SLF Expert report G2011.21

Avalanche mitigation study: Behrends Avenue avalanche path and White Subdivision avalanche path, Juneau, Alaska

Client:

Emergency Programs
City and Borough of Juneau, Alaska
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Juneau, Alaska, 99801

Consultant:

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Davos, 30 December 2011/mar

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Head of SLF: Senior Consultant:

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Davos, 30 December 2011/mar

Content

Appendices

1 Mandate

The WSL Institute for Snow and Avalanche Research SLF in Davos, Switzerland was mandated on 9 September 2011 by the City and Borough of Juneau (CBJ), Alaska, to perform an avalanche mitigation study for the Behrends Avenue and the White Subdivision path on Mt. Juneau. In accordance with Contract MR#11-229 the main objectives of the mitigation study are to provide an overview on the hazard situation in the runout zone of Behrends Avenue and the White Subdivision avalanche path and to propose possible mitigation measures including the artificial release of avalanches to reduce the avalanche risk.

Stefan Margreth (Senior Consultant, SLF, Davos) visited the area between April 7 and 23, 2011. He had several discussions with T. Mattice on the avalanche paths on Mt. Juneau. Further we talked to B. Glude and the staff of the Juneau Forecast office of the National Weather Service Alaska Region.

2 Basic conditions and limitations

The objective of our study is to provide recommendations to decrease the avalanche risk in the runout zones of the Behrends Avenue path and the White subdivision path. Our study does neither include the elaboration of detailed hazard maps nor the preparation of detail layouts for structural or temporary mitigation measures. We only comment the actual hazard maps and discuss the feasibility of different mitigation measures.

Our hazard assessment was based mainly on our personal experience, the information of the field visit, avalanche data, weather data, terrain data, avalanche dynamics calculations and personal communications we obtained during our field visits. We analysed carefully all these information for our evaluation to the best of our knowledge. The City should know that while SLF can and does attempt to uphold the highest professional standards, the state of scientific and engineering knowledge is incomplete, and does not always permit certainty. The complex phenomena involved in avalanches cannot be perfectly evaluated and predicted, and methods used to predict avalanche behaviour change as new research becomes available. While SLF can and will offer its best professional judgment, SLF cannot and does not offer any warranty or guarantee of results.

3 Existing reports

3.1 Letter from April 6, 1949

Around 1950 it was proposed to build the Harborview Grade School below the Behrends Avenue (location of the present Breakwater Inn Motel). A three-man expert committee had to evaluate the proposed location. The committee concluded that the preferred location is not suited and that the school should be built at a less hazardous site. Later the Juneau-Douglas High School was built just outside of the avalanche area south-east of Behrends Avenue (Fig. 1).

3.2 Hart report, 1967 and 1968

In 1967 and 1968, Hart examined the history and character of the avalanche hazard in the Behrends Avenue path and made several recommendations to reduce the avalanche hazard. He analysed the 1962 avalanche in detail and developed the history of the slide path back to 1890. He proposed to construct different rows of avalanche breakers with a height of 6 m and diversion dams at the base of the slope with a height of up to 7.5 m (Fig. 1). We think that the proposed sizes of the avalanche breakers and dams are much too small to retard an extreme avalanche. We agree completely with his statement that the hazard along Behrends Avenue can be only completely eliminated if all houses in the affected area would be removed.

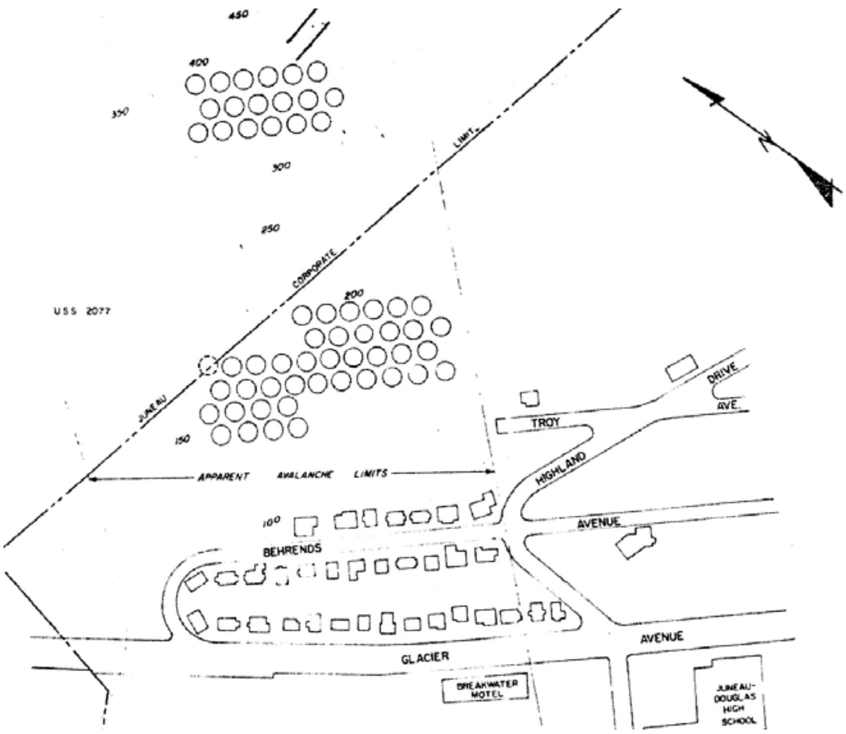

Fig. 1: Terminal zone of Behrends Avenue avalanche path showing approximate location of the avalanche breakers and the two small deflecting dams above the topmost breakers (Hart, 1968).

3.3 La Chapelle report, 1968

La Chapelle investigated in 1968 the Behrends Avenue avalanche path (La Chapelle, 1968). He confirmed all essential points of the reports of Hart and he suggested some additional safety measures. He thought that a substantial gain in safety could be achieved by constructing individual concrete diversion barriers at the uphill wall of each house. However he finally advised not to build such individual barriers because of feasibility and aesthetical aspects. As an alternative protection method he proposed to build a huge catching dam just above the uppermost row of houses above Behrends Avenue. He suggested a minimum height between 30 and 45 m and a steep uphill face of the dam (Fig. 2).

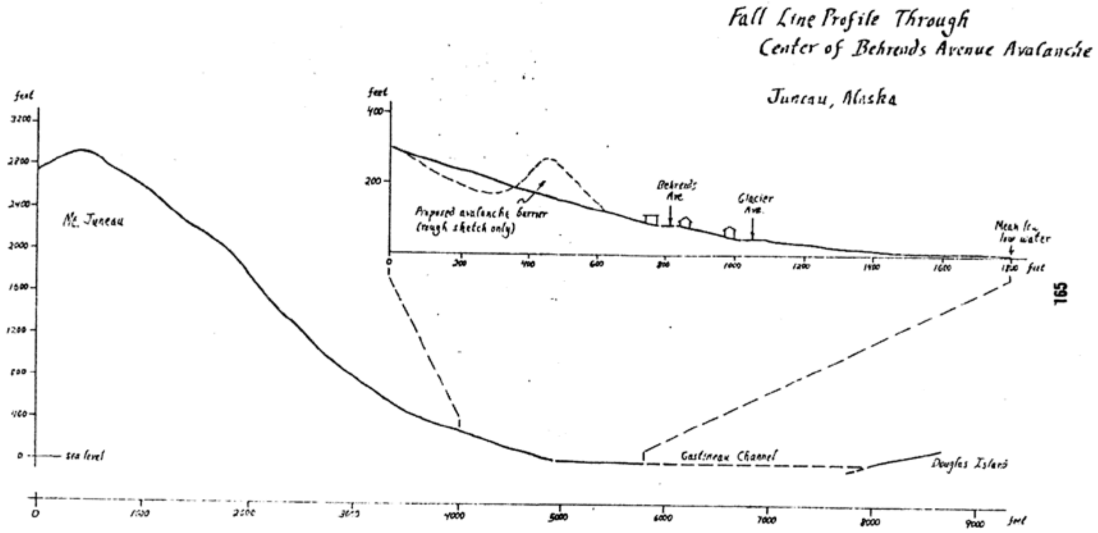

Fig. 2: Terminal zone of Behrends Avenue avalanche path showing the approximate location of the catching dam (La Chapelle, 1968).

However he pointed out that also such a huge dam will not guarantee a 100% protection mainly since a high-velocity avalanche might overrun the barrier. Avalanche dynamics models were not available at that time to verify the necessary height of a dam. Similar to Hart, La Chapelle also concluded that the complete removal of all buildings situated in the avalanche path is the only way to eliminate the hazard from the Behrends Avenue avalanche. Further he strongly urged the city of Juneau to prevent any further development in the Behrends Avenue. He recommended that a survey of all geophysical hazards should be immediately initiated to elaborate upon corresponding hazard maps.

3.4 Geophysical Hazards Investigation for the City and Borough of Juneau, 1972

In 1972 an expert commission investigated the seismic hazards, the mass wasting hazards and the snow avalanche hazards in the area of the City and Borough of Juneau. The snow avalanche hazard was investigated by Frutiger from our institute (SLF) in Davos (Frutiger 1972). For the areas of the Behrends Avenue and White Subdivision path detailed hazard maps were elaborated. For both avalanche paths Frutiger applied the Voellmy avalanche model to calculate runout distances. A maximum return period of 90 years was considered with an impact pressure limit of 30 kPa. Currently in Switzerland a return period of 300 years is used for the extreme avalanches. A return period of 300 years was also considered in the hazard evaluation of 1992 (see section 3.5). In the Behrends Avenue path and White Subdivision path the severe hazard zone (red zone) extends to the Gastineau Channel (Fig. 3). The hazard levels were defined on the hazard map as follows:

- **Blue (in Fig. 3 light red) or special engineering zone**: a pressure of more than 30 kPa and a return period of more than 90 years, or a pressure of 10 to 30 kPa and a return period of more than 30 years.
- **Red or severe hazard zone:** a pressure of 10 to 30 kPa and a return period of 30 years or less, or a pressure of more than 30 kPa and a return period of 90 years or less.

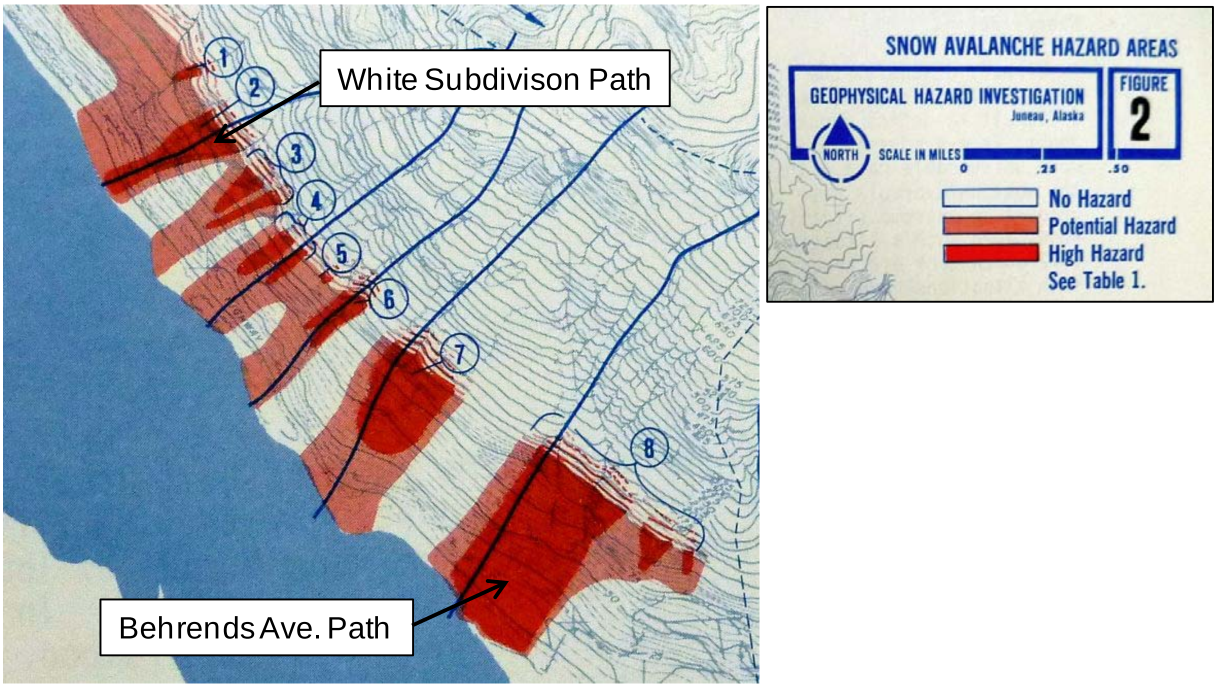

Fig. 3: Avalanche hazard map from the Geophysical hazard investigation (Frutiger, 1972).

3.5 Juneau Area Mass-Wasting and Snow Avalanche Hazard Analysis, 1992

In 1992 Mears, Fesler and Fredston re-evaluated the hazard maps of 1972 (Mears et al., 1992). Additionally they researched all recorded snow avalanche events affecting the Behrends Avenue and White Subdivison avalanche paths. The avalanche history they established is very valuable and provides a good basis for our investigation. The snow avalanche hazard classification was made in three categories. The **severe hazard zones** (red zone) are subject to avalanches with return periods of less than 30 years or impact pressures more than 30 kPa. The **special engineering zones** (blue zone) are subject to avalanches with return periods of more than 30 years, but less than 300 years and impact pressures less than 30 kPa. The runout zones of 1992 in Behrends Avenue are a little smaller compared to the hazard map of 1972 (Fig. 4). The severe hazard zone no longer reaches the Gastineau channel, and its extent in NW-direction is about 90 m smaller compared to 1972. The extent of the hazard zones towards downtown Juneau is very similar in the maps of 1972 and 1992.

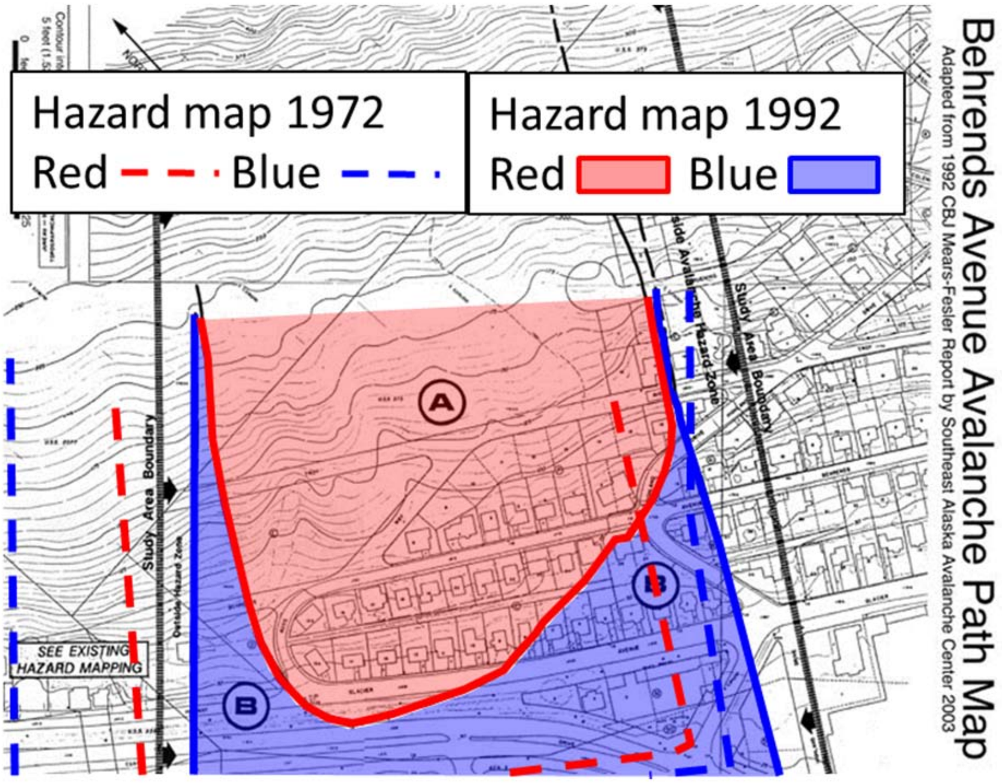

Fig. 4: Behrends Avenue avalanche path map from 1992 (Mears et al., 1992), with the approximate hazard zones from 1972 appended with a dashed line. A = severe hazard zone (red colour), B = special engineering zone (blue colour).

The extent of the 1992 hazard zones for the White Subdivision avalanche path are a little smaller compared to 1972 (Figs. 3 and 5). On the 1972 map the severe hazard zone ends in the Gastineau channel, while on the 1992 map the severe hazard zone ends at Glacier highway.

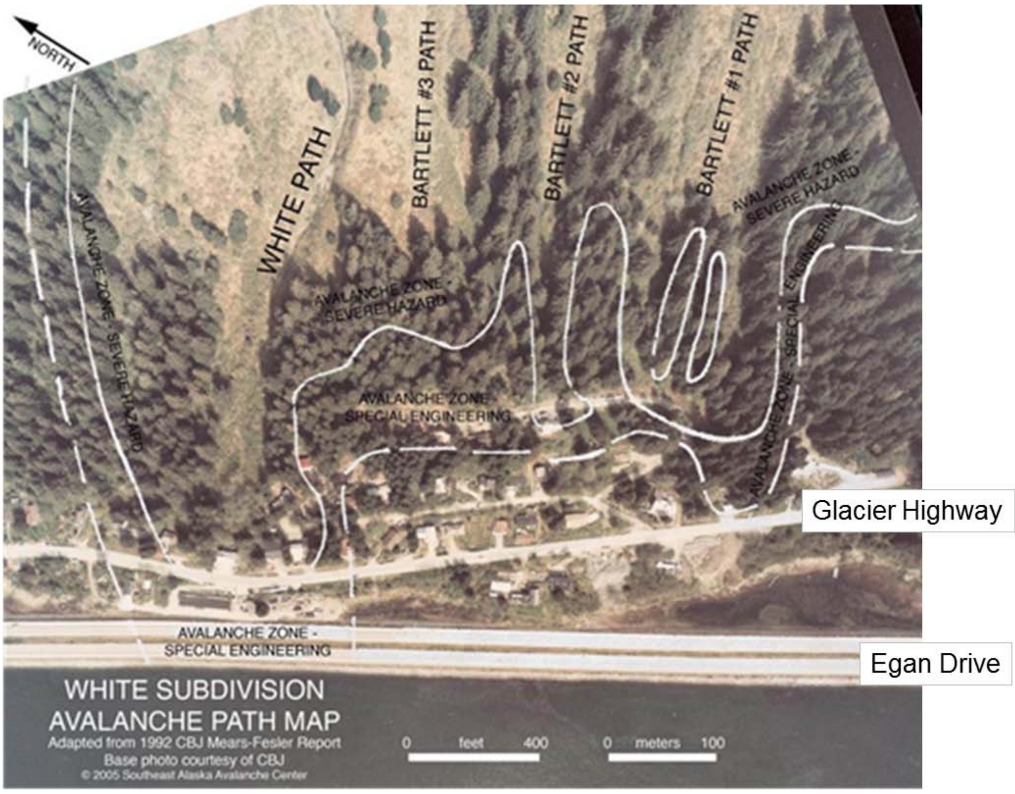

Fig. 5: White Subdivision avalanche path map (Mears et al., 1992).

4 Weather and snow climate

Juneau lies within an area of maritime influences which prevail over the coastal areas of south eastern Alaska, additionally it lies in the path of most storms that cross the Gulf of Alaska. Consequently, the area has little sunshine, generally moderate temperatures and abundant precipitation (Colman, 1986). The predominant wind direction is from the south along the Gastineau Channel. There are periods of comparatively severe cold temperatures, which are caused by strong northerly winds, locally known as Taku winds. On Mt. Juneau these winds (dominantly north-east) can cause important snow drift accumulations in the upper starting zones of the Behrends Avenue avalanche path. The snow line often fluctuates between sea level and the elevation of the starting zones, which causes a wide range of snow conditions in the avalanche paths. Normally the snowpack consists of thawed and refrozen layers. This favours a greater frequency of wet snow avalanche conditions as opposed to extreme dry snow avalanche conditions which can explain why extreme dry snow avalanches occur rather seldom.

Long-term snow data are available from the Alaska Climate Database (National Weather Service) for the weather stations Juneau Airport (5 m a.s.l., data since 1943) and Juneau Downtown (8 m a.s.l., data since 1890). In Juneau (Downtown) the greatest snowfall in one day of 79 cm was observed on 10 January 1972 (Fig. 6). The maximum snowfall recorded over 3 days at Juneau (Airport) was 108 cm, the average annual snowfall amounts to 242 cm and the maximum annual snowfall is 494 cm. A maximum snow height at Juneau (Airport) of 102 cm was observed on 10 March 1972 (Fig. 7). Unfortunately there are no weather stations with a long observation period at the elevation of the avalanche starting zones at Mt. Juneau. The highest weather stations are situated in the ski resort Eaglecrest on Douglas Island (data since 1978, 6 km west of Juneau). At the base of the ski resort (350 m) a maximum snow height of 353 cm was measured on 14 January 2007 and at the top of the ski resort (786 m) a maximum snow height of 587 cm was measured on 17 March 2007. The average annual snowfall at Eaglecrest is around 760 cm.

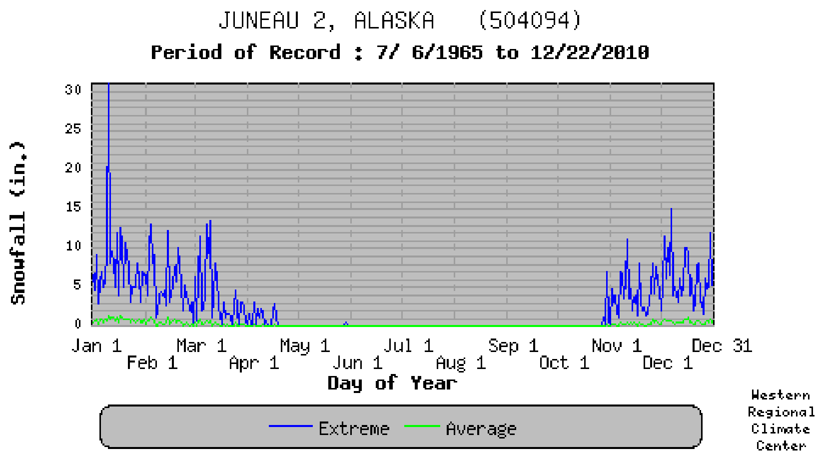

Fig. 6: Maximum snowfall in inches per day in Juneau Downtown.

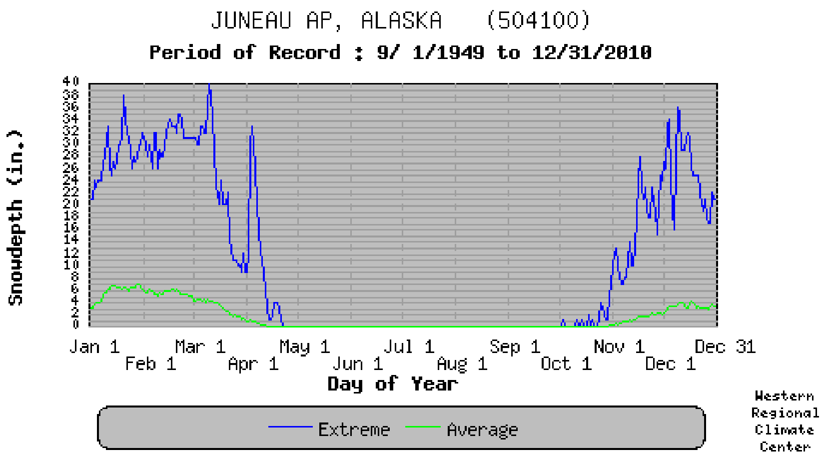

Fig. 7: Maximum snow depth in inches at Juneau Airport.

Mears et al. (1992) estimated that the snow accumulation in the starting zone of Mt. Juneau is a factor of 4 to 5 greater than that at sea level. We think that this estimate is reasonable. The extreme snow heights in the starting zones on Mt. Juneau are estimated to vary between 6 and 8 m, particularly for depressions where larger snow heights must be expected. In the Juneau area fracture depths of extreme avalanches vary typically between 2 and 4 m (personal communication from B. Glude). We assume that an extreme avalanche (return period up to 300 years) on Mt. Juneau might have an average fracture depth of 1.5 to 2.0 m. Frutiger (1972) considered avalanche fracture depths of 2 m in his avalanche calculations for the Behrends Avenue avalanche and for the White Subdivision.

5 Avalanche dynamics calculations

5.1 Applied calculation models

For the hazard assessment and for the determination of the design values for protection measures we performed avalanche dynamics calculations with the 2-dimensional avalanche simulation program RAMMS (SLF, 2009) and with the 1-dimensional avalanche dynamics program AVAL-1D (SLF, 1999).

The software package **RAMMS** (Rapid Mass Movements), developed at the WSL Institute for Snow and Avalanche Research SLF during the last years, combines 2-dimensional process modules for snow avalanches, debris flow and rock fall, together with a protection module (e.g. forest) and a visualization module (GUI) in one tool. RAMMS is based on the Voellmy-Salm avalanche dynamical model and a digital terrain model (DTM). The RAMMS version 1.3 was used. The visualization with RAMMS is helpful for the determination of the endangered areas. With the current version of RAMMS it is not possible to calculate powder snow avalanches.

AVAL-1D is a one-dimensional avalanche dynamics program that calculates runout distances, flow velocities, flow depths and impact pressures of both dense flow and powder snow avalanches. AVAL-1D consists of two independent computational modules - FL-1D (dense flow avalanches) and SL-1D (powder snow avalanches). These modules solve the governing equations of mass, energy and momentum balance using an up winded finite difference scheme. In reality there are always mixed avalanches which are a combination of dense flow and powder snow avalanches. The calculated impact forces are mean values without any safety factors. SL-1D is a pure one-dimensional model. The terrain profile of the avalanche paths and the flow widths have to be determined by expert choice. An enlargement of the width of the avalanche flow cannot be calculated by the model. We evaluated the effect of powder avalanches by the application of AVAL-1D. Further we used AVAL-1D for the verification of the RAMMS simulations.

We performed calculations for avalanches with a return period of 10-, 30- and 300-years.

5.2 RAMMS input parameters

The most important input parameters for RAMMS are:

- (1) Slab thickness d_0
- (2) Release area (and width)
- (3) Friction parameters mu (μ) and xi (ξ)
- (4) Digital terrain model DTM.

(1) Slab thickness (depending on elevation, slope inclination)
In very steep areas (45°-50°) an avalanche release will usually occur earlier compared with release areas around 30° where much more snow accumulation is necessary before a release. Therefore the slab thickness is larger for less inclined slopes compared to steep slopes. For the Behrends Avenue avalanche path a slab thickness of 2.0 m for a return period of 300 years, 1.4 m for a return period of 30 years and 1.2 m for a return period of 10 years (Tab. 1) were applied. Due to the lower elevation of the starting zone at White Subdivision avalanche path we reduced the slab thicknesses for the 30-year and 300-year scenario. We point out that these slab thicknesses are mean values averaged over the whole starting zone. In reality locally much higher slab thicknesses have to be expected.

Tab. 1: Mean values of the slab thickness for the avalanche dynamics calculations

Return period	Behrends Avenue avalanche path	White Subdivision avalanche path
10 years	1.2 m	1.2 m
30 years	1.4 m	1.3 m
300 years	2.0 m	1.8 m

(2) Release area and choice of scenario
The size and the geometry of the release areas are very important input parameters. For the 300-year scenario multiple releases of neighbouring starting zones in the Behrends Avenue avalanche path were considered.

(3) Friction parameters mu and xi
The friction values mu and xi have mainly been calibrated in the Swiss Alps. They depend on the avalanche volume, the elevation, the return period and the ground roughness. RAMMS applies standard elevation limits of 1500 m a.s.l. and 1000 m a.s.l. At lower elevations the friction is higher and the runout of avalanches shorter. Because of the rather specific climatic situation of Juneau (low elevation, coastal climate, abundant precipitation, cold snow conditions at the elevation of the starting zone, wet snow conditions at sea level) we adapted the elevation limits. We used an elevation limit of 500 m a.s.l. instead of 1500 m a.s.l. and 200 m a.s.l. instead of 1000 m a.s.l. We think that with these adaptations the friction parameters better represent the snow conditions in Juneau. For the calculations mostly the friction categories for medium and large avalanches were applied.

(4) Digital terrain model DTM
For the RAMMS calculations we applied the Digital terrain model (DTM) provided by the GIS department of the City and Borough of Juneau. The original grid resolution of the DTM is 6.1 m (20 feet). The simulations were performed with a grid resolution of 10 m. It is very important to state that with a modified terrain (e.g. debris flow or avalanche deposit in the avalanche path) the run out of a natural avalanche can be different from the calculated avalanche run out.

5.2 AVAL-1D input parameters

The release heights and the release areas were chosen similar to the RAMMS calculations. The AVAL-1D friction values mu and xi were also calibrated mainly in the Swiss Alps. To consider the snow conditions in Juneau adequately we increased the elevation of the terrain profile by 800 m (e.g. 1500 m instead of 700 m) and applied the default mu and xi values. For the powder snow avalanche calculations we considered the entrainment parameters calibrated for southern Switzerland.

6 Behrends Avenue avalanche path

6.1 Avalanche situation

The starting zone of the Behrends Avenue avalanche path is situated on the south-west flank of Mt. Juneau (970 m a.s.l.; see Appendix 1 and Fig. 8). The terrain is very complex. There are different small depressions with widths of 50 m to 150 m and mean inclinations between 35° and 45° these are separated by only slightly pronounced ridges. The starting zone is interrupted by several steep cliff bands with heights of 10 to 80 m and estimated inclinations of 50°. Some moderately steep terrain terraces are situated also in the starting zone. The main starting zone is situated between an elevation of 950 m (ridge to the top of Mt. Juneau) and 500 m (top of big cliff band; Fig. 8). The width of the starting zone is up to 500 m. The potential starting zone has an area of 25 hectares (1 hectare = 100 m · 100 m) with a mean inclination of 40°. Between the elevations of 500 m and 250 m the terrain is very steep (mean inclination 42°). This steep part of the avalanche track favours the formation of powder snow avalanches. Two diagonal gullies are situated below the steep part. The 10 m to 30 m deep gullies tend to channel smaller avalanches and deflect them in south-eastern direction. However, large avalanches will only be partly deflected by the two gullies. The cross-section is much too small to discharge the entire avalanche flow. The flow of large avalanches is rather unconfined. At an elevation of 300 m the width of frequent avalanches is captured by the tree damage. Big trees are completely missing along a 270 m wide path. Moreover, the forest along the western limit of the avalanche path seems to be younger compared to the forest stand further east and west of the path (Fig. 9). We estimate the age of the trees to be around

50 to 150 years. Below the elevation of 150 m the track is less than 30° steep and over the last 150 m above Behrends Avenue the slope inclination is 15°. Such inclinations do not retard a dry snow avalanche. The mean inclination from the topmost crown line to Behrends Avenue is 34° (Fig. 10), compared to other avalanche paths this mean inclination is very high. Such high mean inclinations can cause even small avalanches to reach the runout zone. For comparison the avalanche path in Galtür has a mean inclination from the crown line to the destruction area of 29°; in February 1999 an extreme avalanche in this path killed 31 people. If the Behrends Avenue avalanche path would be situated at a higher elevation, for example in the Swiss Alps, large avalanches would probably be frequently observed.

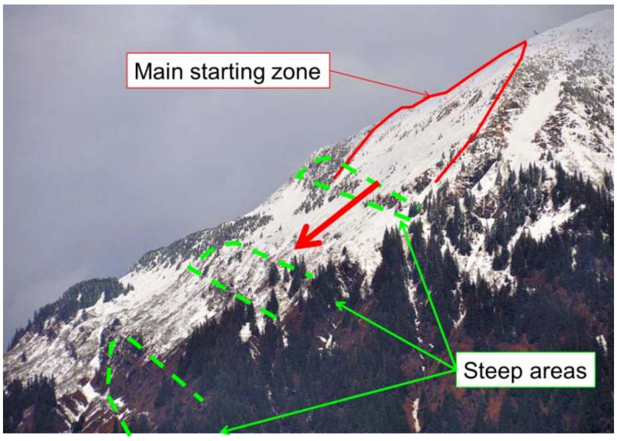

Fig. 8: Main starting zone of Behrends Avenue avalanche path.

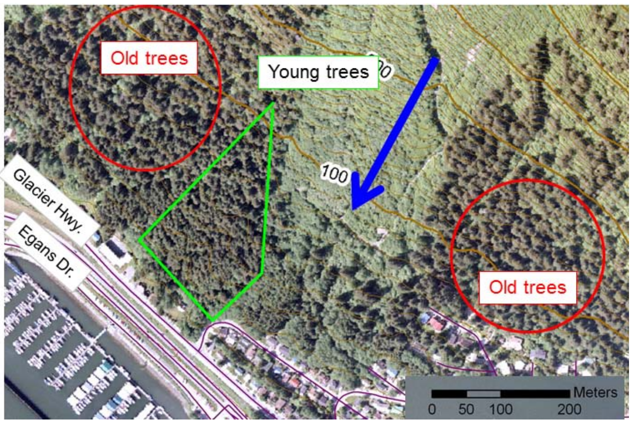

Fig. 9: Runout zone of Behrends Avenue avalanche path with forest pattern.

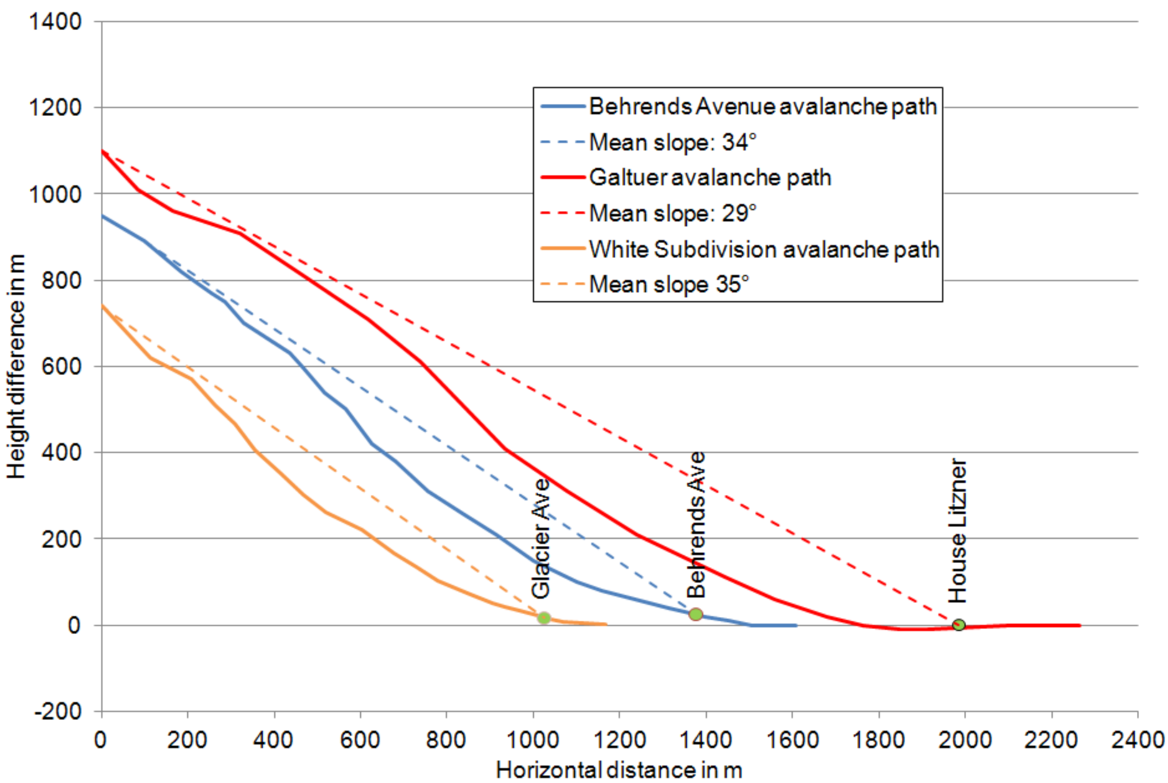

Fig. 10: Terrain profile of Behrends Avenue avalanche path, White Subdivision avalanche path and the “Äussere Wasserleiter” avalanche path in Galtür, where on 23 February 1999 31 people were killed.

The main positive feature of the Behrends Avenue avalanche path is that the starting zone is relatively well structured into different small pockets and that cold temperatures combined with unusual deep snowfalls are relatively seldom. Given these factors we think the release of small avalanches is much more likely compared to the release of the whole starting zone resulting in an extreme avalanche.

6.2 Avalanche history

6.2.1 Overview and interpretation

A comprehensive avalanche history of Behrends Avenue avalanche path was compiled in June 1991 by Fredston and Fesler (Mears et al., 1992). The avalanche history contains avalanche events between 1890 and 1991 (Fig. 11). The analysis of the data shows that prior to the disastrous avalanche of 1962 mainly large avalanches were recorded, and following the 1962 event both large and small avalanches were recorded. In particular the records between 1962 and 1975 seem to be very complete. For example, in the winters 1965/66 a total of 40 mostly small avalanches were observed. However, detailed drawings of the outlines of the observed avalanches, in particular in the starting zone are completely missing. We must therefore rely on the descriptive information and some photographs, especially from the 1962 event.

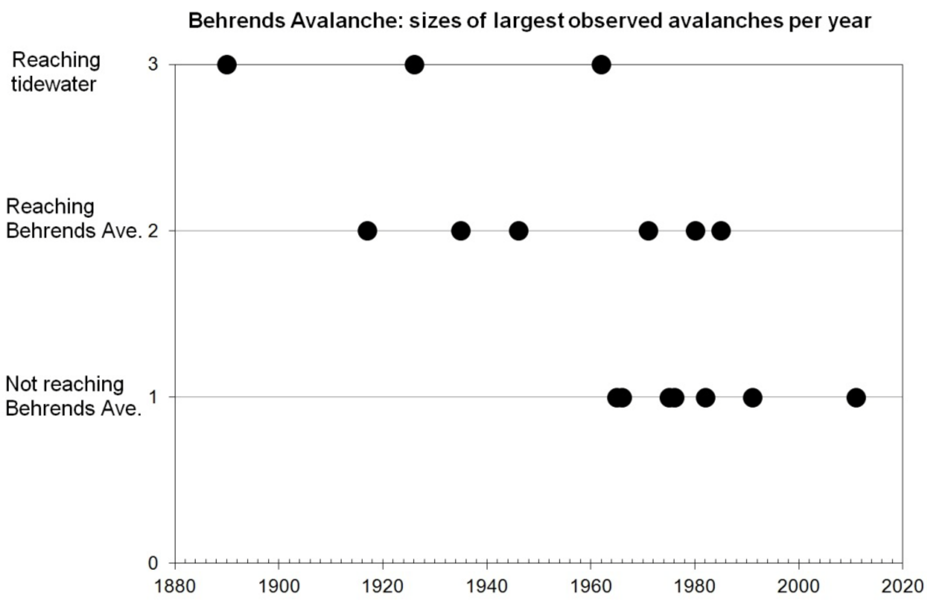

Fig. 11: Sizes of largest observed avalanches per year from 1890 to 2010. The quality of observation is assumed to vary over time.

- The avalanche of 1890 seems to be the largest event in the database. The avalanche reached the Gastineau Channel and deposited hundreds of tons of snow on the road (Glacier Highway?).
- Between 1890 and 2011 the Behrends Avenue avalanche reached tidewater a total of 3 times (1890, 1926, and 1962). In 1962 only the powder cloud reached tidewater, the dense portion stopped above Behrends Avenue. Given this we estimate the return period for an avalanche reaching tidewater to be around 50 to 100 years.
- Between 1890 and 2011 a total of 9 powder snow and dense flow avalanches reached the subdivision (Behrends Avenue, Troy Avenue, Highland Drive; location see Fig. 3). We estimate that 50% of these events caused structural damages (or would have caused structural damages if buildings would already have existed there – settlement started around 1950 in Behrends Subdivision). We estimate the return period for an avalanche that

reaches the subdivision to 15 years, and to 20-30 years for an avalanche that causes damage.
- Small avalanches that stop above the subdivision are observed every winter.
- The last relatively large avalanche was observed on 26 February 1985. The avalanche hit one residential structure (Nr. 226, Troy Avenue). The powder cloud reached Glacier Avenue. Fesler reported that the crown line was between 1.2 and 2.0 m high and approximately 400 m wide. He estimated was estimated that this avalanche represented only 25 to 30% of the total path capacity.
- The forest stands on both sides of the main path provide some more information on the frequency of extreme avalanches. Based on our field analysis and the results of the avalanche dynamics calculations (see chapter 6.3) we assume that an extreme avalanche with a return period of 300 years will have a much wider flow width compared to the present path width of 240 m between the forest stands. We think that such an extreme avalanche will destroy the forest in north-western direction on a width of about 200 m (Fig. 9). We analysed old photographs back to 1922. The distribution of trees was very similar compared to 2011 (Figs. 12 and 13). Especially above the Behrends Avenue we think that there were a greater number of big trees in 1922 than in 2011. In the hazard study of 1972 the age of several trees of Sitka Spruce were determined in the lower part of the avalanche track. An average tree diameter of 56 cm (measured at breast height) corresponds to an age of 75 years. From the distribution of tress we conclude that in the 20th century the extreme avalanche might not have occurred. Furthermore, we point out that we can neither confirm nor exclude that the extreme event had occurred in the 19th century. If we look at the forest pattern it is clearly visible that the trees close to Behrends Avenue and in north-western direction are younger compared to other locations with no avalanche activity (Fig. 9). A 300-year avalanche has only a 63% chance of occurring in a 300-year period.

Fig. 12: Photograph of the Behrends Avenue path taken about 1935-1940. Around the avalanche path is a mature forest with an estimated age of at least 50 years (Photo archive of CBJ).

Fig. 13: Photograph Behrends Avenue path 2011. The forest destructions caused by the 1962 avalanche are still clearly visible.

6.2.2 Avalanche from 1962

The most destructive avalanche in recent years was the 22 March event in 1962 (Mears et al., 1992). Following a period of heavy precipitation arriving from the north-east, a powder snow avalanche with a very small dense portion broke loose. An eye-witness told that the powder cloud traversed Gastineau Channel and reached an elevation of approximately 220 m on the counter slope. On the photographs of the runout zone, there are practically no visible avalanche deposits. The main damages to the houses were caused by the powder blast and by impacts of logs or other debris which were carried away by the avalanche. Regarding the type of constructions (mostly relatively weak wood frame or brick wall buildings), the damages were relatively small. We estimate the impact pressure to have varied in the Behrends Subdivision between 2 and 4 kPa. Approximately 35 houses were damaged. The main impact area was situated in the north-western half of Behrends Avenue (see Fig. 16). The avalanche nearly entirely destroyed the forest belt above Behrends Avenue. A lot of damage was caused by impacts of trees and branches (Figs. 14 and 15). The damages to the forest situated beside the main avalanche path were very small.

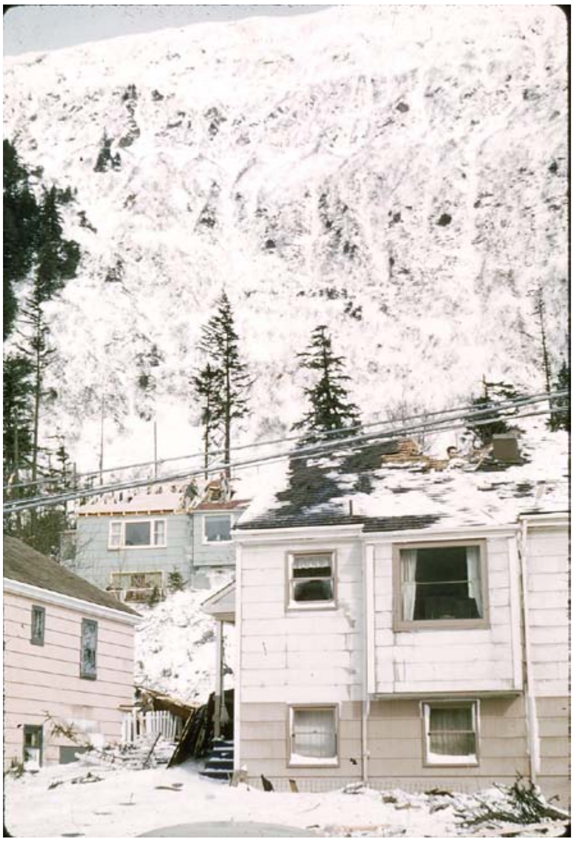

Fig. 14b: Rossway with destroyed forest belt.

Fig. 14a: Glacier Avenue House Nr. 1757 – damaged roof, main structure undamaged, in the background the destroyed forest belt is visible.

Fig. 15: View of Behrends Avenue with Gastineau Channel in the background – collapsed roofs due to overpressure and impacts of trees. The back-walls are not damaged.

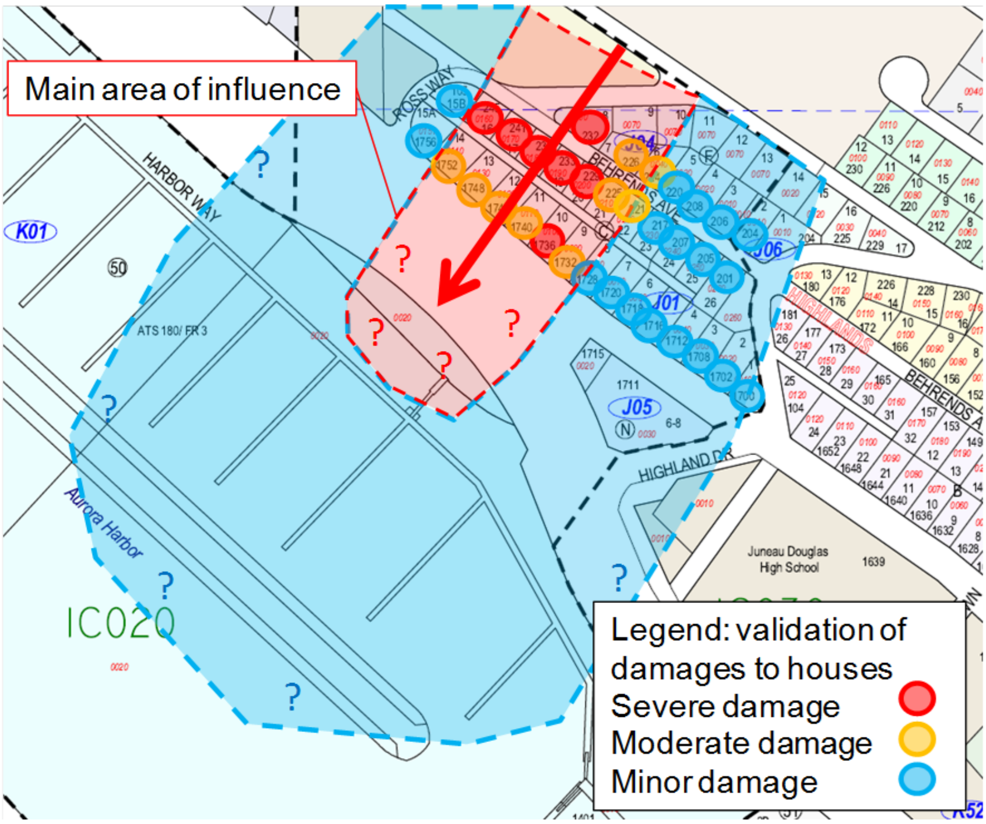

Fig. 16: Overview of the main area of impact of the 1962 avalanche. The assessment of the damages to the houses is based on the 1992 report (Mears et al., 1992). The extent of the main area of influence is situated in the north-western half of Behrends Avenue according to the interpretation of the damages.

6.3 Avalanche dynamics calculations

6.3.1 RAMMS simulations

We performed simulations with three different scenarios with return periods of 10, 30 and 300 years (Tab. 2). The extent of the starting zones was determined by expert choice primarily on the basis of the slope inclination and the topography. The characteristics of the different scenarios are given in Tab. 2. Friction parameters applied in the calculations included shape files representing the forested zones on either side of the main avalanche track. Test calculations showed that the two diagonal gullies do not very much influence the avalanche flow. A reason might be that the depressions are not properly represented by digital terrain model at the resolution used. To increase the influence of the gullies in the simulations, the same friction parameters as for forested areas were applied along the gullies (Fig. 20).

Tab. 2: Investigated RAMMS-scenarios

Scenario	Volume	Volume category	Mean fracture depth
10 years	46’000 m^3	medium	1.2 m
30 years	150’000 m^3	large	1.4 m
300 years	410’000 m^3	large	2.0 m

The main results of the various RAMMS simulations are given in the following Tab. 3, Figs. 17, 18 and 19 and in the Appendices 3.1, 3.2 and 3.3. The different figures show the uncorrected simulation results. For the elaboration of hazard maps the simulation results have to be interpreted by expert choice if necessary.

Tab. 3: Behrends Avenue avalanche path, results of RAMMS simulations

Elevation above sea level	Location in avalanche path	10-year Scenario		30-year Scenario		300-year Scenario	
		Velocity	Flow height	Velocity	Flow height	Velocity	Flow height
100 m	west	6 m/s	0.1 m	24 m/s	0.6 m	39 m/s	2.0 m
	middle	13 m/s	0.9 m	22 m/s	1.7 m	34 m/s	2.7 m
	east	11 m/s	0.5 m	19 m/s	1.2 m	23 m/s	1.4 m
60 m	west	3 m/s	0.3 m	13 m/s	0.3 m	30 m/s	5.7 m
	middle	4 m/s	0.4 m	17 m/s	0.4 m	31 m/s	4.4 m
	east	9 m/s	0.6 m	15 m/s	0.6 m	19 m/s	1.0 m
25 m (Behrends Ave.)	west	-	-	4 m/s	0.7 m	19 m/s	3.8 m
	middle	1 m/s	0.1 m	13 m/s	0.8 m	28 m/s	3.6 m
	east	1 m/s	1.0 m	7 m/s	0.3 m	12 m/s	0.8 m
10 m (Egan Dr.)	middle	-	-	5 m/s	0.1 m	23 m/s	2.7 m
	east	-	-	-	-	11 m/s	0.2 m

- The 10-year avalanche does not reach Behrends Avenue (Fig. 17, Appendix 3.1). The zone with impacts of more than 30 kPa covers the main avalanche area where there are no big trees. The forest stand above the Behrends Avenue will further act to retard the avalanche flow. The two gullies deflect most of the avalanche flow. The two main flow directions are orientated along the main axes of the two gullies.
- The 30-year avalanches stops on Egan Drive (Figs. 9 and 18; Appendix 3.2). The north-western part of Behrends Avenue is in a zone with avalanche impacts of more than 30 kPa. The flow width, especially in north-western direction, is larger compared to the main avalanche area without trees. We think that the simulation slightly overestimates the extent of the avalanche compared to the avalanche history. However, in the forested area the velocities are rather small. The avalanche flow directions are mainly orientated along the two diagonal gullies as well. However the gullies deflect the avalanche only partly. At an elevation of 100 m the avalanche velocity varies between 19 and 24 m/s.
- The 300-year avalanche reaches Gastineau Channel with an intensity of more than 30 kPa (Fig. 19, Appendix 3.3). At Egan Drive the velocity is still 23 m/s with a flow height of 2.7 m. Most of Behrends Avenue is in the 30 kPa zone, here the velocities are up to 28 m/s with a flow height of 3.6 m. Such avalanche intensities are capable of completely destroying massive buildings. The total flow width is much wider than the present main avalanche path. The 300-year avalanche has the potential to destroy a large part of the forest stand north-west of the main path. The influence of the two gullies on the avalanche flow is small, with the major part of the avalanche overflowing the gullies. The highest velocities and flow heights are calculated along topographic depressions. The avalanche flow direction is mainly located, according to the simulation, at the north-western end of Behrends Avenue.

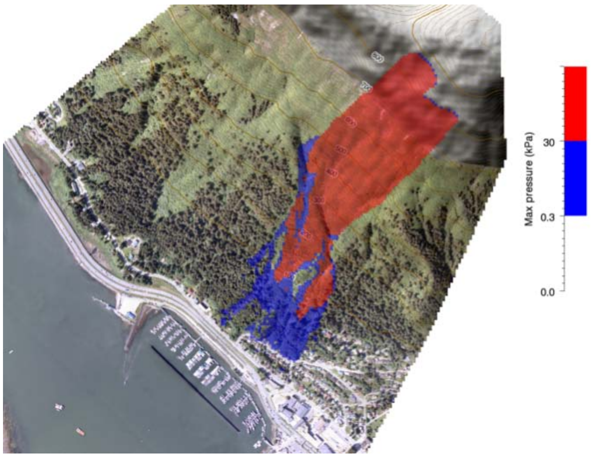

Fig. 17: Uncorrected RAMMS simulation results of the 10-year Behrends Avenue avalanche. Red = impact pressure > 30 kPa and Blue = impact pressure < 30 kPa.

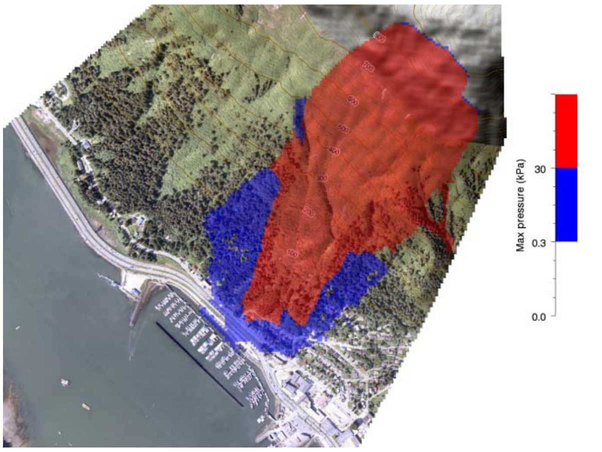

Fig. 18: Uncorrected RAMMS simulation results of the 30-year Behrends Avenue avalanche. Red = impact pressure > 30 kPa and Blue = impact pressure < 30 kPa.

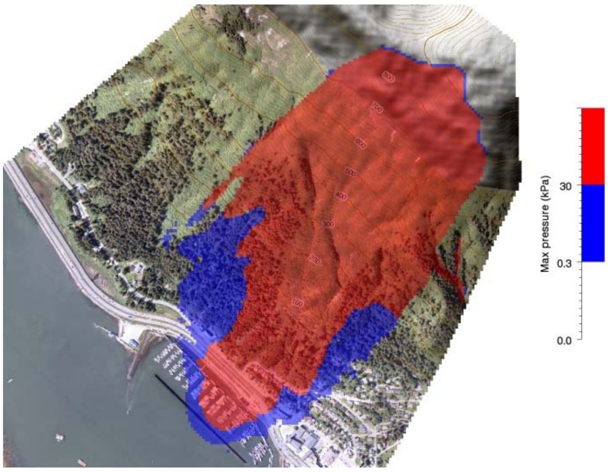

Fig. 19: Uncorrected RAMMS simulation results of the 300-year Behrends Avenue avalanche. Red = impact pressure > 30 kPa and Blue = impact pressure < 30 kPa.

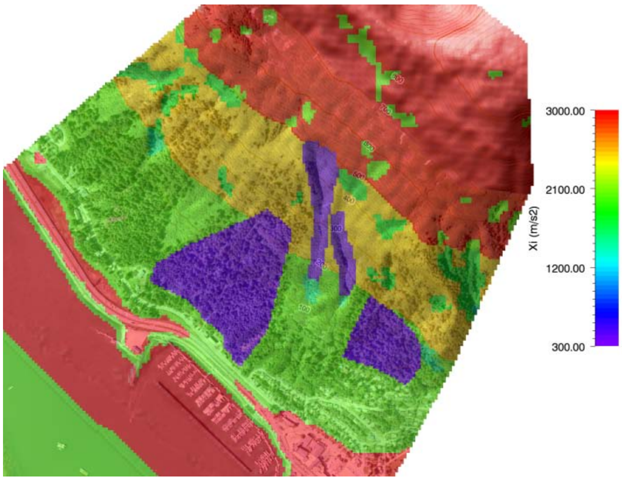

Fig. 20: Friction parameter xi of the RAMMS simulation of the 300-year Behrends Avenue avalanche. The violet areas have an increased friction value (forest and gully).

6.3.2 AVAL-1D simulations

Dense flow avalanche simulation

The terrain profile for the AVAL-1D simulation was selected along the main axis of the slide path and the flow width was selected in accordance with the results of the RAMMS simulations. The avalanche volumes of the 10-, 30- and 300-year scenario are equal to the RAMMS simulations. The main results are summarized in Tab. 4 and Fig. 21.

Tab. 4: Behrends Avenue avalanche path, results of AVAL-1D dense flow simulation

Elevation above sea level	10-year Scenario		30-year Scenario		300-year Scenario	
	Velocity	Flow height	Velocity	Flow height	Velocity	Flow height
100 m	10 m/s	0.7 m	24 m/s	2.1 m	34 m/s	3.6 m
25 m (Behrends Ave.)	-	-	14 m/s	1.8 m	23 m/s	2.4 m
5 m (Egan Dr.)	-	-	9 m/s	1.5 m	18 m/s	1.9 m

The calculated velocities and flow depths are in a similar range to the RAMMS simulations. The RAMMS simulation for the 300-year scenario gives a slighlty higher maximum velocity. The AVAL-1D simulations show that a 10-year avalanche stops above Behrends Avenue. However, the 30-year and 300-year avalanche overflow Behrends Avenue with velocities of more than 10 m/s. The AVAL-1D calculations confirm the RAMMS simulation. However, the lateral spreading cannot be verified with AVAL-1D because the flow width has to be defined by expert choice. We interpret the calculation of the 30-year avalanche as rather conservative.

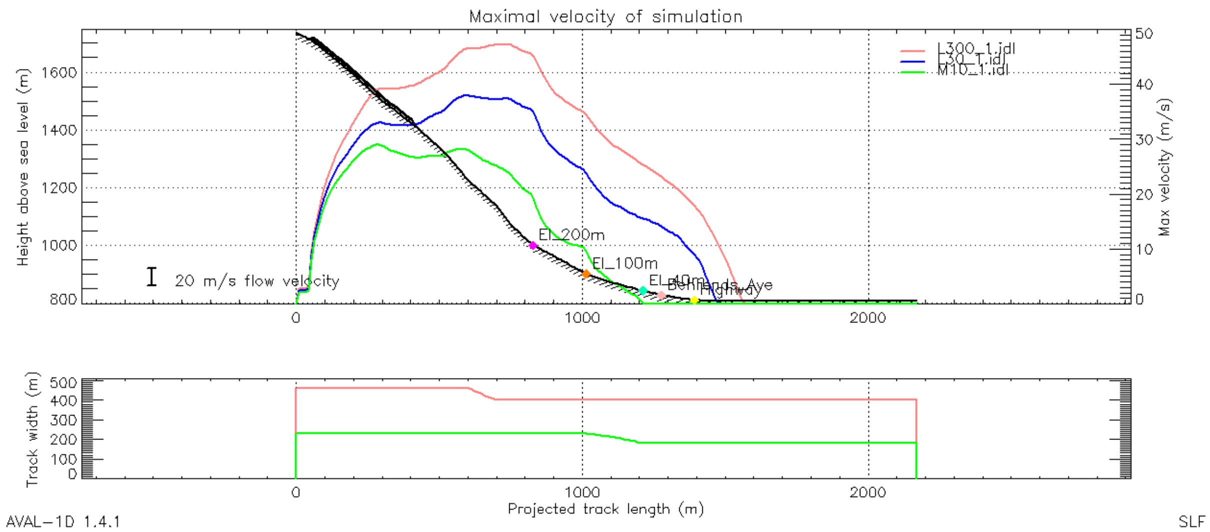

Fig. 21: Maximum velocity of AVAL-1D dense flow avalanche simulation. Red = 300-year avalanche, blue = 30-year avalanche and green = 10-year avalanche. The elevation above sea level was corrected by adding 800 m to take into account the appropriate friction parameters.

Powder snow avalanche simulation

We performed powder snow avalanche calculations for the 30-year and 300-year scenarios. For the 30-year scenario we used a fracture depth of 1.4 m and for the 300-year scenario 2.0 m. The mean snow density was assumed to be 180 kg/m^3. Along the avalanche track we introduced an erodible snow layer with a thickness varying from 2.0 m to 1.5 m and with a mean snow density of 180 kg/m^3 as well. Accounting for the steep topography, we applied an increased suspension rate of 0.25. The suspension rate defines the ratio between the mass of the powder component and the original avalanche mass. The AVAL-1D manual proposes for a “normal” topography (e.g. no cliff bands) suspension rates varying between 0.06 and 0.14. The 300-year avalanche entrains according to the simulation approximately 20% of the snowpack. The entrainment of the 30-year avalanche is much smaller. The uncorrected pressure profiles from the AVAL-1D simulations for the 30-year and 300-year avalanche are given in Figs. 22 and 23. The highest pressures are calculated in the rather thin saltation layer, having a similar effect as a dense flow avalanche. We assume that the saltation layer will be partly stopped by the forest belt above Behrends Avenue. The calculated flow height is 50 m. We think that AVAL-1D underestimates the total flow height. At Behrends Avenue the calculated maximum pressure in the suspension layer of the 300-year avalanche is 9 kPa and for the 30-year avalanche is 4 kPa. Because the lateral spreading of the powder cloud is not considered in the one dimensional calculation the pressure in the suspension layer can be 30% smaller in the lateral boundary area of the powder cloud. We conclude that along Behrends Avenue the maximum pressure in the suspension layer is around 3 to 4 kPa for the 30-year avalanche. Compared to the damages caused by the avalanche from 1962, we think that such a pressure range is reasonable. Within the subdivision a maximum pressure varying between 6 to 9 kPa is developed in the suspension layer of the 300-year avalanche. Such a pressure is capable of damaging a wood-frame house and even destroying it completely. An impact pressure of a powder snow avalanche of 3 to 5 kPa can destroy mature forests. According to the calculations the pressure in the suspension layer decreases to about 1 kPa at a height of 30 m above ground. Such a pressure corresponds to the normal wind pressure applied in structural engineering.

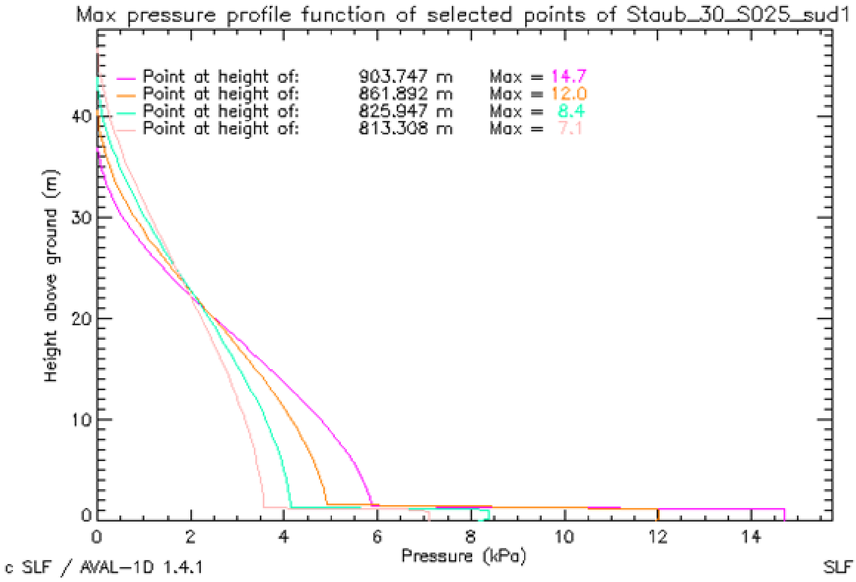

Fig. 22: Maximum pressure profiles of the 30-year powder snow avalanche at different elevations (pink line: 100 m a.s.l., orange line: 60 m a.s.l., light red line: 13 m a.s.l.). The green line corresponds to the location of Behrends Avenue.

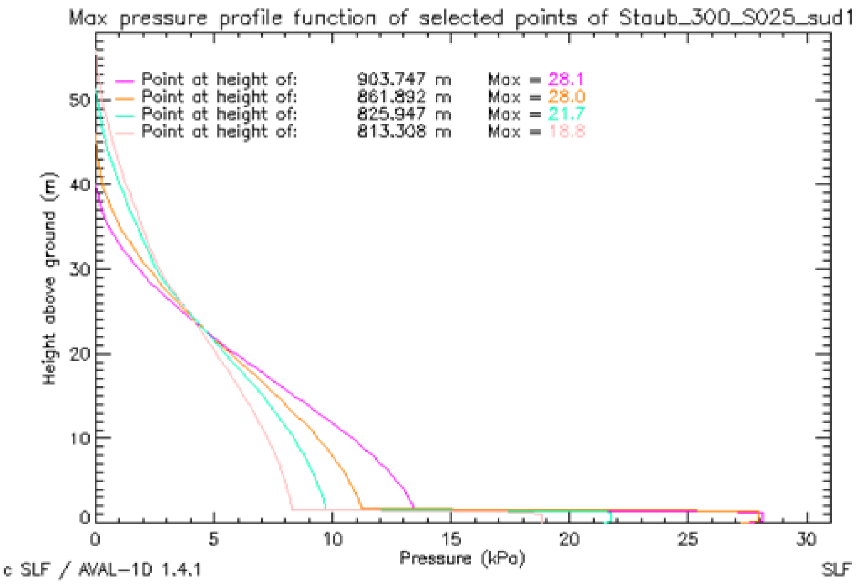

Fig. 23: Maximum pressure profiles of the 300-year powder snow avalanche at different elevations (pink line: 100 m a.s.l., orange line: 60 m a.s.l., light red line: 13 m a.s.l.). The green line corresponds to the location of Behrends Avenue.

6.3.3 Interpretation

Compared to the hazard map of 1992 the RAMMS simulations show a much wider impact area in north-western direction. The severe hazard zone (>30 kPa) is about 120 m wider and the special engineering avalanche zone (<30 kPa) about 180 m wider than in the 1992 hazard map. The severe hazard zone in south-eastern direction is relatively well reproduced in the hazard map of 1992. However, the width of the special engineering avalanche zone is a little too small compared to the RAMMS simulation. We think that the south-eastern boundary area of the hazard map of 1992 is about fine. However, the extent of the hazard zones towards Gastineau Channel and in north-western direction seems to be underestimated as given in the hazard map of 1992. In these areas we think that the hazard map of 1972 is more adequate. To verify the width of the hazard zones towards north-west we propose to make a more detailed investigation. In particular, we recommend that the age of the trees in the endangered forest stand is determined and an analysis is made to asses if there was any avalanche activity 100 or 200 years ago. Based on our assessment the Juneau Douglas High School is not endangered by a 300-year avalanche. We think that only the powder blast of an extreme powder snow avalanche might influence the area. However, we do not expect any structural damages to the building. The Breakwater Inn is situated just at the border to the severe hazard zone.

6.4 Discussion of different measures to reduce the avalanche risk

6.4.1 Introduction

In the following chapter we discuss the application of temporary and structural protection measures to reduce the avalanche risk in the runout zone of Behrends Avenue avalanche path. With the exception of the artificial release of avalanches by explosives, most of the project ideas were previously discussed by Hart (1968) and La Chapelle (1968) after the 1962 avalanche. However to date there are still no structural protection measures in place, which can be attributed to the complexity of the avalanche situation. Today the City and Borough of Juneau has an avalanche forecaster on staff to publish daily public avalanche bulletins and to educate the public about living in a community with avalanche problems. The avalanche bulletins notify the public of times when the danger in avalanche areas is high and these areas should be avoided. The City and Borough of Juneau does not issue orders to evacuate the hazard zones. The avalanche risk in the Behrends Avenue subdivision is very serious and in our opinion – compared to other cases – unacceptable. There are about 28 residential houses in the severe hazard zone. In the special avalanche engineering zone there are about 12 residential houses, 1 hotel, the access road to Juneau and a big boat harbour. We hardly know – worldwide – of a hazard situation with such a damage potential and where no active protection measures were established. We consider the risk situation to be unacceptable.

6.4.2 Artificial release of avalanches

Overview

Artificial release of avalanches is widely used in ski areas and along traffic routes. The standard method for protecting settlements is applying structural mitigation measures such as snow supporting structures or earth dams. New methods for artificial avalanche release (e.g. GAZEX exploder see Fig. 24, Doppelmayer Avalanche guard see Fig. 25, or Wyssen tower see Fig. 26) have been developed over the past few years. These autonomous devices allow remote triggering of avalanches independent of visibility and with good detonation effect. Their application allows local safety services to selectively release avalanches depending on the avalanche situation. There are cases where this technique has been applied to areas above settlements, especially were the costs of structural protection measures were considered to be too high. In general, artificial release by explosives above settlements should be applied with extreme caution and should remain an exception. The main risk of artificial release above settlements is triggering an avalanche that is too large to manage and results in damages. In order to apply artificial release by explosives the avalanche situation must be studied in detail. Important points are evaluating the terrain features in regard to the effectiveness of artificial avalanche release, the potential for triggering secondary avalanches and the existing damage potential. We developed a technical guideline (Stoffel and Margreth, 2009) which defines the most relevant factors for evaluating the safety aspects in case of artificially releasing avalanches above settlements. We evaluate the feasibility of applying artificial release by explosives in the Behrends Avenue and White Subdivision avalanche path according to this guideline.

Fig. 24: Gasex exploder

Fig. 25: Doppelmayr Avalanche guard

Fig. 26: Wyssen tower

Terrain conditions

- Large parts of the release area on Mt. Juneau are very steep. We consider the release probability for avalanches in regard of the slope inclination as good. However, due to the costal and humid climate the snowpack often consists of thawed and refrozen layers which decrease the release probability.
- The potential starting zone is very large (much larger than 20 ha). There are different bowl shaped starting zones which are not very well separated. Under unfavourable conditions large avalanches can be released which is a negative point in the assessment.
- The inclination of the runout zone is relatively steep (>10°). Only small wet snow avalanches are expected to stop above the subdivision. A positive point is the low elevation of the runout zone and the forest stand that slows down small avalanches.
- The steep topography favours the formation of powder snow avalanches. Already small powder snow avalanches can reach the subdivision which is negative.
- A very important point in regard to the feasibility of applying artificial release of avalanches on Mt. Juneau is the problem of **secondary avalanche release**, in particular in the Greenhouse and Flume avalanche paths situated adjacently. The starting zones of the Gnarly and Chop Gully avalanche are within less than 700 m from Behrends Avenue starting zone (Fig. 27), and are not clearly separated from each other. A secondary release of avalanches cannot be ruled out, especially in situations with a wide spread weak layer. If the snowpack is very unstable fracture propagation to the starting zone of the White Subdivision avalanche path cannot be completely excluded. There are no preventive measures in the secondary starting zones. While the damage potential is much smaller compared to Behrends Avenue avalanche path, we have no information on the simultaneous release of the five avalanches (Greenhous to Chop Gully, Fig. 27) in the past. The problem of secondary avalanche release beside the Behrends Avenue avalanche path is considered a negative point.

Damage potential

The damage potential of Behrends Avenue avalanche path is huge. About 28 residential houses are in the severe hazard zone and 12 in the special engineering zone. The Breakwater Inn is also situated in the special engineering zone. We estimate the natural return period for the case that a dense flow avalanche reaches the most exposed buildings to be around 15 years. Most of the buildings have no protection measures (e.g. reinforced back-wall), and seem to be very vulnerable against avalanche impacts. It has already been seen that a small avalanche can cause damages or can throw a tree on a building.

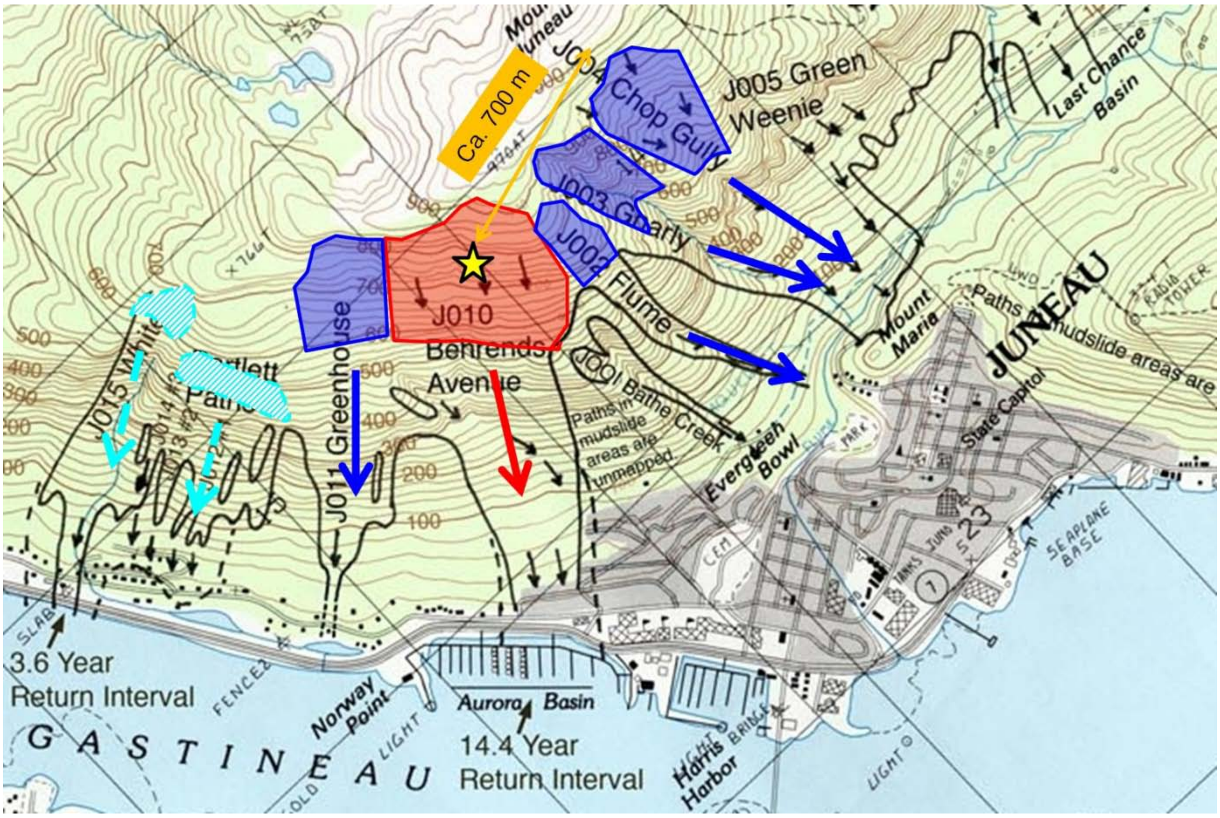

Fig. 27: Avalanche starting zones on the south and south-western side of Mt. Juneau. The starting zones of Greenhouse, Flume, Gnarly and Chop Gully (blue areas) are in a distance of less than 700 m from the Behrends Avenue starting zone (red area). If the snowpack is very unstable fracture propagation to the starting zones of the Bartlett and White Subdivision avalanche path cannot be completely excluded. Secondary releases in the blue and light blue areas cannot be ruled out if avalanche control is performed in the Behrends Avenue starting zone (map source: Bill Glude, Southeast Alaska Avalanche Centre and USGS).

Detonation method and detonation points

In the starting zone of Behrends Avenue avalanche a release system independent of weather, with a high detonation effect and remote control has to be applied. There are several locations with favourable slope inclinations of more than 35°. The effective diameter of a detonation depends on the system and varies between 100 and 240 m. We think that at least 6 detonation points would be necessary. The cost for one system is around 150'000 USD. The detonation points with the highest release probabilities seem to be situated along the top ridge of Mt. Juneau (detonation points 1, 2, 3 and 5; Fig. 28). A problem of this solution is that between 800 m and 500 m there are additional starting zones which are not covered by the proposed 6 detonation points. The installation of fixed release systems in these lower starting zones is problematic as they may be damaged by avalanches releasing above. Moreover, there is the potential that an avalanche, for example triggered at the detonation point 1, might entrain a large volume of snow during its flow and reach a dangerous size. We think that it is very difficult to limit the size of an artificially triggered avalanche in the Behrends Avenue path to a given volume considered to be not dangerous.

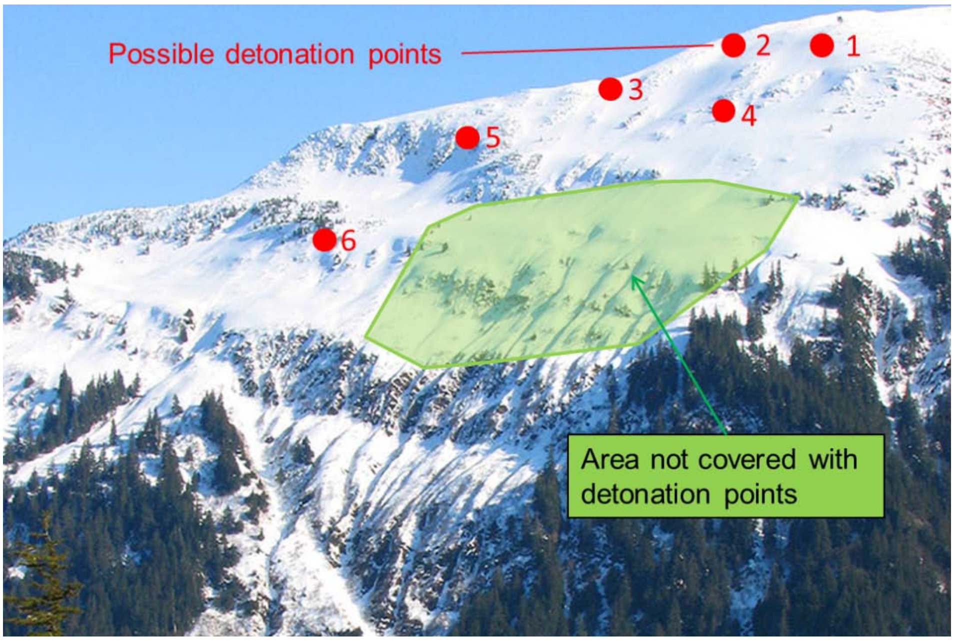

Fig. 28: Possible detonation points in the starting zone of Behrends Avenue avalanche.

Preventive closures and evacuations

The goal of artificial release is to trigger only small avalanches that will not cause damage. A small dense flow avalanche (return period less than 10 years) will not reach the subdivision. However due to the steep avalanche path, the formation of powder snow avalanches cannot be entirely excluded. A small powder snow avalanche has the potential to break trees which can damage buildings in the subdivision. Furthermore, the powder cloud can decrease the visibility on the road. Therefore, it is strongly recommended to at least evacuate the severe hazard zone and close Glacier Highway and Egan Drive during the artificial release of avalanches. We do not recommend triggering avalanches artificially by explosives above the subdivision without any evacuations, since most of the buildings are not reinforced and persons inside will be endangered. It is noted that organizing evacuations and road closures would be quite time consuming. During the discussions it has been learnt that the City and Borough of Juneau did not evacuate people from endangered buildings in the past. We think conditions are very unfavourable for artificially releasing avalanches in the Behrends Avenue avalanche path.

Weather data and check of detonation results

There is an automatic weather station on Mt. Roberts (elevation ca. 550 m a.s.l.), while at the elevation of the starting zone on Mt. Juneau there is no automatic weather station. Snow profiles are made on a regular basis on Mt. Juneau. Although this provides some snow information, we do not think this to be sufficient to adequately assess the snow conditions in the starting zone during a storm period. Also during conditions of poor visibility the ability to check the results of triggering attempts will be compromised.

Conclusions

We do not recommend applying the artificial release of avalanches in the Behrends Avenue avalanche path under the current conditions. The risk to persons and buildings is much too high. We think that the artificial release of avalanches would only be possible in combination with structural measures (see chapter 6.4.3 to 6.4.6) and with the option to evacuate people.

6.4.3 Snow supporting structures

The purpose of supporting structures is to prevent avalanche release, or at least to prevent snow movements that may lead to damage (Fig. 29). Supporting structures are generally required for slope inclinations between 30° and 50°. A major advantage of snow supporting structures is that also powder snow avalanches can be prevented. The area that would require snow supporting structures in Behrends Avenue avalanche path is 25 ha and has a mean inclination of 39.5°. The height of the structures must at least match the extreme snow height anticipated for the area (Fig. 30). A problem of the present starting zone is that there are no long-term snow measurements available. If snow supporting structures are considered an option, we recommend that snow depth measurements are performed as soon as possible, especially in depressions where we expect large snow accumulations. We estimate that the extreme snow depth may vary between 5 and 8 m, which would correspond to a structure height of 3.9 to 6.2 m. Standard snow supporting structures are available up to a maximum height of 4.5 m. We estimated that in total 10'800 m of structures would be required (Fig. 31). According to experience, the cost per meter would be around 3000 USD, with a total cost of at least 32 Mio USD. Due to the steepness of the starting zone, we do not recommend that a financial compromise is sought and only a portion of the proposed structures be built. With such an incomplete solution there would still be the possibility that an avalanche might reach the subdivision. Additionally, the starting zone is considered to consist of unstable ground which would require expensive foundations and high maintenance costs. At the moment we do not recommend the construction of snow supporting structures; further information on the snow height and the ground conditions in the starting zone would be required before a final assessment on the feasibility can be made. The possibilities to finance such a huge project have to be clarified. Further there is no experience with the construction, behaviour and design of snow supporting structures in Alaska. As a first step, the installation of a small test site on Mt. Juneau would be advisable prior to embarking upon such a huge project.

Fig. 29: Snow supporting structures in the Swiss Alps. The structures consist of snow bridges made of prefabricated steel elements.

Fig. 30: The structure height is decisive for their effectiveness and for the structural design. Overfilled structures can be damaged and avalanches can break loose above the structures.

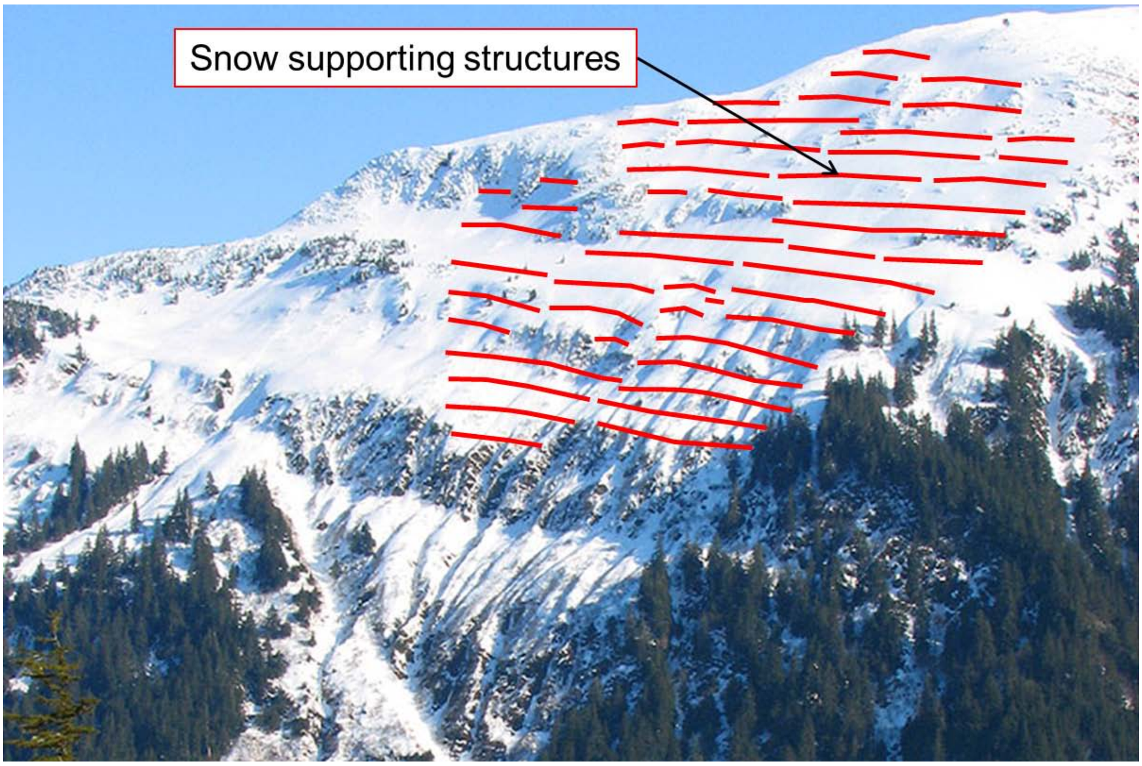

Fig. 31: Principal drawing for snow supporting structures on Mt. Juneau (not to scale!)

6.4.4 Deflecting dams

Option 1: We estimate that a 300 m long deflecting dam could divert the avalanche from the subdivision (Fig. 32). The dam should be built as close as possible to the subdivision. The design velocity for a 300-year avalanche is around 30 m/s at the dam location. The flow depth is expected to be around 3.0 m and the depth of previous snow and avalanche deposits is assumed to be 2.0 m. The deflecting angle which widely controls the necessary height of the dam varies between 45° and 55°. The height of the dam should be at least 25 m. The length of the dam would be around 330 m. The dam would protect the subdivision well from dense flow avalanches. However below the dam there will still be a rather high risk of powder snow avalanche impacts. Avalanche impacts comparable to 1962 cannot be prevented in the subdivision. The main disadvantage of this option is that the deflecting angle of the dam is rather high. Experience has shown that for deflecting dams to perform well deflecting angles of less than 25° to 30° are required. The dam deflects the avalanche in western direction with the disadvantage that the risk to the buildings along Glacier Avenue north-west of Ross Way will be much increased compared to the present situation. The fill volume of the dam would be around 210’000 m^3. The cost of the dam would be around 6 Mio. USD with an estimated standard price of 28 USD per m^3 fill material. No geotechnical pre-investigations were made at the possible location of the dam. The feasibility of the proposed dams must be assessed by further investigations which take into account, not only avalanches but additionally geological, engineering, environmental and infrastructure aspects. In addition, the known and potential mass wasting processes must be considered in the design.

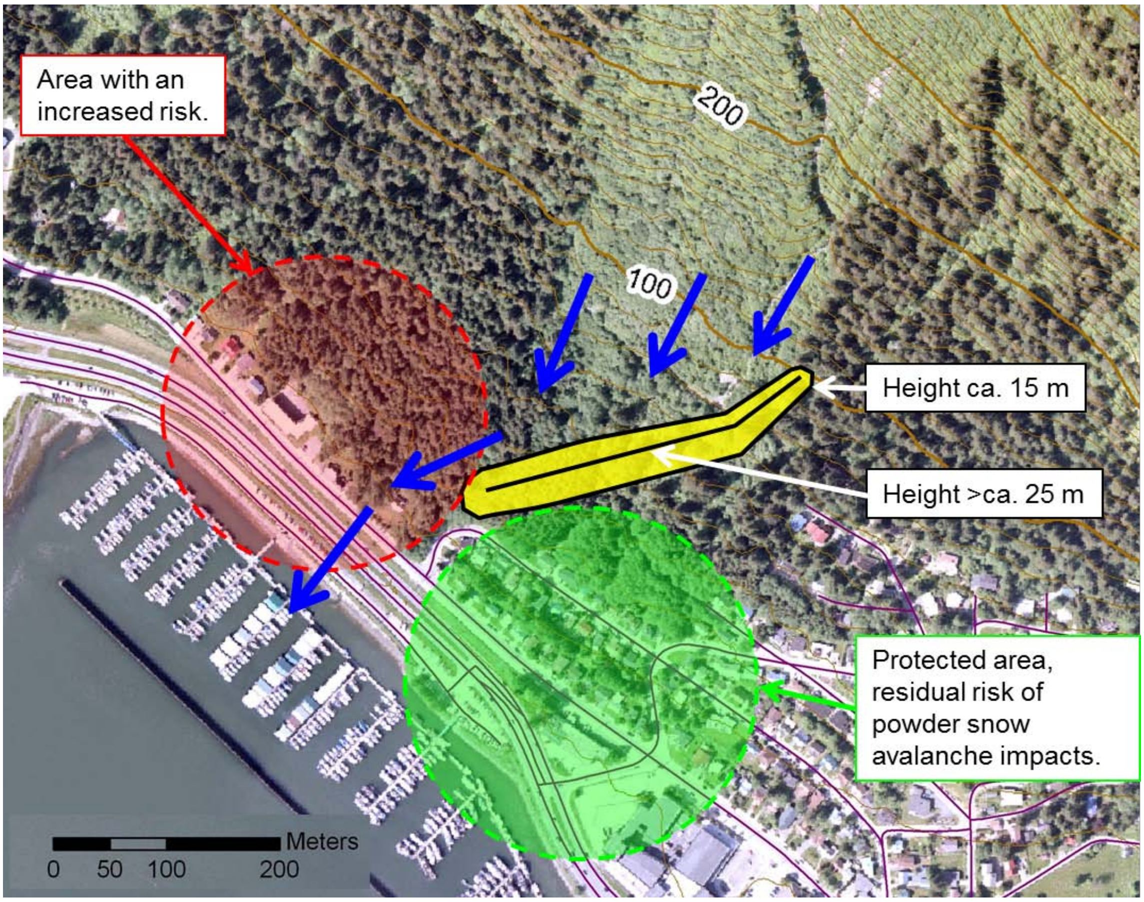

Fig. 32: Avalanche deflecting dam option 1 for the protection of Behrends Avenue.

Option 2: To improve the deflecting angle in comparison to option 1 the deflecting dam would require ending just north of the Breakwater Inn (Fig. 33). This would create a deflection angle of around 30° and the necessary dam height could be slightly reduced to 18 m. The fill volume of the dam would be around 120’000 m^3 with a cost of around 3.4 Mio. USD using the estimate price of 28 USD per m^3 for the fill material. The main disadvantage of option 2 is that it would require that over 25 buildings be dismantled to allow the deflecting dam to be built. Further the avalanche risk on Egan Drive and at the boat harbour will increase locally. In view of the high costs for the construction, the costs for the homes and the most likely poor acceptance of option 2 we think that this option is hardly feasible.

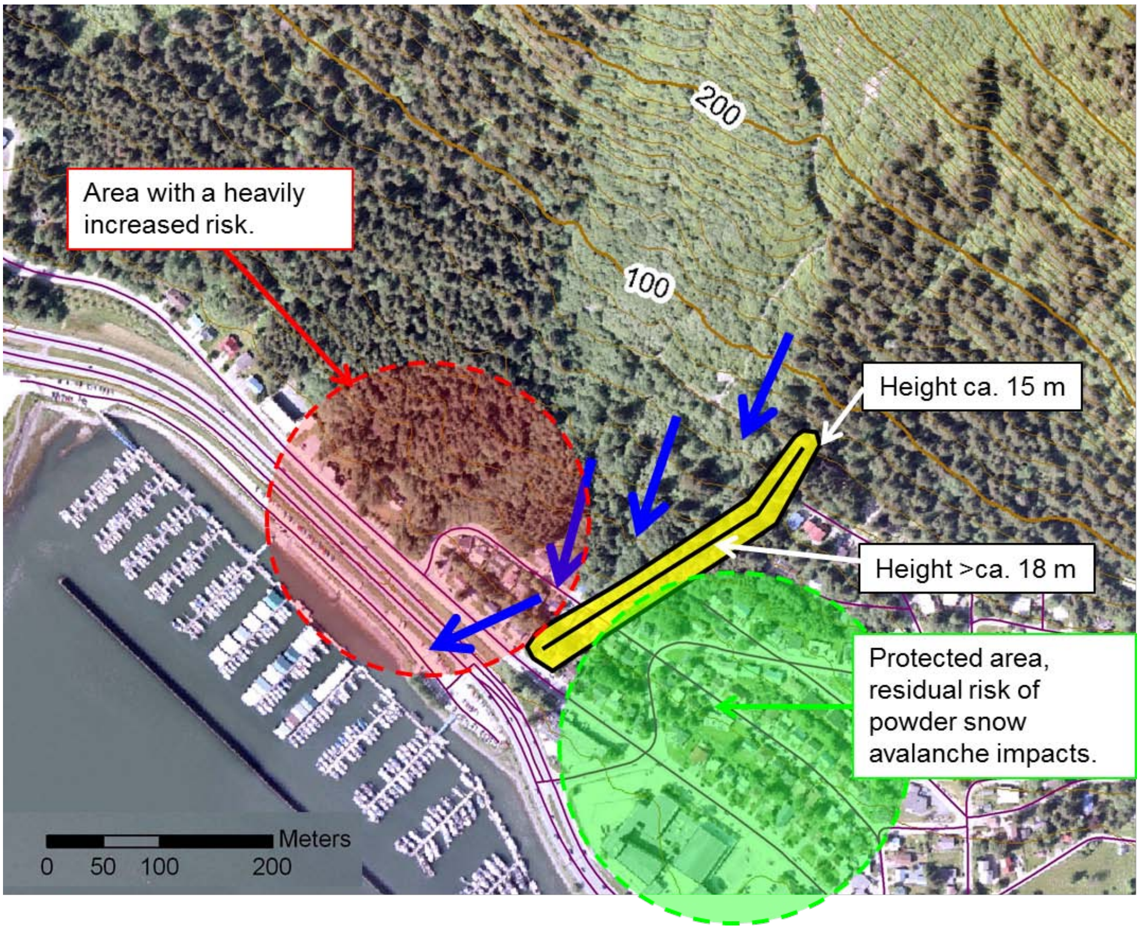

Fig. 33: Avalanche deflecting dam option 2.

We conclude that in regard of the densely populated area a deflecting dam brings the main disadvantage that in some areas the risk will be much higher than before. The realisation of such a structure would cause lengthy discussions and possible lawsuits. Therefore we think that the planning of a deflecting dam neither according to option 1 nor according to option 2 can be recommended.

6.4.5 Catching dams

The goal of a catching is to reduce the runout distance of an avalanche. The design height depends strongly on the avalanche velocity. A design velocity of 30 m/s would require a dam height of at least 35 m! Such a height is very similar to the dam height proposed by La Chapelle (1968). The catching dam should be built as close to the subdivision as possible (Fig. 34). In the present situation the effectiveness of the dam has to be evaluated very carefully given the effect of powder snow avalanches. A powder snow avalanche cannot be stopped by a catching dam. A recirculation zone with intensified turbulences immediately downstream of the dam will be formed (Johannesson 2009). It is not recommended to reduce impact pressures in the wake of the dam within a distance of ~2–3 dam heights downstream. Powder avalanche impacts similar to the avalanche of 1962 cannot be prevented in the Behrends Avenue. The dam height could be decreased to about 25 m if upstream of the dam two lines of breaking mound would be built (Fig. 34). A catching dam has the advantage that the risk is not increased downstream of the structure. Thus also the risk on Egan Drive and Glacier Avenue would be reduced. We estimate the fill volume of a 35 m high catching dam to be around 400'000 m^3. The costs would be around 12 Mio. USD. The feasibility of the catching dam must be approved by further investigations which take into account besides avalanches also geological, engineering, environmental and infrastructural aspects. In addition, the known and potential mass wasting processes must be considered in the design. A catching dam could protect the subdivision also from mass wasting processes.

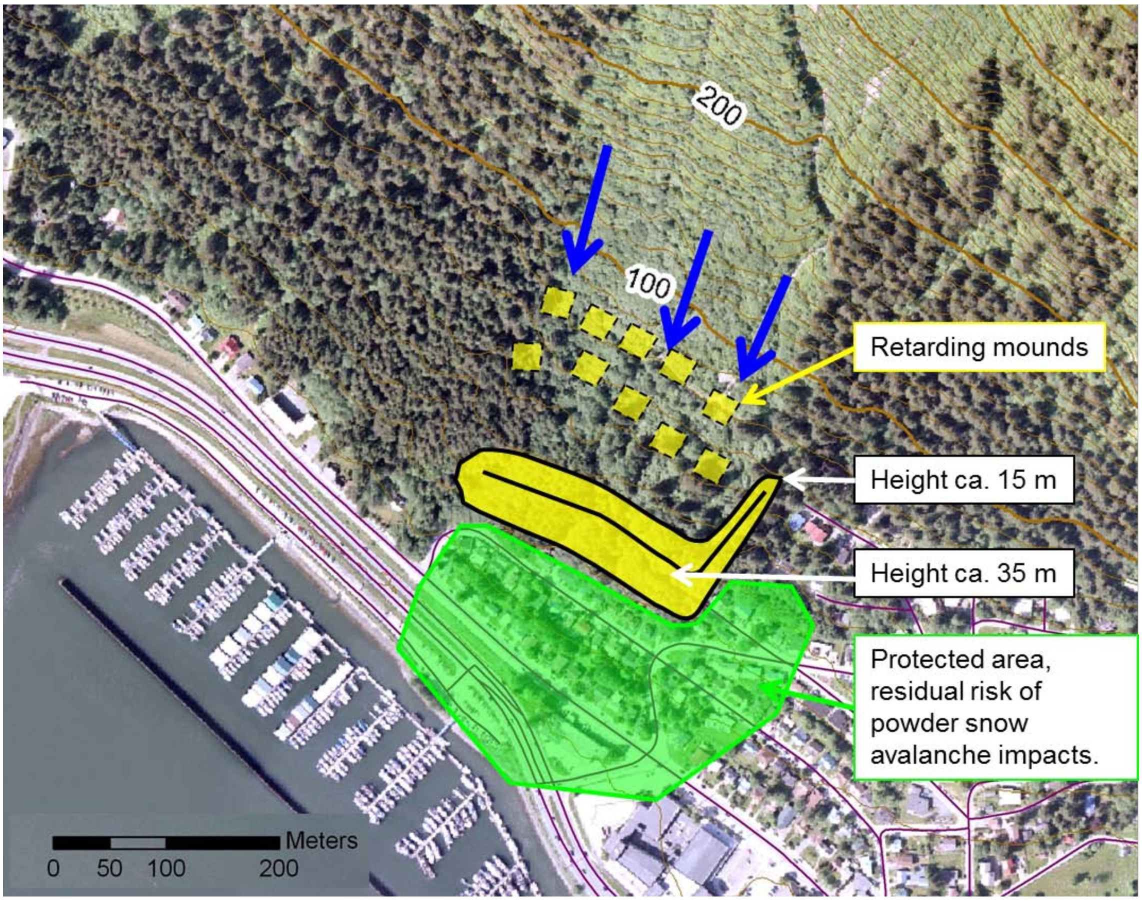

Fig. 34: Avalanche catching dam with two possible lines of retarding mounds.

6.4.6 Direct protection of buildings

The goal of direct protection is to shelter an individual object exposed to avalanche hazards. The most often applied form is the direct reinforcement of the building against avalanche impacts (e.g. concrete back-wall without openings). However, such structural reinforcement is in most cases only feasible for new buildings. The utilization concept of an existing building with entrances or windows makes the direct protection often impossible. In such situations the construction of walls or avalanche splitters is the only solution (Figs. 35 and 36). However in the present situation both possibilities are hardly feasible. There is not sufficient space to build a wall and the costs are estimated to be even higher than the value of the building to be protected. An avalanche splitter would increase the risk to the neighbouring buildings. We conclude that the direct protection of the endangered buildings in the subdivision is not recommendable.

6.4.7 Buyout of homes and prohibiting new constructions in avalanche zones

The most effective way to reduce the avalanche risk in the subdivision would be the buyout of the endangered homes by the Government and to prohibit new constructions or to demand the reinforcement of new buildings in the special engineering zone. In view of the complex avalanche situation where the avalanche risk can be hardly effectively reduced with traditional protection measures the buyout of the endangered homes should be implemented. Appendix 5 shows a priority ranking for the buyout of homes in the severe hazard zone. The ranking is based on the results of the avalanche dynamics calculations, the study of the avalanche history and terrain analysis. The architecture, type of use of the buildings and number of inhabitants were not considered in the ranking.

A less intrusive measure would be to ban the endangered area during the avalanche period (e.g. November – May) and to allow limited activities in summer time. With such a measure the risk of damage to property can however not be eliminated. Furthermore, enforcing the measure during winter time is demanding.

Fig. 35: Avalanche wedge made of concrete to protect an endangered building on an alp (Switzerland). The wedge was built some years after the construction of the hut.

Fig. 36: 10 m high wall for the protection of buildings in Galtür (Austria). The wall was built some years after the construction of the buildings.

7 White Subdivision avalanche path

7.1 Avalanche situation

The White Subdivision is situated on a lower shoulder of Mt. Juneau. The drop height to the subdivision is around 720 m (Fig. 37). The avalanche path is much smaller compared to the Behrends Avenue avalanche path. However the mean inclination from the crown line to the subdivision is 35°, i.e. even a bit steeper compared to the Behrends Avenue avalanche path. The key feature of the avalanche path is that a narrow sloping bench is situated beneath the relatively small bowl-shaped main starting zone. Small avalanches will be slowed or even stopped on the bench. Medium sized avalanches will however overflow the bench. The main starting zone has an inclination of about 42° and the surface area is 3 ha. Below the bench the terrain is very steep with an inclination of 45° to 55°. Avalanches overflowing the bench will accelerate in this section and the formation of powder snow avalanches is likely. Small avalanches can break loose in this steep section as well. However, we assume that during a snow storm in most cases the fresh snow will discharge continuously. Below the steep part the avalanche path is V-shaped and curved. A fast flowing avalanche will break out of the gully and flow directly down slope. The slope inclination of the fan decreases from 35° to 20°. At an elevation of 100 m the forest belt starts. Along the main flow direction there is a 50 m wide clearing in the forest (Figs. 38 and 40). The subdivision is situated around the forest clearing. Below Glacier Highway the inclination of the avalanche track drops to less than 10°.

The Bartlett avalanches 2 and 3 are found south of the White Subdivision avalanche path (Fig. 37). Compared to the White Subdivision avalanche path the hazard potential is much smaller. The forest belt seems to slow down the avalanches. We provide no further investigation of the Bartlett avalanche paths in this report. We refer to the 1992 report (Mears et al., 1992).

Beside avalanches, mudflows occur frequently in the White Subdivision avalanche path.

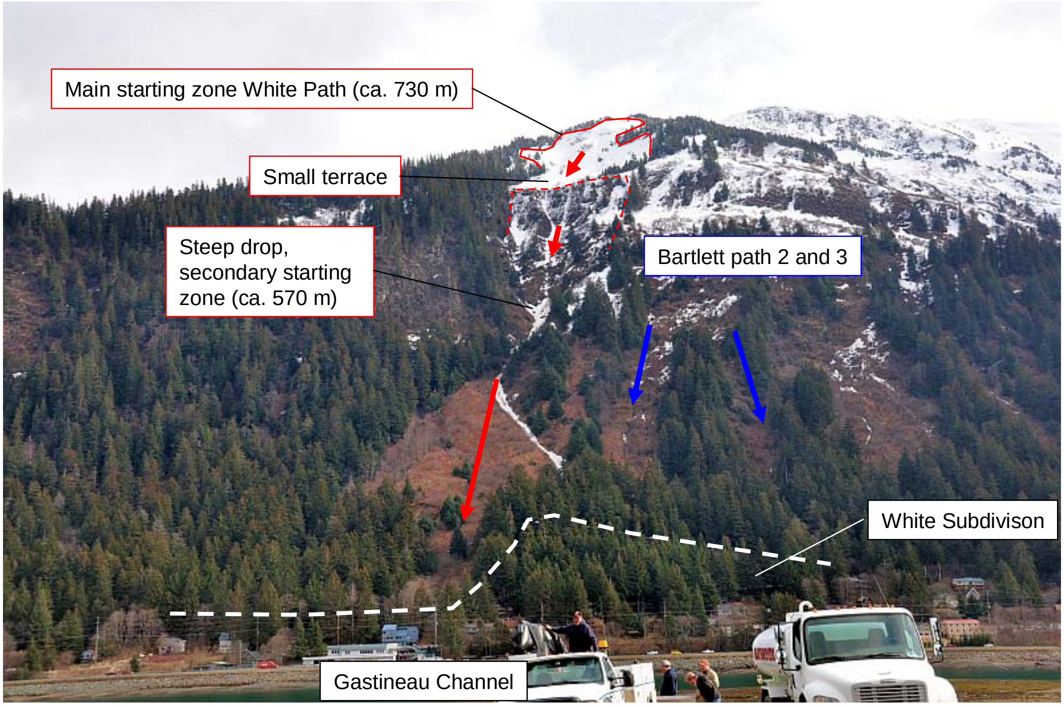

Fig. 37: Overview White Subdivision avalanche path.

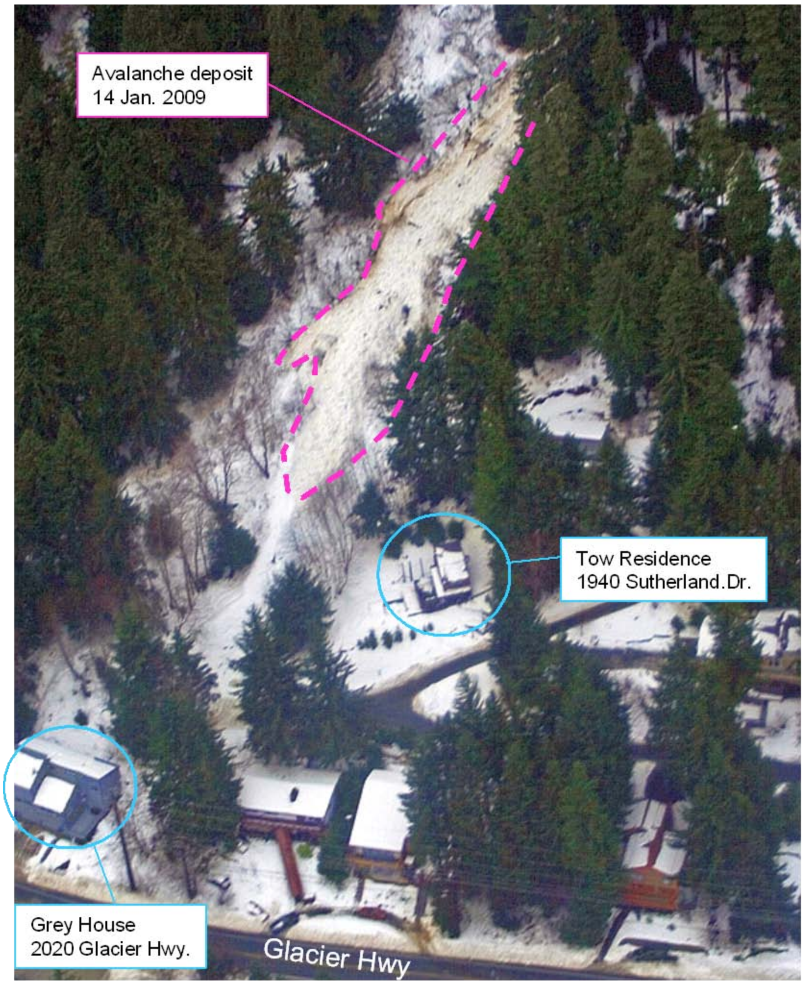

Fig. 38: Avalanche deposit of a small avalanche close to the White Subdivision, 14 Jan. 2009 (Photo M. James).

Fig. 39: The Tow Residence (1940 Sutherland Drive) is one of the most exposed buildings in the White Subdivision. In 1985 four avalanches occurred in the avalanche path and the Tow Residence was hit two times (Photo D. Fesler, 20 Feb. 1985).

7.2 Avalanche history

The avalanche history of the White Subdivison avalanche path is much shorter compared to the Behrends Avenue path. The first events date from 1962. The White Subdivision was hit several times by avalanches. We estimate that the elevation of 30 m a.s.l. (Tow Residence, see Fig. 39) is reached at least every 5 years and the Glacier Highway is reached at least every 10 years. Most of the observed avalanches were rather small. We have no information on structural damages to buildings. We think that no extreme avalanche was observed since 1962. La Chapelle (1968) mentioned in his report that during the 1930's an avalanches reached the Glacier Highway. If we compare aerial photographs from 1926 with the actual situation we can see that the extent of the forest was smaller in 1926 than today (Fig. 40). There was approximately a 30 m wide gap in the forest belt along the White Subdivision avalanche path.

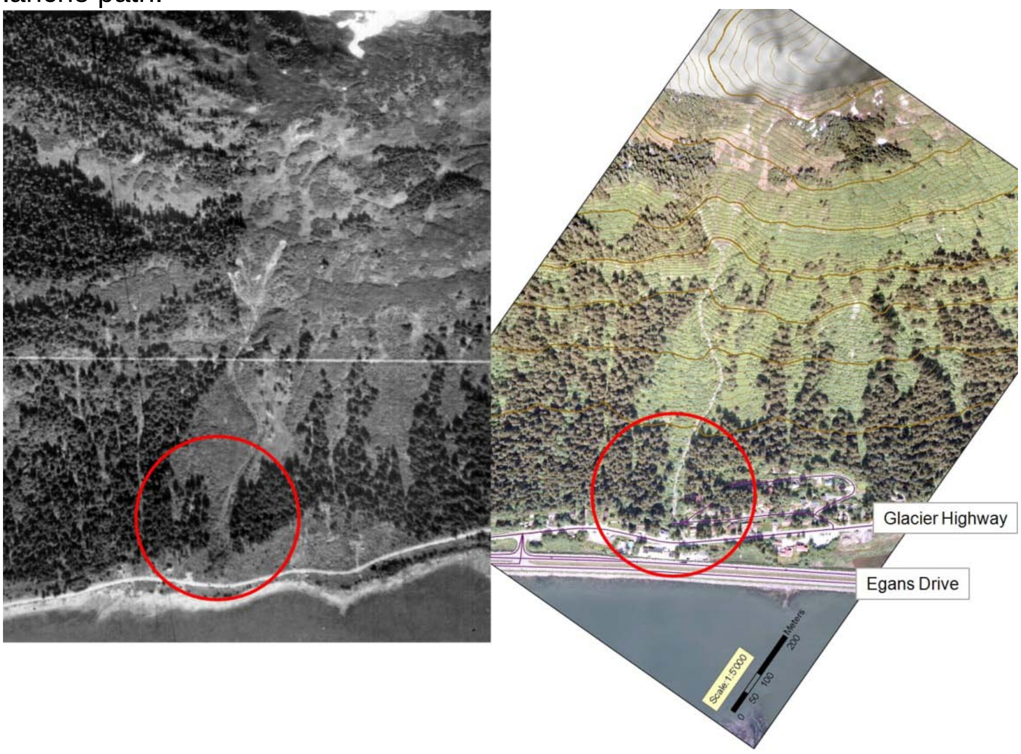

Fig. 40: Aerial photograph from 1926 (source: USGS Photo 29370, 1926) on the left and aerial photograph from 2006 on the right (source: CBJ). The extent of the forest was 1926 slightly smaller than 2006.

7.3 Avalanche dynamics calculations

7.3.1 RAMMS simulations

We calculated three different scenarios with return periods of 10-, 30- and 300-years. The extent of the starting zones was determined mainly on the basis of an expert assessment considering the slope inclination, the topography and the forest pattern. The characteristics of the different scenarios are given in Tab. 5. We applied friction parameters to the calculations accounting for the areas of forest that lie on either side of the main avalanche track (Fig. 44) with the use of a forest shape file. We assumed for the simulations only an avalanche release in the main starting zone. In reality an avalanche would entrain or release also snow below the bench.

Tab. 5: Investigated RAMMS scenarios White Subdivision avalanche path

Scenario	Volume	Volume category	Mean fracture depth
10 years	20’000 m^3	small	1.2 m
30 years	38’000 m^3	medium	1.3 m
300 years	53’000 m^3	medium	1.8 m

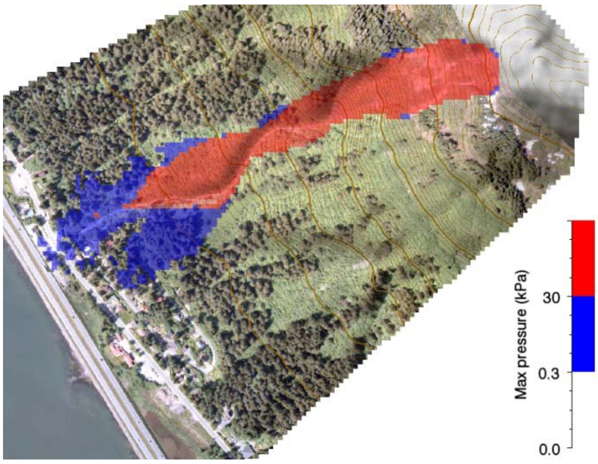

Fig. 41: Uncorrected RAMMS simulation results of the 10-year White Subdivision avalanche. Red = impact pressure > 30 kPa and Blue = impact pressure < 30 kPa.

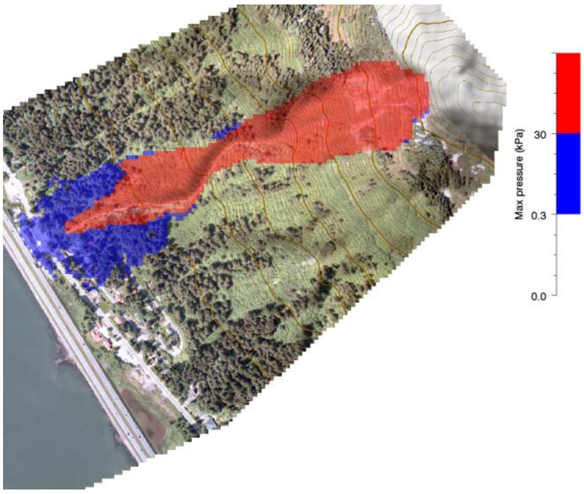

Fig. 42: Uncorrected RAMMS simulation results of the 30-year White Subdivision avalanche. Red = impact pressure > 30 kPa and Blue = impact pressure < 30 kPa.

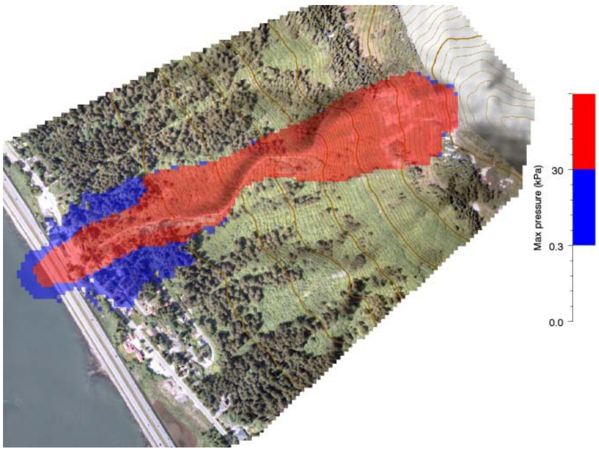

Fig. 43: Uncorrected RAMMS simulation results of the 300-year White Subdivision avalanche. Red = impact pressure > 30 kPa and Blue = impact pressure < 30 kPa.

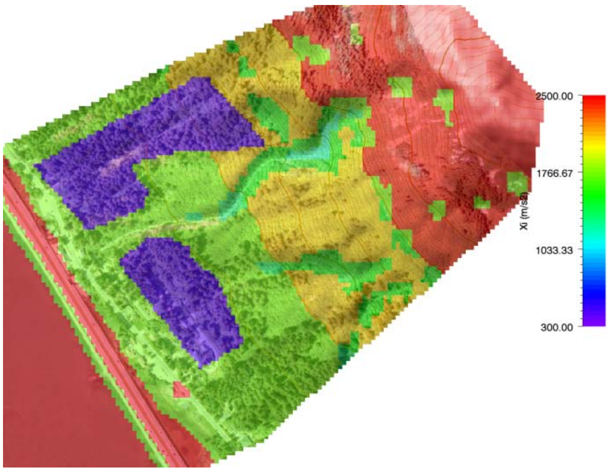

Fig. 44: Friction parameter xi of the RAMMS simulation of the 300-year White Subdivision avalanche. The violet areas have an increased friction value (forest).

The main results of the different RAMMS simulations are given in the following Tab. 6 and in the Appendices 4.1, 4.2 and 4.3.

Tab. 6: White Subdivision avalanche path, results of RAMMS-simulation

Elevation above sea level	10-year Scenario		30-year Scenario		300-year Scenario	
	Velocity	Flow height	Velocity	Flow height	Velocity	Flow height
80 m	15 m/s	0.6 m	33 m/s	1.6 m	41 m/s	1.1 m
60 m	9 m/s	1.2 m	22 m/s	0.6 m	36 m/s	1.2 m
40 m	8 m/s	1.1 m	17 m/s	1.3 m	31 m/s	2.2 m
Glacier Hwy.	0 m/s	0 m	3 m/s	0.3 m	23 m/s	1.4 m
Gastineau channel	0 m/s	0 m	0 m/s	0 m	13 m/s	0.9 m

- The 10-year avalanche stops just above of Glacier Highway. The zone with impacts of more than 30 kPa is not situated in the subdivision (Fig. 41, Appendix 4.1).
- The 30-year avalanche overflows Glacier Highway and stops beside Egan Drive. The zone with impacts of more than 30 kPa is situated mostly outside of the subdivision (Fig. 42, Appendix 4.2). Most of the subdivision is in an area with an impact pressure of less than 30 kPa.
- According to the simulations the 300-year avalanche reaches the Gastineau Channel with an intensity of more than 30 kPa (Fig. 43, Appendix 4.3). The avalanche flows along the flume and flows through the subdivision with a velocity of more than 23 m/s and a flow height between 1.2 and 2.2 m. The flow width of the high intensity zone is around 90 m and the total flow width is around 270 m. Below the steep section the avalanche leaves the gully and flows straight down slope. The extent of the severe hazard zone corresponds well to the existing forest pattern.

7.3.2 AVAL-1D simulations

Dense flow avalanche simulation

The terrain profile for the AVAL-1D simulation was chosen along the main axis of the slide path and with a flow width corresponding to the results of the RAMMS simulations. The avalanche volumes of the 30- and 300-year scenarios are equivalent to the RAMMS simulations. The main results are summarized in Tab. 7.

Tab. 7: White Subdivision avalanche path, results of AVAL-1D simulation (dense flow avalanche)

Elevation above sea level	30-year scenario		300-year scenario	
	Velocity	Flow height	Velocity	Flow height
40 m	15 m/s	1.4 m	21 m/s	1.7 m
Glacier Hwy.	9 m/s	0.9 m	15 m/s	1.4 m
Gastineau Channel	0 m/s	0 m	7 m/s	0.7 m

The calculated velocities and flow heights are in a similar range as the RAMMS simulations (Fig. 45). The RAMMS simulation for the 300-year scenario gives higher maximum velocities and the runout distance is longer. One reason for the discrepancies is that the velocity of AVAL-1D is constant over the whole width of the avalanche whereas the velocity in the RAMMS simulation varies over the width. The AVAL-1D calculations confirm that the severe hazard zone with avalanche impacts of more than 30 kPa should extend at least to Egan Drive.

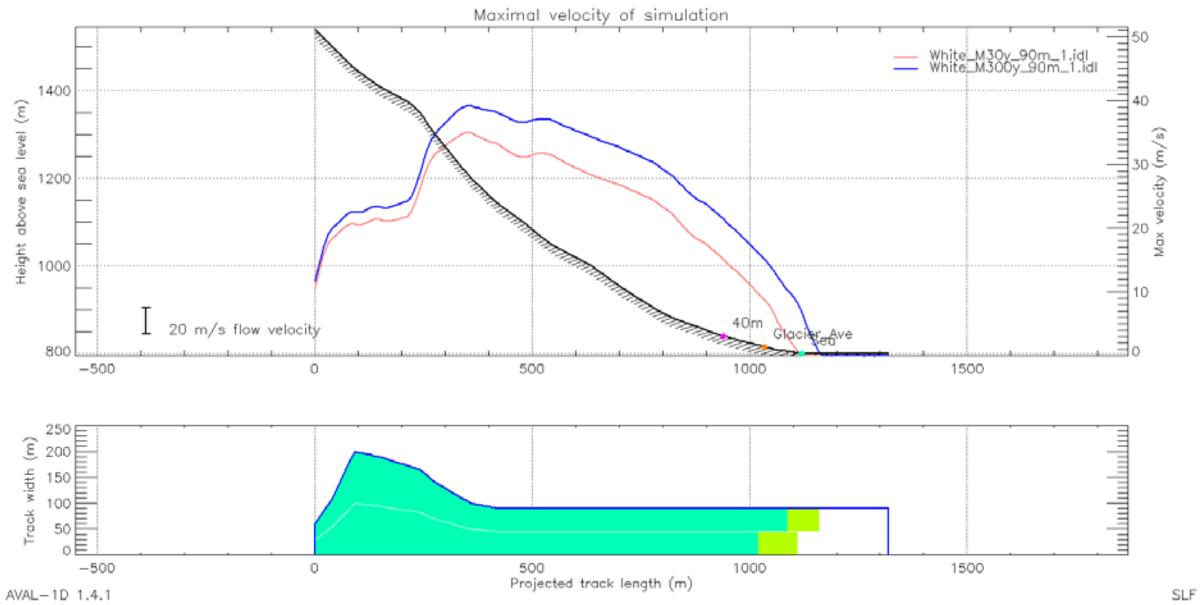

Fig. 45: Maximum velocity of the AVAL-1D simulation of the White subdivision avalanche path (the elevation above sea level was increased by 800 m to better match the friction parameters with regard to the Juneau climate).

Powder snow avalanche simulation

We performed powder snow avalanche calculations for the 30-year and 300-year scenarios. For the 30-year scenario we used a fracture depth of 1.3 m and for the 300-year scenario of 1.8 m. The mean snow density was assumed to be 180 kg/m^3. In addition we introduced an erodible snow layer with a thickness of 1.8 m and with a mean snow density of 180 kg/m^3 along the avalanche track. Because of the steep topography interspersed with cliffs we applied an increased suspension rate of 0.25. This is the same value as applied for the calculation of the Behrends Avenue avalanche. The 300-year avalanche entrains less than 20% of the snowpack. The entrainment of the 30-year avalanche is small. The uncorrected pressure profiles for the 30-year and 300-year scenarios are given in Figs. 46 and 47. The highest pressures are calculated in the rather thin saltation layer which has a similar effect as the dense flow avalanche. We assume that the saltation layer will be partly stopped by the forest belt above the subdivision. The flow height of the powder cloud is calculated to around 40 m. At the elevation of 40 m a.s.l. (i.e. approximately at the elevation of the Tow Residence) the calculated maximum pressure is 3 kPa in the suspension layer of the 30-year avalanche (Fig. 46) and 6 kPa in the suspension layer of the 300-year avalanche (Fig. 47). Because the lateral spreading of the powder cloud is not considered in the one dimensional calculation model the pressure in the suspension layer can decrease by approximately 30% in the boundary area of the powder cloud.

We conclude that in the subdivision the pressure of a powder snow avalanche is about 2 to 3 kPa for the 30-year avalanche and 4 to 6 kPa for the 300-year avalanche. The 30-year powder snow avalanche only has the potential to cause small damage to buildings and forest. However the 300-year powder snow avalanche has the potential to be very destructive.

7.3.3 Interpretation

According to the avalanche simulations the severe hazard zone (>30 kPa) should extend at least to Egan Drive. This is about 40 m further downslope compared to the avalanche hazard map of 1992 where the severe hazard zone ends at Glacier Highway. In the hazard map of 1972 the severe hazard zone reaches the Gastineau Channel. Comparing the simulations to our assessment, the lateral extent of the severe hazard zone and the special engineering avalanche zone (< 30 kPa) as shown in Fig. 5 are acceptable.

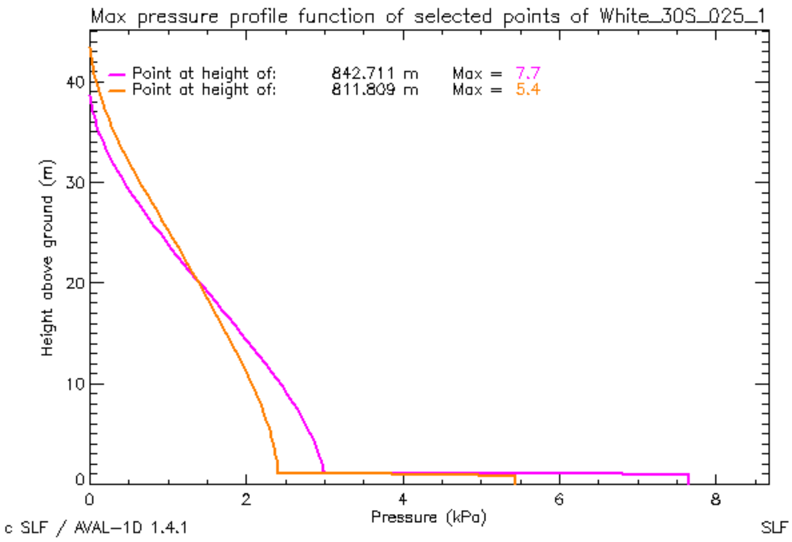

Fig. 46: Maximum pressure profiles for a return period of 30-year at an elevation of 40 m a.s.l. (pink line) and 10 m a.s.l. (orange line).

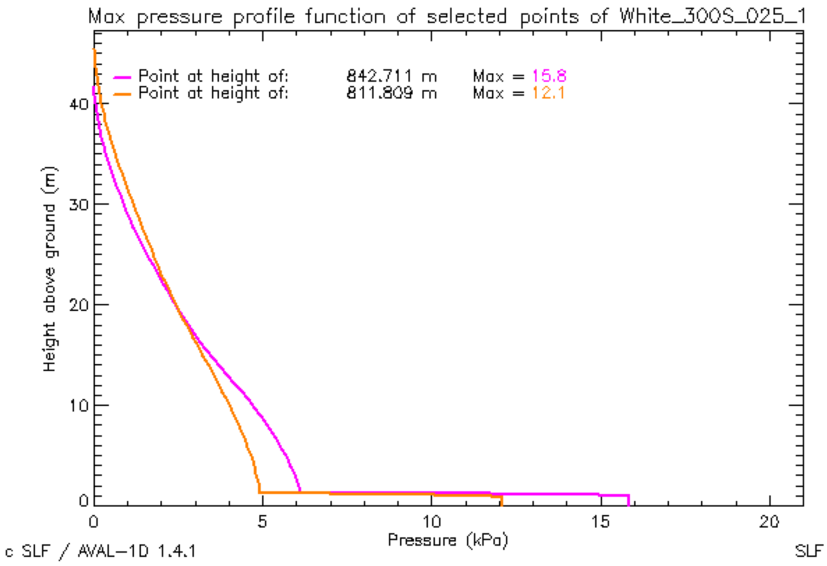

Fig. 47: Maximum pressure profiles for a return period of 300-year at an elevation of 40 m a.s.l. (pink line) and 10 m a.s.l. (orange line).

7.4 Discussion of different measures to reduce the avalanche risk

7.4.1 Introduction

In the following chapter we discuss the application of temporary and structural mitigation measures to reduce the avalanche risk in the runout zone of the White Subdivision avalanche path. So far no protection measures have been investigated for this avalanche path. In the severe hazard zone there are approximately 5 residential houses, and in the special engineering avalanche zone there are about 8 buildings, in addition to a section of Glacier Highway and Egan Drive. The buildings endangered by the Bartlett path are not included in this discussion. Compared to the Behrends Avenue avalanche path there are fewer objects at risk, however the risk situation is still unacceptable. The buildings that are located in the hazard zones have no apparent structural reinforcements.

7.4.2 Artificial release of avalanches

Overview

Similarly to the Behrends Avenue avalanche path, we evaluate the application of artificial avalanche release in the White Subdivision avalanche path.

Terrain conditions

- The main starting zone is very steep. We consider that there is a mostly good release probability for avalanches given the slope inclination.
- The potential starting zone is rather small (much less than 10 ha). However, under unfavourable conditions the release of the entire principle starting zone is likely. A positive point is that the starting zone and the flow direction are well defined.
- The inclination of the runout zone is very steep (>15°). Not even small wet snow avalanches stop above the subdivision. A positive point is the low elevation of the runout zone and the breaking effect of the forest belt.
- The steep topography favours the formation of powder snow avalanches. Already small powder snow avalanches are capable of reaching the subdivision. We consider this a negative point.
- The problem of a **secondary avalanche release** is smaller compared to the Behrends Avenue avalanche path. Especially the Bartlett avalanche paths 1, 2 and 3 are situated very close to the main starting zone of the White Subdivision path (Fig. 48). However a secondary release cannot be excluded, especially in situations with a wide spread weak layer. The starting zones of Greenhouse and Behrends Avenue avalanche path are farther away and a secondary release seems to be in most situations unlikely. We have no information on a simultaneous release of the White Subdivision avalanche path and the Bartlett paths.

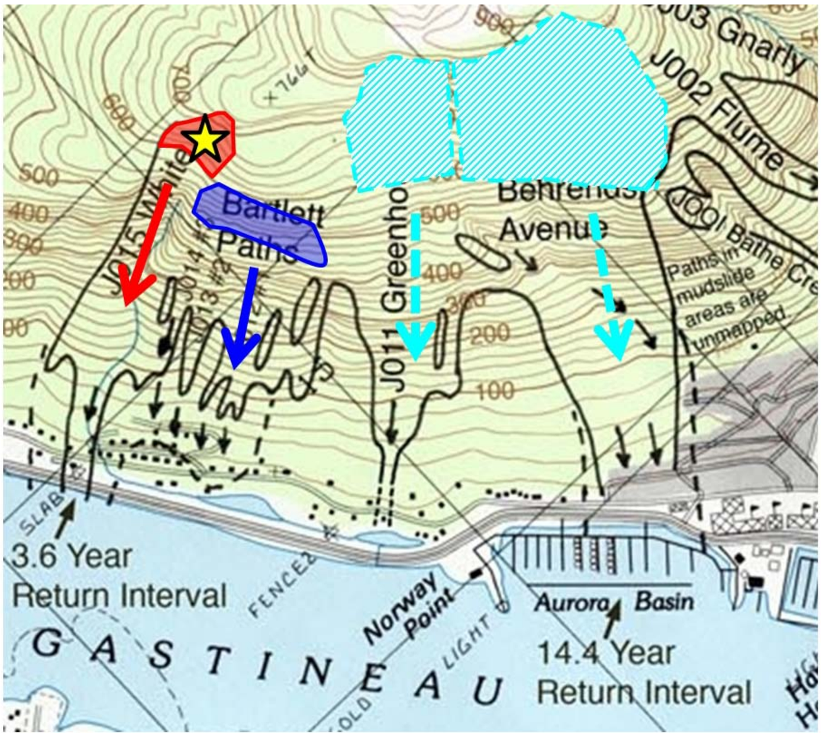

Fig. 48: Avalanche starting zones on the south side of Mt. Juneau. The starting zones of the-Bartlett paths (blue area) border on the White Subdivision path (red area). The Greenhouse and Behrends path (light blue area) lie over 400 m from the White Subdivision starting zone. When releasing avalanches in the White Subdivision starting zone the secondary release of avalanches in the blue and light blue areas cannot be excluded (map source: Bill Glude, Southeast Alaska Avalanche Centre and USGS).

Damage potential

The damage potential of the White Subdivision path consists of approximately 5 residential houses situated in the severe hazard zone and 8 buildings in the special engineering avalanche zone. We estimate the return period of a dense flow avalanche reaching the most exposed buildings to be about 5 years. The exposed buildings are not protected, e.g. reinforced, and seem to be very vulnerable against avalanche impacts. Already small avalanches can cause damages. Today the forest belt gives a certain natural protection to the subdivision against small avalanches. If avalanches would be triggered artificially damages to the forest and a decrease of the protection effect seems to be unavoidable.

Detonation method and detonation points

In the starting zone of the White Subdivision avalanche path a release system independent of weather, with a high detonation effect and remote control has to be applied (see Figs. 24-26). There are several locations with favourable slope inclinations greater than 40°. We think that 3 detonation points would be necessary to cover the whole starting zone (Fig. 49). In regard of the slope inclination and the bowl shaped topography the conditions for artificial release of avalanches are favourable.

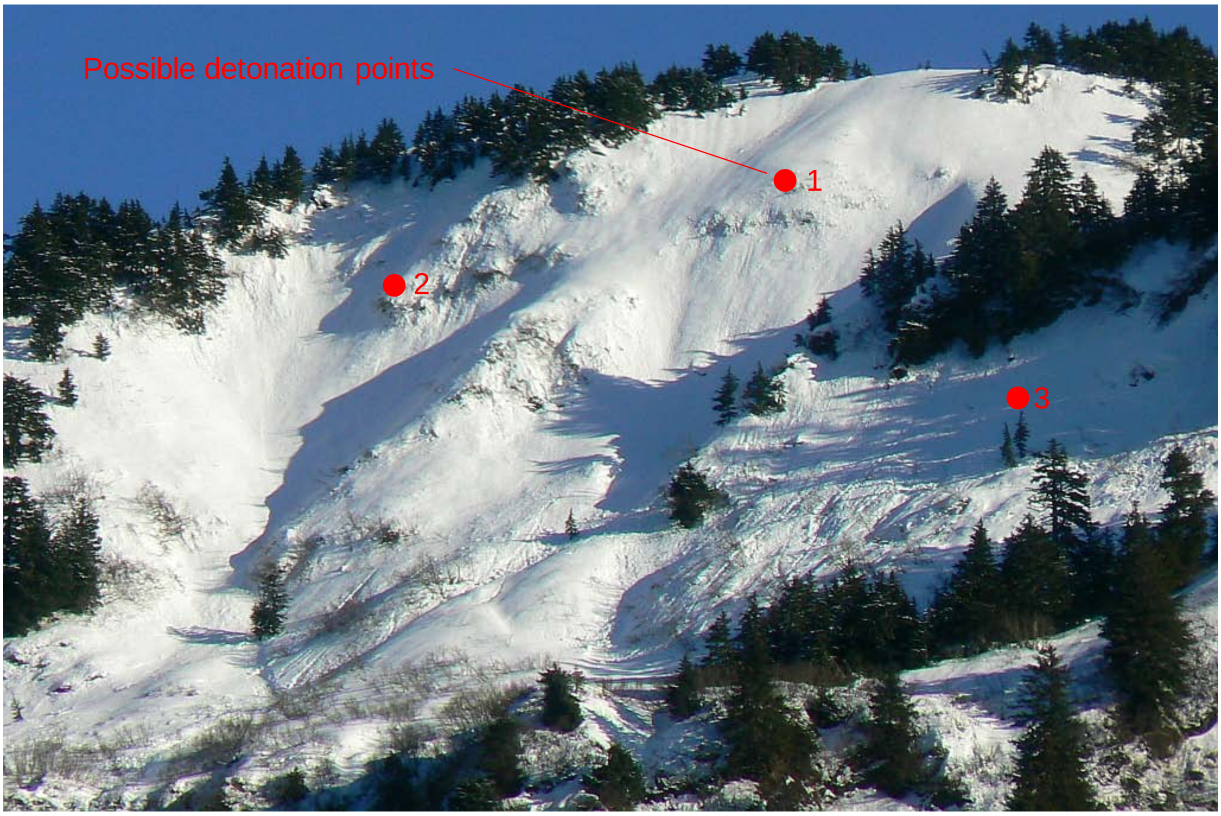

Fig. 49: Possible detonation points in the starting zone of White Subdivision avalanche path (top area above the bench).

Preventive closures and evacuations

Given that small avalanches are known to reach the subdivision, the evacuation of the hazard zones seems to be imperative if avalanches are triggered artificially. Moreover, the Glacier Highway and Egan Drive should be closed during artificial release. The organisation of road closures and evacuations would be easier in comparison to the Behrends Avenue area since the area and the number of endangered homes is much smaller. Without evacuation of the subdivision the application of the artificial release of avalanches is not recommended.

Weather data and check of detonation results

The evaluation of the snow conditions in the starting zone is easier compared to the Behrends Avenue avalanche path, since the starting zone is more sheltered and is situated at a lower elevation. The verification of the detonation results might be difficult if the visibility is poor. An additional automatic weather station at the elevation of the starting zone would improve the amount of data available for assessing the avalanche danger. It is recommended that an automatic weather station close to the starting zones on Mt. Juneau is built. A possible location for this would be an avalanche safe location on one of the two benches between White Subdivision and Behrends Avenue avalanche path at an elevation of about 700 m a.s.l. However, due to the accumulation of rime during winter storms the functioning of such a station might be greatly reduced. This should be considered in the design of the station.

Conclusions

We consider the White Subdivision avalanche path to be better suited for the application of artificial release of avalanches as opposed to the Behrends Avenue avalanche path. However, under the current conditions we do not recommend applying artificial release of avalanches in the White Subdivision avalanche path since the risk to persons and buildings is much too high. We think that artificial release of avalanches by explosives would only be possible if the endangered buildings are reinforced and if the evacuation and closure of the subdivision would be ordered and enforced. Furthermore, it would be necessary to settle a potential damage to properties and the forest in advance (e.g. City and Borough of Juneau has an insurance which would pay for damages from artificially triggered avalanches).

7.4.3 Snow supporting structures

The main starting zone has an area of 3 ha which is relatively small. The difference in elevation is approximately 120 m and the mean slope inclination is 42°. In regard of the topography the construction of snow supporting structures seems to be relatively straight forward. Similar to the Behrends Avenue avalanche path there is no detailed information available on snow heights in the starting zone. We think that a height of at least 4.0 m for the structures should be selected. A structure height of 4 m corresponds to a vertical snow height of 5.4 m. We would propose to install approximately 7 lines of structures with lengths between 80 and 240 m (Fig. 50). In total about 1310 m of snow supporting structures would be required to stabilise the snowpack in the starting zone. According to our experience the costs per meter would be around 3000 USD. The total costs would be around 4 Mio USD. The installation of snow supporting structures would prevent the release of extreme avalanches. Small avalanches which can break loose also below the main starting zone would still be possible. We did not visit the starting zone and therefore we cannot comment if the small-scale topography and the ground conditions are favourable for the construction of snow supporting structures. The next planning steps should be to install snow stakes in the starting zone to gain a better idea of the snow depths and snow distribution. Furthermore, a geotechnical investigation should be performed to assess the feasibility and bearing capacity of ground anchors. According to aerial photographs the starting zone might consist of unstable ground which would require expensive foundations. Mudflows occur frequently in the avalanche path.

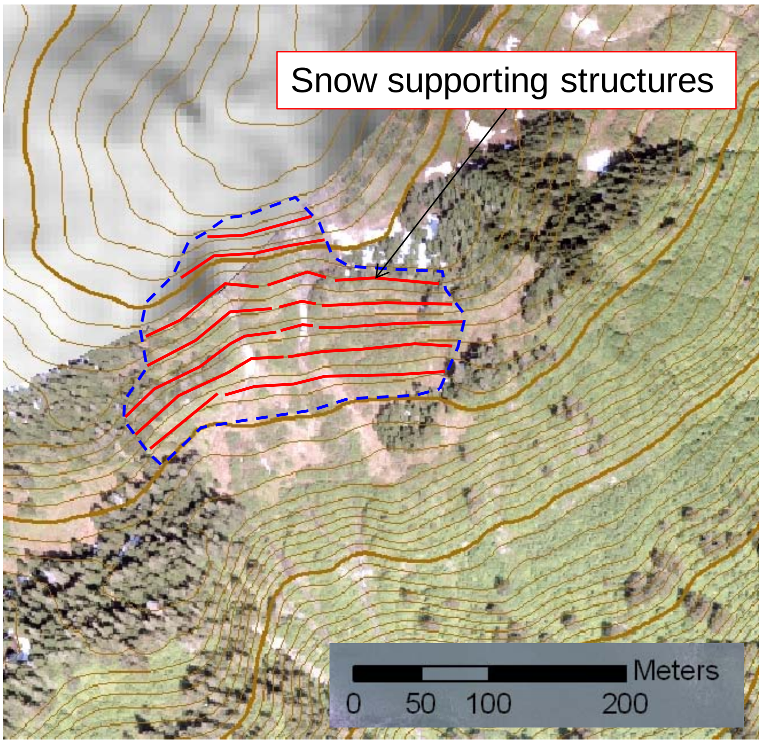

Fig. 50: Possible layout of snow supporting structures in the starting zone of the White subdivision avalanche path. The structures are foreseen in the main starting zone above the bench.

7.4.4 Avalanche dams

Because of the steep topography and the scattered arrangement of buildings the construction of avalanche dams is very difficult. The construction of a deflecting berm is not advisable since it would increase the risk in the direction of deflection. A catching dam could be built at an elevation of 60 m a.s.l. just above the subdivision. The design velocity of a 300-year avalanche would be around 30 m/s with a flow height of 1.5 m. This corresponds to at least a 32 m catching dam. It seems hardly possible to build such a huge dam at this location. A minimum dam height of 18 m would be required to stop a 30-year avalanche. However, an extreme avalanche would overflow a 18 m high dam. Given the risk of mass wasting processes in the White Subdivision path a combined mud-flow/avalanche dam could be built (Fig. 51). The height of such a dam should be at least 10 m so that small wet snow avalanches could be stopped. The effect of a 10 m high catching dam on the extent of the hazard zones would however be negligible.

7.4.5 Direct protection of buildings

The buildings in the severe hazard zone could be protected with individual reinforced walls. Such a wall should be at least 5 m high and the width slightly wider than the building. The impact pressure on the wall would be between 30 and 50 kPa depending on the location of the building. The construction costs for such strong walls might be equivalent to the economic value of the building to be protected; given this their construction is not recommended. However, if existing buildings are rebuilt or if new buildings are planned in the special engineering zone the City and Borough of Juneau should ensure that adequate reinforcements are made and that their construction is controlled by a regulatory body. During the field visit we gained the impression that none of the buildings in the special engineering zone is reinforced.

Fig. 51: Example of a combined avalanche/debris flow catching dam (view downstream). The height of the dam is 17 m. The dam is designed to stop a 30-year avalanche (Tallawine, Klosters, Switzerland).

7.4.6 Buyout of homes

Finally, the Government could also buyout the endangered homes. Contrary to the Behrends Avenue avalanche path we recommend to concentrate first on structural mitigation measures in the White Subdivision avalanche path (snow supporting structures and/or a combined mud-flow/avalanche dam above the subdivision).

8 Recommendations

1. The avalanche problem is very serious in the runout zone of Behrends Avenue avalanche path and White Subdivision avalanche path. According to current standards the risk is far beyond an acceptable level, especially in the Behrends Avenue avalanche path (e.g. in Switzerland the individual risk of death for involuntarily risks taken by a member of the public should be less than 1×10^{-5} according to PLANAT, 2009). We think that the unacceptable risk to the residents in the hazard zones can only be managed in the short term if the City and Borough of Juneau would order evacuations and close endangered areas during periods of high avalanche danger. Because the buildings in the hazard zones have no structural reinforcement people inside these buildings are not safe. An evacuation concept should be elaborated consisting of at least two hazard levels:
   a. Hazard level 1: evacuation and closure of the severe hazard zone
   b. Hazard level 2: evacuation and closure of the severe and special engineering zone, as well as closure of Glacier Highway and Egan Drive.

   Establishing a regular avalanche hazard evaluation and forecasting service in the community during the winter months is recommended and is a very good starting point to develop an evacuation concept. Moreover, educating the public and increasing their awareness about avalanches would be invaluable. While this will improve the situation, we do not think that these measures are sufficient with regard to the more serious avalanche problems. The City and Borough of Juneau should also order the evacuation of people out of endangered homes.

2. The reduction of the avalanche risk in the **Behrends Avenue Subdivision** with structural protection measures is prohibitively expensive and therefore not recommended. Furthermore, the artificial release of avalanches is not advisable mainly because of the danger to people, property and homes. We think that the buyout of endangered homes in the avalanche paths by the government is the only way to effectively reduce the avalanche risk on the long-term. We propose to start the buyout of the most exposed homes in the severe hazard zone (see Appendix 5). The buyout of homes would ensure a permanent solution to the avalanche problem.

3. The **White Subdivision** could be protected with snow supporting structures. We recommend performing further investigations (e.g. snow depth measurements, snow distribution and geotechnical investigation) to better assess the feasibility of this option. We cannot recommend performing artificial release of avalanches by explosives in the White Subdivision avalanche path. Given the high risk of mudflows, a combined catching dam could be planned. The minimal height should be 10 m so that small wet snow avalanches can be stopped. We propose to plan the buyout of homes only if structural mitigations measures turn out to be not feasible.

4. We think that the **extent of the hazard zones in the Behrends Avenue subdivision** is too small on the hazard map of 1992 in the area north-west of Rossway. The extent of the hazard zones on the map of 1972 seems to be more appropriate. We recommend to study the hazard situation in this area in more detail and to make dendrochronological investigations of the forest stand. Based on our assessment the Juneau Douglas High School is not endangered by a 300-year avalanche. We suppose that only the wind blast of an extreme powder snow avalanche might influence the area of the school. However, we do not expect structural damage to the buildings.

5. The **extent of the hazard zones in the White Subdivision** seems to be mostly acceptable. We recommend an extension of the severe hazard zone down slope up to the Egan Drive.

6. The construction of new buildings should be absolutely forbidden in the severe hazard zone. If new buildings are built in the special engineering zone the building standards should include structural reinforcements as mandatory which in addition should be enforced and controlled by the City and Borough of Juneau. Most of the existing buildings in the special engineering zone do not seem to have any structural reinforcement.

7. We recommend installing an additional automatic weather station at the elevation of the starting zones on Mt. Juneau. Such a station would significantly improve the data available for assessing the avalanche danger. However, due to the accumulation of rime during winter storms the functioning of such a station might be greatly reduced. This should be considered in the design of the station.

8. A large avalanche in the White or Behrends Avenue avalanche path can block Glacier Highway and Egan Drive and sweep cars off the highways. Such large avalanches would hinder emergency response and possibly block road access to the hospital and the Airport area. A preventive closure of the highways might also be required due to high avalanche hazard. A second Gastineau Channel crossing (e.g. a bridge between Douglas Island and the Airport area) would allow permanent road access from Downtown to the hospital and the Airport.

9 Documentation

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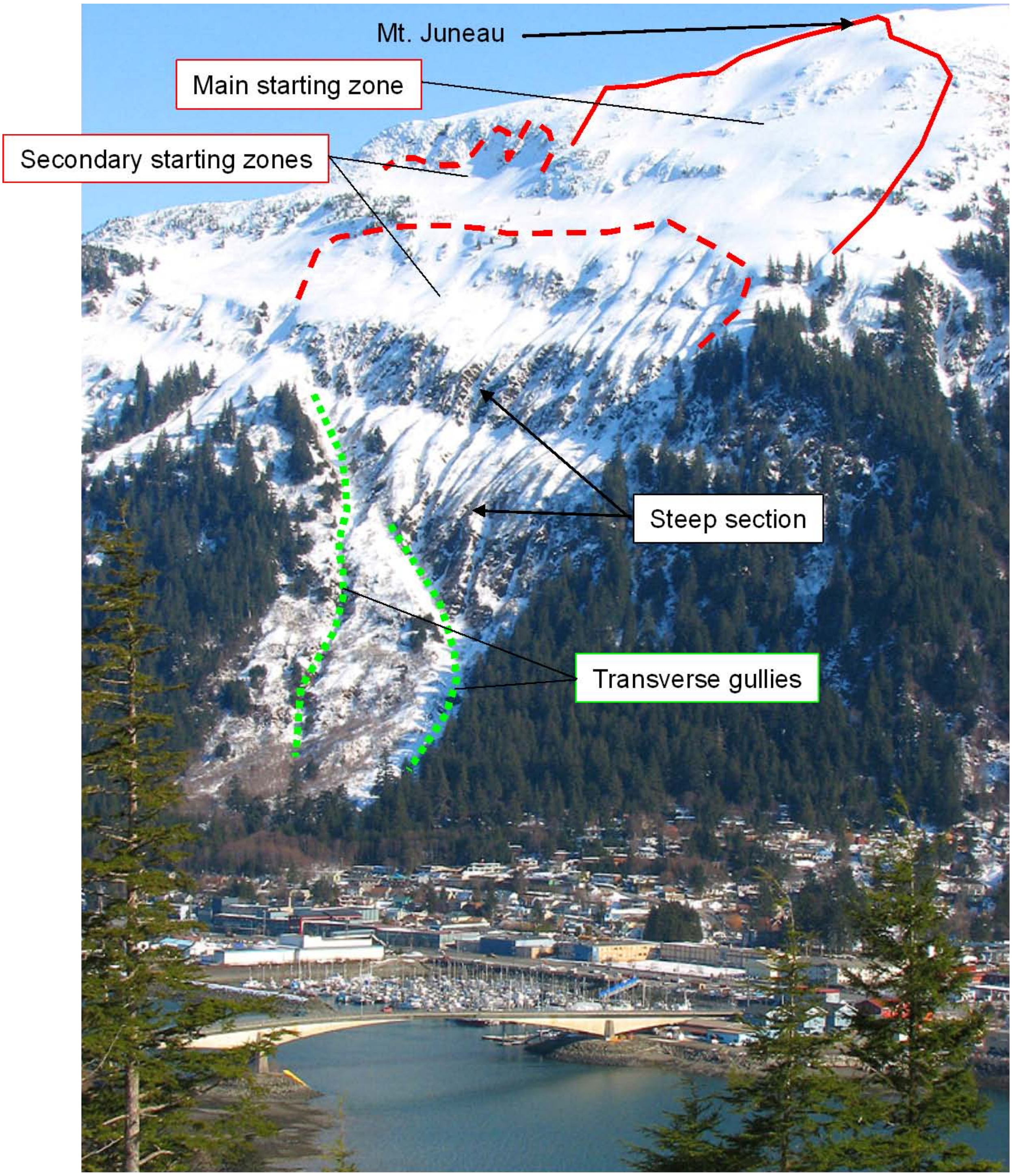
(14) Different photos from the Archives of Tom Mattice, Bill Glude, Alaska Mountain Safety Center and City and Borough of Juneau.
(15) Alaska Climate Database, National Weather Service, Juneau, AK.
(16) Colman, B., 1986: The Winter Climate of Juneau: A Mean of Contrasting Extremes. National Weather Digest, Volume 11, No. 2.
(17) PLANAT, 2009. Strategie Naturgefahren Schweiz – Umsetzung des Aktionsplans PLANAT 2005-2008, Projekt A1.1, Risikokonzept für Naturgefahren, Nationale Plattform für Naturgefahren PLANAT, Bern, 2009.

Davos, 30 December 2011/mar

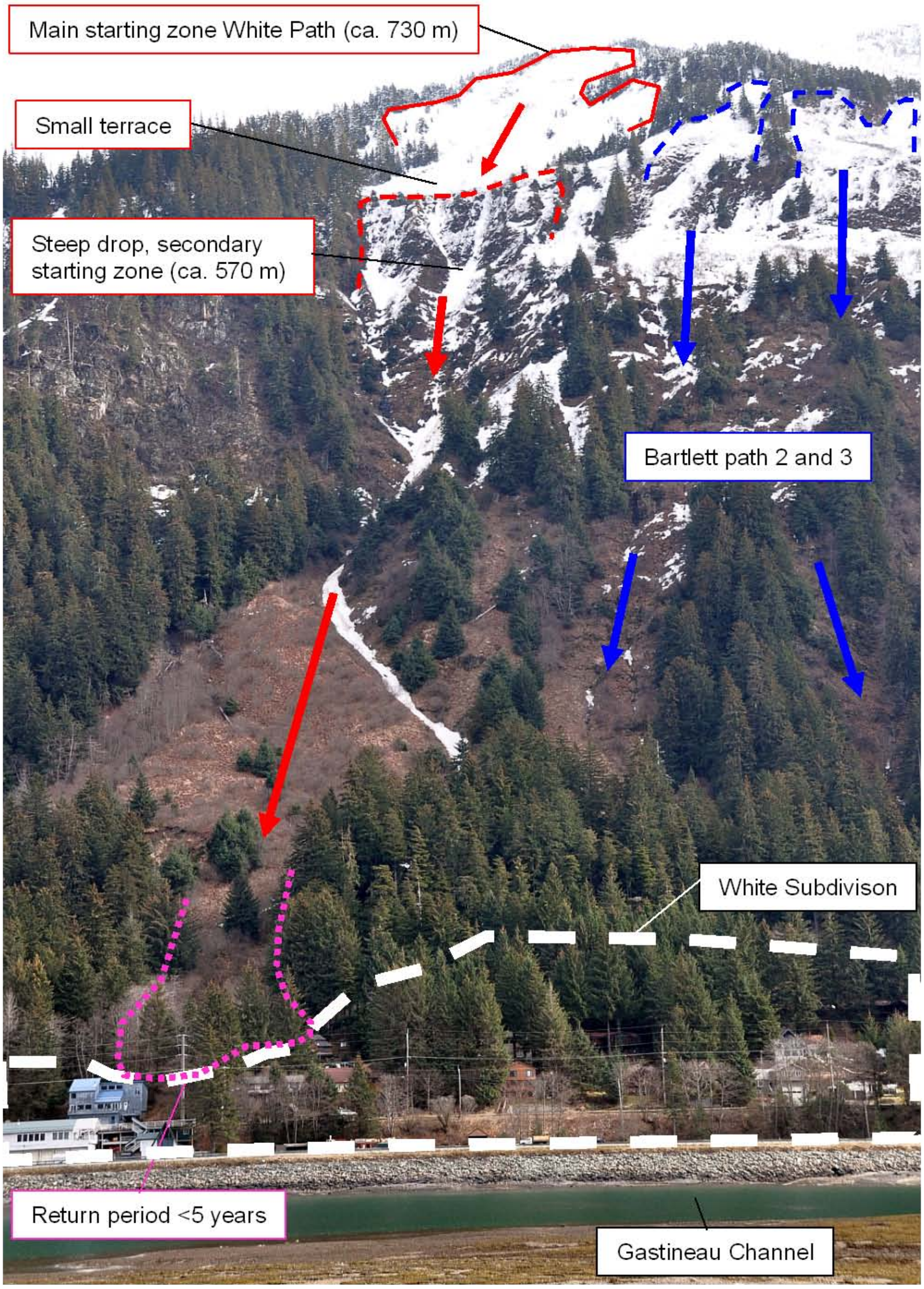
Appendices

Appendix 1: Overview Behrends Avenue path

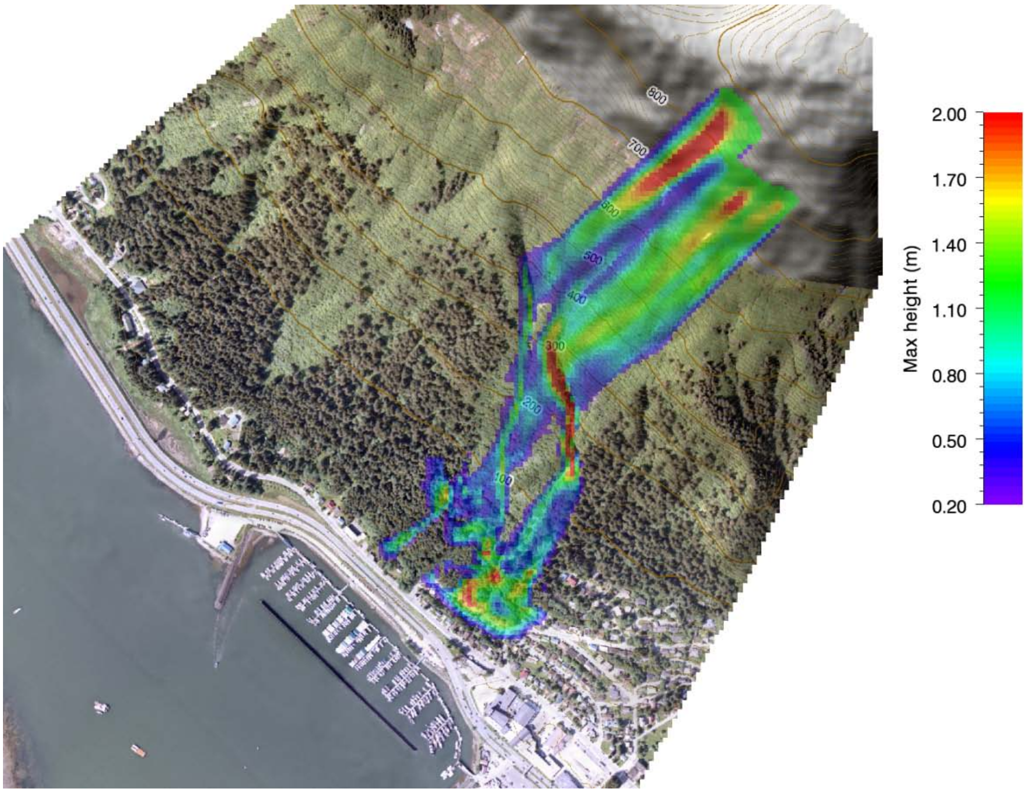


(Photo David Kent, April 3, 2007, http://www.westjuneau.com)

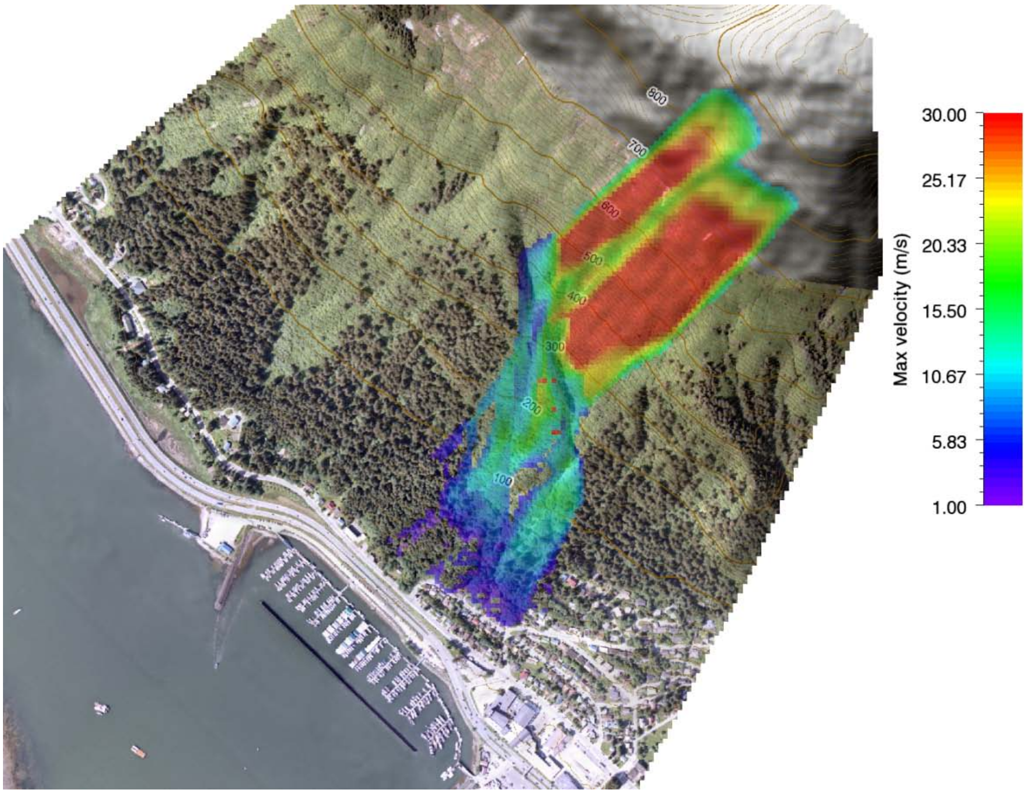
Appendix 2: Overview White Subdivision avalanche path



Appendix 3.1: RAMMS simulation Behrends Avenue avalanche path, 10-year return period

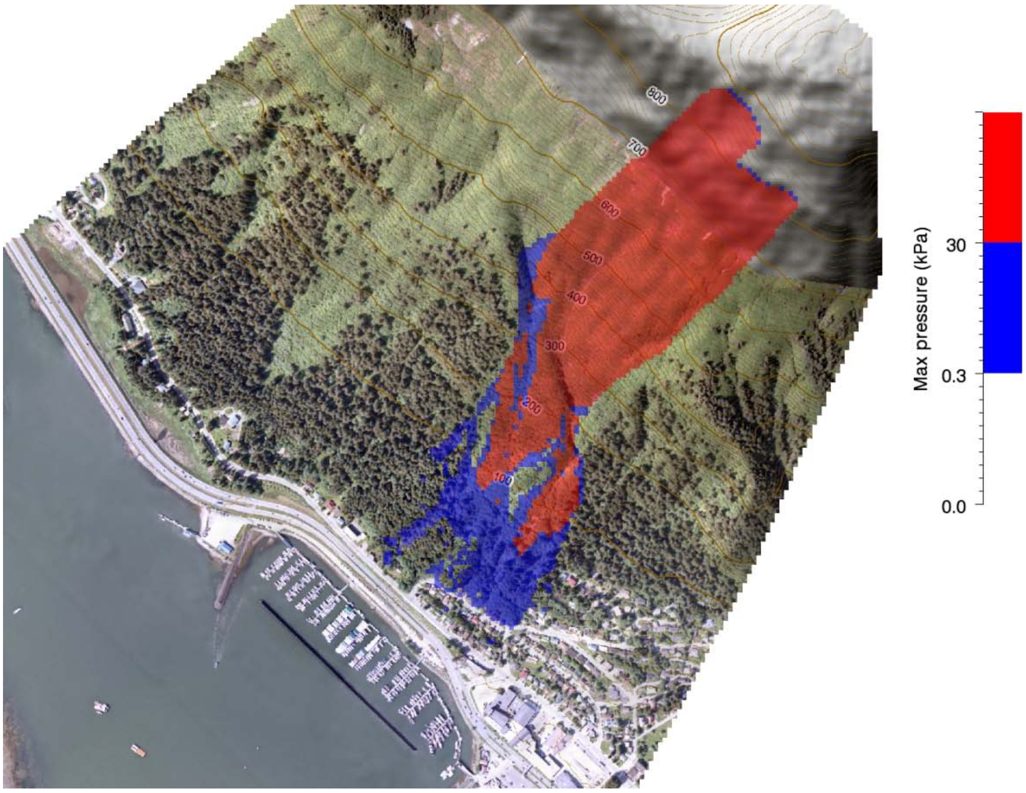


Maximum flow height of the RAMMS simulation of a 10-year avalanche (uncorrected simulation results).

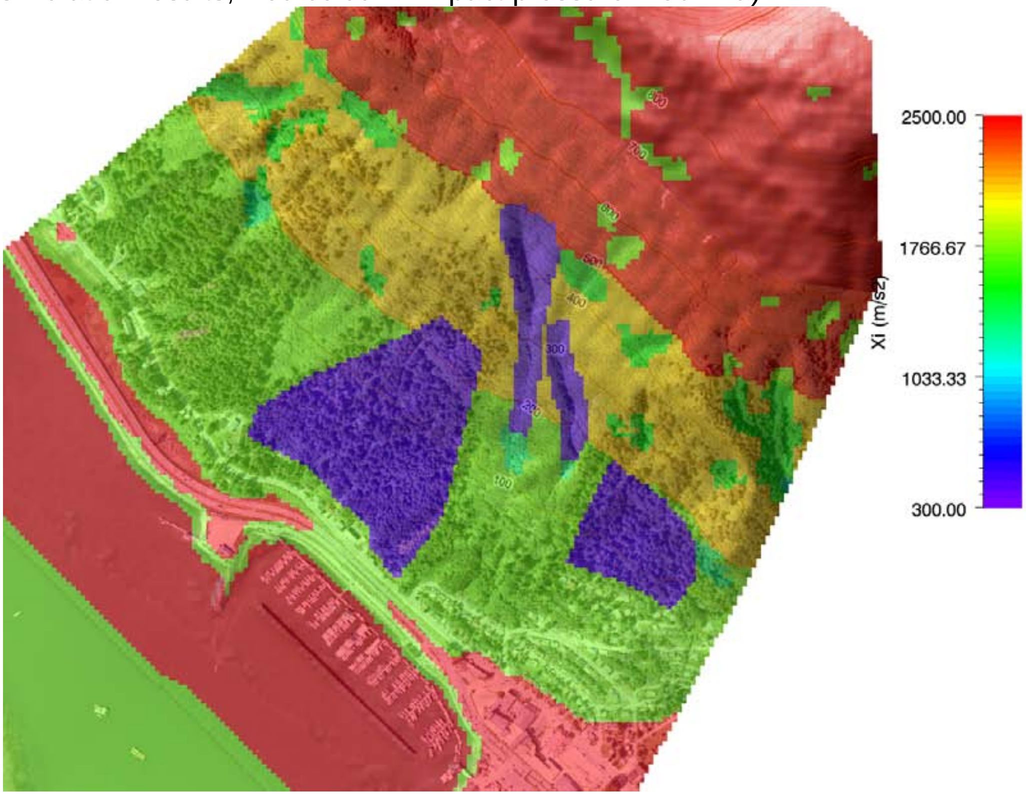


Maximum velocity of the RAMMS simulation of a 10-year avalanche (uncorrected simulation results).

Appendix 3.1: RAMMS simulation Behrends Avenue avalanche path, 10-year return period

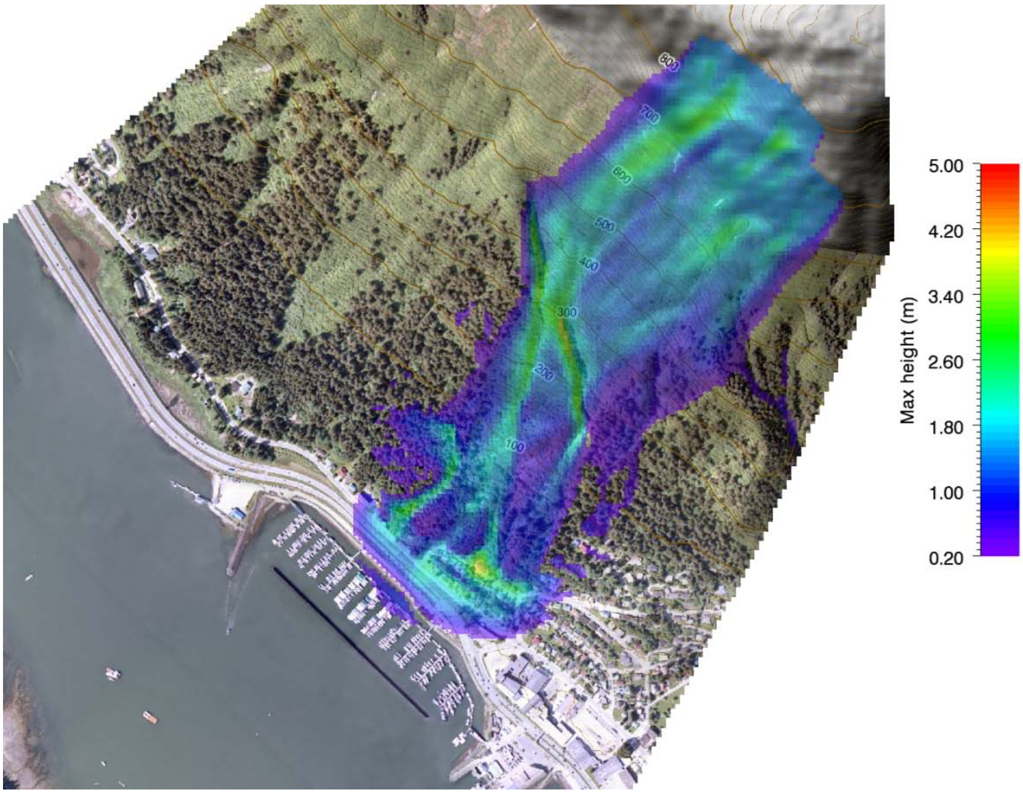


Maximum avalanche pressure of the RAMMS simulation of a 10-year avalanche (uncorrected simulation results; Red colour = impact pressure > 30 kPa).

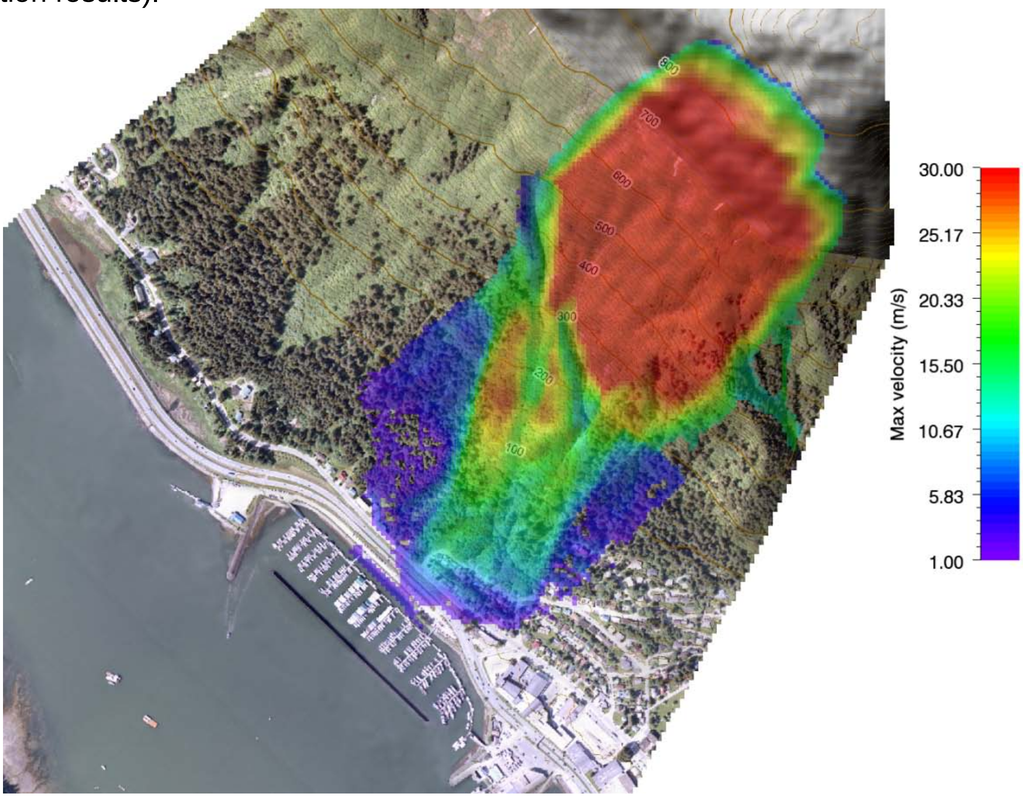


Friction parameter xi applied for the RAMMS simulation of a 10-year avalanche.

Appendix 3.2: RAMMS simulation Behrends Avenue avalanche path, 30-year return period

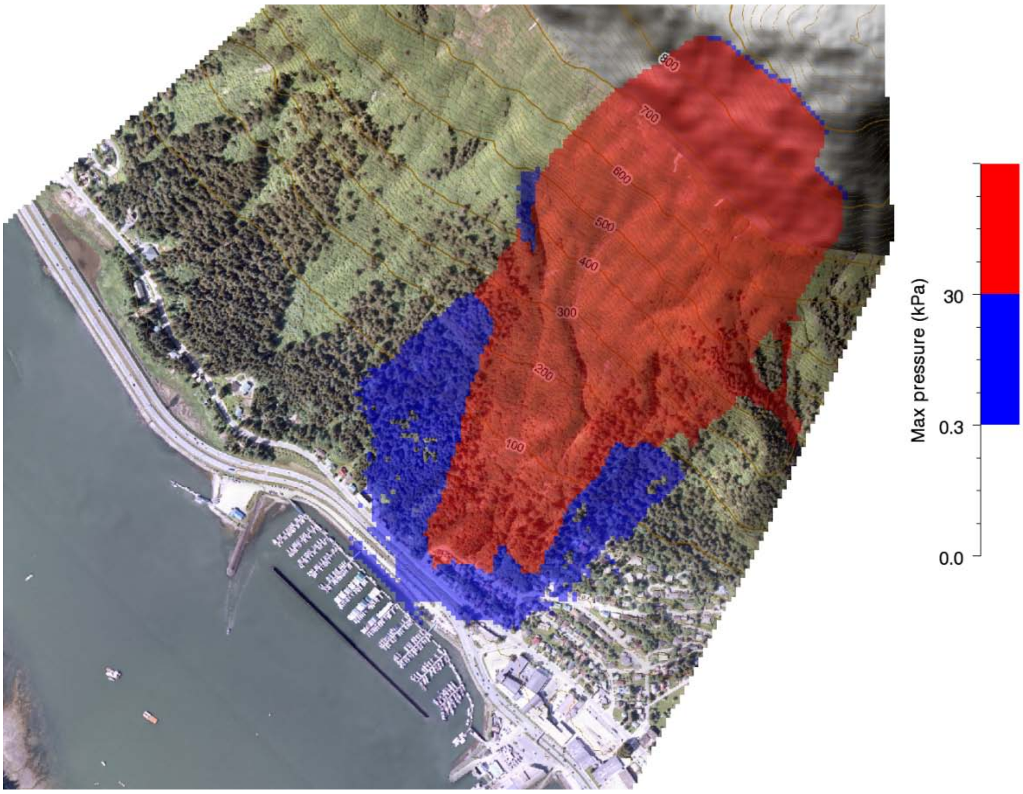


Maximum flow height of the RAMMS simulation of a 30-year avalanche (uncorrected simulation results).

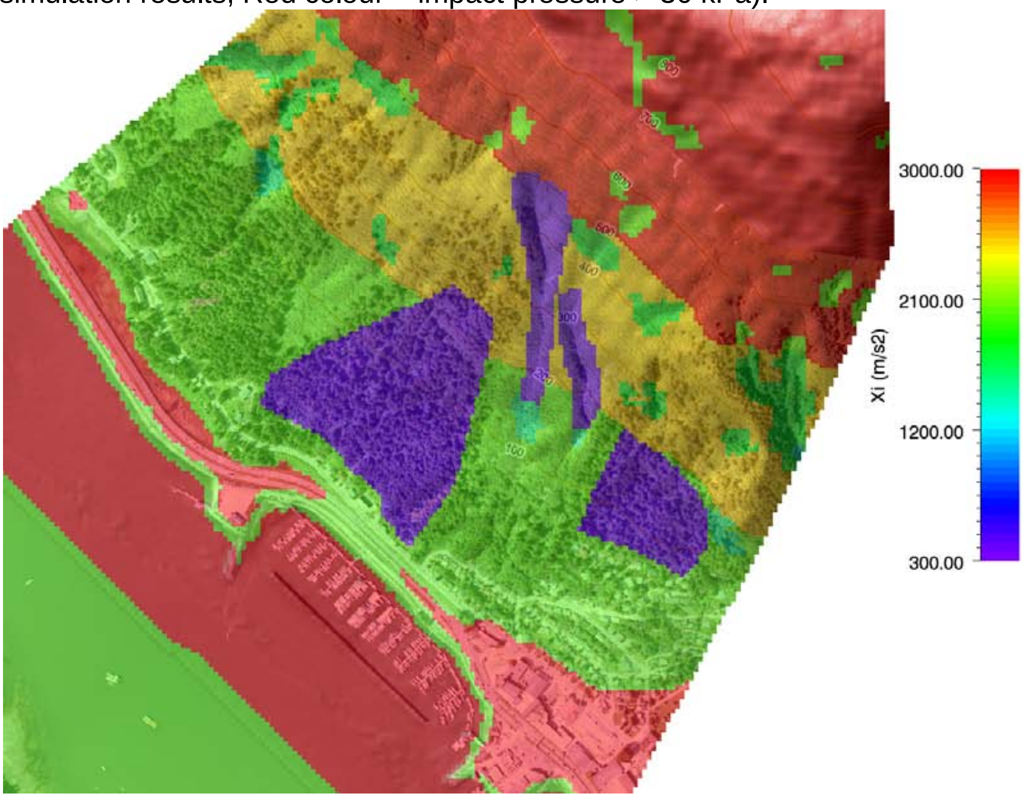


Maximum velocity of the RAMMS simulation of a 30-year avalanche (uncorrected simulation results).

Appendix 3.2: RAMMS simulation Behrends Avenue avalanche path, 30-year return period

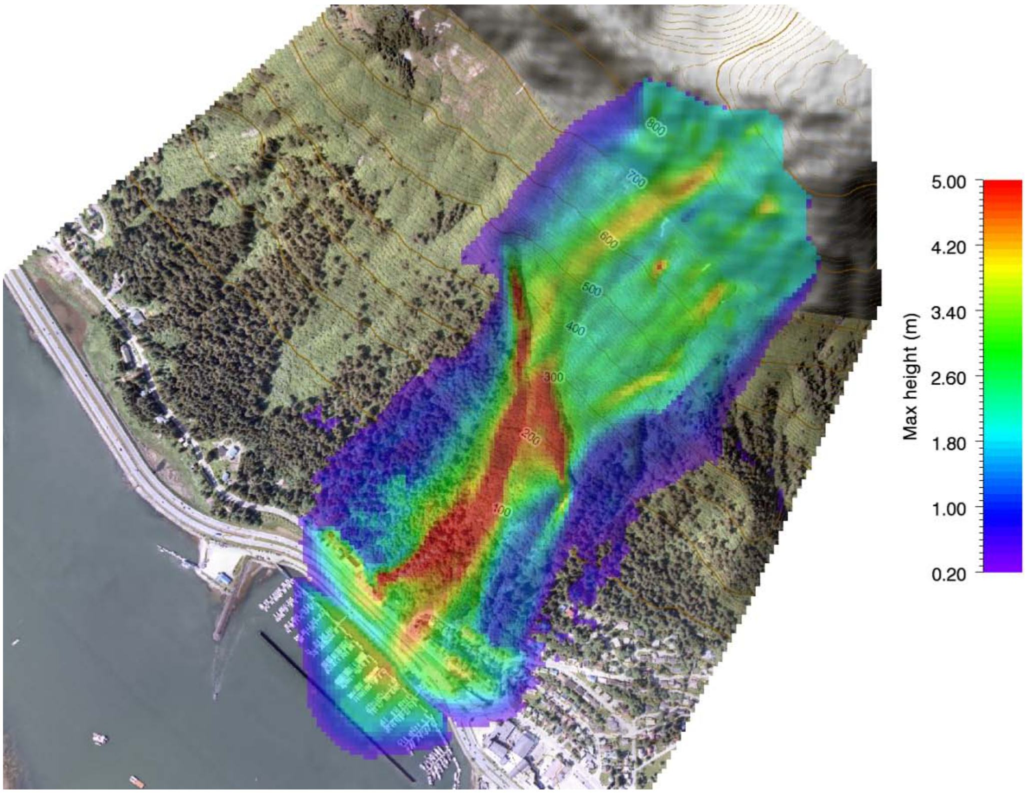


Maximum avalanche pressure of the RAMMS simulation of a 30-year avalanche (uncorrected simulation results; Red colour = impact pressure > 30 kPa).

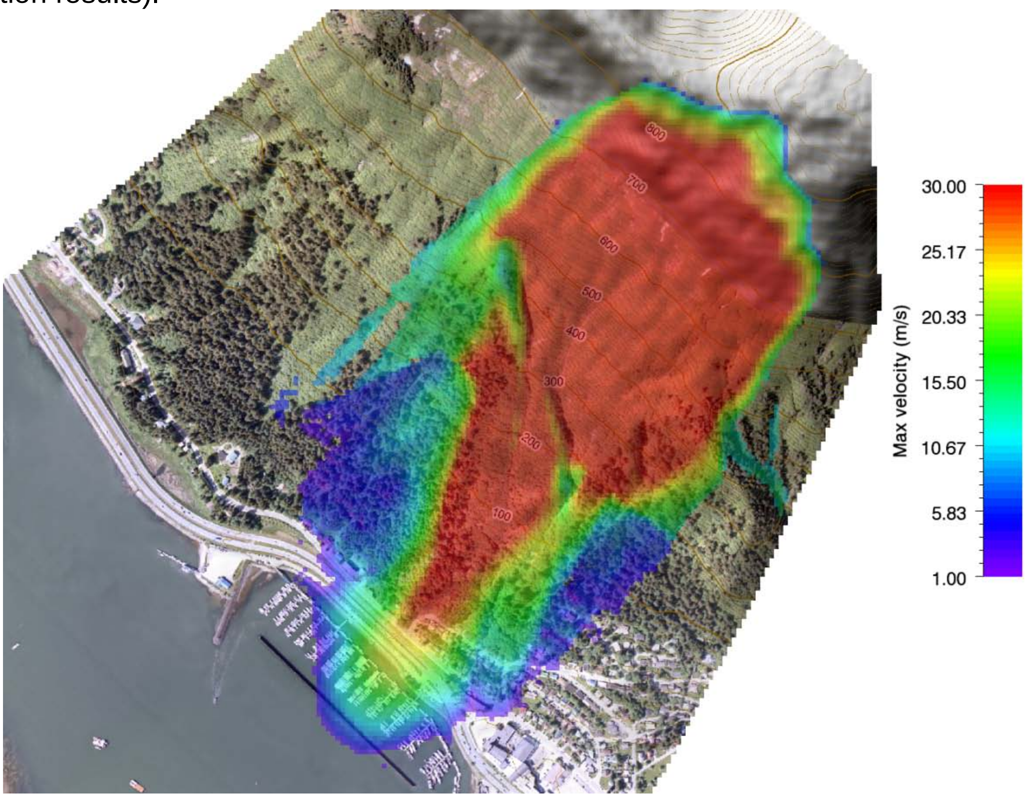


Friction parameter xi applied for the RAMMS simulation of a 30-year avalanche.

Appendix 3.3: RAMMS simulation Behrends Avenue avalanche path, 300-year return period

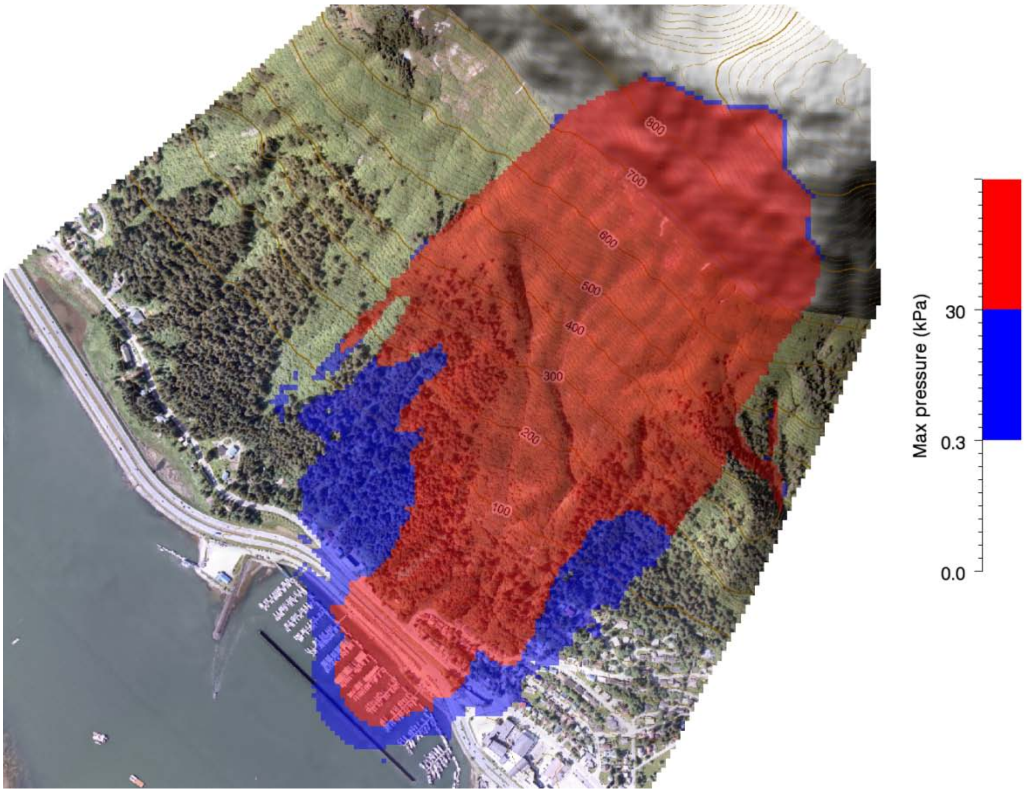


Maximum flow height of the RAMMS simulation of a 300-year avalanche (uncorrected simula-tion results).

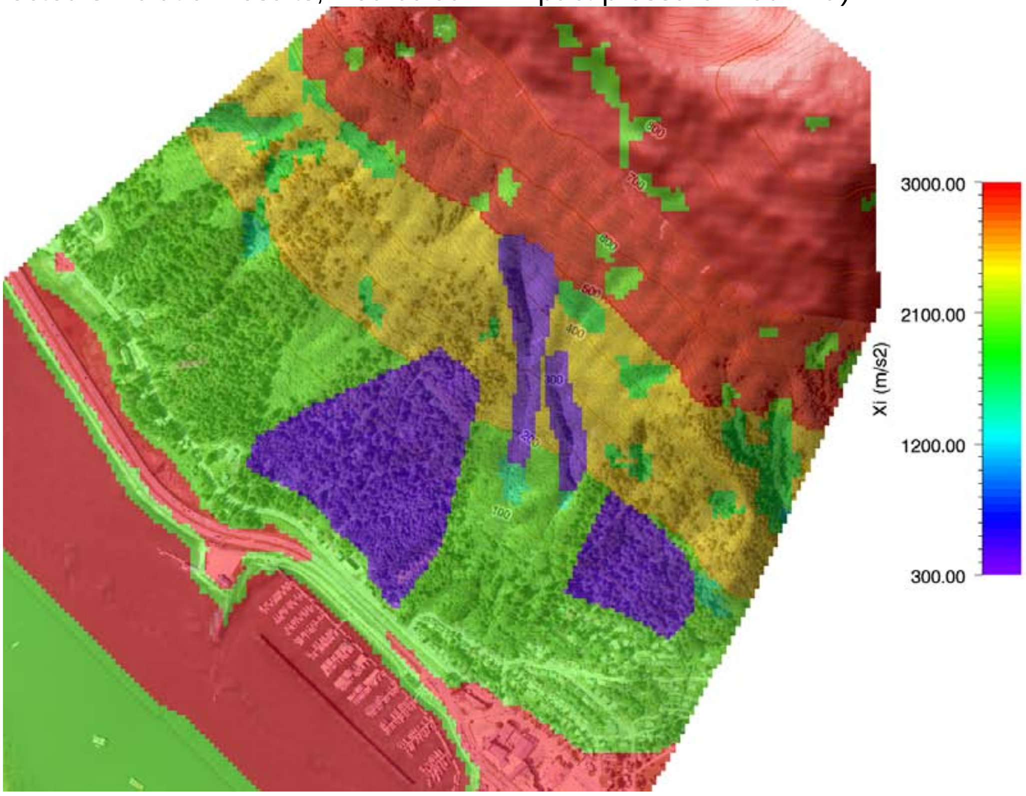


Maximum velocity of the RAMMS simulation of a 300-year avalanche (uncorrected simula-tion results).

Appendix 3.3: RAMMS simulation Behrends Avenue avalanche path, 300-year return period

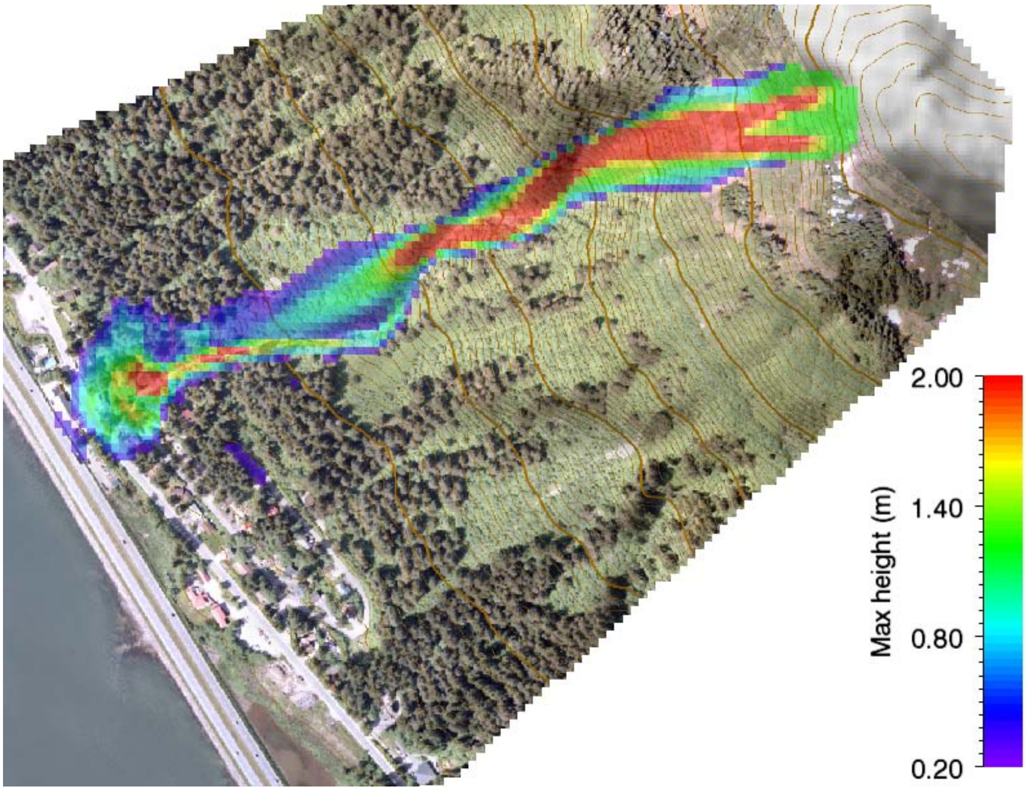


Maximum avalanche pressure of the RAMMS simulation of a 300-year avalanche (uncorrected simulation results; Red colour = impact pressure > 30 kPa).

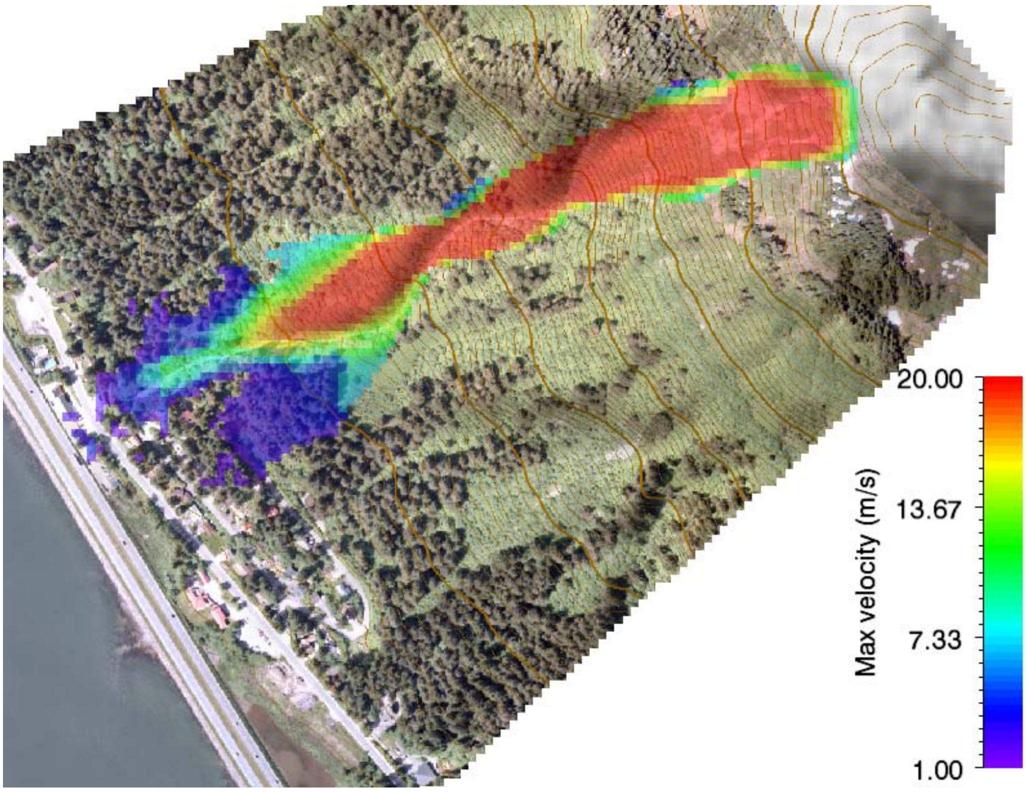


Friction parameter xi applied for the RAMMS simulation of a 300-year avalanche.

Appendix 4.1: RAMMS simulation White Subdivision avalanche path, 10-year return period

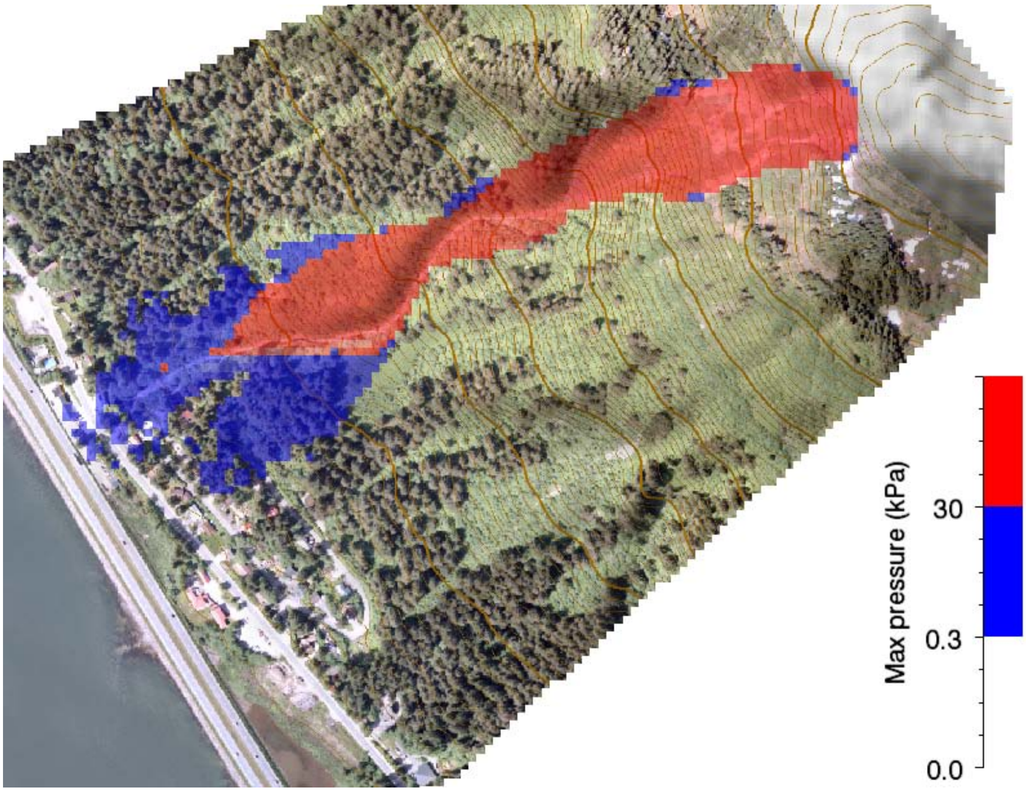


Maximum flow height of the RAMMS simulation of a 10-year avalanche (uncorrected simulation results).



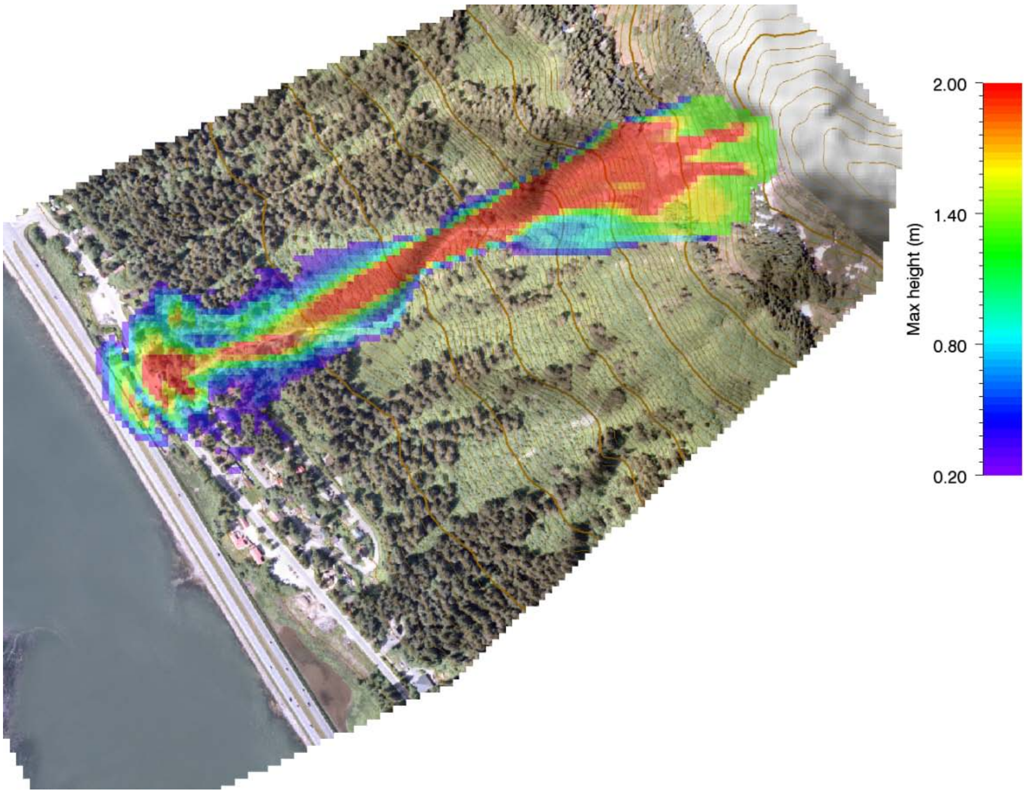
Maximum velocity of the RAMMS simulation of a 10-year avalanche (uncorrected simulation results).

Appendix 4.1: RAMMS simulation White Subdivision avalanche path, 10-year return period

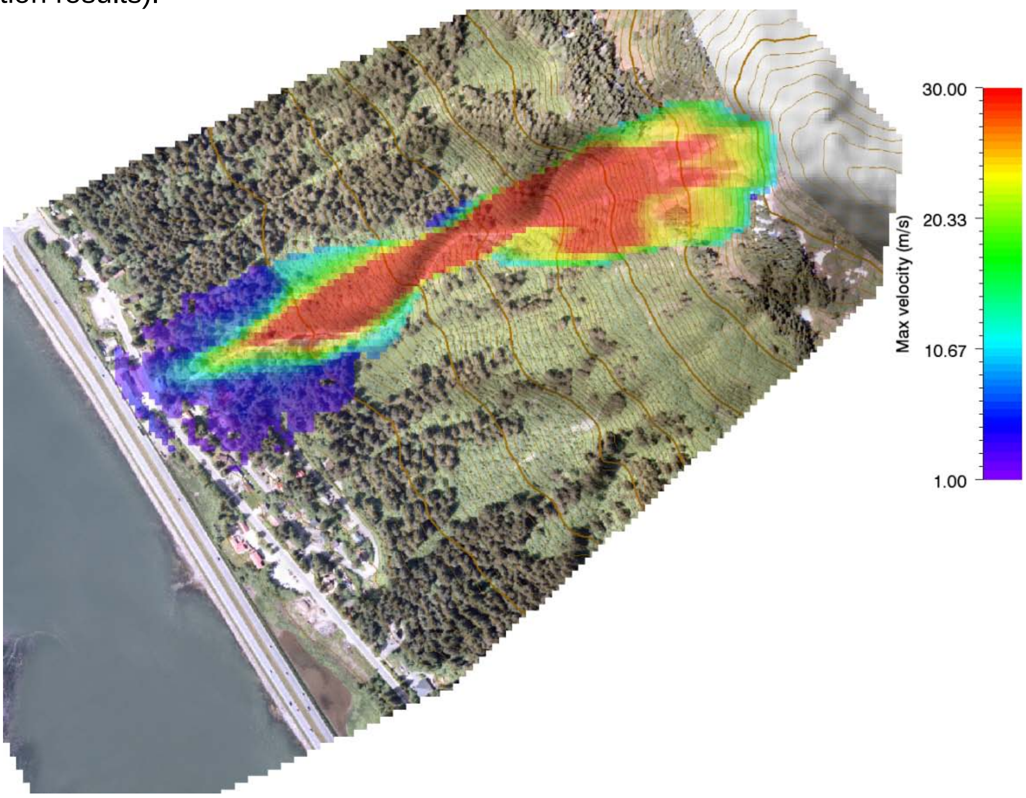


Maximum avalanche pressure of the RAMMS simulation of a 10-year avalanche (uncorrected simulation results; Red colour = impact pressure > 30 kPa).

Appendix 4.2: RAMMS simulation White Subdivision avalanche path, 30-year return period

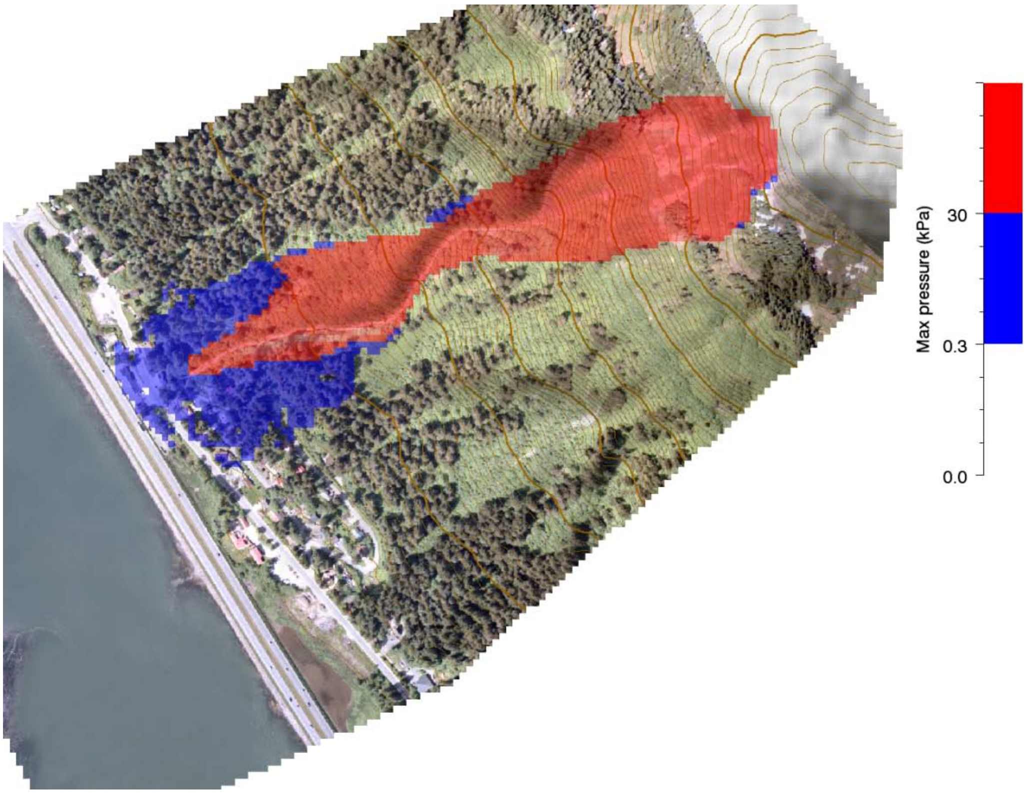


Maximum flow height of the RAMMS simulation of a 30-year avalanche (uncorrected simulation results).

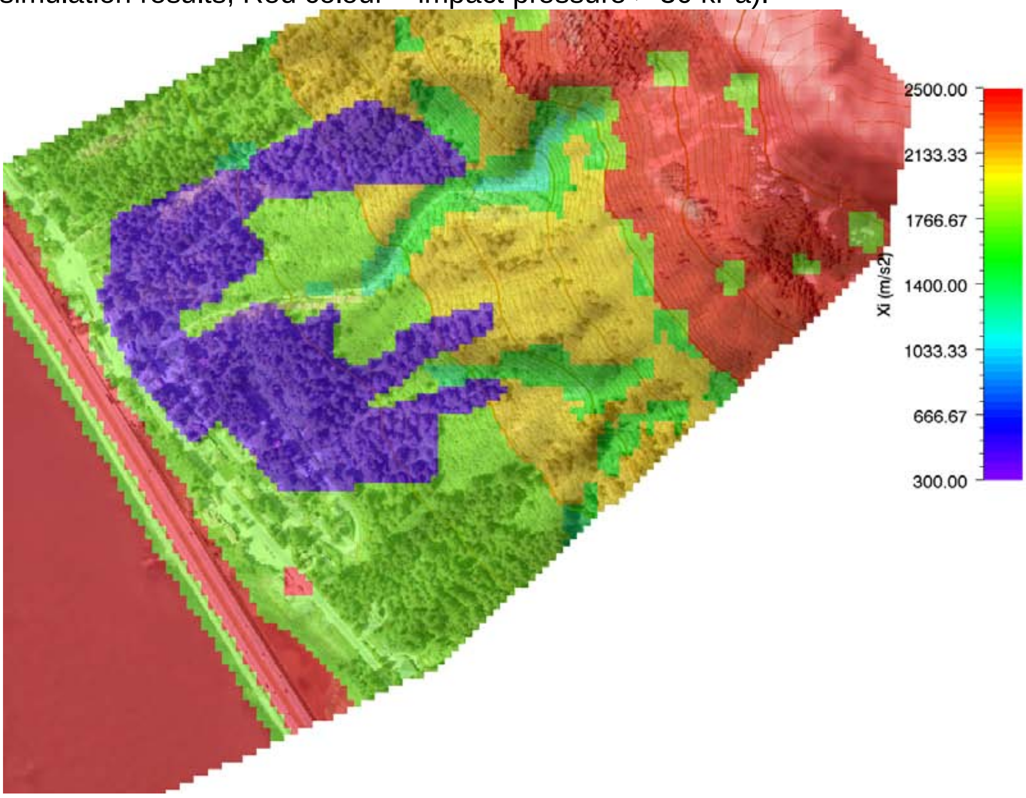


Maximum velocity of the RAMMS simulation of a 30-year avalanche (uncorrected simulation results).

Appendix 4.2: RAMMS simulation White Subdivision avalanche path, 30-year return period

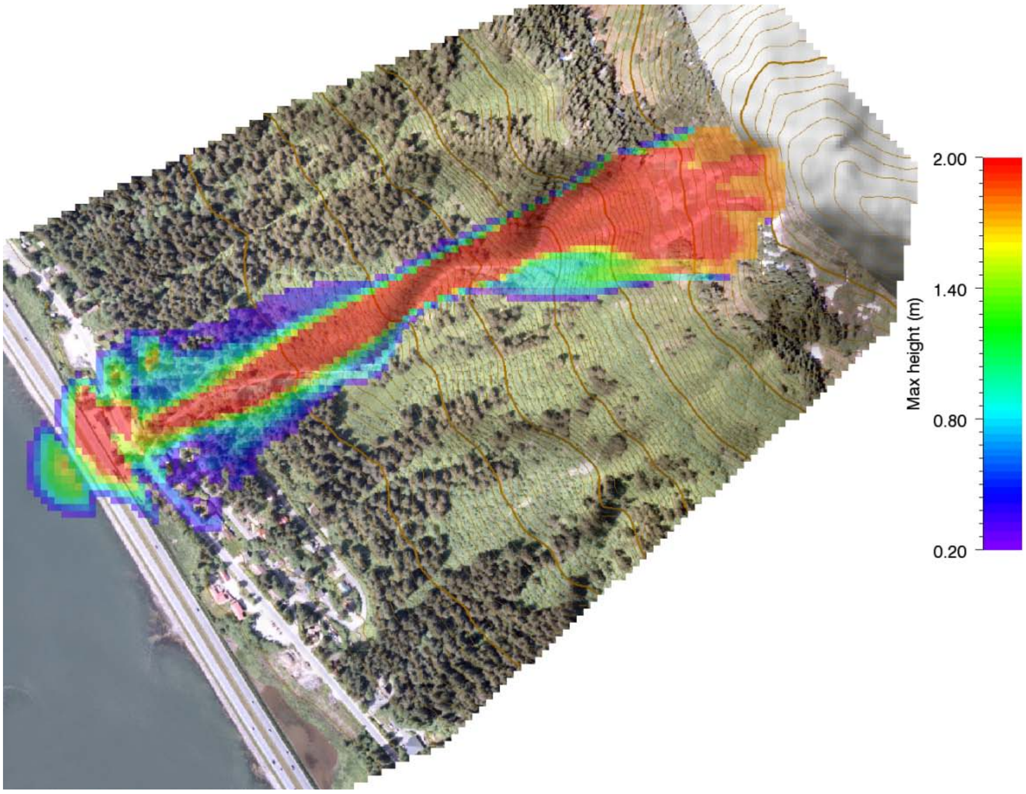


Maximum avalanche pressure of the RAMMS simulation of a 30-year avalanche (uncorrected simulation results; Red colour = impact pressure > 30 kPa).

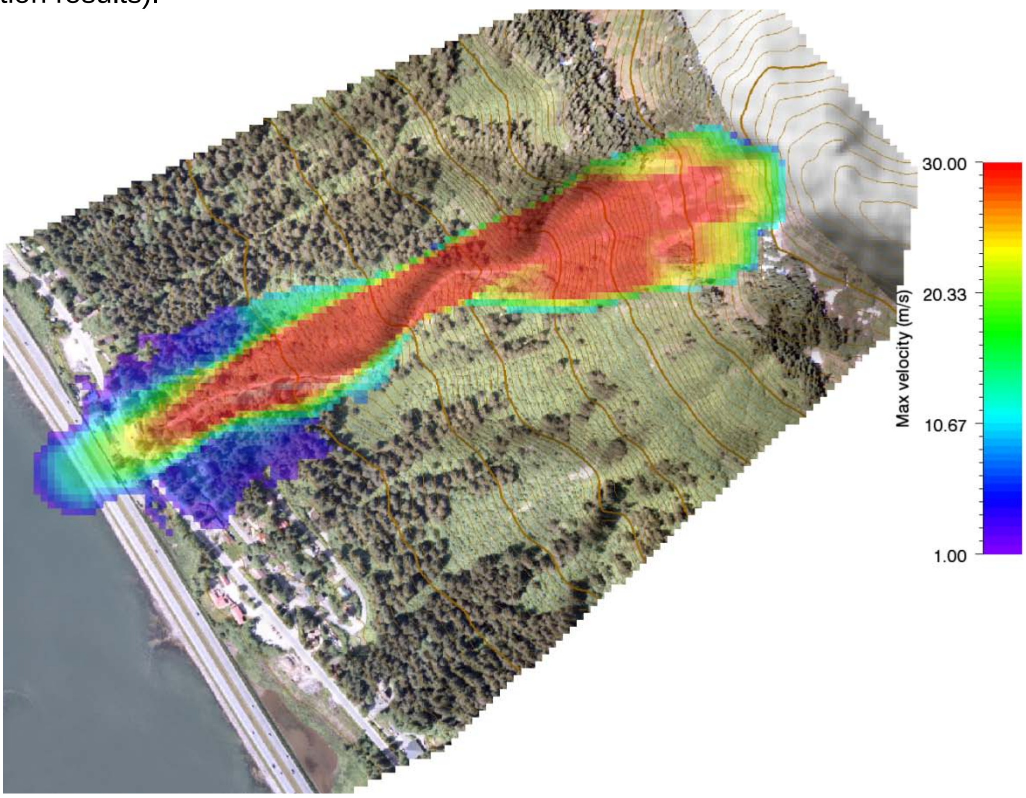


Friction parameter xi applied for the RAMMS simulation of a 30-year avalanche.

Appendix 4.3: RAMMS simulation White Subdivision avalanche path, 300-year return period

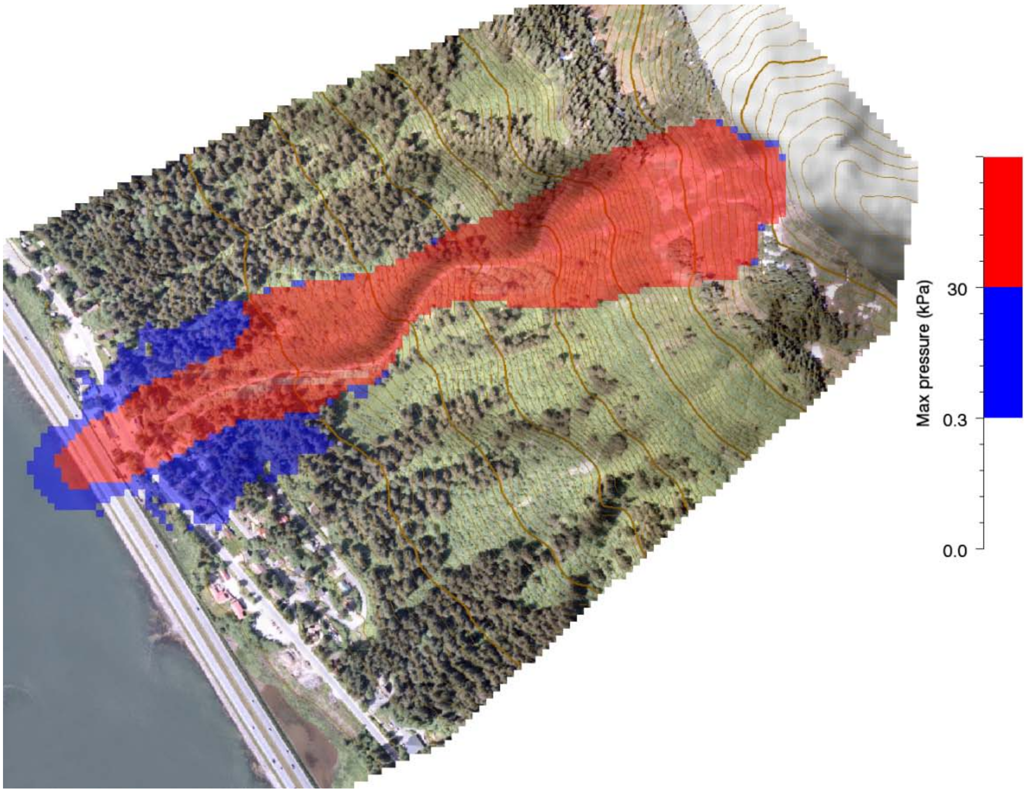


Maximum flow height of the RAMMS simulation of a 300-year avalanche (uncorrected simulation results).

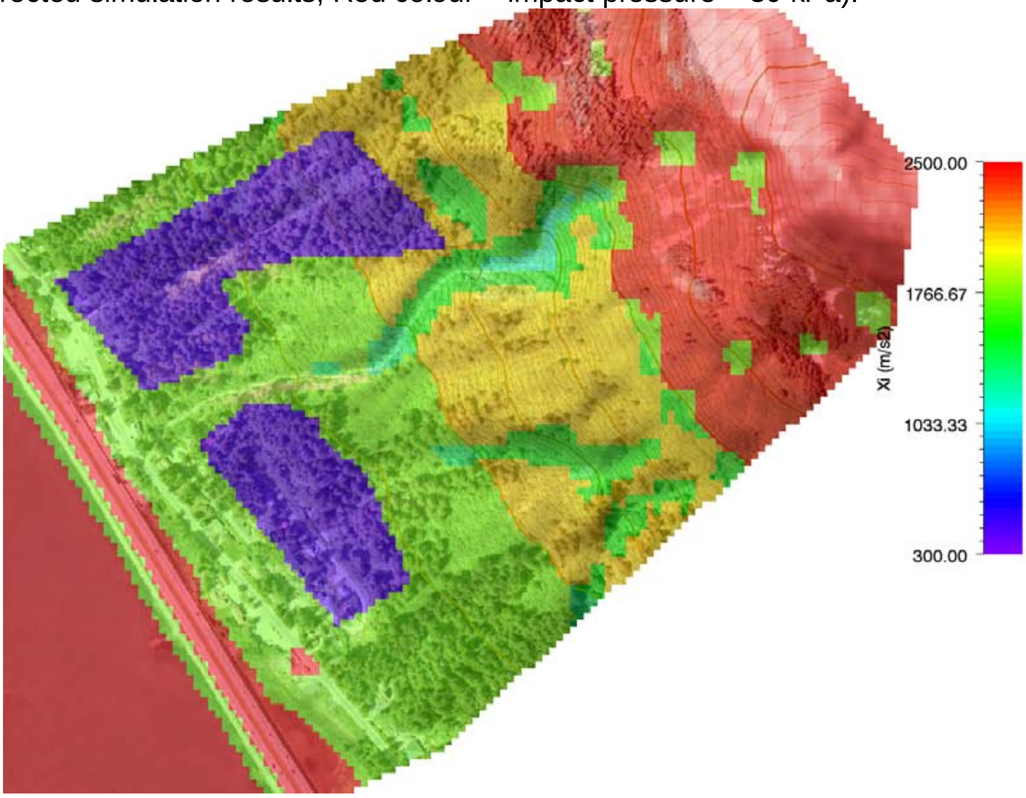


Maximum velocity of the RAMMS simulation of a 300-year avalanche (uncorrected simula-tion results).

Appendix 4.3: RAMMS simulation White Subdivision avalanche path, 300-year return period



Maximum avalanche pressure of the RAMMS simulation of a 300-year avalanche (uncorrected simulation results; Red colour = impact pressure > 30 kPa).



Friction parameter xi applied for the RAMMS simulation of a 300-year avalanche.

Appendix 5: Priority list for buyout of homes in the Behrends Avenue subdivision

Proposition for a priority list for buying out homes in the severe hazard avalanche zone in the Behrends Avenue subdivison. The priority 1 to 5 is based on the results of avalanche dynamics calculations, slide frequency and terrain conditions.