AVALANCHE INFORMATION SYSTEM FOR PROTECTION OF ROADS: THE BONNEVAL-SUR-ARC PILOT PROJECT, SAVOY, FRANCE

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ABSTRACT :

Every winter, avalanches close the access road to the village of Bonneval-sur-Arc in Savoy, France. Large airborne avalanches have deposited up to ten meters of debris on the roadway. During the winter of 1999-2000, the department of Savoy tested a system to improve road closures decisions thereby reducing the avalanche risk to motorists on this road.

Avalanche hazard prediction based solely on the analysis of snowpack factors was deemed to be inadequate. So, the pilot project also incorporated factors commonly used by mountaineers, namely weather factors and direct evidence of avalanche activity. Modified field instrumentation, a data collection system and the application of statistical analysis were incorporated into the pilot program.

In addition to conventional measurements such as precipitation, temperature and wind, blowing snow and natural avalanche activity were recorded acoustically (systems *Flowcapt* and *Arfang*).
In addition, on site data collection of start zones conditions were made on skis. An information system (grouping of geographic information system and data base) was developed to capture all data collected.
The data, once captured, were subjected to statistical analysis to establish a hierarchy of key predictive factors. These factors were then used as inputs of neural network predictors.

The results of this pilot program in avalanche hazard prediction are discussed.

KEYWORDS : avalanche forecasting ; roads security ; information system ; neural networks

1 INTRODUCTION

During February 1999, an outstanding avalanche activity in the Alps showed up difficulties to deal with the closure and then opening of the roads to the traffic. Facing to this situation, the "Conseil Général de la Savoie" (regional government) has chosen to keep going a process started upon before: know better the dangerous areas of the county, in the aim to react more efficiently during the critical periods, and manage long term operations. A private company, TRANSMONTAGNE, has helped it in this task.
After having presented the problems which have identified, we'll expose the main solutions kept: choose a pilot site, keep going measurements and observations in addition with the use of new instrumentation, develop an avalanche information system, and use rigorous statistic methods.
After one season of running of the Bonneval sur Arc pilot site, a first plan is drawn up.
At last, major operations expected for next season are presented.

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2 OUR PROBLEM

2.1 *Need to assume the security of the roads by temporary means*

From a general point of view, the only way to protect completely a road from avalanche hazard is the use of permanent means such as snow shades.
Unhappily, the very important cost of those installations forbids building them on every section wherever the risk exists. So, many road sections in Savoy remain threatened. Some of them are not protected at all; some are protected by too short snow shades, sometime overflowed by big avalanches.
That's why the security on several road sections remain under the dependence of temporary protection means such as avalanche control and/or preventive closure during several hours or several days. This is what we call "critical periods".

During those periods, the responsibility to close and then to open some roads is shared by the mayor and the regional government's president (Conseil General). That's why this last one has decided to keep going a program for a better management of the security during the critical periods.

2.2 *Lack of knowledge for the local prediction of avalanches*

The lack of reliable knowledge for local avalanche prediction appeared during the critical periods of February 1999.
During the abundant precipitation periods, one has quickly come to the decision to close several roads. Avalanche control had been practiced in some areas.
Deciding to open again those roads had been much more delicate. If the dreadful avalanche didn't occur, how to know when a loaded slope is stabilized? What will be the real influence of such meteorological evolution?
However, Maps of Probable Localization of Avalanches (CLPA) had been very useful, to identified under risk areas, and to allow different deciders to localize clearly the problems.

In this context, only the helicopter over fly of dangerous areas gave us some help to come to decisions: areas where big avalanche already occurred had been considered as safe, so as those where the wind had blown the snow away.
Elsewhere, only the personal local experiences could contribute to come to decisions to open roads.

2.3 *The probable influence of past avalanches*

During a precedent study that brought about the daily observation of a gully during several seasons, we had suspected the influence of past avalanches on the present stability [Duclos (1998)]. Along a period of more than 1 month, all the slabs that triggered in the staring zone occurred in distinct places, sometime contiguous. However successive snowfall had occurred, and the lack remained by the slabs had been quickly filled.
We have observed a similar phenomenon in Bonneval sur Arc during winter 1999-2000, with big natural avalanches. After the huge avalanche that occurred in December, other avalanches occurred in February, only where there had been none in December.
This type of observation has leaded us to take into account the avalanches that occurred on a slope since the beginning of the season, for decision making

3 THE TOOLS WE HAVE USED

Methods and tools used in Bonneval sur Arc are intended to improve the security on the access road to the village, for a first step. In a following step, they'll can be applied on other county areas.

3.1 *A pilot site*

The Bonneval sur Arc pilot site has been chosen for at least 4 reasons:

- ✓ The avalanche activity is very important, with diversified situations.
- ✓ The risk is real, since the road is blocked several times each winter, by several meters depth snow deposits
- ✓ The validation of an automatic avalanches detection system is made easy because of avalanche control practiced both on the ski resort and on the road.
- ✓ Some of the slopes that threaten the road being in a national park (Vanoise), the possibilities for avalanche control are

limited and a method for avalanche prediction is essential.

This site is localized in Haute Maurienne, near the Italian boarder. The road section threatened, up to approximately 1800 m high, stretch on a little bit more than 4 km between the villages of Bonneval sur Arc and Bessans. It follows a northwest – southeast direction, then north – south. Slopes of the 2 sides are threatening. Starting zones are above 3000 m high.

3.2 *Manual Measurements and observations on the field*

Nivo-meteorological measurements are performed regularly by the ski patrollers of Bonneval-sur-Arc since several years, managed by Météo France.
In addition, we have mapped avalanches, and have tried to be as exhaustive as possible.
Snow profiles has been performed almost every week in the dangerous slopes, sometimes at the crown of the mapped avalanches.
At last, we waited for information from the security commission of the village, and from the highways department.

3.3 *Automatic measurements*

Two remote stations were in existence in Bonneval-sur-Arc before the beginning of the program
The Electricity Company (EDF) makes use of one station which performs automatic measurements of precipitation (mm water equivalents) and air temperature, at 1 hour intervals. It is localized in the village, at 1830 m high.
In 1996, Météo France has installed a remote station (Nivose) for the regional government (Conseil Général de la Savoie). It performs automatic measurements of snow depth, winds speeds and directions, and air temperature; Data can be obtained at 1-hour intervals. It is on an East Side, at 2740 m high.

This device has been completed to obtain data about blowing snow and precise avalanche activity:

- ✓ One autonomous Fowcapt[3] has been installed in January 2000 at 2500 m high. It was intended to provide data about blowing snow, registered because of the noise made by the shock of the snow particles against a tube in which is a microphone.
- ✓ One Arfang[4] station has been installed in December 1999 at 2400 m high. It was intended to provide data about avalanches in a range of about 3-km distance: avalanche localization, instant and importance.

3.4 *Avalanches information system*[5]

Our past experiences has shown the importance of observation and historic when we one have to come to decisions regarding avalanche protection.
One of the major difficulties is that we don't know yet precisely which are the data useful for prediction. That's why we wanted to built an information system which would be both powerful and flexible, able to store any type of data, to deal with relations between them, and to bring them back easily. That is what we called Avalanche Information System. It could belong to the family of the Environment Information Systems [Gaytes (1997)].

For the present, this tool clusters two others: one Geographic Information System and one Data Base Management System. The software used is ACCESS and MapInfo, because they are used by many organisms and because they are compatible with much other software. However, by having built a strong Data Conceptual Model prior to realize the system, we could now change of software easily, for any reason.

The capture of the maps and of all the georeferenced objects is made by the GIS. The capture of all the alphanumeric data and of the photos is made by the DataBase. Catching modules make the process easier when it has to be manually done. Data files are imported in blocs when they come from automatic measurement stations.

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Query can be done from the DataBase or from the GIS. This functionality allows the user to search avalanches, maps, photos, etc. per date, per localization or per specificity. Relationships are established between the objects depending on the needs. For instance, one avalanche can be linked to photos, maps, snow profiles, etc.
Each map can be visualized as an image in the DataBase. One option also allows opening the GIS from the DataBase to use the map as a "document". So one can use all the GIS functions: zoom, query, etc.

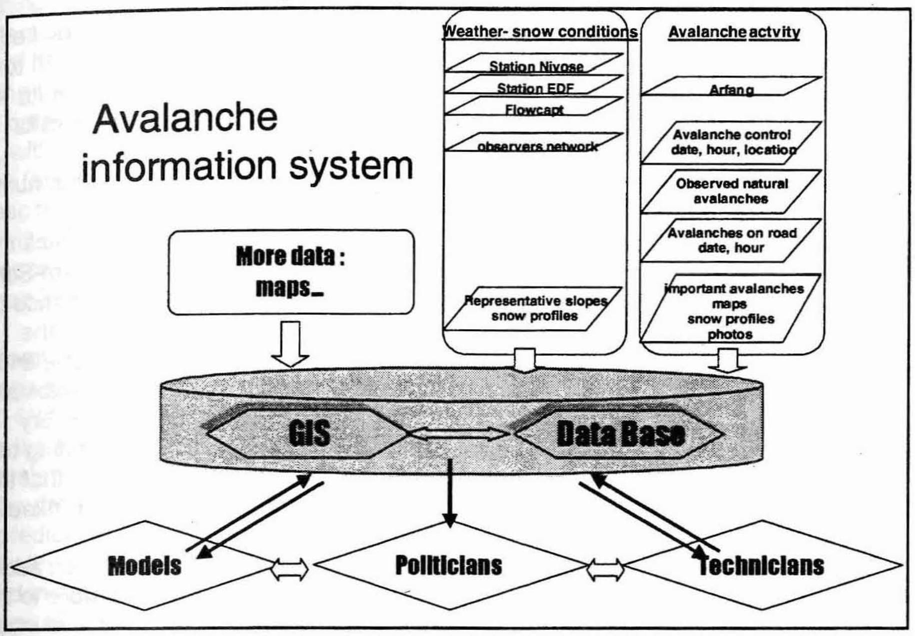


Figure 1. Data registered in the Avalanche Information System for the Bonneval-sur-Arc pilote site, and goals.

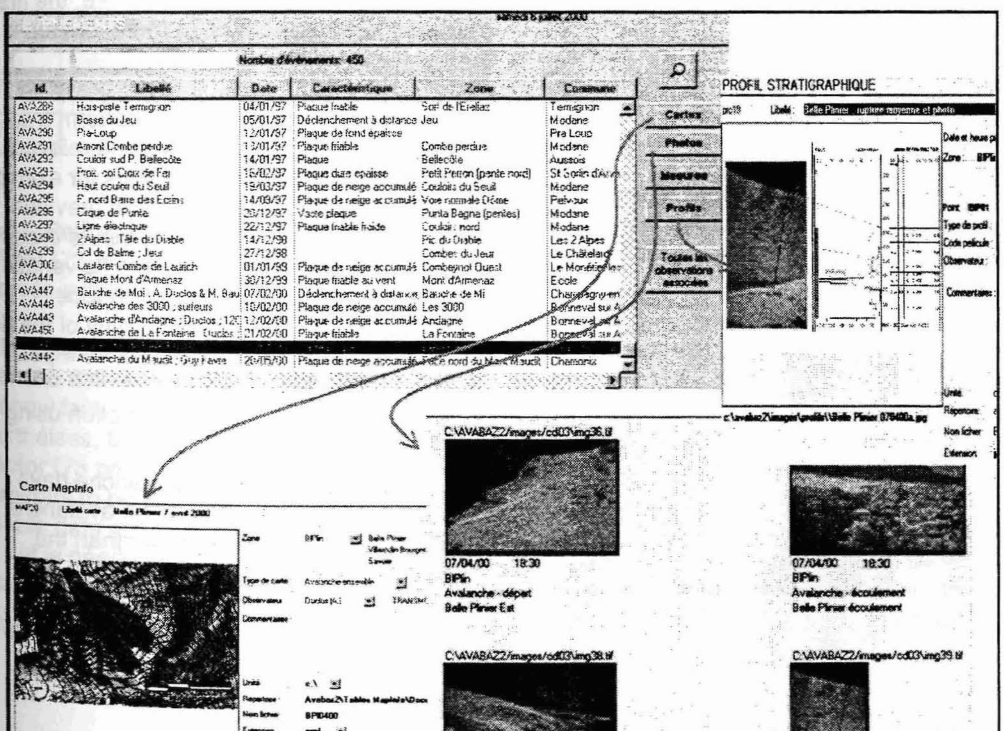


Figure 2. Some functions of the database: avalanches linked with snow profiles, photos and map.

3.5 *Statistics*

To operate the data from our Avalanche Information System, we have chosen to try a method, which gives as few place as possible to subjectivity.

Successive steps of this method are, the ordering of input factors by Gram-Schmidt orthogonalization procedure, the selection of those input factors, and the prediction with neural networks.
A first test of this method for avalanche prediction has been applied on data rigorously collected in Valfrejus Ski Resort (Savoy, France) during the winters 1994-1995 and 1995-1996.

3.5.1 Data

The avalanche data (output) was the number of avalanches recorded daily at Valfréjus. Due to missing data, the avalanche activity of N = 243 days only is available: they consist in 67 avalanche days and 176 non-avalanche days. The goal is to predict the avalanche activity of a given day, from weather and snow factors measured the day before or up to 9AM the same day.
The weather and snow data (input factors) were the same as those usually used for this type of study, measured at Valfréjus: the snow height at 9 AM, the 24h total precipitation of the day before, the penetration of a sounding tube into the snow at 9 AM, etc.
We will also studied whether it is useful to add the avalanche activity of the day before to these inputs.

3.5.2 Input factors ordering and selection

The most relevant input factors were selected by building a polynomial model, by ordering its monomials according to their relevance with an orthogonalization procedure [Chen & Billings 1989], and by keeping the input factors involved in the most relevant monomials [Urbani & al. 1994].

At the end of the ordering procedure, one obtains the ordered list of the monomials, the sums of squared residuals of the corresponding models, i.e. with an increasing number of monomials; the sums of squared residuals decreases with the number or monomials.
The data set being small (N = 243) with respect to the number of inputs, polynomials of at most degree 3 of the above inputs and their variations from one day to the next are considered. We have thus 18 (primary) inputs, and 1329 monomials.
The primary inputs are designed by i.e., snow height at 9 AM, and its variation, 24h total precipitation of the day before, and its variation, precipitation at 9 AM, and its variation, etc.
The output yp is the vector of is the number of avalanches (divided through 10).
When looking at the 12 most significant monomials, as ordered by the Gram-Schmidt procedure, one notices the importance of the snow height, of the wind speed, of the precipitation, of the air temperature, and of the minimal air temperature. But the maximal air temperature does not seem to be very significant; neither does the sounding tube penetration . This may also mean that these inputs are redundant with those ranked before.
The predictions are improved when adding the avalanche activity of the day before to the inputs. For example, with the above inputs only, the first 20 monomials leave 42,6% of the output unexplained, whereas with the avalanche activity of the day before, the first 20 monomials leave 34,7% of the output unexplained.

For selection, we lack data to perform a rigorous statistical selection of the relevant inputs, based on hypothesis tests for example. Nevertheless, on the basis of the previous ranking, we chose to retain all inputs except the maximal air temperature and its variation, and the variation of the sounding tube penetration. The avalanche activity of the day before is added, hence a total of 16 inputs.

3.5.3 Avalanche activity prediction using neural networks

We chose to forecast the avalanche days (desired output +1) and the non-avalanche days (desired output -1), rather than the number of avalanches per day.
The predictors are neural networks with an input layer of 16 inputs (plus a constant input equal to 1), a hidden layer of nonlinear

neurons with hyperbolic tangent activation function, and an output neuron with hyperbolic tangent activation function (see Figure 3). The complexity of a predictor increases with the number of hidden neurons. A network is considered to predict an avalanche if its output is larger than zero.
The training (i.e. the adjustment of their parameters) of predictors with an increasing number of hidden neurons is performed by minimizing the sum of squared errors of the network outputs with respect to the desired outputs, with the Levenberg-Marquardt algorithm (see [Bishop 1995]). For a systematic training and selection procedure, see [Rivals & Personnaz 1998], and for performance estimation, see [Rivals & Personnaz 2000].

The performance of the predictors, i.e. the percentage of correct prediction, is evaluated using 10-fold cross-validation. We also evaluate the percentage of correct prediction for the avalanche days, and that for the non-avalanche days. The maximal percentage of correct prediction for the avalanche days is reached with a 4 hidden neuron predictor. If more hidden neurons are added, the percentage of correct prediction for the avalanche days decreases again. The results are given in Table 1.

	global % of correct prediction	% of correct prediction for the avalanche days	% of correct prediction for the non avalanche days
On the training sets	98.2	94.8	99.5
On the test sets	71.3	55.5	77.8

Table 1. Performance of a 4 hidden neuron predictor (73 parameters) evaluated with 10-fold cross-validation.

So, it seems to be possible to predict the avalanche activity with the available weather and snow factors and a neural predictor. Nevertheless, the complexity needed for the predictor (73 parameters) is too large for its parameters to be estimated correctly with the available data set (N = 243 days). A larger data set is needed to draw definitive conclusions about the adequacy and the performance of the proposed method.

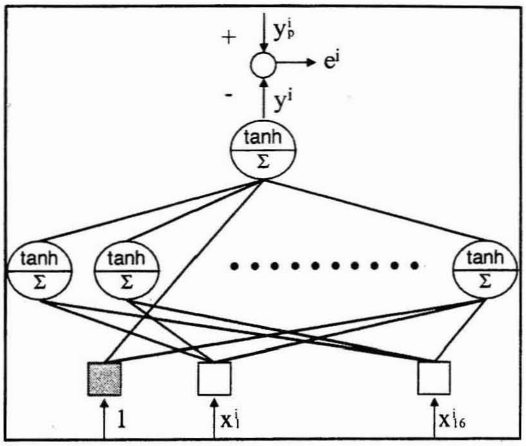


Figure 3. Neural predictors.

4 RESULTS

After a first season of running of the pilot site, results are below what we expected, but they remain very incentive. The new instrumentation worked, but not on a continuous way. So the statistic analysis has not been possible. Nevertheless, some new information has been followed up immediately.

4.1 *New instrumentation evaluation*

The Flowcapt, used for the measurement of the blowing snow, provided data that probably is interesting for avalanche prediction. During several periods, we have noticed an evolution of those data which is different from the one of wind speed or precipitation, but which seems to reflect an important aspect of the reality

DATE	FCSnow	ffmax	RRRR
21/01/00	1307	11	0
22/01/00	386	12	2
23/01/00	157	13	0
24/01/00	1	4	0
25/01/00	0	7	0

Table 2. maximum blowing snow (FCSnow), maximum wind speed (ffmax , m/s) and precipitation (RRRR, mm), between January 21st and January 25th 2000.

For instance, between January 21st and January 25th 2000, rather strong winds have been registered by Nivose station during the 3 first days, and very few precipitation have been registered by the EDF station. Meanwhile, the blowing snow came from "important" to null, although the wind blew again on February 25th (Table 2). This doesn't tell us that the Flowcapt gives some interesting data, but it shows that Flowcapt is measuring something new.

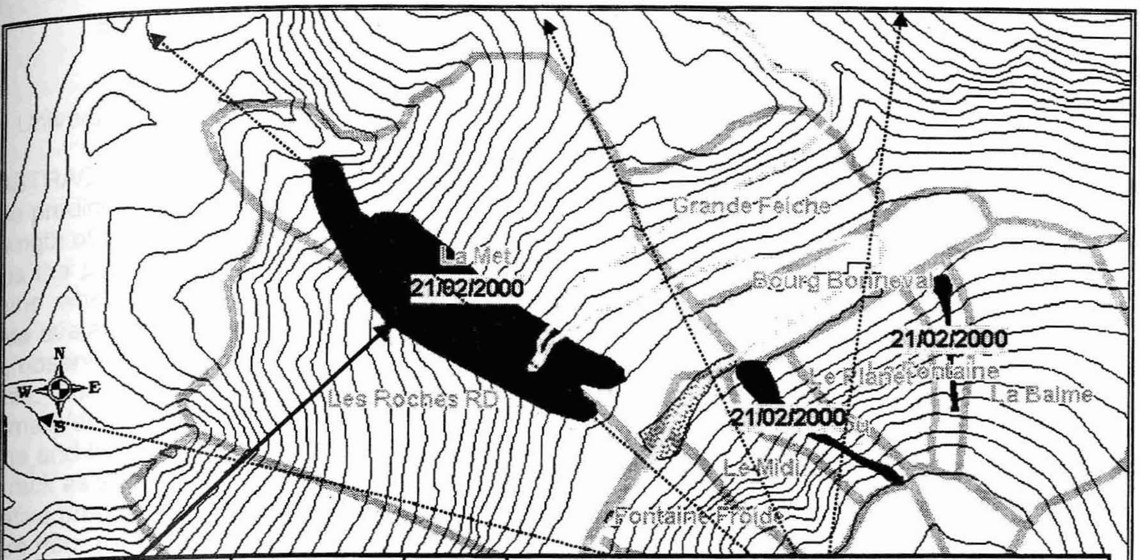
It hasn't been possible to correctly evaluate the working process of Arfang. Indeed, we couldn't regularly consult the system during winter, and in spring, although we had many data, it was no more possible to be sure of the correspondence, or no-correspondence, between some signals registered by Arfang and the reality.
Nevertheless, we have verified how Arfang runs for some important avalanches. It was the case on February 21st 2000. The given information is very interesting because it indicates the exact instant of the avalanche, its localization and its importance, which can be deduced from the duration of the signal (figure 4).

4.2 <u>Some using of the present system</u>

The avalanche information system we have developed and supplied during winter has already had interesting applications.

For instance, it allowed to precise some points for permanent installations of avalanche control (20 AVALHEX).
It also allowed the Regional government to appreciate the extensiveness of some avalanches, which prior hadn't been considered as the more dangerous.

Also, the avalanches descriptions registered in the Information System provide very precise and interesting data for avalanche training programs, for the deciders as well as for the mountaineers.



Date	heure	azimut			duration	area
		min	aver	max		
21/02/00	13:42:40	302	307	318	40	RD : Les Roches
21/02/00	14:35:37	244	266	284	15	RD : Buffettes
21/02/00	14:38:00	359	22	43	20	RD : Bourg" RG : Fontaine - Tchou - Fontaine Froide
21/02/00	17:09:33	5	18	23	15	RD : Bourg" RG : Fontaine - Tchou - Fontaine Froide
21/02/00	17:11:08	13	27	35	17	RD : Bourg" RG : Fontaine - Tchou - Fontaine Froide
21/02/00	17:41:13	303	305	307	25	RD : Les Roches
21/02/00	17:41:50	305	306	308	22	RD : Les Roches
21/02/00	17:53:53	303	305	306	20	RD : Les Roches

Figure 4. Avalanches drawn by the observer on the SIG, and results of Arfang for February 21st 2000.

5 OUR GOAL FOR NEXT SEASON

Even by merging several organism efforts, it hasn't been possible to know precisely the avalanche activity on the Bonneval-sur-Arc pilot site during the winter 1999-2000. That is why our first objective remains the improvement of the avalanche automatic detection, for continuous running and exhaustive reports.

In this aim, next season, Arfang will operate its registrations at 1-hour intervals. In case of avalanche(s) detection, it will send a message of the interested persons' cellular phone. So, it will be possible to verify in real time the correspondence between the signals selected by Arfang and the avalanches.

Another goal will be to evaluate if the use of neural networks is able to provide an interesting prediction. Different data coming from the Flowcapt will be tested as input factors, and probably fed to the neural networks.

At last, after having tested the neural network at the site scale, we shall reflect upon the way it is possible to apply it at a given slope scale.

6 CONCLUSION

The description of the avalanche activity on a site is a long and expensive work. However, it seems to be indispensable if we wish to be able to give scientific arguments to explain some decisions about avalanche protection.

The use of an Avalanche Information System allows information archival and the easy operation by others. The use of automatic stations is indispensable for the continuous collection of data, statistical processing, and help to decision making.

We don't know yet if this process will allow for the development of predictive models that may become better than the local decision maker. Until today, mountaineers have assumed the management of the roads regarding the avalanche risk. So far, there have been no serious accidents. A bit of luck maybe responsible for their success.

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