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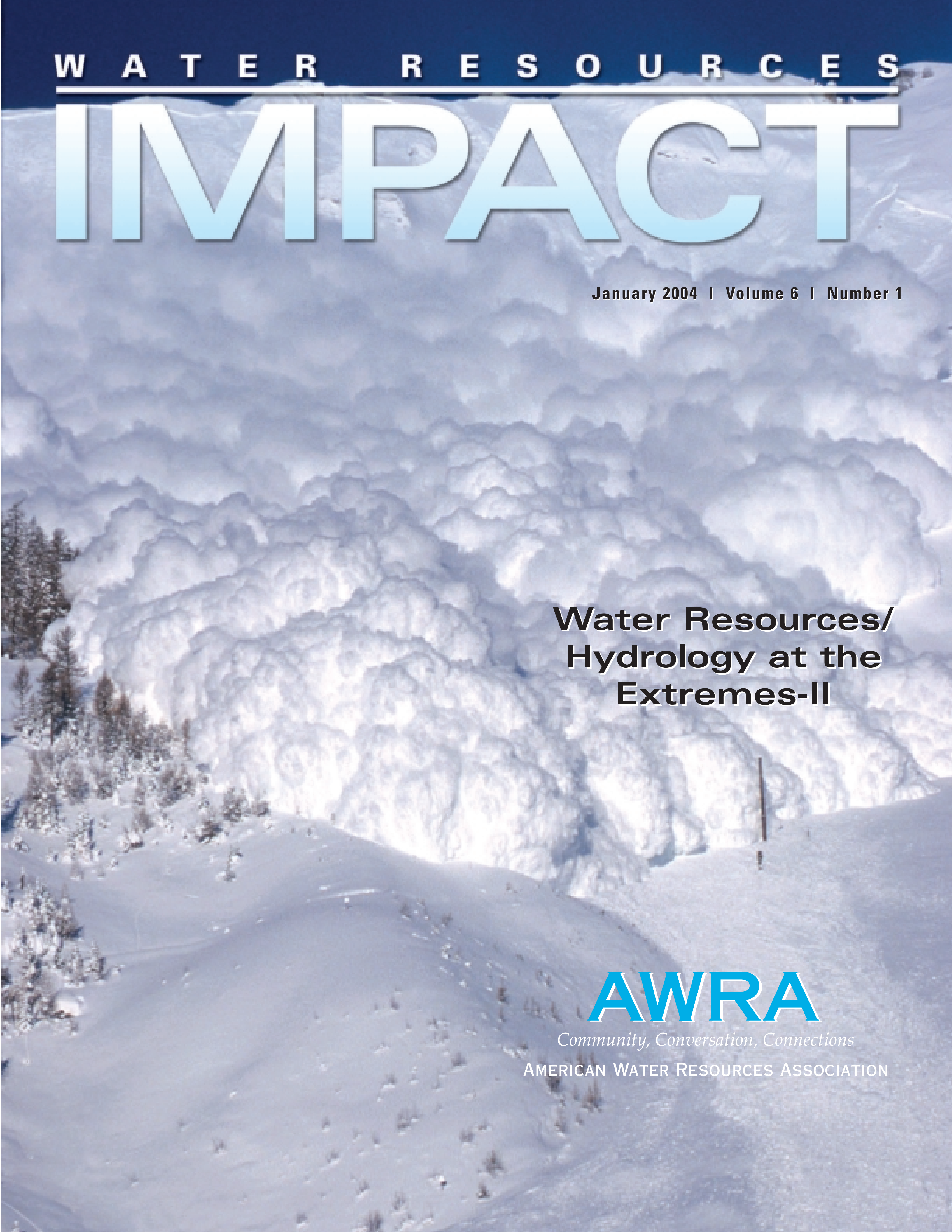

Water Resources/ Hydrology at the Extremes-II

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AMERICAN WATER RESOURCES ASSOCIATION

WATER RESOURCES/HYDROLOGY AT THE EXTREMES-II

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"Extremes" in water management can be viewed in terms of individual events, or climatic setting, or demands for water, or pressures on entire watershed systems. A variety of "extreme" examples are presented in this issue of *IMPACT*. We invite your responses about appropriate approaches to water management issues, be they political, legal, technical, or societal.

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[Cover Photo: Complements of J. Schweizer, SLF, Davos, Switzerland. Artificially triggered dry-snow slab avalanche at Valle de la Sionne, Switzerland. The measurement tower at the front of the avalanche is 20 m high; see related article beginning on pg. 12.)

SNOW AVALANCHES

Jürg Schweizer

INTRODUCTION

Snow avalanches occur in snow covered mountain regions throughout the world and have caused natural disasters as long as mountainous areas have been inhabited. Their occurrences affect ski resorts, roads, railways, power lines, communication lines, forests, backcountry recreationists, residential areas, and industrial facilities (e.g., mining) (Table 1). The number of fatalities per year due to snow avalanches is estimated to be about 250 worldwide. Within the last ten years (1993-1994 to 2002-2003) 419 people were killed in North America (U.S. and Canada) (Figure 1). In Canada, for example, the direct and indirect costs amount to over CAD$5 million per year. Most of the fatalities involve personal recreation on public land (Jamieson *et al.,* 2002).

TABLE 1. Objects Possibly Endangered by Snow Avalanches.

Snow avalanches are relatively rare events. Personal experience is limited and therefore it is important to raise the avalanche awareness of, for example, land managers, consultants, governmental agencies. Snow avalanches threaten (Jamieson *et al.,* 2002):

- corridors for transportation, energy or communication,
- temporarily occupied structures, industrial plants and mine facilities,
- work sites such as construction projects and forest harvesting operations,
- commercial backcountry recreational operations,
- ski areas and the associated lifts and buildings, and
- residential and permanently occupied structures.

Avalanche mitigation includes temporary measures (forecasting and road closure) and permanent measures (landuse planning, protective means such as snow sheds or tunnels, and reforestation). By combining temporary and permanent measures in a cost efficient way, also called integral risk management, the avalanche risk can be reduced to an acceptable level. Since snow avalanches are still relatively rare events, personal experience is limited and expertise is usually not readily available. Therefore, it is essential for hazard mitigation to increase the awareness of land managers, consultants, governmental agencies and individual recreationists about snow avalanches.

AVALANCHE PHENOMENON

Snow avalanches are a type of fast moving mass movement. They can additionally contain rocks, soil, vegetation, or ice. There are two types of release: loose snow avalanches and slab avalanches (Figure 2). Loose snow avalanches start from a point, in a relatively cohesionless surface layer of either dry or wet snow. Initial failure is analogous to the rotational slip of cohesionless sands or soil, but occurs within a small volume (<1 m^3) in comparison to much larger initiation volumes in soil slides.

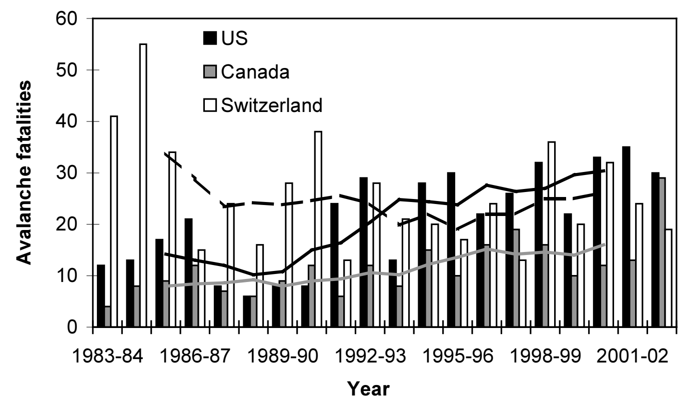

Figure 1. Avalanche Fatalities in the Last 20 Years (1983-1984 to 2003-2003) for the United States, Canada, and Switzerland. Bars indicate the total number of fatalities per year and country, lines are the corresponding five-year moving average. The 20-year average number of fatalities per year is 21 for the U.S., 12 for Canada, and 26 for Switzerland. In the last five years the number of fatalities increased in North America and remained unchanged for Switzerland (five-year average from 1998-1999 to 2002-2003 is 30 for the U.S., 16 for Canada, and 26 for Switzerland). The increasing trends over the last 20 years for the U.S. and Canada are statistically significant (level of significance $p \leq 0.001$). There is a decreasing, statistically nonsignificant ($p > 0.05$) trend for the Swiss data.

Snow slab avalanches involve the release of a cohesive slab over an extended plane of weakness, analogous to the planar failure of rock slopes rather than to the rotational failure of soil slopes. The observed ratio between width and thickness of the slab varies between 10 and 10^3, and is typically about 10^2. Slab thickness is usually less than 1 m, typically about 0.5 m, but can reach several meters in the case of large disastrous avalanches (Schweizer *et al.,* 2003).

... snow avalanches are a fascinating, powerful natural phenomenon, but also are a substantial hazard in snow covered mountain regions

Avalanche size is classified according to its destructive power (Table 2). A medium sized slab avalanche may already involve 10,000 m^3 of snow, equivalent to a mass of about 2000 tons (snow density 200 kg/m^3). Avalanche speeds vary between 50 and 200 km/h for large dry snow slides, whereas wet slides are denser and slower (20-100 km/h). If the avalanche path is steep, dry snow avalanches generate a powder cloud (see cover photo).

Figure 2. Avalanche Types: Loose Snow Avalanche Starting From a Point (top); Dry Snow Slab Avalanche Starting From a Line, Crown Fracture Perpendicular to Failure Surface (bottom).

Most avalanches release from terrain steeper than about 30°. Only a low percentage of dry slabs start on terrain under 30°, but wet slides can occur on slopes under 25°. The slope angle is the most important factor influencing avalanche formation.

TABLE 2. Avalanche Size Classification.

To assess avalanche hazard it is essential to have good historical information on previous avalanche events, in particular on the size of the avalanches. Therefore, not only the date but also the size of any avalanche event should be recorded (e.g., according to the Canadian classification system for avalanche size) (McClung and Schaerer, 1993):

Size	Destructive Potential (definition)	Typical Mass (tons)	Typical Path Length (m)	Typical Impact Pressure (kPa)
1	Relatively harmless to people	<10	10	1
2	Could bury, injure, or kill a person	100	100	10
3	Could bury a car, destroy a small building (e.g. a wood frame house), or break a few trees	1,000	1,000	100
4	Could destroy a railway car, large truck, several buildings, or a forest with an area up to 4 ha	10,000	2,000	500
5	Largest snow avalanches known; could destroy a village or forest of 40 ha	100,000	3,000	1,000

A snow avalanche path consists of a starting zone (usually steeper than 30°), a track and a run-out zone where the avalanche decelerates and the snow is deposited (Figure 3). On large avalanche paths the slope angle is usually less than 15° (27 percent) in the run-out zone (Jamieson, 2001). In general, a snow avalanche will flow from the starting zone, or in analogy to hydrology, the catchment area, downstream, often along creek beds. However, if the track is steep and a powder cloud develops, the powder snow avalanche may run straight down, regardless of the topography (i.e., not follow, for example, any bends in the creek bed). Small avalanches may stop in the track (typically 15-30° steep), but large ones move with approximately constant speed to the run-out zone. Run-out zones are often on alluvial fans – a preferred area for infrastructure, including businesses and residences, in mountain areas.

Most snow avalanches start naturally during or soon after snow storms. Failure is due to overloading an existing weakness in the snowpack. High precipitation rates favor snowpack instability. In general, about 50 cm of new snow within 24 hours (equivalent to about 50 mm of precipitation) is critical for avalanche initiation. Large disastrous avalanches usual follow storms that deposit more than 1 m of snow. Strong winds causing large, irregular snow drifts promote instability as do solar radiation, daytime heating, or relatively warm air masses.

Figure 3. Snow Avalanche Path From the Schiahorn, Davos, Switzerland. Starting zone above, partly with supporting structures, avalanche track in narrow creek bed and run-out zone into residential area. In 1962, a disastrous avalanche was recorded in this path. The avalanche destroyed the forest just above the run-out zone (the gap is still visible) and damaged several houses in the run-out zone. The houses (circle) are the two only ones in the red zone (high hazard) where new buildings are prohibited. See Figure 4 for details of the hazard map (photo: Stefan Margreth, SLF).

The triggering of a snow slab avalanche can also occur artificially by localized, rapid, near surface loading by, for example, people (usually unintentionally) or intentionally by explosives used as part of avalanche control programs. In general, naturally released avalanches mainly threaten residents and infrastructure, whereas human triggered avalanches are the main threat to recreationists (Schweizer *et al.,* 2003).

AVALANCHE MITIGATION

To avoid avalanche disasters, first of all, potential avalanche terrain and accordingly a potential avalanche problem needs to be recognized. Indications include oral and written history of previous avalanche events, vegetation clues and snow depth records, and most importantly terrain. A terrain analysis can be done by identifying all areas steeper than about 25° by using a GIS and a DTM. Obviously, any infrastructure in these potential starting zones is endangered. The next step is to assess the frequency, magnitude, and run-out of avalanches initiating from the identified potential starting zones. This task is typically done by an avalanche expert. If any infrastructure is located beneath a potential starting zone, even as far as 1 km "downstream" from the starting zone, a consultant should be called to assess the avalanche hazard or risk. This will involve estimating frequency and size of avalanches and accordingly establishing an avalanche hazard map (Figure 4) (Jamieson *et al.*, 2002; Mears, 1992). Besides expert knowledge statistical and avalanche dynamics models are applied to estimate the run-out.

Figure 4. Hazard Map for the Avalanche Path Fom the Schiahorn, Davos, Switzerland (same as shown in Figure 3). The red hazard zone is hatched from bottom left to top right, the blue hazard zone from top left to bottom right. In the red zone (high hazard) avalanches are expected that either have an impact pressure larger than 30 kPa with return periods of up to 300 years, or a return period of 30 years or less regardless of the impact pressure. Construction is prohibited. In the surrounding blue zone (moderate hazard) avalanches are expected with impact pressures of less than 30 kPa and return periods between 30 and 300 years. Construction may be permitted but only if designed to withstand an impact pressure of up to 30 kPa depending on the location in the run-out zone. Hotels or other buildings occupied by many people, for example, the bottom station of a cable car or chair lift, are not permitted (McClung and Schaerer, 1993). Due to the fact that landuse planning based on hazard mapping was introduced in the second half of the 20th Century, usually some buildings are found in the red hazard zone. In critical situations, these buildings, and in extraordinary situation even the most endangered houses in the blue zone, would be evacuated.

Depending on the object endangered and the frequency and size of potential avalanches, mitigation measures are planned. If residential areas or areas where development is planned, are endangered, landuse planning measures should be established based on the hazard map so that buildings in hazard zones are avoided, restricted, or designed to withstand potential avalanche pressures. In Switzerland, for example, hazard zones are defined based on avalanche frequency and impact pressure (Figure 4). For residential areas large avalanches with frequencies as low as 300 years need to be taken into account. For roads, typically return periods are much higher, up to several times a year. If a road is endangered by several potentially large avalanches with return periods of less than 10 years, an active avalanche control program (including the use of explosives) and/or the construction of snow sheds should be considered. If the avalanches potentially hitting the road are rather small and or infrequent temporary closures based on an avalanche forecast may be the adequate protection measure (Jamieson *et al.*, 2002).

The various mitigation measures should be applied, usually in combination, in a coordinated manner to reduce the avalanche risk to an acceptable level. This approach is known as integral risk management (Figure 5) (Wilhelm *et al.*, 2001). In general, mitigation measures are grouped into temporary and permanent measures, both of which can be applied actively or passively.

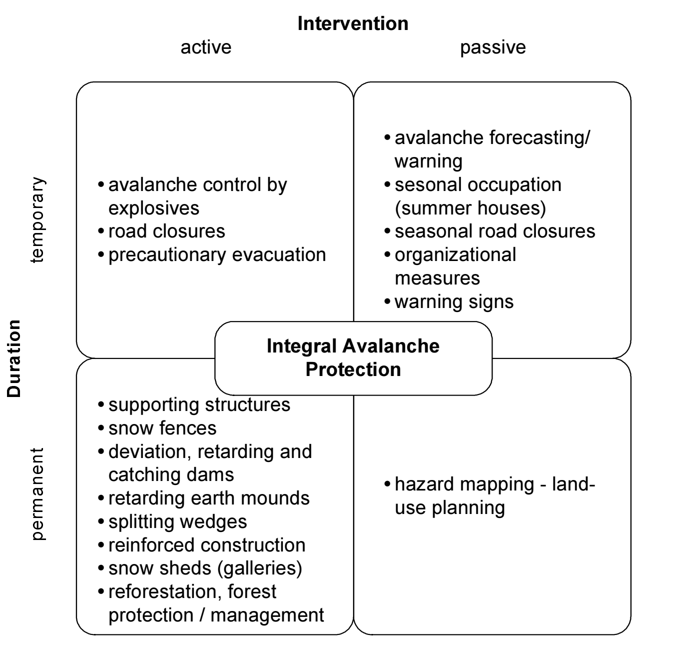

Figure 5. Various Temporary and Permanent Protection Measures That Are Coordinated and Applied in an Optimal Manner to Reduce the Avalanche Risk to an Acceptable Level at Minimal Costs (Wilhelm *et al.*, 2001).

A precondition for successful temporary measures is an avalanche forecast. This implies that avalanche professionals continuously assess the avalanche hazard based on field observations, measurements from automatic weather stations and weather forecasts. In many countries, public avalanche bulletins are issued that reliably warn the public about the prevailing avalanche danger. For highly endangered infrastructure (highways, railways, mining operations, ski areas, etc.) local forecasting services are established that also run the avalanche control program (Schweizer *et al.*, 1998). Other temporary mitigation measures include avalanche control with explosives, temporary (or seasonal) road closures, warning signs, precautionary evacuation and seasonal occupation of, for example, summer houses (Jamieson *et al.*, 2002).

From the starting to the run-out zone various permanent avalanche mitigation measures can be applied. The most common method to avoid avalanche release at all is to build supporting structures in the starting zone (Figure 6). If only a part of the potential starting zone can be stabilized, the release volume is at least reduced, and accordingly the run-out is usually shorter. Below the tree line, protection of forest or reforestation are the preferred measures to stabilize the snowpack. In the run-out zone landuse planning, based on an avalanche hazard assessment (avalanche zoning), and protective construction work (avalanche sheds or galleries over railways and highways, splitting wedges, reinforcements of buildings) are the most common permanent measures (Figure 7). Earth mounds and retarding or catching dams are used to slow down or stop avalanches in the lower part of the run-out zone.

Figure 6. Supporting Structures in a Starting Zone on the Schiahorn Above the Town of Davos, Switzerland. A slab did release at the edge of the protected area, but could not develop into a large avalanche due to the supporting structures.

In general, it needs to be pointed out that presently it is not possible to predict the precise location and time of an avalanche release. This is due to the fact that the release mechanism is not yet fully understood, and in particular due to the partly chaotic nature of the phenomenon. Therefore, dealing with snow avalanches means dealing with uncertainty. This needs to be taken into account when temporary mitigation measures are preferred over permanent protective work.

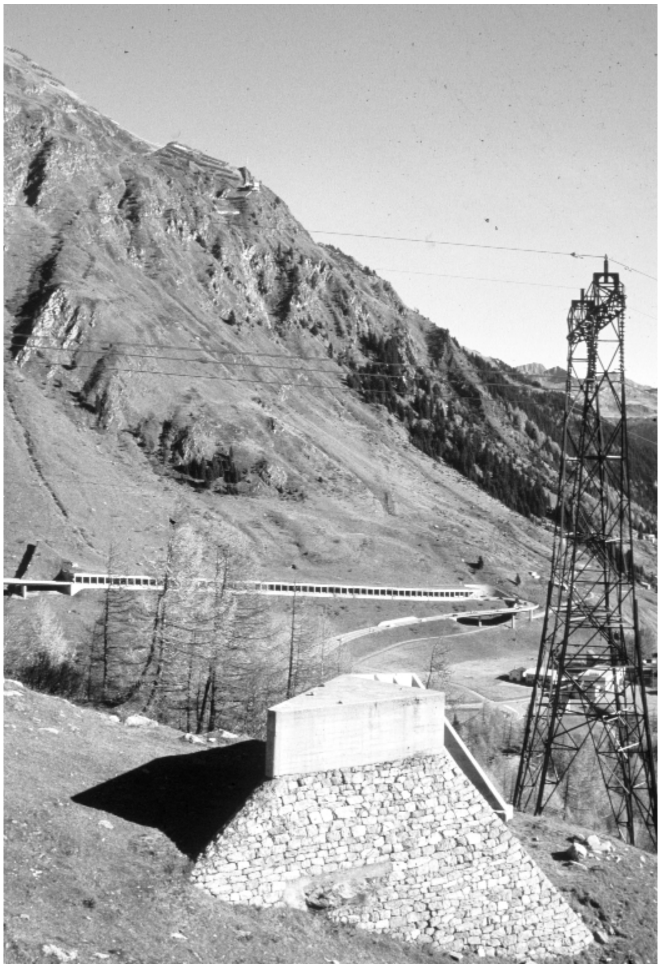

Figure 7. Various Protective Structures on the South Side of the Gotthard Pass, Switzerland. In front, a pylon of a power line is protected with a splitting wedge and a short deflecting wall. In the middle, a snow shed protects the highway, and above, in a starting zone of another avalanche path to the right, supporting structures were built. The left entrance of the snow shed is protected by a splitting wedge so that the avalanche will flow either above the shed or beneath the bridge leading to the shed.

Despite the uncertainty, by combining the two types of protection measures the avalanche hazard can in fact be significantly reduced so that even in densely populated mountain regions avalanche disasters seldom occur. This was demonstrated during the winter 1998-1999 when in the European Alps an exceptional avalanche situation prevailed. Although the disaster was estimated to be a 100-year event, the number of fatalities in the Swiss Alps was relatively low (17) compared to a similar event about 50 years earlier when nearly 100 people lost their lives. The fact that the disaster was limited was attributed to the enormous progress in avalanche protection since 1951 (the date of the first disaster). Over 1.5 billion Swiss francs had been invested for protective work between 1951 and 1999, the avalanche forecasts were improved, and the communities much better prepared for disaster management. Most decisive was the consequent landuse planning established in the previous decades in all mountain communities with the aim to avoid, restrict or specially design buildings in avalanche hazard zones (for more details see text box on pg. 18).

CONCLUSIONS

Snow avalanches are a fascinating, powerful, natural phenomenon, but also represent a substantial hazard in snow covered mountain regions. Avalanche hazards threaten transportation corridors, utility corridors, ski operations, work sites, forestry, and inhabited structures. In the U.S., snow avalanches cause more fatalities on an annual basis than any other type of mass movement (Voight *et al.*, 1990) – with an increasing trend over the last two decades. However, nowadays, avalanche mitigation can efficiently reduce avalanche risk. Among the various methods used are: landuse planning, protection forests, reinforcement and design of structures, protection works such as supporting structures, dams and snow sheds, as well as temporary measures such as avalanche forecasts, explosive control, and closures. The optimal combination of these various and complementary mitigation measures in the form of integral risk management is the most efficient way to reduce the avalanche risk. This approach might also be promising for other natural hazards such as floods and storms.

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AVALANCHE DISASTER OF FEBRUARY 1999 IN THE SWISS ALPS

The winter of 1998-1999 was extraordinary in many ways. Three consecutive, long lasting storms from the northwest hit the Alps. Within 30 days the new snow amounts were up to 500 cm, in particular on the northern flank of the Alps (i.e. more than the usual amount of precipitation for the whole winter). The consequence of the unusual snowfalls was very widespread, intense avalanche activity. Approximately 1200 destructive avalanches occurred – besides thousands of nondestructive ones. In general, intense avalanche activity causing damage to people and infrastructure occurs approximately every 10 years in the Swiss Alps.

During the most disastrous avalanche winter of the 20th century in Switzerland, in 1951, 98 people were killed, 73 in buildings. In February 1999, 28 people were caught in inhabited areas and on roads and 17 of these died (11 in buildings) in Switzerland . About 50 other people were killed in France, Italy and Austria during the same avalanche cycle. The number for Switzerland was relatively small in comparison with earlier disasters despite the fact that there were significantly more people in the mountains due to the growing development of recreational activities. All ski resorts were fully booked at that time of the winter. In 1999 mainly roads, railways, power and communication lines were affected. Their interruption had more severe consequences than 50 years earlier.

The direct and indirect costs amounted to about 770 million Swiss francs. The damage would likely have been very much higher without the avalanche protection work established in the past decades. Approximately 10 km of snow supporting structures in starting zones have been built annually since 1951 and there are over 500 km at present. The annual financial expenses for avalanche protection and forestry projects culminated at around 70 million Swiss francs (55 million US$) in 1990 and have decreased since.

Landuse planning based on hazard maps proved to be an efficient way of avalanche protection. The hazard maps were also used to plan road closures and the evacuation of residential areas. Avalanche defence structures (snow-supporting structures in starting zones, wind fences, deviating structures, retention dams and snow sheds) fulfilled their function efficiently. Despite the fact that many supporting structures were completely filled with snow, they withstood the very high loads and prevented avalanches from releasing. Regular, artificial triggering of avalanches by explosives during the lasting storms played an important role in hazard reduction by avoiding the formation of large avalanches in many areas. However, there was also significant damage caused, confirming that there is also a considerable risk involved with artificial triggering. No avalanches were reported as having been released in forests, confirming their protective effect.

Integral avalanche protection in the form of an optimal combination of various mitigation measures and disaster management was successfully put to test in February 1999. However, it was also confirmed that complete protection, or zero risk, is impossible due to technical, economic, ecological and social limitations. The extraordinary amount of snow precipitation in winter 1999 caused extensive flooding in late spring. The damages (direct costs: 580 million Swiss francs or 460 million US$) caused by the floods exceeded that caused by the avalanches (Ammann, 2000, Wilhelm *et al.*, 2001).

AVALANCHE DANGER SCALE AND SNOW AVALANCHE SAFETY BASICS FOR RECREATIONISTS.

Snow avalanches do not happen by accident and most human involvement is a matter of choice rather than chance. Most avalanche accidents (90 percent) are caused by dry snow slab avalanches that are triggered by the victim or a member of the victim's party. However, any avalanche may cause injury or death and even small slides may be dangerous. Hence read a book (e.g., Tremper, 2001), get some practical avalanche education, learn about actual conditions from the public bulletin and always practice safe route finding skills, be aware of changing conditions, and carry avalanche rescue gear (electronic avalanche rescue beacon, shovel, and probe). Learn and apply avalanche terrain analysis and snow stability evaluation techniques to help minimize your risk. Remember that avalanche danger rating levels are only guidelines. Distinctions between geographic areas, elevations, slope aspects, and slope angles are approximate and transition zones between dangers exist (after Jamieson, 2001). Public avalanche bulletins issued in the U.S. (see www.avalanche.org) use the following danger scale. For public bulletins in Canada, see www.avalanche.ca; in Europe, see www.lawinen.org.

Danger Level	Avalanche Probability and Avalanche Trigger	Travel Suggestions
LOW	Natural avalanches very unlikely. Human triggered avalanches **unlikely**. Generally stable snow; isolated cases of instability	Travel is generally safe. Normal caution advised
MODERATE	Natural avalanches unlikely. Human triggered avalanches **possible**. Unstable slabs possible on steep terrain	Use caution in steeper terrain on certain aspects
CONSIDERABLE	Natural avalanches possible. Human triggered avalanches **probable**. Unstable slabs probable on steep terrain	Be more cautious in steeper terrain. Be aware of potentially dangerous areas of unstable snow
HIGH	Natural and human triggered avalanches **likely**. Unstable slabs likely on a variety of aspects and slope angles.	Travel in avalanche terrain not recommended. Safest travel on windward ridges or lower angle slopes without steeper steeper terrain above.
EXTREME	Widespread natural or human triggered avalanches **certain.** Extremely unstable slabs on most aspects and slope angles. Large destructive avalanches possible.	Travel in avalanche terrain should be avoided and travel confined to low angle terrain well away from avalanche path run-outs.