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IRASMOS

Integral Risk Management of Extremely Rapid Mass Movements

Specific Targeted Research Project

Priority VI: Sustainable Development, Global Change and Ecosystems

D1.3 – State-of-the-art review of methods and technologies for modelling and forecasting extremely rapid mass movements

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SIXTH FRAMEWORK PROGRAMME
PRIORITY VI
Sustainable Development, Global Change and Ecosystems

SPECIFIC TARGETED RESEARCH PROJECT

irasmos

INTEGRAL RISK MANAGEMENT OF EXTREMELY RAPID MASS MOVEMENTS

WORK PACKAGE 1:
FROM CAUSES TO FORECASTING

DELIVERABLE D1.3

State of the art of prediction techniques

Edited by:
RICCARDO RIGON (CUDAM, WP1 LEADER)

Contributions by:

L.H. BLIKRA, F. SANDERSEN, V. KVELDSVIK (NGI)
O. KORUP (WSL)

Reviewed by:
....

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	LIST OF TABLES
Table 1	Morphologic, vegetation and drainage features charactersitic of debris avalanches and debris flows, and their photographic characteristic. [Jakob and Hungr 2005]
Table 2	Sources of information on spatial landslide distribution and inventories for different regions of the world [Glade & Crozier]
Table 3	Sources of information on spatial landslide susceptibility and hazard for different regions of the world [Glade & Crozier]
Table 4	Selection of spatial susceptibility and hazard analysis of debris flow for different region of the world [Glade & Crozier]
Tabe 5	Previous projects on debris-flow and landslides financed by EU
Table 6	Local consequence on road, lives areas and off-track activities
Table 7	Telephone-fax number in the Alps
Table 8	from, B. Zenke : « 20 Jahre Arbeitsgruppe dereuropäischen Lawinenwarndienste »
Table 9	(“Unofficial” English translation of the Avalanche Danger Scale.)
Table 10	Climate data for some locations in Norway; base period 1961-1990 (temperatures are 24-hour average):
Table 11	Overview over the national avalanche warning service
Table 12	Overview over the regional avalanche warning in northern Norway
Table 13	Overview for nowcasting porcedure
Table 14	Overview for forecasting porcedure
Table 15	Danger scale and possible actions concerning traffic and maintenance.
Table 16	Overview over the avalanche warning at national highway 15
Table 17	Overview over the avalanche warning at the Bergen railway
Table 18	Overview over the Easter holiday warning program
Table 19	Overview over the avalanche warning for NATO winter exercises
Table 20	Overview over the ski area warning services

Chapter 1

DEBRIS FLOWS (AND SHALLOW LANDSLIDES)

1.1 Purpose and limits of predictability of debris flow and landslide triggering

Introduction	The prediction of debris flow and landslide triggering concerns the localization in time (i.e. when they occur) and space (i.e where they occur) of the instabilities of a hillslope and a quantification on the total mass (i.e. how much) of sediment that can be moved. Failure estimation can be even given in qualitative terms like 'low', 'medium' and 'high' probability of an occurrence but a quantitative form is preferable. The current knowledge of the processes and the intrinsic heterogeneity of the natural systems involved allows only a relative precision of a prediction either in time or in space. Among the modeling approaches detailed in deliverable 1.2, some allow for the identification of areas where instabilities can occur in a time span of an unspecified duration. On the contrary, other techniques identify the rainfall event type (in term of mean intensity and duration) that generates instabilities, but confined in quite wide areas. The task of the modeler/forecaster is to minimize the time and space uncertainties. Sophisticated methods (as numerical distributed modeling) claim to predict both the timing and the location but actually they rely on parameters of difficult characterization, and their quantitative assessments require Bayesian-like estimates, i.e. 'subjective estimates' that cannot be tested. This fact introduces, even in these models, predictability uncertainties that should be (but seldom are) quantified. According to deliverables 1.1 and 1.2 the methods used to “predict” debris flow and landslide triggering can be grouped in four broad categories: 1 – Susceptibility maps (statistical models) 2 – Rainfall based methods 3 – Distributed models with stationary subsurface hydrology (simplified distributed

	physically based models with stationary hydrological subsurface fluxes) 4 – Real time distributed models (distributed physically based models with transient infiltration and hydrological subsurface fluxes) These methods are briefly summarized below in addition to landslide inventories. Essentially all techniques used at scales beyond local investigations (and presented below) incorporate a landslide inventory map developed by surface mapping of existing slides.
Inferential methods *(Landslide inventories)*	Landslide and debris forecasting methods are assessed on the basis of landslide inventories which shows the spatial distribution of mass movements (Wieczorek, 1984). Methods of landslide mapping have changed little, in principle, over the past few decades when newer data sources are used. Landslides are routinely detected and mapped by a combination of interpretation of airphotos or multispectral digital imagery and selective ground verification (Roering and McKean, 2004), often based on "professional judgement" (Wieckzorek, 1984). Of particular importance are however the records events which detected changes to the terrain surface that can be recognized as landslides or debris flow according to the phenomenology presented in WP 1.1. After the event, terrain movements are recognized in the field from geomorphic features (Varnes, 1984), like *Creeps, *Scars, *Levees, *Transportation tracks, *Deposits with sediment pertaining to upslope areas, *Other characteristics landforms as, for instance, in Benda, 1990, Miller and Benda 20000, Wohl and Pearthree, 1991, and by * Springs, seeps, or saturated ground in areas that have not typically been wet before; * Absence of vegetation or young vegetation or vegetation displaced or tilted; * New cracks or unusual bulges in the ground, street pavements or sidewalks; * Soil moving away from foundations; * Ancillary structures such as decks and patios tilting and/or moving relative to the main house; * Tilting or cracking of concrete floors and foundations * Broken water lines and other underground utilities * Leaning telephone poles, trees, retaining walls or fences * Offset fence lines * Sunken or down-dropped road beds * Sudden decrease in creek water levels though rain is still falling or just recently stopped. * Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb Inventories from field surveys can reasonably include only relatively small areas, yielding landslide counts that may vary substantially from site to site [Robison et al., 1999]. In contrast, inventories from aerial photographs may include a larger area to discern regional trends in the relative density of landslides between forest cover classes. Recently, to overcome the subjective recognition techniques, quantitative methods of landslide classification and change detection were developed [e.g. McKean and Roering, 2004; Miller and Burnett, 2007, Tarantino et al, 2004]. However, often inventories are assimilated into models models of landslide susceptibility (or hillslope stability), which in turn aims to produce new improved inventories. Landslide and debris flow inventories share with the methods for creating susceptibility maps the techniques of analysis presented in ***Figure 1***.

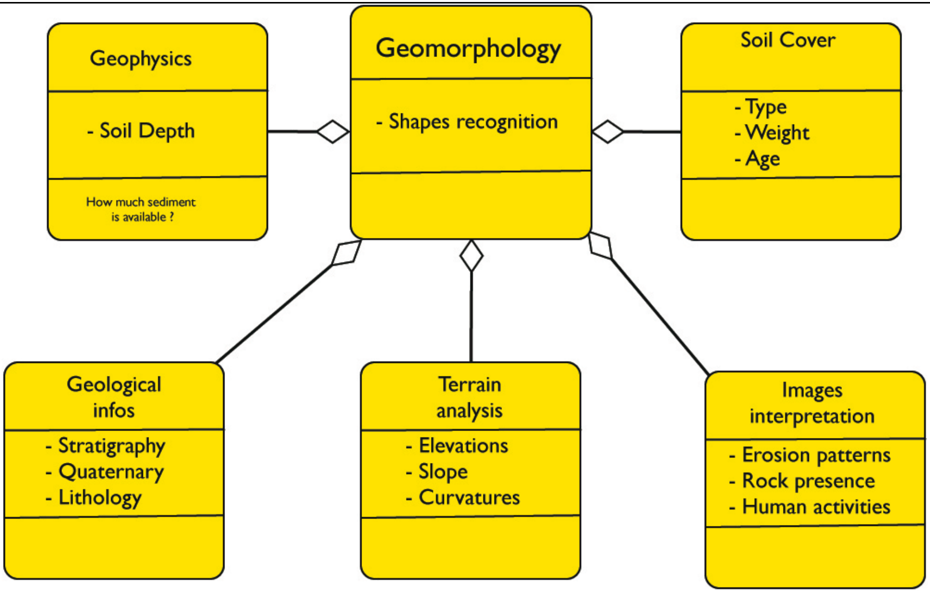
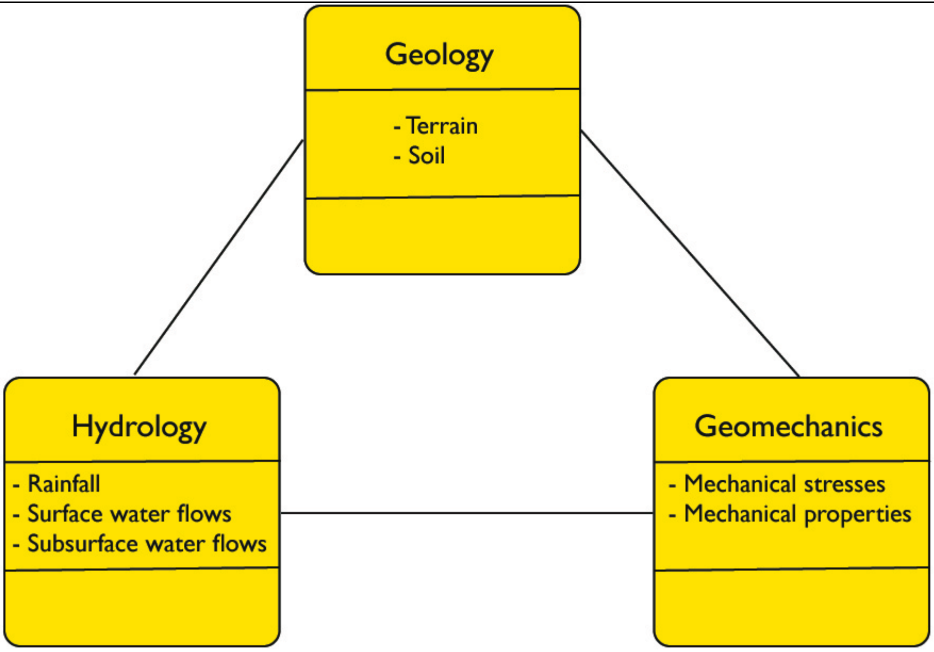
	Eventually the production of geomorphic mapping can be coded in several ways. As an example, a large German scientific project provided on standardising geomorphologic mapping (Leser and Stablein, 1975). This legend key has been adapted to mountain areas by Leser and Schaub (1987) and Kneisel et al. (1998). Within the Icelandic project, specific attributes for landslides have been additionally adopted from the UN working group on the World Landslide Inventory (WLI) and specifically for debris-flow mapping from Gartner (1996) and Holl (1996).
Figure 1 Traditional components of geomorphological analysis besides field survey (attributes are incomplete for space reasons) .	
Temporal and spatial scope of prediction methods	According to the cause of triggering identified in deliverable 1.1 and the modelling classification presented in deliverable 1.2, three broad disciplines interact in giving the predicting debris flows and soil slips: hydrology, geology and soil/terrain mechanics, as presented in ***Figure 1*** above. Geomorphological analysis, in which we include the classical geologic analysis, traditionally regards the components presented in ***Figure 2***. In a geomorphological analysis, not all the components of ***Figure 2*** needs to be present. Shapes recognition, and change detection on the filed or by photo interpretation are the basic components. In addition, current analysis always uses Digital Elevation Models (DEMs).

Figure 2 Information used by prediction methods	
Temporal and spatial scope of prediction methods	<u>Susceptibility Maps</u> The geological/geomorphologic analysis above can be used to produce susceptibility maps, i.e. identification of areas where landslides occurred or (implicitly according to James Hutton's uniformitarianism) areas prone to landslide (with no timing specification). Rainfall data, suitably aggregated, are used to achieve the scope, in addition to geological/geomorphologic analysis. Usually qualitative observations of instability are coupled with multivariate statistical analyses of factors which are assumed to influence instability. This makes the analysis more rigorous (e.g.Coe et al, 2004; Guzzetti et al., 1999; Carrara et al., 1999; Cannon et al., 2004). For this type of techniques, prediction assumes a fuzzy meaning, since no specification of the time of occurrence is usually made; however the related knowledge is useful in several applicative contexts. This approach neglects information from hydrology and quantitative soil mechanics. Despite for the spatial analysis it is possible to produce a reference inventory of all observable landslide morphologies occurring in the study area, for the temporal analysis a monitoring of events with the adequate time resolution has to be carried out: for each landslide or debris flow, in order to establish a quantitative relation, it's necessary to know date and time of occurrence and triggering parameters. <u>Rainfall intensity based methods</u> A different point of view is given when only rainfall and landslide-debris flow inventories. In this case, the user tries to build limit curve in the plane of intensity/duration-of-rainfall plane. This approach usually neglects direct geological investigations and geomechanic analysis. Its validity is limited to the regional areas where the curves where inferred. (See *Figure* 3 below, after Giannecchini 2006). The goals of this method is to identify the events which can cause the triggering of soil slips and debris flow. Yet, their temporal validity is indirect, i.e. considering a

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<td>predetermined database of critical thresholds (rain intensity and duration), when similar conditions are met an alarm is sent. On the basis of this concept, some real time systems were set up, in several part of the world. In fact, debris flow forecasts, preferably coupled with early warning systems, are a major component of debris flow risk management. The various approaches include both regional forecasts and local early warnings. [Jakob and Hungr 2005]. For example rainfall thresholds have been used for regional real-time landslide warning in the San Francisco Bay region [Keefer et al. 1987], Hong Kong [Hanson et al. 1995] and Rio de Janeiro [Ortigao et al. 2003].</td>
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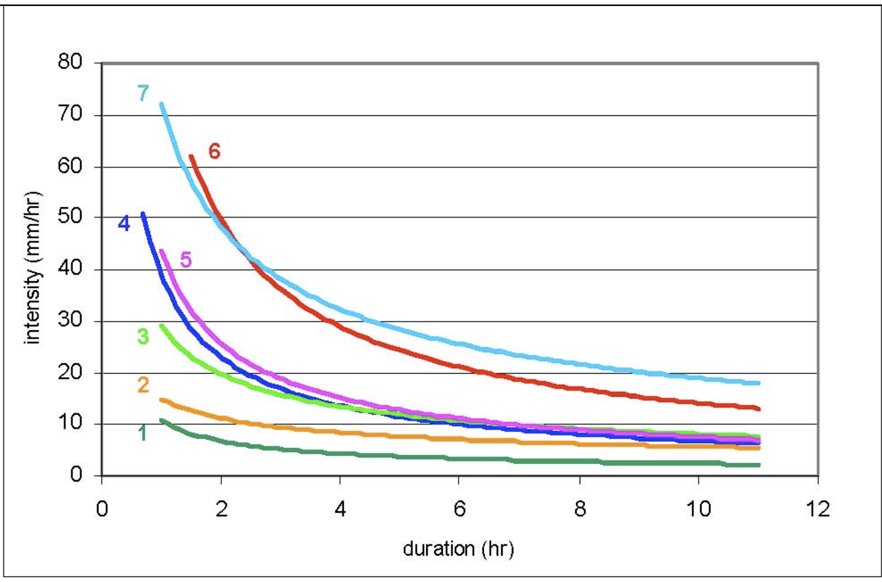
<td>Figure 3 (After Giannecchini 2006) Comparison among duration/intensity curves for shallow landslides of the southern Apuan Alps and other areas in the world 1) California (Wieczorek and Sarmiento, 1988); 2) general (Caine, 1980); 3) general (Jibson, 1989); 4) Apuan lower curve; 5) Valtellina (Cancelli and Nova, 1985); 6) Apuan upper curve (Giannecchini, 2006); 7) Porto Rico (Jibson, 1989).</td>
<td>
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<td>Temporal and spatial scope of prediction methods</td>
<td><u>Simplified distributed models</u>
Physically based geomorphological analysis can be carried out on the basis of the coupling of objective terrain analysis (supported by GIS) and hydrological modelling of varying complexity. In this group of techniques we include all the models which use a (very) simplified subsurface flow modelling (following O'Laughlin, 1987 or Beven and Kirkby, 1979). Remarkable cases as SHALSTAB (Montgomery and Dietrich, 1994) and SINMAP (Pack and Tarboton, 1997) use hydrology, geology (to some extent to determine soil/sediment properties), terrain analysis and geomechanics. However hydrology is limited to a steady state description of subsurface flow (see deliverable 1.2) and thus they are intrinsically unable to forecast the timing of the triggering, even if some exiting works (e.g. Borga, 1998 and 2003) determine the return period of the rainfall causing instabilities. The work, whilst giving some information, stands on weak basis since the rather idealized role played by rainfall intensity in the SHALSTAB-SINMAP-TOPMODEL type of hydrological theories.
These techniques neglect any spatial variability of the phenomena and are often adjusted in comparison with various field observations, as in the analysis based on the geomorphic process domain (GPD named after Montgomery and Foufula, 1993: e. g. Brardinoni and Hassan, 2005 and 2007). This technique aims to predict the processes acting in sloped landscape and, consequently, also to identify landslide-prone areas. The result of the set of phenomena is usually presented as a partion of the slope-area plane. It is not a real prediction technique but it gives, to a certain extent the snapshot</td>
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of phenomena acting in a given subcatchment at a given time (we could talk of “spatial prediction”).

Methodologies inspired to the same simplicity beyond of geomorphic process domain (GPD) for the prediction of triggering due to surface water is Peakflow (Rigon et al., 2004), which improves the one presenteded in Hirano, 1997. These models offer a simplified way to estimate the surface water depth in channels and use the infinite slope approximation to describe the goemechanics.

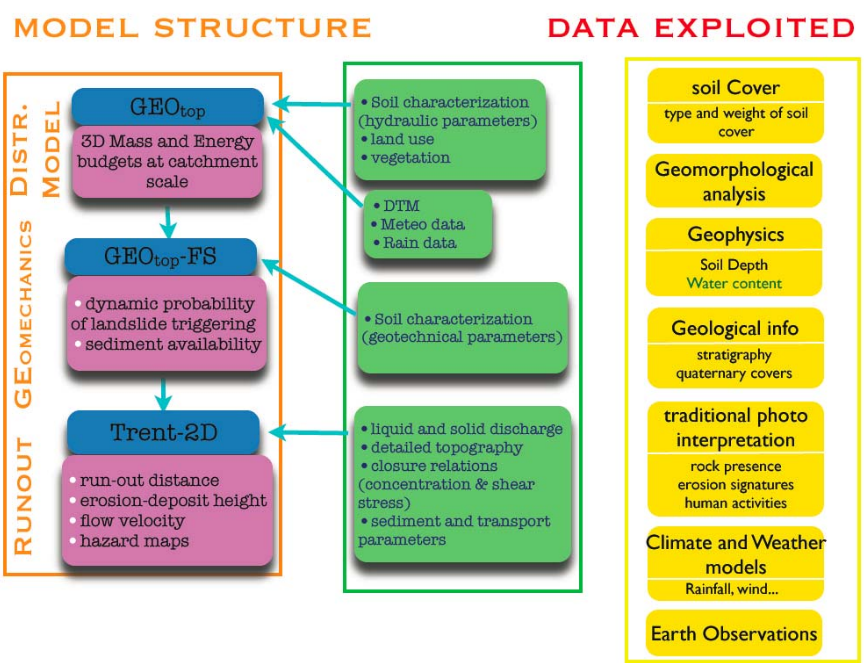
<u>Real time distributed models</u>

In this category of models we include those which account for distributed transient infiltration. A limited but representative list of models, which gives transient subsurface hydrology, is given in deliverable 1.2 and can be completed by Kampf and Burges, (2007). These models work on a grid with a spatial extension varying from some meers to some degrees of latitude and longitude, and they have been conceived to validate and integrate meteorological and EO (earth observation) data. Landslides and debris flows are small-scale phenomena, so they require refined spatial grid, generally smaller than one hundred square meters, and coherent accurate topography. Examples of these models are System Hydrologique European [Abbot et al, 1986], Distributed Hydrological Soil Vegetation Model [Wigmosta et al, 1994], and GEOtop [Rigon et al., 2006]. Among the models specifically developed to determine the temporal triggering of shallow landslides and debris flow are TRIGRS (Baum et al., 2002), CHASM (Wilkinson et al., 2002), IDSSM (Dhakal and Sidle, 2004) and the model presented in Crosta and Frattini (2003).

In a mechanistic interpretation of the outcomes of these models, they provide an accurate localization of the instabilities occurrence. However several limits to predictability, which are intrinsic to natural phenomena, imply that any outcome has to be accepted within a given degree of confidence.

Real time distributed models are data demanding but conversely allow for the exploitation of data sets (as shown in ***Figure 4***) not used properly in other modelling strategies. They can be also coupled with run-out models to obtain hazard mappings (e.g., Simoni et al, 2007).

Figure 4 An example of application of distributed real time models using GEOtop, GEOtop-FS (Rigon et al., 2006) and the Trent-2D run-out model (see deliverables of WP3). Remarkably these models can use real time data sources, as the outcomes from radar, climate or meteorological as inputs (not shown in the figure).



1.2 Key actions, data, and parameters involved in modeling of landslide and debris flow triggering

Different types of modeling require different types of parameters.

In addition to an inventory of landslides, elements relevant to landslide triggering assessment are:

1. The digital elevation models (DEMs);
2. Intensity and duration of precipitations;
3. Amount of debris of sediment/soil available (with information on granulometry).

All these piece of information are normally gathered through both field and laboratory analysis [Godt et al, 2007]. Below we briefly introduce the key actions to acquire these relevant data sets. Subsequently the key action for running the various methods of predictions are enumerated. Since physical modeling is usually coupled to infinite slope model of stability a section is also dedicated to its key parameter and actions.

<u>DEMs</u>

At this time, DEMs interpolated from topographic contour data are probably the most commonly used for landslide hazard mapping mainly because they derived from the pre-existing non digitized maps, thus the user should take care that those maps accurately reproduce enough the terrain surface and features [e.g. Wilson and Gallant, 2000].

Digital Elevation Models (DEMs) are regularly-spaced arrays of elevation. Other digital data structures exist to represent topography, e.g. Triangular Irregular Networks – TINs and adaptive grids (Hutchinson and Gallant, 2000). However, we restrict our discussion here to DEMs, which is however representative of the properties of all the

	gridding systems. The spatial resolution of a DEM is typically described by the distance on the ground represented by the array spacing. The accuracy of the DEM is a function of the accuracy and spacing of the original source data and the accuracy of the interpolation of those data to a regularly-spaced grid. DEMs are generated from a variety of original topographic data sources including: photogrammetrically generated contour maps, ground-based surveys, and remotely sensed data. At this time, DEMs interpolated from topographic contour data are probably the most commonly used for landslide hazard mapping mainly because largescale topographic maps are widely available for many localities. However, elevation data from both airborne and spaceborne sensors are increasingly available and have been used in a variety of landslide applications. Even though it is not difficult to produce a DEM using the appropriate data source, DEMs are usually obtained from national or regional institutions (as USGS in the United States, or Istituto Geografico Militare in italy). Not very precise, but available all over the world are the DEMs produced by the Shuttle Radar topography Mission (www2.jpl.nasa.gov/srtm/), which provides a DEM of approximately 30x30 m over the whole Earth from -60 deg to +60 deg of latitude. <u>Precipitation</u> The spatial and temporal scale of required rainfall data varies in the different approaches. Susceptibility maps require the total amount of rainfall in a location in a user-selected amount of time (see below), as well as the analyses based simply on empirical rainfall thresholds. Transient modeling of infiltration and shallow slope stability benefit from rainfall data with high spatial (kilometer scale) and temporal (at least hourly) resolution. Rainfall estimates from weather radars have been shown to improve model comparisons with landslide inventories both spatially and temporally (Crosta and Frattini, 2003). However, most studies will be likely forced to rely on available rainfall information from gauge networks (Godt et al., 2007). Steady-state models use suitable average rainfall quantities (which should approximate the mean water table recharge). Estimations used in engineering practice require in most of the case the assement of the return period of a rainfall event, which actually requires the availability of sufficient long time series. Precipitation in selected areas, as well as DEMs, are usually recorded by national and regional institutions to which a request must be issued to obtain the data. Usually the data comes from ground measurement points or radar systems. Only recently some satellites have promised to give reasonably accurate rainfall estimates over large areas. <u>Amount of debris available</u>

	The amount of debris available can be determined by field observations, photo interpretation and soil depth modeling. In turn, field observations can range from in-site visual (qualitative) inspection to the use of the most sophisticated geophysical methods. Since collecting sufficient measurements to map soil thickness compatible with the scale of high-resolution DEMs is a practical impossibility, deterministic modeling efforts have typically relied on empirical or theoretical models to create soil depth maps (e.g. Munnik et al., 1984, Boer et al., 1996, McKenzie and Ryan, 1999, Dietrich et al., 1995; DeRose et al., 1996; Casadei et al., 2003; Salciarini et al., 2006; Godt et al., 2007). Below we analyze briefly the three categories of methods **Field observations.** Simoni et al (2007) uses aerial photo interpretation to delimit the sediment areal extension and a mixture of geoelectrical and borehole investigations to get the soil depth. Attempts to correlate field measurements of soil depth with topographic attributes such as total topographic curvature and topographic slope have been applied with varying success and provide somewhat contradictory results. Topographic curvature was shown to be positively correlated with the thickness of colluvial soils in areas of topographic divergence (noses) on low gradient (0 - 25°) slopes in both Marin County, California (Heimsath et al., 1999) and the eastern Australian escarpment (Heimsath et al., 2000); however, little or no correlation with curvature or other topographic attributes was identified on divergent topography in the generally steeper terrain of the Oregon Coast Range (Roering et al., 1999; Heimsath et al., 2001). In convergent, steep (generally greater than about 20°) landslide source areas in the central California Coast Ranges, Reneau et al. (1990) reported data indicating that colluvial depth is poorly correlated with topographic slope. However, in the eastern Taranaki hill country of New Zealand where shallow landslides and debris flows dominate erosion processes on steep hillslopes (Trustrum and DeRose, 1988), DeRose et al. (1991) showed that at the scale of shallow landslides typical of the area, soil thickness in hollows steeper than 20° decreases exponentially with slope. Subsequent study of this area showed that topographic slope explains about 50 percent of the variation in mean soil depth for both convergent and divergent hillsides with slopes ranging from 5 to about 60 degrees (DeRose, 1996). **Soil mantle evolution theory.** Dietrich et al., (1995) proposed a model, later developed by Heimsath and colleagues (1997, 1999), for the computation of the vertical soil depth, h, in soil-mantled landscapes with well developed dendritic drainage patterns. As shown in Bertoldi et al (2006), the model can be solved for concave areas to give the soil depth, even under condition of variable soil properties. The quantitative assessment of the soil depth requires , however, the estimates of soil production rates from cosmogenic nuclide or other dating techniques (e.g. Heimsath et al., 1999). Assuming soil thickness ultimately achieves a local steady state, Heimsat's numerical results agree with field observations for noses with slopes less than about

	25°. Similar models have been used to estimate the spatial variability of soil about 25°. Similar models have been used to estimate the spatial variability of soil thickness for models of regional landslide susceptibility (e.g. Dietrich et al., 1995; Casadei et al., 2003). **Empirical models.** To estimate colluvial thickness in the southwestern part of Seattle for an assessment of rainfall-induced landslide susceptibility, Godt et al. (2007) relied on a set of site-specific correlations between colluvial depth and hillside morphology developed by Schulz et al. (2007). A systematic variation of colluvium thickness among three hillslope landforms (escarpment, midslopes, and footslope) was identified. These landforms were mapped using shaded-relief images of a LiDAR DEM, the Height, and topographic slope of each landform was calculated. A GIS database of borehole locations was created based on the compilation of geotechnical exploration logs (Troost et al., 2007). Four topographic parameters were used as input data in the model: 1) topographic slope angle of the ground surface, 2) slope angle of the escarpment, 3) height of the escarpment, and 4) distance downslope from the escarpment (Godt et al, in press; Schulz et al., 2007). Topographic slope angle was used by DeRose (1996) in an exponential relation with soil thickness described previously to produce map depicting shallow landslide susceptibility. Salciarini et al. (2006) also used an exponential function of topographic slope to map the lower boundary depth for a parametric study of shallow landslide susceptibility in central Italy.
Susceptibility maps	Production of susceptibility maps usually requires field surveys and accurate analyses of the terrain. The use of DEMs to infer terrain characteristics (mainly slope and apect) represent the basic element in the current production of susceptibility maps. In addition, also geology, land use (cover), and some mean rainfall intensity are usually important. Usually a number of control parameters less than six is used, since some of them are de-facto depending on the other (for example, vegetation development can be strongly related to aspect (Morton et al., 2003). The procedure of analysis consists in bulding a table of category for any of the above parameters. Clerici et al. [2002], Morton et al. [2003], and Glade [2005] suggest that an example of these categories could be a subset of: **Slope classes** [degree]: [0,9], [10, 14],[15,19], [20,29]. [30,90]) **Aspect classes** ([North], [North-East],[East],[South-East], [South], [South-West], [West], North-West]. **Bedding-slope relation classes** [degree]: all the data divided in few classes (for example 5 classes) **Geology** reduces to **lithology classes (**here the classes by Clerici et al [2002] are presented but classification of Haberli et al. [1991] or Zimmerman [1990] of material of origin of debris flow could be used): [silty clays], [chaothic scaly clays, etc], [shales,marlstones], [thick-bedded sandstones, thin bedded sandstones and siltstones], [thick-bedded calcareous marlstones, thin–bedded limestones and shales], [poorly cemented sandstones], [alluvial sands and gravels], [moraine deposits, periglacial deposits, talus deposits], [colluvial deposits, palustrine deposits] **Land use classes**: [lakes, stream beds], [dense woodland], [sparse woodland], [scrub],

	[arable and pasture], [outcrops, scarps], [residential] **Rain classes** (mean annual rainfall, or all the rainfall in an antecedent period, for example 1-5 days before the event)**:** all the data divided into few (for example 5) classes. **Sediment available**: a few classes in m of sediment available. The choice of the classes in highly subjective and different from zone to zone. Subsequent to the choice of classes usually a GIS based procedure allows to indentify all their possible combinations present in the analyzed landscape. The key action in predicting landslide susceptibility of a certain region consists in creating unique conditions units (UCU) which consists of areas which share the same features and comparing the occurrence of shallow landsliding in each UCU in a recent period of time.
Rainfall based predictions	To define this method are often use the words "Real time" to indicate that, upon it was built a system which, on the basis of meteorological forecasts, controls hydrological flow step by step in a specific area, and calculates the state of stability over a regional extent. The main feature of this method consists in producing rainfall intensity-duration curves which represent the threshold below which landslide are not expected to occur and above which landslide are expecte to occur. Usually, these curves have a functional relation of power-law (hyperbolic with the catersian axes as asymptote) type. The ***Figure 4*** (after Giannecchini, 2006 and reference therein) clarifies the concept. Key data required to run such models are a long record of **rainfall intensities and duration** measured on the area of interest. Data must cover both intense storm (which cause the actual trigger instabilities) and normal rainfall events, which contribute to produce the antecedent soil/sediment moisture conditions. Key action in this analysis is to record rainfall intensities and duration and to mark those events, which were seen to produce landlisdes in an area. Analyses of various events have shown that debris flow may occur also as a consequence of a mild rainfall and prolonged [Honglian and XianXing, 1988]. Thus, an improvement of the method requires to include antecedent rainfall conditions in the forecasting scenario. For instance, Campbell [1975] and Wieczorek & Sarmiento [1983] have observed in Californian mountains basins the existence of critical values of stagional cumulative precipitation preceding the triggering storm. Observations indicate that landslide events will not occur in case stagional cumulative precipitation does not reach a threshold value which is also regionally dependent. According to Hampel [1968], the return period of debris flows is not equal to the return period of intense precipitations. He classifies debris flows on the basis of the channel

	type: channel carved on rock and channel located on alluvional accumulation areas. In the first case it's necessary to have a gradual accumulation of material between two events, with a steady situation in the between; in the second case, sediments can be destabilized by intense precipitations and thereafter a period with many events and high frequency may begin. These results are also supported by the historical analysis of Crozier&Preston [1999], e Casadei et al., [2003], and Montgomery et al., [2000], that clearly demonstrates that instability concentrates in limited time periods, with subsequent long periods of unconditioned stability, even under severe precipitation conditions. If the data analysis spans over a time period too short for the accumulation of a threshold thickness of soil, the model might consider "not critical" a precipitation that would indeed be, but haven't triggered the landslide just because of the absence of soil.
Simplified Geomechanics (The infinite slope stability models)	In the modelling practice, the stability is usually assessed on the basis of an infinite slope approximation (Skempton 1953), even if the model comes with some strong assumptions, it can have various degree of completeness. In the simplest case, as it can be seen in deliverable 1.2, the leading equation contains one geotechnical parameter: the **angle of internal friction.** Immediately more complex formulation of the infinite slope stability contains **the cohesion of the material.** The above Coloumb strength parameters, which depends on geological history, lithology, porosity of soils and sediments, can be obtained (with some care) from standard geotechnical tests (e.g. Das, 2000; Savage and Baum, 2005). Plant roots are thought to impart significant strength to hillside soils (e.g. Wu et al., 1979; Schmidt et al., 2001; Sidle and Ochiai, 2006); however, the resisting forces imparted by plant roots are typically dependent on failure depth and are not necessarily parallel to the ground surface. Since the above parameters are usually known with coarse approximation, probabilistic approaches were developed to assign, at least cohesion and friction angles in distribution (Pack and Tarboton, 1997; Duan and Grant, 2000, Simoni et al., 2007). Real time distributed model share with simplified models the same stability analysis assumptions, and therefore what said above is valid also for the most complicated models. Notably, however, while the simplified models use the water table depth (in any point) as descriptor of the hydrological state ("dynamics" would not be exactly appropriate), these last models use water pressure (also in the vadose zone) and the stability can be given in term of pore water pressure. Surface and subsurface flow models are coupled to a stability criterion, which is usually the infinite slope stability method. Looking especially to channel beds the material cohesion is neglected and the stability is calculated as for non cohesive

	material (cohesion is neglected). Moreover, traditionally the stability is calculated for concentration of sediment in water. Therefore, the parameters of infinite slope stability in this case are: - **the concentration of sediment** - **the degree of wetting** For engineering applications the concentration of sediment is often assumed to be 0.65, while for the determination of the degree of wetting a stage-discharge relation must be used (e.g Rigon et al., 2003; Hirano, 1997) which introduce additional parameters.
Simplified hydrological modelling	There are at least two types of simplified models. Those models that connect the triggering of instabilities to subsurface flow and those that uses instead surface or channel runoff. SHALSTAB and SINMAP and variations are examples the first class. According to deliverable 1.2, landslide (or debris flow) triggering is analyzed either in the slope-contributing area plane or in the plane water-table-depth versus slope. Time varying data are not required by these models which are by construction atemporal, even if, under suitable assumptions, they can be made partially dynamical (e.g. Casadei et al, 2003). For these models to work, DEMa are obviously a starting data, without which no study can be made (usually must include the whole catchment, or sub-catchment, which contains the area of interest). The main topographic parameters required by the simplified models are - **local slope, s [dimensionless]** - **the upslope contributing area [L^2]** (some authors call it total contributing area) per unit contour length, a (see deliverable 1.2 for a definition) Because only the ratio a/s appears in the stability equations but these data can be obtained more or less objectively from DEMs (e.g Tarboton 1997, Orlandini et al, 2003). The key hydrological parameters to be identified (at hillslopse scale) are: - **mean soil trasmissivity** (T) - **average rainfall intensity** (q, actually the mean weekly water table recharge) These quantitites can be evaluated using different methods (some papers refer even to field measurements), but in practice, because in the stability equation of th models, the two quantitites appear as a ratio, T/q, just the ratio must be assessed. The above models require parameters averaged at the hillslope scale. However, it is easy to envision more complex versions which include soil depth and saturated hydraulic conductivity variability (Rigon et al., 2007). As Brardinoni and Hassan (2005 and 2007) show these simplified methods must be used in conjuntion with accurate field activities to asses the degree of realism implied

	by the model' outcomes. Regarding the models which relate stability to surface runoff, they are essentially rainfall-runoff models (and therefore, with this respect, "dynamical") able to give the surface discharge in a given channelled point, and we limit here to describe (relatively) simplified approaches with lumped hydrological parameters. It is practically impossible to overview all the type of rainfall-runoff models (see for instance, Beven, 2001). For those models which rely on the modern IUH theory (e.g. Brutsaert, 2005; Rigon, 2007), the main parameters can be grouped into two groups: those which are used to determine the **effective rainfall** and those that concern the **flow dynamics**. The first parameters are process dependent, and are different if the runoff is produced by saturation excess or by infiltration excess mechanism (e.g. Brutsaert, 2005). A widespread method which implies (to a certain extend) infiltration excess is the Soil conservation Service (or curve number based) method. The parameter in this method is the **curve number** which, in turn, is derived from tables that associate to any soil cover and antecedent rainfall condition a number in between 1 and 100 (U.S. Dept. of Agriculture, 1986). However usually these table are not of general validity, and are instantiated for different countries and regions (e.g.Garen and Moore, 2005). Methods based on the saturation excess mechanism are founded on the same theoretical bases which give the subsurface flow of SHALSTAB and SINMAP (are essentially the same as those used by the TOPMODEL, Beven and Kirkby, 1979), and require the knowledge of the mean soil trasmissivity, slope, contributing areas and rainfall rate (sometimes provided by a Philip type infiltration, that in turn depends on a couple of parameters). Key dynamical data to any rainfall-runoff model are the varying **rainfall intensities**. However, often, these intensities are deducted as "design rainfall" from intensity-duration-frequency, **IDF curves.** Other parameters involved in this modelling are the surface flows velocities, which are usually distinguished in **hillslope velocities** (or celerities) and **channels velocity**, both given as catchment average. Otherwise, an equivalent number of parameters (two) is usually given. Slightly more complicated models include a third parameter which is, sometimes, a dispersion coefficient (as for instance in D'Odorico and Rigon, 2003). All the flow parameter are given as calibration parameters, i.e. they are evaluated ex-post, after a calibration procedure based on some measured data.
Real time distributed hydrological modelling	Real time distribute hydrological models share, in our definition, a dynamical subsurface flow but can use very different equation for implemting it. Accordingly their needs in term of parameter identification are very different, and it is practically

	impossible to make a comprehensive analysis of all the existing models. The example of GEOtop (Rigon et al., 2006) is taken here. The data can be subdivided in 2 categories: 1 – External forcings; 2 – Process parameters. Characteristics of the distributed models is that (up to a point) they use as parameters observable quantities (which can be measured) and not effective quantities (which, whilst having the name of observable quantities needs to be calibrated). Differently from the simplified distributed models, they provide dynamical variability in time of some quantities, which therefore require to be inizialized. Furthermore, because of the requirement of making hydrological spatial prediction (i.e. in any pixel of the described domain), they would require a spatial characterization of the parameters and a spatial interpolation of the forcings (which indeed can be used as spatially constant if information is missing but introducing additional uncertainties in the results). 1 - Required external forcings The variables strictly necessary to run the GEOtop model are all the meteorological data, usually coming from one or more hydrometeorological stations (in principle some of the data can derive from radar measurement and/or remote sensing). Data must have at least an hourly time step, and must be relative to the period of the analyzed event, and at least some months before the event. In particular, the model requires hourly **precipitation** inputs, but also **hourly data of air temperature**, **relative humidity, wind speed, direct solar radiation which are necessary for the extimation of evapotranspiration and snow mantle evolution.** For working properly these models require detailed identification and georeferentiation of the hydrometeorological stations (the geographic coordinates of the station are required for a proper spatial interpolation of the forcings; the technical characteristics of the station are required as metadata, useful to validate the measurements). 2-Required parameters and data In addition to DEMs and soil depth, a land use map of the river basin (with classification in classes as: urban zones, forests, ground knot, agriculture used ground, pasture used ground), and soil types and texture (in classes as fraction of organic, sand-clay-material - bulk density of the soil, which can be used to determine the soil hydraulic characteristics through, for instance pedotransfer functions), or, in alternative, soil water retention curves estimates (SWRC) (e.g. estimation of van Genuchten parameters and saturated hydraulic conductivity) are required. Some models as TRIGRS uses a simplified formulation of Richards equation for the subsurface frow and require the specification of an effective hydraulic diffusivity. The simulation of phenomena less strictly related to landslide and debris-flow

	triggering, require also, in GEOtop: - Soil and rocks thermal characteristics (required when the energy budget plays a role). Most of the models do not use it but it would be required to detect instabilities generated by freezing–thawing cycles. - Parameters related to snow (required when snow plays a role). Most of the models do not use it but it would be required to detect instabilities generated by freezing–thawing cycles. - Radiation parameterization (radiation is not derived from complex models of the atmosphere but parametrized according, for instance to Brutsaert, 1973). Required when radiation plays a role. Most of the models do not use it. Provided that the saturated hydraulic conductivity of soils with similar textures derived from the same parent material, can vary over several orders of magnitude, laboratory tests, using either constant or falling head instruments, are typically used for measuring saturated conductivity (Godt et al., 2007). Laboratory tests to determine the moisture content – pressure head relation or SWRS and hydraulic conductivity function (HCF) should be obtained using a wetting process to simulate rainfall infiltration. Examples include the so-called Bruce and Klute experiments for measuring soil-water diffusivity in which the water is allowed to imbibe into a horizontal column (Bruce and Klute, 1956; Clothier and Scotter, 2002). These tests are typically performed on repacked materials, and as bulk density has a significant influence on soil hydraulic properties, care should be taken to replicate field densities or account for variation. Other laboratory tests include those using constant-flow permeameters that can be used to determine the SWCC and HCF for either the wetting or drying process (Wildenschild et al., 1997; Lu et al., 2006). In-situ tests on hillside materials in field areas probably provide the most representative estimates of material properties at the scale of shallow landslides. Data from well and ring permeameter tests of unsaturated materials can be used to estimate the field saturated hydraulic conductivity (Reynolds et al., 2002). The term field saturated is often used for these types of tests because air is usually entrapped in the soil by infiltrating water, which is typically the case during natural rainfall. Permeameter data can also be reduced to estimate unsaturated-zone parameters as well. Disc permeameters provide measurements of hydraulic conductivity at small negative pressures and data can be reduced to estimate soil-water characteristic curves and diffusivity (Clothier and Scotter, 2002). Prediction of SWRCs from more easily measured soil parameters such as particle size distributions has been performed using both empirical and theoretical approaches (Brackensiek et al., 1981; Haverkamp and Parlange, 1986). The theoretical or physically based models (e.g. Arya and Paris, 1981) typically link the cumulative

	particle size distribution and other properties such as bulk density with the SWCC. Empirical pedotransfer functions (PTFs) are used to predict soil hydraulic properties from readily available soil information such as bulk density and soil texture using regression or neural network techniques (Leij et al., 2002). Where soils mapping is available, this approach, combined with field and laboratory analysis may yield reasonable estimates of the spatial variability of material parameters for model input. More detailed information on empirical, field, and laboratory techniques to determine soil hydraulic properties can be found in the relevant chapters of Dane and Topp (2002) and Lu and Likos (2004).
	1.3 Issues related to the application of models
	Many of the above discussed hazard assessment and prediction methods can be used as general management tools. Most are designed for application at the regional level, some can be applied globally, and others can be adopted for local conditions. One of the major challenges related to landslide hazard assessment and prediction is the need to better link specific land management activities with the models, as well as terrain hazard mapping. Although some of the current terrain hazard mapping programs address practices like forest road construction and timber harvesting [Howes and Kenk 1988, Oregon Department of Forestry 2003], no clear distinction is made to discriminate between these very different impacts of slope stability and few quantitative literature exists.
Landslide Inventories	Landslide inventories are usually oriented to map the whole mass movement (including the detachment area, the runout region and the deposition sites), and not only the initiation area, which would be more appropriate for the triggering studies. The proportion of missed landslides in photo mapping (false negative) can be large and is influenced by a number of factors, including: photo scale, quality, and type (e.g., black and white or color); the shape, position and age of the landslide scars; and the experience of the photo interpreter [Guzzetti et al., 2000]. In addition, small landslides are more visible in unforested areas on aerial photographs, which introduces bias in landslide counts between forest cover classes [Brardinoni et al., 2003; Pyles and Froehlich, 1987]. Moreover, it is quite difficult to use the inventory methods in rugged terrain covered with dense vegetation. In particular, vegetated older dormant slides with subdued topographic expression may be unrecognizable on airphotos or multispectral digital imagery (e.g. Wills and McCrink, 2002). As a result, the quality of the mapping and its utility largely depends on the resources (e.g. geology and soil maps) and expertise available, as well as the commitment to

	investigations on the ground. However, the identification of landslide locations is subject to interpretation, and considerable differences are apparent when comparing results from hillshade map interpretation with those based on field surveys made by different people [Wills and McCrink 2002, van Den Eeckhaut et al. 2005]. Also, studies of landslide inventory mapping typically focus on outlining slide boundaries and neglect the wealth of information revealed by internal deformation features, which could be important for modelling. Sumamarizing, all models "data-based" and not based on process modellations are very sensitive to the quality of the data used to retrieve quantitative relations. Being uncertainty to landslide survey very high, in many cases a classification with reduced spatial detail is preferable. It's obvious that susceptibility maps are more sensible to data resolution, i.e. to the detail of the grid adopted.
DEMS	Most of the models and methods use DEMs as a starting point of the analysis. All the terrain characteristics are derived from DEMs and their influence on the final outcomes is large. For any application , the grid size of the DEMs should be adequate an up-to-date. Users should be aware that blind interpolation operations do not increase the informative contents of the DEM, and the original resolution and metadata related should be preserved and transmitted. In addition, interpolations should preserve the curvature characteristics of the terrain which were found to affect water fluxes and hillslope stability. Deterministic shallow landslide susceptibility modeling requires DEMs of adequate resolution to capture landslide features in a given study area. Since most of these study areas are likely to be in highly dissected terrain with high relief, highresolution data (5-10 m) are typically required (Zhang and Montgomery, 1994). Slope angle calculations and other elevation derivatives such as curvature and contributing area are dependent on the scale of the source elevation data and the grid-cell spacing of the DEM (Garbrecht and Martz, 1994; Zhang and Montgomery, 1994; Thieken, et al., 1999; Claessens et al., 2005). Finer grid spacing typically produces steeper slope angles and at very fine spacing (e.g. < 5 m) large local variability of curvature results from small-scale topographic features such as animal burrows and mounds surrounding vegetation (Heimsath et al., 1999). Elevation errors in DEMs also have an effect on the calculation of topographic derivatives such as slope and contributing area (e.g. Holmes et al., 2000). Haneberg (2007) shows that elevation errors in a 1-m LiDAR and 10-m USGS DEMs lead to errors in the calculation of topographic slope that may be as large as ±3º. The state-of-the-art production of such maps uses LIDAR topography detection and SAR imaging (see section below) which should be preferred to the other maps when available.

Precipitation records	Precipitation measures are affected by large errors, which should be properly reported in simulations. In any case the precipitation record should be long enough to make possible the estimation of the antecedent soil moisture conditions. One major bias introduced by rainfall estimation, measured in a monitoring station, is that usually it is not located in proximity of the landslide or debris flow event. Since rainfall intensity is highly variable in space, this can introduce severe errors in the rainfall thresholds evaluation or, in any case, in the rainfall amount. Actually, for forecasting purposes a spatial interpolation of the datawould be required. This would need the application of suitable techniques (for instance the use of Thiessen method -known as Voronoi in computational geometry – or of kriging technique). Radar or satellites, give directly spatial multitemporal data. However, the translation of these radiation measures to the real rainfall is not free of error.
Soil depth	Many field investigations have shown that soil depth can vary up to an order of magnitude over several meters of slope distance [e.g. Okunishi and Iida 1981, Tsuboyama et al. 1994a, D'Amato Avanzi et al. 2004]. If (see the above 1.3.1 paragraph) new techniques are being developed in the recent years to make quantitative estimates of the soil/sediment depth, these have been applied only in recent case studies and their reliability is yet not well assessed.
Susceptibility maps	Empirical methods that assess landslide trigger mechanism as well as multi-factor analyses are specific to the region in which they are developed. Multi-factor analyses that incorporate only rudimentary data and do not exploit clearly cause and effect relationships may not be useful for landslide susceptibility assessment. Additionally, few multi-factor empirical assessments assess land management issues in a meaningful way, except for the inclusion of very general land cover classes [e.g. Kienholz et al. 1984, Anbalagan 1992]. It is important to emphasize the remarkable sensitivity of these models to some modalities of data treatment: **Thematism classification**: thematic cartography involves the classification of many thematisms in various categories: soil utilization, stratigraphy, lithology and slope angle. Statistical test application (logistic regression or variance analysis) implies a uniform distribution of occurrence for all possible combinations. Yet, in case many combinations of categories have a null occurrence, statistical tests may not be reliable. This may happen when data sets with several categories for each thematisms are used, therefore the possible obtainable combinations become too numerous, and the number of null combinations too high [Agresti, 2002]. As far as the application of the discrimination analysis is concerned, it is requested that each categorical variable is transformed into a numerical variable. The problem to assign a numerical value to one lithology becomes thus stringent.

	Territory's subdivision in elementary area: for all statistical methods it's indispensable to fix a representative elementary area (called UCU above): this can be rectangular or irregular (connected with topography), or an elementary basin in the study zone with a minimal area. Statistical relationship between landslide occurrence and indicators value is calculated for each area: so the choice of UCUs is very important for the final results. The calculated susceptibility in each area is of course homogenous.
Rainfall only based methods	Frequent temporal rainfall data, derived by remote sensing (i.e. from Doppler radar), can provide the necessary information for assessing regional slope stability on a detailed spatial basis almost near real time. Afterwards, post-event comparison of ground based rainfall measurements with remote-sensed data for major storms is needed, particularly in areas with major topographic relief, in order to improve the understanding of storm processes and the techniques of rainfall estimation. Improved use of remote-sensing rainfall data for landslide hazard assessment and warning will depend upon shorter time intervals between measurements, to allow sufficient time for analysis, communication and public response to warning [Wieczorek et al. 2003]. Very seldom the warning system based on this simple threshold were found to be effective in the past, if antecedent soil moisture conditions and the information about the presence of transportable sediment were nont included in the decision.
Infinite slope stability method	The physical based models, as presented above, demands the stability analysis to the infinite slope stability method, which is here discussed separately. According to Sidle and Hirotaka [2006] the application of semi-quantitative stability analyses to natural hillslopes has difficulties and limitations which tend to reside in two general areas: 1. Difficulties in characterizing and assessing the variability of factors that influence slope stability; 2. Inappropriateness of the inherent limit equilibrium methods for certain types of slope failures or strain conditions. Such limitations should be considered when applying an analytical method for evaluating the safety factor. The topographic, geotechnical, and hydrological properties of the soil that affect stability analyses, exhibit some level of anisotropy and heterogeneity in field sites. Additionally, some parameters may vary over time or related to wetting conditions. Such natural variability can lead to errors in stability calculations. Most studies or summaries of the spatial variability of soil shear strength parameters indicate that c (cohesion) is more variable than the friction angle [see Schultze 1972, Fredlund and Dahlman 1972, Lumb 1962 and 1975, Buchannan and Savigny 1990,

	Maharaj 1995]. Hawley [1981] noted that the spatial variability of the material cohesion and the internal friction angle was higher in the upper 1 to 2 m of the soil profile, Yee and Harr [1977] found that friction angle in two cohesionless soil was strongly affected by wetting: the higher values for the friction angle measured in dry soil were attributed to aggregation. Given that factor of safety is more sensitive to the cohesion than to the friction angle for typical ranges encountered in the field [Gray and Megahan 1981, Sidle 1984b], and given the generally higher natural variability in the cohesion measured in most studies, it is apparent that variations in the cohesion may strongly affect slope stability calculations. Variability of soil properties that influence water movement and the dynamics of pore water pressure can strongly affect the stability of materials with friction strength. Moreover, small-scale variations in rooting strength of vegetation have received little study but can contribute to large variations in factor of safety calculations over small slope distance [Roering et al. 2003, Dakal and Sidle 2004]. As a consequence, no deterministic forecasting is really reliable and a probabilistic approach should be used. Finally, it has to be remarked that the infinite slope stability model is an equilibrium model which assume that the soil matrix is rigid, and it does not contain any information about the mechanical deformation of the soil or for "neighbouring effects" once the limit equilibrium is gained.
Simplified physical models	The outcomes of these models can be seen as a partion of the slope-area plane in regions where different geomorphic processes are dominating. The position of the boundaries between processes depends on parameters which can be identified as effective trasmissivities, effective cohesion, effective friction angles, and effective water table recharge on a certain location. The physical soundness of the complex of these models seems to be more apparent than real since, usually their parameter are assumed to constant through the study area under analysis (despite the known variability of the corresponding physical variable with the same name in the field) and often are calibrated (ex-post) on maps of landslide. To be more precise, practice suggests calibrating the ratio of trasmissivity over water table recharge, and give field or literature derived values for cohesion and friction angles. Hence, considerable uncertainty must be accepted in models' results. Thus, correctly, in the GPD as applied by Brardinoni and Hassan, 2006, the modelling is used to guide extensive field campaigns that eventually support the "prediction" of the acting phenomena and the production of the processes maps.
Distributed physical models	Distributed physically based models are potentially the most powerful tools in landslide hazard analyses, particularly when they incorporate DEM data based on LIDAR [Dietrich et al. 2001], actual rainfall inputs [Baum et al. 2002, Dhakal and Sidle 2003]. However, widespread application of these models has been limited because they require distributed input data (including DEMs) and expertise with GIS

	and computer modeling. While some input data can be augmented by remote sensing and extracted from DEMs, to be effective, these models require accurate distributed data on soil depth and other critical soil properties and such data are not typically readily available. On the other hand , models which do not use distributed data, as those documented in the above boxes can perform reasonable forecasts only for those observables which derive from average hillslope properties and not for local heterogenous characteristics. To obtain precise results with distributed models, many prescription should be kept in mind, about the following issues: **Space and Time Resolutions**: How are the space and time resolutions selected? In terms of spatial discretization, the model uses grid-based DEMs with varying depths for individual grid boxes and a temporal resolution of any calculations or forcings (e.g. Richards equation, energy balance, channel flow time steps, etc.). What are the considerations which leaded to space-time resolutions and computational burden, also in terms of the numerical solution strategies adopted ? **Addressing subgrid variability**. Once spatial and temporal variability are chosen in order to produce consistent results, the modeler should assess wheter the spatial variability within the grid is addressed consistently. The same problem, however, applies to any other model which uses gridded information. **Computational Burden**: As a general rule, distributed models are computationally expensive. The authors should address the computational limitations, if any, of the model, in particular for watershed applications which involve comparison to remotely sensed imagery. What tradeoffs are required between computational expense and the space-time resolution of the model? **Non calibrated parameters**: An example is given by the parameters related to the soil properties, including soil depth, that derive from a mixing of field measurements, laboratory estimations, and their spatial extension (for this see also the paragraph below) with procedures that can vary from case study to case study, depending on the data available. A literature review should be given for these parameters. For the specific case of soil properties, some operative suggestions and procedures are given in the papers by Simoni et al., 2006 and Simoni (2007). It can be seen that many procedures involve critical decisions on open scientific issues and this makes even more important an open discussion. Other parameter usually fixed from literature include the atmospheric boundary layer (ABL) parameterization, topic which have a introductory discussion in Endrizzi (2007). **Calibration Strategy**: A calibration strategy should be documented. The calibration strategy should explicitly indicate the time period for which it is performed (e.g. event, seasonal, annual), what the data are used for calibration (e.g. discharge, soil moisture),

	what parameters are related to which data sets or portions of the data (e.g. hydrograph peak or recession). In many hydrological studies a split sample test is used to validate the calibrated model w.r.t. events not used in the calibration period. It must be remarked that the calibration to a single flood event in any hydrological model is an extremely weak test of model performance and especially when the concern is on soil moisture spatial distribution, other quanties should be used as a validation. This is actually an issue also for the simplified models previously. **Model initialization.** Modelers need to adequately describe initial conditions and be aware of their effects on the simulations, which is particularly critical for a distributed model with vertical profiles of soil moisture and temperature and a water table position. For example, the model should run for a sufficiently long period of time prior to ensure both static and dynamical equilibration in the surface and subsurface states prior to the analysis period. This can be performed by running a drainage experiment starting from totally saturated conditions in each basin (with no ET or rainfall) and allowing the basin to drain for sufficiently long periods. This will lead to a 'static' equilibrium condition which is particularly adapted to each terrain, soil depth, channel network combination. A 'dynamical' equilibrium condition can be achieved by forcing the model with the meteorological conditions repeatedly (periodic forcing) lasting sufficiently long and then analyzing the results from a period after various periodic cycles have passed. This allows each combination of prognostic quantities to dynamically adapt to the forcing. Either techniques minimize initialization errors. In particular, two processes have a very slow adaptation to "mean conditions", the soil water content and temperature in the ground, say below 1 m. This implies that incorrect initial conditions at the bottom layer can influence the time evolution of the system for several years. Thus the dynamic equilibrium can be very far from a set of arbitrary initial condition and the modelers always needs to make an "educated guess" to be successful in his/her simulations. A rule of thumb for the initial soil moisture distribution is to take an equilibrium condition, which implies hydrostatic distribution of pressure in both the vadose and saturated zones (e.g. Cordano and Rigon, 2006). The latter condition, in turn, implies to guess the initial position of the water table, which could be below the bottom boundary of the control volume. Obviously some measures of this quantity would help, however local (in a point) measurements imply to search a method for their spatial extensions (see below). Either if the water table is above of below the bottom layer, a flux or gradient condition must be given at the bottom. One reasonable assumption to build this condition is to use the state of the system itself, especially to give the hydraulic conductivity. Clearly this boundary condition is dynamic with the varying soil moisture contents at the bottom. Please, note that assuming constant water content throughout the ground layers, would imply a constant water input into the considered volume. A rule of thumb for the bottom temperature would be to assign at some depth (1.2 m,

	for instance) the mean annual air temperature (which is spatially varying). These last hints are of general validity, however for particular sets of simulations, other choices can be made. What it is important is to discuss consciously the choices made. **Spatial series of soil properties**. These include soil depth, soil permeability, and van Genucthen parameters (if the van Genuchten parametrization has been chosen). Soil depth can be assessed locally by measurements and, assuming an equilibrium soil profile, using the Heimsath theory as in Bertoldi et al. (2006). Many aspects of the issue are still to be addressed as it is evident from the discussion above. **Spatial time series of meteorological data**. A prerequisite for any model is to provide it with the best input data as it is reasonably possible. If these data are of poor quality, then the entire hydrologic simulation is flawed from the outset. Particularly in mountainous areas, where complex interactions among topography, vegetation canopies, and climate exist, it is essential that spatial interpolation methods that account for these effects be applied to estimate the spatial fields of meteorological input. A good and up-to-date reference for method of interpolation is Garen and Marks (2005) (and references therein). In that paper, the authors show show a combination of limited measurements, models, and carefully applied spatial interpolation methods can be used to develop the spatial field time series of the forcing data required for the simulation of the development and melting of the seasonal snowcover. The arguments of the paper apply with almost no change to the general case of simulating the hydrological cycle. The meteorological input includes spatial field time series of precipitation, air temperature, dew point temperature, wind speed, and solar and thermal radiation. These variables have particular characteristics and levels of data availability that make it necessary to use a variety of procedures to develop spatial fields of each. It is also essential to consider the effects of the forest canopy on the solar and thermal radiation. **Spatial characters of soil hydrological properties.** Numerous investigations have reported that most soil hydrologic properties (e.g. hydraulic conductivity, infiltration capacity, water flux) are lognormally distributed [Warrick et al 1977, Luxmoore et al. 1981, Bronders 1994, Mallants et al. 1997, Regalado 2005]. Moreover, recent measurements of pore water pressure in unstable hillslopes indicate a high degree of spatial variability that may be affected by local site conditions such as preferential flow paths, anisotropic K values, bedrock unconformities, soil heterogeneities and topography [Pierson 1980b, Sidle 1984a and 1986, Iverson and Major 1987]. Such variability is enhanced by the effects of macropores and interconnected preferential flow pathways [e.g. Mallants et al 1997, Noguchi et al. 1999]. Given the strong influence of pore water pressure on slope stability calculations, the temporal and spatial variability needs to be considered in such analysis. One possibility is to use a probability-based approach for estimating either the hydrological properties in the model or the pore pressure response to rainfall inputs [e.g. Wu and Swantson

	1980, Reddi and Wu 1991, Popescu et al. 1998, Dai and Lee 2003]; however, such modelling approaches cannot hope to capture the spatial locations of actual landslides, only in probability.
	1.4 Modern instruments for parameter identification
Introduction	Various remote sensing methods can improve landslide investigators to understand and mitigate landslide hazard. A detailed landslide characterization and inventory of events is usually necessary to this scope. Recent advances in remote sensing techniques (see paragraph 1.6) and the development and application of contour based digital elevation models (DEMs) can improve terrain hazard mapping, especially when processed within geographic information system (GIS) [Sakellariou and Ferentinou 2001, Lee et al. 2002, Dhakal et al. 2002, Mizukoshi and Aniya 2002]. In particular, satellite imagery and Light Detection And Ranging (LIDAR) are useful for assessing landslide locations as well as developing detailed DEMs and hillshade [e.g. Lee et al. 2002, Wills and McCrink 2002, van Den Eeckhaut et al. 2005]. High resolution DEMs produced from airborne laser altimetry can be used to assess surface characteristics of active and dormant landslides, as well as delineating detailed topographic information useful in predicting areas of future landslides [Dietrich et al. 2001, Haugerund et al. 2003, McKean and Roering 2004]
Aerial camera	The highest spatial resolution in imagery for landslide inventories comes from panchromatic (black and white) film taken by a quality aerial camera. This is the product that has been most commonly used for qualitative or interpretative evaluation. An important rule when choosing film photography for landslide studies, is to select a spatial resolution greater than half the size of the landform to be observed [Jakob and Hungr 2005].
Digital imagers	Spectral band associated with digital cameras can be used for image rectification and restoration, image enhancement, image classification, data merging and Geographic Information System (GIS) integration. Restored, enhanced or classified images facilitate landslide identification and characterization in hazard studies. An image analyst can use these products, in combination with field studies, to assist in the landslide interpretative process as with film imagery [Jakob and Hungr 2005]. Some studies were made [Ramli et al. 2002, Whitworth et al. 2002] in order to define which and how many band is to use for the best result.
Passive microwave sensors	Passive microwave sensors operate in the same spectral range as radar (30 cm), except that they sense the naturally available microwave energy within the field of view rather than emitted energy [Lillesand et al. 2004]. An important skill of importance in landslide studies is the ability to measure soil temperature (from frozen soils) and soil moisture, properties often indicative of potentially unstable areas. Another capability yet to be fully exploited is the ability of multispectral microwave radiometry to peer through overburden to detect geologic structure, material type and subsurface voids [Jakob and Hungr 2005].
Lidar sensors	The term lidar is an acronym for light detection and ranging and is the optical

	equivalent to radar. Lidars designed for sensing terrain are typically energy-detectors and transmit a laser pulse that travels in the ground, reflects off rocks and bushes, and then returns to the sensor. The time it takes for the light to make the round trip is precisely timed, then converted into the distance or range to the objects. The resulting lidar data is displayed as either a cloud of 3-D plotted points or as a range image. Lidar has proven useful for the monitoring of ground movements. A ground-based lidar system with a 2-km range has been used to monitor debris/rock slide movement in the Alps [Paar et al. 2000]. A similar work was completed in Austria [Scheikl et al. 2000] and in England [Rowlands et al. 2003]. An advantage of lidar is its ability to detect the ground surface under a fairly dense tree canopy, like highlights from a series of specific tests [Carter et al. 2001].
Synthetic aperture radar (SAR) sensors	Radar imagers such as the SAR, scatter millimetre wave or radio wave energy off objects in the scene, and then sense the amplitude and phase of return energy to determine the object reflectivity and range. Unlike lidar, SAR does not directly observe the power of each individual echo. D-InSAR (using two antennae on the same platform for third dimension) enables small soil or rock displacements, of the order of few centimetres [Raney 1998, Leva et al. 2003, Dzurisin 2004]. Alternatively, airborne or ground-based SAR provides much higher resolution and a capability of measuring fine movement. Some of the earliest ground-based work on landslides was completed by Tarchi et al. [2002]. More recently, Leva et al. [2003] used a ground-based D-InSAR to study the dynamics of the same debris avalanches head scarp studied by Paar et al [2000]. In the following table (***Table 1***) a summary of terrain features frequently associated with slope movements is given, together with the relationship of these features to debris avalanches and debris flows, and their characterization on aerial photographs.

Table 1 Morphologic, vegetation and drainage features charactersitic of debris avalanches and debris flows, and their photographic characteristic. [Jakob and Hungr 2005]

	Terrain features	Relation to slope stability	Photographic characteristics
Morphology	Semicircular back scarp and steps	Head part of slide with outcrop of failure plane	Light-toned scarp, associated with small slightly curved lineaments
	Hummocky and irregular slope morphology	Micro relief associated with shallow movements or small retrogressive slide blocks	Coarse surface texture, contrasting with smooth surroundings
	Berms or levees parallel to a stream channel in a gully or canyon	Micro relief associated with the deposition of debris during a debris flow	Raised ridges immediately adjacent to and on one or both sides of a stream
	Concave-convex slope features	Landslide scar associated with deposit	Concave-convex anomalies in stereo model
	Step-like morphology	Retrogressive sliding	Step-like appearance of slope
Vegetation	Lack of vegetation immediately below breaks in slope	Removal of vegetation by translation sliding at debris avalanches head scarps	Light-toned elongated areas at the head of gullies or just below breaks in slope
	Irregular linear swaths of denuded vegetation or new regrowth	Slip surface of debris avalanches and the path of debris flow	Light-toned bare soil tracing a path down the fall-line of the slope
Drainage	Areas of stagnated drainage	Landslide hollow, back-tilting landslide blocks, and hummocky landslide topography	Tonal differences and darker tones associated with ponds or wet areas
	Seepage and springs in hillslope hollows	Naturally wet areas on slopes sometimes naturally occur at debris slide head scarps	Dark patches in hollows sometimes enhanced by differential vegetation
	Interruption in drainage lines	Drainage anomaly caused by a head scarp	Drainage line abruptly broken by a break in slope
	Anomalous drainage pattern	Streams curving around the lobe of a debris deposit	Stream disruption by a debris fan deposit

1.5 References of previous case studies

In the following tables (***Table 2, Table 3, Table 4***) sources of information on spatial distribution and susceptibility of landslide and debris flow are reported. Finally, in ***Tabe 5*** a summary of previous projects on debris-flow and landslides is presented.

Table 2 Sources of information on spatial landslide distribution and inventories for different regions of the world [Glade & Crozier]

Continent	Country	Region	Type of analysis	Reference (s)
Catchement and regional scale				
Africa	Nigeria	General	Information	Schoeneich and Bouzou 1996
		Southern Nigeria	Distribution	Okagbue 1994
	Southern Africa	General	Distribution	Paige-Green 1989
Asia	China	Yunnan Province	Inventory	Tang and Grunert 1999
		Gangsu region	Distribution	Derbyshire et al. 1991
		Hong Kong	Inventory	Brand et al. 1984; Chan et al. 2003; King 1999; Pun et al. 2003; Wong and Hanson 1995
	India	Darjeeling	Inventory	Basu 2001; Jana 2000; Sarkar 1999
		North-eastern India	Susceptibility	Gupta 2000
	Japan	Hokkaido	Inventory	Yamagishi et al. 2002
		Kobe	Distribution	Sassa et al. 1999
	Jordan	Northern & Central	Distribution	Farhan 1999
	Korea	Gyeonggi Province	Susceptibility	Kim et al. 2001
	Taiwan	Western Foothills	Frequency and spatial distribution	Chang and Slaymaker 2002
		Central Range	Inventory	Hovius et al. 2000
Europe	Croatia	Medvednica Range	Distribution	Jurak et al. 1998
	Czech Republic	Vizovická vrchovina Highland	Distribution	Kirchner 2002
	France	Mercantour Massif, French Riviera	Inventory	Julian and Anthony 1996
	Germany	Bonn Region	Inventory	Grunert and Schmanke 1997; Hardenbicker 1994

			Rheinhessen	Inventory	Dikau and Jäger 1995
			Hessen, Thüringen	Inventory	Schmidt and Beyer 2001; Schmidt and Beyer 2002
			Schwäbische Alb	Inventory	Bibus and Terhorst 1999; Schädel and Stober 1988; Thein 2000
			Fränkische Alb	Inventory	Moser and Rentschler 1999; Streit 1991
			Bavarian Alps	Inventory	Mayer et al. 2002; von Poschinger and Haas 1997
		Great Britain	Isle of Wight	Distribution	Hutchinson and Bromhead 2002
			Scotland	Distribution	Ballantyne 1997
			South coast	Temporal and spatial distribution	Brunsden and Ibsen 1994
			South Kent	Distribution	Bromhead et al. 1998
		Hungary	Danubian Bluffs	Inventory	Kertész and Schweitzer 1991
			Hernád Valley	Distribution	Szabó 1999
		Italy	Calabria	Distribution	Sorriso-Valvo 1997
			Cardoso T. basin	Inventory	D'Amato Avanzi et al. 2000
			Cortina d'Ampezzo	Inventory	Panizza et al. 1996, 1997; Pasuto and Soldati 1999
			Naples	Distribution	Calcaterra et al. 2002
			Northern Calabria	Inventory	Carrara and Merenda 1976
			Central Calabria	Distribution	Antronico and Gullà 2000
			Pizzo d'Alvano	Distribution	Gudagno and Zampelli 2000
			Sicilia & South-	Distribution	Nicoletti et al.

			eastern		2000; Pantano et al. 2002
			Umbria region	Inventory	Guzzetti and Cardinali 1990; Guzzetti et al. 1994; 2002b
		Poland	Carpathians	Inventory	Alexandrowicz 1993; Alexandrowicz 1997; Margielewski 2002; Ostaficzuk 1999; Starkel 1997
		Portugal		Distribution	Zezere et al. 1999
		Romania	General	Inventory	Ielenicz et al. 1999; Rosenbaum and Popescu 1996
		Slovakia	Orava region	Distribution	Janova 2000
		Spain	Asturias, Meredela valley	Distribution	Cuesta et al. 1999; Sánchez et al. 1999
			Barranco de Tirajana basin, Gran Canaria	Distribution	Lomoschitz 1999
			Izbor basin, Granada	Inventory	El Hamdouni et al. 2000
			Los Guajares Mountains, Granada	Inventory	Fernandez et al. 1996; Irigaray et al. 1996
			La Pobla de Lillet area	Inventory	Santacana et al. 2003; Santacana and Corominas 2002
			Río Serpis basin	Inventory	van Beek 2002
			Sorbas Inventory &	Distribution	Hart and Griffiths 1999
			Southeastern Pyrenees	Distribution	Moya et al. 1997
		Sweden	Kärkevagge	Distribution	Jonasson et al. 1997
		UK	Broadway area	Distribution	Whitworth et al. 2000
			Scarborough coast	Distribution	Lee and Clark 2000

	Northern America	Canada	Alberta	Inventory	Cruden 1996
			Capilano Watershed, British Columbia	Inventory	Brardinoni et al. 2003
			Queen Charlotte Islands	Inventory	Martin et al. 2002
			Vancouver Island	Inventory	Guthrie 2002
		Puerto Rico	Tropical region	Inventory	Larsen and Torres-Sanchez 1998
		USA	New Mexico	Inventory	Brabb et al. 1989; Dikau and Jäger 1995; Reneau and Dethier 1996
			Northridge, California	Inventory	Harp and Jibson 1995
			San Fransisco Bay	Inventory	Ellen and Wieczorek 1988; Wieczorek 1984
			Utah	Inventory	Hylland and Lowe 1997
			Lewis County, Washington	Inventory	Dragovich et al. 1993
	Southern America	Brazil	Rio de Janeiro	Inventory	Amaral and Palmeiro 1997; Amaral et al. 1996; Jones 1973
		Chile	Antofagasta	Distribution	Van Sint Jan 1994
			Rinihue	Distribution	Erickson et al. 1989
		Colombia	Cudinamarca	Inventory	Forero-Duenas and Caro-Pena 1996
			Paez region	Distribution	Martinez et al. 1995
			Different regions	Inventory	van Westen 1994
		Ecuador		Distribution	Schuster et al. 1996; Tibaldi et al. 1995
		El Salvador	Corillera Costera	Distribution	Agnesi et al. 2002a
		Peru	Nevados Huascaran	Distribution	Keefer 1984; Plafker et al. 1971

	Pacific	Fiji	Viti Levu, Wainitubatolu Catchment	Distribution	Crozier et al. 1981
		Philippines	Luzon	Distribution	Arboleda and Punongbayan 1999
		Salomon Island	MISSING	Distribution	Trustrum et al. 1990
	South Pacific	Australia	Bumbunga Hill	Distribution	Twidale 2000
		New Zealand	Hawke Bay	Inventory	Glade 1997; Harmsworth et al. 1987;Page et al. 1994
			Taranaki	Distribution	Crozier and Pillans 1991; DeRose et al. 1993
			Waipaoa	Distribution	Page et al. 1999
			Wairarapa	Inventory	Crozier et al. 1980; Glade 1997; Trustrum and Stephens 1981
			Wairoa	Distribution	Douglas et al. 1986
			Wellington	Inventory	Brabhaharan et al. 1994; Crozier et al. 1978; Eyles et al. 1974, 1978; Glade 1997
	National scale				
	Asia	Armenia		Distribution	Boynagryan et al. 2000
		China		Inventory	Yin et al. 2002
	Europe	Austria		Inventory of large landslides	Moser 2002
		France		Inventory	Asté et al. 1995
		Hungary		Distribution	Juhász 1997
		Italy		Inventory	Guzzetti et al. 1994
		Spain		Distribution	Ferrer and Ayala-Carcedo 1997
		United Kingdom		Inventory	Jones and Lee 1994; Lee et al. 2000
	Nirth America	USA		Inventory	Brabb et al. 1999; Eldredge 1988; Wieczorek 1984
	South Pacific	New Zeland		Inventory	Glade 1996; Harmsworth and Page 1991

Table 3 Sources of information on spatial landslide susceptibility and hazard for different regions of the world [Glade & Crozier]

Continent	Country	Region	Type of analysis	Reference (s)
Ctchement and regional scale				
Africa	Ethiopia	Blue Nile Basin	Susceptibility	Ayalew 2000
Asia	China	Gansu Province	Hazard	Meng et al. 2000
		Hong Kong	Susceptibility	Dai and Lee 2001, 2002; Lee et al. 2001
		Lawngthlai, Southern Miziram	Susceptibility	Khullar et al. 2000
	India	Darjiling, Himalaya	Susceptibility	Basu 2000
		Garhwal Himalaya	Susceptibility	Anbalagan et al. 2000
		Munipur River basin	Susceptibility	Nagarajan 2002
		Rakti Basin	Susceptibility	Bhattacharya 1999
	Iran	Jiroft watershed	Susceptibility	Uromeihy 2000
		Khorshrostam area	Susceptibility	Mahdavifar 2000
		Shahrood drainage basin	Susceptibility	Feiznia and Bodaghi 2000
	Japan	Amahata River basin	Susceptibility	Aniya 1985
		Fukushima Pref.	Susceptibility	Sasaki et al. 2002
		Hanshin district	Susceptibility	Kamai et al. 2000
		Higashikubiki region	Susceptibility	Iwahashi et al. 2003
		MISSING	Susceptibility	Kubota 1994
		MISSING	Susceptibility	Massari and Atkinson 1999
	Jordan	Wadi Mujib Canyon	Susceptibility	De Jaeger 2000
	Korea	Yanghung area	Susceptibility	Lee et al. 2002
		Yongin	Susceptibility	Lee and Min 2001
	Nepal	Kulekhani watershed	Susceptibility	Dhakal et al. 2000
	Ukraine	Southern region	Susceptibility	Cherkez et al. 2000
Europe	Austria	Bad Ischl	Susceptibility	Fernández-Steeger et al. 2002
	Belgium	Manaihant	Susceptibility	Demoulin and Chung submitted
	Czech Republic	North Bohemia	Susceptibility	Hroch et al.

					2002
		Germany	Bonn region	Susceptibility	Schmanke 2001
			Rheinhessen	Susceptibility/ hazard	GLA 1989; Jäger 1997
			Schwäbische Alb	Susceptibility	Thein 2000
			Hessen and Thüringen	Susceptibility	Schmidt and Beyer 2001; Schmidt and Beyer 2002
			Bratica T. Basin	Susceptibility	Clerici 2002
		Great Britain	Barbados, Scotland	Susceptibility	Hodgson et al. 2002
			Starkholmes, Derbyshire	Susceptibility	Thurston and Degg 2000
		Italy	Calabria Region	Susceptibility	Carrara et al. 1977b
			Centenora catchment, Northern Apennines	Susceptibility	Casadei and Farabegoli 2003
			Corniglio	Hazard	Froldi and Bonini 2000
			MISSING	Susceptibility	Carrara 1989
			Mignone basin	Hazard	Del Monte et al. 2003
			Forlì-Cesena, Emilia Romagna	Susceptibility	Pistocchi et al. 2002
			Lecco province, Lombardy region	Susceptibility	Frattini and Crosta 2002
			Messina Straits Crossing site	Susceptibility	Baldelli et al. 1996
			Orcia drainage basin	Hazard	Del Monte et al. 2003
			Potenza region	Susceptibility	Ferrigno and Spilotro 2002
			Trionto basin	Hazard	Del Monte et al. 2003
			Umbria, Marche regions	Susceptibility and haxard	Carrara et al. 1995; Guzzetti et al. 1999
		Portugal	Coimbra region	Susceptibility	Tavares and Soares 2002
			Fanhoes-Trancao Region	Susceptibility	Fabbri et al. 2002; Zêzere et al. 2000
		Slovak Republic	Handlovská kotlina Basin	Susceptibility	Paudits and Bednárik 2002
			Kosice region	Susceptibility	Petro et al. 2002
		Spain	Deba Valley,	Susceptibility	Fabbri et al.

			Province Guipuzoa		2002
			Rio Aguas	Susceptibility	Griffiths et al. 2002
			Malorca Island	Susceptibility	Mateos Ruiz 2002
			La Pobla de Lillet area	Susceptibility	Baeza and Corominas 1996; Santacana et al. 2003
			Jerte Valley	Susceptibility	Carrasco et al. 2000
		Turkey	Mengen	Susceptibility	Gökceoglu and Aksoy 1996
			Yenice	Susceptibility	Ercanoglu and Gokceoglu 2002
	North America	Canada	Hull-Gatineau region, Quebec	Susceptibility	Clouatre et al. 1996
			Lilloet River watershed, British Columbia	Susceptibility	Holm et al. 2004
		USA	Anchorage	Susceptibility	Dobrovolny 1971
			Cincinnati, Ohio	Hazard	Bernknopf et al. 1988
			Cincinnati, Ohio	Hazard	Bernknopf et al. 1988
			Oregon Coast Range	Susceptibility	Schmidt et al. 2001
			San Mateo County	Susceptibility	Brabb 1993; Brabb et al. 1978 Roth, 1983 #2940
			Travis County, Texas	Susceptibility	Wachal and Hudak 2000
			Washington State	Hazard	Harp et al. 1997
		Jamaika	St. Andrew	Susceptibility	Maharaj 1993
		Argentina	Mendoza province	Susceptibility	Moreiras 2004
	South America	Brazil	Rio de Janeiro	Susceptibility	Barros et al. 1991; Fernandes et al. 2004
		Colombia	Chinchina region	Hazard	Chung et al. 1995; Chung et al. 2003; van Asch et al. 1992
		El Salvador	Corillera del Balsamo	Susceptibility	Agnesi et al. 2002b
	Pacific Islands	Fiji	Viti Levu	Susceptibility	Crozier 1989;

					Greenbaum et al. 1995
		Papa New Guinea	Ok Tedi	Susceptibility	Crozier 1991
	South Pacific	Australia	Southeast Queensland	Susceptibility	Hayne and Gordon 2001
		New Zealand	Hawke Bay	Susceptibility	Glade 2001
			Wairarapa	Hazard	Wilson and Crozier 2000
	National scale				
	Africa	South Africa		Zonation based on expert judgement	Paige-Green 1985
	Asia	China		Hazrd mapping and management	Tianchi 1996
	Europe	Germany		Qualitative assessment	Dikau and Glade 2003; Glade et al. In prep

Table 4 Selection of spatial susceptibility and hazard analysis of debris flow for different region of the world [Glade & Crozier]

Continent	Country	Region	Type of analysis	Reference (s)
Regional and catchement scale				
Asia	Japan	Miyakejima volcano	Distribution	Yamakoshi et al 2003
	Kazakstan	Southeast	Susceptibility	Medeuov and Beisenbinova 1997
	Nepal	Kulejhani watershed	Distribution	Dhital 2003
	Taiwan	Chen-You-Lan River basin	Hazard	Lin et al 2000
		Central Taiwan	Distribution	Cheng et al 2003
Europe	Austria	Salvensen valley	Distribution	Becht and Rieger 1997
	Germany	Faltenbach valley	Susceptibility	Becht and Rieger 1997
	Iceland	Gleidarhjalli area	Hazard	Decaulne and Saemundsson 2003
		Northwestfjords region	Susceptibility	Glade and Jensen 2004
	Italy	Serre Massif – Calabria	Distribution	Calcaterra et al. 1996a
		Circum-Vesuvian areas & Sarno Mountains	Distribution / Hazard	Calcaterra et al. 2000; Cinque et al. 2000 ; D´Ambrosio et al. 2003a; 2003b; Del Prete et al. 1998; Fiorillo et al. 2001; Pareschi et al. 2000
		Isarco valley	Distribution	Villi and Dal Pra´ 2002
		Lecco area, Lombardy	Susceptibility	Bathurst et al. 2003
		Versilia, Garfagnana	Susceptibility	Martello et al. 2000
	Spain	Upper Aragón and Gállego valley, Central Pyrenees	Bivariate Statistics	Lorente et al. 2002
	Switzerland	Mattertal, Wallis	Distribution	Dikau et al. 1996
North America	USA	Honolulu of Oahu, Hawaii	Hazard	Ellen and Mark 1993; Ellen et al. 1993; Reid et al. 1991
		Madison County, Virginia	Hazard	Wieczorek et al. 2003

			Mount Rainier, Washington	Hazard	Hoblitt et al. 1995; Iverson et al. 1998; Schilling and Iverson 1997; Scott et al. 1995
			Northwestern California	Distribution	Reid et al. 2003
			Noyo watershed, California	Susceptibility	Dietrich and Sitar 1997
			Oakland, California	Susceptibility	Campbell and Bernkopf 1997; Campbell et al. 1994
			Oregon Inventory &	Susceptibility	Hofmeister 2000; Hofmeister and Miller 2003
			San Mateo County, California	Susceptibility	Mark 1992
			Santa Cruz Mountain, California	Inventory	Wieczorek 1984
			Blue Ridge of Central Virginia	Hazard	Wieczorek et al. 2000
			Wasatch Front, Utah	Distribution	Wieczorek et al. 1989
	South America	Ecuador	Pichincha massif	Hazard	Canuti et al. 2002
		El Salvador	San Salvador, San Vicente & San Miguel volcanoes	Hazard	Major et al. 2003
		Venezuela	Northern region	Distribution	Lopez et al. 2003
	South Pacific	Australia	Montrose, Victoria	Hazard	Fell and Hartford 1997
			Wollongong	Distribution	Flentje et al. 2000
	National scale				
	Europe	Austria		Distribution	Andrecs 1995
		Switzerland		Distribution	Rickenmann 1990; Zimmermann et al. 1997
	North America	USA		Inventory of debris flow, avalanches, and mud flows	Bert 1980; Brabb et al. 1999

Tabe 5 Previous projects on debris-flow and landslides financed by EU	3HAZ CORINTH	The project will contribute to better measure, model, and predict the processes leading to earthquakes, landslides, submarine slides and tsunamis, and their effect in term of hazard. The target area is the rift of Corinth, well known for its exceptionnal activity with respect to these hazards. This work will focus on the western end of the rift, close to the cities of Patras and Aigion, where the risk is highest.
	ALARM Assessment of LAndslide Risk and Mitigation in Mountain Areas	ALARM is a 3-year research project (2001-2004) funded within V Framework Programme of the European Union (EC-DG Research, Environment and Sustainable Development) and the Polish State Committee for Scientific Research. ALARM is an acronym of the project Assessment of LAndslide Risk and Mitigation in Mountain Areas. Its objective is to improve the ways of preventing and limiting landslides and landslides related risk in Europe. It was landslides risk in mountain areas that made the Polish Geological Institute Carpathian Branch, a research unit for many years dealing with landslides processes in the Polish Carpathians where anthropopression constantly rises, enter the project.
	ARMONIA Applied multi Risk Mapping of Natural Hazards for Impact Assessment	The overall aim of the research project ARMONIA (Applied multi Risk Mapping of Natural Hazards for Impact Assessment) is to provide the European Commission with a new harmonised methodology for producing integrated risk maps to achieve more effective spatial planning procedures in areas prone to natural disasters in Europe.
	Damocles Debris fall Assessment in Mountain Catchments for Local End-Users	Will develop and apply advanced modelling technologies to assess hazards posed by rapid slope failures in mountain areas and will disseminate these technologies to local end-users for applications in land use planning. In order to accompish these goals, the project integrates reaserch-based model development with the direct involvement of local planning and civil protection authorities as data suppliers, advisors, and recipient of the project results.
	LESSLOSS Risk Mitigation for Earthquakes and Landslides (Contract Number: GOCE-CT-2003-505448)	Earthquake and landslide risk is a public safety issue that requires appropriate mitigation measures and means to protect citizens, property, infrastructure and the built cultural heritage. Mitigating this risk requires integrated and coordinated action that embraces a wide range of organisations and disciplines. For this reason, the LESSLOSS IP is formulated by a large number of European Centres of excellence in earthquake and geotechnical engineering integrating in

		the traditional fields of engineers and earth scientists some expertise of social scientists, economists, urban planners, information technologists. The LESSLOSS project addresses natural disasters, risk and impact assessment, natural hazard monitoring, mapping and management strategies, improved disaster preparedness and mitigation, development of advanced methods for risk assessment, methods of appraising environmental quality and relevant pre-normative research.
	SLAM Service for LAndslides Monitoring	SLAM is a service able to generate three products oriented to landslide monitoring and mapping. The products are conceived for the hydrogeological risk management. The SLAM products derive from integration of data acquired by traditional methodologies and by Earth Observation into a GIS environment. The SLAM project is funded by the European Space Agency (ESA) within the framework of the DUP program (Data User Programme).
	THARMIT Torrent Hazard Control in the European Alps. Practical Tools and Methodologies for Hazard Assessment and Risk Mitigation.	The main aim of the project is to increase the control of torrent hazard by a deeper understanding of practical tools and methodologies for risk assessment and mitigation, focusing on prevention and reduction of risks.
	GALAHAD - Advanced Remote Monitoring Techniques for Glaciers, Avalanches and Landslides Hazard Mitigation	GALAHAD addresses to landslides, avalanches and glaciers -related hazard mitigation, through the development of advanced monitoring techniques and the improvement of forecasting methods and tools. The GALAHAD project aims at developing innovative and fundamental functionalities of remote monitoring techniques, namely Ground Based SAR Interferometry, derived from satellite applications, and Terrestrial Laser Scanning, enabling the improvement of reliability, precision and operative usefulness of the measurements and of the forecasting capacity of the interpretation tools. The objectives of GALAHAD are: 1. Reducing landslide, avalanche and glaciers risks in Europe and worldwide, improving the forecasting capacity and therefore the pre -disaster management effectiveness, through advanced techniques for terrestrial remote monitoring.

		2. Increasing the scientific and technological knowledge in the fields of landslides, avalanches and glaciers hazards, providing innovative instruments of investigation, and improving and validating the interpretation tools. 3. Providing operational, effective and low cost solutions for remote monitoring and interpretation methods, which will become a standard at European level.

Chapter 2

SNOW AVALANCHES

2.1 Introduction

Introduction

Since people began to live in, play in and travel through mountains, the increasing number of avalanche fatalities increased the need for improved forecast methods and broader area coverage. Reducing avalanche accidents relies on avoiding avalanches terrain during time of unstable pack conditions. Therefore the determination of these times and the level of the danger is the main task of avalanches forecasting. Even if in Europe scientifically based avalanches forecasting originated in the early 1900s [LaChapelle, 1980], modern approach is a sophisticated yet inexact endeavour. New computer based models are growing fast but the forecast is still based on so called “conventional techniques” relying on an analysis of terrain with respect to the factors defined by Atwater [1954] half a century ago. Then, the most important variable in valuing the level of hazard is the personal experience and knowledge of the forecaster, thus resulting into a high level of arbitrariness to the process, which is eventually based on educated guess.

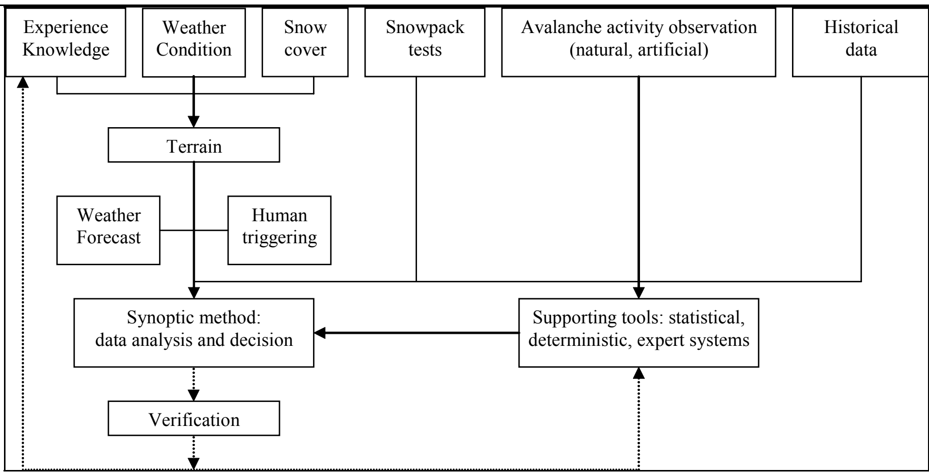
Avalanche forecasting consists essentially in the daily assessment of the avalanche hazard for a given region. The thereof derived warnings should describe the avalanche situation, *i.e.* give information about the place, the time and the probability of release for a specific type of avalanches. This information are summarized using an international code; in Europe five levels are considered:

1 (low):

The snowpack is generally well bonded and stable. Triggering is possible only with high additional loads on a few very steep extreme slopes. Only a few small natural avalanches (sluffs) possible. No hazard from avalanches. Virtually no restrictions on off-pists & back-country skiing & travel.

2 (moderate)

	The snowpack is moderately well bonded on some steep slopes, otherwise generally well bonded. Triggering is possible with high additional loads, particularly on the steep slopes indicated in the bulletin. Large natural avalanches not likely. Virtually no hazard from natural avalanches. Generally favorable conditions. Routes should still be selected with care, especially on steep slopes of the aspect and altitude indicated. 3 (considerable) The snow pack is moderately to weakly bonded on many steep slopes. Triggering is possible, sometimes even with low additional loads. The bulletin may indicate many slopes which are particularly affected. In certain conditions, medium and occasionally large sized natural avalanches may occur. Traffic and individual buildings in hazardous areas are at risk in certain cases. Precautions should be taken in these areas. Off-pists and back-country skiing and travel should only be carried out by experienced persons able to evaluate avalanche hazard. Steep slopes of the aspect and altitude indicated should be avoided. 4 (high) The snow pack is weakly bonded in most places. Triggering is probable even with low additional loads on many steep slopes. In some conditions, frequent medium or large sized natural avalanches are likely. Avalanches may be of large magnitude. In hazardous areas, closure of road and other transport is recommended in some circumstances. Off-pists and back-country skiing and travel should be restricted to low-angled slopes; areas at the bottom of slopes may also be hazardous. 5(very high) The snow pack is generally weakly bonded and largely unstable. Numerous large natural avalanches are likely, even on moderately steep terrain. Extensive safety measures (closures and evacuation) are necessary. No off-pists or back country skiing or travel should be undertaken. However, the forecast procedure can be carried out at different levels. The main aim of the modern techniques is to minimize the uncertainty of the prediction with regard to the temporal and spatial variability of the snow cover, any incremental changes in snow and weather conditions and any variations in human perception and estimation [McClung, 1998]. Therefore it seems reasonable to base a classification of avalanche forecasts on an analysis of its spatial and temporal scale. Thereby, the goodness of the estimation depends on the spatial and temporal scale of the used data. The variables usually employed in a forecast analysis are of three types: Snow and weather data measured at or above the surface, mostly numerical; Snow pack factors, data from snow pit analysis, mostly non-numerical; Stability factors, data such as stability tests or observed avalanche occurrence which give direct information about past and present avalanche activity, non-numerical character. In general the lower the number of classes involved in the analysis, the lower the accuracy level of the forecast. Following this concept, the forecasting predictions are placed into three main categories in terms of availability and informational accuracy of singular data [Hageli and McClung, 1999].

<table>
<tr><td></td><td>The first one is a true forecast, where the probability of avalanche occurrence is determined before the incremental changes in weather and snow conditions have happened. In this case, all three data classes are purely predicted. The only inputs are used of snow stability data and past avalanche observation: therefore this forecast can only be valid on the synoptic scale (e.g. significant portion of a mountain range). This type of prediction is typical of avalanche bulletins which depend heavily on the accuracy of weather forecast and on the personal experience of the decision maker.
The second type of forecasts is made while the incremental changes are happening or immediately after they have occurred. The characteristics of the situation are observed (stability tests are performed) and even some data about weather (early morning observation), snow and snowpack are known: this type of forecasts is generally applied to meso-scale areas and often include individual mountain passes or ski resorts.
The third kind of predictions are sought when forecasts are made for the micro-scale (e.g. individual terrain features), and therefore they are the ultimate goal of every forecast process. They are made after the incremental changes in snow and weather conditions have taken place, extensive data sampling has been made, avalanche occurrences have been scanned, and skiing has been performed. At this stage the forecaster has so much accuracy in information at hand that profound predictions can be made on the micro-scale (e.g. individual ski run or terrain feature). This type of forecast is generally expensive and is used for example in helicopter skiing and backcountry travelling.
However the most common forecast belongs to the first group and the results of this practice are the daily avalanche bulletins.</td></tr>
<tr><td>Avalanches bulletin</td><td>Since dry slab avalanches represent the main threat for skiers and in general for human activity, the forecasts usually focus on these phenomena. The framework used is almost the same in all Europe differencing only in some preliminary measurements and in some supporting tools. The core is formed by the so called “synoptic method” (Figure 5) and consists essentially in combining information from field observations, weather forecasts and forecaster experience of the particular situations on the investigated area.
The main uncertainty factor is certainly the weather prediction especially in alpine regions where conditions can change rapidly, in space and time. Therefore, field measurements and observations are a precious base for the forecaster even though they are time consuming and require relevant effort</td></tr>
<tr><td>Figure 5 The Synoptic method for forecasting the avalanche hazard with supplementary supporting tools (Shweizer and Fohn, 1994)</td><td>
</td></tr>
<tr><td>Spatial and temporal</td><td>Unlike the debris flow or the rock avalanche forecasting, avalanche forecasting must be</td></tr>
</table>

scale	considered at different spatial scales especially : o The massif scale (~500 km^2) where one can consider that there is, on average, a good spatial homogeneity of the meteorological parameters in term of elevation, aspect and slope, and where a certain number of weather and snow observations are daily performed. At that scale, one can still neglect the local effects mainly linked to the orography and to the snowdrifting and one can so make the assumption that the snowcover and its afferent dangers are directly forced by the weather conditions. The homogeneity of the snowpack inside the massif (which has been chosen in function of this constraint) allows so the drawing up of a diagnostic of an avalanche danger also in term of elevation, aspect and slope without any direct reference to a precise geographic localisation. The hazard assessment at that scale will be mainly described in the following items; one can however consider that in the different European countries, this assessment is operational with good results. o The local scale of the avalanche path where the small scale phenomena play an important role such as spontaneous avalanche and local sluff ; all these effects are combining with each others and so increase the number of degrees of freedom of the whole system and make more difficult a fine estimation of the danger. At that scale, an increased effort in matter of observation and human skill is still necessary because the forecasting automatic procedures cannot work without all these basic information. One can consider that automatic systems at that scale are still relevant of research and experiment area. One will find yet thereafter the description of some attempts as the operational applications of road protection in Val d'Aran in Spain by the General Council services or the protection of the Col des Montets road by Météo-France The different notions of avalanche forecasting and protection can also imply two temporal analysis levels: o The time forecasting of avalanche hazard which takes into account the time evolution of the snow cover characteristics and is concretized generally by bulletins and reports for information or alert , by temporary decisions (road closure for instance) and also by artificial triggering for security. o The protection, which is mainly based on historical and past avalanche knowledge, will give indications for structural mitigation measures and for the elaboration of avalanche localisation maps. These maps imply also a necessity of determination of different characteristics of the mentioned avalanches as intensity (especially impact pressure) and possible maximum extent.
	2.2 Snowpack tests
Snowpack Tests	Information on the structure and stability of the snow pack within an area is essential to assign current and future avalanche conditions. The snow pack tests are the main way to collect it. Test profiles are the most common type of snow profile. The first step is to define the most representative points for test making, depending on the information required. The

location could be on a possible fracture line, but even on the slope or in other sites, especially when starting zones are not safely accessible.

The main observed parameters are: the new snow depth, the snow pack temperature, the location of each major layer boundary, the snow hardness, observed performing the hand hardness test [Pielmeier and Schneebeli 2002], the grain form and size [Colbeck et al, 1990], the liquid water content [Colbeck et al, 1990] and snow density. The collection of these values is usually reported in a hand made graphical representation (***Figure 6***).

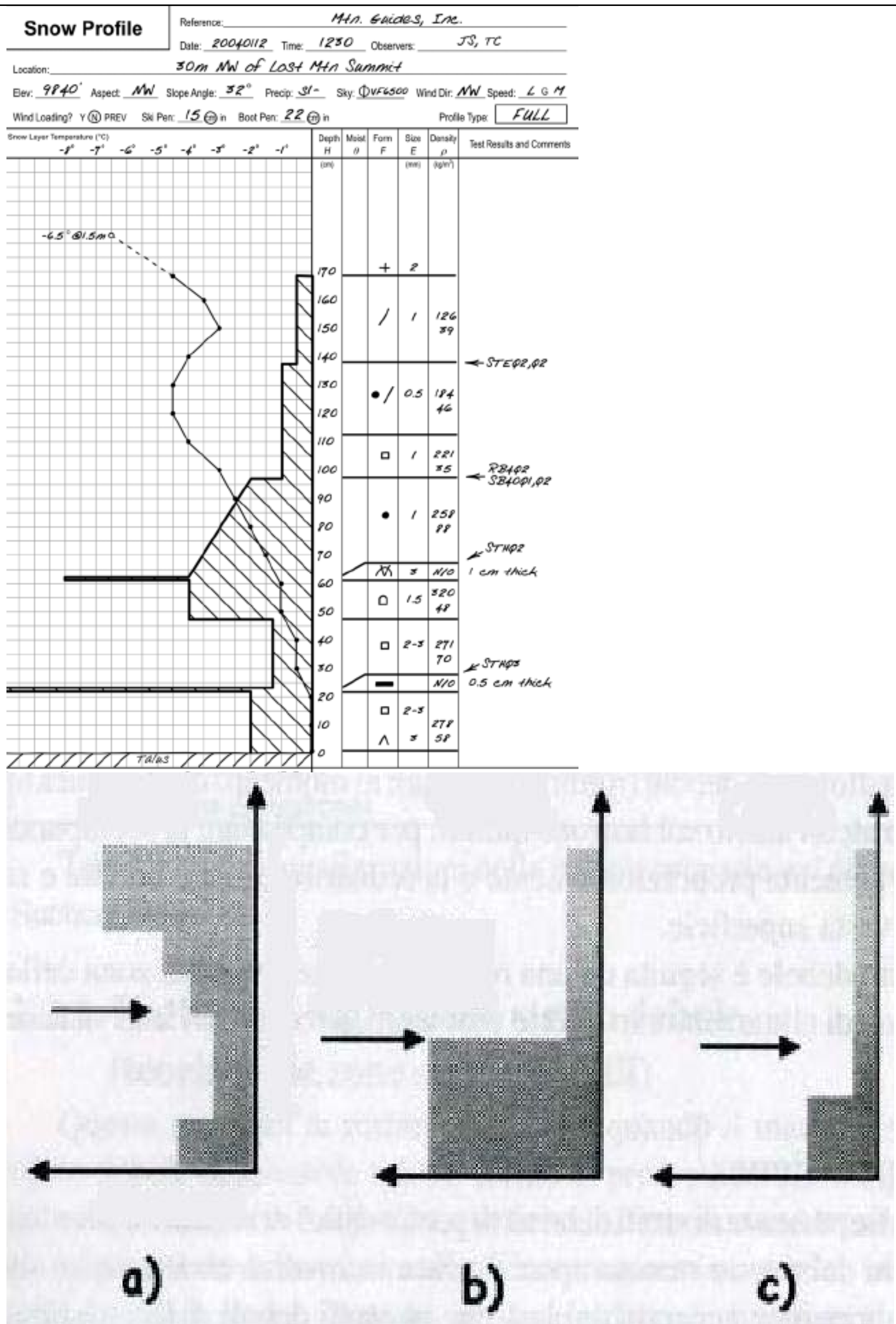


Figure 6 Snowpack representation and weak layer evaluation. In case c the hoar weak layer is not visible from field observation (Barbolini, 2005)

As we said in section 3.2.1, sometimes weak layer can not be seen with a standard snow pack observation and some other stability tests have to be performed. Here the most used in Italy are reported.

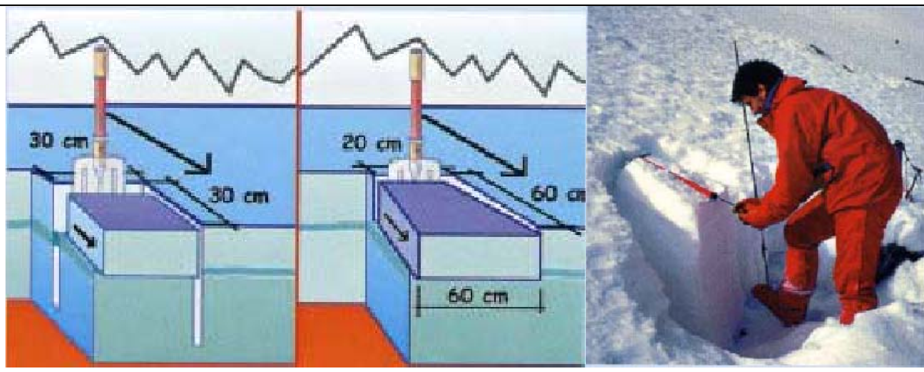
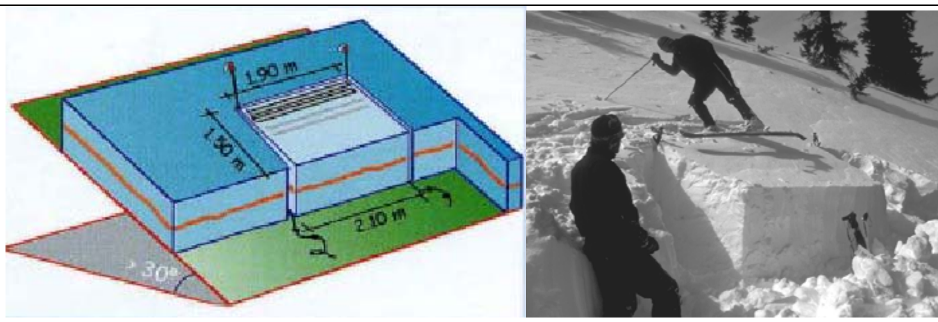
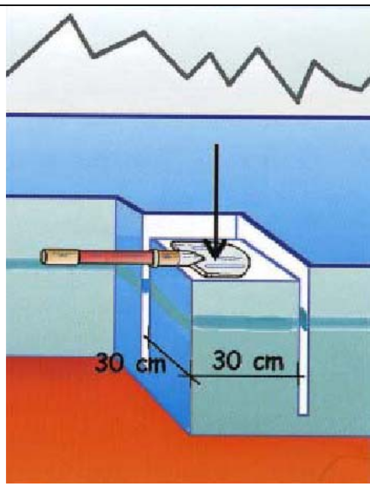
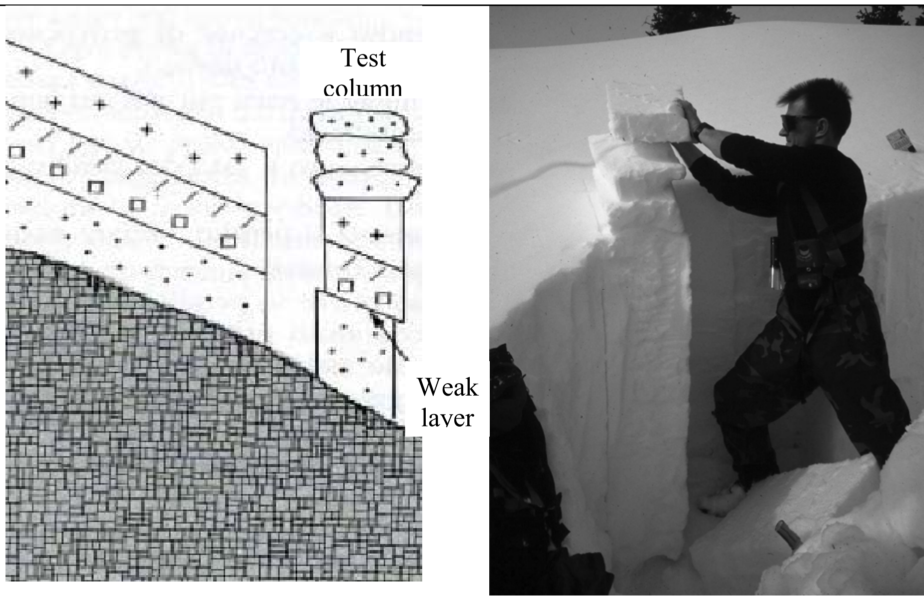
Shovel Shear test	This test provides information about the location where the snow could fail and a qualitative assessment of weak layer strength. Usually, it does not produce useful results in layer close to the snow surface. It consists in making vertical cuts in the snow pack, so obtaining a column with a cross section measuring 20cm x 60cm x 60cm (***Figure 7***). First insert the shovel in the back cut and then, applying a force in the downslope direction, mark when the failure occurs in a smooth shear layer. By repeating the test two times at least it is possible to estimate the equivalent shear strength and the position of the weak layer.
Figure 7 Shovel shear test scheme (Barbolini, 2005)	
Rutschblock Test	The *rutschblock* test is a slope test developed in Switzerland in the 60s. A snow block is isolated on four sides and then is loaded by increasing loading steps (first just approaching the block from above and finally jumping on it) (***Figure 8***). The level of the pressure applied and the position of the eventual sliding surface give useful information about snow pack characteristics; one noticed that this is not a one-step stability evaluation. The results, as in all the other stability tests, must be coupled with snowpack and weather histories, shear quality, snow structure.
Figure 8 Rutschblock Test (Barbolini, 2005)	
Compression Test	The compression test was born in Canada in the 1970s. This test identifies weak layers and is most effective at finding layers in the upper portion of the snow pack, the same layer usually most sensitive to human triggering (***Figure 9***). The tester taps a shovel placed on the top of an isolated column of standard size until the failure is reached. Limitations of the compression test include sampling a relatively small area of the snow pack and possible variation in force applied by different observers.

Figure 9 Compression test scheme (Barbolini, 2005)	
Loaded column Test	This test allows the observer to estimate how much additional mass a weak layer might support before it will fracture (***Figure 10***). Although this test can produce a precise value of the pressure, this number is regarded only as an indicator of the additional load that the snow pack can sustain, because many other factors could occur and the dynamics of the trigger are much more complex than the ones performed by the test.
Figure 10 Loaded column test (Barbolini, 2005)	
	The procedure consists in isolating a standard column on snow from the pack and simply adding one by one different blocks of snow since the failure is reached.
	2.3 Supporting tools
	Despite a lot of electronic tools included nowadays in the process of avalanche forecasting, the avalanche hazard can not fully be calculated in a strict sense (by algorithms). Even if none of the supporting tools are, so far, reliable enough to substitute the human expert, they may become an objective partner of the forecaster. For instance, numerous operational systems based on the statistical approach using a long term data base were developed in several countries and are widely used [McClung and Tweedy, 1994] both for local and for regional avalanche forecasting. The two most popular methods are the discriminant analysis and the nearest neighbours

	[McClung and Schaerer, 1993]. Usually, data from observations of weather, snow and avalanche activity are considered and starting from the assumption that similar environmental conditions should lead to similar avalanche situations, a prediction of potential avalanche activity is possible. These models can only improve the work of inexperienced forecasters and may influence experienced forecasters, but may rarely be a decisive help in determining the degree of hazard for a region. Another approach is the purely deterministic one: it simulates avalanches on the basis of a model of snow cover and using principles of fracture mechanics. The SNOWPACK [among others, Lehning *et al.*, 2000 and Raderschall *et al.*, 2005, for n applicaton of SNOWPACK in Italy] model of such approach is an example. It was developed by the Swiss Federal Institute for Snow and Avalanche Research and allows to simulate the evolution of the snowpack on the basis of only meteorological parameters (wind speed, radiation, snow and air temperature, fresh snow amount) observed by automatic sensors. This snow pack model is able to integrate hand made field observations, offering information even regarding sites that are partially or totally inaccessible during winter. The last type of models is the "expert systems" that represent the idea of simulating the "decision making" process of an expert. Most of them are symbolic computing systems, *i.e.* use rules which were formulated explicitly by human experts *e.g.* MEPRA [Giraud, 1991] and AVALOG [Bolognesi, 1993]. Not only numerical instruments should be considered. To improve the avalanche forecasting it is possible to act on all the part of process: for example the step of verification of the prediction could be more efficient. An Italian project [Pedrazzoli *et al.*, 1999] tries to make systematic the phase of valuation of the forecast giving specific guidelines to the evaluator. The proposal is to eliminate as possible all subjective factors in the verification and to optimize the field work steps since they are one of the most expensive phases in the process.
	2.4 Some example of the territorial organisation of the avalanche hazard forecasting in several European countries
	The main aspect to notice here is that the geographical and administrative organisation of the avalanche hazard estimation is very different from one country to another one in Europe. Two main kinds of organisation exist : A system with a central office providing information on the whole country (ex : France, Switzerland, Norway). Some of these centres are also meteorological institutions, other not. A system based on the territorial organisation where this task is devoted to regional centres, sometimes depending on regional public administrations. (ex : Italy, Austria …)
Introduction	The main aspect to notice here is that the geographical and administrative organisation of the avalanches hazard estimation is very different from one country to another one in Europe. Two main kinds of organisation exists: – A system with a central office providing information on the whole country (ex. France, Switzerland, Norway…). Some of these centres are also

	meteorological institutions, other not. – A system based on the territorial organisation where this task is devoted to regional centres, sometime depending on regional public administrations (ex. Italy, Austria…)
In Italy	The editing and diffusion of bulletins in Italian Alps is charged to the different regional and provincial services, which act separately and autonomously to accomplish the local needs. Anyway, the uniformity and the coordination of information are guaranteed by the AINEVA (Interregional Snow and Avalanche Association), with his main office in Trento. The central information contained in the bulletin are: - New snow amounts present and forecasted at different altitudes; - Snowpack conditions; - Present hazard level; - Weather conditions (cloud cover, temperature, wind, precipitation) at the time of release and a forecast for the next 24-48 and 72 hours (only on Friday); - Avalanche hazard level forecasted including the possible type of avalanches and the most dangerous local areas. The data base used for this forecast includes: - 147 automatic meteorological stations located all over the Alps, in the most representative points; - 159 permanent areas where daily are registered hand made observations of snowpack parameters and avalanche activity; - 137 points where penetrometric tests are weekly carried out; - 70 times a week tests are carried out including stability tests in the most sensitive zones in base of the particular needs. The bulletins are usually published 3 times a week (on Monday, Wednesday and Friday), but sometimes, in particularly dangerous conditions, they are diffused daily. The spatial scale regards the regional area, but some indications about geo-climatic sub-regions (***Figure 11***) are often given.

Figure 11 Regional and sub-regional division of Italian Alps for avalanche bulletin (www.aineva.it)

In France (www.meteo.fr/montagne)

The avalanche hazard forecasting is an organic task of Météo-France and the covered mountainous area is about 20000 km^2 inside the Alps, Pyrenees and Corsica. The system implemented by Météo-France with the help of his partners, mountain professionals, is based on different structures :

<u>Several local centres of Météo-France specialized « snow and mountain »</u>

These local centres are geographically located according to the terrestrial French « departemental » organisation. They concentrate and analyse the data provided by the observation network. They make and distribute the bulletins of avalanche hazard forecasting for the massifs of their own « departement ». 9 centres perform these tasks: Chamonix, Bourg-Saint-Maurice, Grenoble, Briançon, Nice, Perpignan, Toulouse, Tarbes et Ajaccio.

<u>Two « focal points</u>

- The focal point « Alpes-Corse » is at the charge of the Grenoble centre.
- The focal point « Pyrénées » is at the charge of the Tarbes centre.

These are specific structures created by Météo-France for survey and alert purposes when the avalanche danger becomes high and worrying for the security of people and goods. These « focal points » are also contacts for the different media

<u>The Snow Study Center (CEN)</u>

This specialized centre is a laboratory of the research branch of Météo-France (Centre National de Recherches Météorologiques – CNRM) and has been located in Grenoble for 35 years. The centre is in charge of the national coordination of the avalanche hazard forecasting actions in Météo-France. Its main activity still remains in the research area : improvement of the knowledge of snow material, building and tuning of helping tools for a better assessment and a performing forecasting of the avalanche

	hazard in an operational framework. One of the main modeling result of the centre is the SCM (see §4.6.3) chain composed of the models Safran / Crocus / Mepra aiming at simulating the time evolution of the snowpack as well as the avalanche hazard. <u>The snow-weather observation network, in charge of the observation and the local interpretation</u> This network includes nearly 180 observation points located at medium elevation (between 1500 and 2000m a.s.l) as well as about 20 (30 in the forthcoming years) automatic stations between 1500 and 3000m a.s.l. Most of the observers are people from the ski resorts (snow patrollers) ; but some agents from different Administrations as Equipment, Forests, Mountain Services of Police and Gendarmerie (Army), High Mountain Military School participate also to these measurements. The training of all these observers is provided by Météo-France
In Switzerland	The central SLF avalanche warning service, in Davos, works from a combination of many observations : the development of the now cover throughout the winter, the current snow situation, and the current weather and its expected development. The covered area is about 27000 km^2. A dense network of on-site SLF observers and automatic measuring stations continuously delivers first-hand information on snow depth, wind, temperature and other factor such as local avalanche activity. Weather data flow in from numerous sources, for example from MeteoSchweiz. Modern computer systems collect, process and evaluate the information. In parallel, SLF specialists regularly examine the snow profile in potential avalanche rupture zones. Even with all these data to hand, avalanche forecasting is no ordinary office job. Warmly wrapped, the specialists regularly leave their desks to make personal observations and scrutinise changes in the snow profile, applying their experience and technical know-how to use SLF's latest aids. Beside the daily reports to the public, the SLF provides running information on imminent avalanche danger to local services, enabling them to take action for the safety of settlements and transport lines in good time.
In Spain	Due to the territorial organisation of Spain, the avalanche hazard forecasting is performed by different institutes. In the Western part of Pyrenees, INM (Institut National of Météorology) has this charge, in the Eastern part it is done by the ICC (Instituto Cartográfico de Cataluña).
In Austria	With the Imperial Resolution of the 23 of June 1851, Emperor Franz Joseph authorised the establishment of "a central institute for meteorological and magnetic observations", to become the Central Institute of Meteorology and Geomagnetism, which can be traced back to an initiative of the Austrian Academy of Science. Today, as a partially incorporated federal establishment, the Central Institute is a modern service provider, with regional offices for Salzburg and Upper Austria, Carinthia, Tyrol and Vorarlberg, and Styria.
In Norway	NGI is a private foundation for research and advisory services, located in Oslo, Norway. NGI was established in 1953 and currently employs a staff of 136 persons of which 95 have university degrees. As the Norwegian topography, geology and climate cause a relatively large number of snow avalanches and slides, the Norwegian Parliament has decided in 1972 that snow avalanche research and advisory services in Norway should be placed at NGI and the avalanche warning at the Meteorological Institute. Since then NGI has been involved in R&D and consultant work on different

	items related to snow avalanches, quick clay slides, rock slides and debris flows, as well as all kinds of subaqueous gravity mass flows. It includes: risk analysis, hazard zoning, risk evaluation and analytical/numerical simulations.
In Germany	The organization and coordination of the avalanche warning tasks in Bavaria is at the charge of the different safety and disaster control authorities (municipalities, district administration offices, district governments of Upper Bavaria and Swabia) in cooperation of the Avalanche Warning Centre which is located in the Bavarian National Office for Environment. It exists also different avalanche commissions which are consulting committees for the security authority (municipality, district administration office). They are composed of local well-informed and mountain-experienced specialists and make appropriate recommendations for avalanche safeguards. The avalanche danger is based on an estimate of the situation by the local avalanche commission. No important avalanche accident within the supervised zones have occurred since the establishment of the avalanche warning service Bavaria in the year 1967.
In other European countries and areas	Slovénia : (tel : 6619822) The Environmental Agency is a branch of the Ministry of the Environment and Spatial Planning. It performs expert, analytical, regulatory and administrative tasks related to the environment at the national level. Thus the Agency mission is to manage, analyse and forecast natural phenomena and processes in the environment, and to reduce natural threats to people and property. Scotland : (tel : 1463713191) : (http://www.sais.gov.uk/about_avalanches/). The Scottish Avalanche project began as an avalanche forecasting service funded by the Scottish Sports Council. The Scottish Avalanche Information Service (SAIS) avalanche forecasts has begun on the 20th of December in 1993. The web site is hosted by the Computing Science Department at the University of Glasgow. Poland : (http://www.topr.pl/) Tatrzańskie Ochotnicze Pogotowie Ratunkowe, 34-500 Zakopane, ul.Piłsudskiego 63a, tel. (+48)(18) 2014731 fax : (+48)(18) 2015560, E-mail: topr@topr.pl , telefon ratunkowy: (+48) 601-100-300 Iceland : (http://www.vedur.is/english/) THE ICELANDIC METEOROLOGICAL OFFICE (IMO) is in charge of the avalanche hazard forecasting. Bustadavegur 9, 150 Reykjavík, Tel: (354) 522 6000, Fax: (354) 522 6001 Slovakia : (http://www.laviny.sk/) Lavínovej situácii: tel.: 044 / 5591 695, Stredisko lavínovej prevencie**,** tel.: (044) 5591695, **,** 0903 624 130**,** fax: (044) 5591 637 Czech Republic: (http://www.horskasluzba.cz/laviny/) **.** The Horska Sluzba has the charge of delivering forecasts and advices for avalanche danger. Roumania**:** Avalanche hazard forecasting has started since January 2004 at National Météorological Administration (Admistratia Nationala de Meteorologie) of Roumania by a bilateral cooperation with Météo-France. The organisation is presently in test.
	2.5 Avalanche Hazard Forecasting at the mountain massif scale
Forecast centres in France (from Météo-France)	9 snow and weather centres (stations of Météo-France, generally called « mountain centre ») are in charge of the synthesis of the data coming from the observation network of their territorial area (the French territorial « departement » organization). They study and describe daily the snowcover state and, in function of the expected meteorological conditions, forecast the snow evolution and the afferent risks and dangers for the next days. They cover 23 massifs in the French Alps, 11 in the

	Pyrenees and 2 in Corsica. An automatic application allows (cf. § 4.6.6) the different functions of recording, controlling, monitoring and sending both data and forecast reports which are available between 3 and 3 pm for the next day. A full chain (SCM ; cf § 4.6.4) of numerical simulation of the snowcover at the scale of the massif gives a first guess to the forecasters about the stability and the structure of the snowpack. This indication is particularly precious at the beginning or the end of the winter season when the observation network is quite scarce. The mountain centres ensure also the technical visits and a close contact with local observers of the snow-weather observation network. They execute also some complementary field measurements , especially expert reports in case of avalanche accidents.
Forecast centres in Switzerland (from SLF)	The specialized WSL/SLF service analyses twice a day the snow and weather situations. Forecasters have a daily meeting during the afternoon (3 pm). Based on the day observations and the results of numerical models for meteorological forecasts they draw up a snow and stability 24h forecast which is described in a bulletin available near 5 pm and in different maps (danger areas, snow depths …). Toward 6 am, the morning, the bulletin is updated in order to include the observations of the past night. The forecasters have also the results of the snow model SNOWPACK (cf 4.6.4) running in different observation points.
Regionalized forecast centres in Italy.	REGIONE PIEMONTE ARPA Piemonte, works in the area of the regional activities in matter of environment, Tel 011 3168203 - fax 011 3181709 http://www.arpa.piemonte.it; with a covered area of about 12000 km^2. The used forecasting method is mostly inductive and based on the experience of the forecaster in analyzing the data. REGIONE AUTONOMA VALLE D'AOSTA ,Direzione Tutela del Territorio Ufficio Valanghe ,. Tel 0165 776600/1 - fax 0165 776804 http://www.regione.vda.it with a covered area of about 3262 km^2. The used forecasting methods are human strongly dependent on the forecaster's experience. REGIONE LOMBARDIA ARPA Lombardia, Centro Nivometeorologico - Dipartimento di Sondrio, Tel 0342 914400 - fax 0342 905133 http://www.arpalombardia.it/meteo with a covered area of about 8000 km^2. The used forecasting methods are mostly deterministic, manual on homogeneous areas of about 2000 km^2 (forecast range 48-72 h) PROVINCIA AUTONOMA DI TRENTO Ufficio Previsioni e Organizzazione , Tel 0461 494877 - fax 0461 238309 http://www.meteotrentino.it/aspweb/index.asp with a covered area of about 6208 km^2. Synoptic methods are mainly used. PROVINCIA AUTONOMA DI BOLZANO Ufficio Idrografico, Servizio Prevenzione Valanghe e Servizio Meteorologico Tel 0471 414740 - fax 0471 414779 http://www.provincia.bz.it/valanghe with a covered area of about 7400 km^2. At regional scale, deterministic methods; smaller area divisions can be used when required. REGIONE DEL VENETO ARPA Veneto,Centro Valanghe di Arabba Tel 0436 755711 - fax 0436 79319 http://www.arpa.veneto.it/csvdi with a covered area of about 5400 km^2 .Synoptic method are used with the aid of the snow model SNOW PACK (cf § 4.6.5).

	REGIONE AUTONOMA FRIULI - VENEZIA GIULIA Direzione centrale risorse agricole, naturali, forestali e montagna, Servizio territorio montano e manutenzioni, Ufficio valanghe Tel 0432 555877 - fax 0432 485782 http://www.regione.fvg.it/valanghe.htm with a covered area of about 3200 km^2. Inductive forecasting methods based on the experience of the forecaster in analysing the data are used at the geographical scale of a mountain group (a sector of the Alps) and temporal scale of 48 h.
Different forecast centres in Spain	INM: the competences of the National Institute of Meteorology (INM) are defined in the royal Decree 1477/2004. It provides mountain and snow information through its « Territorial Units » of Sarragoza and Barcelona. The total covered area is about 7150 km^2. :Navarra, 2300 km^2 , Jacetania, 1260 km^2, Gállego, 710 km^2 , Sobrarbe1120 km^2 , Ésera, 1760 km^2 . ICC has been created in 1982 in Barcelona by the Parliament of Catalonia as an autonomous organism and one of its tasks is the avalanche prediction in the Pyrenees of Catalonia and the emission and diffusion of a bulletin of estimation of the avalanche danger (BPA) as well as other task of cartography, climatology and studies. The covered area is about 4000 km^2 and is composed of 7 areas. Val d'Aran . The Regional Council in Val d'Aran (CGA) has implemented local forecast methods in order to protect the Bonaigua Pass Road. The protected area covers about 15 km^2.
Different forecast centers in Austria	Vorarlber area: (http://www.vorarlberg.at/lawine/) The Region of Vorarlberg supports the organizations and authorities who are responsible according to the terms of the "Sicherheitsgesetz" (safety law) and "Katastrophenhilfegesetz" (disaster assistance law), and was the first federal state to establish an Avalanche Warning Service back in 1953. The goal of the Avalanche Warning Service is to optimize avalanche protection and prevention in areas affected by the natural disaster of avalanches. This is achieved using short and long-term safety measures, a cross-regional warning system, and thorough publicity work. It is not possible to eliminate the hazard of avalanches completely, and for this reason it is important to fence off potential hazard zones and make them safe. Its responsibilities concern the observation, climatology, report bulletins, the advices to administration and individual, training, publicity works, certificates to administrations and information to different users. The covered area is about 1700 km^2. Salzburg area: (http://www.lwz-salzburg.org/defaultnew.asp), about 4000 km^2. Kärnten area (http://www.lawine.at/kaernten/index.html) Oberösterreich area(http://www.ooe.gv.at/lawinenwarndienst/) Steiermark area (http://www.lawine-steiermark.at/) Tirol area (http://www.lawine.at/tirol/index.html)
Other countries	Slovakia: Several massifs are covered by local avalanche forecasts: Vysoké Tatry, Nízke Tatry – sever, Nízke Tatry – juh, Západné Tatry – sever, Západné Tatry – juh, Veľká Fatra, Malá Fatra – Vrátna, Malá Fatra – Orava, Slovenský raj Poland: 1 day forecast is provided for the Tatras mountain areas (Zakopane) Scotland: The Sport Scotland Avalanche Information Service publishes daily forecasts of avalanche hazard, snow and climbing conditions for 5 mountainous areas of

Scotland during the winter season which are :

- Glen Coe :Glen Coe and Glen Etive.
- Lochaber : Ben Nevis and Aonach Mor.
- Creag Meagaidh :Creag Meagaidh and some surrounding hills.
- Northern Cairngorms :Northern Corries and Loch Avon Basin.
- Southern Cairngorms : Lochnagar, in Glenshee, and some coverage of the Southern Cairngorms

<u>Czeck republic:</u> Avalanche reports and forecasts are available on massifs:

- Krkonoše, +420 602 448 338 nebo 155
- Jeseníky+420 554 779 020 nebo 155

Roumania: The avalanche hazard forecasting is now quite operational and during the 2005/2006 winter a daily forecast bulletin was realized but only diffused to limited chosen users for testing. The mountainous massifs concerned by avalanche hazard forecasting are presently limited to those of Bucegi and Fagaras which are located in meridional Carpates. Each of these massifs are about 300 to 400 km2. Two forecast centres produce each one his turn the daily forecast bulletin (with a turn of about three or four days). These centers are the Regional Meteorological Center of Southern Transylvania in Sibiu and the GVPAS (Checking group of forecast and statistical adaptation) in Bucaresti. Avalanche forecasting is performed by 4 people (2 in Bucuresti and to in Sibiu). The avalanche forecast is based on the analyse of the data issued from the mountain meteorological observation centers. The weather forecast from the National forecasting Center of ANM is used to evaluate the snowpack evolution and its stability. As tools, two French models from Météo-France are used; one for the data analyse (GELINIV) and another one for the snowpack evolution and stability (CROCUS-MEPRA-PC).

2.6 Forecast of avalanche hazard and possible triggering at local scale

As seen before, the notion of avalanche hazard is well performed at the massif scale by several concerned services with quantified results. The triggering possibilities, at this massif scale, are seen through the interpretation of the different levels of the European Avalanche Scale (see § 4.5.1). Each level corresponds to a growing and well described probability of natural (spontaneous) or accidental (forced) avalanche triggering. These two kinds of triggering appears explicitly in the definition of each levels until the maximum level 5 which characterises a generalised instability of the snow cover where accidental risks are no more pertinent. Without doing again a fine analyse of the terms and words used for defining the triggering probabilities at the massif scale, one can note that this probability is declined in term of avalanche intensity (small, medium or large extent), of slopes (extremely steep, steep, numerous ..) with complementary explications in the associated bulletin. This bulletin is indeed, completely indissociable of the scale in précising areas and concerned elevations. The May 2005 meeting at Davos of the main European Avalanche Services has also adopted several matrices aiming at harmonizing three factors: the avalanche index, the number of involved slopes and the spontaneous or accidental avalanche triggering probabilities.
However, at a smaller scale, all these forecasting processes are trickier and generally less put into practise by the different national or regional services. In this part, the local scale is very often an avalanche path, or a set of avalanche paths as for a road

protection. Because of the multitude of the avalanche paths inside a massif considered as homogeneous, with several different characteristics, such a forecast at local scale can only be performed on well-known, monitored and documented sites. The task is so to refine the massif scale indication to the path scale but this job can only be performed by adding some new information input.

All the snow and environmental factors have to be taken into account. The triggering, that one can see here as an equilibrium failure inside the snowpack in the starting area of the considered paths, depends both on the local structure of the snow cover and also on topographic and environmental parameters. These last factors have a double action; they influence both the snow characteristics as the depth, the extent and the stratigraphy (due to the slope, elevation, path profile, aspect, geographical masks, local induced winds, snow drifting, precipitation redistribution) and also the triggering processes trough the anchorages, surface rugosity, (surface state, vegetation), surrounding slopes and paths.

This local forecasting requires so an important knowledge on all these factors so as the history of the path during the season (as previous draining) in order to know as best as possible the real snow state. Climatology over the previous seasons is also useful in order to know the response of the considered path to different snow and weather solicitations. An important need of local and accurate observations is so evident. This set of local information, well updated, is added to the current and forecasted situation at the massif scale in order to elaborate real information on the local stability and the triggering probabilities. This way of doing illustrates well the importance of the past behaviour of the path (database system) and of the tools managing all these information. Only the very well instrumented or monitored sites could be benefit to such methods of local forecast.

None European service realizes routinely such forecasts on all his mountain zones at this scale. Only some sensible sites are actually well instrumented and so monitored at path scale and the services in charge of this task and afferent forecasts are generally regional or local. The treated sites are generally important road or rail paths or important structures which can be at risk during winter (high altitude sanatorium, houses and buildings, equipment or infrastructures of value). On can quote

some high pass like “Col des Montets” or “Col du Lautaret” in French alps or “Col du Bonaigua” in Spain. On this last site, the General Council of Val d’Aran, has developed an operational structure for the local avalanche forecasting and the safety of exposed some roads (C28). The system is based on two stations with human observers completed by two automatic stations which provide the needed data in complement of the massif scale forecast. In output, the local forecaster give a local avalanche hazard probability for the next 24hrs on a three degrees scale (possible $0<p<0.3$, probable $0.3<p<0.7$, very probable $0.7<p<1.0$). The size of the forecasted avalanches is also estimated on a three degrees scale (“Small”, “Medium”, “Big”). Small avalanches can partially bury the road and damage a person. Medium avalanches will bury completely the road and destroy a car and the road protections. Big avalanches cross the road, destroying everything in their path (heavy trucks, protections, forest…). A similar experiment is led in France for the road of Col des Montets (near Chamonix) by the local Météo-France station. A daily report, sent in the morning, of avalanche hazard forecast valid for both the current and the next day is established. Additional

	information on the snow cover state are given. The avalanche risk is defined through a four indices scale and concerns the probability to reach the road ("very small", "small", "big", "very big"). A 48h forecasted tendency is also given. The method used is mainly expert and human with the help of the different Météo-France tools, models and observations. As mentioned in the previous examples, the most used method among the few operational experiences at that scale is this of a local human expert who knows very well the sites on which a specific set of sensors is deployed and uses suited system of data collecting and monitoring. Under some circumstances, the expert will perform some snow stability tests as those of the rutschbloc or the shovel as close as possible of the critical areas. Generally, the expert will be also in charge of the preventive artificial triggering by different ways and he can also manage interdiction measures (as closing roads) or evacuations. Beside its own data, the basic information stays the operational bulletins at massif scale (daily and weekly) which must be completed and refined according local circumstances in using the "sensible local" expertise and the daily survey of the exposed areas. Some statistical software or nearest neighbours methods as ASTRAL [Guyomarc'h G. and Mérindol L., 1994] or NXD [Buser, 1989] and some integrated acquisition and visualisation local data software as GELINIV [Dumas J-L and Gendre C., 1997] allow to follow the state and the local evolution of the snow pack. Some others methods are also actually used, as expert models, by example AVALOG [Bolognési and al., 1995] . This last method follows and studies a set of avalanche paths, typically all avalanches paths inside a geographical sector of a ski resort area. For each path, a base of rules, synthesised through the past knowledge of human experts, gives an indication for the local avalanche probability. On can also quote the NGI (Norway) experience in matter of local adaptation of the European Avalanche Danger Scale (described in § 4.1.5) about the relationship between the different degrees of hazard and the local consequences on road, lived areas and off-track activities (***Table 6***).

Table 6 Local consequence on road, lives areas and off-track activities

Degree of hazard	For traffic & residential areas	For off-piste & back-country activities
1 (low)	No hazard from avalanches.	Virtually no restrictions on back-country skiing &
2 (moderate)	Virtually no hazard from natural avalanches.	Generally favourable conditions. Routes should still be selected with care, especially on steep[3] slopes of the aspect[5] and altitude indicated.
3(considerable)	Traffic and individual buildings in hazardous areas are at risk in certain cases. Precautions should be taken in these areas.	Off-piste and back-country skiing and travel should only be carried out by experienced persons able to evaluate avalanche hazard. Steep[3] slopes of the aspect[5] and altitude indicated should be avoided.
4 (high)	Avalanches may be of large magnitude. In hazardous areas, closure of road and other transport is recommended in some circumstances.	Off-piste and back-country skiing and travel should be restricted to low-angled slopes; areas at the bottom of slopes may also be hazardous.
5 (very high)	Extensive safety measures (closures and evacuation) are necessary.	No off-piste or back country skiing or travel should be undertaken.

2.7 Avalanche characteristic forecasting

An avalanche is a rapid snow (or snow and others soils materials) movement due to the gravity. Its main characteristics, as speed, pressure, volume, areas, depend strongly on the initial conditions as the amount of fresh snow in start zone, but also on the conditions during the movement in the path as the fine scale topography of the path or the quantity of captured snow during the run. Forecasting avalanche characteristics, in terms of risks, implies so to estimate the intensity and the end, or deposition, zone.

Avalanche hazard bulletins at the massif scale give only general and very coarse information on the expected sizes and endangered areas. According to the European avalanche scale description, the size of the avalanches is defined by three adjectives: small, medium or large. The large avalanche is automatically associate to generalised instability.

Small size avalanches correspond to flow and deposit volumes lower than 1000m^3 with

	path length of about 100m; they general stop by themselves in deep slopes (30-35°) and represent a danger only for carried away people. Medium size avalanches correspond to flow and deposit volumes lower than 10000m^3 with path length of about 1000m; they general reach the lower part of deep slopes (30-35°) and can damage trucks or destroy cars and small buildings or break trees. Large size avalanches can cross flat zones, reach the valley and destroy railways wagons or large buildings and break forest areas. As seen in the questionnaire sent to the different European avalanche service by the IRASMOS project (and presented in this document) , we can notice that the avalanche characteristic forecasting at fine scale is less developed and not really performed on an operational mode. The main given indications are those deduced from a good interpretation of the European Avalanche Scale, even if it is mainly representative of the massif scale. The French, Swiss, and Spanish services work in this way even if some additional specifications can be given occasionally in Spain. Some Austrian or Italian centres as well as Catalonia give more indications on the expected avalanche characteristics as size, type, space extension; some estimations concerning triggering thresholds or flow density can also be found. Many of these centres use conceptual models based on the snow and weather conditions. As presented in the previous item, some operational attempts are yet tried especially in the Val d'Aran (in Spain) and in the Col des Montets (near Chamonix in France) and are based on very experienced forecasters who know how to transfer and adapt large scale information to local places; they are also helped by local observations near the avalanche paths.
	2.8 Data required
Data required at local and massif scales	Data are the base of the local scale forecasting and they are indispensable to any forecast. The must be of good quality and regularly done from the beginning to the end of the season, but also from a season to the next one. **<u>What must be observed</u>** o Meteorological conditions: air temperature (instantaneous, minimal, maximal), wind (speed and direction), solid and liquid precipitations and fresh snow depth, nebulosity and indication of snow drifting occurrence. o Surface and in depth snow conditions: In surface: snow depth, ram penetration length, density, nature of snow, crust occurrence and corresponding thickness. By sounding methods, every snow layer must be documented in term of: ram hardness, temperature, crystal types, hardness, humidity, density, liquid water content. In the framework of particular snow conditions additional soundings have to be done. Sometime, a wise possibility in matter of efficiency and time saving is to only analyse the upper part of the snow mantle with a limited measurement protocol. o Stability tests (see next item) o Avalanche activity: date and localisation of the event, its nature (artificial with the triggering way and the explosive quantity, spontaneous, forced., thickness and width of the fracture, elevations of the starting and depositing areas, path length, deposit thickness… For forced and unintentional triggering, it can be

	important to observe if it is a remote triggering and the magnitude of the overloading. **Where to observe**: The quality of the local forecast is strongly depending of the localisation and of the diversity of the observation sites. There are two kinds of observation sites, depending on whether soundings are performed. The main characteristics of these sites are : o The field observation site must be reached easily along all the season under all possible snow and weather conditions. Safety must be guaranteed and a quick access is preferable. o The observed data must be as representative as possible of the snow and weather conditions prevailing in the avalanche stating areas. o A good complementarily with the other observation network is important. o Preferably, a flat area, less exposed to wind, but this condition can be not respected if one wants a site representative of a given avalanche starting area ; in that case one will choose a topographic environments as close as possible of the studied avalanche site. This can also imply a quite large exposition to the wind. One will so avoid to set an observation site in the following areas : o areas exposed to avalanches, floods, rock or cornice falls…. o urbanised areas, valleys, paths, wind drifting areas, forest edges … o complex topography o crowded areas near public places. **When and how to observe**: The observation planning (time and frequency) must be consistent with rules in usage in the considered area. It consists generally in two observations daily of weather and snow surface conditions (8 am and 13 pm) and a weekly snow pit and snow sounding. In some cases only one daily observation (preferably 8 am) can be performed. The measure protocol must follow the rules in usage so as the used instruments.
Multi- risks observation	In the framework of the IRASMOS project it is pertinent to recall that many kind of measurements are common and well suited for different risks as for example those concerning meteorological surface parameters (rainfall, snowfall, radiation …). This important aspect has to be taken into account in the definition of the different observation networks related to these different risks as well as for the measure protocols. One can so quote the Météo-France "climatology" observation network which many sites are used simultaneously both for snow and hydrological purposes by Météo-France and others partners.
Improvements to be done	However, some improvements would be beneficial in the area of the snow and avalanche measures and the IRASMOS project could so do interesting requirements: o Snowdrifting is very few measured. Some indirect indications of this phenomenon are daily observed and sent through the standard code but no systematic or standard use of that information is done, and the forecaster has to modify his levels of risk according to this effect, generally in increasing them. The general effects of the wind on the snow are well known. The snow redistribution can cause in some places important accumulations that often produce an increase of natural risks during the snowdrift event; in parallel some other locations can be completely or partially eroded. A change in the

	forced risks can also occur when important variations of snow depth make a buried weak layer closer or not of the surface. Very few devices are suited for this observation; we can quote yet those developed serially by Bolognési [1995] which are composed of different horizontal tubes according different expositions and those distributed by the IAV company (V. Chritin) and named "flowcapt". More observations would be also very fruitful for the validation of the different modelling efforts in the different research centres. o Snow pits and stability tests are generally performed every week in some precise locations. The main problem is the spatial representativity of such measurements. In order to extrapolate these data to a whole area, one must postulate a homogeneity hypothesis which implies that in the neighbourhood of the observation site the snow cover would have the same properties according the same aspects, altitudes and slopes. Different local factors do that this assumption cannot be always true and many illustrations of that fact are well known. More sounding measures both in time and space would so be necessary. The time needed by a snow pit or a stability test is yet in the order of one to two hours on an average with at least two people. Some new way of performing such measures have to be found such as remote sensed methods (see § 4.6.2). A manual practical solution can also be found in a more widely use of sophisticated rammsonde systems as the PANDA in France or as the Snow-Micropen developed in SLF (M. Schneebely – Davos). This last device is the more complete and allows measuring spatially continuously the vertical forces to fracture snow structural elements; with this instrumenting it so possible to explore and sound quickly large snowy areas and to deduce a lot of its mechanical properties so as other parameters as temperatures. o Air humidity, cloudiness and the different radiations (solar and atmospheric) are important parameters for the snow surface energy budget. They are also parameters which can exhibit large time variations even at a hourly time step, but they are less observed and there are fewer available data than of other parameters as temperature or wind in mountainous areas. An increase of the number and the frequency of such data would be a quick reachable objective which would be very useful for the different operational modelling attempts of the snow cover.
	2.9 Data available: the human snow and weather observation and measurements networks
In France	This observation network is composed of about 180 observation points located at medium elevation (between 1500 and 2000 m a.s.l) so as about 20 (increasing to 30 in a near future) high elevation automatic stations (between 1500 and 3000 m a.s.l). The major part of the human observers are ski patroller or employed by the ski resort services but some people of the Equipment or the Forest services and from public security services (as CRS or Gendarmerie) participate also to these measurements. The training of all these observers is provided by Météo-France. As recommended, these different sites do o Every day: 2 series of « surface » measurements at 8 am and 1 pm.

	Cloudiness, wind, temperatures, precipitation, snow depth, surface snow characteristics, blowing wind occurrences on crests and observed avalanches are carefully noted, coded, locally used and sent to the « departemental » Météo-France centre. o At least once a week, a snow sounding or snow pit is performed in order to detect and characterise the different superposed snow layers : hardness, temperature, density, humidity, liquid water content will so allow to estimate the snowpack stability.
In Switzerland	About 160 human observers are working at these tasks of weather observation, snowpack characterization, avalanche phenomena observation, snow stability evaluation and past forecasts evaluation.
In Austria	<u>Vorarlberg area :</u> 8 human stations (parameter: weather, cloudiness, snow / rain; temperature (air / snow) wind, snow-surface; ram penetration depth, (results of blasting), hazard level <u>Salsburg area</u> : 20 human stations with 10 observed parameters
In Spain	<u>At INM</u>, 15 human observation sites transmitting 12 NIVOMET messages at 08 am, 4 at a 1 pm) with 13 meteorological parameters and 9 snow and avalanche parameters) and 4 weekly snow pits. <u>At ICC</u>, the human network consists of 15 spots of daily snow and weather observations (French NIMET parameters). 25 spots mainly weekly with snow profiles from which 6 includes the rutschblock test and the showel test and 7 with only rutschblock test. Snow distribution and avalanche activity is also reported. <u>In Val d'Aran</u> (local forecast), two meteorological stations. They record the complete NIMET, plus the crust or the surface hoar thickness; one of them twice a day and the other once. Three snow pits and tests weekly (complete pit, rutschblock and shovel test)
In Italy	<u>REGIONE PIEMONTE</u> : 36 stations AINEVA Model 1 & 6, (snowprofiles, ram penetrometer data, stability test), weather forecast (Snowpack numerical model output, currently in test state). <u>REGIONE AUTONOMA VALLE D'AOSTA</u> . :16 stations AINEVA Model 1 (weather conditions, cloudiness, visibility, wind at high altitude, snowdrifting, air temperature, minimum-maximum temperature, snowpack thickness, new snow thickness, density, snow temperature, ram test, surface layer characteristics, surface roughness, surface hoar, characteristics of observed avalanches, hazard level degree). 18 stations about AINEVA Model 2, 3, 4 (ram penetrometer data, stratigraphy, snow grain data, air temperature, snow density and temperature) and AINEVA Model 6 (snow cover distribution and depth, snow surface layer, observed avalanches). <u>REGIONE LOMBARDIA</u> : 30 stations AINEVA Model 1 and snowprofiles at different locations. <u>PROVINCIA AUTONOMA DI TRENTO</u> : 29 stations MOD 1+ MOD 2/3, 3 stations MOD 2/3, 4 moving observers. <u>PROVINCIA AUTONOMA DI BOLZANO</u> : 18 stations Mod 1 AINEVA; 18 snow fields with daily measurements; 38 snow fields with weekly measurements. <u>REGIONE DEL VENETO</u> : 1 station MOD 1, 22 stations MOD 23, 20 areas MOD 6 with 6 moving observers. <u>REGIONE AUTONOMA FRIULI - VENEZIA GIULIA</u> : 17 stations Mod 1 Aineva

	(daily), 23 stations Mod 4 Aineva (weekly), about 6 moving observers Mod. 4 Aineva (on skitouring areas) (snowprofiles, ram penetrometer data, stability test, meteo forecast).
In Roumania	5 human mountain stations are working in the 2 massifs where avalanche hazard forecasting is performed. The data of 2 other stations in the vicinity of these massifs are also used. These centres are composed of about 4/5 persons. In these different centres, snow surface data are produced twice a day and a weekly snow profile is performed with stability tests.
Automatic observation networks in France	<u>The « Nivose » network</u> The basic mountain automatic observation station in France is the « Nivose » model which third generation is presently in deployment. Presently about 20 stations have been installed, the expected number in a near future is about 30, all of them being of the last generation (Nivose 3, ***Figure 12***). These very strongly build stations are well suited to high elevation mountainous conditions and are deployed in Alp, Pyrenees and Corsica in an elevation range of about 1500 to 3000 m a.s.l. Their main characteristics are :
Figure 12 Nivose 3 station (general view)	
	<u>The « Radome » network</u> The « Radome » network is the standard automatic observation network of Météo-France (***Figure 13***). About 554 stations are being deployed over the whole country. Each station has to be representative of an homogeneous area of about 1000 km^2. These stations participate to the WMO observation watch program and their data are so free of charge according to the WMO 40 resolution. As they are also implemented in mountainous areas, but at elevations under 1600 m a.s.l., they are considered as a good complement to the more specialized Nivose network. An additional snow depth sensor will soon equipped the stations situated in altitude in the next year. They provide hourly information to snow and avalanche forecasters as precipitation (heated rain gauge) temperature and wind and meet some needs of the short time forecast when meteorological condition are changing quickly. These hourly data are also assimilated by the SCM chain. (cf 4.6.3).

Figure 13 La Mure (Isére, 884m a.s.l.) station of the Radome network.	
Automatic observation networks in Switzerland	About 85 automatic stations, each **(**with a few exceptions) is constituted by a snow station in a wind free position, and a wind station in a suited location. Parameters: snow height, new snow height, wind (average and maxima), temperature (surface and inside snow cover), radiation, humidity
Automatic observation networks in Austria	<u>Vorarlber area</u> : About 20 stations with different parameters; (rain, snowpack, wind, temperature, radiation, humidness); the time frequency is from 1 to 24 hours; mostly 3 hours <u>Salzburg area</u> : 12 auto stat, temp snow height, wind, rel hum, radiation, prec., snow temp.
Automatic observation networks in Spain	<u>INM</u> : 11 automatic stations (precipitation, wind, temperature, moisture) <u>ICC:</u> The automatic network consist of 11 nivometeorological stations registering hourly the next parameters: air temperature, air humidity, wind direction, wind velocity, global solar radiation, depth snow, snow precipitation, snow cover thermal gradient. In addition 3 “flowcapts” (snowdrift sensors) are available via Internet. Data can be consulted on http://www.meteocat.com/marcs/marcos_observacio/marcs_dades.htm <u>Val d’Aran:</u> Two Campbell automatic weather stations (Temperature, humidity, solar radiation, wind speed and direction, snow thickness, liquid equivalent of precipitation, snow temperature, snow cover thermal gradient). One “flowcapt” station (wind speed and direction, snowdrift)
Automatic observation networks in Germany	15 automatic stations measuring : wind speed, air temperature, fresh fallen snow, snow depth
Automatic observation networks in Italy	<u>REGIONE PIEMONTE</u> : 76 automatic nivo-meteorological stations (parameters: Hs, Ta, RHa, Tn, VV, DV, rain; sending data by radio or by satellite every 30 minutes) <u>REGIONE AUTONOMA VALLE D’AOSTA</u> 23 automatic stations continuously providing air temperature and snow thickness data; 11 of these measuring also wind direction and speed. <u>REGIONE LOMBARDIA</u> : 15 automatic stations (every 30 min. on the average, samplig of all nivo-meteorological parameters) <u>PROVINCIA AUTONOMA DI TRENTO</u> : 10 automatic stations (querying time of 60’: parameters: HS, TA, UR, VV, DV, T snow)

	PROVINCIA AUTONOMA DI BOLZANO : 7 automatic stations: (air temperature and humidity, snow temperature profile, wind direction and strength, snow height, direct and reflected radiation) REGIONE DEL VENETO 17 automatic stations with querying time of 30'; parameters: HS, TA, UR, VV, DV, RI, RR, T snow, T snow surface (4 stations). REGIONE AUTONOMA FRIULI - VENEZIA GIULIA : 16 automatic nivo-meteorological stations (parameters: Hs, Ta, VV, DV, some with rain measurements; sending data by GSM every hour.
	2.10 Type of results and related uncertainty
Main snow and avalanche bulletins distributed in France by Météo-France.	These different bulletins focus on the Alps, Pyrenees and Corsica. These areas are divided up into mountainous massifs or specific areas which surface is about some hundreds of km^2. The information are given at that scale (massif or areas) with, every time when it possible, some precisions on the elevation ranges, aspects and time periods. They are only available outside securized and opened ski areas and are addressed to the general public. o by answer phone : 32.50 o by answer phone: 08.92.68.10.20 *(This extension can be called from foreign countries)* o by answer phone: 08.92.68.02.XX *(XX = « departement » number)* o by internet : access trough the Météo-France web site : www.meteo.fr. o by minitel : 3615 METEO Avalanche following up bulletin (« Bulletin de suivi avalanche » - B.S.A.) These special bulletins are sent by the two « focal points » (« Alpes-Corse » and « Pyrénées ») when the avalanche level reaches the scale 5 according to the European Avalanche Scale (cf § 4.5.1) which indicates a very high level of hazard on at least one massif of its responsibility area. In that case, buildings, traffic ways or technical infrastructures can be affected by large magnitude avalanche events. These bulletins complement the « Vigilance Chart » of Météo-France where, in that case, the concerned « departement(s) » are plotted in orange or red colours according the nature exceptional or not of the avalanche event. They are sent to a addressee list of different media and administrative levels, national, regional, "departmental", in charge of security and rescue affairs. They are also at the disposal of the general public on the Météo-France web site (www.meteo.fr) through a link at the level of the vigilance map. Avalanche hazard estimation Bulletin (« Bulletin d'estimation du risque d'avalanche « -B.R.A.) BRA are sent daily from mid-December to the end of April by the local centres of Météo-France specialized « snow and mountain ».. They are available between 3 and 4 pm and include 5 sections : o An estimation of the avalanche hazard per massif for the 24 next hours according to the European Avalanche Scale (level of danger and description). o A meteorological overview with a brief information on the forecasted parameters which influence the snow cover.

	- The snow conditions : upper and lower vertical extents of skiing areas, general assessment on the snow conditions and the state of snow surface layer. - The stability of the snowpack : report of previous fresh snow falls, state and evolution of the snowcover, consequences on the stability, nature and intensity of the avalanche hazard. - Time tendency (facultative) : estimated trend of the hazard for ranges at least of 48 hrs. These bulletins (BRA) are also sent by the local centres of Météo-France specialized to different public services or private organisms. Each centre has a particular own addressee list. All the ski resort which are members of the snow-weather observation network receive free the BRA. From the beginning of November to mid December, then from the beginning of May to mid June, more concise information (snow and avalanche information) are delivered at least twice a week on Monday and Thursday. <u>Weekly synthesis bulletin (« Bulletin de synthèse hebdomadaire » - B.S.H.)</u> The BSH bulletin summarizes the main outstanding phenomena of the past week and emphasizes more particularly the strong wind events, the variations of the 0 degree isotherm, the global amount of fresh snow. Although the BSH is not an avalanche hazard estimation bulletin, it applies particularly to off-piste and back-country skiers and to the mountain professionals who need to know the snow and weather conditions of the past days. This bulletin is available by answer phone, web site and on “minitel” from Thursday to Sunday from mid December to end April. <u>Snow and Mountain Bulletin (« Bulletin montagne et neige « - B.M.N.)</u> The BMN bulletin is also proposed during the winter season. The mountain user can so have access to a meteorological forecast adapted to the massifs of the « departement » of his choice and supplemented by some information on the vertical extents of the skiing areas, on the general characteristics of the snow cover and on the recent fresh snow falls. <u>Updating and Improvment Bulletin (« Bulletin d’amendement »)</u> This kind of bulletin is recorded on the morning when the observed meteorological conditions differ enough from those forecasted the day before and imply significant changes of the snowpack <u>Meteorological press release (« Communiqué Météorologique de Presse « - C.M.P.)</u> These press release can be sent in some situations of high avalanche hazard, mainly when avalanches can be easily triggered by skiers in many slopes (or when the avalanche level reaches the level 4 [high degree of hazard] or when some outstanding snow conditions occur either by overabundance or by scarcity).
Main snow and avalanche bulletins distributed in Switzerland by SLF (Davos)	The main centre for avalanche hazard forecasting is located in Davos with different local branches in some « cantons ». The bulletins, information and maps are more particularly available on the web site: http://www.slf.ch/avalanche/avalanche-en.html as well as by other ways (fax, Snow Info on WAP, Alpen-Info, Swiss-Snow …). One can so find : National avalanche hazard bulletins (sent near 5 pm) in German, French and Italian

<table>
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<td>which includes :
o Avalanche hazard map for national bulletin (color) / (b&w)
o Archived products
Regional avalanche hazard bulletin (updated at 8 am) for different areas :
o Eastern Part of the Northern Slope of the Alps (color) / (black and white)
o North- and Central Grisons (color) / (black and white)
o Sud Grisons (color) / (black and white)
o Swiss Plateau (color) / (black and white)
o Bernese Oberland (color) / (black and white)
o Eastern part of Valais (color) / (black and white)
o Western part of Valais - in French (color) / (black and white)
o Map of avalanche danger in regional reports (color) / (black and white)
Maps for Switzerland
o Snow cover conditions
o Snow depths at 2000m / 2500m (color) / (black and white)
o Snow depth deviation from a long tem mean value (color) / (black and white)
o Fresh fallen snow depth (color) / (black and white)
o Fresh snow accumulation over 3 days rs (color) / (black and white)
o Stability of the snowpack
One can also find different information and security elements about avalanches.</td>
</tr>
<tr>
<td>Main snow and avalanche bulletins distributed by the Avalanche Warning Center (Austria) http://www.lawinen.at/austria/)</td>
<td><u>In Vorarlberg</u> : Bulletins are available by phone every day (++43-5574-501-21126) and by internet (http://www.vorarlberg.at/lawine/) and are sent near 7.30 am on morning from December to April (about 150 bulletins per season). They content also a geographical map of the avalanche hazard as well as meteorological information. The web site includes also information on the observation networks, some notions about the responsibility in mountain and a glossary of the used terms in avalanche risk forecasting.
<u>In Salzburg</u>, (http://www.lwz-salzburg.org/defaultnew.asp)
In the different areas, the information can be found on the following web sites and phone numbers :</td>
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<table>
<tr><th>Region</th><th>Internet</th><th>Phone (++43)</th></tr>
<tr><td>Vorarlberg</td><td>http://www.vorarlberg.at/lawine/</td><td>(05522) 1588</td></tr>
<tr><td>Salzburg</td><td>http://www.land-sbg.gv.at/lawinen/</td><td>(0662) 1588</td></tr>
<tr><td>Oberösterreic</td><td>http://www.ooe.gv.at/lawinenwarndienst/</td><td>(0732) 1588</td></tr>
<tr><td>Tirol</td><td>http://www.lawine.at/tirol/</td><td>(0512) 1588</td></tr>
<tr><td>Steiermark</td><td>http://lawine-steiermark.at</td><td>(0316) 1588</td></tr>
<tr><td>Kärnten</td><td>http://www.lawinenwarndienst.ktn.gv.at</td><td>(0463) 1588</td></tr>
<tr><td>Niederösterre</td><td>http://lawine-steiermark.at/noe</td><td></td></tr>
</table>
</td>
</tr>
<tr>
<td>Avalanche bulletin in Spain</td>
<td><u>At INM,</u> a report is produced daily during winter period (15 Dec.-30 April)
<u>At ICC,</u> the avalanche bulletin (BPA) from Monday to Friday is published each day at 14:00 and it is valid from that time until 24:00 of the next day. It includes a short trend for the next 48 and 72 hours. The forecast during Saturdays is valid from 14:00</td>
</tr>
</table>

<table>
<tr><td></td><td>Saturday until 24:00 Monday. In case of level 4 or 5 a special additional warning is issued and is valid for 24 hours but can be updated before in function of the situation.</td></tr>
<tr><td>In Italy (unique telephone number for weather and avalanche information over the whole alpine arc : 0461 230030)</td><td>During the winter season avalanche danger bulletins are emitted regularly several days per week. In case of meaningful variations of the avalanche situation re-actualised reports are emitted. The danger scale is represented on maps by several colours in order to represent in synthetic way the danger degree. Some indication of avalanche accidents are also plotted. Bulletin avalanches are available by email, fax, telephone and WAP. The bulletin can obtained free of charge by “email”. The different local centres have the responsibility of the different Italian mountainous massifs (Table 7):</td></tr>
<tr><td>Table 7 Telephone-fax number in the Alps</td><td>
<table>
<tr><td><u>PIEMONTE</u>
1 Alpi Liguri e Marittime
2 Alpi Cozie
3 Alpi Graie meridionali
4 Alpi Pennine orientali
5 Alpi Lepontine
tel/self fax 011 3185555
3 reports per week, valid 48h to 72h
extra reports possible</td><td><u>VALLE D'AOSTA</u>
6 Alpi Graie settentrionali
7 Alpi Pennine occidentali
tel 0165 776300
4 reports per week, valid 48h</td><td><u>LOMBARDIA</u>
8 Alpi Orobie
9 Alpi Retiche occidentali
10 Alpi Retiche centrali e orientali
tel 848 837077 polling 0342 901521
3 reports per week, valid 72h</td></tr>
<tr><td><u>ALTO ADIGE</u>
11 Alpi Venoste e Aurine
12 Gruppo Ortles Cevedale
13 Dolomiti settentrionali
tel/self fax 0471 270555
3 reports per week, valid 24h-72h
extra bulletins possible</td><td><u>TRENTINO</u>
14 Dolomiti di Brenta e Adamello
15 Dolomiti occidentali
16 Prealpi trentine
tel 0461 238939 self-fax 0461 237089
3 reports per week, valid 24h-72h
extra bulletin possible</td><td><u>VENETO</u>
17 Prealpi venete
18 Dolomiti orientali

tel. 0436 780007 polling 0436 790009

self-fax 0436 780008 – 79221

2 reports per week, valid 24h-72h

extra bulleteins possible</td></tr>
<tr><td><u>FRIULI-VENEZIA GIULIA</u>
19 Prealpi Carniche
20 Alpi Carniche
21 Alpi Giulie
22 Prealpi Giulie
tel-self-fax 800 860377
3 reports per week, valid 48h to 72h.
extra bulletins possible</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>In Norway (http://www.snoskred.no/)</td><td>NGI undertakes avalanche forecasting for key transportation arteries in Southern Norway. Since 1981, NGI has monitored and evaluated the avalanche hazard along Highway 15 for the Norwegian Public Roads Administration. NGI provides daily forecasts using the inter-national avalanche hazard scale. Similar forecasting is also provided for the Norwegian National Rail Administration along the avalanche- prone areas between Oslo and Bergen. When the avalanche risk is characterized as greater than or equal to "high", a notification is sent out. NGI bases its forecasts on observations of meteorology and avalanche activity in the areas and long experience. Data from remote automatic weather stations, weather forecasts and field observations are coupled with models and analyses of avalanche probability.</td></tr>
<tr><td>In Roumania:</td><td>The avalanche forecasting bulletin is daily elaborated. It is only diffused at this time, internally at ANM and to special organism of security as mountain rescue (Salvamunt and National Gendarmerie in mountain) and alpinism club, for testing. It is also °available on internet at the following addresses: www.alpinet.org; www.clubalpin.ro; www.Osalvamont.ro .</td></tr>
<tr><td>Slovakia:</td><td>1 day forecast area provided for the following areas: (http://www.laviny.sk/)
Vysoké Tatry ☎052/4422820 0903 624 869
Nízke Tatry - sever ☎044/5591678 0903 624 070
Nízke Tatry - juh ☎048/6195326 0903 624 078</td></tr>
</table>

Nízke Tatry - juh	048/6195326	0903 624 078
Západné Tatry - sever	043/5395101	0903 624 066
Západné Tatry - juh	044/5586218	0903 624 061
Veľká Fatra	048/4199724	0903 624 049
Malá Fatra - Vrátna	041/5695232	0903 624 028
Malá Fatra - Orava	043/5863104	
Slovenský raj	053/4297902	0903 624 092

Reliability indices in several countries:

Reliability results for BRA bulletins (cf 4.4.1) in the French Alps for 12 winter seasons 1993-1994 to 2004-

Number of avalanche accidents compared with the forecasted degrees of hazard*

Comparison between scale degrees use* frequencies and accidents frequencies

(12 winter seasons, 1993-1994 to 2004-2005, all massifs)

	Forecasted degrees of avalanche hazard*					
	1	**2**	**3**	**4**	**5**	
Scale degrees use* frequency (FI)	13.9%	40.9%	35.9%	8.3%	1.0%	100%
Number of accident	1	73	316	236	15	641
Accidents fréquency (FA)	0.2%	11.4%	49.3%	36.8%	2.3%	100%
Fréq. accid. / Fréq. degree. (FA/FI)	0.0	0.3	1.4	4.4	2.3	

*relatively to the different levels of the European Avalanche Danger Scale (cf. §4.5.1)

Indication of reliability of avalanche forecast report in Switzerland and the number of deaths in avalanche events during 11 winter seasons. (from S. Henry, SLF)

Number of avalanche deaths per danger level*

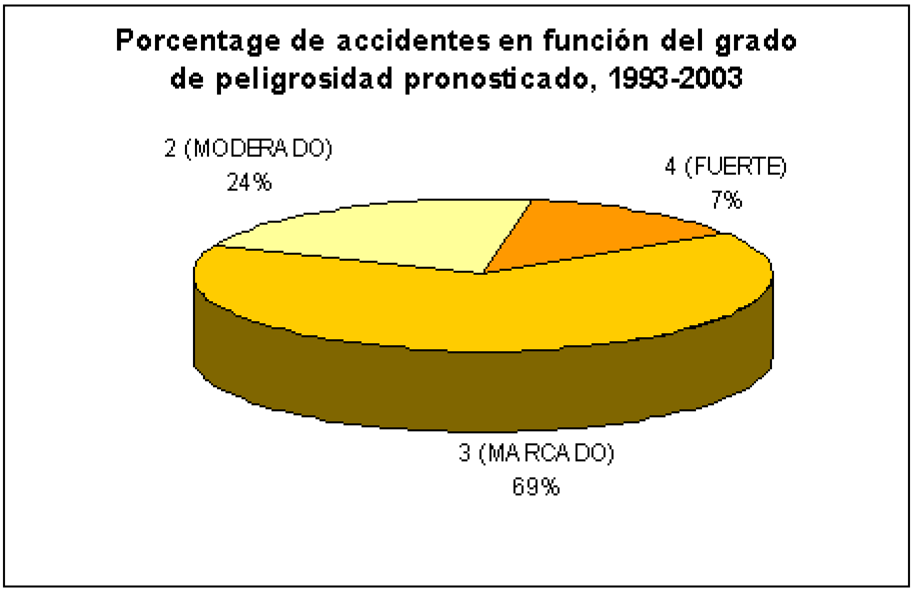
(11 winters, 1987-1988 à 1998-1999, all massifs)

	Forecasted danger level*					
	1	**2**	**3**	**4**	**5**	
Number of deaths	15	74	112	45	2	248
Fréquence of deaths	6%	30%	45%	18%	1%	100%

* relatively to the different levels of the European Avalanche Danger Scale (cf. §4.5.1)

Indication of reliability of avalanche forecast report and the number of avalanche accidents in Catalonia over 1993-2003 (***Figure 14***).

Figure 14 Number of avalanches in Catalonia



Most of accidents take place when the danger has average values medium or low. ***Figure 15*** shows less accidents in level of danger 4 than in level 5 where no accident has been observed. It emphasizes the danger 3 in which they take place almost 70% of the accidents, while in danger 2, situations seem to underestimate the danger.

- Indication of reliability of avalanche forecast report and the number of avalanche accidents in Italy over the last 15 years (from :. Anselmo Cagnati, Alberto Luchetta, Mauro Valt, Stefano Sofia and Renato Zass, "Incidenti da valanghe e condizioni nivometeorologiche in Italia negli ultimi 15 anni**",** ARPA, Arraba)

The European scale of avalanche danger has been used from the Italian services avalanches since 1994. During the period of use of the scale 274 avalanche incidents have been recorded with 129 victims. The degree of danger where the greater number of accident (60%) occurs is the "3" marked. With extreme degrees ("1": low, "5": much high), only 5 and 1 accidents respectively have been observed. From 1994 to now 46 incidents from avalanches (17% of the total of the period) have happened during to beginning or the end of the winter season in absence of the regional bulletin avalanche.

Figure 15 Avalanches accidents and danger degree

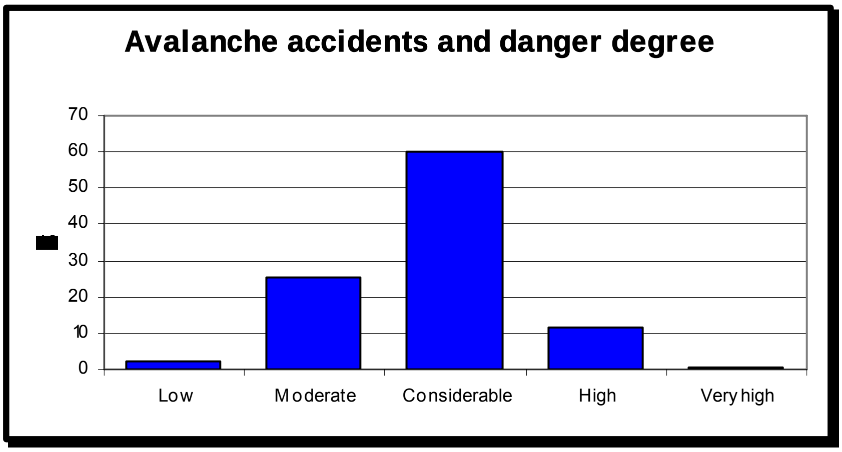
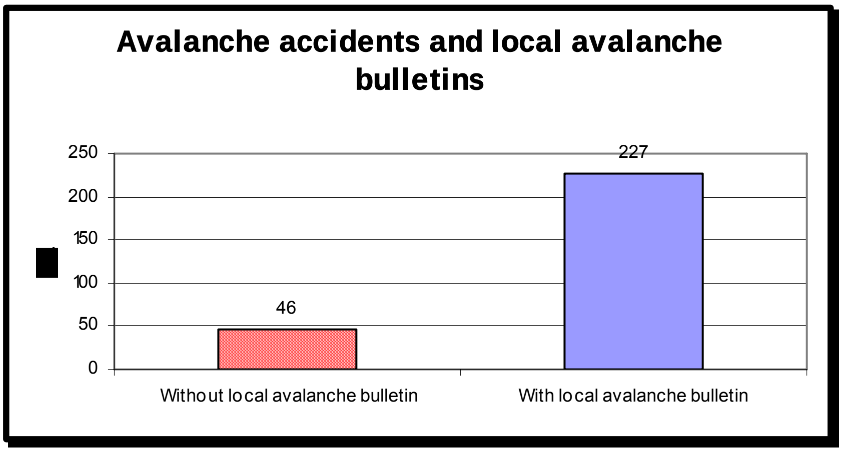


Figure 16 Avalanches accidents and local avalanche bulletins



Most of the other centres perform also verifications and validations of their forecasts and products. On can find in the attached questionnaire (question 4) an estimate of different skill and success rates.

2.11 Hazard scenarios and risk

European Avalanche Danger Scale

The degree of hazard is evaluated according to a 5 levels scale which has been used by most of the European Avalanche Alert services since 1993. These degrees of hazard are based on the increase and the geographical extent of the snowpack instability. This scale has so only a meaning on enough broad areas with complex orography as the mountainous massif previously described. Each degree or level characterizes the stability state of the snowpack with, therefore, the forecasted avalanche activity in terms of the avalanches number and size. For the levels 1, 2, 3 and 4, one distinguishes between spontaneous and forced triggering; for the level 5, so important is the instability that this distinction is no more necessary (see ***Table 8*** and ***Table 9***). Each degree, suited to backcountry skiers and users out of open and securized tracks, provides by itself only limited information and cannot be used in an isolated way. Only the avalanche warning bulletin (in France the BRA) states precisely the snow conditions, the kind of hazard so as their localisation according to the elevation, aspect, slope and time.

Table 8 from, B. Zenke : « 20 Jahre Arbeitsgruppe dereuropäischen Lawinenwarndienste »

Europäische Lawinengefahrenskala

Escala Europea de Perill d'Allaus

Medzinárodná stupnica lavinového nebezpecenstva

échelle Européenne de risque d'avalanche

	GB	SL	I	E	D	F	SK
1	low	majhna	debole	feble / débil	gering	faible	malé
2	moderate	zmerna	moderato	moderat / moderado	mäßig	limité	mierne
3	considerable	znatna	marcato	marcat / marcado	erheblich	marqué	zvýšené
4	high	velika	forte	fort / fuerte	groß	fort	veľké
5	very high	zelo velika	molto forte	molt fort / muy fuerte	sehr groß	très fort	veľmi veľké

Evropska petstopenjska lestvica nevarnosto proenja sneznih plazov

Escala Europea de peligro de aludes

European avalanche hazard scale

Scala Europea del pericolo di valanghe

Table 9 ("Unofficial" English translation of the Avalanche Danger Scale.)

Degree of hazard	Snowpack stability	Avalanche probability
1 (low)	The snowpack is generally well bonded and stable.	Triggering is possible only with high additional loads[2] on a few very steep extreme slopes[4]. Only a few small natural[6] avalanches (sluffs) possible.
2 (moderate)	The snowpack is moderately well bonded on some[1] steep[3] slopes, otherwise generally well bonded.	Triggering is possible with high additional loads[2], particularly on the steep[3] slopes indicated in the bulletin. Large natural[6] avalanches not likely.
3 (considerable)	The snowpack is moderately to weakly bonded on many[1] steep[3] slopes.	Triggering is possible, sometimes even with low additional loads[2]. The bulletin may indicate many slopes which are particularly affected. In certain conditions, medium and occasionally large sized natural[6] avalanches may occur.
4 (high)	The snowpack is weakly bonded in most[1] places.	Triggering is probable even with low additional loads[2] on many steep[3] slopes. In some conditions, frequent medium or large sized natural[6] avalanches are likely.
5 (very high)	The snowpack is generally weakly bonded and largely unstable.	Numerous large natural[6] avalanches are likely, even on moderately steep terrain.

Notes

[1] Generally described in more detail in the avalanche bulletin (e.g. altitude, slope aspect, type of terrain, etc.).

[2] **Additional load:** high - e.g. group of skiers, pistemachine, avalanche blasting; low - e.g. skier, walker.

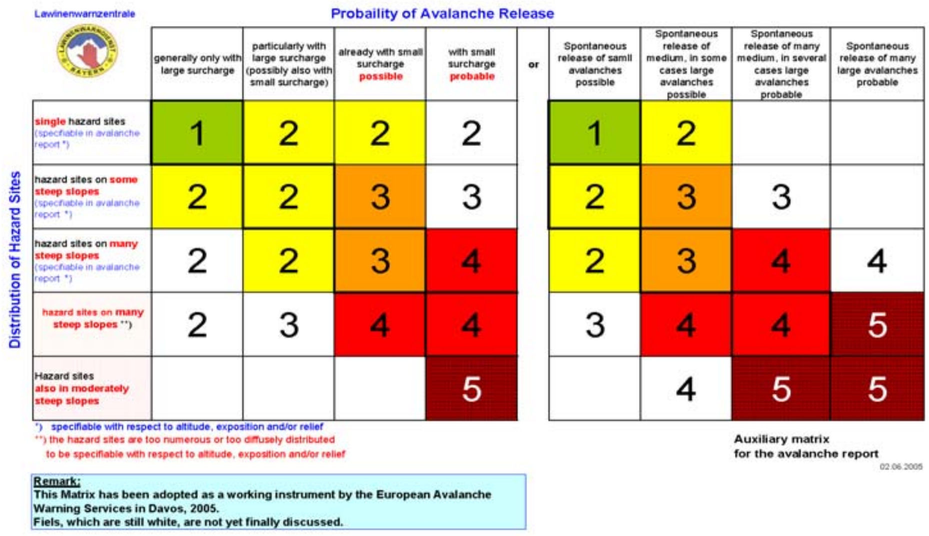
[3] **Steep slopes:** slopes with an incline of more than30 degrees.

[4] **Steep extreme slopes:** those which are particularly unfavourable in terms of the incline, terrain profile, proximity to ridge, smoothness of underlying ground surface.

[5] **Aspect:** compass bearing directly down the slope.

[6] **Natural:** Without human assistance.

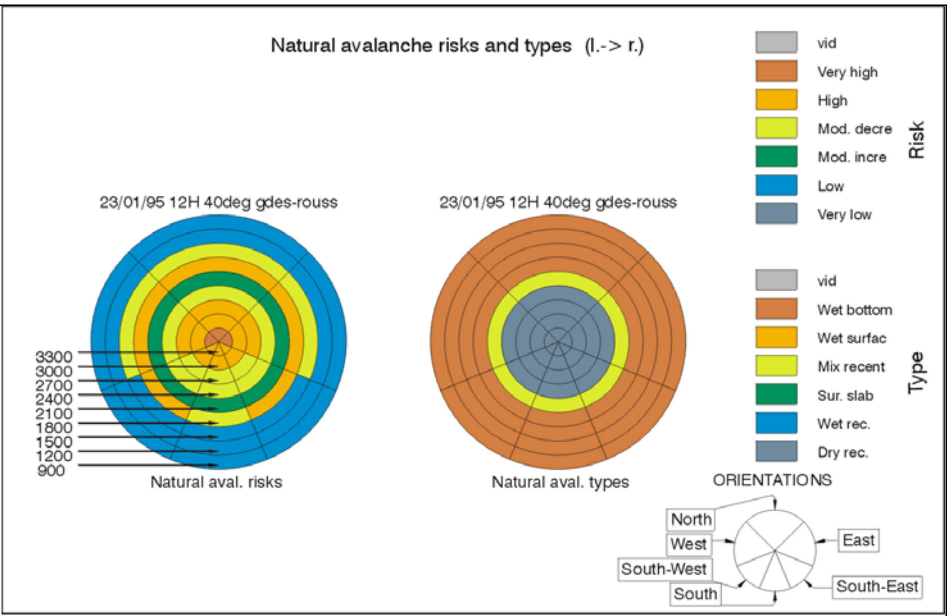
<table>
<tr><td></td><td></td></tr>
<tr><td></td><td>Avalanche warning services in Europe have used the European Avalanche Danger Scale since 1993. They shared their experience through a working group that have tried to go further in the harmonisation of the use of this danger scale by European forecasters. Since 2004, most of the avalanche warning services have used “Bavarian Matrix” (Figure 17) that is a help to the determination of the avalanche danger level in function of the probability of avalanche release and the distribution of the hazard sites. Next step will be a collection of different documented typical situation for each danger level.</td></tr>
<tr><td>Figure 17 The “Bavarian Matrix”.</td><td>



</td></tr>
<tr><td>Automatic Hazard estimation by the automatic software MEPRA (cf 4.6.4.3 §).</td><td>The automatic avalanche hazard message from MEPRA (Figure 18) is composed of 4 parts

A description header over 3 lines indicating the name of the Météo-France mountain centre or of the station addressee of the message, followed by the name of the concerned massif and the numerical simulation date.
A minimal information on the scenario used by SAFRAN in forecast mode at the 1800 m a.s.l elevation, with the 24h rainfall amount and the air temperature at 30hr forecast range (D+1, 6 am).
The spontaneous (or natural) avalanche hazards with a banner specifying the kind of risk, the simulated slope angle and a summary about the used MEPRA 6 levels scale with the corresponding number : 1 = very low, 2 = low, 3 = moderate increasing, 4 = moderate decreasing, 5 = high, 6 = very high. The different hazard messages, both in analyse mode (ana.) or in forecast mode (pre.) are in tabular form which main columns correspond to a given date (6 am and 6 pm the current day, 6 am and 3 pm the day after) and sub columns correspond to the 4 main aspects (North, East, South, West). Each row corresponds to an elevation level of the massif by step of 300m.
The last part of the message concerns the forced avalanche risks. It has the same format as the previous part. However the used scale is relevant to this particular risks with 4 degrees of risks : 1 = very low, 2 = low, 3 = moderate, 4 = high.
</td></tr>
</table>

Figure 18 Symbolic representation (elevation and aspects) of MEPRA natural avalanche risks and types on the "Gdes-Rousses" massif for one slope (40 deg) in a typical winter situation (1995/01/23 at 12 UTC). These data are used for building the MEPRA message with the same risk code.



Methodology for avalanche hazard prevention.

<u>Spatial methods : (mapping)</u>

In France, CEMAGREF has been in charge since 1971 of the making of the « Avalanche Zoning Map » (CLPA) which is a hazard registration and geomorphic map but not really a hazard zoning map. This map is based on recent observations , photo interpretations, historical studies. It is so an mapping inventory of the different avalanches which paths have been identified (by photo interpretation in orange colour, by field inquiry in pink colour). This information however important it may be , does not give any information on the avalanche frequency, nor on the date of the event and nor on the precise characteristics (dust, melting …)

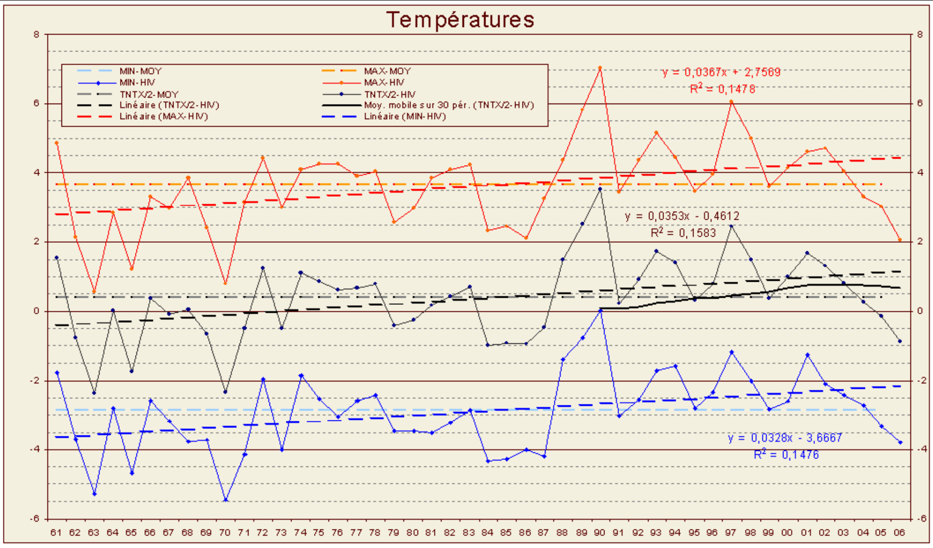
In the ski resorts or mountain municipalities, an inventory of the different avalanche paths (PIDA) is done in order to make easier the artificial avalanche triggering so as the monitoring of the different prevention tools. This kind of zoning is also used in different other countries as Andorra, Catalonia and generally takes into account the return period of the involved phenomena.

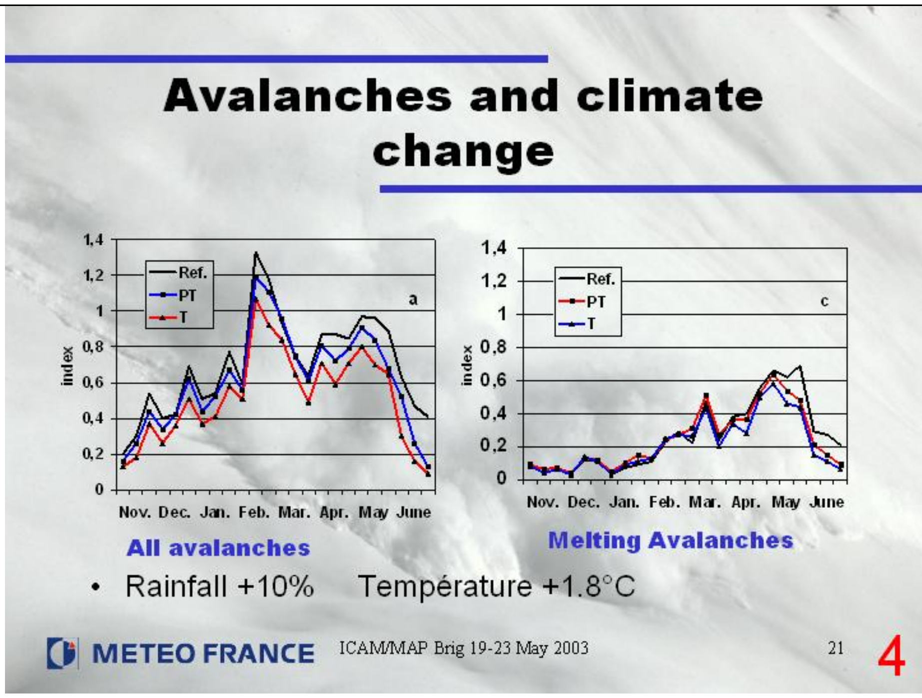
<u>Normalization combining time and space aspects.:</u>

In the framework of the avalanche Hazard and Risk, the notions of avalanche concerned areas and of possibly avalanche covered areas induce two kind of sensible zones:

- the altitude or upper zones, generally uninhabited, which roughly correspond to the avalanche starting areas or the upper part of the track. The stated problem is so rather an instability forecasting and a localization of the different possible avalanche paths.
- the lower elevation zones with people and infrastructures which can be reached by the flow of an avalanche coming from an upper area. In these areas the problem is not really a matter of instability but the estimation of the avalanche energy (speed, volume, stress, …) and of the localization of the deposition zone in taking into account other phenomena as snow capture, friction during the flow together with the different other environmental factors as topography.

	In France, the old Risks Exposure Plan (PER) has been changed by a new document, the Risks Prevention Plan (PPR). These two documents use the notion of return period for a reference avalanche over given areas and classify the different zones of an exposed area into 3 classes (white = supposed safe, blue = area with less risks where it possible to build with some constraints, red = dangerous areas without allowed buildings). The reference avalanche is so the important factor of these documents but its definition is sometime difficult to set depending on whether one considers only the damages to building or also people safety. Indeed a centennial or bicentennial reference occurrence can be acceptable for building but less for people. The main physical parameters used are: o the avalanche intensity is mainly defined by the impact pressure at a given point and so characterizes it destruction power. This pressure is function of the speed and the nature of the flow so as the topographic factors. o the avalanche extent reached by the reference avalanche with damages even low. This corresponds roughly to impact pressure of about 1 kPa. The determination of such parameters is performed by three complementary approach : historical studies, morphological study (field investigation) and modelling through deterministic models unfortunately strongly dependant on the initial conditions and tuned parameters. This last method is widely used for the estimation of the reference avalanche. For this purpose one chooses generally the worst snow conditions which have a centennial probability of occurrence and are generally deducted from the amount of fresh snow in the starting zone which is linked to the crown or fracture thickness and practically to the past 3 days snowfalls. The reference avalanche is so assimilated to a 3days centennial snowfall amount, although the return period and the synchronization of these two events do not always match. For practical reasons, one retains a mapping with only four levels on these administrative maps: o a high degree (A3) with pressures > 30 kPa o a moderated degree (A2) with pressures between 1 and 30 kPa o a low degree (A1) with pressures non measurable or less than 1 kPa o areas with negligible danger According to studies done by the SLF Office in Davos (CH), an overpressure of 30 kPA can be considered as the maximum possible for a braced building. For lower pressures, the building needs some specific dispositions in order to protect people inside. After the recent dramatically events of these past years, the French Environment Minister has decided a new avalanche intensity scale with 5 degrees. This scale covers different natural extreme events as tempests, floods, debris flows, avalanche, forest fires… The purpose is so to better qualify each new event ant to compare them with past events. The different degrees are relatively independent of the vulnerability of each site and are representative of both the magnitude and the damages of the event. For avalanche, the physical used parameters are the affected area, the mobilized snow thickness, the carried volumes and the impact pressure. The effects on people (carried away persons), buildings and goods are also considered and are presented on this

<table>
<tr><td></td><td>limited version of the scale:</td></tr>
<tr><td>Climate change problematic :</td><td>These zoning and mapping, and in particular, those which use return periods can be sensible to the different changes induced by climate modifications (Figure 19). The statistical set, built for being used as a reference to the computation of these return periods, is based on a stationary hypothesis of the studied phenomenon. The changes, as much for temperatures as for precipitations (quantity and phase) will induce modifications of the snow depths and of the internal temperature gradients and therefore of the metamorphism mechanisms. As the effects are so indirect, the impact on the avalanche hazard has to be studied with care.</td></tr>
<tr><td>Figure 19 Illustration of the temperature trend at the Col de Porte (1360m a.s.l, Chartreuse massif near Grenoble) in black colour (winter averaged temperature), red colour (winter averaged maxima), blue colour (winter averaged minima) since 1961 and showing a variation of about 2°C over this period.</td><td>


</td></tr>
<tr><td></td><td>However present studies do not indicate a real trend in the avalanche activity in case of climate change. Under different climate change scenarii the avalanche activity decreases only slightly in case of temperature or rainfall increase (Figure 20).</td></tr>
<tr><td>Figure 20 Illustration of the variability of the avalanche activity (in y-axis) in French Alps during the winter season months (x-axis) for two climate change scenarii (“T”: temperature increase of 1.8 °C, “PT” : same as T with an additional rainfall increase of 10%); the “Ref”- black curve indicate the present situation)</td><td>


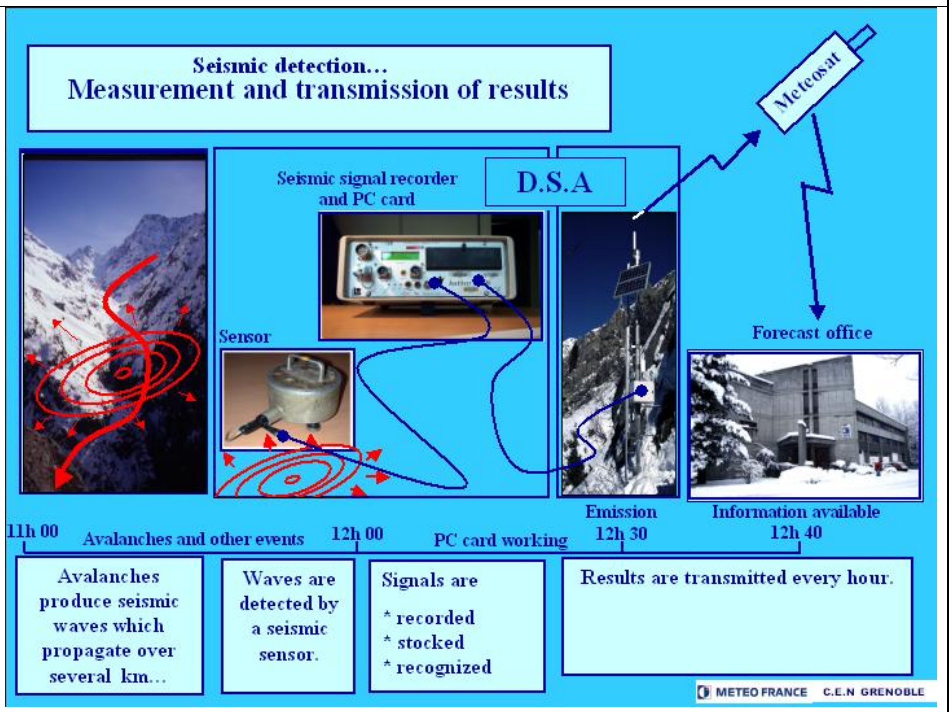
</td></tr>
<tr><td>Areas use changes problematic</td><td>The diminution of the agricultural activity in mountain as the decrease of the worked areas or the lack of mowing in some non mechanized slopes induces an increase of the risk especially for snowpack of small depths; gliding snow implying easier cracks in</td></tr>
</table>

	some weak snow cover. The same phenomenon occurs with the disrepair of natural countermeasures or the vanishing of maintained forests (as in France in Bareges). However, these changes of use can also carry on a bigger safety with the extent of the ski resort areas where important countermeasure are built and maintained.
Multi-risks interaction in IRASMOS	Rock avalanches or cornice falls can be at the origin of overloading which can trigger some snow avalanches. The wet snow avalanches can carry big amount of several materials until very low elevations as it is clearly visible in valley areas where numerous deposition zones are still present far in the spring season. The consequences of such events can be dramatically as the mud flows at the « Plateau d'Assy » in 1970. The mountain hydrological balance is also strongly influenced by the melting period and associated wet snow avalanches and concerned rivers suffer large discharge variations Dryness at the beginning of the winter season combined with cold temperatures can create snowpacks of very small depths which are mainly composed of layers without any cohesion which are an important component of weak structures especially after a snow drifting event. Periodically, many accidents at the beginning of the ski season are due to these effects. On the other hand, excesses of precipitation on the snow pack can imply a superposition of risks, as for instance avalanches and floods as observed over a large part of the Alpine Arc in 1957. However, these important precipitations are always a major cause of debris flows at low elevation but their impact on avalanche is strongly depending on the season, and one can not neglect a possible interaction between these risks.
Interdiction or evacuation measures.	These measures are suited for the protection of large areas at low financial costs ; they are at the charge of local or central authorities according on the countries. Even if the initial decision is very difficult to take, the following procedures and the reopening decision are also challenges. Often the authorities in charge try to get the scientifically experts to take the final decision ; an example can be found in Isere (France) when an altitude sanatorium was at risk during the events of February 1999. Another interesting example to quote is the current Icelandic organisation, which has been set after the dramatically avalanche events of 1995 where more than 20 deaths inside buildings have been deplored. The Icelandic Met-Office (Vedurstoffa Islands / VI) is in charge of the avalanche zoning but also of the evacuation procedures. Risk areas are dived into 3 categories with different procedures. VI gives directly the evacuation orders and so has a responsibility that generally owns to political actors in other countries. In parallel, VI works with several foreign institutes (Cemagref, NGI…) in order to develop an important set of static countermeasures and can also use during crisis events the results of the SCM chain running in Island (Coop. Météo-France). In Norway, NGI is also an important actor in matter of interdictions measure.
	2.12 New developments and technology: application (remote sensing, numerical modelling, automated observation networks)
Surface remote sensed observation	The most classical application of such devices is the snowdepth measurement which is performed by an ultrasonic sensor (as seen on the Nivose illustration in § 4.3.2.1) in

comparing the elapsed time between emission and reception of the ultrasonic pulse without any contact with the controlled snow surface. This device is widely used in many countries.

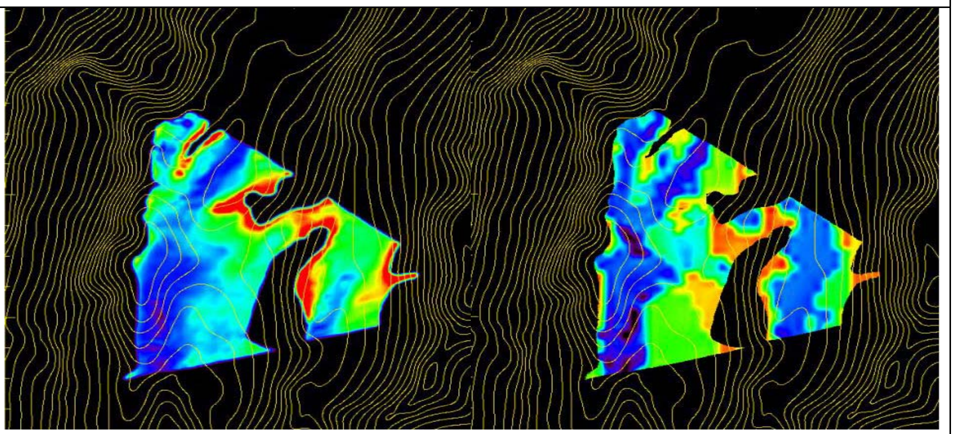
The seismic detection of the natural avalanches supplements the human observation which is very partial and incomplete due the visibility conditions (night, bad and unsafe weather conditions). This knowledge of the avalanche activity is of prime importance for many purposes as zoning, mapping and forecast verifications. The avalanches produce, during their flow, seismic waves which can be detected at many kilometres of the origin point. Some technical applications are presently used in Switzerland, France and Catalonia in order to detect and record the seismic waves and, above all, to identify the avalanche phenomena with a possible estimation of their characteristics and localizations. In France, two systems are operational and provide hourly information on the avalanche activity of the massifs of Oisans and Belledone (***Figure 21***). These systems are also used for the local protection of roads and sensible points but their main limitation is the problem of separating avalanche seismic sources from all the other ones as earthquake, rivers, road activity. Another routine application of these devices is the confirmation of the explosions and possible avalanche occurrences during the artificial avalanche triggering.

Figure 21 Schematic view of the French operational system installed in Oisans



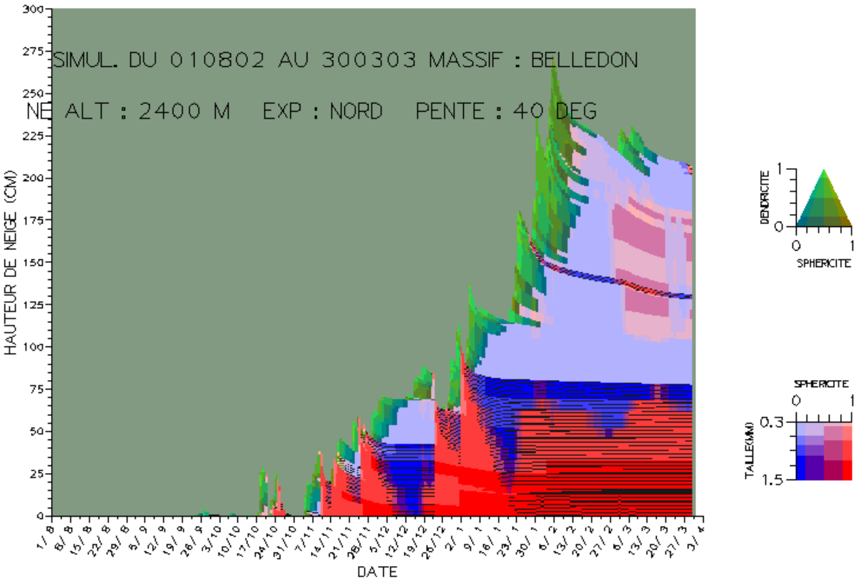
Several systems of automatic detection of the avalanches are developed and used. These systems are based on the detection of the flow of the avalanche and use various methods of measurements of the physical phenomena generated by this movement. Some of these devices are a part of the permanent defence structures and are integrated into a more general alarm system; other devices are used for the estimation of the avalanche activity of a site or an area.

- The « mechanical » detection is mainly composed of a « mechanical » sensor hanging in the in the avalanche path and activated by the flow. This kind of device can control alert traffic lights on the exposed roads.
- Doppler radars are able to measure the wave reflection on a moving

	avalanche ; they can be temporarily used in Austria for testing the result of artificial triggering as in Austria. They are also used in research mode in the test site of La Sionne in Switzerland. • The acoustic detection use several specialized microphones which receive the infrasound signal emitted by an avalanche. The different characteristics (intensity, frequency, polarization) of the recorded signals by the different microphones are then analysed on order to determine if this signal corresponds or not to an avalanche source ; as a matter of fact, this system is very sensitive to different other sound sources as wind, roads, helicopters …For these reasons, its application stays rather limited. However other applications are quite rare and not yet routinely performed in the various observation networks. As for space based remote data (see next §) the main used sensors of this kind are active microwave radars and lidars. The surface structure of the snowcover with its very different crystal types and the possibility to have ice or liquid water make the reflection of a signal very variable. Depending on the frequency, the signal can also deeply penetrate inside snowpack and interact with its internal structure. For instance the snow reflection of a lidar at 1.5 µm is rather low and the reflectivity values can vary between 0.5 and 10 % for oblique incidence depending on snow structure. The snow reflectivity at the 0.9 µm laser wavelength is much higher, more than 50 % for fresh snow [Larrson and alii,SPIE 5791, 2005, 293-307]. For some application as hydrology, snow melting rates, hydropower production, ground-penetrating radar (GPR) measurements are used to assess snowpack characteristics by recording the travel time of the radar pulse through the snow cover; these results could be linked to the forecast of wet snow avalanches. Some research applications are based on the automatic determination of snow surface albedo by using terrestrial digital photography at near infrared frequencies (***Figure 22***). The relationships between albedo, crystal shapes and snowdrifting gives complementary information on the accidental avalanche possible risks and can be compared to modelled results.
Figure 22 Albedo estimated from photography (panel a) and modelled (panel b) on February 18th, 2003 at the Col du Lac Blanc, French Alps. The colour code does not represent absolute values but a relative gradation from lower values (blue) to higher ones (red).	
Space remote sensed observation	Some space remote-sensed data are already used in avalanche hazard estimation but their use is still incomplete although former. They have been practiced since 1972 with few channels and very large spatial definitions. It is difficult to present briefly all the current available space information with its different sensors and possible applications. One can however summarize in separating the current applications in two large parts;

	the first concerning mapping and zoning and is mainly based on images extracted from optical satellites or synthetic aperture radars (SAR), the second one treating of the remote observation of physical snow parameters.
mapping and zoning applications	In the CLPA (cf §4.4.8.1), done by Cemagref, an intense use of air stereo-photography is done. An operator detects on the pictures the tracks of possible past avalanche; this information is then compared to other sources of information in order to do an estimation of the maximal extent of these events. In a next future, high resolution visible satellite pictures (<1m) of platforms as SPOT5 could be used instead the very expensive aircraft pictures. The main current applications is however the mapping and the monitoring of snow covered areas. Purposes are generally the equivalent snow water estimation for hydrological or hydroelectricity applications. Such applications need a good temporal sampling for images and different ancillary data and modelling result in order to deduce the equivalent snow water from the images. Some similar technologies are also used for monitoring the mass balance of different glaciers. Other current applications concern the altimetry and are used in high-resolution GIS for the fine mapping of vulnerability charts leading to administrative procedures. These high resolution products and deduced DEM are also used for research and numerical modelling; in a next future, they will also be used in case of avalanche crisis management. The optical satellite are very well suited for these applications but their lack of ability to produce images in case of darkness or clouds can be disturbing for real time applications. SAR sensors can overcome this problem but at the price of very rare and sophisticated devices and more difficulties in the interpretation; but their ability to penetrate ice and snow at some wavelengths is very promising. Some used satellite sensors are so: HRG : imaging sensor of the SPOT5 series (2.5 to 10m horizontal resolution) HRS : altimetry sensor of the SPOT5 series (5 to 15m accuracy) ASAR : advanced synthetic aperture radar onboard Envisat satellite. Radarsat(1 and 2) satellite series carries also a full polarimetric aperture radar. In a next future the GMES initiative will provide interesting capacities to survey the environment in mountainous areas and to collect data for use in different systems of monitoring and forecasting.
Snow parameters observation	These applications are more relevant of research activities. One can first separate passive (determination of brightness temperatures) and active (scattering phenomena between different interfaces, surface and volumes) methods depending on whether a signal is emitted or not. The main problem is the gap between different factors as: spatial accuracy, time sampling, ability to get measurement in bad weather conditions. Presently, no boarded device meets all these requirements and it is so impossible to have fine scale data (<10m), very often in time and under any meteorological conditions. We have to keep in mind that in mountainous areas, the snowpack variability is very forced by the fine scale orographic conditions (scale of the avalanche path) and also by the time changing meteorological parameters (for example heavy precipitation) and generally avalanche crisis are concomitant with severe and cloudy meteorological events. It is so impossible to have a survey of a sensible area (an avalanche path) continuously at fine scale. The

	state will change in the future when more satellites will be in use. However, research works have yet shown that different surface characteristics of the snowpack could be inferred by several satellite sensors. One can so quote albedo (global, bi-directional, at different frequencies), surface emissivity, surface temperature, snow surface crystal characteristics. These different results have been obtained by different sensors are passive radiometers (as SSM/I) in several wavelengths (visible and infra-red) and by SAR image treatments. Another interesting device, using also microwave signal polarized or not, is the airborne lidar which begins to be used for snow depth determination at medium scale (~100m). A promising way is the ability to perform sounding of the snow pack and perhaps to detect weak and instable internal layers. This possibility would so allow to prevent also artificial avalanche dangers when the avalanche triggering cause is the overloading due to the skier weight without close heavy snowfalls in the past. Some interesting works are conducted in this way by using the ability of microwave radiances to penetrate inside the snowpack and to interfere with it. Improvements in these techniques are expected by exploring the possibilities of new frequencies (Ku instead C band presently) and by the interferometric use of two radars sources. Such technologies are also used in fully iced areas. However the difficulties are numerous, especially due to the fact that snow is a granular medium including 2 or 3 water phases. The different shapes of the snow crystals imply complicated scattering phenomena as well as the vertical discontinuities due to the superposition of the different layers making the snow cover. On can also quote the radar altimeter (as the D2P) which provides similar measurements as the lidar but the strongest return signal comes from the snow/ice interface instead of the surface of the snow which makes the snow depth difficult to quantify on a large scale.
The chain SAFRAN/CROCUS/MEPRA (SCM) (ref : Durand et al., 1999)	This complete automatic system of three numerical models simulates snow cover stratigraphy and avalanche risks for operational avalanche forecasting. The first model called SAFRAN estimates relevant meteorological parameters affecting snow pack evolution. The second model, CROCUS, is a snow numerical model which simulates the physical processes inside the snow pack and its stratigraphy (***Figure 23***). The last model, MEPRA, is an expert system; based on assessment of snow pack stability, it deduces natural and accidental avalanche risks. To describe the great variability of the snow pack and the associated avalanche risks, this automatic system simulates the snow cover evolution and its stability for many typical slopes, elevations and aspects representative of the different French massifs. Although the routinely obtained results do not still take into account all the small scale effects as the wind transport, they have been considered as a valuable information by avalanche forecasters since 1992-93 and operationally used since this date. They are also considered as a precious help during the beginning and the end of the winter season when the observations are quite scarce. The results are used by the forecasters together with other sources of information in order to specify their own diagnostic. The SCM chain starts yearly at the 1st of August without any snow and is never reinitialized all the year long ; snow cover being created, modified and melted automatically so as the relative avalanche hazard.

<table>
<tr>
<td>Figure 23 Crocus snowpack simulation for the full winter 2002-2003 for the Belledone massif, 2400m elevation, North aspect and 40° slope. Time scale on x-axis, snow depth on y-axis, colour code according to the different crystal types declined in term of sphericity, dendricity and size.</td>
<td>
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<tr>
<td>Crocus Mépra / PC</td>
<td>This version for « PC » computers of the models CROCUS and MEPRA allows the numerical snow cover simulation and the avalanche hazard estimation on different sites chosen by an operator (Figure 24). Unlike the SCM chain, a manual initialization of the initial parameters of the snow profiles on the chosen sites as well as the meteorological conditions along the running time is necessary.
This application gives the possibility to make easily complex numerical simulations locally by an operator close of the concerned sites. It allows also to run easily different scenarios both in analysis mode or in forecast mode in modifying slightly some input parameters as the snowfalls in order to compare the obtained risks. It is also an useful computer assisted teaching tool..</td>
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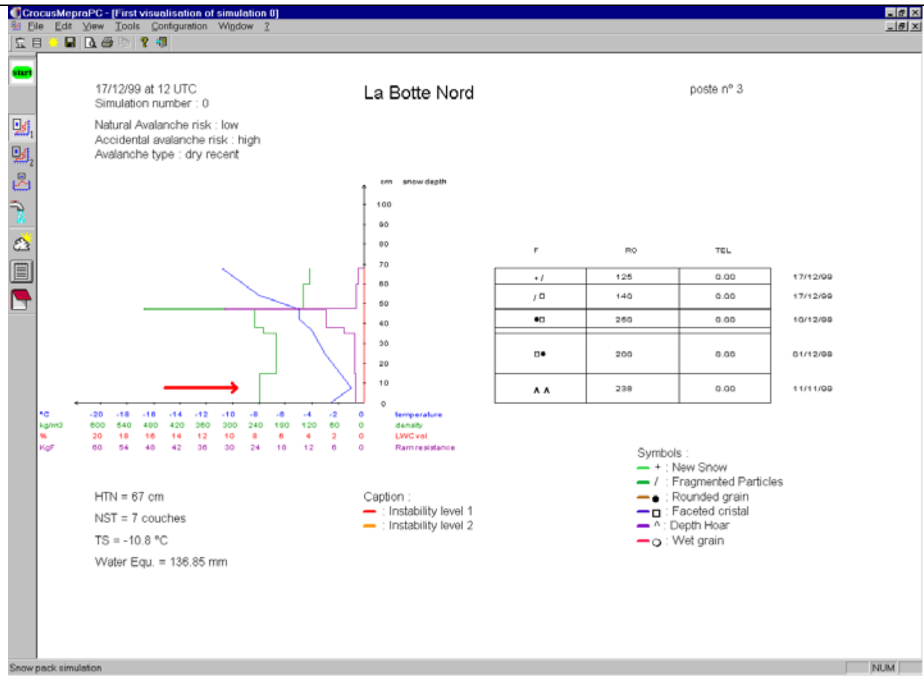
<td>Figure 24 Mepra /PC : display and stability analysis of a snow profile</td>
<td>
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<tr>
<td>The French DOLMEN</td>
<td>Created in 2004, the French named DOLMEN project (Figure 25) was created with</td>
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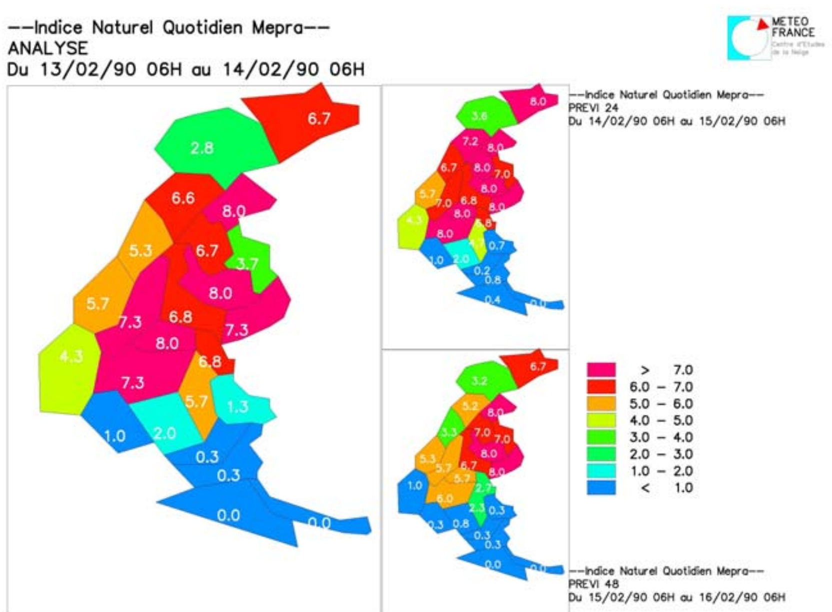
</table>

application.	different purposes : o To continue and make easier the operational developments of the SCM chain in a coherent way with other software applications. o To provide the whole current set of numerical results produced by the SCM chain to the Météo-France "departemental" centres with adapted graphical interfaces o To develop common and friendly accesses to all the available information (model, observation, bulletins) on the daily working station of the departmental avalanche forecasters. To achieve these objectives, the project has so implemented : o Safran on the central computing centre of Météo-France in Toulouse. Four daily runs provide results (hourly interpolation and 24h analysis) which are encoded in BUFR (International OMM codification) and transmitted over RETIM2000 (French meteorological diffusion network via satellite). o Crocus and Mepra in each departmental centre of Alps, Pyrenees and Curse, on their own computer servers, running over a geographical zone limited to the department and its neighbour massifs. The DOLMEN departmental working station is so the main snow and weather tool allowing both several computations, their visualization, their validation so as their integration into the other applications of the centre. This application is presently operational.
Figure 25 Analysed and forecasted averaged spontaneous level of danger produced by Mepra at the massif scale displayed on the DOLMEN working station.	
SNOWPACK (ref : Lehning et al., 1998)	SNOWPACK is a one-dimensional snowcover model that is based on finite-element numerics and is used operationally by the Swiss Federal Institute for Snow and Avalanche Research. It runs on the input data from approximately 50 automatic weather and snow stations in the Swiss Alps. One important characteristics is that the amount of new snow is determined from the measured total snow depth and the model-calculated settling rate together with an estimation of the new snow density. For the energy balance, Dirichlet and Neumann boundary conditions can be used. Using an improved formulation for snow metamorphism and linking the snow metamorphic rate to the viscosity and thermal conductivity, the mass and energy balance of the model

	compares well with independent measurements. It is shown that the model can be used to determine high Alpine snow precipitation rates. These estimations are more accurate than standard precipitation gauge measurements. Since in addition the ablation period in spring is modelled correctly, the model appears to be an appropriate tool for hydrologic applications in high Alpine environments.
Avalog/NXLOG/NXD.	AVALOG is a numerical tool assuring both the description and the analysis of the avalanche danger. It has been developed by Bolognési (Bolognési, 1993) and exploits artificial intelligence techniques in including machine learning functions in order to improve its reliability as long as its database expands. It is implemented on PC and is composed of a database (AVABASE), a documentation procedure (AVADOC) and a system of localization of the avalanche dangers (AVAMAP). The knowledge base is based on the field experience of many snow professional and several rules have been defined. The principle of the process is to use the observations of local events of the past as well as theoretical and practical rules. This software is widely used in several ski resorts in different countries. The new diagnosis support system called NXLOG 2.0 is the result of merging two existent and proven systems: NXD (Buser, 1989) and AVALOG. NXLOG 2.0 contains a data manager and a diagnosis model. It needs as input a description of the situation, and gives as output the probability of an accidental avalanche for each triggering point of the supervised area. The system also gives the user some intermediate results like the events observed for the 3 nearest cases.
Géliniv / Astral	GELINIV is the main software tools of local observer the in the French Alp and Pyrenées. All the used data and observations can be processed and displayed in various screens to help him in his observation, transmission and local forecast tasks. About 80 observation points of the snow-weather observation network (cf 4.1.1.1) are equipped. This software can include the model ASTRAL of local estimation of the avalanche danger by a nearest neighbours method based of the daily snow observations stored and monitored by GELINIV.
Oasis	OASIS is a commercial software (M. Gilet) allowing the acquisition, recording, and display of the past avalanche events. It can be coupled with Astral and runs on « PC » computers. Every detail, including the way of triggering in case of artificially release so as and the number of unsuccessful attempts are kept. A numeric picture can be added to every event. The application manages all the activity concerning artificial releases as well of the operating details as the explosive quantity. In addition to the event management, OASIS allows also to fulfil to the administrative requirements in term of interventions and triggering points.
Observation software used in Austria :	WLP for the monitoring of human observation DATAWIN & METWIN : for the monitoring of automatically measurements
Observation software used in Catalona	Analysis: ADQMSI (soft to store and visualize automatic stations data), self-made programme DB4 based to visualize and graphic representation of conventional human network (snow pits and daily snow and weather observations)
Observation software used in Italy	Yeti32 (recording AINEVA models), Oracle DataBase, HYDSTRA (for automatic stations), SNOWPRO (monitoring and observation visualization).

	2.13 NORVEGIAN CONTRIBUTE
Introduction	The EU project IRASMOS has the overall aim to collect information of the state of the art methods used to meet the challenges emerging from rapid mass movements in alpine terrain. This report gives an overview over the avalanche warning and forecasting methods applied in Norway. By the year 2006, no national warning service for avalanches is established in Norway. Avalanche warning is issued only for selected areas, based on projects that are financed by the local authorities. Therefore, different projects will be presented
Topographical conditions	The terrain in Norway is characterized by the Scandinavian Mountains (***Figure 26***), reaching from the south coast all the way up to the North Cape, and the last glaciation's period: Most of Norway was covered by the Scandinavian ice shield. The ice formed the fjords of the west cost and transported sediments to the valleys and plains. Since the ice retreated, Norway has been subject to a significant land rise. Therefore large parts of southeastern Norway are covered by former marine sediments. The total area of Norway is 324 220 km^2, of which 2.7 % are arable land. The remaining 97.3% remain relative wild terrain. ??% of the terrain feature a steepness over 30 degrees. The highest point is the mountain Galdhøpiggen (2469 m). Areas prone for avalanches are mainly found in the mountain range and along the steep fjords along the west and northern coast. Avalanches can reach from more than 1500m altitude down to the sea shore, crossing two climate zones on their path. The fjords and narrow valleys often feature a U form, carved by the glacier action. In the fjords, the valleys continue several hundreds of meters under the sea surface, leaving only a very narrow shelf to settlements and farming areas. Norway is a part of the Fennoscandian (or Baltic) shield. The Geology is dominated by old bedrock, mainly metamorphic rocks such as gneisses. The oldest rocks (2500 -3100 Ma) can be found in northeast Norway. The archipelago of Svalbard with its main island Spitsbergen is dominated by large glaciers and plateau mountains. Ca. 90% of the land area are covered by permanent ice and the remaining area consists of wide valleys with steep mountain sides.

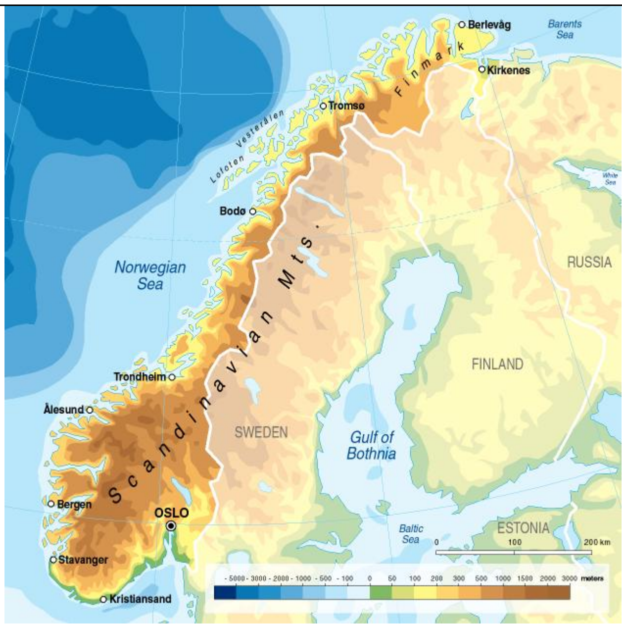
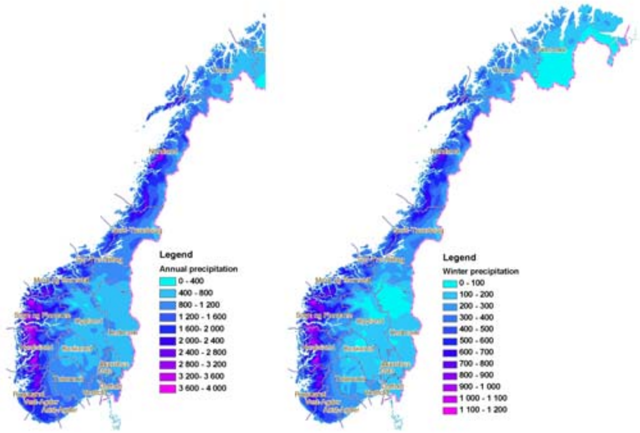
Figure 26 Topography of Norway (source: Adapted from ETOPO5, NOAA, 1988.)	
Climatic conditions	Norway covers 2000 km of coastline from 58 to 71 degrees latitude. The country can be divided into three major climate zones, the maritime climate of the southwest coast, the more continental climate of southeast Norway and the colder maritime climate of northern Norway. In general, the climate in Norway is relative temperate for its high geographical latitude. Additionally the typical altitudes of climate zones are decreasing towards the north with high alpine conditions at sea level on Spitzbergen. The mild climate is caused by the North Atlantic Current and mild air coming from the southwest. The sea is rarely frozen along the coast and temperatures are very moderate. The southwesterly winds transport large amounts of precipitation to Norway such that the Norwegian west coast becomes one of the wettest areas in Europe. The three different climate zones will be discussed in detail: The southwest coast and mountain regions in southern Norway are the wettest regions in the country (***Figure 27***). It is directly located in the west wind belt and subject to a high low pressure activity. Wet air from the Atlantic Ocean is pressed upwards at the mountains leading to an orographic lift effect. This effect amplifies the precipitation significantly just some kilometres inland from the coast. Brekke in the district of Sogn og Fjordane has the highest annual precipitation with 3575 mm. In some locations the annual precipitation can exceed 5000 mm in mountain areas near the coast. The innermost parts of the west coast fjords suffer already from the effect of a rain shadow and are significantly drier with an annual precipitation in Geiranger of 1351 mm and in Lærdal of only 491 mm. Precipitation events are normally long lasting but still of rather high intensity. The precipitated snow in wintertime is often wet. Temperatures in this regions show little annual variations, due to the equalizing effect of the open sea (Fig. 3.2). The difference in normal monthly mean temperature from January to July is from 12-14 °C. This effect is increasing with distance from the coast and altitude in the mountains.

Figure 27 Annual and winter precipitation. Based on 1961-1990



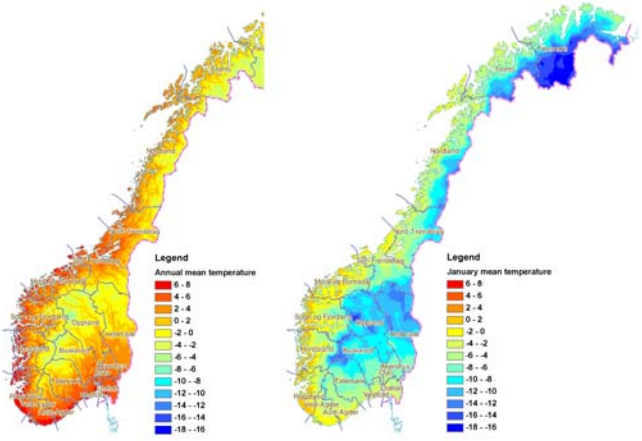
The snow cover in winter time is strongly dependent on temperature. Along the coast, at sea level, a complete snow cover is rare. Normal snowline elevation is above 500 m at the cost and falling towards the inland. The snow cover is frequently warmed to zero °C and subject to rainfall during the entire winter, leading to a complex snow structure. Contrary, long cold periods with little precipitation can lead to the formation of a continental snow cover within a short period of time.

The southeast of Norway is located east of the mountains and receives considerably less precipitation, usually less than 1000 mm a year. Valleys surrounded by mountains can be very dry: Skjåk has the lowest average annual precipitation on the mainland with only 278 mm. Intensive precipitation events are usually caused by a special weather situation with wet southerly air. During summer, this area can suffer from intensive thunder storms, causing local floods and shallow land slides. Longer dry periods during the summer are causing the shallow soils to dry out fast causing a high danger for forest fires.

Annual variations in temperature are higher than at the coast, reaching 21 °C in Oslo and 24 °C in Lillehammer. Long cold periods in wintertime can last for several weeks. The coldest temperatures are measured in Røros close to the Norwegian border, and show a record of -50°C.

Northern Norway is also divided into two main climatic regions (***Figure 28***). The coastal islands of southern Lofoten, just north of the Arctic Circle, are the northernmost location in the world where all winter months have an average temperature above 0°C. Still, this is due to the influence of the warm ocean water.

The influence of the North Atlantic Current weakens in the far northeast of the country (east of North Cape), furthermore the frequent mild and moist air from the southwest is often blocked by the Lyngen Alps in northern Troms, thus the interior of Finnmark gets less than 450 mm precipitation and has the coldest winters in the country.

<table>
<tr>
<td>Figure 28 Annual and January mean temperatures. Based on 1961-1990</td>
<td>


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<td></td>
<td>Precipitation events at the coast of northern Norway can be intense both in summer and winter time. Rain on snow events is frequent at sea level and cause a large number of slushflows.
A special case is the archipelago of Spitsbergen. These islands are located in the Barents sea at 78° north. Here, the climate is cold, no higher plants exist on the land and large areas of the landmass are covered by glaciers. Large parts of the central islands are very dry. The snow pack is usually thin and subject to heavy constructive metamorphism. In addition all snow on Spitsbergen is modified by wind transport, due to the lack of vegetation and constant adiabatic winds from the inland ice masses.
Normal monthly averages range from -17.1°C in January in Karasjok 129 m a.s.l. to 17.3°C in July in Oslo - Studenterlunden 15 m.a.s.l. The warmest year average temperature is 7.7°C in Skudeneshavn in Karmøy, and the coldest is -3.1°C in Sihcajarvi in Kautokeino (excluding higher mountains and Svalbard).</td>
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</table>

Table 10 Climate data for some locations in Norway; base period 1961-1990 (temperatures are 24-hour average):

Location	Elevation	Temperature (°C)			Precip / year	Growing season (days)	Summer (days)	Snow >25 cm (days)
		Jan	Jul	year				
Blindern / Oslo	94 m	-4.3	16.4	5.7	763 mm	188	133	30
Lillehammer	242 m	-9.1	14.7	2.9	660 mm	165	108	110
Sognefjellhytta / Lom	1413 m	-10.7	5.7	-3.1	860 mm	58	0	244
Kristiansand	22 m	-0.9	15.7	7.0	1380 mm	205	145	21
Sola / Stavanger	7 m	0.8	14.2	7.4	1180 mm	215	144	0
Florida / Bergen	12 m	1.3	14.3	7.6	2250 mm	215	143	3
Molde / Romsdal	20 m	0.5	13.5	6.7	1640 mm	195	120	no data
Værnes / Trondheim	12 m	-3.4	13.7	5.0	892 mm	180	114	14
Nordøyan Fyr/Vikna	33 m	0.5	12.5	6.0	800 mm	188	98	1
Svolvær / Lofoten	10 m	-1.5	13.0	4.7	1500 mm	165	87	19
Langnes / Tromsø	8 m	-3.8	11.8	2.9	1000 mm	139	65	160
Honningsvåg / Nordkapp	10 m	-4.5	10.3	2.0	765 mm	115	40	110
Kirkenes	10 m	-11.5	12.6	-0.2	450 mm	125	65	140
Longyearbyen / Svalbard	28 m	-14.6	6.5	-6.0	210 mm	50	0	34

Growing season: Number of days/year with 24-hour average temperature at least 5 °C.
Summer: Number of days/year with 24-hour average temperature at least 10 °C.
Snow: Number of days/year with at least 25 cm snow cover on the ground; 1971-2000 base period.
Sognefjellhytta: Mountain lodge; large diurnal temperature variation is common in summer.
Nordøyan Fyr: Lighthouse, August is warmest month and is used in place of July.
Snow cover data from nearby locations: Skrova is used for Svolvær, Repvåg for Honningsvåg, Neiden for Kirkenes
and Svalbard Airport snow data (1976 - 2000 base period) is used for Longyearbyen.
Tromsø: Snow cover data is from a station 100 m a.s.l., Langnes will have slightly less snow.
Honningsvåg is on the southern coast of Magerøya, the Nordkapp plateau (307 m.a.s.l.) will be ca 2-3°C colder.

As seen from the ***Table 10***, Norway's climate shows large variations. Following the Köppen climate classification there is:

- Maritime mild temperate / marine west coast climate (Cfb) at the south and west coast
- Hemiboreal / humid continental (Dfb) in the southeast
- Marine west coast - cool (Cfc) at the coast of Northern Norway
- Subarctic (Dfc) at the north coast
- Polar tundra (ET) on Spitsbergen

In addition, large mountain areas have alpine tundra climates, and might have several climate zones below the treeline with decreasing altitude, depending on location and aspect.

During the past 10 years or so, temperatures have tended to be higher. Using the same data source but with the years 1991-2005 as base period, this results in average January temperatures for the same stations that are 1 °C to 2.5 °C higher, while the July 24-hr average temperatures increases by approximately 0.5 to 1 °C.

As a consequence of this, snow the cover has tended to decrease in those lowland areas where winter temperatures often hover around freezing.

2.14 Available data

In Norway, on a national level, no special observation programs for the purpose of avalanche warning are available. Existing standard meteorological data from various

	sources has to be used. This chapter will describe some of the datasets currently collected in Norway and their availability for the avalanche warning
Meterological institute	The Norwegian Meteorological Institute was founded in 1866 as one of the first national meteorological services in Europe. Its tasks today are the collection and maintenance of observations, weather forecasting, and research and climate studies. The meteorological institute operates today ca. 400 stations in Norway and on the islands of the Svalbard archipelago (***Figure 29***, ***Figure 30*** and ***Figure 31***). The majority of the stations is located along the coast at low altitude. These stations give limited information for the purpose of avalanche warning. The met.no products both from the observation network as well as from the forecasting models are partly available for the avalanche warning. The new software DIANA will hopefully improve the accessibility to the data and allow specially designed products for the avalanche warning. The products available for the avalanche warning today are shown in following figures.

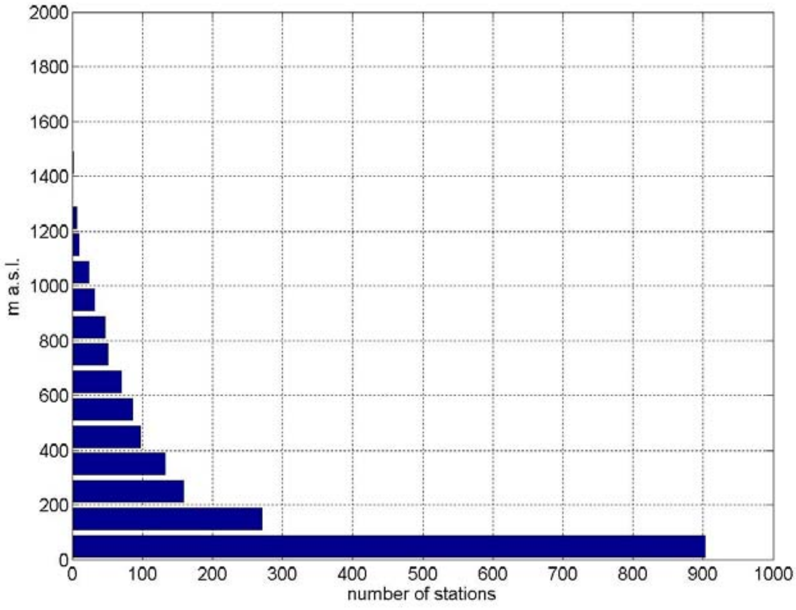
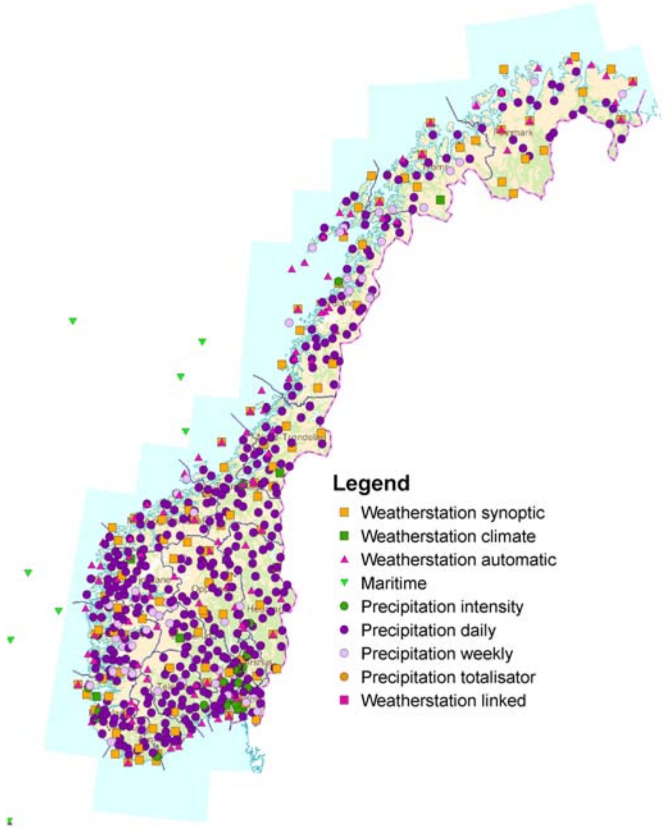
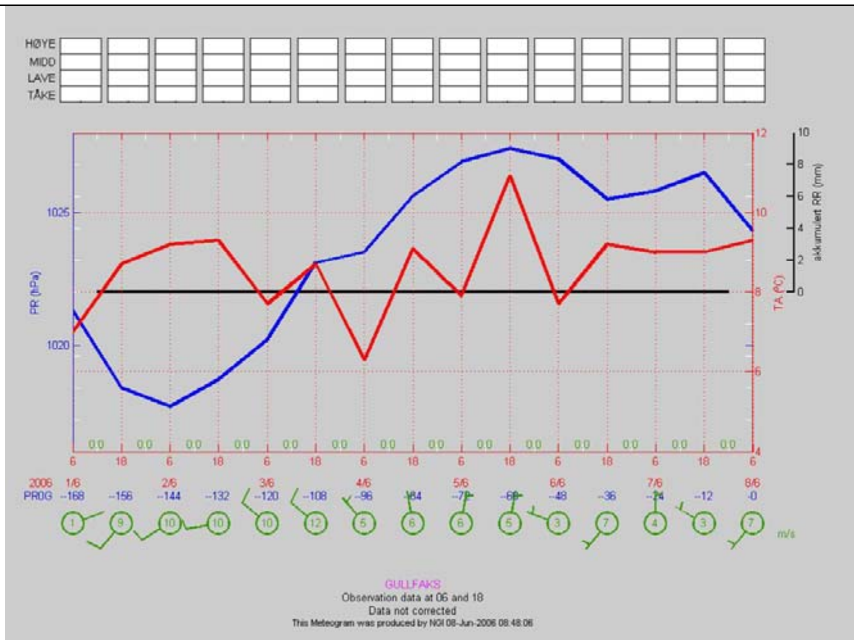
Figure 29 altitude distribution of weather stations operated by the Meteorological institute	
Figure 30 Location of meteorological observation stations in Norway	

Figure 31 Overview over available data offered by the meteorological institute

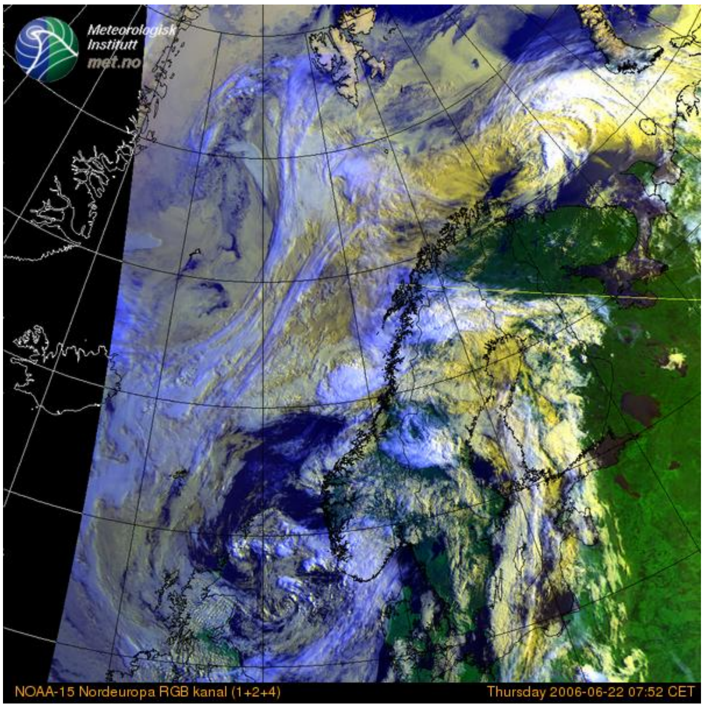


Data set	Parameters	Daily updates	Access
Synoptic observation network	Parameter set depends on station type	Every 6 hours	Partly accessible

Figure 32

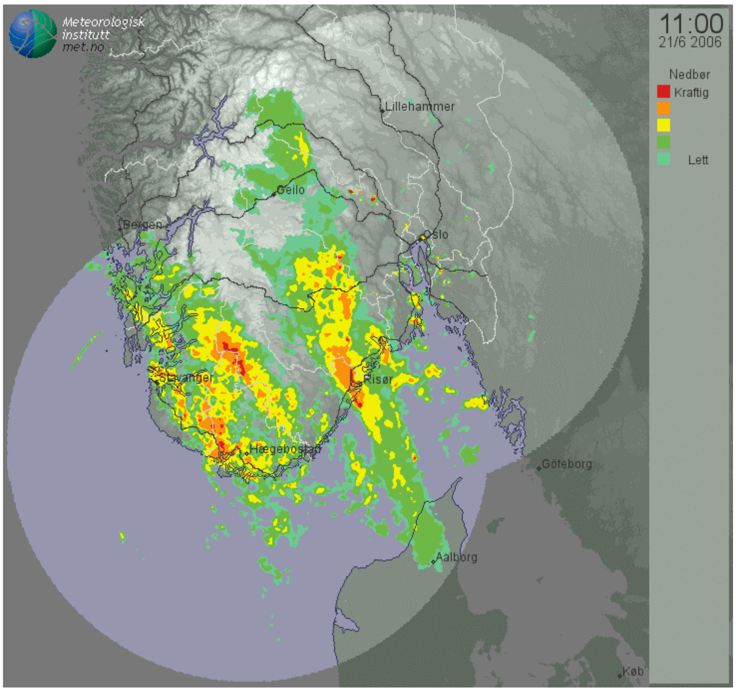
Data set	Parameters	Daily updates	Access
Interpolated observation maps of temperature, snow and precipitation	Precipitation last 24h Precipitation last week Snow cover New snow amount Temperature last 24h Etc.	Once a day (currently 24h delayed)	Fully accessible

Figure 33



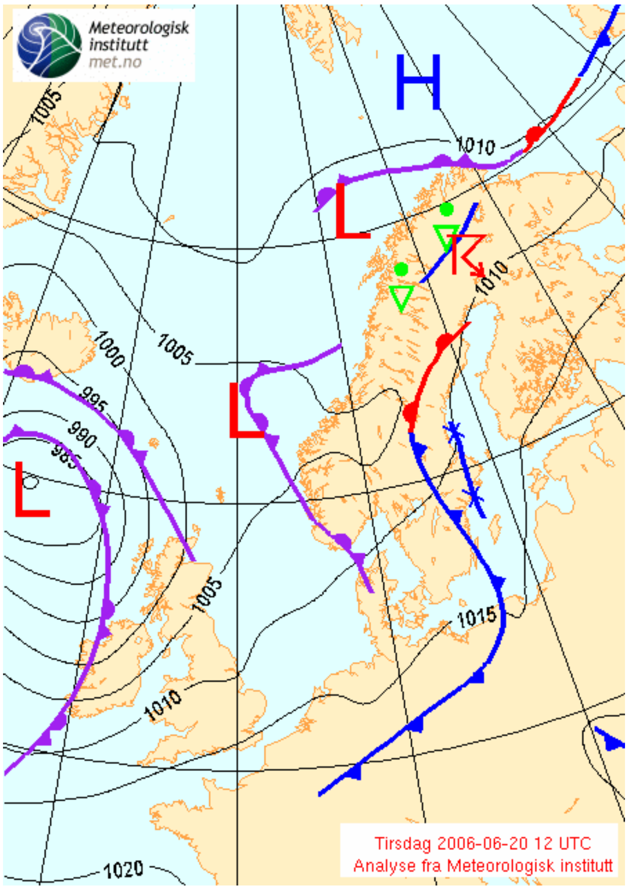
Data set	Parameters	Daily updates	Access
Satellite pictures	Visual impression of current situation	Ca. 48 updates a day	Partly accessible

Figure 34



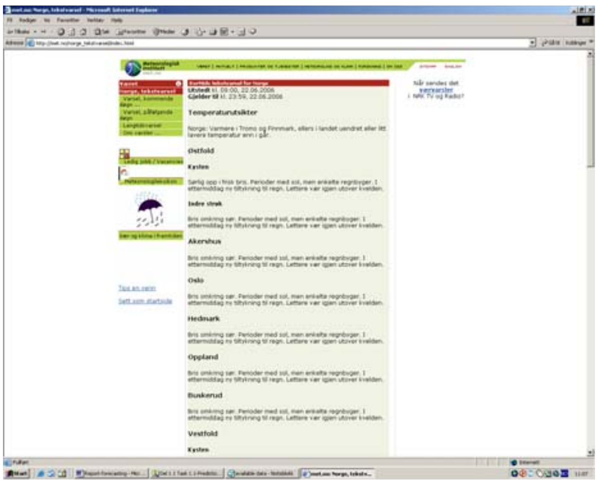
Data set	Parameters	Daily updates	Access
Weather radar	Precipitation intensity	Every five minutes, one hour delayed	Fully accessible

Figure 35



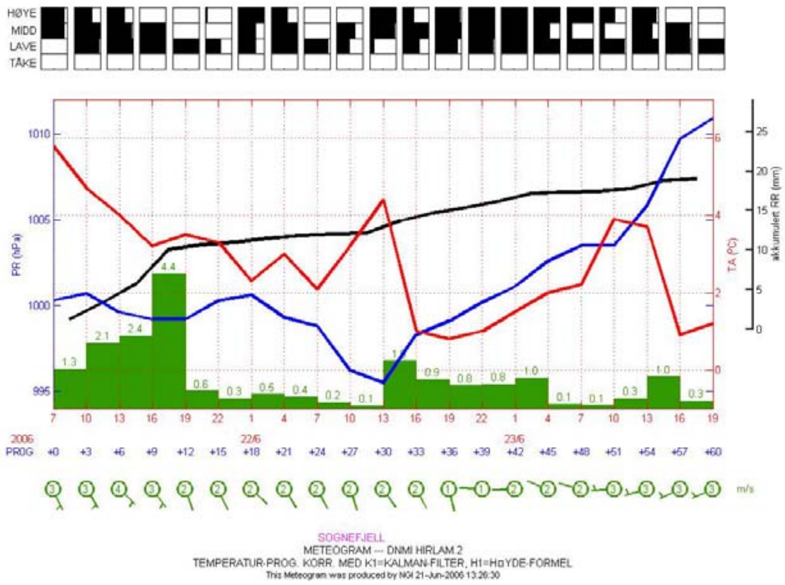
Data set	Parameters	Daily updates	Access
Reanalysis	Pressure fields Fronts	Four	Fully accessible

Figure 36



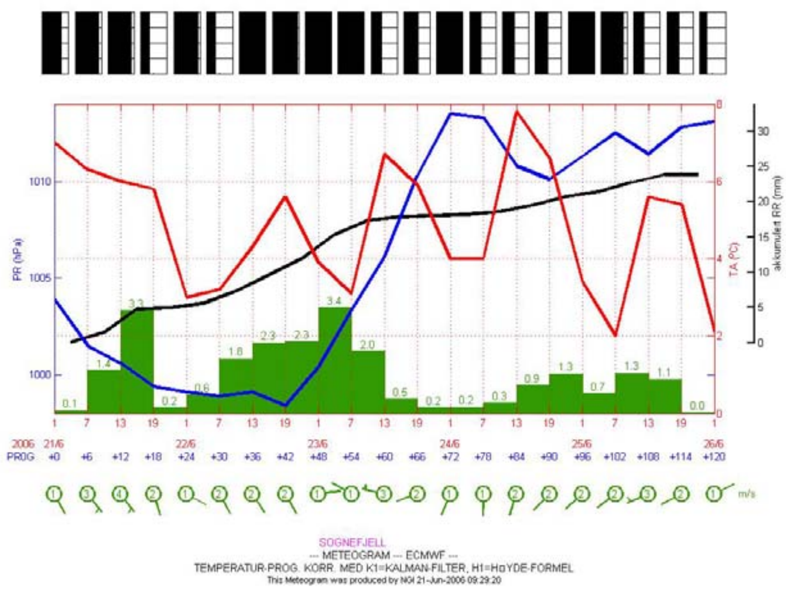
Data set	Parameters	Daily updates	Access
text warnings	Wind Temperature Precipitation Special warnings	two	Fully accessible

Figure 37



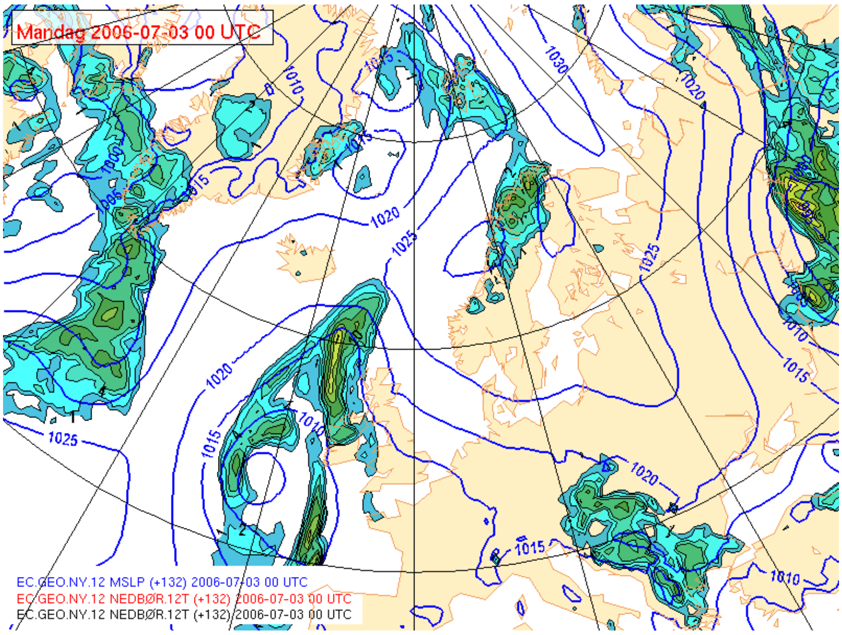
Data set	Parameters	Daily updates	Access
HIRLAM 12 km model results as time series	Cloud cover Pressure Precipitation Wind Accumulated precipitation Relative humidity	Two	Access is limited to a selection of 200 stations in Norway

Figure 38



Data set	Parameters	Daily updates	Access
ECMWF 50 km model results as time series	Cloud cover Pressure Precipitation Wind Accumulated precipitation Relative humidity	Two	Access is limited to a selection of 200 stations in Norway

Figure 39



Data set	Parameters	Daily updates	Access
ECMWF 50 km model results as time series	Cloud cover Pressure Precipitation Wind Accumulated precipitation Relative humidity Etc.	Two times	Very limited access

Road authorities

The Norwegian road authorities maintain a network of automatic weather stations all over the country (***Figure 40***). The stations usually observe air and pavement temperature, precipitation and sometime wind velocity. Additionally, some of the stations are equipped with web cameras.

The data from the stations is partly available through password secured web sites. The access to these sources for avalanche warning is not officially approved.

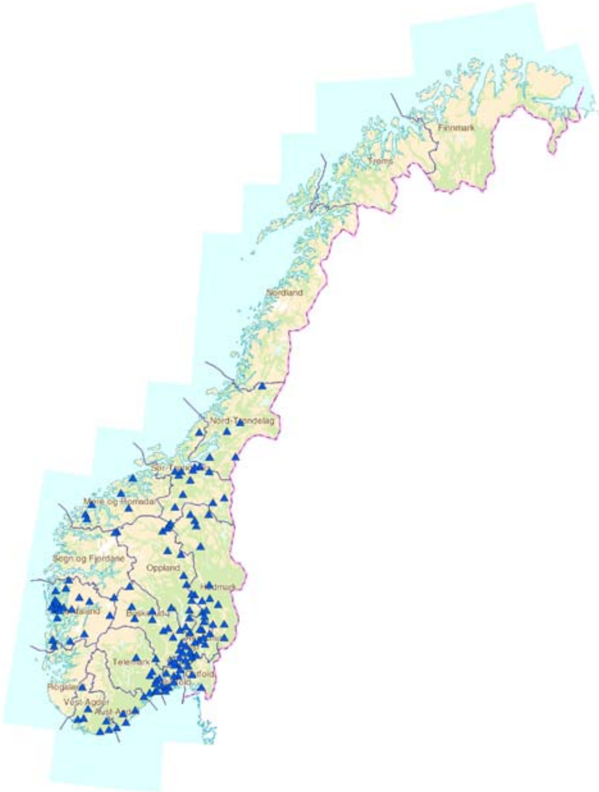
Figure 40 Map of Norway showing the location of weather stations operated by the road authorities	
Power supply companies	Norway is covered by a large network of hydro power facilities (***Figure 41***). Many of these have installations high up in the mountains. Most of the larger hydro power plants have their own weather and snow observations. These observations have to be reported to the Norwegian Water Resources and Energy Directorate (NVE). Nevertheless, the data is classified, since weather and snow data is considered to be decisive for the economical value of the sold electricity. The data from these stations is therefore not available for the purpose of avalanche warning.

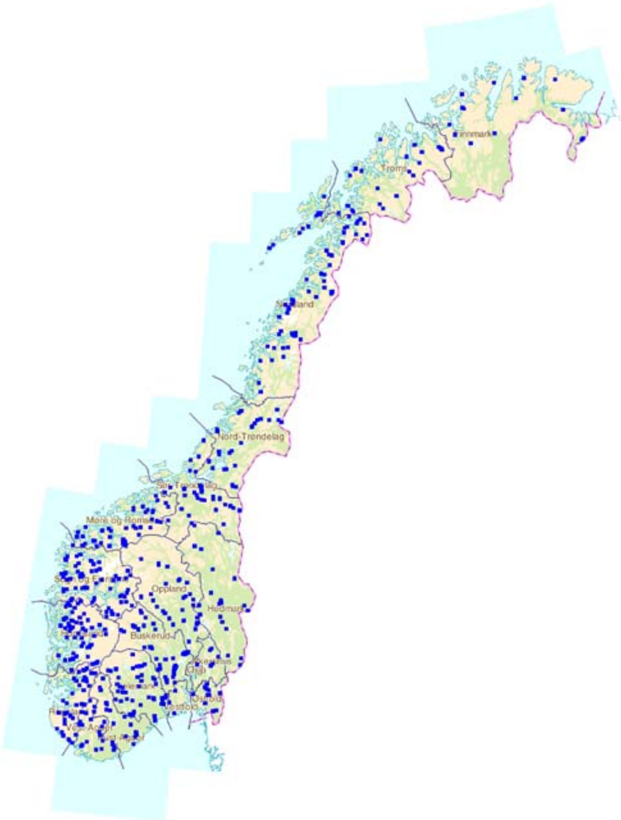
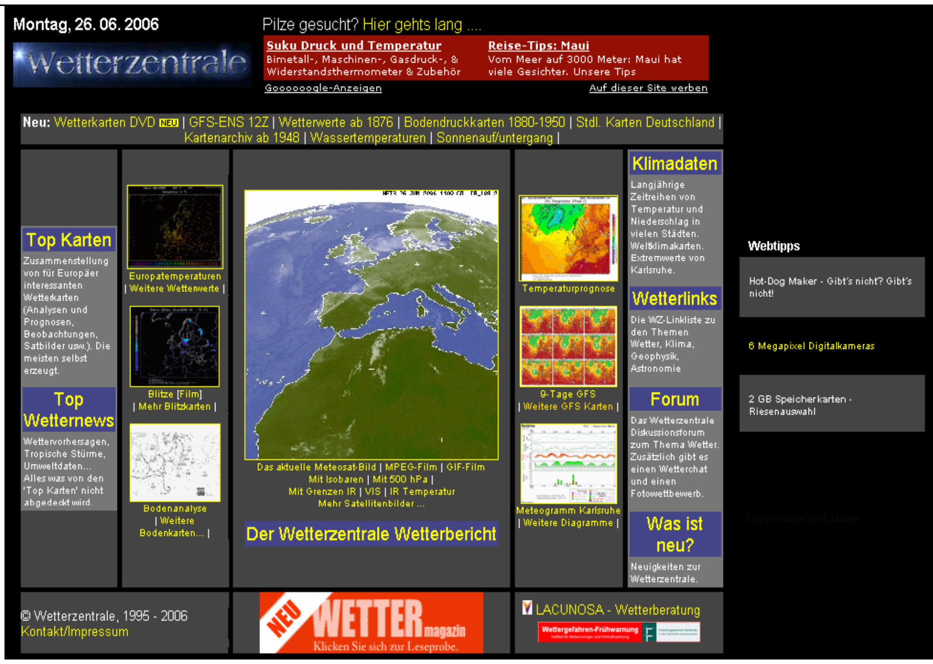
Figure 41 Map of Norway showing the location of hydro power plants	
National defence forces	The weather stations of the national defence forces are often located in areas highly interesting for avalanche warning procedures. The stations are installed in connection to radar and survey installations on mountain tops along the coast. Officially the weather data is not classified any more, but access is nevertheless limited. Wind data from two mountain tops is used by the meteorological institute in Tromsø for the purpose of avalanche warning. Further stations will be available as soon as they are connected to online systems
Free internet sources	The internet offers a wide range of different sources for weather observations and forecasting. The favourite site used in Norway is www.wetterzentrale.de (***Figure 42***). This web page is mainly based on the results from the American GFS (Global Forecasting System). The data is presented in different graphical ways, both in time and space. Additionally many other European weather resources are linked to this site, such that it is the perfect hub for weather information in Europe. The services of the site are free.

Figure 42 Screen plot of the popular wetterzentrale homepage



2.15 Avalanche warning and forecasting methods

Nearest neighbour method

The forecasting method of nearest neighbour was first introduced in Switzerland by Othmar Buser (1983). In Norway, NGI started developing a similar system based on standard meteorological data from weather stations operated by the Norwegian Meteorological Institute. The observations are taken three times per day, 07, 13 and 19 local time, and the parameters of interest are temperature, wind speed, wind direction, snow depth, and precipitation the last 24 hours, 72 hours and 120 hours. There are not performed radiation measurements on standard observation stations, the cloud cover is observed manually. Recording of avalanches hitting roads started in the middle of the seventies, and in some districts the records are quite good. In short, the nearest neighbour system can be expressed wit the following equation:

Difference $\boldsymbol{\Delta_J^2 = \Sigma\, k_i\, (\, x_i - x_{iJ}\,)^2}$

- *Temperature*
- *Precipitation one day*
- *Precipitation three days*
- *Precipitation five days*
- *Wind direction*
- *Wind speed*
- *Snow depth*

This might be illustrated by the sketch below (***Figure 43***) where R is the distance between the actual and former observation:

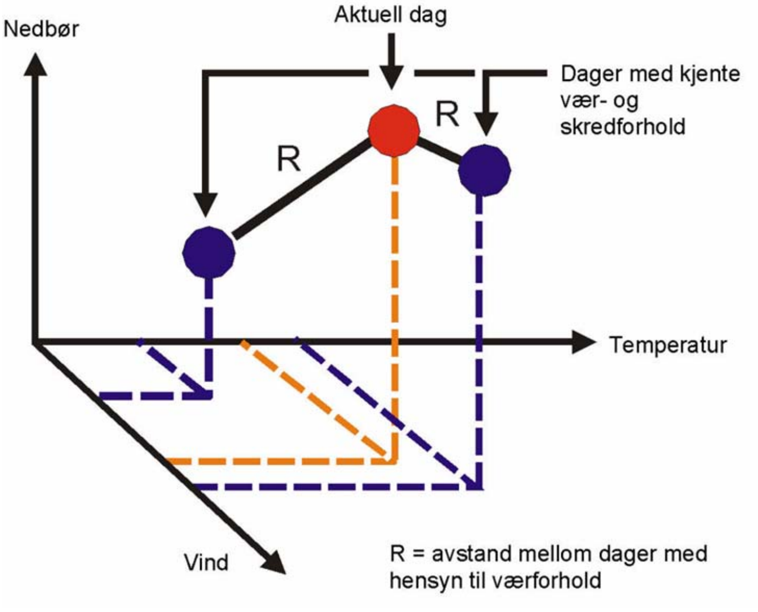
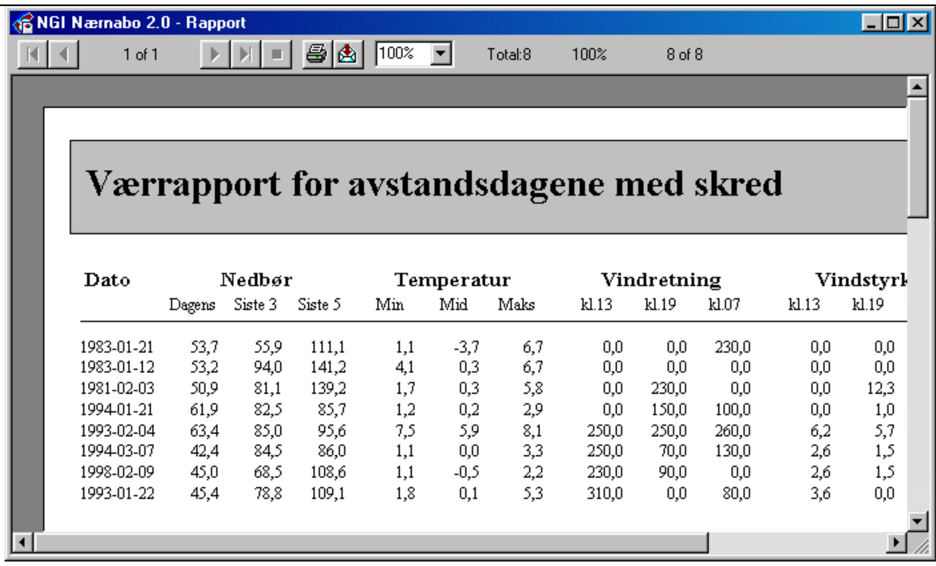


Figure 43 Graphical presentation of the nearest neighbour method

Development of the system started in 1989, and as a tool for calculation, Paradox database engine was used. This work was sponsored by the Road department, and data from the NGI research station at Strynefjell was used as test dataset. Thereafter, a dataset for the Møre district of Western Norway used the system operative with manual observations of the meteorological parameters. However, the manual input of data into the system did not work, when the avalanche hazard was low, the interest for the model was low, and when the avalanche hazard was high, the maintenance crew were busy with removing snow. Therefore it seemed necessary to install automatic weather observation equipments (***Figure 44***). In addition, the development of new operating systems on the PCs, forced it necessary to reprogram the system. The program is now written in Visual basic using Microsoft Access for the database.

Figure 44 Map showing the location of nearest neighbour application sites	
	In addition to Møre and Strynefjell, the system was introduced in Odda district in Southwestern Norway, later also in Hyen between Odda and Møre. For the winter season, the system is used in the Tromsø district in Northern Norway. The areas where the system is in use, are presented on the ***Figure 45*** below. A professional programming company working for the Public Roads has worked with the interface between the user and the program. The program is now easy and logistic to use, and the data for avalanches are found on the main server for the Public Roads. The weather data is mostly available via FTP-servers on Internet or from local weather stations close to Public Road offices. There are different prints from the calculations, the best hits are printed first and you might have as many hits as necessary. Below is a screen shot giving data and dates for the best hits. There are possibilities to change the weighting factors for the different parameters according to the snow situation. Usually one set of weighting factors are used for cold days with subzero conditions while an other set is used when there is a melting situation in the release area for the avalanche.

Figure 45 Screen shot from the software implementing the nearest neighbour method



Dato	Nedbør Dagens	Siste 3	Siste 5	Temperatur Min	Mid	Maks	Vindretning kl.13	kl.19	kl.07	Vindstyrk kl.13	kl.19
1983-01-21	53,7	55,9	111,1	1,1	-3,7	6,7	0,0	0,0	230,0	0,0	0,0
1983-01-12	53,2	94,0	141,2	4,1	0,3	6,7	0,0	0,0	0,0	0,0	0,0
1981-02-03	50,9	81,1	139,2	1,7	0,3	5,8	0,0	230,0	0,0	0,0	12,3
1994-01-21	61,9	82,5	85,7	1,2	0,2	2,9	0,0	150,0	100,0	0,0	1,0
1993-02-04	63,4	85,0	95,6	7,5	5,9	8,1	250,0	250,0	260,0	6,2	5,7
1994-03-07	42,4	84,5	86,0	1,1	0,0	3,3	250,0	70,0	130,0	2,6	1,5
1998-02-09	45,0	68,5	108,6	1,1	-0,5	2,2	230,0	90,0	0,0	2,6	1,5
1993-01-22	45,4	78,8	109,1	1,8	0,1	5,3	310,0	0,0	80,0	3,6	0,0

Threshold value

A standard method to give avalanche hazard evaluation can be visualized with a matrix with the hazard scale versus the precipitation for a certain period, most commonly used is three day precipitation. In addition, a weighing due to wind in the period is performed (de Quervain, 1972). A practical example from an avalanche path at Framruste, Skjåk, is presented in ***Figure 46***.

Figure 46 Avalanche hazard according to wind and three days precipitation

Wind(m/s) **Precipitation 3 last days(mm)**	**<6**	**6 - 11**	**11 - 16**	**17 – 21**	**>21**
0 – 10	1	2	3	4	5
10 – 30	2	3	4	5	5
30 – 60	3	4	5	5	5
60 – 80	4	5	5	5	5
>80	5	5	5	5	5

In 1986, NGI presented a probabilistic approach in the avalanche hazard warning (Bakkehøi, 1987) where for a certain avalanche path, the accumulated precipitation before a release were sorted and plotted on cumulative probability distribution paper, see ***Figure 47***.

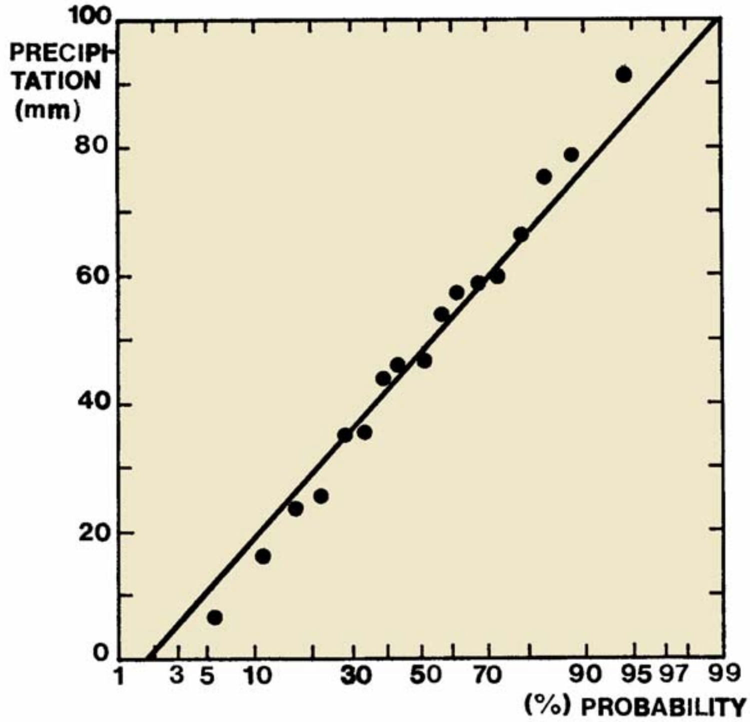
Figure 47 Cumulative probability distribution of three day precipitation at Raffelsteinfonn causing avalanche occurrence	
	The avalanches used in the investigation, were dry snow avalanches released in situations accompanied by wind in the release zone. The different amounts of precipitation ahead the release are therefore mostly functions of snow fall intensity, different wind speed and the snow stratigraphy in the release area. There are achieved different probabilistic curves for different avalanche paths in the same region, this is due to different steepness in the starting zone and different aspects which give another building of the snow pack. Curves from five different avalanche tracks are presented in ***Figure 48*** and the avalanche profiles are presented in ***Figure 49***. The gentle slope Lifonn needs more precipitation before it starts sliding than the steeper ones, a 20% probability of release for the Lifonn avalanche needs 47 mm of precipitation while for the same probability Raffelsteinfonn avalanche which is much steeper in the release area, only needs 27 mm of precipitation. This method of avalanche hazard warning is used in the warning system for highway 15 passing Strynefjell.

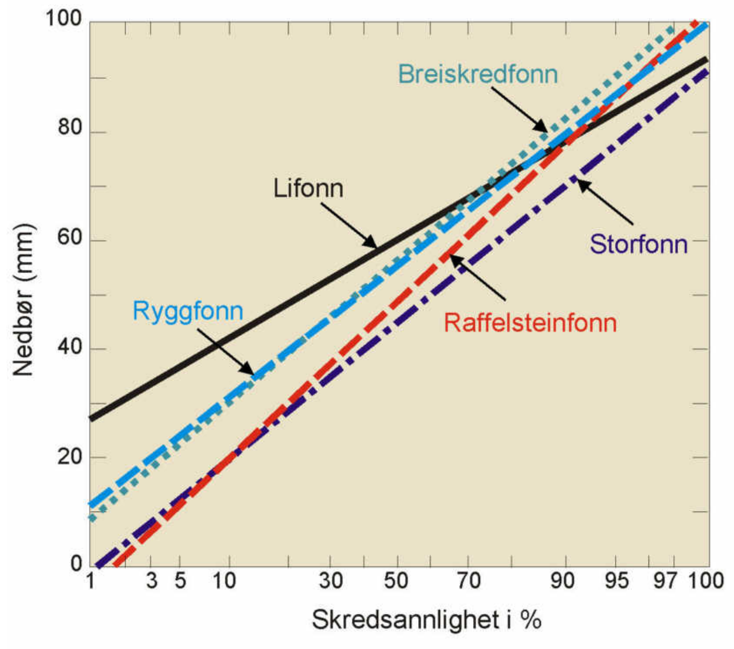
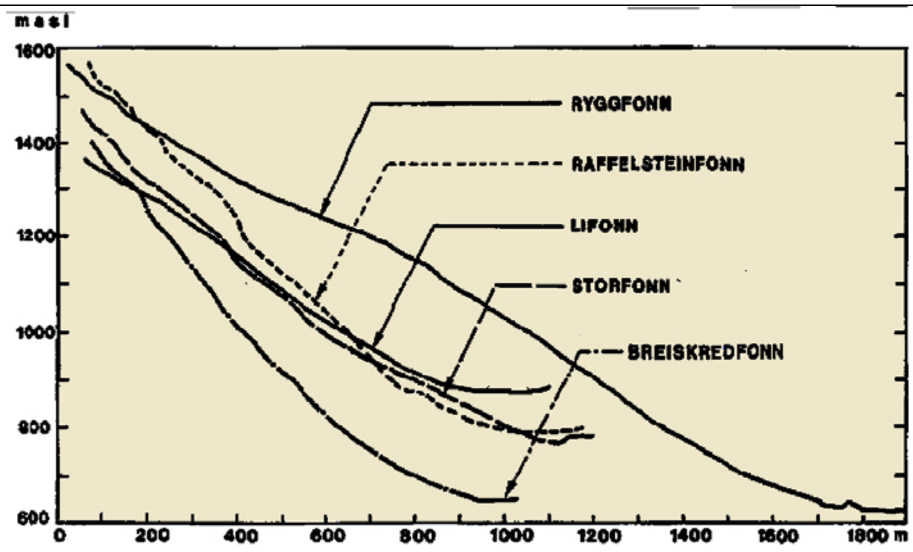
Figure 48 Distribution of curves for five avalanche paths	
Figure 49 Terrain profiles for the five investigated avalanche paths in Grasdalen, Stryn	
	Another important factor for avalanche release is the precipitation intensity in combination with wind drift. The snow layers are stabilizing with a certain factor during the snow fall, and if the precipitation intensity is below certain values, it might snow for days without avalanche release. If, on the other hand, the snow intensity is high, the avalanche might be triggered with only a little amount of new snow. NGI developed a precipitation gauge in 1985 based on vibrating strain gauges, the Geonor precipitation gauge which is weighing the temperature. Using this gauge, it is possible to have a continuous recording of the precipitation, and this is a good tool in evaluating the avalanche hazard. An example of records is presented in ***Figure 50*** where it was released an avalanche the 1997-03-02 between 01:50 and 02:50 where the snow fall intensity was up to 3.7 mm (as melted water) per hour.

Figure 50 Weather observations from Grasdalen, Strynefjell 1. and 2. of March 1997

Dato	kl	ref	T_{inn}	FF m/s	FFg m/s	DD	TT	TT	NN	SS cm	nn	ΣRR mm	ΔRR mm
970301	1351	572	15.4	3.1	19.7	325	-1.9	-3.1	19	257	1002	230.3	
970301	1450	572	15.5	3.2	10.4	182	-2.0	-3.1	19	258	1021	230.9	0.6
970301	1550	572	15.7	2.2	5.4	129	-2.1	-3.2	20	258	29	231.8	0.9
970301	1650	572	15.8	1.0	3.3	85	-2.0	-2.9	20	260	60	232.8	1.0
970301	1750	572	15.9	2.2	6.0	151	-1.4	-2.3	20	260	70	233.2	0.4
970301	1850	572	15.9	1.7	5.4	102	-1.3	-2.2	20	257	89	233.7	0.5
970301	1950	572	15.9	1.9	4.8	123	-0.7	-1.7	20	385	104	234.3	0.6
970301	2050	572	16.0	1.6	5.1	136	-0.7	-1.8	20	385	133	235.2	0.9
970301	2150	572	16.0	1.9	5.1	130	-0.6	-1.7	20	385	180	236.8	1.6
970301	2250	572	16.1	1.6	3.6	166	-0.3	-1.5	20	385	233	238.5	1.7
970301	2350	572	16.2	0.7	2.7	55	-0.2	-1.5	20	385	322	241.5	3.0
970302	0050	572	16.2	0.0	0.3	134	-0.2	-1.5	20	385	401	244.2	2.7
970302	**0150**	**572**	**16.3**	**0.0**	**0.3**	**122**	**-0.3**	**-1.6**	**20**	**385**	**497**	**247.4**	**3.2**
970302	**0250**	**572**	**16.2**	**0.0**	**0.3**	**141**	**-0.2**	**-1.6**	**20**	**385**	**606**	**251.1**	**3.7**
970302	0350	572	16.3	0.0	0.3	122	-0.2	-1.5	20	385	702	254.3	3.2
970302	0450	572	16.3	0.0	0.3	124	0.0	-1.2	20	385	771	256.7	2.4
970302	0550	572	16.3	0.0	0.3	138	-0.1	-1.3	20	385	821	258.4	1.7
970302	0650	572	16.4	0.0	0.3	179	-0.2	-1.2	20	385	859	259.6	1.2
970302	0750	572	16.4	0.0	0.3	140	0.3	-0.9	20	385	866	260.0	0.4
970302	0850	572	16.4	0.0	0.3	311	0.3	-0.8	20	385	974	263.4	3.4
970302	0950	572	16.5	0.6	3.6	148	0.5	-0.7	20	385	1001	264.3	0.9
970302	1050	572	16.6	1.0	3.6	210	0.5	-0.7	21	385	39	266.4	2.1
970302	1150	572	16.6	2.3	9.0	130	-0.6	-1.8	21	385	69	267.5	1.1

Snow stability evaluation

The forecasting procedure can roughly be divided into two main tasks, i) the evaluation of the snow stability at present, and ii) the prediction of how this will change in the near future, as a result of external or internal processes. Snow stability is traditionally defined as the ratio between strength and stress within a snow layer, but in avalanche forecasting work it is more often described as the probability of release, and usually in the terms given in the first column of five-degree European Danger scale.

In avalanche forecasting programs, the evaluation of the *present* snow stability is the starting point. The forecasting itself can be seen as the assessment of whether the stability will *change* or remain constant in the area in question.

In order to establish the present stability state of a snow cover in a given area, several approaches are being used. For a local forecasting program as the Highway 15 mountain road, the following procedures are employed:

- Monitoring of avalanche activity
- Standard snow stability tests
- Non-standard tests
- Snow profiles

Monitoring of avalanches activity

Monitoring of the avalanche activity is done within the forecasting area, and it's near vicinity. Special attention is given to so called "indicator avalanches". These may be avalanches outside the forecasting area, which tend to release early in an avalanche cycle and thus give useful clues of the general snow stability. Information about avalanche occurrences on the road itself are obtained more or less continuously from road maintenance personnel. Observations of avalanches outside the road are intermittent and very dependent on visibility and the presence of an observer. During avalanche cycles many avalanche are covered by new snow and will be invisible when the weather clears.

The quantitative stability assessment is based on the number and magnitude of the observed avalanches, although for the lower danger levels (1-3) this procedure does not always give valid results.

Standard snow stability test

The standard snow stability tests are done as often as required to have an updated assessment of the snow stability situation. This usually means that they are performed when ever significant changes in the weather occur. In addition, the standard snow stability tests are often done in connection with a snow stratigraphy investigation. The

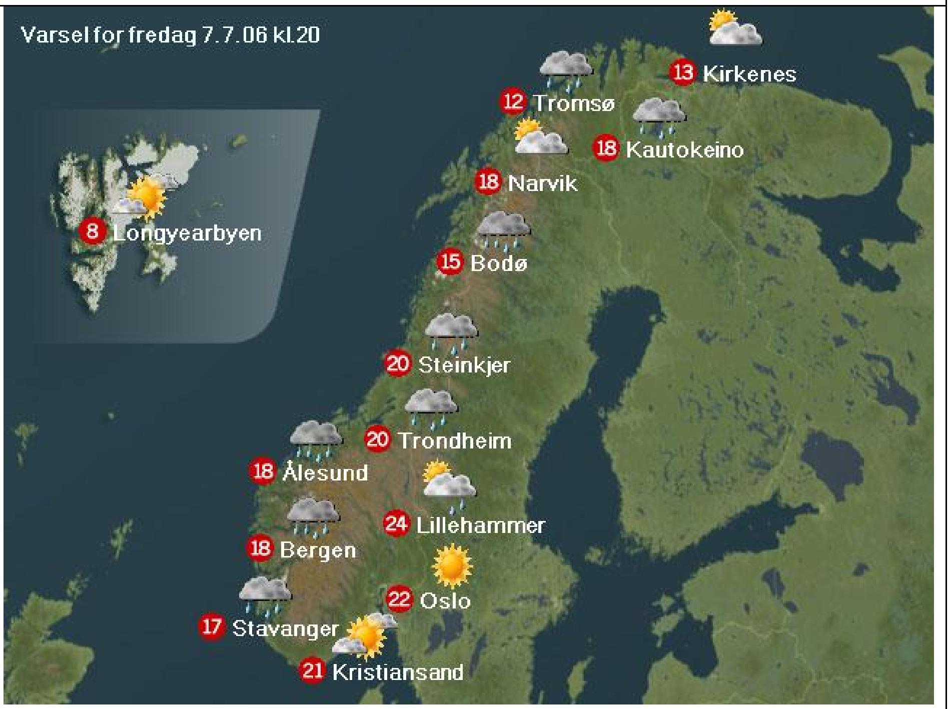
	test methods are described in various observational guidelines (a Norwegian guidelines is in preparation) and they include the shovel shear, the rutschblock and the column-compression tests. The tests take place at chosen safe locations that are presumed to be representative of the slope(s) that are being assessed at the time with respect to altitude, aspect, inclination and snow distribution.
Non-standard tests	Non-standard tests and additional observations outside formal data collection procedures can contribute valuable information. These include ski-testing and the use of explosives in slopes. Although the results of these tests are not readily quantifiable, they often contribute with valuable information.
Snow stratigraphy porfile	Snow profiles to investigate the snow stratigraphy are done every fortnight, or sometimes more often when significant changes of snow cover are expected. The investigations either take place at specific now study plots or at chosen safe locations that are thought to be representative of the slope(s) that are being assessed at the time with respect to altitude, aspect, inclination and snow distribution. Snow stratification profiles alone give only an indirect measure of stability, since no actual testing is done.
Expert evaluation	Experts in complex real-world situations often use their recognition of a specific situation to assign it to a typical a class of situations, and mentally test the outcome of a scenario. In contrast to most models, an expert will use several types of information, both formal and informal and he will usually reach a more accurate conclusion in a shorter time than any formal evidence-based analysis will. The accuracy of the assessment naturally depends on the size of the expert's experience base. However, the lack of transparency in this kind of assessment poses a serious problem for avalanche warning programs, especially when assessments are challenged from the outside. Experts are also not immune to personal biases, conflicts of interest, outside pressure, etc. In this context it is therefore a great asset to be able to use methods like the nearest-neighbour and other statistical procedures mentioned above, to support the expert assessment.

2.16 Case study

	National avalanche warning services in Norway are only offered in a general way for large parts of the country as a whole. Still there exist a number of regional and local warning systems that were established to serve the need of one particular region or local customer. Generally, the warnings are based on the international avalanche danger scale. Warnings are usually only issued when danger level four or five is reached. Procedures differ from project to project and the responsibility for the local safety, closures and evacuations are not taken by the avalanche forecasters, but by the local authorities. The annual budgets for the projects are very small and offer only the possibilities to realize a minimum standard in the warning procedures. Different case studies are presented here to give an overview over the avalanche forecasting currently going on in Norway.
National avalanche warnings	In 1972, Norwegian parliament decided that the Meteorological Institute will be responsible for the avalanche warning in Norway. At the same time the NGI got the

	mandate to be the national research centre for avalanches. The Meteorological Institute issues avalanche warnings for larges geographical areas such as counties and parts of the country. The warning issued is based on the international five level avalanche danger scale. The institute limits its warnings to the two highest danger levels “high” and “very high avalanche danger”. These warnings are posted under the category of special warnings which also includes storm or forest fire warnings. If the situation is evaluated to reach the danger level “very high” in extended areas in the country an extreme weather warning is issued on national radio and TV. The warnings of the Meteorological office are based on threshold values. They are automatically applied on the results of the regional meteorological forecasting model HIRLAM. If the threshold values are exceeded the meteorologist on duty gets a warning and will consider the avalanche situation for his next forecast.
Precipitation; amount and intensity	The avalanche danger is high whenever: - the forecast shows 50 – 80 cm of new snow and a wind speed of 7 m/s or less - the forecast shows 30 – 50 cm of new snow and a wind speed of 10 m/s or more The accumulation is reset to zero if the wind changes direction such that the snow transport and accumulation changes character. But also the precipitation intensity is important, e.g. 1 cm snow per hour equals 72 cm within three days, which leads to high avalanche danger. This is a relative low intensity where the snow has the chance to stabilize itself during the snowfall. The intensity for high avalanche danger is at least 2-3 cm/h Rain on snow leads to high avalanche danger is possibly the most usual reason for warnings to be issued.
Wind	Wind in itself is not considered as criteria in the automatic system. Wind effects will be considered by the meteorologist on duty.

Figure 51 Weather map as used on the national TV. High avalanche danger ( )is indicated in the southern part of Norway



Temperature	Temperature is considered mainly in combination with rapid melting and rain on snow

events.

Generally no ground observations are used as input to the avalanche danger evaluation

Table 11 Overview over the national avalanche warning service

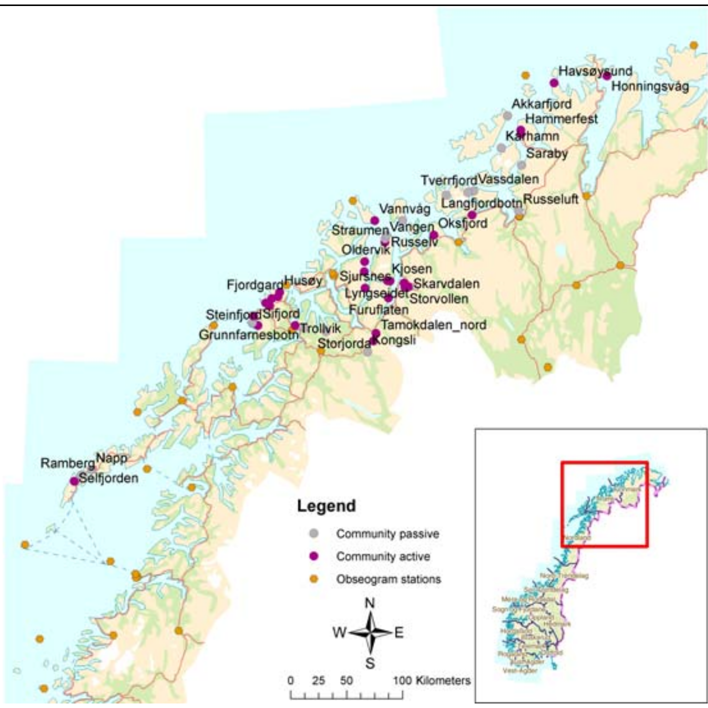
Parameter	National warning system
Resolution in time How many warnings a day?	Warnings are only issued at danger level 4 or 5
Resolution in space What areas are covered?	Covers large areas such as counties or parts of the country
Classification national, regional and local scale	National
Data used	Primarily weather forecast model data
Verification used	The reductions in the avalanche danger level are not announced.
Quality control of the warnings	None
Annual budget	No special budget for the avalanche warning

Local avalanche warning for selected settlements in Northern Norway

In northern Norway (***Figure 52***) many small communities along the coast are exposed to large avalanches. The avalanches can reach the houses during exceptional conditions that favour a long avalanche run out. Normally, that means dry snow conditions down to zero altitude and strong loading of the release areas by precipitation and/or wind.

In 2002, a number of communities decided to cooperate in a local avalanche warning system. On the initiative of the county emergency office, 15 communities participated. The project is coordinated and administrated by the county emergency office. The meteorological office in Tromsø monitors the weather, the NGI evaluates the avalanche danger and the local police are responsible for evacuation of the inhabitants in exposed areas.

Figure 52 Map over Northern Norway showing the communities involved in the avalanches as well as the locations of the available weather stations.



The participating communities are spread over a large area covering more than 700 km of coast line from the Lofoten islands in the south to Hammerfest in the North. The network of weather stations in the area is limited. But the biggest problem is the lack of real time data. Only the very southern part of the area is covered by weather radar.

The warning is based on a three level approach. Every day, the metrological office in

Tromsø monitors the weather and calls the contact person at the NGI if the agreed threshold values are exceeded.

The avalanche situation is then evaluated by two NGI experts who also can consult local observers in the area. If the avalanche danger is reaching danger level four or five, the county emergency office is alarmed and both the meteorological offices as well as the NGI follow the situation.

If the situation produces a high probability for avalanches in a certain area, the police will evacuate the houses. Eventually, NGI experts will join the local emergency team and support them with their advice.

Table 12 Overview over the regional avalanche warning in northern Norway

Parameter	Regional avalanche warning in northern Norway
Resolution in time How many warnings a day?	Warnings are only issued at danger level 4 or 5
Resolution in space What areas are covered?	Covers large areas such as counties or parts of the country
Classification national, regional and local scale	Regional
Data used	Primarily weather forecast model data, local observers
Verification used	The reductions in the avalanche danger level are not announced.
Quality control of the warnings	Two NGI experts discuss each warning
Annual budget	30.000 €

The national highway 15

The national highway Rv. 15 is a main artery that connects the west coast regions of the Førde-Måløy-Sunnmøre area with the main north-south transport corridor, the European highway E6. It is the only ferry-free connection to the east from this region and possible detours are considerably longer. To reach eastern Norway, the road has to cross Strynefjellet which is part of the main east-west water divide of the Scandinavian peninsula (***Figure 53***). Strynefjellet is the highest point of the road at around 1050 m a.s.l.

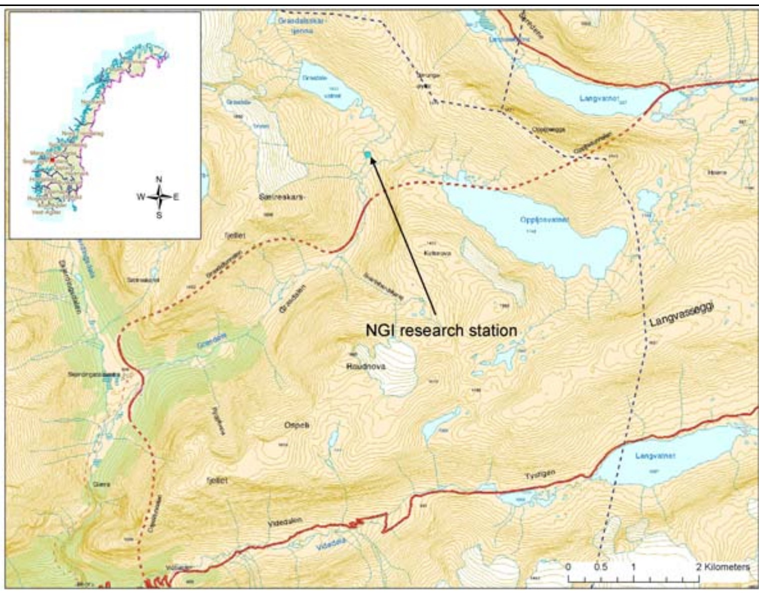


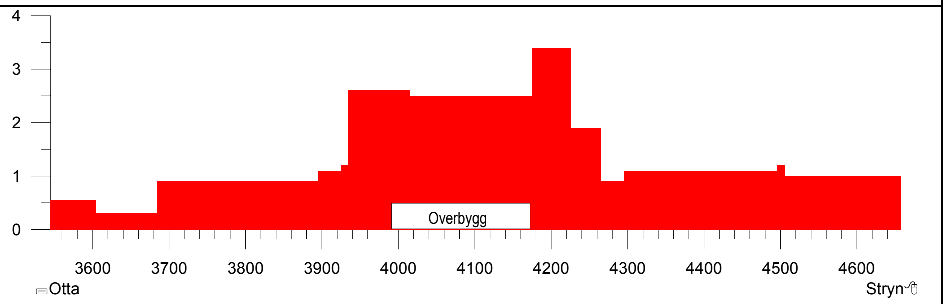
Figure 53 Map of Strynefjellet. The short section between tunnels of Highway 15 in the middle of the map is subject to high avalanche danger .

The all-season road over Strynefjellet was built in the 1970-ies and it passes through three tunnels of up to 5 km length. Before the tunnels were constructed, the area was largely inaccessible during winter. Thus there were very limited information about avalanches in the area. The building of the road was also forced by political and economic pressure. In hindsight it can be stated that not enough consideration was taken of the avalanche conditions.

The main avalanche bottleneck is the 922 m long unprotected stretch of road in Grasdalen. This stretch has a high frequency of avalanches and only limited protective measured (***Figure 54***). The risk of accidents is high, both for the users and maintenance personnel. At present mitigation consist of avalanche forecasting, closing of the road and blasting of remotely controlled explosive charges in part of the starting zones. These measures are estimated to reduce the individual risk for road users to about ¼ of what it would be without any measures taken. However, the price paid for this risk reduction is longer closures and a reduction of regularity. Because of the industry's demands of "just-in-time"-production and delivery, the pressure to keep the road open at all times is steadily increasing. There is now reason to believe that a cost/benefit analysis that takes into account costs to society as a whole, would favour more permanent avalanche protection measures, such as extended tunnels or galleries.

Closure frequency and duration vary a great deal. The annual closures have lasted from between 12 hours up to 720 hours (30 days). The median for the last 15 winters is around 300 hours /(12.5 days).

Figure 54 Annual frequency of avalanches along the Highway 15 in Grasdalen. The road is divided into 10 segments, but a single avalanche can cover up to 500 m of the road.



Contract

The avalanche forecasting program is a contract project for the National Road Administration and the forecasting period normally runs from December 1st to April 30th. NGI shall provide the decision makers with two daily avalanche danger assessments, with a probability of avalanches reaching the road in the coming 12 hour period. It is then up to the road authorities to decide what actions to be taken. Some actions are given in the road maintenance guidelines, but so far the general risk acceptance level has not been specified for road users.

Procedure

For data acquisition, the forecasting program relies partly on the data obtained from NGI's field research station Fonnbu, 800 m northwest of the road at about the same height, at 920 m a.s.l. The station has an automatic weather station (AWS) and provisions for snow investigations and stability tests near the starting zones above the road (***Figure 55***).

The AWS at the research station measures hourly precipitation with a Geonor T200 precipitation gauge, and wind, temperature and snow height every 10 minutes. A supplementary summit AWS is placed on an ridge across the valley opposite the main staring zone at 1420 m a.s.l. This station measures wind and temperature.

Figure 55 Summit automatic weather station opposite the main staring zone. The Highway 15 runs in the valley below.

The forecasting procedure for Highway 15 can be divided into five different tasks;

1. Determination of the present state (NOWCASTING)
2. Assessment of the likely development (FORECASTING)
3. Quality control of the forecast
4. Documentation and distribution
5. Verification in hindsight and adjustment

Each of these steps are possible sources of error and the reliability of the forecasting program depend on the total performance.

The table below (***Table 13*** and ***Table 14***) gives an overview of the forecasting procedure

Table 13 Overview for nowcasting porcedure

NOWCASTING

Procedure	Data	Source
Snow stability	-Avalanche observations, -"Indicator avalanches" -Snow conditions -Result of blasting	-Own observations and reports from other sources -Snow profiles and stability tests, every two weeks, or as required -Preplaced charges in starting zone
Local weather data	-NGI AWS-data -Summit AWS-data -Local data from AWS near by -Updated pictures	Project web-site Webcameras (project web-site)
Regional weather Synoptic weather	-Updated radar images -Satellite images, weather maps	-Norwegian Met. Inst. -Norwegian Met. Inst. -Different national and international weather services

Table 14 Overview for forecasting porcedure

FORECASTING

Procedure	Data, result	Source
Local weather forecast	Meteograms	HIRLAM: Norwegian Met. Inst. ECMWF
General weather forecasts	Weather maps	-Norwegian Met. Inst. -Different national and international weather services
Nearest neighbour	Similarities with previous situations	NGI: -Past and forecast weather -Avalanche data base -NN-model
Probabilistic analysis	Probability	NGI: -Past and forecast weather -Avalanche data base -Model
Expert evaluation	Probability	All information

QUALITY CONTROL

1st forecaster	Fill out checklist	Prepared checklist
2nd forcaster	Consensus	Short discussion

DOCUMENTATION

Procedure	Data, result	Source
Formulation	Main danger degree Additional text: Present situation Forecast Time span Area Time for next forecast	Standard forecast template European danger scale
Distribution	Signed facsimile, e-mail SMS	List of recipients
Data storage	Checklists Distributed forecasts	Data base Paper file

The table below (***Table 15***) show what actions may be taken as a result of the forecast. For practical reasons the terminology of the European Danger Scale definition is applied to describe the probability of avalanches reaching the road in a given period (***Table 16***). This may not correspond to the use of the scale in other circumstances.

Table 15 Danger scale and possible actions concerning traffic and maintenance.

Danger scale	**Probability of avalanches reaching the road during specified period in specific area.**	**Traffic** actions	**Maintenance** actions
1. Low	**< 1 %**	**No restrictions**	No restrictions
2. Moderate	**< 5 %**	**No restrictions**	No restrictions
3. Considerable	**5-20 %**	**No restrictions,** but stopping not allowed.	Work in exposed areas only in daylight (except fast ploughing).
4. High	**20-50 %**	**Road may be closed** but stopping not allowed. Monitored traffic, closure if bad driving conditions.	After release: Clearing only in daylight with avalanche watch. (assessment of secondary avalanche probability first)
5. Very high	**> 50 %**	**Road is closed**	No activity in avalanche exposed area

Table 16 Overview over the avalanche warning at national highway 15

Parameter	**Avalanche warning on national highway 15**
Resolution in time How many warnings a day?	2
Resolution in space What areas are covered?	5 km
Classification national, regional and local scale	Local
Data used	Local AWS-data, local snow data, local forecasts
Verification used	Avalanche observation, snow stability tests
Quality control of the warnings	Two NGI experts discuss each warning
Annual budget	30.000 €

The Bergen Railway

The Bergen Railway is the highest situated railway in Norway reaching 1222 m above sea level at Finse station (***Figure 56***, ***Figure 57*** and ***Figure 58***). From Geilo to Mjølfjell it is passing through some big avalanche paths with are released with a frequency one per 5 – 10 years up to one per 100 year. In addition there are some smaller avalanches which can be released one ore more times per year. Train has passed this mountain region since 1908, and most of the problems with the winter regularity have been in connection with heavy snowfall blocking the tracks. It seemed necessary to build huge snow blowers to clean the track.

Figure 56 Map showing the mountain section of the Bergen Railway

Since 1993, NGI has supported the railway company with avalanche hazard forecasts in the period from mid December to may 15. The procedure is to some extent equal the procedure used for highway 15. In addition to the meteorological stations drifted by the Norwegian Meteorological Institute, there is a station in the western part of the railway at Myrdal 867 m above sea level. This station is giving valuable information as a base for the avalanche hazard prognosis. The avalanche hazard warnings are only distributed to the railway company when the avalanche hazard is high or very high. When the danger is high, they are visiting the line more frequent, and the speed limit for the trains is 40 km/hour. With very high avalanche hazard, the precautions will be discussed in each situation with the avalanche experts. The weather conditions during periods with avalanche hazard level 5, give usually great difficulties in keeping the tracks free of snow, and the have to shut down the line (***Table 17***).

Figure 57 Typical terrain for the Bergen Railway passing Hallingskeid. The snow galleries are not for snow avalanches, but for heavy snow cover.

Figure 58 A snow avalanche has removed the snow shelter

Table 17 Overview over the avalanche warning at the Bergen railway

Parameter	Avalanche warning on the Bergen railway
Resolution in time How many warnings a day?	Warnings are only issued at danger level 4 or 5
Resolution in space What areas are covered?	Covers a section of 90 km of the Bergen railway, 15 km is most intensive evaluated
Classification national, regional and local scale	Local
Data used	Primarily weather forecast model data
Verification used	Feedback from the maintenance workers on the railway
Quality control of the warnings	Two NGI experts discuss each warning
Annual budget	30.000 €

Easter holiday warning program

The Easter holiday warning program (***Table 18***) started as an ad hoc program with co-operation between NGI, the Norwegian Meteorological Institute and the Norwegian Red Cross Search and Rescue.

The program is aimed at recreationists and lasts from the weekend before Easter Holiday to the Easter Holiday itself.

Table 18 Overview over the Easter holiday warning program

Parameter	Avalanche warning for the Easter holiday
Resolution in time How many warnings a day?	0.5 or as required for one week
Resolution in space What areas are covered?	Countrywide
Classification national, regional and local scale	National (actually, several regions)
Data used	Data from NGI field station, observations in the field by NGI and Red Cross personnel, weather data and forecasts
Verification used	Media, reports from observers
Quality control of the warnings	Two NGI experts and a meteorologist discuss each warning
Annual budget	None, each organization support their workers

Norwegian Army avalanche warning

The fatal accident in Vassdalen, North Norway in 1986 with 16 soldiers killed in one avalanche, caused a more intensive way to handle the avalanche hazard during the military winter exercises in Norway. An official commission was established, and one of their tasks was to give proposals to make a better avalanche hazard evaluation.

Figure 59 The army avalanche group during a winter exercise

At first, an update of the avalanche hazard maps seemed necessary, the maps in use were maps with records of avalanches, not maps with potential avalanche hazard areas. This work has been performed by NGI since 1986 on maps on scale 1 : 50.000, and a total of 87 maps each covering an area of approximately 500 km^2 have been worked out. An example of the map is seen on ***Figure 60***. The avalanche zones have been divided in two, the release areas and the runout areas due to different actions in the terrain with different avalanche hazard warnings. The official military hazard scale has been divided in four like the old European scale, and this suit well with how the avalanche maps are used even though it would have been suitable to use the international hazard scale with five levels. The release areas for snow avalanches are prohibited areas during exercises with winter conditions. The runout areas are prohibited when the avalanche hazard is high or very high

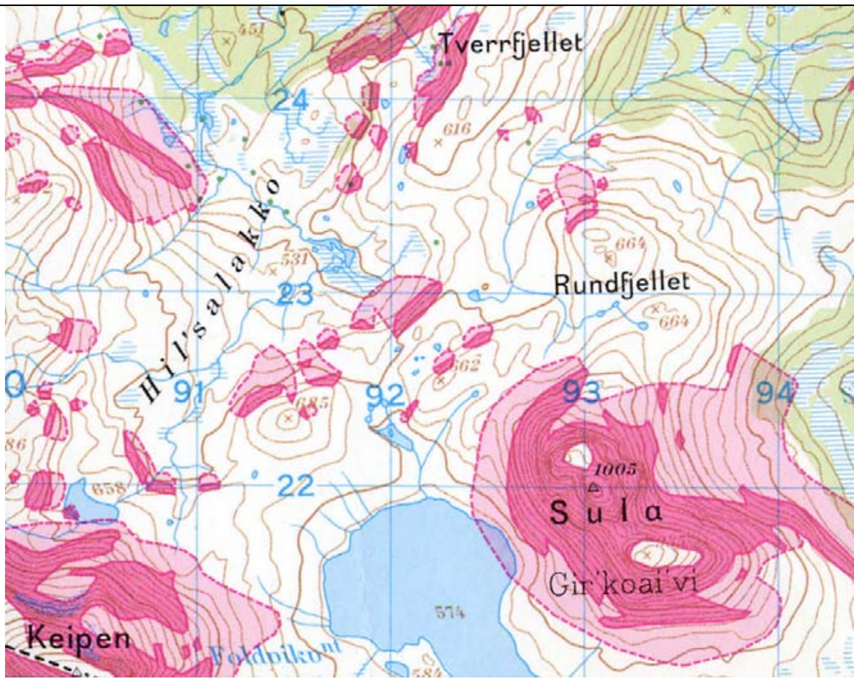
Figure 60 Detail from a typical military avalanche map. Release areas in red, run out areas in pink	
	During winter exercises, the directing staff is establishing an avalanche team which responsibility is to maintain the safety for the soldiers in the exercise area. The snow conditions will be checked every day together with the weather forecasts, and an avalanche hazard warning will be issued every afternoon after the field check. For the yearly big winter exercise with soldiers from many different countries, not only NATO countries, the avalanche team will be supplied with two civilian experts from NGI. The avalanche team will then consist of six to eight experts. Two and two of the experts will go out in the terrain either dropped by helicopter high in the mountains with skis making snow investigations on the way down or using skidoos to get out into the field. All the snow information is presented to the group when returning in the afternoon, the situation is discussed, and an avalanche hazard warning is prepared also taking into account the weather forecast. This forecast is sent to all troops. In addition, the weather forecast is checked every morning in order to find out if there is a important change in the forecast. If so, a new avalanche hazard warning might be forwarded to the troops.

Table 19 Overview over the avalanche warning for NATO winter exercises

Parameter	Avalanche warning for NATO winter exercises
Resolution in time How many warnings a day?	24 hours. One per day, if change in weather, two per day.
Resolution in space What areas are covered?	Exercise area might be 5.000 – 10.000 km^2
Classification national, regional and local scale	Four level scale (old European scale)
Data used	Snow pit data, weather prognosis and observations
Verification used	Observations of avalanches.
Quality control of the warnings	Two NGI experts discuss each warning together with the military experts.
Annual budget	30.000 € (for NGI experts)

Avalanche warning in developed skiing areas	The two major skiing areas in Norway, Trysil and Hemsedal, both offer extensive free ride terrain outside the controlled slopes. Increased interest in using these areas for free ride (***Figure 61***) activities initiated a more active approach towards the safety of the customers

Figure 61 Free ride skiing in the ski resort Hemsedal

Both resorts have established weather and snow observations and motivate the skiers to use this information for planning their offpist activities. An information folder is available, showing dangerous areas and giving tips for preparation, equipment and behavior. The ski schools offer freeride classes that include the absolute basic of avalanche danger evaluation and rescue methods. The ski patrol and lift operators are all trained to take the right actions if an avalanche should occur and can also give advice to skiers that want to ski out of bounds.

Avalanche as an important factor is rather new in Norwegian skiing areas and the approaches chosen today need testing in practice and further development in the future to meet the increasing pressure on free ride areas

Table 20 Overview over the ski area warning services

Parameter	Ski area avalanche warning
Resolution in time How many warnings a day?	Once a day in the morning
Resolution in space What areas are covered?	Covers the ski area
Classification national, regional and local scale	Local
Data used	National weather forecasts, local weather and snow observations
Verification used	Ski patrol
Quality control of the warnings	??
Annual budget	Part of the normal ski patrol activities

Conclusion

Avalanche warning and forecasting in Norway is based on a project based approach that covers selected local areas. The national avalanche warning only gives very general information that is not useable for forecasting certain areas or objects. Despite limited funding and limited access to meteorological data, many local projects are established, that meet the need of the customers. A new national avalanche warning centre is proposed by the NGI and pending the decision of the Norwegian authorities

Chapter 3

ROCK AVALANCHES

3.1 Introduction

Any meaningful predicition of an extremely rapid mass movement should give some quantitative indication as to its likelihood of occurring within a given area and a specified period of time. Rock avalanches are the largest and most rare members of extremely rapid mass movements. It is necessary to choose appropriate spatial and temporal scales of prediction.

Ideally, pediction of rock avalanches should address the following key issues at various scales:

- Where in a given region is it likely that rock avalanches will occur? Can this be done in a spatially explicit manner, i.e. can individual hillslopes be identified?
- What are the minimum data requirements (lithology, geometry of discontinuities, seismic activity, etc.) that are needed to predict regional and local occurrence with a minimum degree of reliability?
- When will a given (usually previously identified) hillslope prone to rock avalanching eventually fail?

This set of questions is usually preceded by reliable recognition of empirical evidence that indicate the likely occurrence of rock avalanches in the past. If such evidence of rock avalanches has been identified in a specified area, the path towards prediction should ideally involve the collection of as many relevant data as possible. This means that (a) the evidence of former rock avalanches (e.g. detachment scars, deposit morphology, deposit sedimentology) should be as complete as is feasible; and (b) complementary geoscientific data should be collected or be made available.

While for snow avalanches and debris flows, the art of prediction benefits strongly on the advanced understanding of the underlying physical processes that govern initiation and motion, which are encapsulated in sophisticated numerical models, some of the physics that govern rock-avalanche occurrence and motion remain unclear. The lack of a unifying theory on rock-avalanche susceptibility, triggering, and runout impedes the reliability of prediction. Consequently, most efforts aimed at predicting rock avalanches have remained necessarily empirical in nature, and still need to grow in complexity towards physical-based relationships as understanding increases.

3.2 Spatial prediction of rock avalanches

Based on the findings from a scientific literature review on the causes, triggers, and thresholds of rock avalanches, it becomes clear that there have been no previous attempts to spatially explicit predict the occurrence of rock avalanches. This does not mean that some of the initial conditions are unknown. It rather suggests that the combination of factors that render rock slopes susceptible to rock avalanching is not very well constrained.

While the occurrence of volcanic debris avalanches is by definition restricted to the flanks of volcanic edifices and their history activity, there are few unifying characteristics that would allow a characterization of potential rock-avalanche sources in mountainous terrain. In fact, it may be the diversity of factors of susceptibility that seem to characterize the occurrence of rock avalanches. Among these, active tectonics in concert with well-developed, but not necessarily extraordinarily steep, topography seems to exert a first-order control on the magnitude and frequency of rock avalanches.

Another prerequisite for rock avalanching appears to be the availability of a substantial volume of rock, as only large (>10^6 m^3) rock-slope failures are associated with excess runout characteristics. Hence, any attempt to spatial prediction needs to take into account edifice size or potential failure volume as a constraining initial condition.

Other factors, such as major lithological units or climate, do not serve as sufficiently reliable constraints on the occurrence of rock avalanches, and cannot be used for spatial prediction at the mountain-belt scale. Rather it is the threedimensional pattern of rock-mass discontinuities at the hillslope scale that control rock-slope stability. This pattern is seldomly resolved sufficiently at the scale of drainage basins or larger, thus further limiting an automated spatial prediction based on a few constraining variables. Precursory rock avalanches at a given site are often useful to qualitatively indicate the potential for future events in the nearer vicinity, where similar rock-mass conditions prevail. This is an important distinction that needs to be taken into account when attempting to distinguish prediction of rock-slope failures in general and prediction of large catastrophic rock avalanches, more specifically.

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3.3 Temporal prediction of rock-avalanches

The temporal prediction of rock avalanches for a specified area is in many respects a slightly more simple undertaking than their spatially explicit prediction. This is mainly because of two reasons:

(1) Empirically derived inventories of previous rock-avalanche events in a given region allow first-order estimates of the average annual probability of occurrence of rock avalanches above a given size threshold. The derivation of such statistical relationships depends on the choice of statistical model, the number of samples, reliability of size estimates, accuracy of geochronological dating methods used, erosional censoring, and the assumption that no significant events had occurred that would have favoured the coeval occurrence of rock avalanches, such as high-magnitude earthquakes.

(2) Once identified, a potentially unstable or metastable rock slope may be prone to rock avalanching, especially given supportive evidence of previous events in the region, and if the destabilised mass is sufficiently large. The recognition that rock avalanches may represent catastrophic culminations of deep-seated rock-mass creep, together with empirical measurements of surface deformation rates, helps put constraints on predicting the timing of catastrophic rupture.

Empirical estimates of average *a posteriori* recurrence intervals of large rock-slope failures are dependent on the chosen size of study area as well as the chosen time interval. Estimates for various mountain regions throughout the world range between 10^{-7} to 10^{-9} events/km^2/yr for the last 10000 years.

Based on the nature of failures in rock slopes the most favoured and commonly accepted, if not only method of managing the risks from catastrophic failure, is the development of an effective warning system. As pointed out by Crosta and Agliardi [2003], remedial countermeasures are normally not useful when dealing with large catastrophic rockslides or rock avalanches. This is because of the extremely high kinetic energy involved, which causes high impact forces. Suitable emergency planning is thus the only effective tool to reduce any advserse consequences by means of evacuation, road closure and other active measures. These need to be linked to real-time measurements of rock-slope deformation in order to define critical threshold velocities for action. One of the most challenging tasks is therefore to develop realistic monitoring thresholds that are not too conservative resulting in excessive false alarms, but provides adequate warning should an event occur (e.g. Froese, 2006).

3.4 Case example – Akneset rockslide, Norway

From the above summary, it is clear that the prediction of rock avalanches at a previously identified unstable rock slope is largely a function of reliable monitoring and early warning data. The following case example describes a monitoring network established at Akneset, Storfjorden, Norway. There, a rock slope constituting a steep fjord wall has shown evidence of tension cracking and gradual slope deformation since the late 20th century. Given a well-constrained record of prehistoric rock-slope failure scars and depsoits preserved on the fjord bottom together with several historic accounts on rockslide-triggered tsunami disasters, this particular site has been chosen for an intensive monitoring programme. A major national effort supported by various European collaborators is currently underway to explore the ongoing deformation of this rock slope. Although many of the instrumentation are state-of-the-art technology, though not necessarily novel, it is the density and combination of monitoring and early warning methods that make this site rather unique.

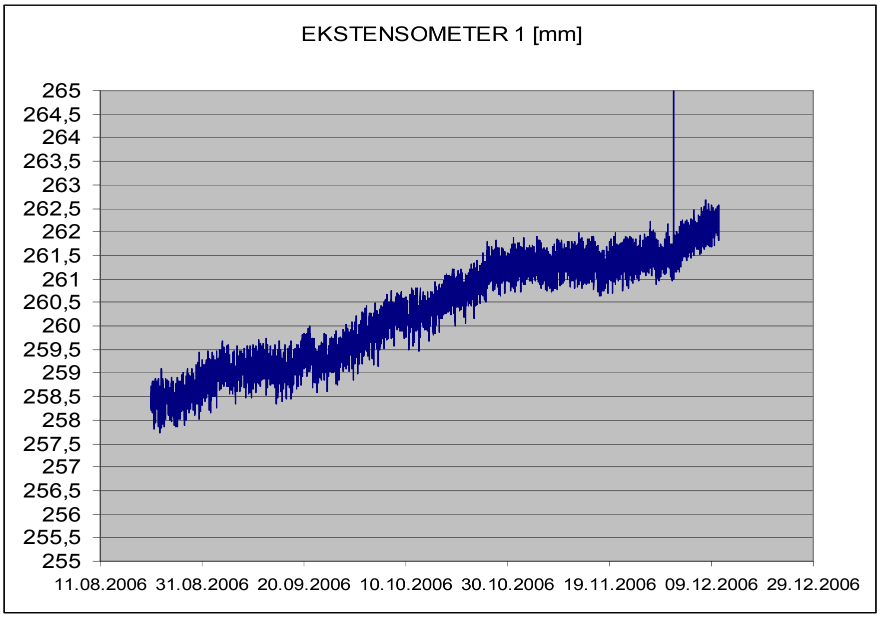
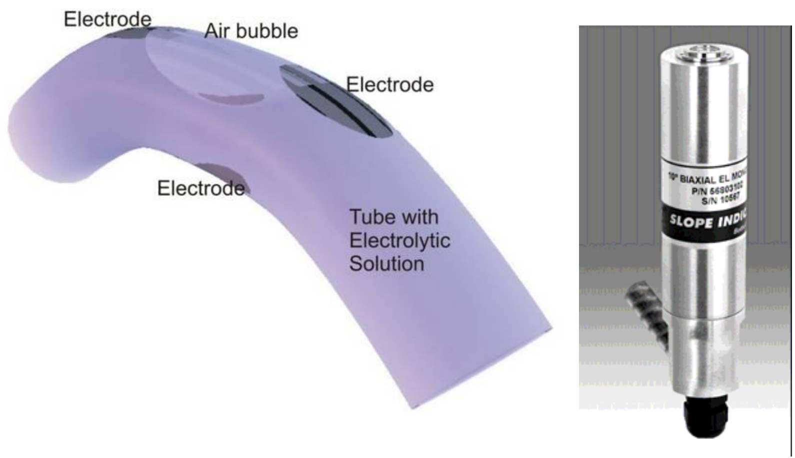
In order to establish a reliable continuous monitoring network for large rock slopes potentially prone to rock avalanches, a series of methods needs to be used, which operate both on the surface and subsurface (e.g. boreholes). The array of sensors needs to provide as complete information as possible in order to cover the entire slope and sectors of the unstable areas. This requirement is in turn offset by a series of practical limitations in terms of distance from measured points to the monitoring instrument, local slope conditions, rockfall and snow-avalanche hazard and problematic atmospheric conditions.

The design of monitoring systems is largely controlled by a number of predefined rock-slide/rock avalanche scenarios, which are derived following careful analysis of the deformation pattern at the monitored sites. This normally requires a detailed and orechstrated geological and kinematic investigation program. The possibility to provide a reliable forecast for a given rock-avalanche event size is largely dependent on a good understanding of the threedimensional deformation pattern of the destabilized rock mass. This requires a series of different monitoring instruments, which can detect deformation on the surface and subsurface, in addition to both at a local scale (e.g fractures) as well as at a larger scale (e.g absolute and differential slope movements).

Surface monitoring

There are a series of available methods and sensors for measuring movement and deformation on the surface. These are both local measurements across fractures and

	clefts, and more global measurements detecting total displacements on the slope.
Crackmeters and extensometers	Crackmeters are instruments that measure the distance between open fractures; they are comparatively basic and cheap monitoring systems. There are several types, and the most common is the vibration wire system. These instruments can detect sub-millimeter-scale displacements. In additiona, there are also special wire extensometrs that can measure long distances.
Figure 62 *Typical extens0meters installed at Akneset rockslide, Norway*	
Figure 63 *Tension-crack depth is several meters, view towards the east with fjord in background*	

Figure 64 Example data from an extensometer at the Åknes rockslide in the second half of 2006: cumulative displacement vs time.	
Tiltmeters	A tiltmeter measures very small changes in inclination deviations from the horizontal level, either on the ground or in structures. Modern electronic tiltmeter use a simple bubble-level principle, as known from the common carpenter level. The arrangement of electrodes senses the exact position of a bubble in an electrolytic solution to a high degree of precision. Any small changes in the level are recorded using a standard data logger. Importantly, this arrangement is quite insensitive to temperature, and can be fully compensated, using built-in thermal electronics. Tiltmeters are relatively cheap monitoring systems that can be important during stages of large displacements. They can also be used for the evaluation of the deformation mode, e.g. if the rockslide is undergoing rotational movement.
Figure 65 Schematic setup of tiltmeter principle	
Single laser measurement devices	Distance laser sensors measure the distance from the sensor to a target or reflector on the detaching target area. This can be a particularly important system in areas with large distances between open cracks, which preclude the use of extensometers or crackmeters. The target can also be a set of large reflector plates, which under certain climatic conditions can be heated in order to avoid snow and ice on the target. The resolution can be better than 1 mm, but as all measurement signals have pass through

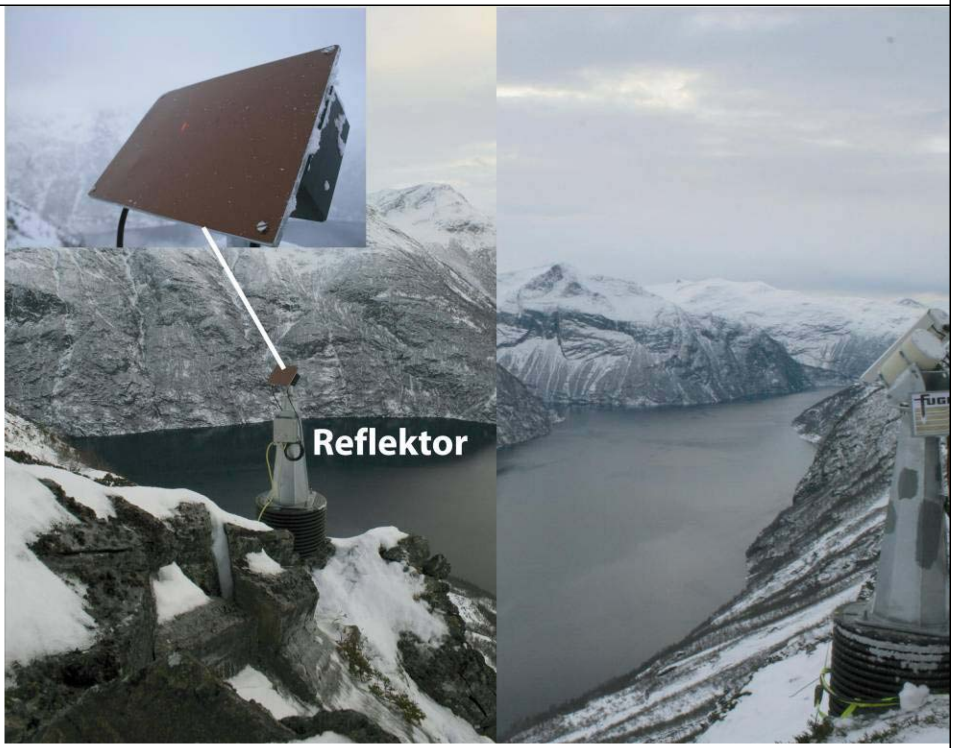
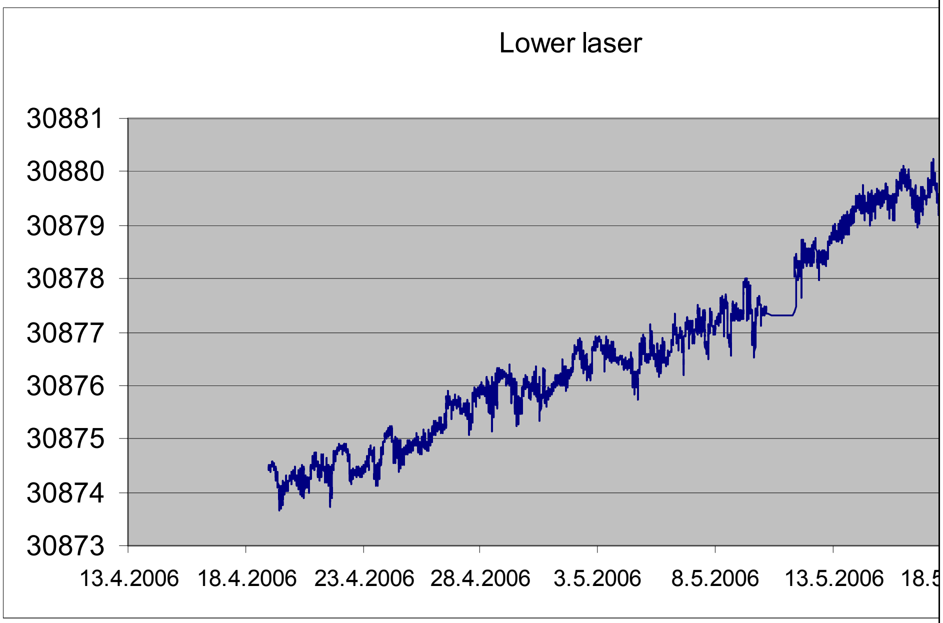
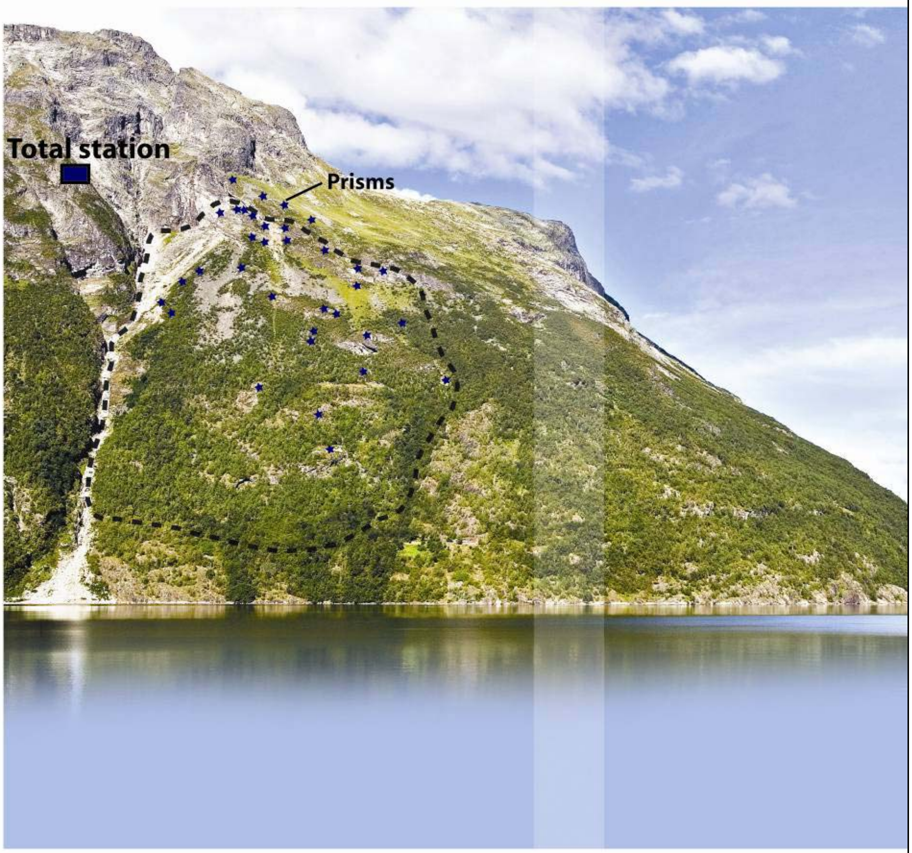
	air, the data are affected and changing due to atmospheric conditions, e.g. temperature and humidity.
Figure 66 Example of one of the single lasers that are established at the Åknes rockslide, including reflector plate and web camera.	
Figure 67 Example of data from single laser at the Åknes rockslide: cumulative deformation vs. time..	
Total station	A total station is a robotic optical survey system that measures the distance to numerous prisms located on unstable sectors of actively deforming rock slopes. The system is important in order to get an overall overview of displacements. The position on each prism can for example be performed at fixed frequencies.

Figure 68	
Figure 69 Overview of the location of total station and prisms at the Åknes rockslide.	
Global positioning system (GPS)	A GPS network was established in Åkneset to detect movement in areas where it is difficult to use Lidar scanning or ground radar owing to poor visibility. Two of the GPS are established in stable areas acting as reference points. The data are transformed by radio signals automatically to a PC. The GPS points are localized to areas assumed to be critical for the overall stability condition. The resolution can typically be down to 1 mm.

GPS antenna at Åkneset rock avalanche site	
LIDAR scanning	LIDAR (Light Detection and Ranging) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The prevalent method to determine distance to an object or surface is to use laser pulses by measuring the time delay between transmission of a pulse and detection of the reflected signal. Lidar scanning can be used to scan movement on larger surfaces. The instrument must be placed at a location with good view to the unstable rock mass. By comparing two images taken at a different time, relative movements can be estimated.
Ground-based synthetic aperture radar (SAR)	Synthetic aperture radar (SAR) is a form of radar in which sophisticated post-processing of radar data is used to produce a very narrow effective beam. It can only be used by moving instruments over relatively immobile targets, but it has seen wide applications in remote sensing and mapping. To cover large areas they can be satellite borne, or they can be ground based covering smaller areas. SAR technology can be used to detect movement of unstable mountain sides. As a first step to cover large areas overall hazard mapping of possible rock avalanches, satellite borne SAR is a uesful technology. Ground-based radars with frequent recordings can also be used to detect daily movements implemented in operational early warning systems to detect surface movement in smaller areas. A ground-based radar has been established at Åkneset.
Figure 70 Ground-based radar used to detect movements at Åkneset on the opposite side of the fiord	

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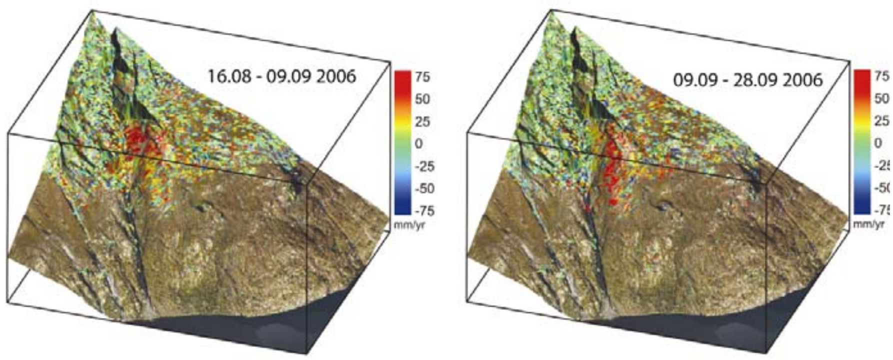
<td>Figure 71 Surface movements detected at Åkneset by means of ground based radar</td>
<td>
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<td>Seismic network</td>
<td>The objective of permanent passive seismic monitoring systems is to record seismic events that are related to deformations in the rockslide zone. The network at the Åknes rockslide consists of eight 3-component geophones (4.5 Hz). These geophones need to be oriented and solidly cemented to the sliding rock mass. The individual instruments are then connected to a central acquisition system in a concrete bunker by up to 300 m long reinforced cables that are fixed with bolts to the ground in order to withstand surface destabilisation by snow creep. The acquisition system at the Åknes rockslide consists of a digitizer (Geode), an industrial computer (PIP6) with very low power consumption, a GPS-clock, an Ethernet hub and a GSM telephone relay that allows to switch on/off the individual components, while sending a SMS-warning to the early warning center in case of power failure. An important task is to establish a reliable transfer of large amount of data. The current monitoring in continuous mode at Åknes with a sampling frequency of 125 Hz results in about 1Gbyte of data per day.

The rate of seismic activity may be indicative for the current state of the slope, and an increase in seismicity may point to an acceleration of the movement.</td>
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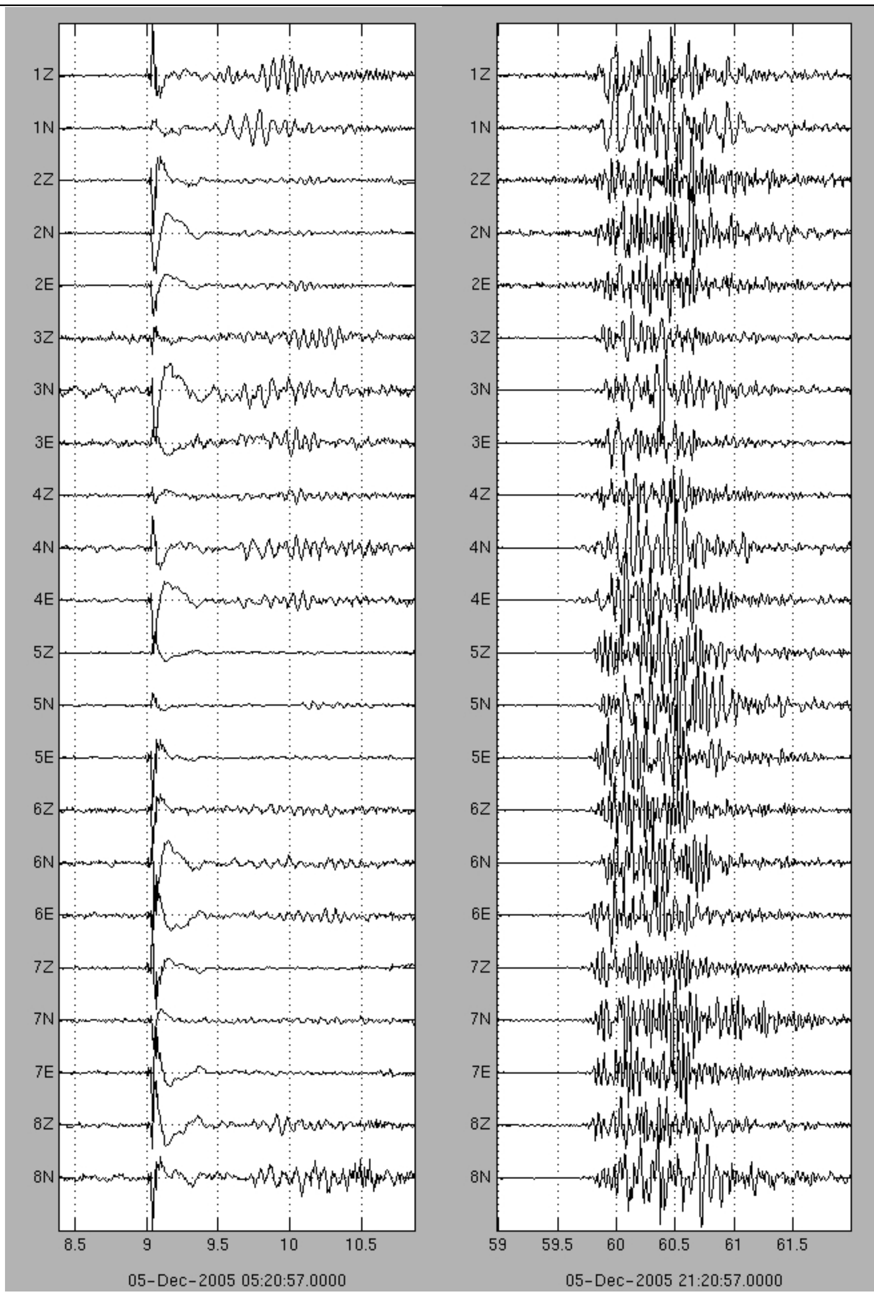
<td>Figure 72 Seismic signals recorded at the Åknes rockslide, western Norway (Roth, 2006). Left: A very strong seismic event that could be the result of a sudden movement in the uppermost part of the slope. Right: A complex seismic signal that could be the result of a rockfall.</td>
<td>
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<tr>
<td>Subsurface monitoring</td>
<td>The choice of subsurface monitoring in boreholes is largely dependent on what type of rock-slope deformation is going to be monitored. It is also possible, if not desirable, to integrate several types of sensors in the same borehole (e.g. inclinometers and pietzometers).</td>
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Figure 73	
Borehole inclinometer	Inclinometers detect small changes in the inclination of the borehole and can thus be transferred into horizontal displacements. There are now digital systems available that can configure a series of sensors in one column.
Figure 74 From the establishment of instrumentation of the DSM column at the upper borehole at Åknes. The 50-m long DMS column contains 50 individual inclinometers at evenly spaced intervals, 50 temperature sensors, and two pietzometers.	
Borehole extensometer	The borehole extensometers are well suited to measuring predominant extension in the subsurface, e.g compression and buckling that can give upward movements. Borehole extensometers can also be used in more horizontal boreholes in order to detect horizontal displacements.
Piezometer	Piezometers are measuring the pore pressure or the water level in the borehole. Typical usage includes either single pietzometers in open pietzometric pipes or solutions with several piezometres if there are more complex hydrological conditions (e.g. perched water levels).
Supplementary	The displacements need often to be related to climate data, in particular precipitation

monitoring	and snowmelt. A meteorological station would normally include sensors giving temperature, precipitation, snow depth, wind speed, ground temperature and insolation. Also measurements of discharge in springs in lower part of the rockslide can give valuable data about changes in the hydrological conditions, which is often critical for rockslide displacements.
Figure 75	
Integration of monitoring systems	The data handling and interpretation is an important aspect of all monitoring projects. It is thus of major importance that the data are processed, stored and visualized in an effective manner. In critical situation with increased displacements it is vital that the experts can get data fast with predefined visualization tools and with the possibility to do proper analysis. Also, complementary historical data are important for the analyses of movement behaviour and velocity trends. This will be the basis for establishing site-specific threshold values for the different levels of warning.
Power and communication	One of the major challenges related to monitoring in remote areas is the power supply and data transfer. This is often crucial for the quality and reliability of the entire early-warning system.
Redundancy and reliability	In order to have redundancy and optimize the reliability of the monitoring systems there are several important aspects that is needed to be taken into account: • Needs several different monitoring systems in order to cope with problematic situations were one or several system may be out of order • Large changes in weather and atmospheric conditions, especially prominent in fjord areas • Snow-avalanche and rock-fall hazard in the monitored slope slope • Optimal and reliable system for power and data transfer (Several locations)

	The experience from some of the large international monitoring projects may indicate that the different systems can be grouped according to their importance and reliability in operational early-warning systems (this is often site-specific): <u>Primary sensors: Reliable and robust</u> • Surface crackmeters/extensometers • Surface tiltmeters • Single lasers (needs caution during bad weather) • Borehole inclinometers • Borehole extensometers <u>Secondary: not yet reliable for full operational monitoring</u> • Laser Ranging (EDM), • GPS • Ground-based radar • Microseismic sensors <u>Tertiary: Support/Information Sensors</u> • Meteorological station • Pietzometers • Weir
Early warning	A fully operational early-warning systems (monitoring centre) needs to include the following important aspects: • Reliable and redundant monitoring network, including power and data transfer • Full operational monitoring (technical and geoscientific) • Warning procedures, including evacuation routes and implemented warning systems.
	3.5 Conclusions
	Common trigger mechanisms of rock avalanches include earthquakes, high-intensity rainstorms, and fluvial undercutting. Importantly, several historic rock avalanches occurred without any observed triggers (e.g. McSaveney, 2002). In these cases failure is likely to result from gradually exceeded intrinsic stress thresholds, and may represent the catastrophic culmination of preceding slope movements.

	The predictability of earthquake- or rainfall-triggered rock avalanches depends on the knowledge of the spatio-temporal distribution of the trigger events, i.e. their magnitude, frequency, intensity, and any critical thresholds thereof that may need to be exceeded to mobilise a rock avalanche in the first place. Earthquake-triggered rock avalanches are as difficult to predict as are earthquakes in general, i.e. the chance of successfully forecasting coseismic events is very low. The same applies to those triggered by fluvial undercutting or gradual loss of rock-mass strength beyond a critical stress threshold. Quantification of the dynamics of local geotechnical parameters is scarce, and usually requires a well-defined and cost-intensive monitoring programme, usually reserved for case studies of imminent threat to population or infrastructure. The potential of predictability theoretically increases where rock avalanches are preceded by slow-moving deep-seated slope deformation, although such low-activity phases may extend from decades to millennia, before catastrophic “creep rupture” (Radbruch-Hall, 1978). Although several cases of such catastrophic culmination of gravitational slope deformation are known, it remains highly challenging to approximately predict the timing, magnitude, and type of resulting rock-slope failure from preceding slope deformation. However, such early warning is rarely feasible, since it most often depends on the detection and successful monitoring of suspected failure sites in the first place (Crosta and Agliardi, 2002). Sophisticated numerical (process) modelling and real-time monitoring (Willenberg et al., 2002; Tarchi et al., 2003), though readily available, are limited to selected case studies of large-scale rock sliding (Sartori et al., 2003; Segalini and Giani, 2004). Hence, they rarely provide means of application to larger regions. Until now, knowledge of critical physical processes triggering rock avalanche is limited, and more experience is needed to verify the accuracy of the prediction systems. Until such experience is gained, prediction is encumbered with high uncertainty and should be used with great caution. However, as physical measures normally are not applicable, evacuation of people in endangered zones based on early warning normally is the only way risk can be reduced.

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Debris Flows

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Annexe : IRASMOS « QUESTIONNAIRE « and answers:

Avalanche forecasting and modelling (D1.3)

1. What is the size of the area (km^2) covered by your forecast?
2. How many times a week do you issue a forecast?
3. How long is your forecast valid for?
4. How high (%) do you estimate the hit rate (percentage of correct forecasts) of your forecast? Do you carry out some kind of verification?
5. Which datasets and observations (snow, avalanche, weather) are available to you for avalanche hazard assessment?
   5.1. human observation (number of stations, parameters)
   5.2. automatic measurements (number of stations / parameters / time frequency {periodic? after events? other?})
6. What tools or methods do you use to collect and process these data?
7. Which methods do you use for avalanche forecasting? (deterministic / statistical / expert …; human/ automatic …… spatial and temporal scale)
8. Do you forecast triggering probabilities? (spatial and temporal scales?)
9. Do you predict or estimate avalanche characteristics in your forecasts? (flow/ speed/ pressure/ extension/ density/ snow taken up along the path ….) and, if yes, by what methods?

Answers of some European Centres

	SLF **(Davos, Switzerland)**	**Austria - Avalanche Warning Service** **(Vorarlberg, Austria)**	**Servei Meteorològic de Catalunya** **(Barcelonna)**	**Conselh generau d'Aran:** **Local forecast for the Bonaigua Pass Road**	**Austria - Avalanche Warning Service** **(Salzburg, Austria)**	**Météo-France (France)**	**INM (Sarragosse, Spain)**
1	27000 **km²**	arround 1700 **km²** (sea level: 1000 m - 3300 m)	The Catalan Pyrenees covers 4000 **km²** divided into 7 different zones due to theirs nivometeorological ,climate and avalanche behaviour.	About 15 **km²**. We do the systematic forecasting for two mountain roads, with avalanches affecting some buildings and infrastructures. There are 20 km of road affected by more than 60 avalanche corridors.	Approx 4000 **km²**	20000 **km²** (23 massifs in Alpes, 11 in Pyrenees and 2 in Corsica)	Navarra, 2300 **km²** Jacetania, 1260 **km²** Gállego, 710 **km²** Sobrarbe 1120 **km²** Ésera, 1760 **km²** Total, 7150 **km²**
2	14 times: 1 national at 5 pm 1 regional (7 regions) at 8 am	Daily during wintertime (Dez –April: around 150 forecasts)	Six times per week (from Monday to Saturday). In case of extreme conditions (5 level of the European Scale) the number of	From 0 to 7, depending on the needs	7 per week	During winter season: 1 daily reports (BRA for avalanche danger / BMN for meteo and snow conditions)	Daily during winter period (15 Dec.-30 April)

			bulletins could be more.			1 weekly abalysis report (BSH) Several danger reports in case of high avalanche dangers (CMP + BSA + Vigilance procedures)	
3	24 h forecast, 72h tendencies	24 (6 hours and account / process for 18 hours); trend for 2 days	The avalanche bulletin from Monday to Friday is published each day at 14:00 and it is valid from that time until 24:00 of the next day. We include a short trend for the next 48 and 72 hours. The forecast during Saturdays is valid from 14:00 Saturday until 24:00 Monday.	24 hours but depending on the situation could be updated before.	Until next forecast	36 hr	36 hr
4	75-80 % by observers, higher by consumers	We estimate around 80-85 %; we also make simply verification – but not every day	Up to 2002-2003 season we applied a field verification (Italian field verification) according which we estimate the 78% of correct forecasts for 24 hours period	About 80%, with more than 95% of hits or overestimation s. As we don't forecast accidental hazard, we can do a simple verification using the avalanche activity.	80% depending on hit criteria, indirect, qualitative verification		Recorded avalanches events (14% in case of 4-5 risk, 12% otherwise) No avalanche recorded (25% in case of 4-5 risk, 49% otherwise)
5.1	totally 160 observers. Parameters: weather, snow properties, seen avalanche events, estimation,	8 human stations (parameter: weather, cloudiness, snow / rain; temperature (air / snow)	The human network consists of 15 spots of daily weather and nivometeorolo gical observations	Two meteorological stations. They record the complete NIMET, plus the crust thickness and	20 stations with 10 observed parameters	About 180 stations coding in the International NivoMet code.	15 human observation sites transmitting 12 NIVOMET messages at 08hr, 4 at 13 hr) with 13

	judgment of last day's SLF-forecast.	wind, snow-surface; penetration depth, (results of blastings), hazard level	(French NIMET parameters). 25 spots mainly weekly with snow profile from which 6 includes the rutschblock test and the showel test and 7 with only rutschblock test. Snow distribution and avalanche activity is also reported.	the hoar thickness. One of them twice a day and the other once. hree pits+tests a week (complete pit, rutschblock and shovel test)			meteorological parameters and 9 snow and avalanche parameters) and 4 weekly snow pits.
5.2	85 automatic stations, each (with a few exceptions) by consisting by a snow station in a wind free position, and a wind station in a free wind position Parameter: snow height, new snow height, wind (average and maxima), temperature (surface and inside snow cover), radiation, humidity	we kann use around 20 stations with different parameters; (rain, snowpack, wind, temperature, radiation, humidness); the time frequency is from 1 to 24 hours; mostly 3 hours	The automatic network consist of 11 nivometeorolo gical stations registering hourly the next parameters: air temperature, air humidity, wind direction, wind velocity, global solar radiation, depth snow, snow precipitation, snow cover thermal gradient. In the other hand we consult 3 flowcapts that are avalailable in Internet.	Two Campbell automatic weather stations (Temperature, humidity, solar radiation, wind speed and direction, snow thickness, liquid equivalent of precipitation, snow temperature, snow cover thermal gradient). One Flowcapt station (wind speed and direction, snowdrift)	12 auto stat, temp snow height, wind, rel hum, radiation, prec. Snow temp	20, increasing 30 high altitude stations (4 parameters) completed by the standard national meteorological network (about 50 stations) at medium elevation	11 automatic stations (precipitation, wind, temperature, moisture)
6	Data base, visualization tools	we have 2 different tools: WLP for infos of human observation; DATAWIN & METWIN for automatically measurements	Collection: Phone, Internet, GSM and satellite phone Analysis: ADQMSI (soft to store and	Collection: GSM Phone, Internet Analysis: Nivolog software, ADQMSI (soft to store and	METWIN	Geliniv / DOLMEN data bases under ORACLE system.	Collection: fax, telephone, FTP.

			visualize automatic stations data), self-made programme DB4 based to visualize and graphic representation of conventional human network (snow pits and daily snow and weather observations)	visualize automatic stations data) and Snowpro software for graphic representations (snow pits).				
7	Meteo models extensively Snow pack models only rudimentary, still in its beginnings	we use human methods for spatial and temporal forecast based on avalanche hazard scale 1-5	Deterministic and expert using a spatial and temporal scale . In the other hand we consult the Safran Crocus Mepra Models that have an output for our 7 zones.	Deterministic and expert,...human ,... Both spatial and temporal	Mostly human, but also statistical	Mostly human with deterministic tools (SCM)	Deterministic methods, conceptual models, use of the SCM chain.
8	Only qualitatively (until now there is now common standard to define probability w.r.t avalanche realease)	We forecast probabilities based on avalanche hazard scale 1-5	Qualitative descriptions about triggering probabilities but not quantitative because it is a regional forecast not a local one. For instance possible, likely, very likely. The spatial scale is the 7 zones described above.	Yes, both spatial and temporal. We use "not possible, possible (0-30%), likely (30-70%), very likely (>70%)" indicating witch corridors are affected by this triggering probabilities.	Yes, according to the European danger scale	Qualitative through the European danger scale use.	Yes.
9	No, only qualitative in the sense of characterizing the avalanche size and type.	No	We only forecast the size, type and threshold of overload needing to trigger the avalanche	We only forecast the size of the avalanches, in a scale adapted to the needs of the road management	Yes, human, extension, types of avalanches, terrain features	Indications provided through the European danger scale use.	Yes characteristics from the definition of the European danger scale.

			avalanche	management. “Small” avalanches can partially bury the road and damage a person, “Medium” avalanches will bury completely the road and destroy a car and the road protections, “Big” avalanches cross the road, destroying everything in their path (heavy trucks, protections, forest…)			Occasionally, specification of the avalanche characteristics (type and extension). Use of a conceptual model based on the snow characteristics and weather conditions.

Answers of some European Centres (continued ….)

	Regione Valle d’Aosta (Italy)	**Regione Piemonte (Italy)**	**Regione Lombardia (Italy)**	**Provincia Auonoma Trento (Italy)**	**Provincia Autonoma Bolzano (Italy)**	**Regione Veneto (Italy)**	**Regione Friuli Venezia Giulia (Italy)**
1	The Regione Valle d’Aosta is 3262 km^2 wide.	12.000 km^2	8000 km^2	6208 km^2 (4955 above 800 m a.s.l.)	7400 km^2	5400 km^2 (area above 500 m a.s.l.)	About 3.200 km^2
2	We issue a forecast four times a week.	3, extra bulletin in case of critical meteorological conditions	3	3 times a week, extra bulletin in case of critical meteorological conditions (80 - 90 seasonal bulletin)	3 times a week, extra bulletin if the conditions change in 24h.	2 times a week, extra bulletin in case of critical meteorological conditions (70 - 85 seasonal bulletin)	3, extra bulletin in case of critical snow and meteorological conditions
3	Our forecast is 48 hours valid.	48 h, or maximum of 72h	3 days	24-72 h	24/48 h	24-72 h	48 h or maximum of 72 h for the we.
4	We don’t make any particular verification but we could estimate the percentage of correct forecast around 80 %.	We don’t apply any particolar methods, but, from our weekly field work and from the opinions of our collaborators on field, we can estimate a percentage of correct forecast	80%, verification in some homogenoeus areas	95% for a 24h forecast, 90% for a 48h forecast, 70% for a 72h forecast	The bulletin analyzes the present time situation; the forecast is given synthetically in the trend.	93 % for a 24h forecast, 89% for a 48h forecast, 71% for a 72h forecast [Cagnati A. Valt M.,e Al. (1997), A field method for avalanche danger level	Sometimes, during our field work, we apply a method suggested by AINEVA and we can estimate a percentage of correct forecast around 80%.

		of 70-80%.				verification Annals of Glaciology, Vol. 26, 343-346]	
5	We collect: • daily regional weather forecast • daily AINEVA Model 1 • weekly AINEVA Model 2, 3, 4 and 6 • continuous and real time reports from automatic weather stations.	Mod 1, mod6, snowprofiles, ram penetrometer data, stability test, meteo forecast (Snowpack numerical model output, currently in test state)	MOD 1,2,3 with snowprofiles in different places + data from the automatic stations.		•18 snow ields with daily neasurements •38 snow ields with veekly neasurements •7 height ltitude automatic station		Mod 1, mod6, snowprofiles, ram penetrometer data, stability test, meteo forecast
5.1	*See text.*	*See text*	*See text*	*See text*	*See text*	*See text*	*See text*
5.2	*See text*	*See text*	*See text*	*See text*	*See text*	*See text*	*See text*
6.	2.Yeti 32 to record AINEVA Models 3.Report Neve to collecting data from the automatic weather stations.	Yeti 32, Database Oracle	Yeti	YETI per mod 1, MOD23, MOD 4. Software Hydstra for the automatic stations.	oc	YETI per mod 1, MOD23, MOD 4 e MOD .6, SNOW PRO MOD 4. Marte, Polifeno for the automatic stations.	Yeti 32, Personal computer, program Yeti for the snow data, Oracole for the avalanche database.
7	*See text*	*See text*	*See text*	*See text*	*See text*	*See text*	*See text*
8	We do forecast avalanche triggering probabilities both on temporal and spatial scale.	no	Forecast of dimension and spatial distribution (densità) of the avalanches	Based on the European avalanche danger scale.	10	Based on the European avalanche danger scale.	We give indications about the probability that some avalanche events happen.
9	In our forecasts we generally estimate flow, size, density and amount of the expected	We give generic information about the avalanche type (ground or		No	We evaluate he characteristics of possible avalanche according to	no	We give generic information about the avalanche type (ground or

	events. We do such estimation evaluating recent events (in the last 24-48 hours), snow cover distribution and depth, snowpack stability to micro-scale.	surface, dry or wet, small or big avalanches) through an inductive method based on the snowpack characteristics.			the usual classification; we distinguish between slab avalanches and loose snow avalanches, full-depth slab avalanches and surface-layer slab avalanches, with size and snowpack state		surface, dry or wet, small or big avalanches) through an inductve method based on the snowpack characteristics.