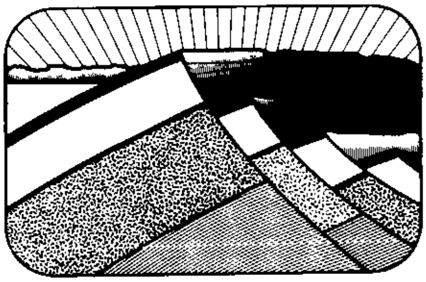

Slope Stability and Land Use in Mountain Valleys

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Summary

Recreational activities and increasing resource development in the highest parts of the Canadian Cordillera will result in permanent high-density settlements along the flanks of hitherto secluded mountain valleys. In this environment the possibility of damage to human works, such as transportation routes and towns, by debris flows or large-scale slope failure has to be appraised, preferably prior to the onset of major construction activity. Two millennia of documented adjustments of settlement pattern to a variety of slope conditions in the densely populated European Alps offer a number of alternatives in approaching this problem by active (technical) or passive (zoning) measures and by the recognition of the residual risk. For areas of proposed permanent housing, mass movements with a projected rate of recurrence of more than one event in 100 to 300 years should be assessed seriously. In precipitous mountain valleys there are very few areas for which risk can be assumed to be nil - particularly if projected time intervals are in excess of 500 years. A certain amount of residual risk thus has to be accepted by those inhabiting or moving through high mountain terrain. Quality of sloping terrain will also figure increasingly in comprehensive resource management (forests, tourism, fishing, and transportation).

Introduction

The expansion of a variety of recreational activities into high mountain valleys appears to have no end. Because scenic flatland terrains of western Europe and North America are disappearing at an alarming rate under concrete and because many a suburban home has been engulfed by industrial and urban growth, the desire for vacations or a second home in a more 'unspoiled environment' has set off unprecedented development activity in remote mountain valleys. In central Europe where church and inn used to be landmarks of small agricultural mountain villages, mobile remote-control cranes are now equally permanent fixtures in traditional communities or new tourist towns. Many mountain valleys are narrow, and flat land is generally swampy or at the mercy of floodprone rivers; some of the valley bottoms are pre-empted by agriculture, transportation routes, or hydroelectric reservoirs. Under these conditions newly established communities in high mountain valleys have to confront the problems of population densities on a par with or even exceeding those of more conventional suburban centres in flatland areas.

This poses a perplexing array of challenges to those who have to plan or create the relaxing setting that people expect to find once they have negotiated their way over hairpin turns and through heavy traffic to the destination of their choice. This challenge is not limited to the development of the narrow bottoms of mountain valleys, but increasingly extends onto the flanking slopes or elevated depositional cones of tributary torrents, both geomorphic features that are commonly the result of a subtle natural balance between what will stay where it is, and what will not!

In spite of the natural limitations imposed by sloping terrain, mountains have always provided food, shelter, minerals, and energy - provided that the physical limitations of the environment were understood. Indeed, inaccessibility and rugged setting have permitted the survival of unique cultural patterns in the face of changing political currents. The terrace cultures of Asia and pre-Hispanic America demonstrate particularly well to what extent sloping land can be improved to serve human needs (Fig. 1).

Japan, a densely populated mountain country, has a long history of defense against debris disasters in sloping terrain. The art of preventive and protective measures against unstable debris ('Sabo') has always been highly visible to the eye of the public. Ikeya (1979, p. 83-84) reports that as early as . . . 'in the third year of Tenwa - 1683 - the water of the Kinu River was intercepted by a slide in the vicinity of the present Ikari dam site. As the area was governed by the Aizu feudal clan at that time, the clan attempted to construct a canal for draining the impounded waters. But the project resulted in failure and the streets of Utsunomiya on the lower Kinu River were inundated with water about 1 metre deep. It is put on record that out of a sense of responsibility the person in charge of the project performed harakiri . . .'. Even more relevant to the future problems to be faced in the mountains of the Canadian west is the historical experience of the European Alps. There, 2000 years of chronicles and oral traditions illustrate a variety of possible adaptations to natural and self-inflicted mass movements on sloping terrain (Eisbacher, in prep.).

The invasion of a largely urban society into high mountains, whether it be in search of mountain adventure or sports, probably finds the Alps somewhat better prepared than Canadian Cordillera, but not by much; great population densities magnify the problem of Central Europe by an order of magnitude. In western Canada development of mountain valleys so far has been restricted largely to single communities or camps serving as temporary centres for the exploitation of minerals and timber. Some of the remote camps have been abandoned and old access roads have been lost to readvancing forests. The new conquest of mountain valleys in the west will be different: costly housing, speculative landownership, a wide range of public services, expensive road maintenance, and a safety-conscious consumer attitude will require a long-range outlook in quest of the most harmonious form of development. The problem, by its very nature, is interdisciplinary and on the professional level should involve at least regional planners, architects, engineers, geologists, foresters, geographers, and developers.

to the stability of mountain slopes, the state of the art as presently practised in the Alps is a natural starting point. Having become the most developed mountainous tourist region in the world, enormous effort and financial resources are being allocated in Switzerland, Austria, France, and northern Italy to manage the problem of recurrent mass movements. This review attempts to summarize a year's field effort and many hours of discussion with workers in the Alps. Although divergent philosophies and traditional wisdom have developed into different administrative or technical schemes, the singularly unforgiving environment has resulted in considerable consensus as well. It is possible that some of the basic concepts may hold in western North America as well.

The following sections deal with slopes as hazard, with slopes in cities, with slopes related to forests and fish, and with slopes for skiing. Not included are

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the closely related natural hazards arising from floods and snow avalanches whose mechanics and rate of recurrence are somewhat better understood than the frustratingly individualistic behaviour of the geological materials which underlie mountainsides.

Because it would be impossible to cite the large body of technical papers pertaining to specialized aspects of slope stability and regional problems in the Alps and the North American Cordillera, I have included only some of the principal references that historically set the stage to further work on the land use - slope stability problem in high mountain environments.

Mountain Slopes as Hazard

After snow avalanches and floods, debris flows and landslides are the main natural hazards of mountain terrain. A complete spectrum of processes ranging from excessive bedload transport in torrential rivers to massive failure of high bedrock cliffs contributes to the hazards of mountain living. It is convenient to discuss the subject under three headings: debris flows, large-scale slope failure, and acceptable risk.

a) Debris Flows. A debris flow is a mass of rock fragments, soil, sand, mud, trees, and water that moves along preexisting torrent channels or ravines before it debouches, often with catastrophic force, onto the floor of a mountain valley. In general a debris flow contains more solids than water (Ikeya, 1979). Where water predominates, the term debris flood might be more appropriate. Debris flows orginate in many different geological settings, most of them related directly to terrain instabilities in the upper drainage basins of mountain torrents. In fact the very term 'torrent' (*torrente* in Italian, *torrent* in French, *Wildbach* in German) implies irregularity and suddenness of discharge. The transition from massive discharge of water to gravity-driven debris flows along mountain torrents is commonly difficult to define. In mountainous terrain the study of torrents necessarily implies the study of sporadic debris flows. Many torrents go through short periods of violent movement of debris and long periods during which a torrent regains a deceivingly harmless aspect. Since debris flows tend to move as much as three orders of magnitude more material than the 'normal' annual discharge, a torrent system can be appropriately described as being either dormant or active (Fig. 2).

Four geomorphic-geologic elements contribute to the debris flow hazard in the torrent system (Fig. 2): (1) a *catchment* (or drainage) *basin* which collects runoff from upland slopes; (2) a *debris source* (or sources) where masses of debris are mobilized along slumps, debris chutes, ravines or gullies; (3) a *gorge* where debris from the source area concentrates into coherent flows and thus gains potentially destructive momentum; and (4) a *cone* or *fan* on which debris flows spread before some of the material reaches the receiving river of the valley bottom (Fig. 3).

The source area of potential debris flows is always smaller than the catchment basin. Nevertheless, in many high-gradient torrent systems a large percentage of the catchment basin may be underlain by unstable terrain. Such torrent systems tend to result in seemingly oversized cones whose volume cannot be explained by the trickles of water that normally flow towards the receiving river. The significance of the four elements of a

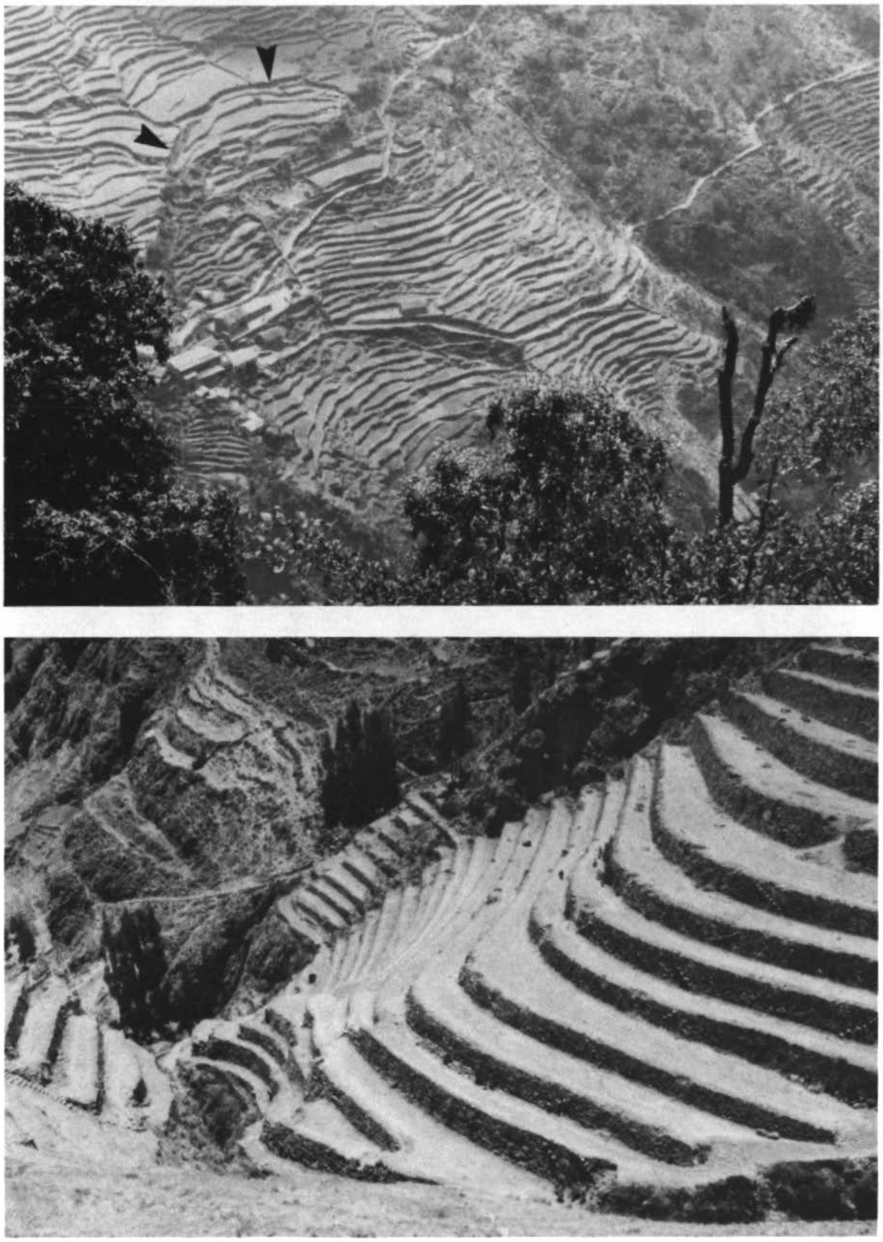

Figure 1 *Agricultural terracing for intense use of steep mountain slopes. Top: Terraces for the cultivation of rice on a deeply weathered slope near Ulleri, Nepal Himalayas; the berms retaining the water during the monsoon season are composed of stony soil and have to be carefully maintained to avoid gullying and debris slumping; note that the buildings and the trails are located on a large incipient slope failure that can be recognized by the distinct downward-concave headscarp above the upper trail (arrow); morphology and vegetation on the right of this area suggest a previous slope failure. Bottom: Agricultural terraces constructed within the domain of the fortified Inca settlement of Pisaq, Peruvian Andes; meticulously laid out retaining walls of stone and runoff ditches have survived 400 years of neglect.*

torrent system in the evolution of real-life debris flows was first dealt with concisely in a classical monograph by Stini (1910).

The primary mechanism of debris flows is oversaturation of unstable terrain with water or simple erosion. The structural geology of bedrock slopes, the distribution of surficial deposits, the location of gullies and ravines control the details of the source area mechanism. In addition, the state of the vegetation cover will influence the degree to which incipient instabilities develop into active source areas. Thus, no debris source area will be identical with another one. Nevertheless, as regional geology determines the composition and geometry of the source areas of adjacent torrent systems, the latter often can be classified into broad groups. Source area characteristics and vegetation can be mapped, and provide a first hint of the potential of the torrent system to create debris flows.

In contrast to the relatively fixed geological and biological parameters of a debris flow system the extreme meteorological events that trigger (or 'cause') damaging debris flows are very difficult to appraise. Weather records extending over many decades, particularly the registration of peak rainfall intensities, are generally lacking in remote mountain valleys, not only in western Canada, but in many densely populated mountain districts of the European Alps as well. The shorter the meteorological record of a region the less predictable is the incidence of debris movements.

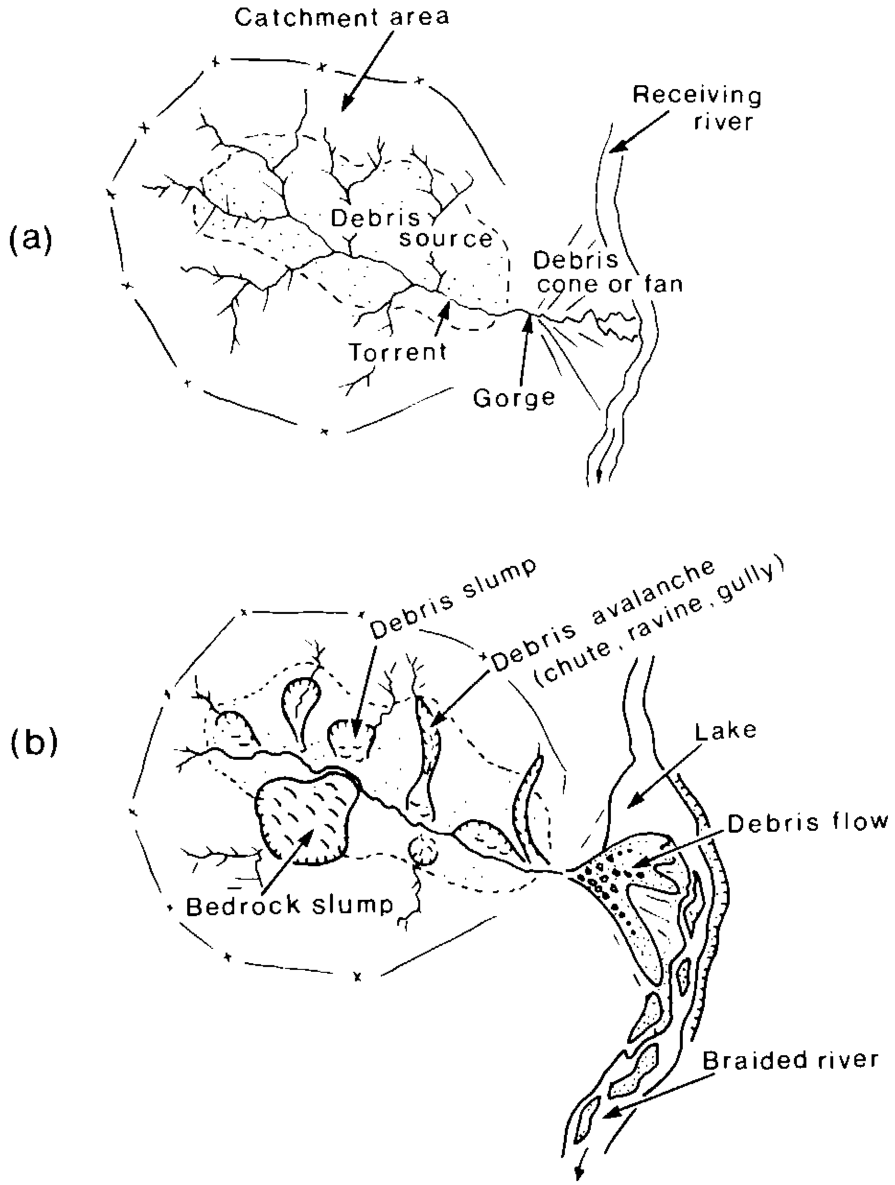

Figure 2 *Schematic illustration of the geomorphic-geologic elements characteristic of (a) dormant and (b) active torrent systems. For explanation see text.*

There are essentially four types of extreme meteorological situations that trigger destructive debris flows: repeated or sustained regional rainstorms, delayed snowmelt, local cloudbursts, and ice floods. *Repeated or sustained regional rainstorms* (e.g., with more than 300 mm of precipitation in 48 hours) are especially disastrous if they begin with snowfall and continue with warm rain (such as in 1740 and 1859 in the French Alps, 1868 in Switzerland, 1882 and 1966 in southern Austria and northeastern Italy, 1935 in southwestern British Columbia). Failure of saturated colluvial veneers during such rainstorms occurs during local squalls (Ikeya, 1979; Eisbacher and Clague, 1981). Linear downslope depressions are particularly susceptible to failure and convergence of avalanching debris onto swollen torrents generally launches debris flows. The sudden burst of water and debris along colluvial slopes has been appropriately described as 'slope water explosion' (Fuxjaeger, 1975). During sustained regional rainstorms an intact forest cover adds some natural strength to thin noncohesive colluvial slopes via its network of roots. In western Canada the coastal and insular mountains are frequently exposed to extended rainstorm periods.

The second type of meteorological trigger-cause is *delayed springtime snowmelt*. If a winter's snowpack remains intact far into spring or even summer, snowmelt may be both sudden and enhanced by torrential rains. This results in concentrated release of water along the ground-snow interface: the detachment of snow avalanches commonly also involves underlying colluvium and bedrock. Masses of snow, rocks, and trees may block torrent channels to the degree where the swollen torrents 'clear their throats' in massive debris flows. The main protective function of the forest is its provision of shade (Aulitzky, 1975). The southern Canadian Cordillera sporadically experiences such delayed springtime snowmelts (e.g., 1948 and 1894).

The third type of trigger-cause is the localized *thunderstorm-cloudburst* (e.g., more than 50 mm of rain in an hour). Concentrated runoff from bare uplands may lead to deep scour along pre-existing ravines or gullies in unconsolidated deposits. Minor temporary blockages of the passage of bedload through the gorge tend to result in pulses of debris onto the cone. In the Alps and elsewhere the historical records are full of these highly localized debris flow disasters (Mougin, 1914; Montandon, 1933; Stini, 1938;

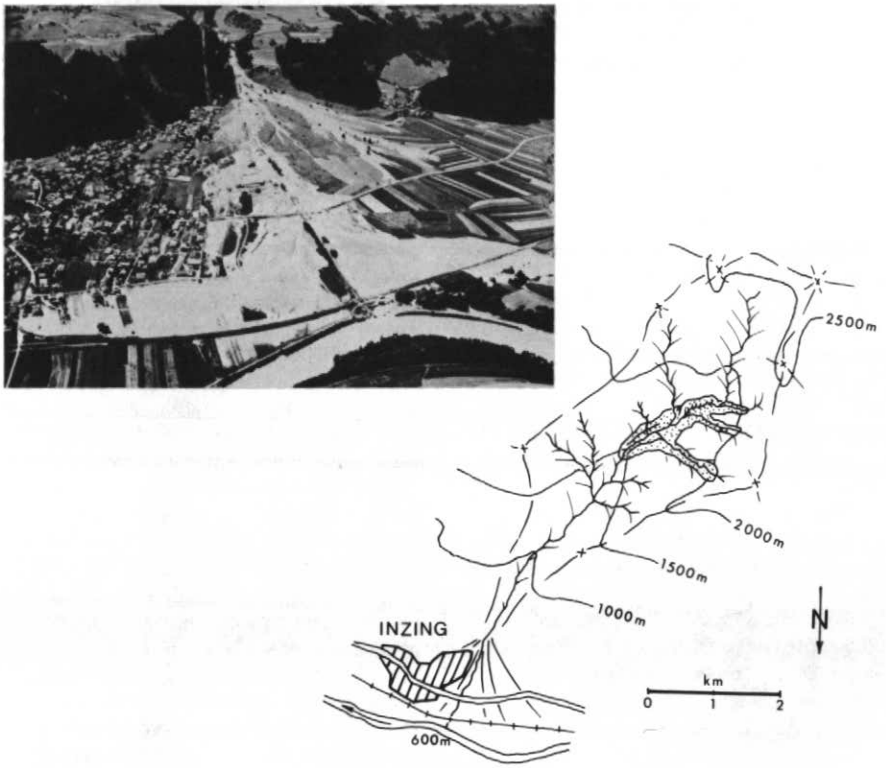

Figure 3 *Example of a debris flow into a recently expanded agricultural community. The flow engulfed parts of Inzing, Austria, in 1969, demolished buildings, and claimed several lives. Blocky debris was mobilized during a local cloudburst from a source area composed of relict Pleistocene colluvium which, in this figure, is outlined by the dotted pattern. Note how traditional wisdom used to restrict building activity to the eastern flank of the cone. Much of the damage in 1969 was to buildings that had been constructed to serve the recent tourist boom. Extensive control works in the uplands (see Fig. 7), a protective dam at the apex of the fan, and relocation of the channel on the cone have been completed since the catastrophe. Notice the protective forest along the steep colluvial terrace rims (Photo Alpine Luftbild).*

Figure 4 *Elevated channel across the fan of a formerly notorious torrent that used to ravage the Medieval mining town of Schwaz, Austria. In this century, the upland debris sources have been brought under control by reforestation, check dams, and snow-avalanche fences; in addition, two protective dams above the fan apex provide for a safe setting of the built-over debris cone: thus modern homes (on the right) have been erected directly on the elevated flanks of the old stone masonry dams.*

Stacul, 1979; Hanausek, 1975). The beneficial role of the forest during such intense thunderstorms is limited to minor interception of rain by the canopy and some reduction of initial scour along the tributary branches of torrents. In western Canada destructive mass movements triggered by local thunderstorms are probably most significant in the eastern front ranges of the Cordillera (Eisbacher, 1980).

A fourth climatic cause for the development of debris flows is exceptional summer heat in presently glaciated catchment basins. *Ice-debris floods* (jökulhlaups, debâcles) start with the burst of glacial lakes, the sudden release of englacial water pockets, or ice-rock avalanches into high-gradient torrents. The detailed mechanisms of glacial debris flows vary greatly with the topographic - geologic setting (Walcher, 1773; Richter, 1889; Rabot, 1905; Röthlisberger, 1979; Lliboutry *et al.*, 1977; Eisbacher, in prep.). In the past a number of measures have been applied to forestall the mobilization of debris by ice floods or at least to neutralize their impact on human works. The most common techniques involve the drainage of accumulated water bodies by tunnels (in ice or rock), the construction of reinforced overflow channels, and the preparation of retention reservoirs below the glaciers. The potential for ice flood-debris flows exists in the highest parts of the Canadian Cordillera (Clague and Rampton, in press; Mathews, 1973; Jackson, 1979).

Based on a long experience with sporadic outbursts of debris from gorges of generally harmless torrents, Alpine communities historically tended to cluster near the incised heads of debris fans or on protected bedrock ledges between the fans. The advantages of a location near the head of a fan were obvious; the torrents drove the mills, supplied clean water throughout most of the year, irrigation channels could be checked regularly, and the channel embankments of the incised fan head offered protection against minor debris flows. In addition, the community was safe from annual floods of the river in the valley below and was spared some of the icy fogs in winter! The natural risks and hardships, although not eliminated by any means, were thus reduced to a tolerable level. Prehistoric tribes knew about the advantages of fan-head sites and so did Roman military men. Only as small settlements expanded were more hazardous parts of debris cones occupied. This required confinement of the torrents by so-called water walls ('Archen'), systems of primitive dikes flanking the channel of the torrent across towns. Over time these early protective structures tended to lose their effectiveness, because sporadic voluminous mass flows completely filled the channels between the walls. The floor of a channel was thus raised. To counteract the renewed threat of spillover, the annoying debris was removed from the channel or the height of confining walls was increased. Debris flows in mountainous terrain commonly exceed volumes of 10,000 m^3 and therefore the option to raise the walls, rather than to lower the channel, was chosen after many debris flow disasters. However, in this manner the torrents continued to elevate their beds until they were higher than adjacent streets and houses (Fig. 4). If a large flow now jumped the channel walls, the deluge onto the adjacent town was of catastrophic proportions - streets and buildings disappeared under masses of debris. Nevertheless, once initiated, walls and dikes across threatened towns grew to impressive size. Meanwhile the debris sources of the uplands might have expanded on account of unchecked logging practices, overgrazing, or extreme weather patterns.

Modern defensive works on the cone therefore are supplemented by techniques that carry the struggle to the root of the problem: the containment of unstable debris in the source area. The choice of technical works against debris flows is based on a study of the debris flow history as revealed by historical records or deposits on the cone, a geological study of the source area characteristics, and a geobotanical investigation of actual and potential tree cover in the catchment area (Stini, 1910 and 1931; Strele, 1934; Bunza, 1975; Stern, 1975; Kronfellner-Kraus, 1974; Ikeya, 1979; Schiechtl, 1980). This information serves to determine the most effective technical works ('active measures') that can be designed in a specific situation. The active measures encompass protective structures on and above the cone, control works in the source area, and reforestation in denuded catchment areas.

Protective structures (deflection dams or walls, transverse stone-concrete-steel dams, retention basins) inhibit or neutralize debris flow activity on the fan and directly protect buildings or other human works. Many types of protective structures have been developed in the Alpine countries during the last 300 years.

Deflection dams and walls, much used in the past (Fig. 5), are applied where a sector of the fan can be set aside to accommodate excessive flows. Deflection structures increase in efficiency if the sector set aside for debris accumulation is lowered by excavation to provide additional space in the form of a debris retention basin. Commonly the material excavated can be incorporated in the construction of the deflection dam, including boulders for the smooth stone block armour on the side of the dam facing potential flows.

Transverse protective dams, in recent years, have developed into sophisticated structures involving rough blockwork, stone masonry, concrete, and steel beams in a combined design (Fig. 6). Retention capacity and strength of such structures in general provide against design flows of up to 300,000 m^3 in volume and impact forces of blocks several metres in diameter. The selective discharge section of steel or concrete bars, strong enough to contain destructive flows, allows the passage of normal bedload and thus avoids premature aggradation behind the structure. Revetments and masonry walls along the torrent channel below the protective dam guide bedload material or small debris flows into the receiving river. The area immediately above a transverse dam can also be excavated to permit greater debris retention.

Control works (check dams, drainage, retaining walls) are used to stabilize erosional scars on colluvial slopes in the source area. Check dams are transverse stone-masonry or concrete structures *without* direct protective function. They serve, particularly in stacked arrays, to create a stepped longitudinal profile through a potentially dangerous debris source (Fig. 7). Aggradation behind the dams adds stability to the toe of upstream enbankments; the rising wings, merging with the topography of the flanking slopes, force the flow of the torrent to the centre of the channel. A gently concave discharge section should accommodate small debris flows by avoiding stresses in the abutments. The main function of check dams therefore is to neutralize the erosional forces of the torrent on its banks and reduce the chance of blockages during abnormal runoff. The principles of check dam design were first clearly expressed by the Tyrolean engineer Duile (1834) in a pioneering monograph. The technique of source area control by check dams has found wide application throughout the Alps, Japan, and elsewhere. Check dams have tranquilized many a torrent noted for its notorious debris flow activity, particularly if their emplacement was accompanied by the design of appropriate drainage works, retaining walls, and revegetation of erosional scars.

Assignment of *protective-forest* status to the catchment basins of dangerous torrents can contribute a great deal in containing the growth of shallow erosional scars. The correct choice of trees, proper forest management, and long-range cost-benefit analysis are fundamental to the success of this approach (Schiechtl, 1980).

In some cases hazard of debris flows merges with the hazard arising from large-scale slope failure. Where the toe of a large sagging bedrock slope pushes

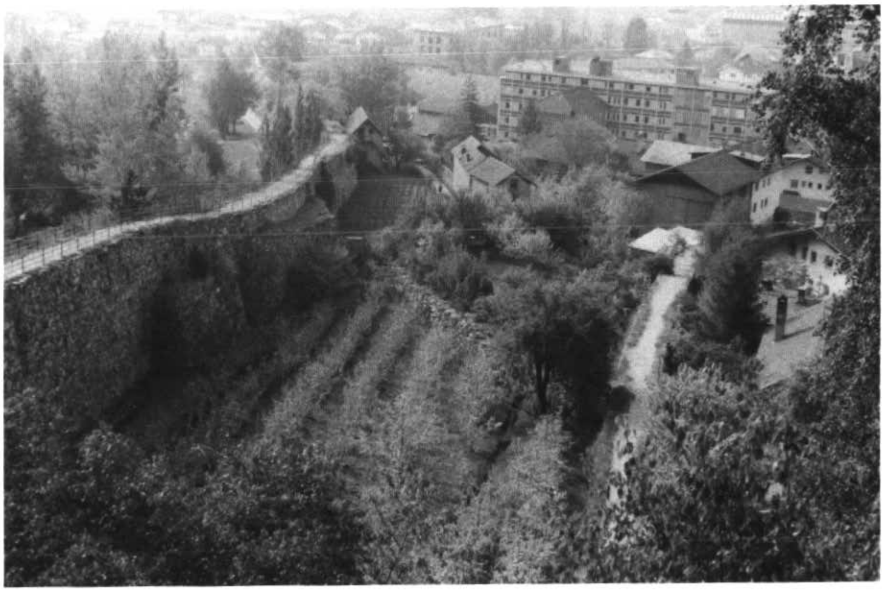

Figure 5 *Two generations of protective debris-diversion dams at Schlanders, Italy. The older dam (on the right) was breached and practically buried during a debris flow catastrophe in 1731. A larger dam which eventually reached a length of 300 metres and a height of 10 metres (on the left) has served its purpose well since 1760. Due to accretion behind the dam the channel of the torrent (located on the left of the photo) now is 5 metres above the level of the adjacent cone. Orchards in the foreground and modern hospital building in the background rest on thick debris lobes deposited in 1731.*

across the narrow channel of a high-gradient torrent subsidiary slumps provide a steady source of debris. Remedial measures tend to be expensive and often futile (Kronfellner-Kraus, 1974 and 1980). Lateral stresses from sagging slopes simply crush well-meaning check dams (Fig. 8). During extreme climatic events subsidiary slumps completely block the flow of the torrent and subsequent mass movements from the slide material may have to be prevented by extremely strong retaining structures (Fig. 9).

In summary, there are a number of active measures which have been used successfully to limit the impact of debris flows. The choice of structures will be dictated by topography, geology, vegetation, and economic limitations. In general, however, these techniques are feasible only for mass movements with volumes of less than 500,000 m^3. If projected costs or natural setting do not allow the application of active measures one might have to consider restrictive land use zoning (passive measures). *Used diligently and early in the development* of a torrent basin, passive measures are probably more economical than active measures (see section on acceptable risk further on).

b) Large-Scale Slope Failure. Failure of mountain sides occurs in a great number of geological settings. In size slope failures vary from small roadside slumps to sagging slopes or rock avalanches with volumes in excess of 1,000 x 10^{6}m^3. Their rate of movement may range from slow creep (a few centimetres per year) to bursting speed (in excess of 100 metres per second). The mechanisms involved depend greatly on the regional climate, physiography, and geology (for the Canadian Cordillera see Eisbacher, 1979b).

During the last 100 years a number of landslide classifications have been proposed to describe the great variety of natural slope failures, their different rate of movement, and the geological setting. The detailed classifications of Heim (1932) and Varnes (1978) have had the widest impact and can be easily adapted, expanded, or modified to serve the need for special regional conditions (e.g., Humbert, 1972; Venzo, 1976; Moser, 1980). However, a universal classification, adoptable to all languages and regional settings is a most complex task. As is the case with well known ore deposits, the largest and best known historical slope failures refuse to fit into the pigeon-holes provided for them.

As far as land use is concerned, the most important parameters are the

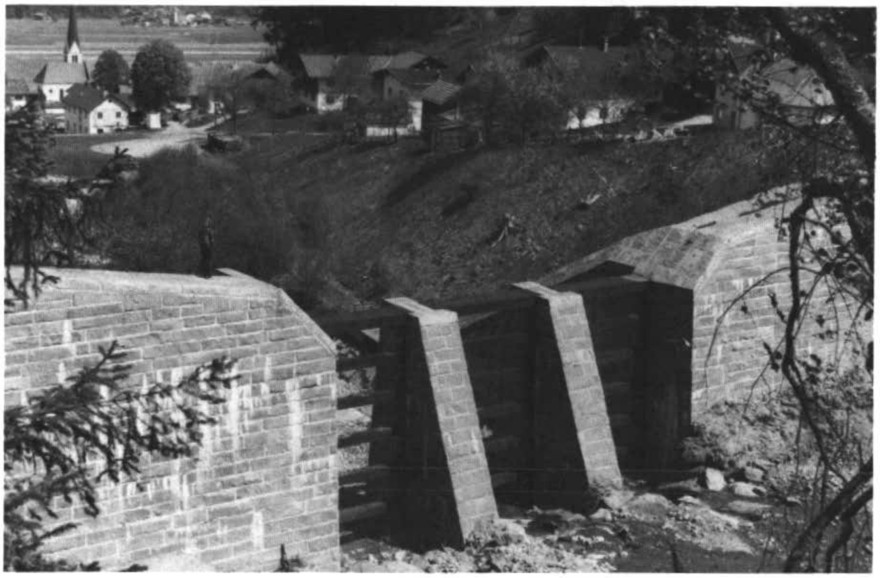

Figure 6 *Two examples of transverse protective dams. Above: Semi-circular protective dam with massive uphill-facing stone block armour and a selective discharge section, designed against rock fall - debris avalanches near Altdorf, Switzerland. Below: Transverse protective dam with steel-concrete wings, masonry armour, and selective discharge section of steelbeams, designed against debris flows; location above the village of Flaurling, Austria.*

Figure 7 *New check-dams along a deeply scoured source area of residual colluvium near Inzing, Austria. These dams, arranged in a stacked pattern, confine the torrent to a central line and create a more balanced profile, thus preventing erosional instabilities along the embankments. Note the gently rising stone carapaces on either side of the discharge section of the check-dams; they are designed to accommodate the passage of small debris flows without endangering the lateral abutments.*

Figure 8 *Wing of a check-dam, being slowly crushed by lateral pressure resulting from deepseated creep along unstable flanks of a torrent channel near Crodo, Italy.*

volume and rate of movement of a landslide: on one end of the spectrum small slumps and rock falls can be dealt with by the application of well known engineering methods such as fences, retaining walls, drainage systems, or redistribution of the slope material (Müller, 1963; Peckover and Kerr, 1977; Schiechtl, 1980; Piteau and Peckover, 1978); on the other end massive slope failures, e.g. in excess of 1 x $10^6 m^3$, if in rapid motion, are almost impossible to control or the costs of control works are prohibitively high. If known to be a threat to human works, a large incipient slide mass simply ought to be avoided. Great costs for remedial measures can be justified only for projects whose total cost is gigantic, as is the case with hydroelectric installations. Transportation routes exposed to recurrent threats of massive rock falls are increasingly protected by strong concrete galleries or by being placed into tunnels. Tunnelling has become the most effective - albeit expensive - technical solution to perpetual closures of important year-round mountain passes.

Fortunately, truly large slope failures are relatively rare, their recurrence at any one locality being generally less than one in a thousand years - a time interval during which major climatic or seismic parameters may change. In the Alps, many prehistoric and historic landslide deposits have been built over (Fig. 10) and the risk of possible recurrent failure along adjacent cliffs seems to have been widely accepted (Eisbacher, in prep.). However, even in the most densely populated mountain valleys of the Alps, some rock avalanche deposits are being approached only up to a *respectful distance* because of poor building conditions, fear, superstition, and tradition. Many rubbly surfaces that owe their origin to rock avalanches or large debris flows have legends attached to them that tell of disappeared towns, raging giants, and infuriated dragons. (e.g., Dalla Torre, 1913).

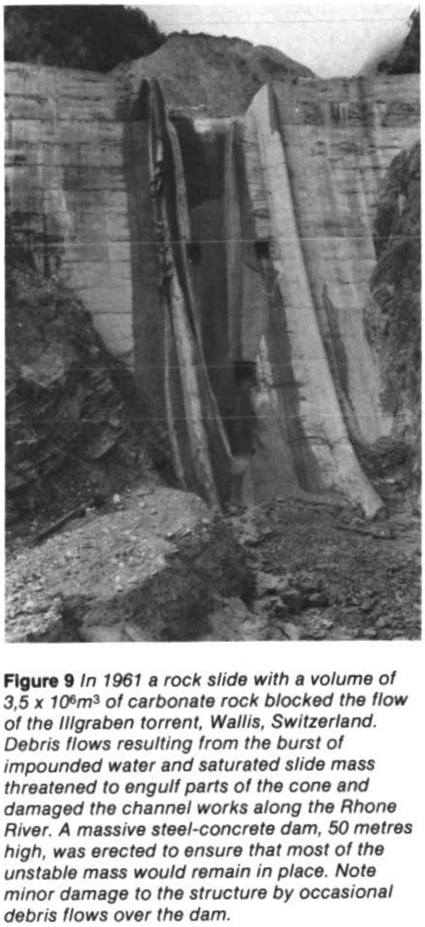

Figure 9 *In 1961 a rock slide with a volume of 3,5 x $10^6 m^3$ of carbonate rock blocked the flow of the Illgraben torrent, Wallis, Switzerland. Debris flows resulting from the burst of impounded water and saturated slide mass threatened to engulf parts of the cone and damaged the channel works along the Rhone River. A massive steel-concrete dam, 50 metres high, was erected to ensure that most of the unstable mass would remain in place. Note minor damage to the structure by occasional debris flows over the dam.*

In western North America, historical experience with slope stability hazards is short and native legends dealing with massive cliff collapse are rare. Nevertheless, natives along both sides of the Mackenzie Mountains talked about giants that used to inhabit the central parts of the mountain range (Keele, 1910), an area now known to host huge rock avalanche deposits (Eisbacher, 1979a). It might be comforting to know that long ago a similar species of supermen also roamed through the Alps and the Peruvian Andes! The few catastrophic slope failures that have occurred in western Canada during the last 150 years (Frank, Hope, Jane Camp-Brittania Mine, Spences Bridge, Davastation Glacier etc.) have attracted considerable attention. The degrees to which these events could have been avoided and to what extent they have to be classified as 'Acts of God' or 'acceptable risk' are still being debated. As in other parts of the world such massive slope failures or the threat of similarly destructive debris flows have opened a discussion as to what constitutes an acceptable risk from debris flows and slope instabilities in steep-walled mountain valleys.

c) Acceptable Risk in Areas Exposed to Debris Flows and Large-Scale Slope Failure. The impact of slope hazards increases with increasing height and relief of mountains. Debris flows, landslides, and rock falls are the processes which progressively change and sculpture the natural mountain landscape. The earliest settlers of Alpine mountain valleys took a well measured risk if they invaded the domain of these elementary forces: the repeated experience of floods, avalanches, and debris flows led to appropriate patterns of land use, housing and remedial measures. If a group of settlers misjudged an apparently tranquil debris fan deep in a newly conquered Alpine valley, and then saw their belongings disappear underneath a deluge of mud and rock, they usually considered this as an expression of evil supernatural forces or punishment at the hands of superior powers - calling for repentance and new struggle. Only rarely would they search for a culprit amongst their own. Floods and landslides were part of life just as epidemics and fire. The hazards were particularly great in the period after the main clearing of the high valleys of the Alps between the 11th and 14th centuries. At the same time the climate began to change for the worse and some of the hard-won terrain had to be ceded to advancing ice and snow. Extensive mining activity beginning in the 15th century added an almost insatiable demand for timber and charcoal, and many steep basins lost their tenous forest cover. From that time onward the upper forest limit in many torrent basins of the Alps remained considerably below its potential height, not only because of established grazing and logging rights but also because snow avalanche tracks and debris chutes, once developed, impeded the readvance of the tree line.

In many parts of the Alps the protective function of a healthy forest cover against debris flows, rock falls, and snow avalanches was recognized long before the first works were being written on the subject in the early 19th century. A so-called Bannwald (= a protective and protected forest) obviously impeded the free run of snow and debris above the threatened villages; new settlers or forceful invaders who ignored the simple rules generally had to learn the lessons anew. Similarly, in periods of war, economic stress, and mining booms, old self-imposed rules tended to be forgotten and a heavy price for reconstitution had to be paid afterwards. The preservation of the thin soil, the maintenance of trails, and management of running water in these upland areas became a most important communal task. Negligence had its predicable effects. If an extreme rainfall swept away the precious earth, the people had to carry it back up the hill and retain it by stone walls - it was simply not enough to just sit back, wait, and see! In times of distress the whole community had to help its afflicted members - thus sites known to be unsafe were kept free by the community elders as a simple matter of self interest (F. Fliri, pers. commun., 1981).

It is also significant that regional legislation concerning a more careful use of steep mountain terrain has been most successful if passed immediately after catastrophes of national impact: in France after the debris floods of 1856 and 1859, in Switzerland and Italy after the avalanches and floods of 1868, in Austria after the floods and debris flows of 1882. These catastrophes led to systematic application of torrent control methods on a regional scale (Demontzey, 1878; Seckendorff, 1884; Salis, 1892). In the Alps, schemes of disaster prevention were closely tied into the legal framework governing the use of lands and forests, and national governments approached the problem by way of their educational and research institutions.

By the end of the 19th century mechanization made it impossible for the farmers of the highest mountain valleys to compete with the farmers of the lowlands and the focus of agricultural activities of Alpine countries shifted to the forelands. While depopulation of high valleys continued far into the present century, ever stronger waves of tourists and temporary dwellers streamed into the same remote places. Although the modern tourist expects most of the amenities of his urban existence he is only rarely aware of, or prepared for, the responsibilities of mountain living. In the Alps catastrophic snow avalanches and debris flows in recent years (e.g., 1951, 1965/66, and 1970), have led to an increased concern for general standards relating to the safe accommodation of temporary and permanent populations in newly invaded mountain terrain (Aulitzky, 1974). This required difficult and locally tough decisions, as it was obvious that in some high valleys the attractive *and* acceptably safe building lot within servicable communities had become a rare commodity. With suburbanization of tightly built villages the costs of protective works against debris flows and snow avalanches soon exceeded the means of the communities. The regionally supported subsidies to mountain farming, torrent control, and avalanche prevention had to be supplemented by hazard zoning or restrictive building regulations ('passive measures'). Enforcement of these regulations largely

Figure 10 *Three examples of built-over rock avalanche deposits in the Alps. Shown at the top is the modern ski village of Clusaz, France, which is in the process of growing around a (prehistoric?) rock avalanche deposit that is the result of a dip-slope failure in well-bedded carbonate rocks. Shown at the centre are the built-over deposits of a rock avalanche which resulted from the failure of a scarp-face of carbonate rocks that buried the mining town of Radmer a.d. Hasel, Austria, in 1540. Shown at the bottom is the town of Alt-Felsberg, Switzerland, whose church rests on a slab of a prehistoric rock fall from the dip-slope of carbonate rocks behind the settlement; a period of serious rock fall activity in the middle of the nineteenth century prompted an effort to relocate the town to a new site called Neu-Felsberg; today both Alt-Felsberg and Neu-Felsberg continue to expand below the cliff.*

remained with the local approving authority (i.e., community council).

In summary, the historical evolution of high-mountain protective measures in the Alps began with early passive measures dictated by experience (e.g., Bannwald and communal decisions), were followed by increasingly sophisticated active measures (torrent and avalanche control) by regional governments, and, in the present development boom, are again aided by passive measures (land use regulations). The present system allows for a dynamic interplay between three levels of government.

In the mountains of western Canada the balanced use of active and passive measures is still in its initial stages. The great variety of physical settings will require that the basic rules dictating hazard appraisal are flexible. The most important - and most difficult - task is to appraise the acceptable and unacceptable risk in areas of known recurrence of debris flows or massive slope failures.

With regard to debris flows the appraisal has to include the cone *and* the catchment basin. The mapping of relative hazard on the cone is only possible where information is available on the rate of past debris flow recurrence and the location of preferred debris flow tracks. The analysis is based on historical records, wherever available, or on a variety of "hazard indicators' (the silent witnesses or 'Stumme Zeugen' of Aulitzky, 1973). The most important hazard indicators for areas on the debris cone are the size of blocks strewn about, number and thickness of debris layers, scarred tree trunks, channel-surface gradient, and lack of channel incision. Occasionally potential impact forces can be calculated from past damage to vegetation (Mears, 1977). In addition the conditions in the uplands have to be considered: erodibility of debris and incipient bedrock slumps across the torrent. Where debris fans are relicts from a geological period with entirely different climate - such as those in the dry interior parts of British Columbia - this method cannot be used. If, however, a torrent system can be shown to be dormant or active the evidence of recurrent mass movements of the past can be used to extrapolate the potential behaviour of the system into the future - still a difficult task. The analysis assumes minimal long-range environmental changes (e.g., climate, forest cover, seismicity, human activity) and in the end can never be more than semi-quantitative and somewhat subjective (Zeller, 1972). Nevertheless, there *are* cones whose suitability for permanent dwellings can be questioned (Fig. 11). In such cases building restrictions can be viewed in terms of an extension of classical building codes to the high mountain environment. Complete freedom from such restrictions necessarily implies assumption of the risk by the builder and/or owner. Some recent case histories in the Alps suggest that at the community level, restriction of residential building on debris cones is most readily accepted where damage or 'close shaves' have been experienced within human memory.

There always remains an unknown residual of hazard beyond that derived from hazard indicators and historical experience (Antoine, 1978; Zollinger, 1976). For this reason anybody living in or visiting mountain country probably has to accept a minimum of self-responsibility: if an area is declared 'unsafe' in terms of recurrent mass movements it should not be automatically assumed that the area outside it is absolutely 'safe'. A professional charged with preparing a hazard map from a variety of hazard indicators or historical records therefore has to avoid oversophistication and indicate areas of 'known' (large or moderate) as opposed to 'unknown' hazards. A system now increasingly popular in the Alps is the three-fold *traffic light* approach: 'red' - unsafe, 'yellow' - proceed with caution, 'green' - as far as the investigator can determine no danger. Areas not investigated are left blank. Many debris cones in high mountain terrain are also runout zones of snow avalanches. This commonly requires the preparation of combined hazard maps for snow avalanche, slope stability, and debris flow problems (Kienholz, 1977).

A progressive Austrian regulation, dealing with the restrictive zoning of areas threatened by snow avalanches and debris flows, recognizes the problem of residual risk: although major events recorded in local chronicles are taken into consideration by field workers, it is mainly the destructive event with a recurrence rate of 'more than one in 150 years' that is shown on a zoning map. Hazards resulting from rare debris flows beyond this time frame seem to be commonly accepted. Confronted with the question of what is being done in the Alpine countries to circumvent the possibility of catastrophic debris flows with a very low rate of recurrence, say one event in 1000 years, dozens of workers answered with almost the same words: ". . . if we considered this possibility there would be no more subdivisions anywhere . . .". This is the consensus of people who have the difficult task to protect well-established or growing Alpine tourist centres! A similar time frame for safe operation is also adopted for most high-altitude hydroreservoirs that have to contend with the vagaries of glaciers (i.e., ice avalanches, bursting englacial water pockets etc.). Since glacial catastrophes are generally related to changes in the position of the ice margins, the time of projected safety cannot exceed 50 years by much and the importance of continuous surveillance is obvious (Röthlisberger, 1974). It is also generally recognized, that if an area suddenly becomes known as hazardous by

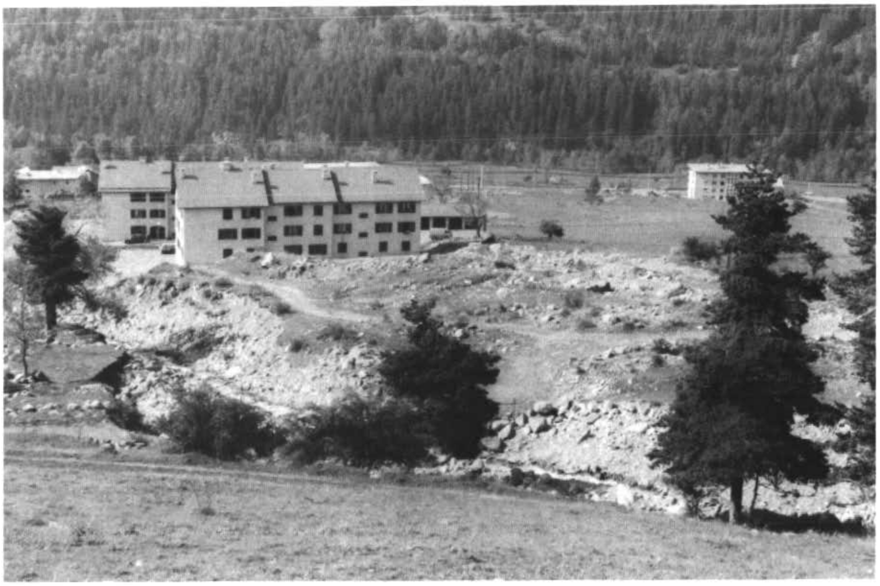

Figure 11 *New apartment buildings located on blocky deposit of a historical debris flow near Briançon, France. In recent decades the forest cover of the catchment area of this torrent has improved markedly over the state it was in at the turn of the century, but whether or not the better forest cover of the uplands would impede debris flows during an extreme weather situation is difficult to say.*

the incidence of an extreme event or by new scientific insights no compensation for lost land value can be claimed. This apparently inhibits speculation with land of marginal safety (Aulitzky, 1975).

The threat of single large-scale slope failures (i.e., greater than 1 x 10^6m^3) is even more difficult to appraise than that of debris flows with low recurrence rates. Incipient creep along steep bedrock slopes is commonly initiated by earthquakes or a succession of years characterized by extreme precipitation. Failure mechanisms and runout distance of rock avalanches depend in a complex fashion on the structural geology of the breakaway zone, lithology, height of fall, topography, etc. (Abele, 1974; Hsu, 1976, Eisbacher, 1978 and in prep.). Where alternate land is available, localities with known rock fall history are best avoided (Nasmith, 1980). Where this option is not open, geological mapping, regular inspection, and repeated surveys are probably the most economic approach to the problem. Regular surveys also sharpen the attention of the inhabitants to topographic changes and prevent a false sense of security or speculative land sales. Some continued surveys in the Alps have resulted in remarkable predictive success, but also in a few false alarms. A clear case of a successful prediction of a rock avalanche after repeated surveys and a timely evacuation of a threatened settlement was the Motto d'Arbino rock slide in southern Switzerland in 1928 (Knoblauch and Reinhard, 1939). The most dramatic misjudgement of an approaching slope failure was the well-known catastrophe of Vaiont in northern Italy in 1963 (Müller, 1968). In any case, the decision of what constitutes an acceptable level of safety for buildings near cliffs with a potential for rock slides often escapes the principles of scientific procedure. Because of uncertainty regarding future climatic, cultural and seismic patterns a statement on the overall stability of a rock mass with a volume of more than 1 x 10^6m^3 beyond a projected time of 300 to 500 years probably lies outside the domain of human competence.

In the high French Alps, foundations have also been laid for the systematic mapping of areas with chronically unstable slopes. The frustrations and advancing know-how in this field are well demonstrated by the series of ZERMOS maps (ZERMOS = Zones exposées a des risques liés aux mouvements du sol et du sous-sol) on scales 1:20,000 or 1:25,000. These maps are based on geological field work and air photo study by geologists familiar with the regional geology and are published by the Bureau de Recherches Géologiques et Minières (Humbert, 1977). Three zones, 'red' (to be avoided), 'orange' (geotechnical study required), and 'green' (no obvious instabilities) are differentiated. The maps serve as technical *alerte* and have not much legal significance.

From this discussion it is clear that passive or active measures against slope hazards are strongly coloured by human experience and that their application rests entirely on how well geological processes can be extrapolated from the recent geological past to the near future. In the Alps appraisal of slope stability and debris flow potential is based on historical chronicles and increasingly on hazard indicators. In western Canada the basic parameters for land use planning in mountain valleys are still poorly known: documentation of the climatic-geological variables responsible for 'rare' voluminous mass movements, recurrence potential, and possible active or passive counter measures. Where decisions on land use cannot be delayed a rational approach to the problem could start from: a) a consideration of mass movements with a projected rate of recurrence of more than one event in 100 to 300 years; b) special care for forests and water in the uplands of notorious torrents; c) documentation and surveillance of potential debris sources and instabilities. The cost of active or passive measures has to be balanced against potential losses.

Slope Stability and Cities

Every city profits from the best geological input it can get to set out its buildings, transportation systems, water works and recreational land (Legget, 1973). In mountainous regions the significance of geology is magnified: cities are more confined and sloping terrain cannot be avoided, particularly if flat land has agricultural or industrial functions. A building site on a steep slope is either more costly or more risky than a site on flat land. In return, it offers a considerably better view of the world, a widely appreciated asset. To assure appropriate long-range safety and low maintenance costs on developed sloping terrain the natural setting generally has to be modified to the extent that the 'wilderness' or 'country' character of the individual home site is lost for good. Such modifications involve control of storm runoff in well-contained channels, provision of temporary retention ponds, erection of retaining walls, and revegetation of scarred construction sites and road cuts.

The most common trouble arises along *terrace rims*, a common feature in all mountain cities. Such rims, whether along sand-gravel-till benches (as on the coast of British Columbia), lacustrine silt banks (as in the Interior of B.C.), or shale scarps (in the Cordilleran Foothills), are notorious for their instability. Traditionally they have been most desirable development land, because, as the saying goes, 'nobody can build in front of you'. Stabilization by retaining structures or deep foundations is often deemed too expensive or is opposed on environmental grounds. Thus geological processes continue to operate freely and soon a building may be the unwilling object of an otherwise fascinating demonstration of the principle of uniformitarianism (Fig. 12).

One response to the problem has been the legislation of a required setback distance of, say, five to twenty metres from the edge of a terrace. This is a well meaning gesture, but requires the cooperation of natural geological processes which, if unchecked, might reduce this distance to zero within the lifetime of the building. Thus set-back regulations to be effective may have to be supplemented by engineering works aimed at curbing the forces of gravity and water. Another approach to the terrace-rim problem has been zoning. However, to declare an area off-limits, and then proceed to build around it, may not be without serious consequences if the unstable off-limits terrain sends debris flows and slides into the adjacent built-over land. The potential of such situations exists in many towns of the Canadian west coast (Eisbacher and Clague, 1981). Both solutions, setback and zoning, raise the question at what stage a safe and technically landscaped site is preferable to a romantic, but risky home lot. The choice is one that home owners, planners, city engineers, architects and developers ought to make in good spirit *before* they meet in court!

Slopes, Forests, and Fish

Traditionally, the tree has been the natural adornment of steep mountain sides; fish have added life to mountain streams. In western Canada the cedar has supplied the raw-material that went into buildings, clothes, boats, tools, and energy for a vigorous indigenous population, while the migrating salmon provided much of the food stocks. An amazingly rich and complex culture developed from this resource base. Today, a modern logging industry is still the principal component in the economic life of the west coast and our salmon are appreciated around the world.

Investigations carried out for more than 200 years have clearly shown two principal functions of the forest with respect to slopes. Firstly, an intact forest absorbs some of the rain during storms and results in less runoff or at least a somewhat delayed runoff. Secondly, a living system of roots binds the colluvial veneer to the substratum, adding some strength to the slope. It must be kept in mind that these two basic functions of a healthy forest depend greatly on climate, geology, aspect, inclination, elevation of a site, and on the tree species. Also, truly catastrophic rains may devastate perfectly 'normal' forest lands (Clar, 1959; Williams and Guy, 1973). But this should not lead to the fatalistic conclusion that, tree cover or no tree cover, it makes little difference to the stability of a slope. Tree cover does make a significant quantitative difference, particularly along oversteepened torrent channels, gullies, and ravines during extreme meteorological events. The problem of large clearcuts is generally compounded by unmanaged access roads which commonly are the first sources of debris avalanches into adjacent torrents (Fig. 13). There are many historical examples of innocent looking scars along haulage roads which developed into almost unmanageable sources of debris. During the construction of access roads into logging zones particular attention needs to be paid to cuts in colluvial slopes and along topographic reentrants (Burroughs *et al.*, 1976).

The two resources most directly threatened by slope instabilities on clearcut slopes are fisheries and the attractive landscape. It takes only a minor debris flow to destroy the spawning bed of a salmon stream. The cost of rehabilitation may be great and an important local source of food may be diminished. The economic and political questions surrounding this problem are very complex, but the physical - biological principles involved are relatively simple: a clearcut slope and a crude network of roads, if located near a spawning site, are no problem until the first intense rainstorm hits the region. As it takes as much as 10 to 15 years before a logged-over surface develops a new healthy forest (Swanson and Dryness, 1975) the critical period for debris generation may be in the same order of magnitude. Thus, the appraisal of slope stability with regard to a logging zone begins with the careful mapping of those areas with great debris potential - deeply incised unconsolidated deposits and incipient slumps. Maps showing the inclination of slopes alone are insufficient to plan the access and logging pattern in a steep mountain basin.

Figure 12 *Shallow failure of surficial debris along a steep terrace rim along the eastern coast of Vancouver Island. Failure occurred during an intense rainstorm in December 1979.*

Slope Stability and Ski Runs

The final section could be entitled 'The desert is alive, why should ski slopes be dead?' This question involves a slope-management decision at a very early stage of resort planning that may either pay handsome dividends or cost a lofty price later on. Many a recreation area in a mountain setting takes its start from a good winter-season lasting three months. Eventually, the volume of business reaches such a level that in order to justify the expense of an ever more complex infrastructure a second season is needed. The success of achieving a summer season in a traditionally winter-oriented resort area depends most of all on the quality of the landscape surrounding the site. Logged-over slopes and scoured gullies may be covered in wintertime, but the most attractive site layout means little if it is set against a backdrop of deeply disturbed slopes. It is of little use to declare an area a park or give it protected status if tourist-related facilities compete with resource activities in turning the border area into unsightly networks of neglected roads and debris chutes. Unfortunately, examples of this approach abound near most ski areas of the world, and it is little wonder why some of them 'simply can't get going in summer'. In the design and logging of ski runs a few geological rules can help.

Schists, slate, and shale make better ski terrain than slopes underlain by bedrock of carbonate or granite. Slopes on schist or slate are generally smooth, deeply weathered, and covered by clay-rich soil. This means that there is more water on them, regeneration of vegetation is relatively easy and inadvertent scars in the vegetation tend to close by soil creep. Fortunately, such terrains are plentiful in western Canada (e.g., Shuswap Metamorphic Complex and the Windermere Supergroup). If major bedrock slumps can be avoided, and if scour along established ravines can be kept to a minimum by proper forest management, the potential for attractive resort terrains in western Canada is almost unlimited.

Slopes in carbonate and granite terrain are more difficult to handle. They are commonly interrupted by precipitous cliffs and narrow ledges. Only interbedded shale units result in undulating surfaces. Carbonate slopes are notoriously dry. The lack of water and clay minerals results in thin organic soils poorly attached to the underlying bedrock. Shallow roots of subalpine conifers tend to penetrate directly into cracks of rubbly bedrock. If this tenuous hold is broken little soil remains in place. Therefore, removal of forest cover from carbonate slopes is soon followed by the gradual disappearance of the humus layer, particularly in areas where the ski runs are groomed with heavy machinery. This pattern is also observed on granular soils overlying granitic bedrock (Fig. 14). The first scars on such slopes tend to appear after the release of abnormal springtime wet-snow avalanches (Laatsch and Grottenthaler, 1973). Springtime snow-slides often break away along well established 'traverses' and other repetitive ski patterns which, over the years, may convert a slope into a stony wasteland. Of course, tracked vehicles aid this process. Once a few scars are opened, gullies and bowl-shaped scour pans progressively combine into almost unmanageable debris sources.

The most lasting ski runs therefore tend to follow argillaceous rock units or descend through areas with healthy stands of subalpine trees left standing for the skier to avoid and for the summer visitor to enjoy . . .

Conclusions

Appropriate patterns of land use in densely populated mountain valleys have developed from trial-and-error. In the Alps, an area with a long and well-documented history, major adjustments in the use of sloping terrain have been made after catastrophes of regional impact. In western Canada high-density development of mountain valleys is a very recent phenomenon proceeding within the context of a safety-conscious consumer attitude. If risks to human beings, deterioration of sloping environments, and cost to the public are to be kept within acceptable limits, passive (zoning) or active (technical) measures will have to be applied increasingly to neutralize the impact of debris flows and landslides. However, it is most important to recognize that in rugged mountain terrain even the most sophisticated human countermeasures cannot provide for an absolutely safe setting. A certain amount of individual risk probably has to be accepted by anybody living in or visiting high mountains. In order to serve as a basis for practical decisions, slope management should seriously consider mass movements with *anticipated average rates of recurrence of more than one event in 100 to 300 years.* Because of the uncertainties inherent in short-term aberrations and long-term changes of the earth's climate (or seismicity) predictions of slope failure involving volumes in excess of 1 x $10^6 m^3$ with projected recurrence beyond 500 years tend to leave the realm of scientific or technical competence.

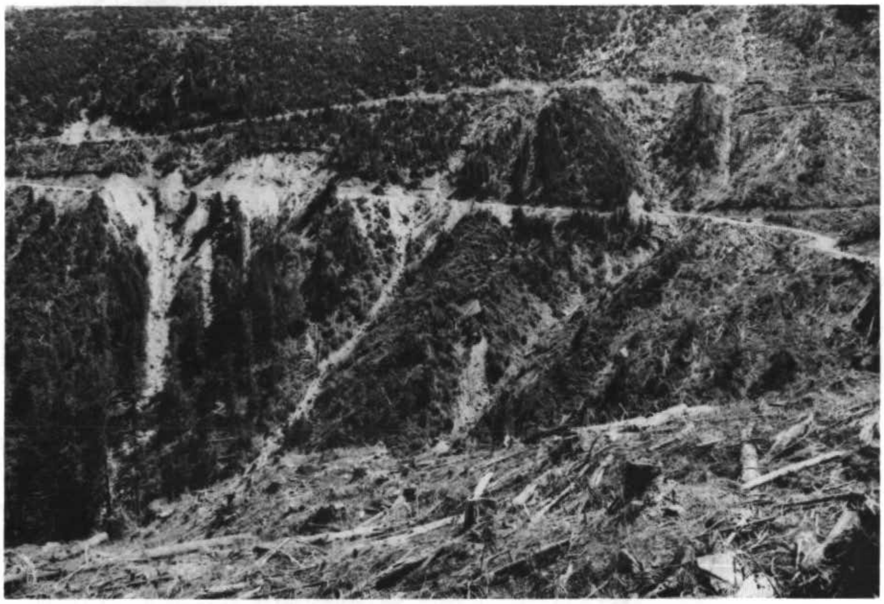

Figure 13 *Debris chutes along pre-existing ravines across unmanaged access road in the logging area of a high basin in southwestern British Columbia.*

Figure 14 *Ski slope on granitic colluvium near Meran, Italy. The alpine grass cover is scarred deeply by gullying and debris slumping. This type of deterioration of ski slopes is commonly set in motion by springtime snow creep and snow slides involving not only a tightly compressed snowpack but also some of the underlying soil. Note the three types of check dams across the gully (concrete, gabion, masonry) for the purpose of counteracting depth erosion and embankment failures along the exposed noncohesive colluvial veneer.*

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References

Abele, J.A.E., 1974, Bergstürze in den Alpen: Wissenschaftliche Alpenvereinshefte, No. 25, 230 p.

Antoine, P., 1978, Glissements de terrains et aménagment de la montagne: Bull. des Laboratoires Géologiques Université de Lausanne, v. 74, p. 1-14.

Aulitzky, H., 1968, Analyse der Schadenursachen von Unwetterkatastrophen zum Zweck der Vorbeugung: Österreichische Wasserwirtschaft v. 20, p. 90-97 and 114-154.

Aulitzky, H., 1973, Hydrologische und orographische Grundlagen zur Orientierung der Raumordnungspolitik in den Alpen: Berichte zur Raumforschung und Raumplanung, v. 17, no. 6, p. 13-29.

Aulitzky, H., 1974, Endangered Alpine Regions and disaster prevention measures: Nature and Environment Series 6, Council of Europe, Strasbourg, 103 p.

Aulitzky, H., 1975, Beurteilung und Ausscheidung der Gefahrenzonen in den Alpen einschliesslich der Tallagen: Symposium Interpraevent Innsbruck, v. 2, p. 159-187.

Bunza, G., 1975, Geomorphologische Kartierung und Beurteilung von Wildbachgebieten mit unterschiedlichen Lockermassen: Symposium Interpraevent Innsbruck, v. 2, p. 199-208.

Burroughs, E.R., G.R. Chalfant, and M.A. Townsend, 1976, Slope stability in road construction: Bureau of Land Management Oregon State Office, 102 p.

Clague, J.J., and V. Rampton, in press, Neoglacial Lake Alsek: Canadian Jour. Earth Sci.

Clar, E., 1959, Geologische Beobachtungen von der steirischen Unwetterkatastrophe vom August 1958: Geologie und Bauwesen, v. 24, p. 131-140.

Dalla Torre, K.W., 1913, Naturführer Tirol, Vorarlberg, und Liechtenstein: Junk-Berlin, 409 p.

Demontzey, P., 1878, Études sur les Travaux de reboisement et de gazonnement des montagnes: Paris.

Duile, J., 1834, Über Verbauung der Wildbäche in Gebirgsländern: Innsbruck, 179 p.

Eisbacher, G.H., 1979a, Cliff collapse and rock avalanches (sturzstroms) in the Mackenzie Mountains, northwestern Canada: Canadian Geotech. Jour., v. 16, p. 309-334.

Eisbacher, G.H., 1979b, First-order regionalization of landslide characteristics in the Canadian Cordillera: Geosci. Canada, v. 6, p. 69-79.

Eisbacher, G.H., 1980, Debris torrents across the Alaska Highway near Muncho Lake, northern British Columbia: Geol. Survey Canada Paper 80-1C, p. 29-36.

Eisbacher, G.H., in prep., Destructive mass movements in the mountain environment.

Eisbacher, G.H., and J.J. Clague, 1981, Urban landslides in the vicinity of Vancouver, British Columbia, with special reference to the December 1979 rainstorm: Canadian Geotech. Jour., v. 18, p. 205-216.

Fuchsjäger, B., 1975, Analyse der Wildbachkatastrophen in Osttirol: Österreichische Wasserwirtschaft, v. 27, p. 175-185.

Gedney, D.S., and W.G. Weber, 1978, Design and construction of soil slopes: *in* R.L. Schuster, and R.J. Krizek, eds., Landslides - Analysis and Control: Transportation Research Board Special Rep. 176, p. 172-190.

Hanausek, E., 1975, Wildbach und Lawinenschutz in Tirol: in H. Aulitzky, ed., Hochwasser - und Lawinenschutz in Tirol: Innsbruck, p. 108-128.

Heim, A., 1932, Bergsturz und Menschenleben: Beiblatt zur Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, v. 77, p. 1-217.

Hsu, K.J., 1975, Catastrophic debris streams (sturzstroms) generated by rock falls: Geol. Soc. America Bull., v. 86, p. 129-140.

Humbert, M., 1972, Les mouvements de terrains: Bulletin du Bureau de recherches géologiques et minières, Ser. 2, Sect. 3, No. 3, p. 13-28.

Humbert, M., 1977, La cartographie ZERMOS: Bulletin du Bureau de recherches géologiques et minières, Ser. 2, Sect. 3, No. 1/2, p. 5-8.

Ikeya, H., 1979, Introduction to Sabo works: The Japan Sabo Association, Tokio, 168 p.

Jackson, L.E., 1979, A catastrophic outburst flood (jökulhlaup) mechanism for debris flow generation at the Spiral Tunnels, Kicking Horse River basin, British Columbia: Canadian Geotech. Jour., v. 16, p. 806-813

Keele, J., 1910, A reconnaissance across the Mackenzie Mountains on the Pelly, Ross, and Gravel Rivers, Yukon Territory and Northwest Territories: Geol. Survey Canada, Publ. No. 1047.

Kienholz, H., 1977, Kombinierte geomorphologische Gefahrenkarte 1:10,000 von Grindelwald: Geographica Bernensia, G4, 204 p.

Knoblauch, P., and Reinhard, M., 1939, Erläuterungen zum Geologischen Atlas der Schweiz, Atlas Blatt 516-Jorio.

Kronfellner-Kraus, G., 1974, Die Wildbacherosion im allgemeinen und der Talzuschub im besonderen: '100 Jahre Forstliche Bundesanstalt', Wien, p. 309-342.

Kronfellner-Kraus, G., 1980, Neue Untersuchungen in Wildbächen - Der Talzuschub in Abhägigkeit von Niederschlägen: Symposium Interpraevent Bad Ischl 1980, Vol. 1, p. 179-192.

Laatsch, W., and W. Grottenthaler, 1973, Labilität und Sanierung der Hänge in der Alpenregion des Landeskreises Miesbach: Bayrisches Staatsministerium für Ernährung, Landwirtschaft, und Forste, 46 p.

Legget, R.F., 1973, Cities and Geology: McGraw-Hill, 624 p.

Lliboutry, L., B. Morales Arnao, A. Pautre, and B. Schneider, 1977, Glaciological problems set by the control of dangerous lake in Cordillera Blanca, Peru: Jour. Glaciology, v. 18, p. 239-290.

Mathews, W.H., 1973, Record of two jökullhlaups: in Symposium on the Hydrology of Glaciers: International Association of Scientific Hydrology, Publ. No. 95, p. 99-110.

Mears, A.I., 1977, Debris flow hazard analysis and mitigation: Colorado Geol. Survey, Information Series No. 8, 45 p.

Montandon, F., 1933, Chronologie des grands éboulements alpins: Materiaux pour l'etude des calamités, No. 32, Genève, p. 271-340.

Mougin, P., 1914, Les torrents de la Savoie: Grenoble, 1250 p.

Mougin, P., 1931, La restauration des Alpes: Paris, 582 p.

Moser, M., 1980, Stand und Problematik der Ausscheidung von Gefahrenzonen in Hangbereichen im alpinen Raum: Symposium Interpraevent Bad Ischl 1980, p. 93-102.

Müller, L., 1963, Der Felsbau: Enke Verlag, Stuttgart, 624 p.

Müller, L., 1968, New considerations on the Vaiont slide: Felsmechanik und Ingenieurgeologie, v. 6, p. 1-91.

Nasmith, H., 1980, Catastrophic rockslides and urban development: in Proceedings of 'Slope stability problem in urban areas', Canadian Geotechnical Society, Toronto, 8 p.

Peckover, F.L., and J.W.G. Kerr, 1977, Treatment and maintenance of rock slopes on transportation routes: Canadian Geotech. Jour., v. 14, p. 487-507.

Piteau, D.R., and F.L. Peckover, 1978, Engineering of rock slopes. in R.L. Schuster, and R.J. Krizek, eds., Landslides - Analysis and Control, Transportation Research Board Special Report 176, p. 192-228.

Rabot, C., 1905, Glacial Reservoirs and their outbursts: Geograph. Jour., v. 25, p. 534-548.

Richter, E., 1889, Die Hilfsmittel gegen Ausbrüche von Eisseen: Mitteilungen des Deutschen und Österreichischen Alpenvereins, 1889, p. 291-295.

Röthlisberger, H., 1974, Möglichkeiten und Grenzen der Gletscherüberwachung: Neue Züricher Zeitung, 29 April 1974, No. 196, 15 p.

Röthlisberger, H., 1979, Glaziologische Arbeiten im Zusammenhang mit den Seeausbrüchen am Grubenferner, Gemeinde Saas-Balen (Wallis): Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, No. 41, p. 233-256.

Salis, A.V., 1892, Die Wildbachverbauung in der Schweiz: Bern, 2 Vol.

Schiechtl, H., 1980, Bioengineering for land reclamation and conservation: University of Alberta Press, 404 p.

Seckendorff, A.V., 1884, Verbauung der Wildbäche, Aufforstung, und Berasung der Gebirgsgründe: Wien, 319 p.

Stacul, P., 1979, Wildbachverbauung in Südtirol, gestern und heute: Autonome Provinz Bozen-Südtirol, 116 p.

Stern, R., 1975, Hydrogeologische und vegetationskundliche Kartierungen im Trattenbach: Mitteilungen der forstlichen Bundesanstalt Wien, v. 112, p. 25-42.

Stini, J., 1910, Die Muren: Wagner-Innsbruck, 139 p.

Stini, J., 1931, Die geologischen Grundlagen der Verbauung der Geschiebeherde in Gewässern: Springer-Wien, 120 p.

Stini, J., 1938, Über die Regelmässigkeit der Wiederkehr von Rutschungen, Bergstürzen und Hochwasserschäden in Österreich: Geologie und Bauwesen, v. 10, p. 9-31 and 33-48.

Strele, G., 1934, Grundriss der Wildbachverbauung: Springer-Wien, 279 p.

Swanson, F.J., and C.T. Dyrness, 1975, Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon: Geology, v. 1, p. 393-396.

Varnes, D.J., 1978, Slope movement types and processes: in R.L. Schuster, and R.J. Krizek, eds., Landslides - Analysis and Control: Transportation Research Board Special Report 176, p. 11-33.
Venzo, G.A., 1976, Proposta di classificazione pratica delle frane: Studi Trentini di Szienze Naturali, Nuova Serie, v. 53, No. 5A, p. 3-8.
Walcher, J., 1773, Nachrichten von den Eisbergen in Tyrol: Wien 96 p.
Williams, G.P., and H.P. Guy, 1973, Erosional and depositional aspects of Hurricane Camille in Virginia, 1969: United States Geol. Survey, Prof. Paper 804, 80 p.
Zeller, J., 1972, Die Schwierigkeit einer technisch korrekten Festlegung der Wildbachgefahrenzonen: in 100 Jahre Hochschule für Bodenkultur Wien, v. 4/2, p. 169-186.
Zollinger, F., 1976, Die Ausscheidung von Gefahrenzonen: Dokumente und Informationen zur Schweizerischen Orts -, Regional -, und Landesplanung No. 42, p. 28-38.

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