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Comparing Landslide Hazard Maps

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Abstract. The objective of the method explained in this paper is to obtain a better insight in the decision rules applied by geomorphologists in the direct mapping of landslide hazard. This can be obtained by forcing geomorphologists to specify for each unit (polygon) in their hazard map the criteria that they used to classify the unit as high, medium or low hazard. When this is done systemically for an entire area, it is possible to analyze those criteria statistically, and to evaluate whether they can be grouped into general decision rules, or whether these criteria are completely site specific. The same area in the Alpago region in Italy was mapped at 1 : 5000 scale by three teams of experts individually. The different methods are presented and the results are compared.

Key words: landslides hazard, direct methods, indirect methods, GIS, geomorphology, Alpago area.

1. Introduction

Many techniques have been proposed in literature for landslide hazard zonation (Hansen, 1984; Van Westen, 1993). These can be generally divided into two groups:

Direct hazard mapping, in which the degree of hazard is determined by the mapping geomorphologist, based on his experience and knowledge of the terrain conditions.

Indirect hazard mapping, in which either statistical models or deterministic models are used to predict landslide prone areas, based on information obtained from the interrelation between landscape factors and the landslide distribution.

Landslide hazard studies conducted by experienced geomorphologists can result in very reliable maps, on the condition that the mapping was done with care. If the resulting map is checked statistically with the input landslide occurrence map it can be stated that the percentage of misclassification is 0, which means that all landslides actually occur within the high hazard zones. Such low values can never be obtained using indirect methods, in which the analysis is considered a success if for example less than 20% of the landslides are not within the high hazard zones (Carrara, 1988). The main disadvantage of direct mapping is, however, that the quality of the resulting hazard map is completely depending on the experience, skill, and commitment of one individual or mapping team. The reasoning behind the outlined hazard classes is often not presented on the hazard map. It can be expressed that the map is made "in the mind of the geomorphologist".

The reproducibility of indirect hazard maps is generally much larger. The decision rules are obtained using statistical analysis, and the resulting hazard classes can be presented with the decision rules used to classify them as high, medium or low hazard. The importance of each factor contributing to slope instability can be expressed as a weight value, either in the form of a favourability function in bivariate statistical analysis (Chung *et al.*, 1995) or as a value in a regression function (Carrara *et al.*, 1992) in multivariate statistical analysis. The statistically based landslide hazard maps however have a large disadvantage; generally the factors leading to slope instability have to be generalized for the entire area. Which means that one has to assume that the combination of factors leading to slope instability is the same throughout the study area. A special combination of factors (e.g., a certain combination of a rock type, slope class and land use type) that leads to instability in a certain part of the area, may not lead to instability in another part. It is difficult to take this into account in statistical landslide hazard analysis. Hazard maps derived from statistical landslide hazard assessment are more reproducible then those from direct hazard mapping, since the weight values are derived from the data and not from the expert. However, it cannot be said that this kind of analysis is more objective than the direct methods, since a large degree of subjectivity is incorporated in both the collection of the input data (Carrara *et al.*, 1992), as well as in the selection of the relevant factors for the analysis. It is difficult for the researcher to include his expert opinion in the direct methods, as the decision rules are statistically derived from the relation between landscape factors and landslide distribution. Especially in multivariate statistical analysis the resulting regression formula should be taken as it is, and can only be modified by running a new regression analysis on another set of factors. Although the influence of the expert is larger in bivariate statistical analysis (he/she can change the favourability functions) it is difficult to account for the complex combination of factors that occurs in specific parts of the terrain.

2. Objectives

The objective of the research presented in this paper is to obtain a better insight in the decision rules applied by geomorphologists in their direct mapping approach, in order to improve the GIS-based indirect mapping techniques. This can be obtained by forcing the geomorphologists to specify for each mapping unit (polygon) in their hazard map the criteria that they used to classify the unit as high, medium or low hazard. When this is done systemically for the entire area, it is possible to analyze those criteria statistically, and to evaluate whether they can be grouped into general decision rules, or whether these criteria are more site-specific. Up till now such kind of analysis has not been executed.

When the decision rules resulting from direct geomorphological mapping are known they can be compared to those derived from the indirect mapping approach, either using bivariate or multivariate statistical analysis. This comparison will give insight in those situations where the statistically derived decision rules will cause an oversimplification of the hazard classification. Based on this comparison modifications in the statistical methods can be suggested which will increase the influence of expert opinion in establishing decision rules. In the statistical methods presented by Chung *et al.* (1995) it is possible to modify the statistically derived "favourability values" of the units in the factors maps (e.g., geological units, or slope classes) so that these values more represent the expert's opinion. It will also be a first step towards the construction of an expert system for landslide hazard zonation.

3. The Mapping Teams

The field mapping should be done by expert geomorphologists with large experience in direct landslide hazard mapping. For this project three teams of geomorphologists participated in the mapping:

- A team from the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands, consisting of Ir. R. Soeters, and Dr. C. J. van Westen. The members of this team have experience with geomorphological mapping in many different countries, mostly in South America, and Asia, but also in Spain and Italy (Van Westen, 1993);
- A team from the University of Ferrara (UNIFE) in Italy, lead by Dr. F. Mantovani, and assisted by L. Trasforini, Dr. S. Silvano and M. Di Geronimo from Padova from the National Research Council (CNR-IRPI) in Padova. The members of this group have experience with landslide hazard mapping, mainly in Italy. They were also the only group that had been working before in the proposed fieldwork area (Mantovani *et al.*, 1976);
- A team from the University of Amsterdam (UVA), the Netherlands, consisting of Dr. J. Rupke, and Dr. A. C. Seijmonsbergen. This team has over 20 years experience in detailed geomorphological mapping in the Alpine region, such as in Vorarlberg Austria, Liechtenstein, and Switzerland (de Graaff *et al.*, 1987).

With regard to the experience of the three teams, it should be noted that the leader of the team of the University of Ferrara, Dr. F. Mantovani, followed part of his training at ITC in the seventies, and that the teamleader of the ITC team, Dr. C. J. van Westen, graduated from the University of Amsterdam. All teams were instructed to work independently according to their own mapping method, and to generate a final hazard map with the same classes, so that the results could be compared.

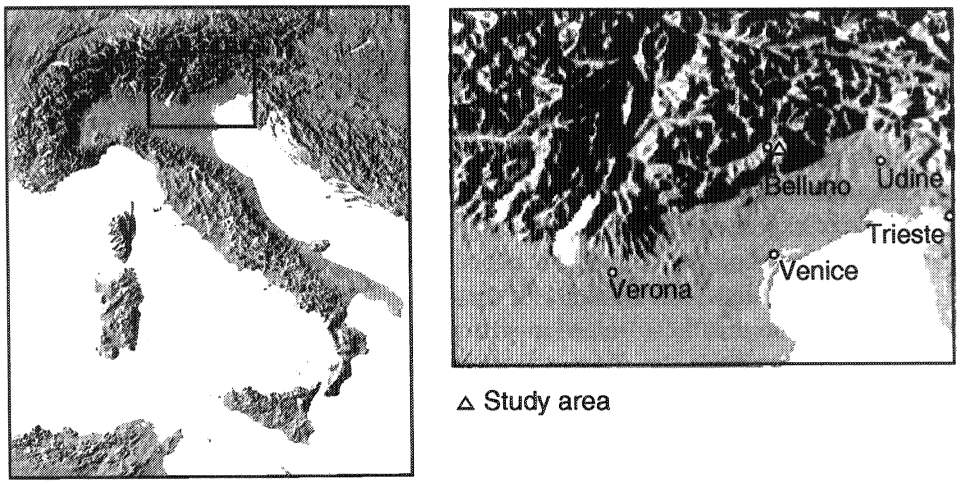

Figure 1. Location of the study area.

4. The Study Area

The hazard maps were prepared for a test site in the Alpago Basin, located to the East of Belluno (northeastern Pre-Alps, see Figure 1).

A geomorphological map of the study area is shown in Figure 2. This small area, of 20.8 km^2, is located East of Chies d'Alpago and consists of two catchments: the Borsoia catchment to the South with the villages Palughetto, Borsoi, Lavina, Tambre and Tambruz, and the Boccolana catchment in the North. The NE border of the area is formed by a steep mountain ridge that rises up to more than 2000 meters, while the SE part of the area has a more gentle, undulating morphology with an altitude of around 1200 meters. Gentler slopes characterize the central zone of this morphostructural basin, formed within a large syncline with a NW–SE trending axis.

The oldest rocks outcrop in the eastern part of the study area, above 1100 meters. They belong to the Jurassic–Cretaceous calcareous Formation of *Monte Cavallo*, and consist of bioclastic limestones with stratification ranging from beds of 1–2 meters in thickness to thinner beds containing many levels up to 30–40 cm thick (Mantovani *et al.*, 1976). The stratigraphic sequence continues with marly and marly-limestone belonging to the Cretaceous-Paleocene Scaglia Formations (*Scaglia Grigia* Formation and *Scaglia Rossa* Formation). The Formation of Middle Eocene Flysch outcrops in most of the area at altitudes lower than 1100 meters.

The Quaternary cover is very extensive and locally very thick, and covers about 75 percent of the area. Ablation moraine deposits, of Würm and Early Holocene age, partly of local provenance and partly derived from outside the basin are found at an altitude around 1100 m., representing the maximum extend of the last gla-

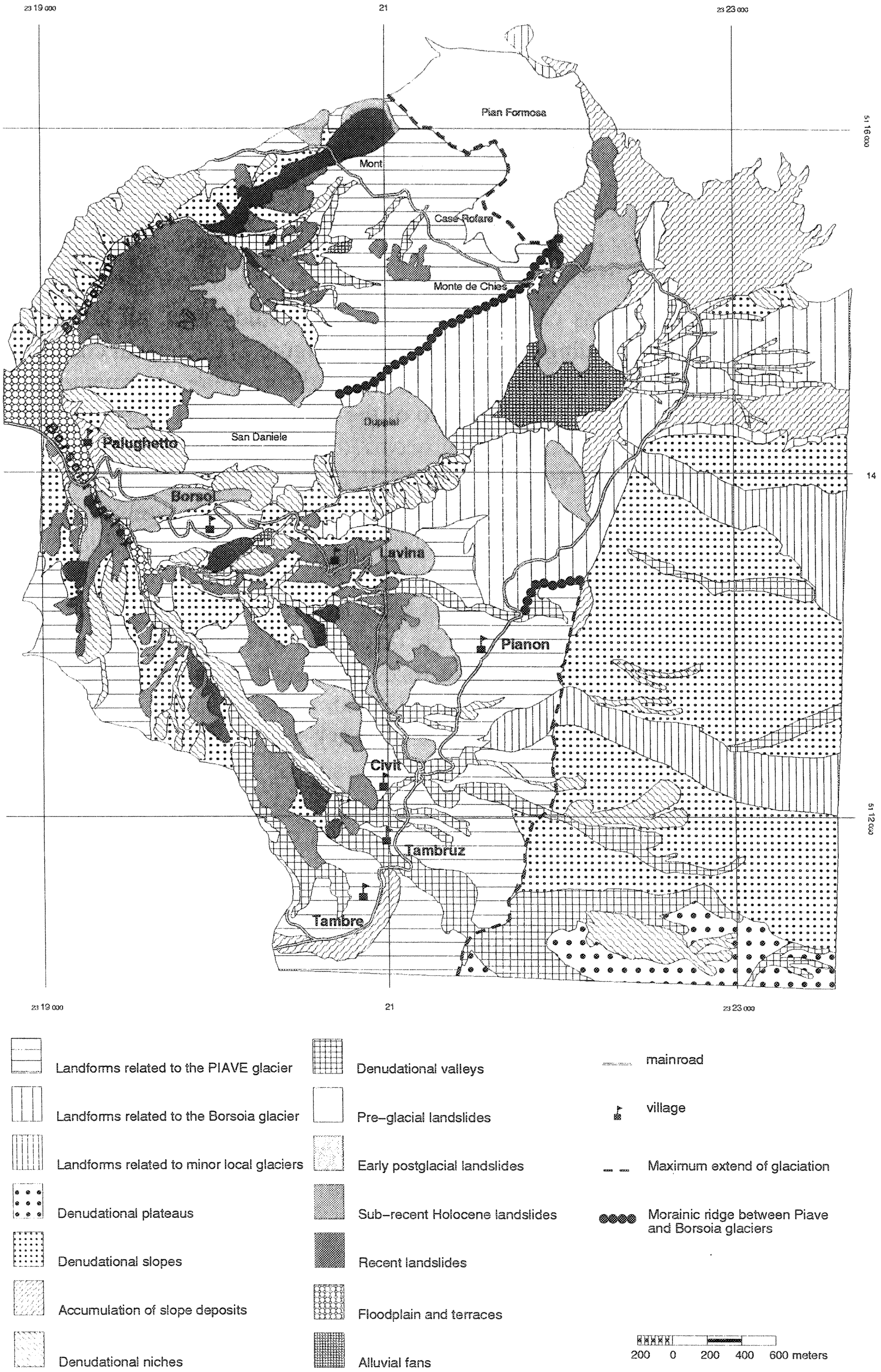

Figure 2. Geomorphological map of the study area, indicating the main geomorphological units as mapped by the ITC team.

ciation. Large areas below 1100 m are covered by subglacial till deposits, and fluvioglacial deposits.

Slope deposits, derived from old landslides and scree material, are found extensively as well. In the NE of the study area, the scree material, derived from limestone, is partly cemented.

5. Geomorphological Evolution of the Study Area

5.1. PRE-GLACIAL LANDFORMS

Some pre-glacial landforms can still be found in the study area, all above 1100 meters. In the area surrounding Pian Formosa (see Figure 2) the terrain consist of a number of flat areas, separated by steeper slopes, and consisting of cemented scree material. This area was interpreted by two of the three teams (ITC and University of Amsterdam) as a large landslide that occurred on a former scree slope, which was partially cemented. The toe of the landslide is included in the lateral morainic ridges of the main Piave glacier. Based on this evidence, it was concluded by the two teams mentioned before that the landslide is of pre-glacial age. The team from the University of Ferrara did not agree with this and considered the entire area to be of glacial origin. Two other areas, near Case Rofare and Monte de Chies, have geomorphological evidences that they were originated by landslides before the last glaciation. They both have a niche-like form, representing the erosional part of a landslide, but lack the depositional part. In both areas glacial and fluvioglacial landforms (morainic ridges and fluvioglacial fans), are found within the niches. This lead the two teams of ITC and the University of Amsterdam to conclude, individually, that these landforms represent pre-glacial landslide areas that have been modified during the last glaciation. The team of the University of Ferrara mapped both areas as recent landslides.

5.2. LANDFORMS ORIGINATED DURING THE MAXIMUM GLACIATION

During the maximum extension of the last ice age the main Piave glacier covered nearly the entire study area up to an elevation of approximately 1100 meters, as evidenced by a series of ice-marginal complexes (see Figure 3(A)). The morainic materials show ice-pushed structures, as well as collapse structures. The smaller and local Borsoia glacier did not have the opportunity to advance very far, against the large Piave glacier. A contact zone of the two glaciers is found in the area NE of Pianon (see Figure 2), which was identified by all three teams. Also some other, even smaller local glaciers existed. The teams from ITC and UVA (University of Amsterdam) mapped a large area between Tambre and Pianon as a series of levels with a thick deposit of sub-glacial till. The UNIFE team mapped these areas as glacis.

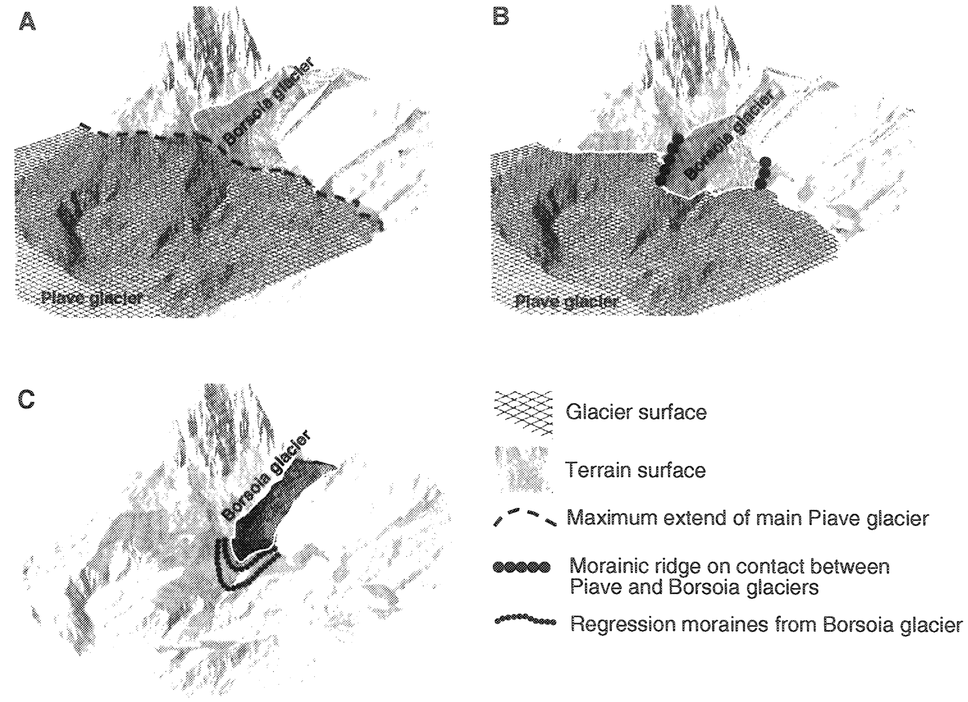

Figure 3. Three-dimensional views illustration the deglaciation history of the study area. A: Situation during the maximum of the last glaciation; B: Situation during early deglaciation; C: Situation during late deglaciation.

5.3. LANDFORMS ORIGINATED DURING THE EARLY DEGLACIATION PHASE

After the maximum glaciation phase the regional Piave glacier, with its source area located far more to the North, retreated. This allowed the local Borsoia glacier, with its source area directly East of the study area, to advance (see Figure 3(B)). A large medial moraine, recognized by all mapping teams, was formed in the area between Duppiai and Monte de Chies. Also some fluvioglacial fans were formed during that period, partly covering the sub-glacial till material. These were interpreted differently by the UNIFE team as being glacis. Due to the geotechnical characteristics of the sub-glacial till, this material is very vulnerable to landslides. Large retrogressive landslides initiated in the sub-glacial till level. All teams mapped the largest one of these landslides, East of Pianon. The ones of Lavina and Civit were only mapped by the teams of ITC and UVA.

5.4. LANDFORMS ORIGINATED DURING THE LATE DEGLACIATION PHASE

At the end of the last glaciation, the main Piave glacier retreated from the area, leaving a series of ice-marginal levels in the area surrounding San Daniele (see Figure 2). The Borsoia glacier still remained (see Figure 3(C)), building up a series of morainic ridges in the area E of Duppiai. Large landslides occurred, due to glacial oversteepening, especially in the area NW of San Daniele, where a large dipslope failure occurred, and in the Duppiai area, where a large rotational failure took place, with only small overall displacement. The morainic ridges from the eastern side of the landslide can still be traced on the landslide itself, although at a lower elevation. In the Tambre area a series of flowslides in the sub-glacial till level took place. Only the teams from ITC and UVA mapped these landslides, the morainic ridges and the ice-marginal levels. The UNIFE team mapped them as local morainic deposits, colluvial and glacis deposits. Another area, with large flowslides, East of Monte de Chies was mapped similarly by the three teams.

5.5. LANDFORMS ORIGINATED IN THE LATE HOLOCENE

During the Holocene mass movement activity remained high in the area. Older landslides were reactivated and many new ones occurred, due to the following unfavourable conditions: stream undercutting, dipslopes in Flysch rocks, the loading of rockfall on top of fine-grained materials, and the contact between permeable and impermeable materials. In historic times also deforestation is assumed to have contributed substantially to the occurrence of landslides. During the last decades many of the agricultural areas have been abandoned, and there has been a shift from agriculture to tourism. A large erosion control program was executed in the last decades, during which many checkdams were built in the main streams. In several places these checkdams are now already destroyed by landslides, which tend to close the valleys, and by stream undercutting.

6. The Mapping Method

6.1. GEOMORPHOLOGICAL MAPPING

Many different geomorphological mapping systems have been proposed in the literature, either for universal application or for specific areas (e.g., mountaineous terrain). Demek and Embleton (1978) present overviews of geomorphological mapping systems at medium and large scales. In common practice many different systems are being used, and unfortunately there is no universally accepted system that is adequate for mapping in different environments.

Given the fact that each of the three mapping teams within this project (ITC, University of Amsterdam, and University of Ferrara) used its own mapping system, it was decided not to attempt to agree upon a common geomorphological mapping system. This would divert the project too much from its original objective, which was the comparison of the resulting hazard maps, and not the geomorphological maps themselves. It would also require too much time to train the three groups in mapping the same way, and it might be disadvantageous for the independent mapping by the three teams.

The teams were instructed that they should pay special attention to the landslide inventory mapping. For landslide classification, a slightly modified version of the "UNESCO Working Party for World Landslide Inventory" classification was used (Krauter, 1993). For each landslide a description is made of the following items: *type, style, activity, movement, development, depth, and individual landslide features (scarp and accumulation area).* The geomorphological maps were generated after extensive airphoto-interpretation and fieldwork.

6.2. DIRECT HAZARD MAPPING

This was the main target of the project: the production of direct hazard maps, with accompanying tables containing the rules for the hazard classification. The three teams made the hazard maps after the preparation of the geomorphological base maps.

Unlike the geomorphological mapping, a fixed method was used for the preparation of the hazard map, consisting of the following steps:

1. Delineation of homogenous geomorphological units based on the geomorphological map, and drawing of these units as polygons on a separate overlay map;
2. Digitizing of the homogeneous unit polygons, and the assignment of a unique identifier value to each one of them;
3. Definition of the hazard class for each polygon, which was stored as an attribute in a table related to the digitized map;
4. Definition of the rules used to classify each polygon. These rules are also stored as attributes in a table.

With respect to the definition of the classes for the hazard map, it was decided that the hazard map would be aimed for use in municipal planning. This means that only the hazards were evaluated that are relevant for the construction of small engineering works such as local roads, houses, and other buildings, which require relatively small excavations. The same map cannot be used for evaluating the hazards related to large engineering works, such as highways, railroads, tunnels etc. In that case the hazard will depend a lot upon the specific design criteria (cut slopes, fills etc.), and a large amount of additional information would be required (geotechnical properties of the materials, hydrological information etc.).

The legend was kept simple, using only three classes (high, moderate, and low). Other information, regarding the type of landslides, and whether landslides are confirmed, inferred or suspected were written in the list of criteria.

The following definitions of the hazard classes were used:

- *Low hazard.* In these areas no destructive phenomena (landslides, rockfall, inundation, etc.) are expected to occur within the coming years, given that the land use situation remains the same. Inadequate construction of infrastructure or buildings may lead to problems, however.

- *Moderate hazard*. In these areas there is a moderate probability that destructive phenomena will occur within the coming years, that may damage infrastructure or buildings. However, the damage is expected to be localized and can be prevented or evaded by relatively simple and inexpensive stabilization measures.
- *High hazard*. In these areas there is a high probability that destructive phenomena will occur within the coming years. These are expected to damage infrastructure or buildings considerably. It is advised not to construct new infrastructure or buildings, or at least only after detailed study.

In the hazard map the existing quarries (rock-quarries and gravel pits) were excluded from the analysis, and entered as a separate legend unit, since the hazard degree is related to the quarrying activities.

7. Results

Results from the three teams can be summarized as follows:

7.1. METHOD FOLLOWED BY THE ITC TEAM

The hazard map produced by the ITC team was constructed with the so-called "direct hazard mapping" method (Van Westen, 1993). First a detailed airphoto-interpretation was performed with four sets of airphotos from 1954 to 1980, having scales ranging from 1 : 10,000 to 1 : 30,000. A detailed fieldcheck was made and the resulting geomorphological units were drawn on 1 : 5,000 scale topographical maps. Two different layers of geomorphological information were prepared:

- Main geomorphological units, consisting of 425 different polygons in 52 legend classes, which show information on the genesis and material types, and
- Geomorphological sub-units, which are subdivisions of the geomorphological units, consisting of 1774 different polygons in 81 legend classes, which contain detailed descriptions on each slope segment.

Based on these layers of information a separate hazard map was prepared, consisting of 55 polygons classified as low, 92 as moderate and 23 as high hazard. For each hazard polygon the deciding factors for the hazard classification were recorded in a database. For about 90% of the hazard polygons, the geomorphological information, contained in the main- and sub-unit layers were sufficient for providing these decision criteria. Besides of the hazard class, also the type of hazard was entered (small rockfall, large rockfall, landslides, flowslides, flows, erosion, flooding and snow avalanches). The hazard map was digitized in a GIS (ILWIS), together with the main-unit and sub-unit map, the infrastructure, the land use, and the contour information. From the contour lines a Digital Elevation Model was generated. The final digital hazard map allows a user to read for each polygon the deciding factors from the database. Also a paper version of the hazard map was made with the help of a cartographic package (ACE). A fragment of this map is presented in Figure 4, showing the various layers of which the map is composed. Figure 5 shows the resulting hazard map of the ITC team.

7.2. METHOD FOLLOWED BY THE TEAM FROM THE UNIVERSITY OF AMSTERDAM (UVA)

Traditionally, the Alpine Geomorphology Research Group of the University of Amsterdam has been active in constructing large scale colored geomorphological maps, based on line and point symbols (De Graaff *et al.*, 1987, Seijmonsbergen and Van Westen, 1988, Seijmonsbergen, 1992). The use of transparent overlay maps containing information on natural hazards, in combination with the original geomorphological data, has successfully been applied in a number of case studies with local authorities in Austria, Switzerland and Liechtenstein. Since most paper printed geomorphological maps at scales of 1 : 500–1 : 50,000 are not polygon based and cannot be linked to a relational database directly, a new key legend was developed and tested in the Alpago-Basin area.

The following steps were taken by the team from the University of Amsterdam to construct the geomorphological hazard map:

1. Mapping at scale 1 : 5,000 using the traditional symbol and line-based legend. This manually constructed geomorphological map provides information on the geometry, morphography, hydrography, materials, direction of transport, processes, and genesis of the landforms by using lines, symbols, hatchings, and colors. Air-photo interpretation plays a crucial role in the understanding and recognition of landslides and other morphological features, in the pre-field stage and during the field stage. A fragment of the geomorphological map is shown in Figure 4(E).
2. Delineation of terrain mapping units (TMU's), homogeneous units in the sense of materials, geology, geomorphology and process type. This resulted in approximately 1300 individual polygons, each having a unique combination of geometry, material, process type (direction and intensity) and genesis (including age relationships). This map was digitized. A legend was defined, to convert as much basic geomorphological information as possible to the digital map (database). This resulted in 7 tables, containing information on the geomorphological environment, geomorphological subenvironment and landunits, semi-elementary landforms, superimposed process or conditions, quaternary materials, interpreted geomorphological forms and units, or complexes of form and units, and the hazard degree. The location, type and relative activity of processes can be read from the geomorphological map (both the paper version and the digital version with related tables). Additional minor observations

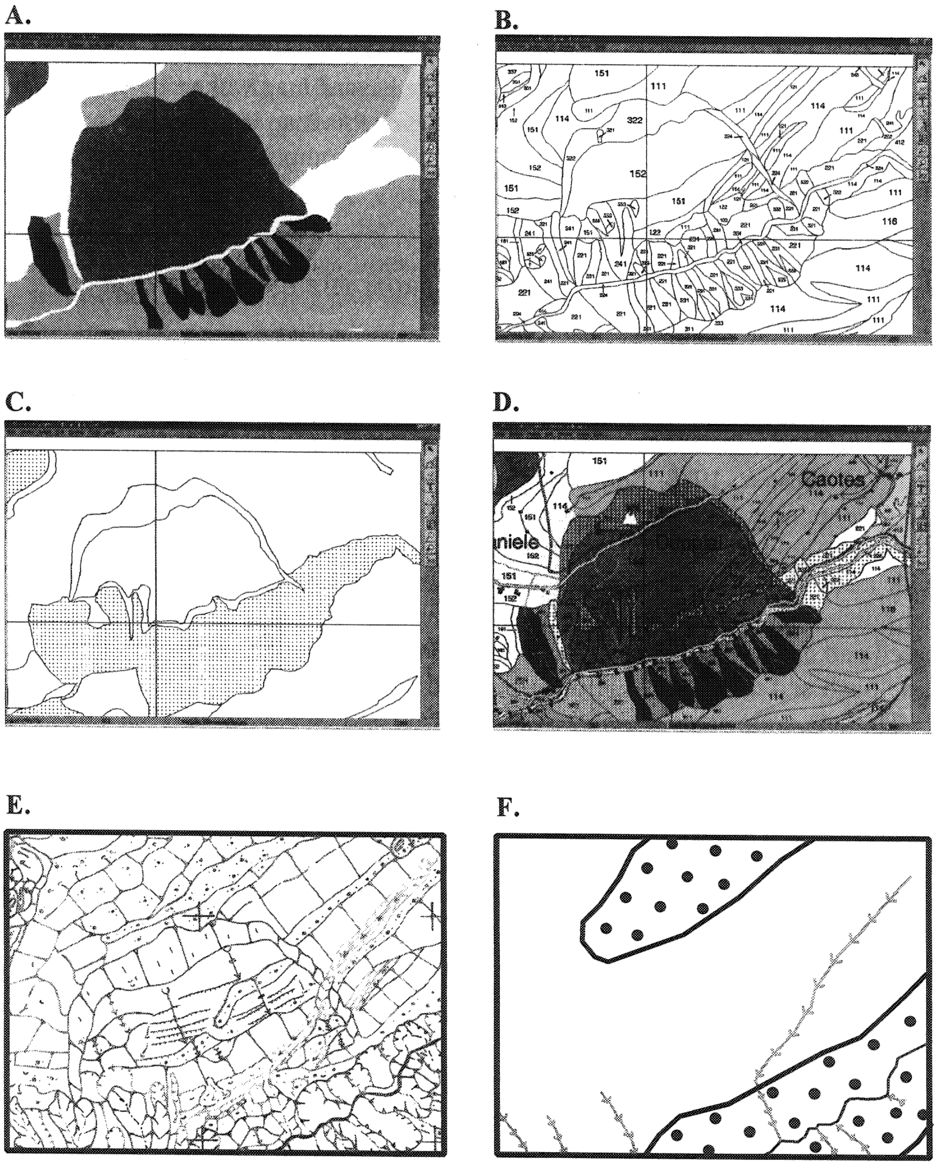

Figure 4. Small fragment of the geomorphological maps of the same area produced by the three teams. A: Main geomorphological units from the map by the ITC team, shown in the map as colored areas; B:. Geomorphological subunits from the map by the ITC team, indicated by a code; C: Hazard classification from the map by the ITC team, indicated by a hatching; D: Combination of all layers of the map by the ITC team; E: Fragment of the geomorphological map of the UVA team; F: Fragment of the geomorphological map of the UNIFE team.

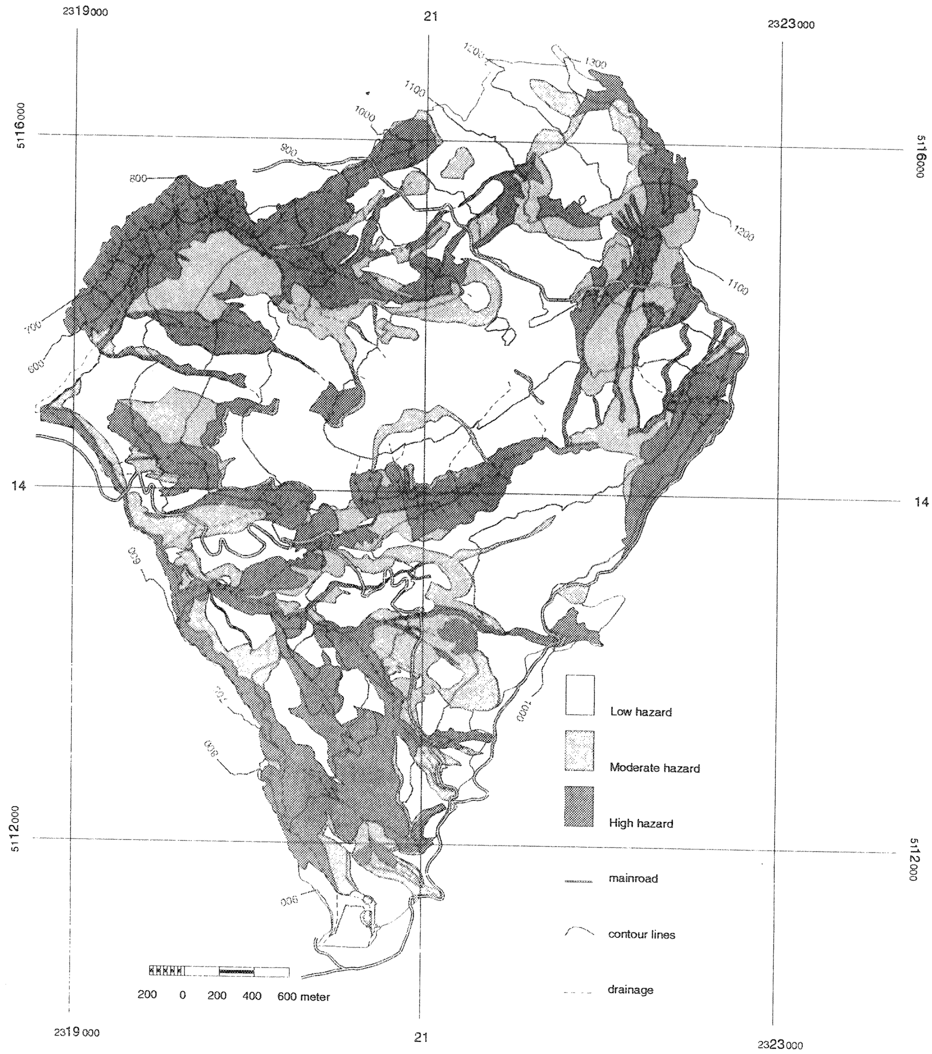

Figure 5. The hazard map produced by the ITC team.

are necessary in the field (freshness of rupture surfaces, vegetation cover and others) to decide on the hazard class.

It is stressed that the geomorphological mapping and evaluation method of the University of Amsterdam has been designed for multipurpose functionality. In this applied case study the geomorphological hazards were highlighted. Other tables can be added, depending on the required end product; the recognition of TMU's will not be different. Starting point remains the original geomorphological line-symbol map from which manually stored cartographic geo-information of the

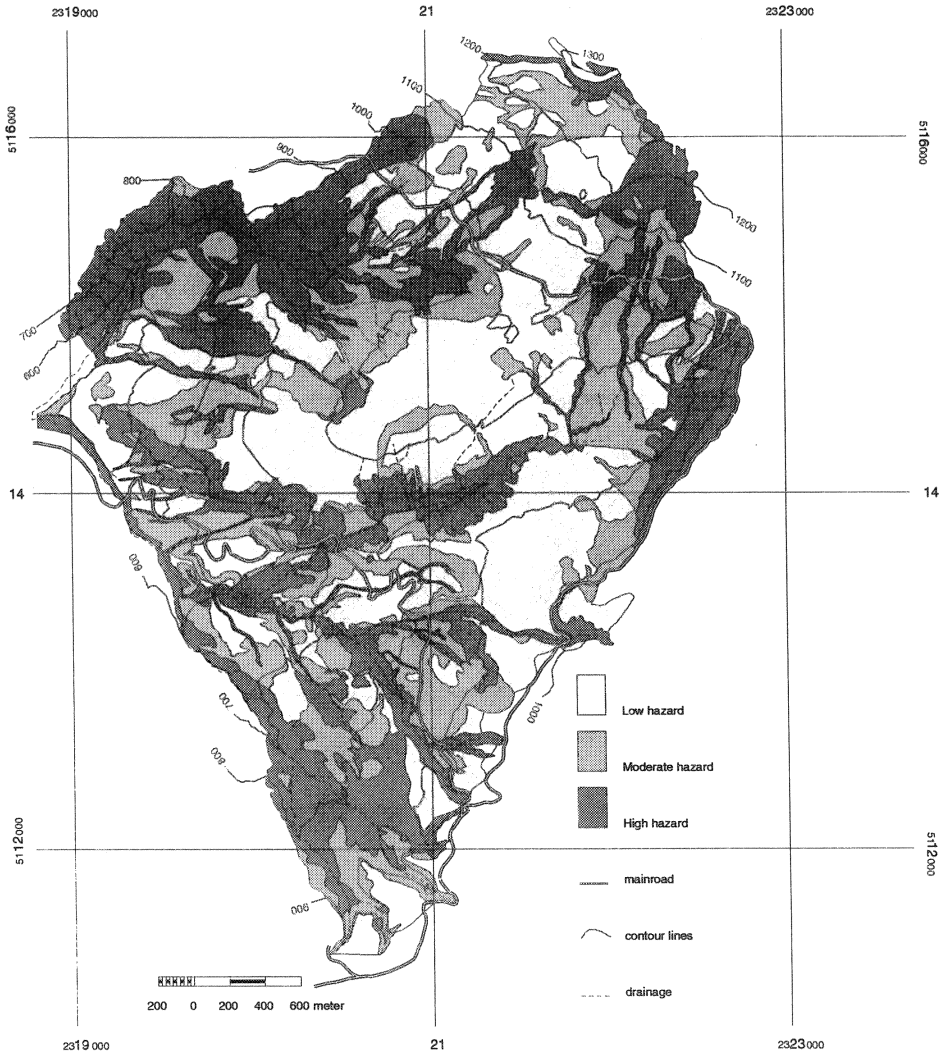

Figure 6. The hazard map produced by the team form the University of Amsterdam (UVA).

geomorphological expert is converted into a digital geomorphological GIS database. The resulting hazard map of the University of Amsterdam (see Figure 6) contained 52 polygons with low, 105 with moderate and 15 with high hazard.

7.3. METHOD FOLLOWED BY THE TEAM FROM THE UNIVERSITY OF FERRARA (UNIFE)

The Ferrara University team produced three maps of the study area:

- A geomorphological map according the method of Panizza (1973). The map contains information on the lithology for the rock outcrops as well as some structural information (dip direction). Surficial deposits are mapped, using different symbols and colors that represent the morphological process by which they were produced. Colors are also used to differentiate active or inactive landslides and scree slopes. Landslides are subdivided in slide, flow and creep processes. Gully and river erosion, as well as escarpments (of valleys, terraces and landslides) are indicated with line symbols. A fragment of the geomorphological map is shown in Figure 4(F).
- A landslide inventory map, in which a total of 20 individual mass movements were mapped, some of which consisted of several units. This map was digitized. Landslide attributes (such as type, subtype, activity etc) were stored in an attribute table linked to the map. The preparation of a separate landslide inventory map is not a standard procedure in the method of the team of Ferrara University, and was tried here for the first time.
- A landslide hazard map (see Figure 7), consisting of 14 polygons with low, 14 with moderate and 11 with high hazard. It is important to note here that the team from the University of Ferrara only considered the hazard related to landslides proper, and did not include the hazard due to other processes (inundation, erosion, rockfall etc.).

8. Comparison between the Hazard Maps made by the Three Teams

The three hazard maps prepared by the teams from ITC, UVA and UNIFE are presented in Figure 5, 6 and 7. The three digital maps were combined in a GIS to evaluate their similarity. First the three maps were compared pair-wise. The results are shown in Tables I, II, and III.

When the hazard maps made by the teams from the University of Amsterdam (UVA) and ITC are compared (see Table I) it can be concluded that both maps have a remarkable similarity. The visual comparison of both maps (Figure 5 and 6) reveals that the overall pattern of hazard classes is almost identical, and that there are differences in classification only in details. The map of the University of Amsterdam shows a slightly higher detail than the one from ITC. The areas mapped as low (ITC: 45% of the study area versus UVA: 37%), moderate (ITC: 23% versus UVA: 28%) and high (ITC: 32% versus UVA: 35%) are in the same order of magnitude.

The two teams mapped 75% of the area (33.31 + 14.61 + 27.22) exactly the same. An important indication of the similarity is also that the areas that are mapped completely different (e.g., high by one group and low by the other or vice versa) are very small (1.08 + 2.50 = 3.58% of the entire study area). More difference exists between the areas classified as having a moderate hazard. This is mostly due to small differences in the interpretation of the possible future

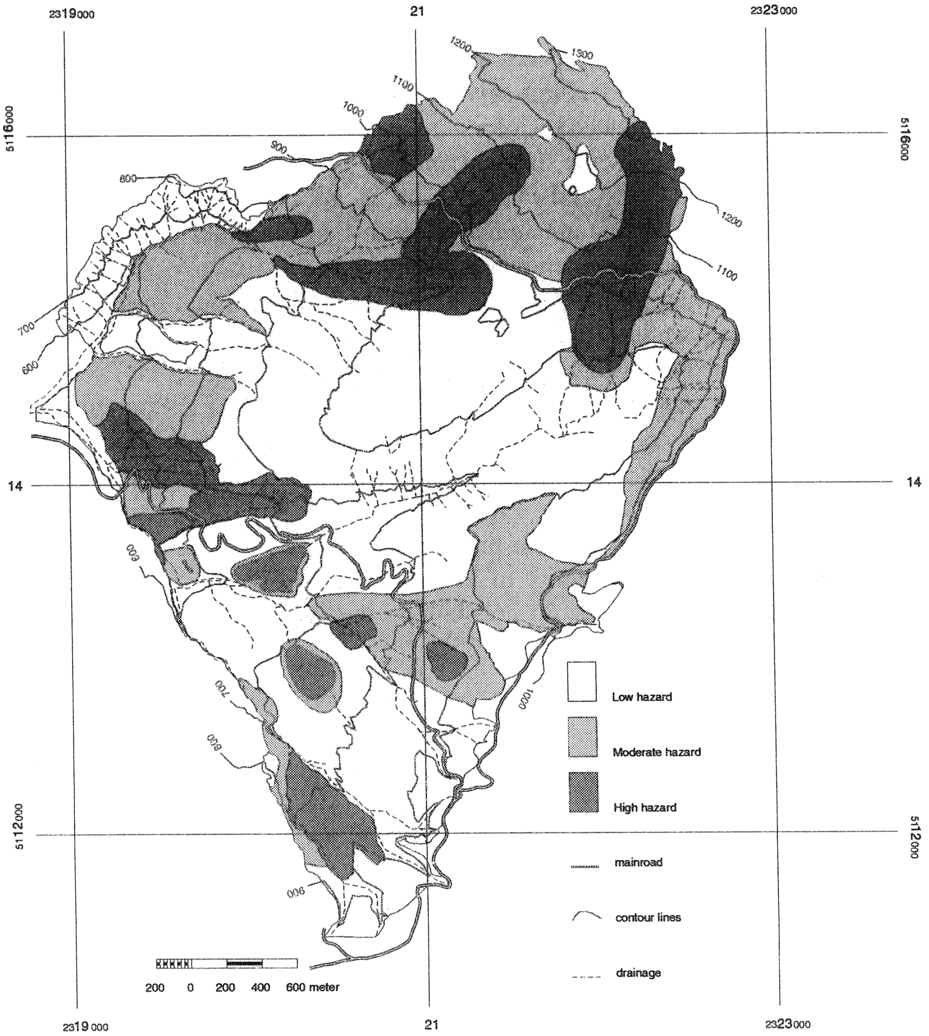

Figure 7. The hazard map produced by the team of the University of Ferrara (UNIFE).

Table I. Comparison between the hazard maps from the University of Amsterdam (columns) and ITC (rows). The values indicate the percentage of the total study area

	Low	Moderate	High	
Low	**33.31%**	**9.47%**	**2.50%**	**45.28%**
Moderate	**2.48%**	**14.61%**	**5.71%**	**22.80%**
High	**1.08%**	**3.62%**	**27.22%**	**31.92%**
	36.87%	**27.70%**	**35.43%**	**100%**

Table II. Comparison between the hazard maps from the University of Ferrara (columns) and ITC (rows). The values indicate the percentage of the total study area

	Low	Moderate	High	
Low	**28.18%**	**14.49%**	**2.61%**	**45.28%**
Moderate	**8.35%**	**8.90%**	**5.55%**	**22.80%**
High	**13.48%**	**9.03%**	**9.41%**	**31.92%**
	50.01%	**32.42%**	**17.57%**	**100%**

Table III. Comparison between the hazard maps from the University of Ferrara (columns) and the University of Amsterdam (rows). The values indicate the percentage of the total study area

	Low	Moderate	High	
Low	**23.13%**	**12.03%**	**1.71%**	**36.87%**
Moderate	**12.36%**	**9.52%**	**5.81%**	**27.69%**
High	**14.52%**	**10.86%**	**10.06%**	**35.44%**
	50.01%	**32.41%**	**17.58%**	**100%**

activity of landslides that are currently inactive. Both maps are based on detailed geomorphological base maps.

The comparison of the hazard maps of UVA and ITC with the one from the University of Ferrara (UNIFE) shows a very different situation. As can be seen from Figure 7 the overall pattern of hazard classes in the UNIFE map is less detailed, and contains larger units.

What is especially striking is the large difference in detail of this map. The final hazard map prepared by the ITC team contains 511 different polygons, and the one from the UVA team 1278, whereas the hazard map from the UNIFE team only contains 39 polygons. As can be seen from tables II and III the level of agreement between the map prepared by the UNIFE team and the other two is low. Agreement exists for only 46.48 percent of the area in comparison with the map from ITC (28.18 + 8.90 + 9.41) and for 42.71 percent with the one from the University of Amsterdam (23.13 + 9.52 +10.06). There is strong disagreement especially when the area mapped as low hazard is compared with the area mapped as high by the other two teams (13.48% and 14.51%).

The differences can be evaluated better if all three maps are compared at the same time (see Figure 8 and Table IV).

Table IV. Comparison between the overlap of the hazard classification of the teams of ITC, the University of Amsterdam (UVA) and the University of Ferrara (UNIFE). All values indicated refer to the percentage of the commonly mapped area

ITC	UVA	UNIFE	Percentage	Total
All three teams agree				
Low	Low	Low	21.60	34.92
Moderate	Moderate	Moderate	5.26	
High	High	High	8.06	
Only ITC and UVA agree				
Low	Low	Moderate	10.36	40.22
Low	Low	High	1.35	
Moderate	Moderate	Low	5.54	
Moderate	Moderate	High	3.81	
High	High	Low	11.68	
High	High	Moderate	7.48	
Only ITC and UNIFE agree				
Low	Moderate	Low	5.44	11.57
Low	High	Low	1.14	
Moderate	Low	Moderate	1.16	
Moderate	High	Moderate	2.48	
High	Low	High	0.15	
High	Moderate	High	1.20	
Only UVA and UNIFE agree				
Low	Moderate	Moderate	3.23	7.80
Low	High	High	0.47	
Moderate	Low	Low	1.11	
Moderate	High	High	1.53	
High	Low	Low	0.42	
High	Moderate	Moderate	1.04	
All three teams disagree				
Low	Moderate	High	0.80	5.50
Low	High	Moderate	0.90	
Moderate	Low	High	0.21	
Moderate	High	Low	1.70	
High	Low	Moderate	0.51	
High	Moderate	Low	1.38	
			100.00	100.00

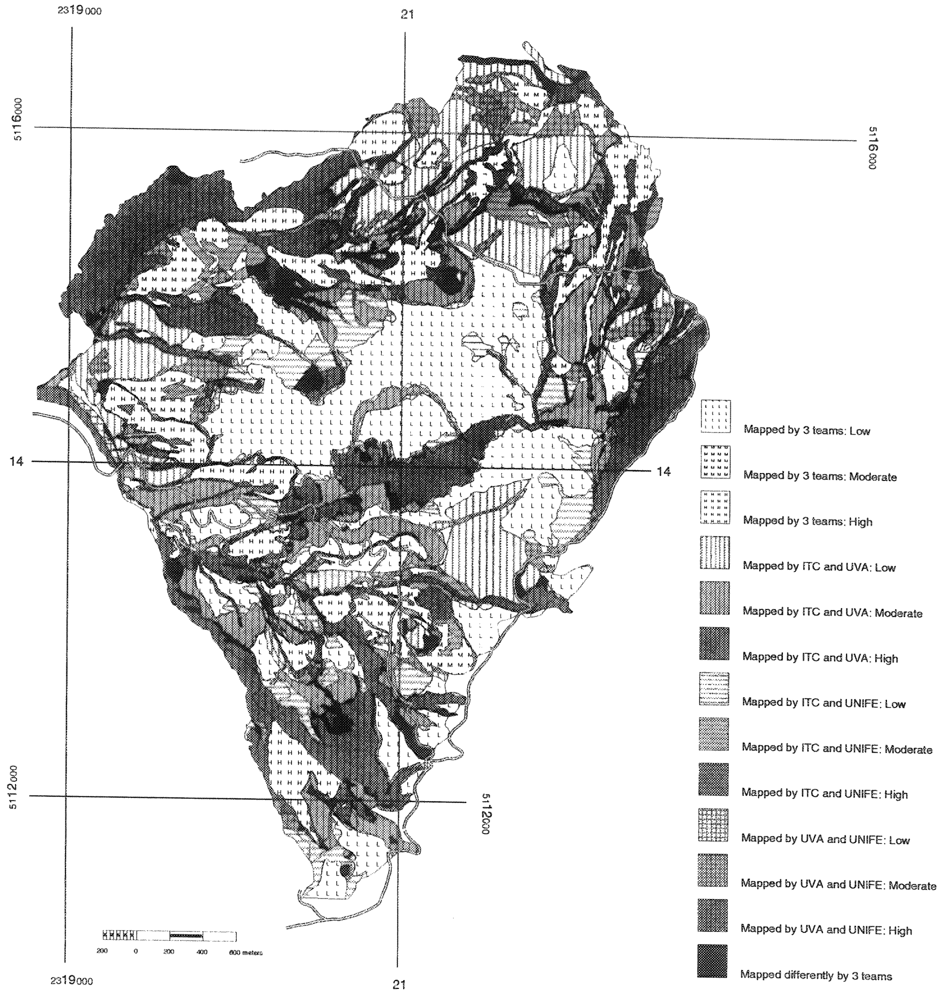

Figure 8. Comparison between the three hazard maps.

The area mapped equally by all three teams is only about one third of the study area (34.92%). Another 40.22 percent of the area is mapped similarly by the teams from ITC and UVA, but differently by UNIFE. A large part of this is formed by areas mapped as high by ITC and UVA, but as low by UNIFE (11.57 percent). An example of this can be seen in the NW of the study area, where an area consisting of near vertical cliffs is classified as low by the UNIFE team and high by the others. The same is true along the main valleys of the areas. This is partly caused by the fact that the UNIFE team only considered the hazard for landslides, excluding the hazard for other mass movement processes, gully and stream erosion and inundation.

Also the landslide occurrence maps prepared by the three teams show the same degree of difference: the ITC and UVA teams mapped approximately 150 different landslides in the area, whereas the UNIFE team mapped only 20. Although the UNIFE team mapped fewer landslides, the sizes of the individual landslides that were mapped are generally larger than the ones mapped by the other teams.

Apart from the fact that the UNIFE team prepared only a hazard map for landslides (excluding other processes) and was less familiar with the mapping method than the other two teams, a large part of the difference in hazard mapping can be contributed to different opinions concerning the geomorphological evolution of the study area.

The large pre-glacial landslide in the NE of the study area (Pian Formosa, see Figure 2), mapped by the ITC and UVA teams, was interpreted as morainic deposits by the UNIFE team. The UNIFE team also disagreed with the other two on the existence of two large landslides around San Daniela. Both the ITC and UVA teams mapped the area N of San Daniela as a very large and complex dipslope failure, which shows different phases of reactivation. The older part of the landslide had only a small displacement, with a scarp of less than 10 meters, in ice-marginal levels. This part of the landslide is currently inactive. Further downslope parts of this old landslide were reactivated several times during later periods, as can be seen from a series of scarps. Consequently, the hazard maps of ITC and UVA only indicate the most recent reactivations as having a high hazard. Other parts are mapped as moderate, or even as low in the oldest parts of the landslide, where no reactivation is expected anymore.

Another area of disagreement is a large rotational landslide near Duppiai (see Figure 2). Only the ITC and UVA teams recognized this as a landslide, and observed a series of morainic ridges from the local Borsoia glacier, that were displaced from a few meters to several tens of meters along the eastern side scarp of the landslide. The slope also shows a clear bulging, and due to the forward movement of the landslide, the opposite valley slope has experienced heavy erosion.

However, the UNIFE team also disagreed on more recent and active landslides in the areas W of Lavina, Pianon and Civit.

After the preparation of the hazard maps, the three teams met again to discuss the differences of opinion. During a short field visit at the end of the project, the area was revisited together, but unfortunately some of the differences in opinion could not be resolved in the short time available.

9. Conclusions

A common method for evaluating the accuracy of landslide hazard maps is to compare these with the existing landslide occurrence map and calculate the percentage of landslides within each hazard class (Carrara *et al.*, 1990, 1991; Gee, 1992). However, the landslide occurrence maps themselves may contain a large degree of uncertainty. It has been recognized in literature that creation of landslide occurrence maps contain a large subjective element (Fookes *et al.*, 1991; Carrara, 1992; Carrara *et al.*, 1992; Van Westen, 1993).

Another way of assessing the reliability of hazard maps that was attempted in this study was the comparison of hazard maps of the same area made independently by different teams. It has proven to be a rather difficult exercise, given the differences in background, knowledge of the area and time allocated to do the mapping.

Given the situation that two of the three hazard maps are almost identical and one map differs greatly, it can be concluded that landslide occurrence maps, and landslide hazard maps can be very different when made by different teams. In fact they can be so different, that an objective reader may ask himself whether they are from the same area.

This may not lead to the conclusion, however, that landslide hazard maps are unreliable. Two of the maps prepared for this study showed a remarkable agreement, with 75 percent mapped equally and only 3.5 percent mapped completely different.

A comprehensive understanding of the geomorphological evolution of an area, combined with a thorough and detailed mapping by expert geomorphologists is essential in order to derive at a reliable hazard map.

The degree of difference in the geomorphological maps of the three teams will not only affect the result in a direct hazard mapping method. When the landslide occurrence maps from the three teams, with the differences discussed earlier, would have been used as input maps in a statistical analysis, this would have resulted in equally different indirect hazard maps. Currently research is being carried out to compare landslide hazard maps prepared by statistical methods, with maps made by direct hazard mapping, and the effect of different input maps on the result.

Whether it is decided to use a direct or indirect method, the geomorphological expertise of the person collecting the data is crucial. In the training of earth-scientists to become landslide hazard experts, the geomorphological interpretation of aerial photos and field data collection should be given high priority.

References

Carrara, A.: 1988, *Multivariate Models for Landslide Hazard Evaluation. A "Black Box" Approach*, Workshop on Natural Disasters in European Mediterranean Countries, Perugia, Italy, pp. 205–224.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., and Reichenbach, P.: 1990, *Geographical Information Systems and Multivariate Models in Landslide Hazard Evaluation*, ALPS 90 Alpine Landslide Practical Seminar, 6th International Conference and Field Workshop on Landslides, Aug. 31–Sept. 12, 1990, Milano, Italy, pp. 17–28.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., and Reichenbach, P.: 1991, GIS techniques and statistical models in evaluating landslide hazard, *Earth Surface Processes and Landforms* **16**(5), 427–445.

Carrara, A., Cardinali, M., and Guzzetti, F.: 1992, Uncertainty in assessing landslide hazard and risk, *ITC-Journal* **1992**(2), 172–183.

Carrara, A.: 1992, *Landslide Hazard Assessment*, Proc. 1er Simposio Internacional sobre Sensores Remotos y Sistemas de Informacion Geografica (SIG) para el estudio de Riesgos Naturales, Bogotá, Colombia, pp. 329–355.

Chung, C. J., Fabbri, A., and Van Westen, C. J.: 1995, Multivariate regression analysis for landslide hazard zonation, In: A. Carrara and F. Guzetti (eds), *Geographical Information Systems in Assessing Natural Hazards*, Kluwer Academic Publishers, pp. 107–133.

Demek, J. and Embleton, C. (eds): 1978, *Guide to Medium-Scale Geomorphological Mapping*. IGU Commission on Geomorphological Survey and Mapping, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany.

De Graaff, L. W. S., de Jong, M. G. G., Rupke, J., and Verhofstad, J.: 1987, A geomorphological mapping system at scale 1 : 10,000 for mountainous areas, *Zeitschrift für Geomorphologie, N.F.* **31**(2), 229–242.

Fookes, P. G., Dale, S. G., and Land, J. M.: 1991, Some observations on a comparitive aerial photography interpretation of a landslipped area, *Quarterly Journal of Engineering Geology* **24**, 249–265

Gee, M. D.: 1992, *Classification of Landslide Hazard Zonation Methods and a Test of Predictive Capability*, Vol. 2, Proc. 6th International Symposium on Landslides, Christchurch, New Zealand, pp. 947–952.

Hansen, A.: 1984, Landslide hazard analysis, In: D. Brunsden and D. B. Prior (eds), *Slope Instability*, Wiley & Sons, New York, pp. 523–602.

Krauter, E. (ed.): 1993, *The Multilingual Landslide Glossary*, International Geotechnical Societies' UNESCO Working Party for World landslide Inventory.

Mantovani, F., Panizza, M., Semenza E., and Piacente, S.: 1976, L'Alpago (Prealpi Bellunesi), Geologia, Geomorfologia, Nivopluviometria, *Boll. Soc. Geol. It.* **95**, 1589–1656.

Panizza M.: 1973, Proposta di legenda per carte della stabilita geomorfologica, *Boll. Soc. Geol. It* **92**, 303–306.

Seijmonsbergen, A. C. and Van Westen, C. J.: 1988, *Geomorphological-, Geotechnical- and Natural Hazard Maps of the Hintere Bregenzerwald Area (Vorarlberg, Austria) Set of 12 Maps + Overlays + Explanation*, Gebr. Borntraeger, Stutgart, Germany.

Seijmonsbergen, A. C.: 1992, *Geomorphological Evolution of an Alpine Area and its Application to Geotechnical and Natural Hazard Appraisal*, PhD Dissertation, University of Amsterdam.

Van Westen, C. J.: 1993, *Application of Geographic Information Systems to Landslide Hazard Zonation*, PhD Dissertation, Technical University Delft, ITC-Publication Number 15, ITC, Enschede, The Netherlands.