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Avalanche Hazard Mapping with Satellite Data and a Digital Elevation Model

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ABSTRACT

Today avalanche hazard mapping is a very time-consuming affair. To map large remote areas, a method based on satellite imagery and digital elevation model has been developed. For this purpose, two test-sites in the Swiss Alps were selected. To simulate the avalanche hazard, the existing Salm-Voellmy model was modified to the computer environment and extended to the characteristics of avalanches within forested terrain. The forests were classified with Landsat-TM data. So far, only a single forest-class was established. The separation of forest, shrub, and non-forested area along the timberline poses a problem. On the other hand, a classification of small openings and avalanche tracks within the forest could be achieved.

A comparison with the existing avalanche cadastral map revealed that 85 per cent of the risk areas were correctly classified. On the other hand, the separation into the defined red and blue danger zones was not satisfactory. For the model's application to become operational, further improvements are needed. However, the general approach is very promising, and should lead to more reliable hazard maps for planning purposes, as well as to new and better insights into the mutual effects between snow and forest.

INTRODUCTION AND OBJECTIVES

The aim of avalanche hazard mapping is to prevent catastrophic damage to people, animals, settlements and transportation facilities. In the Himalayas neither large-scale maps nor long-term observation records exist. The Snow & Avalanche Study Establishment (SASE) at Manali, is supporting efforts to establish similar large-scale maps for the Indian part of the Himalayas as a planning tool for transportation and touristic infrastructure projects. But the extent of the region to be mapped is much larger and the areas are more remote than in the Alps, requiring a different methodological approach. Remote sensing techniques together with mathematical models are particularly suited to assist in solving these problems, and for producing adequate planning documents.

Therefore, the objective of our study is to evaluate the potential of high resolution satellite imagery (Landsat-TM, SPOT-XS) for avalanche hazard mapping, and to develop an appropriate method for mapping vast, remote mountain areas, like those in the Himalayas. Indispensable prerequisites are precise references on the topography, e.g., on altitude, slope angle and aspect, which are only traceable using a digital elevation model (DEM). Hence, the availability of high resolution DEMs of about the same spatial resolution as the satellite imagery is essential.

For a fast and thorough development of the method, the existing, broadly approved model of Salm-Voellmy was used and modified to the computer environment and the specific conditions of the region. Then, the method was tested in two sites in the Swiss Alps. Both areas have excellent long-term observation records on

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climate, vegetation, snowcover and avalanche statistics, dispose of a high-resolution DEM, and are easily accessible. This allows for a detailed evaluation of the results achieved and enables the necessary adjustment of the model parameters.

2. THE MODEL

2.1 Avalanche Hazard Maps

Avalanche-cadasters (avalanche register) list and map all observed avalanche events. Avalanche hazard maps give evidence on potential avalanches in new regions caused by extreme conditions or changed environmental circumstances. Run-out distance and dynamic force are the criteria to divide an area into different hazard zones. In Switzerland, avalanche hazard maps usually show three different degrees of hazard, which are coloured red (high hazard), blue (moderate hazard), and white (no hazard). They always consider the so-called 'extreme' avalanches, i.e., the avalanche which occurs once in 30 and 300 years. The criteria selected, therefore, differ considerably from those taken from 'normal' avalanches.

2.2 Salm-Voellmy Model

In the Swiss Alps, the model by Salm-Voellmy is used to determine avalanche hazard zones. It is also used as a basis for our research task. The model is described in detail and illustrated by several practical examples Salm, *et al*[1]. Therefore, it is not discussed here specifically, but the fundamental aspects necessary for the understanding of its implementation into the computer environment is explained briefly. The model was extended by also considering the effects of the vegetation cover, in particular the forests. Structure, density and health of mountain forests are critical parameters, which can be derived from satellite imagery.

2.2.1 Determination of the Avalanche Track

The determination of an avalanche track is undertaken by assuming the flowing-down of the avalanche snow as illustrated in Fig. 1. Proceeding from the zone of origin, characterised by a treeless area with a slope angle of 28 °-50 °, the volume discharge of snow is calculated at the lower end of the zone of origin. The avalanche on its way downhill is then assumed to enter the zone of transition. Here, the speed and height of the avalanche can be calculated at any point of interest. At the lower end of the track (near point P in Fig. 1), the representative slope angle used for the calculation of the speed and the height of the avalanche at the beginning of the run-out zone, are determined.

For the transition stretch between point P and the actual beginning of the run-out zone (point P is characterised by a slope angle that is 3.5° steeper), the model presumes that the avalanche parameters do not change. The results evaluated for point P are then used directly for the calculation of the run-out zone.

2.2.2 Parameters

Important snow parameters are:

(i) Average thickness of the snowpack in the zone of origin,

(ii) Factor of turbulent friction, and

(iii) Friction coefficient.

Important relief parameters are:

(i) Slope angle in zone of origin, zone of transition, and run-out zone,

(ii) Largest horizontal extension of zone of origin,

(iii) Beginning of run-out zone (point P), and

(iv) Width of avalanche at point P.

2.2.3 Determination of the Avalanche Track in Forested Areas

Avalanches are generally not influenced by surface roughness[2]. But roughness can matter when there is only a light snowcover (e.g. in early winter). Then, the surface roughness may severely hamper the snow movement. However, with increasing snowpack thickness, this effect vanishes almost completely. Trees and shrubs have a great influence on the formation and dynamics of avalanches. Dense forest represents a major obstacle for avalanches. But not every forest offers sufficient protection. Trees get continually damaged by the flowing snow masses and by the rocks transported therein. These interactions too will have to be carefully investigated.

2.2. 1 Starting of an Avalanche in Dense Forests

Air temperature, precipitation, wind, short-and long-wave radiation, etc. differ remarkably in dense forests in comparison with tree-free areas of similar location, resulting in a very different avalanche hazard

Table 1. Critical size of openings to initiate an avalanche (after Gubler and Rychetrik[3], p. 22)

Slope angle	Minimum length of opening (m)	Minimum width of opening (m)
45°	30	10
35°	50	10

as on the forest density. Gubler and Rychetnik[3] have carefully analysed these parameters with the following results: if an avalanche composed of dry snow reaches a speed of 20 m/s, a powder snow avalanche may develop. These avalanches are much more dangerous to a forest than a normal gliding avalanche, since their pressure waves have a direct impact on the tree-crowns, and damage the stems. All avalanches reaching a forest at a speed higher than 20 m/s are a potential source of danger, they have constructed a diagram (Fig. 2) with a critical speed of 18 m/s comprising all important criteria.

The slowing-down effect of forests on avalanches cannot be exactly quantified. Gubler and Rychetnik[3] state that in dense forests, an avalanche with a depth of flow of more than one metre, will lose a great deal of its material, but generally will traverse the forest. It will not decelerate till the slope angle is less than 10°. The only physical variable in the model that clearly separates forest from non-forested areas is the friction coefficient, which has to be determined empirically.

3. PROCEDURE

3.1 Test Sites and Data Used

The two selected test sites of Beckenried and Davos in the Swiss Alps are characterised by strong relief, and consequently are well suited to avalanche hazard mapping. Moreover, avalanche maps and potential hazard maps have existed for a long time. Both areas are easily accessible for ground control and verification. Landsat-TM satellite data were used for the forest classification by taking a scene from 3 July 1985. To verify the classification results, the forest in the official topographic map 1:25,000 was scanned and an output was produced for the Beckenried test site. For the Davos site, the data set[4] from the MAB-Davos Project was

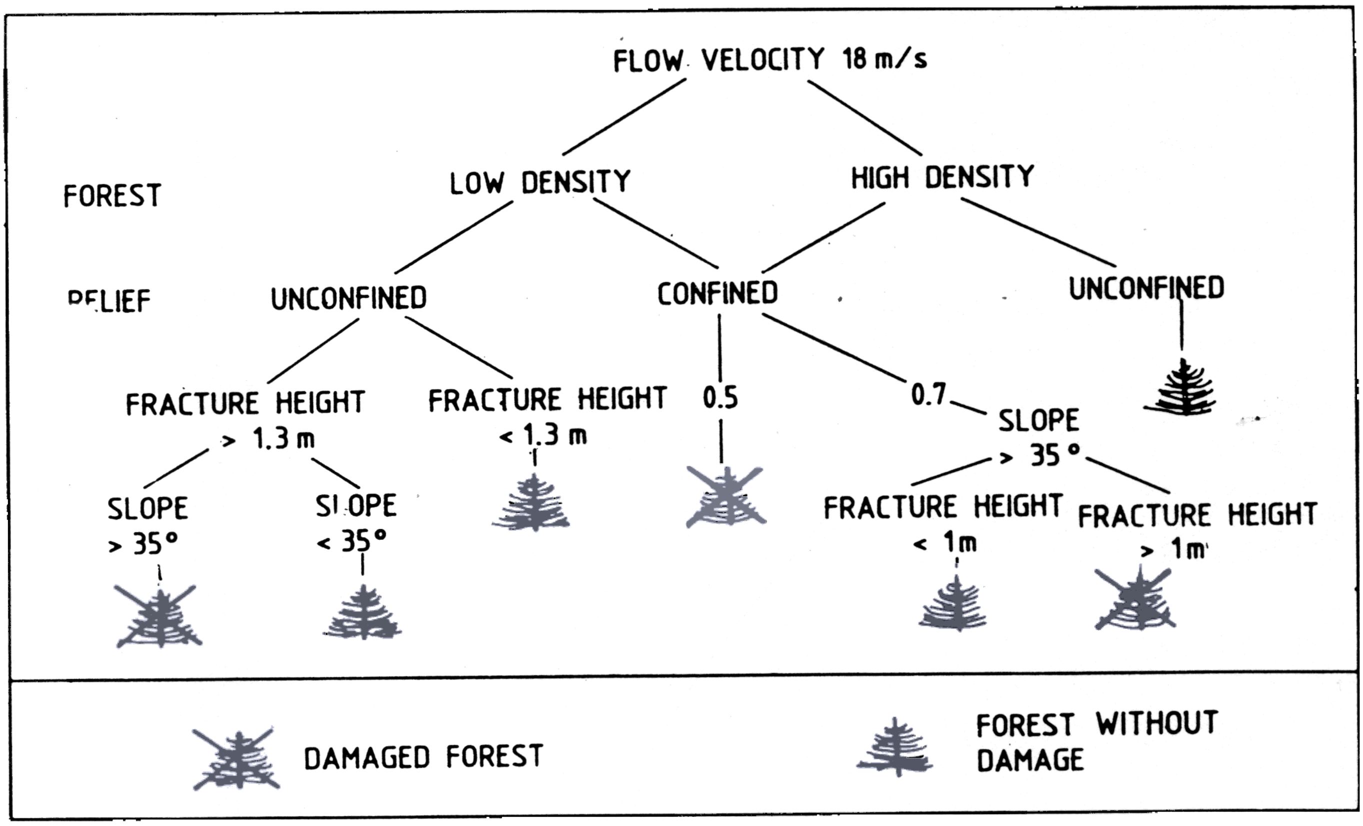

Figure 2. Decision tree for damage to forests for confined and unconfined flows of avalanche (after Gubler and Rychetrik[3], p.27).

used. These comparative data sets are designated as ground truth.

For the Beckenried test site, a DEM with a grid-size of 25 × 25 sq m and for the Davos test site, a DEM with an original resolution of 100 m, were at our disposal.

3.2 Forest Classification

Based on the 'strategy of the worst case' that is applied to the avalanche hazard mapping, the classification procedure is adjusted in such a way that no treeless or shrubless areas get classified as forest. Although a classification of forest as non-forested area would only enlarge the avalanche risk zone, yet it would not be as aggravating as its reverse. In a preprocessing procedure, geometric and radiometric corrections were carried out. To classify forest with Landsat-TM data, an hierarchical classification system based on a PPD algorithm was applied, as outlined in Fig. 3. The goal was to determine small clearings and valleys as well as to eliminate woodland and open forests. The remaining parts then represent the category 'dense forest', which is used directly as input parameter to the avalanche hazard model.

A similar forest classification was realised for the Manali area. However, in the absence of an appropriate DEM and ground control, the results are not yet of an adequate quality.

3.3 Implementation

The necessary software packages for the preprocessing and processing of the satellite data are available in the IBIS library of the Department of Geography, University of Zurich[5]. Consequently, the avalanche hazard model was implemented for this system too. One of the main objectives was to set up

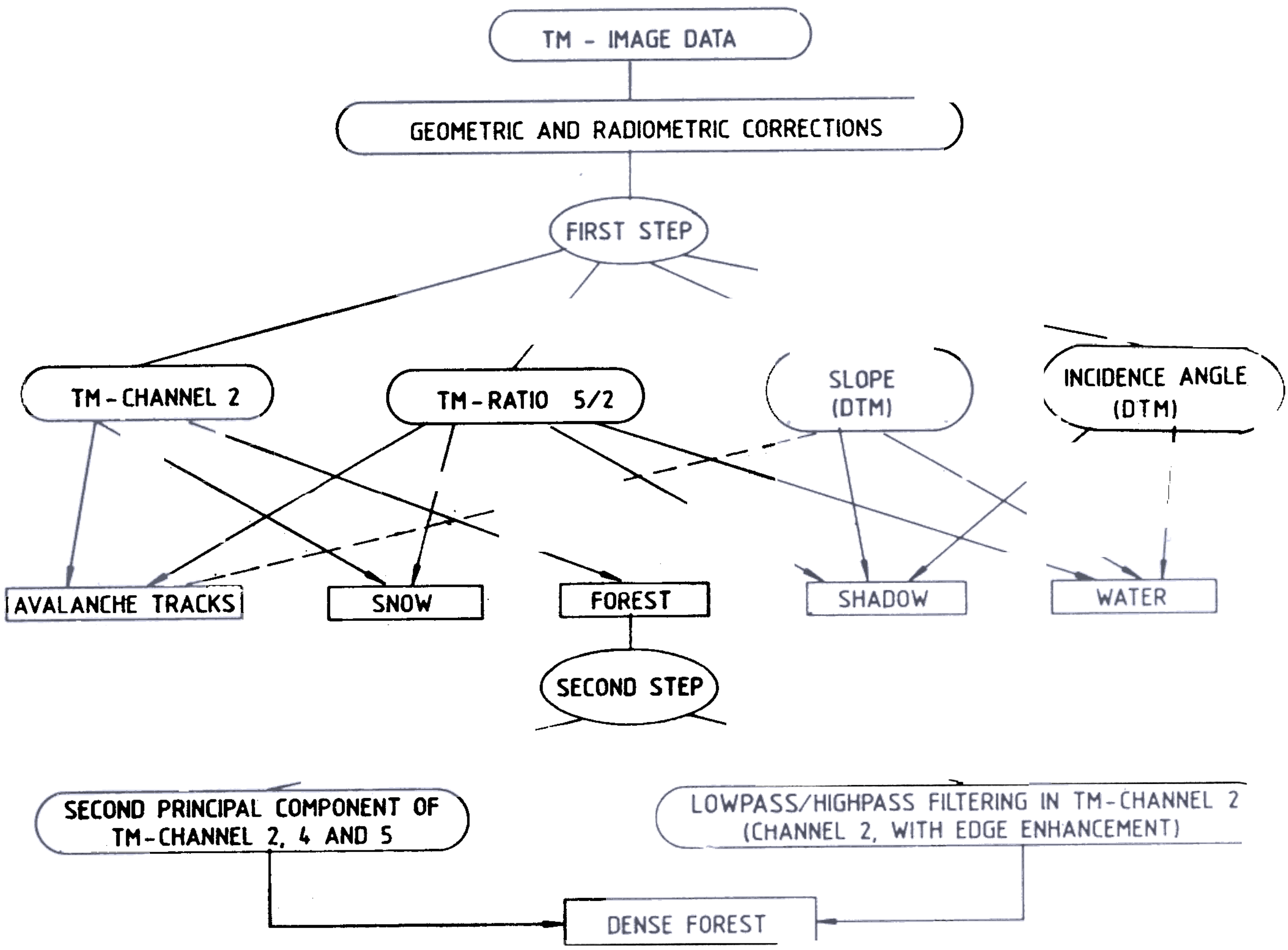

Figure 3. Flow chart of the hierarchical forest classification. The arrows show which data-sets were used to classify each class.

the programs in such a way that each individual input parameter could be manipulated easily. This allows a careful evaluation of its influence on the determination of the run-out zone.

3.4 Modified Salm-Voellmy Model

The model is given in Fig. 4 on the right. On the left, a flow chart shows how to calculate the avalanche hazards, and how to establish an avalanche hazard map. Using this approach, the development of two extreme avalanche events-the 30 year and the 300 year avalanche-was computed and mapped. This has yielded two different simulation maps. The test site is always classified into ten categories according to the path sections, the damage potential of the forest, and the influence of forest regarding the thrust and run-out distance. The combination of both simulation results provides the final avalanche hazard map (Fig. 5).

In the modified model, the necessary parameters are derived automatically from the DEM, and from the satellite data classification. For the calculation, the avalanche is not regarded as a whole but is divided into vertical strips of 25 m width (avalanche strips). The calculation is made separately for each strip, equal to the 25 × 25 sq m pixel-size. This can cause errors because an avalanche always has the tendency to equalise its forces across the entire width. Consequent to the calculations for each strip, different path sections are subdivided into the red and blue hazard zones according to the criteria given in Table 2.

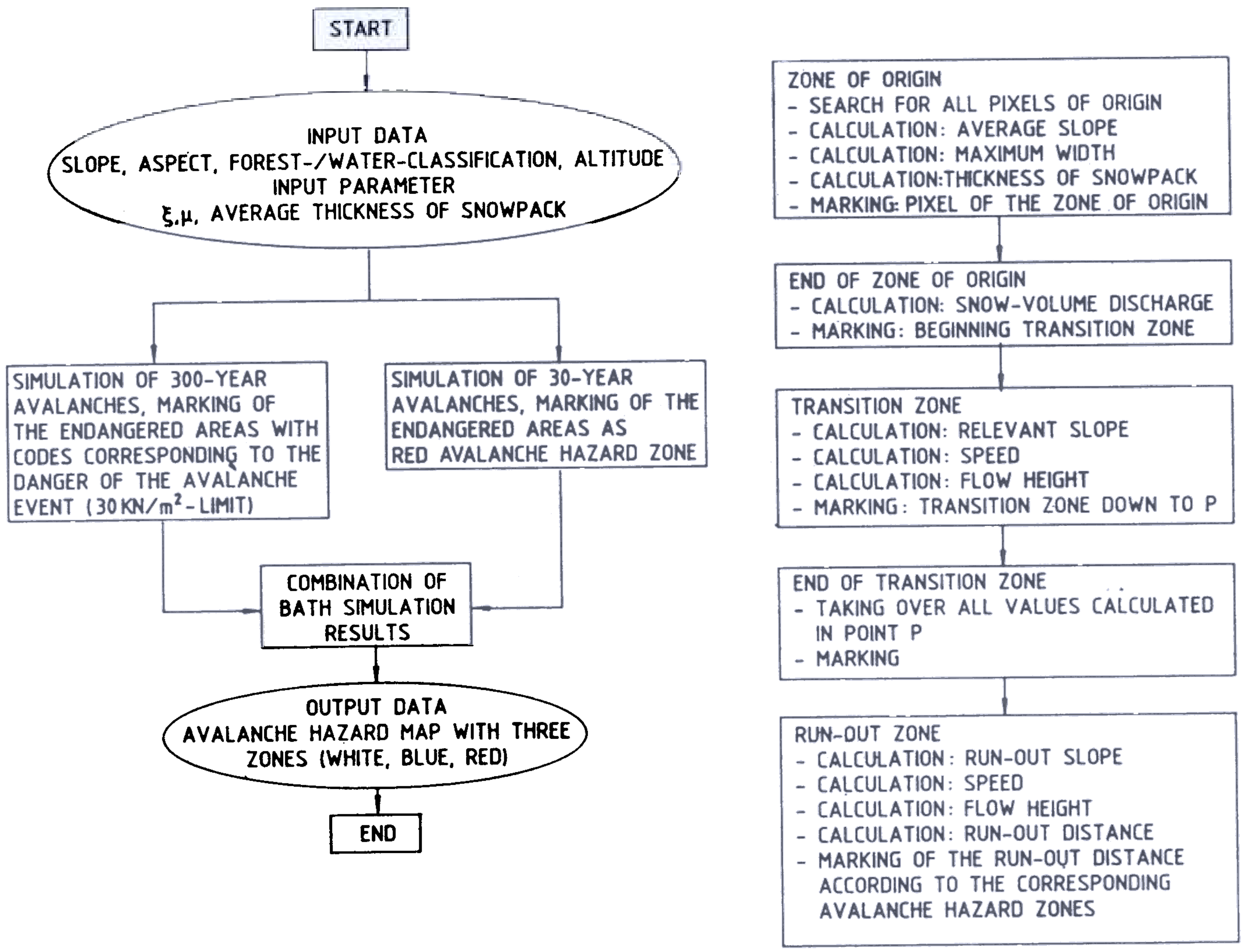

Figure 4. Modified Salm-Voellmy Model : conceptional overview of avalanche hazard mapping model (right) and the various steps to simulate the course of the avalanche (left).

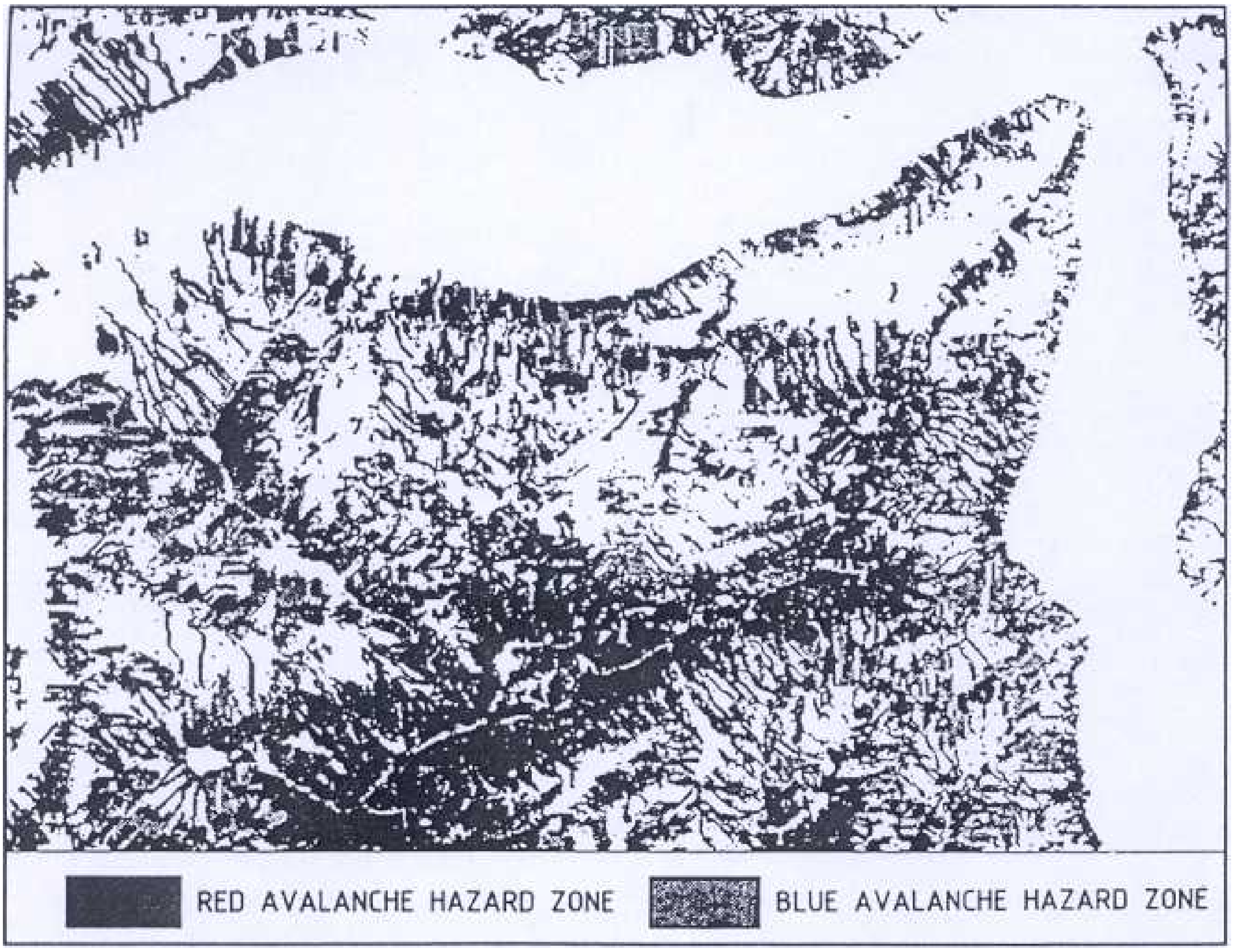

Figure 5. Avalanche hazard map of test-site Beckenried, South of the Lake of Lucerne.

Table 2. Criteria for the division into the red and blue hazard zones

Red Zone	Blue Zone
Zone of origin, 30-year-simulation (30 y) as well as 300-year simulation (300 y)	Little endangered forest (30 y/300 y)
Treeless zone of transition; avalanche influenced by the forest situated above this zone (30 y/300 y)	Regions below little endangered forest (30 y/300 y)
Treeless homogeneous passage between point P and the beginning of the run-out zone; avalanche is not influenced by the forest situated above this zone (30 y/300 y)	Highly endangered forest of 300 y
Treeless run-out zone of 30 y	Regions below highly endangered forest of 300 y
Regions above the 30 kN/m^2 limit of 300 y	Regions below the 30 kN/m^2 limit of 300 y
Highly endangered forest of 30 y	
Regions below highly endangered forest of 30 y	

4. RESULTS

4.1 Classification of Forest

The results from the satellite classifications are summarised in Table 3. Based on a similar study[6], it could be demonstrated that the use of a DEM slightly improved the results.

Table 3. Forest classification accuracy for the test-site Beckenried

ıtegory	Accuracy
Forest correctly classified	75.2 % of forest
Forest classified as non-forested areas	7.3 % of non-forest
Classification accuracy	87.7 %

An analysis shows that most of the forested areas not classified as forest are located along the timberline. Here, forest pixels classified as non-forested areas as well as vice versa occur. In addition, some deciduous tree-stands were also classified as non-forested areas. This happened because the trees at the upper limit are small and in open stands, as well as due to a rather restrictive selection of the classification parameters in favour of an optimum separation of the small clearings within the forests.

Quite a few avalanche tracks registered as forest in the avalanche-cadaster were classified correctly as non-forested areas. One of the advantages of the satellite classification is its timeliness; it represents the most recent situation of the area under investigation, while topographic maps often are slow in updating.

In summary, the achieved results for the forest classification are sufficient for the subsequent use in the avalanche hazard model.

4.2 Classification of Avalanche Hazards

The results are judged in two ways. First, the avalanche simulation results are compared with the avalanches that are listed in the avalanche-cadaster (Sec. 2.1). The purpose is to find out if all avalanche events are registered by the model. These results are very promising; approximately 85 per cent have been classified correctly. Secondly, a comparison with the existing avalanche hazard maps shows the accuracy of detection and their assigning to one of the two potential danger zones, viz, 'red' or 'blue'. These classification results are summarised in Table 4.

Table 4. Comparison of the results of the avalanche hazard mapping for the test-site Beckenried with the existing avalanche hazard map

Zone	Avalanche Hazard Map (Oberdorf[9]) (%)
Red zone correctly classified	33.2
Blue zone correctly classified	66.3
Red zone classified as blue zone	32.3
Blue zone classified as red zone	19.5
Red zone not classified	34.5
Blue zone not classified	14.1
Red zone overlarge	78.8
Blue zone overlarge	77.6

The analysis reveals that the results regarding the allocation of the danger zones are not yet satisfactory. In general, the run-out zones stretch too far. The main reasons are summarised in the succeeding paragraphs.

4.2.1 Determination of Danger Zones in Forested Areas

Within the test site Beckenried, only one third of the 'red zone' was classified accurately. Another third was classified as 'blue zone', the rest as non-danger zone. The problems occur primarily in densely forested regions. It appears that the determination of the two zones in the cadaster was reached empirically, and not by applying the model. It can be assumed that the separation of zones was often taken casually and not scientifically. Zones of origin are included within the forest also. This leads to additional misclassifications, since the model is based on the stipulation that no avalanches get started inside a dense forest.

4.2.2 Length of the Zone of Origin

The Salm-Voellmy Model does not consider the length of the zone of origin, but assumes that the length is not relevant to the volume discharge of snow, avalanche speed or flow height. But it is not realistic to suppose that an avalanche with a zone of origin of only 50 m in length will penetrate equally deep into the forest as one with a length of several hundred metres. An avalanche with a short zone of origin will get stopped earlier than an avalanche with a large one. Gubler and Rychetnik[3] proposed to solve this problem by adding another parameter, which determines the possible run-out distance in a forest, depending on the size of the zone of origin as well as speed and flow height. However, an exact criterion is yet to be found. For this, additional empirical data have to be gathered.

4.2.3 Uniform Friction Coefficient for the Entire Test Area

The current model can handle only one friction coefficient for the entire non-forested area or test site. But since this friction coefficient depends on the altitude of the zone of origin, and the average depth of the snowpack, the possibilities for misclassifications are substantial. In lower areas, the friction coefficient used is not sufficient, leading to too long run-out distances.

In conclusion, it may be mentioned that there are clearly identified problem areas for improving the model for an operational application.

5. ADVANTAGES AND DISADVANTAGES OF TWO APPROACHES

5.1 Advantages of the Classification from Satellite Imagery

(i) Small forest clearings and avalanche paths in forested areas could be determined.

(ii) The achieved accuracy of approximately 88 per cent equals the one of the forest classification in other mountainous areas.

5.2 Advantages of the Avalanche Simulation Model

(i) Approximately 85 per cent of all avalanche risk zones as recognised in the avalanche-cadaster maps could be identified. In areas, where the forest does not represent the dominant surface feature, this drops to approximately 80 per cent.

(ii) The model directly considers the most important factor, the forest, for a simulation of the avalanche hazard ones.

(iii) The many possibilities for adapting the various input parameters of the model to local or seasonal conditions allow for distinct solutions for specific regions. By experimenting with the input variables, specific problems and objectives of avalanche hazard mapping may be analysed.

5.3 Disadvantages of the Classification from Satellite Imagery

(i) It was not possible to reach a satisfactory separation of different forest-cover density categories. The vegetation classification had to be restricted to a differentiation into the categories dense forest and non-forested areas.

(ii) A separation of forest and shrub along the timberline is the most critical part of the classification procedure, having severe implications on the accuracy of the subsequent avalanche hazard simulation.

5.4 Disadvantages of the Avalanche Simulation Model

(i) Presently, the model allows for the application of only one single friction coefficient for the entire area.

(ii) A separation into the different avalanche danger zones could not be achieved satisfactorily. In particular, for areas within the forest, new classification criteria should be tested.

(iii) The track taken by an individual 'avalanche strip' is determined pixel by pixel, by choosing between the three possible follow-on pixels. Hence, an exact and continuous determination of the track taken by an avalanche strip is not always possible.

(iv) Similarly, avalanches are not considered as a whole, but are divided into independent, parallel running avalanche strips. Consequently, the interactions between these neighbouring strips cannot be taken into account, resulting in different speeds and run-out distances within the same avalanche.

6. DISCUSSION AND OUTLOOK

An operational application of the model is not yet feasible, especially in remote mountain areas with insufficient ground records and cartographic documentation (maps, DEM). A careful testing and verification is essential before operational applications can be carried out. Nevertheless, the first results are promising, and by further improvements, the model may become a most valid planning tool. In particular, the following additional problem areas will be investigated further:

(i) A separation of the forest into needleleaf and broadleaf as well as density categories is necessary and can be achieved by means of satellite remote sensing. But it is only useful, if the results are considered as a direct input variable to the model. To make use of this parameter, more information on the behaviour of avalanches in different forest types must be gained[3].

(ii) A satellite classification of sufficient accuracy for forests, shrubs and non-forested areas along the timberline has yet to be achieved. It has to be emphasised that powder snow avalanches have not been taken into account by the current model. Further developments have to integrate aspects of powder snow avalanche mechanisms as well.

(iii) With a data set based on the vector principles instead of the raster format, and the addition of GIS, the track of an avalanche could be determined more precisely. Hegg[7] has developed a vector-based software program for the GIS-ARC/INFO system, which could be most helpful for avalanche hazard simulations. Variations of the different parameters will allow an adaptation to specific local situations and meteorological conditions.

REFERENCES

1. Salm, B.; Burkard, A. & Gubler, H.U. Berechnung von Fliesslawinen..Eine anleitung fur praktiker mit beispielen. Mitteilungen des Eidgenossischen Instituts fur Schnee und Lawinenforschung, Davos, Nr. 47, 1990.
2. Salm, B. Lawinenkunde fur den praktiker. Verlag des Schweizerischen Alpen-Clubs, Bern, 1982.
3. Gubler, H. & Rychetnik, J. Effects of forest near the timberline on avalanche formation. IAHS Pub No. 205, 1991; pp. 19-36.
4. Seidel, K.; Baumann, R.; Burkart, U.; Haefner, H.; Itten, K. & Martinec, J. Satellite data for evaluation of snow reserves and runoff forecasts. Proceedings of the hydrology and water resources symposium, Christchurch, New Zealand, 1989.
5. IBIS, Benutzerhandbuch des Interakttiven Bild Interpretationssytems, Dept. of Geography, University of Zurich, 1992 (unpublished).
6. Itten, K.I.; Meyer, P.; Kellenberger, T.; Leu, R.; Sandmeier, S.; Bitter, P. & Seidel, K. Assessment of the impact of topography on remote sensing forest mapping of alpine region, Dept. of Geography, University of Zurich, ESA study Nr. 90/E56, 1991.
7. Hegg, C. Einsatzmoglichkeiten des geograpischen informations systems ARC/INFO im problemkereis geschiebeverlagerung in wildbachen. Master thesis (unpublished). Dept. of Geography, University of Berne, 1991.