300 hectare alpine cirque at elevations ranging from 2890 to 3180 m. The average starting zone slope angle is 29.5°. An extensive fetch area includes the south Fork of the Stanislaus River Canyon, providing favorable alignment for orographic lift and prevailing southwest storm winds. Treeline is about 2760 m. The track is channelized with a typical width of 280 m. The α angle for the February 1986 avalanche was 13.1°; the β angle is 19.5°.

The February 1986 avalanche was extraordinary because of its long runout on a gentle slope and the destruction of mature timber. It ran over 1000 meters on a 4.6 degree slope and destroyed several hectares of forest, including some trees that were 300 years old. The trimlines are clearly visible and outlined on Figure 7. Table 2 compares extreme runouts for large dry new snow avalanches in Switzerland (Buser & Frutiger, 1980; Gruber and Margreth, 2001).

Table 2: Comparison of Extreme Runouts

Location	*Date*	*Dist.*	*Slope*
Leavitt Cr, USA	Feb. 1986	1030m	4.6°
Malbun, FL	Jan. 1951	620m	6.4°
Malbun, FL	Feb. 1999	600 m	6.2°
Pardenn/Klosters, CH	Feb. 1970	660m	4.3°
Geschinen, CH	Feb. 1999	1070m	5.3°

3.4 *Model assumptions & input*

The DEM is a 30 meter resolution from the USGS National Elevation Data Set (NED). We used a RAMMS simulation resolution of 10m. We assumed a slab release varying from 2.0 to 4.5 meters thick with an average thickness of about 3.5 meters. Initially, we applied the RAMMS default friction parameters for a large 300-year return period avalanche above elevation 1500 meters. Friction was reduced in subsequent models, including a constant low friction of mu=0.14 and xi=4000 at all elevations, and only below elevation 2800 meters.

3.5 *Model Predictions and Calibration*

Figure 8 shows RAMMS predictions for maximum flow height and maximum velocity using default friction parameters for a 300-year large avalanche above 1500 m elevation. The approximate release area and the maximum runout distance are outlined on Figure 8. The runout distance is underestimated and lateral flow boundaries differ from the 1986 trimlines.

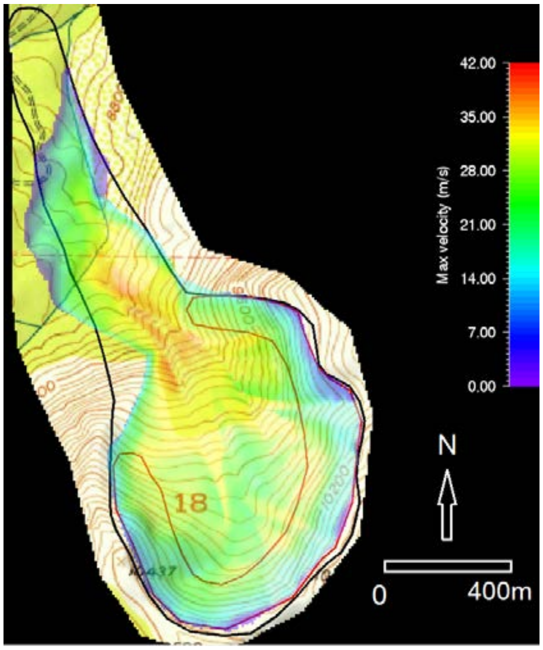

Fig. 7: Leavitt Creek Release Area and 1986 Runout Limits with RAMMS predicted maximum velocity for 300-year 1,400,000m^3 release

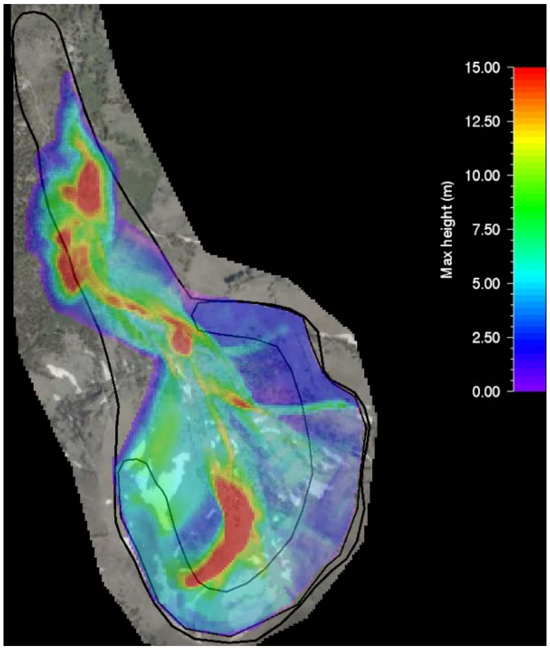

Figure 8 - RAMMS predicted maximum flow heights for 300-year large avalanche

The model underestimated runout distance by about 300 meters using the lowest friction parameters for any conditions in the RAMMS manual. In addition to underestimating runout, the model did not match the path trimlines in the lower-mid track or near the end of the runout. Figure 8 shows how the model predicted a flow trajectory to the northwest near mid-track, then back to the north, following the valley near the end of the runout. The trimlines indicate a straighter path that does not follow the topography as faithfully as predicted by RAMMS.

Based on descriptions of energy-meltwater effects described by Vera & Bartelt (2013), we further reduced friction in the runout (μ=0.12 and ξ=4000 below 2800m), but still did not match the lateral trimline from the 1986 avalanche (Figure 9).

We speculate that flow convergence caused a very deep flow at start of runout, similar to that predicted by RAMMS. The deep flow probably had relatively low shear strength and was sliding forward at about 30m/s. This caused the flow to extrude outward through internal shear, thinning as it spread. Established momentum defined the straight trimlines. The flow then piled up on itself at the very end, breaking limbs on pine trees at the very distal tip to 10m high (Figure 10). Large (300 year old) trees in the lower 100-200m of runout were uprooted, not snapped off up high.

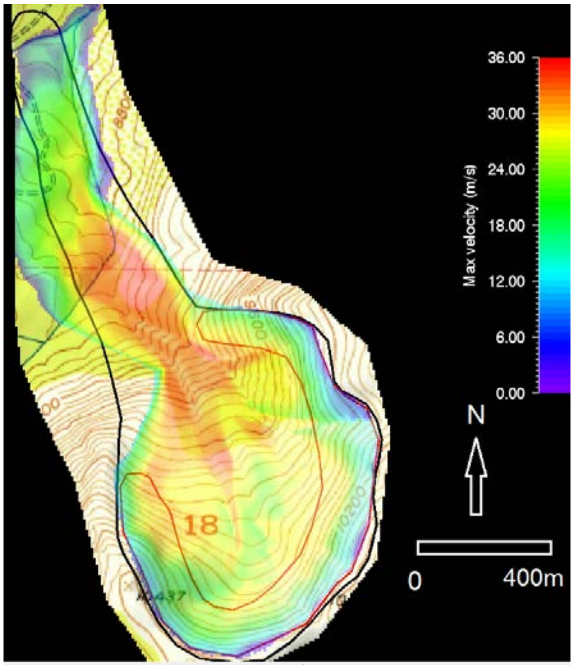

Figure 9 - RAMMS predicted maximum flow heights and velocities for 1,400,000m^3 release and reduced friction parameters below elevation 2800m

Figure 10 – Photo of runout limit of 1986 avalanche taken in 2013

4. CONCLUSIONS

The two long-return period avalanches described in this paper illustrate both the usefulness and limitations of current avalanche dynamics models. In the Colorado example, it was possible to reasonably calibrate the model using release volume and two friction parameters. Nearly 50 years have passed since the March 1965 avalanche. Since that time, land values in Aspen have risen and very large and expensive homes have been built in the runout zone. Avalanche zoning has successfully prevented exposure to the highest energy locations. Modern avalanche dynamics modeling provides objective support for the avalanche zoning established more than three decades ago.

In the Sierra Nevada, California example, friction parameters had to be reduced below the widely used range of values. And even with very low friction, the lateral boundaries of the flow were not predicted very well.

These examples, and other cases, demonstrate that avalanche dynamics models are essential methods for avalanche mapping and engineering designs. Used in combination with other methods, including careful field observations, historic records, aerial imagery and terrain data, they reduce uncertainty in a process that entails large uncertainty. Despite the excellent advances in models, judgment and experience are also required.

CONFLICT OF INTEREST STATEMENT

RAMMS is a commercial software product available from the WSL-SLF, Davos Switzerland. None of the authors is endorsing this software, nor do any of the authors have a financial interest in the sales or promotion of RAMMS or any other avalanche dynamics software.

REFERENCES

Birkeland, Karl W. and Mock, Cary J., 2001, The Major Snow Avalanche Cycle of February 1986 in the Western United States, Natural Hazards 24: 75–95.

Burak and Walker, 2006, Snow Climatology of the Eastern Sierra Nevada, Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado.

Buser, Othmar and Frutiger, Hans, 1980, Observed Maximum Run-out Distance of Snow Avalanches and the Determination of the Friction Coefficients μ and y Journal of Glaciology, Vol. 26, No. 94.

César Vera and Perry Bartelt, Modeling, 2013, Wet Snow Avalanche Flow with a Temperature Dependent Coulomb Friction Function, ISSW 2013, Grenoble.

Christen, M., Kowalski, J., Bartelt, P., 2010. RAMMS: numerical simulation of dense snow avalanches in three-dimensional terrain. Cold Regions Science and Technology 63 (1–2), 1–14

Frutiger, H., 1990, Maximum avalanche runout mapping: a case study from the central Sierra Nevada, Proc. 1990 Int. Snow Sci. Workshop, Bigfork, Montana, pp. 245–251.

Gruber, U.; Margreth, S., 2001: Winter 1999: a valuable test of the avalanche-hazard mapping procedure in Switzerland. Ann. Glaciol. 32: 328-332.

Jamieson, B., S. Margreth, and A. Jones, 2008, Application and limitations of dynamic models for snow avalanche hazard mapping, in Proceedings of the ISSW, pp. 730-739, Whistler.

Margreth, S.; Mattice, T., 2012: Re-evaluation of avalanche mitigation measures for Juneau. In: Proceedings International Snow Science Workshop "a merging of theory and practice", ISSW 2012, Anchorage, Alaska. 150-156

Voellmy, A., 1955. Über die Zerstörungskraft von Lawinen. Schweizerische Bauzeitung 73, 159-162, 212-217, 246-249, 280-285