Embedding a geographic information system in a decision support system for landslide hazard monitoring

Marco Lazzari & Paolo Salvaneschi

ISMES - via Pastrengo, 9 - 24068 Seriate BG - ITALY
tel +39 035 307 243/237   fax +39 035 302 999
email {mlazzari, psalvaneschi}@ismes.it

SUMMARY

In this paper we present an application that exploits a geographic information system as a front-end of a complex information system supporting the management of landslide hazard in Valtellina, an alpine valley in Northern Italy.

A decision support system (EYDENET, operational since October 1996), incorporating a geographic information system and a data interpreter based on artificial intelligence techniques, processes the readings of the 250 most significant instruments of a monitoring net of about 1000 sensors installed on different landslides in several alpine valleys.

Data gathered by extensometers, clinometers and pluviometers, to check both movements of rocks and climatic conditions which could affect them, are processed by EYDENET, that provides on-line interpretation of data, helps the users analyse them, and generates natural

language explanations and alarm messages for the people responsible for the environmental management and the civil protection.

THE CONTEXT: LANDSLIDE HAZARD MANAGEMENT

In the summer of 1987 a ruinous flood affected large areas of the Valtellina (Northern Italy) and caused many landslides.

Debris flows dammed the Adda river in the evening of July 18, forming a small lake that reached a maximum elevation of 1062.5 m.a.s.l., approximately 10 m above the Adda riverbed, and an extension up to 266,000 m^2.

On July 19 the Adda river overflowed and partially cut the dam, reducing the extension of the lake to 124,000 m^2.

On July 28 a large mass of rock, estimated to be 34 millions m^3, suddenly moved down towards the Adda valley, destroyed the village of Morignone, fell into the small lake and generated a large wave that moved upstream and destroyed the villages of Poz, S. Antonio

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Morignone and Tirindrè, which had been evacuated some days before. Then the wave reached the village of Aquilone, approximately 2,300 m upstream from the unstable area, that had not yet been entirely evacuated, and as a result 27 people were killed (fore more details on the Valtellina landslides see Azzoni et al., 1992).

The management of the critical stage of this emergency involved several actions, such as data collection and interpretation, decision making and prompt-intervention. This experience taught the lesson that the emergency must be tackled through the creation of an organisation that manages the knowledge of the actual conditions and their evolution as provided not only by basic studies, but also by instrumentation networks that monitor the most critical phenomena.

As a consequence, the regional authorities and the Italian Department of Civil Protection appointed ISMES to develop a system to check and monitor the stability of the slopes affected by the landslides.

ISMES implemented in 1988 a hydrogeological monitoring net in the area of Val Pola and Valmalenco, and an information system to help the people responsible for the safety management.

Several monitoring sub-systems check hydrogeological and climatic aspects of the sites (slope instability, geology, rainfall); the sensors (about 1000) are connected to remote data acquisition units, and their signals are transmitted via radio to a central acquisition system, where they are stored and analysed by geologists charged with the safety management.

Recently, the whole monitoring system and its front-end have been redesigned, and we have implemented a new decision support system, called EYDENET[1], to support data interpretation and analysis; EYDENET exploits artificial intelligence techniques for interpreting data, and a geographic information system for representing them.

THE MONITORING SYSTEM

To provide for the requirements stated above, ISMES developed an information system (INDACO) that comprises a real time automatic *monitoring* system, a *telemetry* system and a *data base* with processing functions[2].

The preliminary selection of the quantities and points to be checked was based on the interpretation of the morphological, lithological and geostructural investigations carried out both *in situ* and on aerial photographs, and was intended to provide an indication of the possible instability mechanisms.

Although manual instruments were initially used to measure displacements, the use of automated monitoring systems was soon suggested by several reasons:

❑ the extent of the area to be monitored;

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[1] EYDENET is called from Ey de Net (Eye of the Night), the young hero of an Italian folk-tale, something like an Iliad of the Dolomites; Ey de Net was a brave warrior, famous for his long sight, who fought gallantly to defend his country against the enemy. We think that EYDENET may be a name of good omen for a net of eyes (the monitoring instruments) for the surveillance of our Alps.

[2] INDACO, a PC-based system, was originally developed for dam monitoring, and has been installed at about 40 sites in Italy and abroad for monitoring large dams and monuments.

- ❏ the inaccessibility of some of the measuring points;

- ❏ the exposure to risk for those charged with the manual measurement.

Data acquisition devices are provided with autonomous supply sources and linked via radio to the central acquisition centre.

The net of monitoring devices consists of:

- ❏ surface strain-gauge networks;

- ❏ topographical and geodetic benchmark network;

- ❏ inclinometer networks;

- ❏ settlement-meter networks;

- ❏ cracking gauge networks.

Furthermore, other instrumented networks located all over the territory are linked to the monitoring system; among them, the hydro-meteorological monitoring system is of particular importance because of the close connection between slope stability problems and hydrological and hydraulic factors. This network comprises rain gauges, snow gauges and thermometers.

Since the instruments are installed over a wide area (five different zones are monitored), their data have to be sent through a telemetry system to a central computer, where they are loaded into a data base and preliminary processed by INDACO, that checks them and their rate of variation against thresholds.

Periodically INDACO prints reports on the current state of the instruments and when a measurement overcomes a threshold, it warns the users, who can access the measurements through the system (Anesa et al., 1989).

ADVANCED SOFTWARE TECHNIQUES FOR SAFETY MANAGEMENT

In the last decade ISMES has been charged with developing several software systems to deal with different problems in the field of safety management, such as seismic vulnerability assessment of buildings, dam safety, monitoring of seismic and volcanic regions.

In this field artificial intelligence (AI) concepts and technologies can assist engineers by providing additional components to be integrated into existing information systems, which may perform *intelligent* processing of data related to safety management.

Therefore, for its safety management software systems ISMES used AI technologies, that provided powerful tools for the design of intelligent modules: causal networks of processes, qualitative modelling, model-based reasoning, hierarchical object-oriented representations were largely used.

Moreover, AI techniques, such as rule-based systems, pattern matching and neural networks, in conjunction with conventional ones, were also employed for implementing those representation and reasoning schemes.

As a result, we have developed several AI based software tools for safety management, which are currently operational, such as MISTRAL and KALEIDOS, for the on-line interpretation of monitoring data of dams and monumental structures; DAMSAFE, for the off-line support of dam safety management procedures; IGOR, to support the seismic vulnerability assessment of masonry buildings (for a discussion of these systems see Salvaneschi et al., 1996a).

Furthermore, we have taken advantage of geographic information systems (GIS) for a variety of tools, exploiting their powerful representation of georeferenced data. This effort led

to the development of several applications, such as CAIFA, the catalogue of Italian seismogenic faults (Gusmini et al., 1996), and SCENARIO, a system for reducing seismic risk through construction of simulated damage scenarios (Salvaneschi et al., 1996b).

On the ground of this experience, we have decided to exploit both AI and GIS to implement EYDENET, a supporting system to help people manage and evaluate the heterogeneous data generated by the monitoring system of the landslides in Valtellina.

This new system is linked with the existing monitoring devices, and can evaluate the measurements coming from them and classify and filter the anomalies by using different types of knowledge gathered from the experts and formalised through AI based techniques (e.g. geometrical and physical relationships modelled through qualitative reasoning).

Furthermore, EYDENET can consider the whole set of measurements related to a monitored zone to identify its global state and to explain it. This allows to overcome the limits of conventional monitoring systems, which usually handle only one instrument at a time and one reading at a time for each instrument, and therefore generate warning messages for any behaviour - of either the monitored object or the instruments - that is not consistent with the reference model.

As a result, the system enables on-line performance of part of the expert interpretation, a performance that reduces the requests for expert intervention and the associated costs and delays, and increases the reliance upon the safety of the monitored area.

On the other hand, GIS may be helpful to show to the users the results of the evaluation process in a very effective way, by localising on a map the state of instruments, zones, and active physical processes.

A DECISION SUPPORT SYSTEM FOR INTERPRETING LANDSLIDE MONITORING DATA

EYDENET is a decision support system for the interpretation of data gathered by the hydrogeological monitoring system of the Valtellina (Figure 1).

EYDENET operates in real time and is linked to the automatic monitoring system; it processes the measurements of the main instruments of the monitoring network (about 250 sensors), providing a global interpretation and explanation of the state of the areas which are monitored and evaluating this state against a desired state.

EYDENET includes the following modules (Figure 2):

- ❑ *communication* module: manages the data communication from the data acquisition system to EYDENET;

- ❑ *evaluation* module: identifies the state of the monitored areas;

- ❑ *explanation* module: generates a natural-language explanation of the deductions carried out by the evaluation module;

- ❑ *man/machine interface*: lets the user access the computation results;

- ❑ *database management* module: manages an internal database of measurements and evaluations;

- ❑ a *main* module that co-ordinates the other ones.

The *communication module* calls the monitoring system and receives the data gathered during the last acquisition (normal real-time procedure) or collected while EYDENET was,

for some reason, not active: the monitoring system and EYDENET exchange data through a data server over a local area network.

The instruments are grouped in five main areas, which can gather measures asynchronously, and are therefore processed separately; on each area, data are acquired every hour in normal conditions, every 30 minutes in alarm situations (every 30 and 15 minutes for hydrological data).

The *evaluator* and the *explainer* process these data and store their results into the internal database.

Essentially, the evaluation is a process of *evidential reasoning*, which transforms data states into states of the instruments and of the monitored areas, and interprets them in terms of alarm states. Then the explainer maps these states into the proper messages.

The first step of the evaluation is a numerical analysis of the data, that computes statistical indicators such as, for instance, the average over the last 4 and 24 hours.

Then EYDENET synthesises the results of the numerical processing, defining a *status* and a *qualitative index* for each instrument. The *status* can be regarded as an internal parameter, useful for computational purposes, in order to record the history of the measurements, whereas the *index* is a measure of the *anxiety* that safety managers are expected to derive from the current measure of the instrument, and therefore it is used as an output parameter, that might range from *normal* to *high anomaly*[3].

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[3] Currently, at most four values are used: normal, low anomaly, medium anomaly, high anomaly; for some objects, only a subset of these values is appropriate.

The mapping from measures to indexes is performed by a *rule-based processor* that is based on the knowledge of the past behaviour of the measures.

Finally, EYDENET applies to these symbolic data an other set of rules that incorporates expert knowledge on the influence that groups of homogeneous measures have on safety (a senior geologist was involved in its design). This processor identifies the current state of the five areas, the state of physical processes which might be active (e.g. slope instability, rock falls) and the estimated hazard for zones that could be affected by them.

To clarify the interpretation process, imagine that after the numerical processing, the following rules are applied:

```
IF   status WAS alarm
     AND rate of change 1 WAS second level
     AND rate of change 2 WAS first level
THEN status IS prealarm2
     AND index IS medium anomaly

IF   status WAS normal-to-prealarm2
     AND rate of change 1 WAS first level
THEN status IS prealarm1
     AND index IS low anomaly

IF   status WAS normal-to-prealarm2
     AND rate of change 1 WAS second level
     AND rate of change 2 WAS first level
THEN status IS prealarm2
     AND index IS medium anomaly
```

where *status* and *index* are the aforesaid parameters, *rate of change 1* is the variation of the measure over the 24 hours and *rate of change 2* is the variation of the measure over the 4 hours, both codified by checking them against a set of thresholds which define a quantity space (normal, first level, second level, etc.).

The first rule may be interpreted as follows: if the status recorded by the previous processing is *alarm*, and the variation of the measure over the latest 24 hours overcomes the second

threshold, but the variation over the latest period (4 hours) is not higher than the second threshold, then the status of the instrument can be changed from *alarm* to *prealarm2* and the index of the instrument has to be set to *medium anomaly*.

As soon as the indexes for the instruments of an area have been set, other rules are applied to set the index of the area itself; they are used both to define the global state of the area and to filter false alarms, that is anomalies arising from a single instrument, but not supported by the behaviour of correlated instruments which should provide sufficient evidence for an abnormal situation. Although the interpretation process is rather more complex, for the sake of simplicity a rule can be rearranged like this:

```
IF    index of extensometer 303 IS medium anomaly
      AND
      index of extensometer 304 IS normal
      AND
      index of extensometer 305 IS normal
THEN
      index of area IS normal
```

The rule processor is also able to identify physical processes currently going on, such as rock falls, and assign to them an *activation index*, that is taken into account to define the global index of a zone. Moreover, whenever a process is active, EYDENET identifies the geographical zones that could be affected by this process (e.g., the sites that could be reached by a slide).

From the trace of the execution, the *explanation module* generates natural language messages that describe the current state and the deductions of the system. These messages clearly tell the users about the state of each area, so that they can understand which operational procedures they must activate (additional manual measurements, calls to Local

Authorities or Civil Protection). Moreover, the explanations summarise detailed information about the instruments: for instance, the users are told about which instruments overcame the safety thresholds.

Users can access the results of the processing through a *window-based interface* (Figures 3-5 are screenshots taken from a simulation). The main window of the system interfaces a GIS, that is integrated within EYDENET to exploit its cartographic facilities and offer a powerful representation tool to *navigate* through data.

In the cartographic window EYDENET may show maps of the monitored areas and represent on them the different instruments through coloured lights, using a colour scale based on their state: we use colours ranging from green to red, using grey for representing missing information (for instance, malfunctioning instruments).

Representation options allow the user to show only the most interesting subsets of the instruments, on the ground of (combinations of) their type (*don't show pluviometers*) and their state (*don't show instruments in normal state*). Users can also exploit standard features of GISs , such as zooming functions to highlight sub-areas they want to analyse.

Moreover, cartographic layers are used to represent the activation state of physical processes and the hazard level for the zones affected by them (Figure 5), by colouring on the map the sites where a physical phenomenon is active and those that can be influenced by its evolution.

While dealing with a single area within the GIS window (the largest window within the screenshots of Figures 3-5), the user is informed on the state of the whole monitored region by a set of coloured lights (on the right), each of which corresponds to one of the five areas processed by EYDENET. These lights are always visible, and give the user immediate feeling

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of what is happening: whenever EYDENET processes an area, the corresponding light is highlighted, and the relevant explanation is shown in a small text window (upper-right corner), and therefore the user may understand whether something has changed, even when dealing with an other zone within the GIS window. A scrollbar allows to examine the latest explanations provided by EYDENET, whilst the explanation of the state of the area currently under examination within the GIS window can be recalled by pushing the button in the lower-right corner labelled as STATO GLOBALE.

Through the interface the user can also activate functions (e.g. print screen), unable/disable instruments' evaluation (for instance, to exclude some malfunctioning instrument from the interpretation process) and access the archive. All these functions are accessed via menus, whereas the most frequently used cartographic functions are driven by buttons always visible on the bottom bar.

EYDENET provides the users with a database collecting all the data related to the monitoring system (measurements, evaluations, explanations). It is possible to select a past situation from the data base and show on the screen its graphic representation, measures and explanations.

THE TECHNOLOGY

EYDENET was developed on a personal computer (Pentium) with MS-Windows 3.X using Visual Basic (main process, communication, numerical processing, interface), Prolog2 (evaluation and explanation), MapInfo (GIS) and Access (database). Visual Basic uses Prolog

as a DLL (Dynamic Link Library), while shares data with MapInfo via OLE (Object Linking and Embedding).

EYDENET has been operational since October 1996 at the *Monitoring Centre for the Control of Valtellina*, set up by the Regione Lombardia at Mossini, near Sondrio; it is operated by a senior geologist and a team of engineers of the Regione Lombardia.

EYDENET is installed on a personal computer connected to a net of PCs, which form the distributed automatic acquisition system; it gets from them the data to be processed via a data server. The system is also connected to external acoustic devices (through serial port), to warn the people of the monitoring centre of alarm situations.

FUTURE DEVELOPMENTS

We are currently extending the capabilities of EYDENET in several directions:

- new areas will be monitored;

- the evaluator will perform analogical reasoning, to identify the degree of similarity between the current situation and significant past ones;

- a hypertextual help will be linked to EYDENET, that comprises documents which could support decision making at the control centre.

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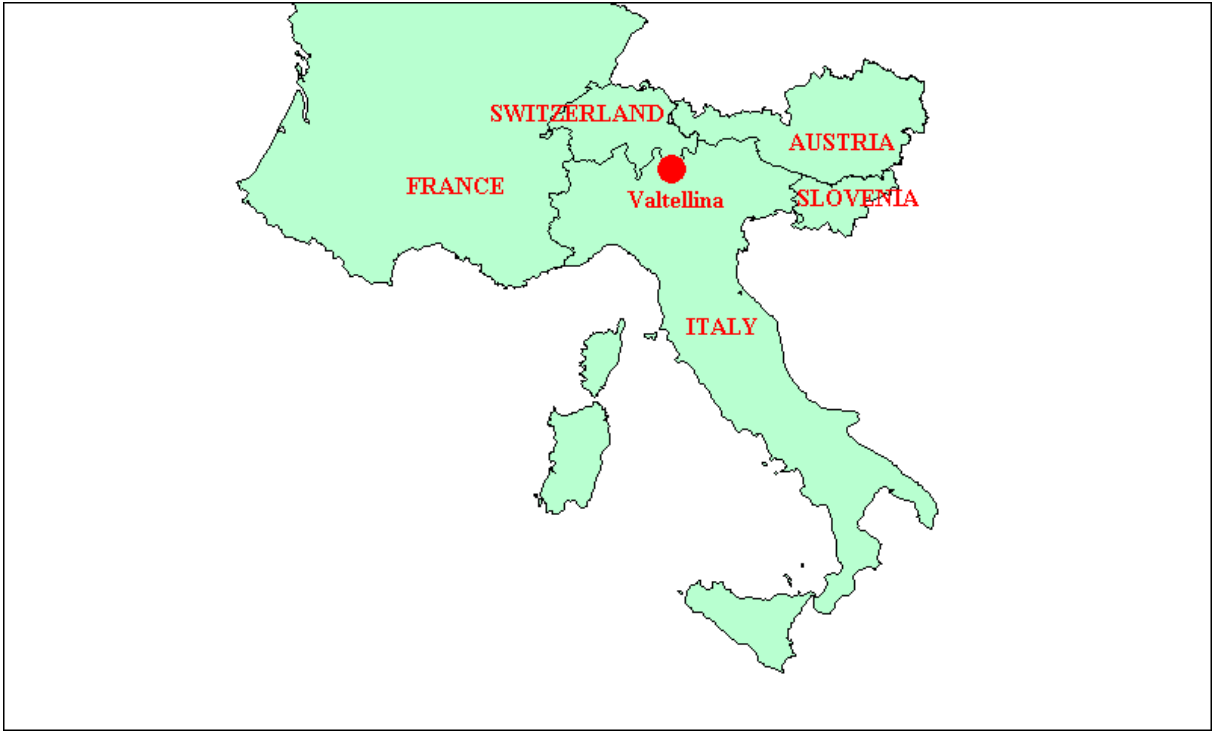
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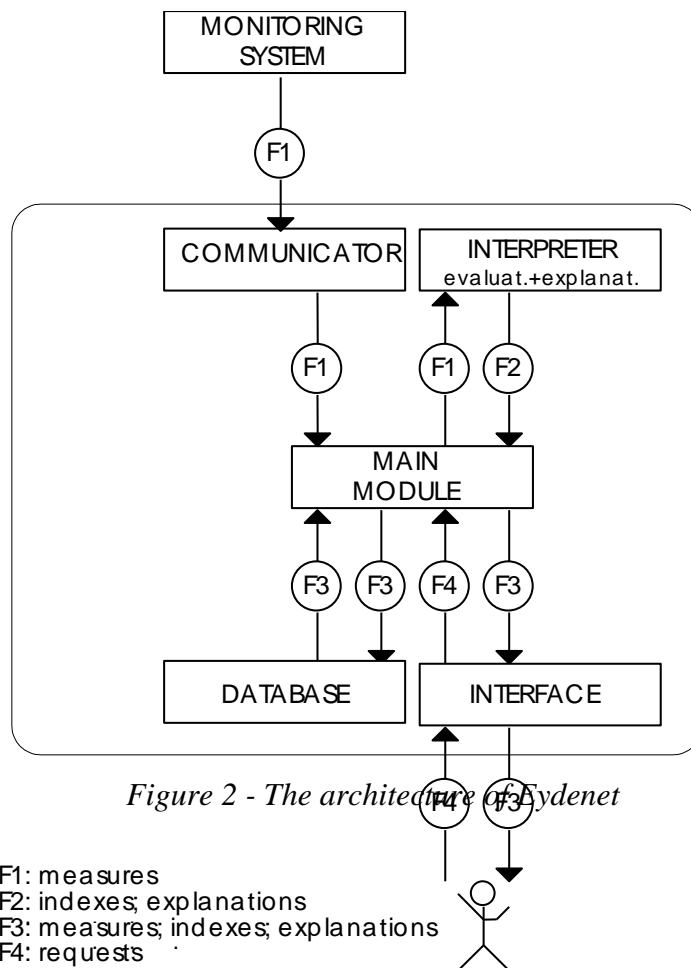
Figure 1 - The area assessed by Eydenet

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Figure 2 - The architecture of Eydenet

F1: measures
F2: indexes; explanations
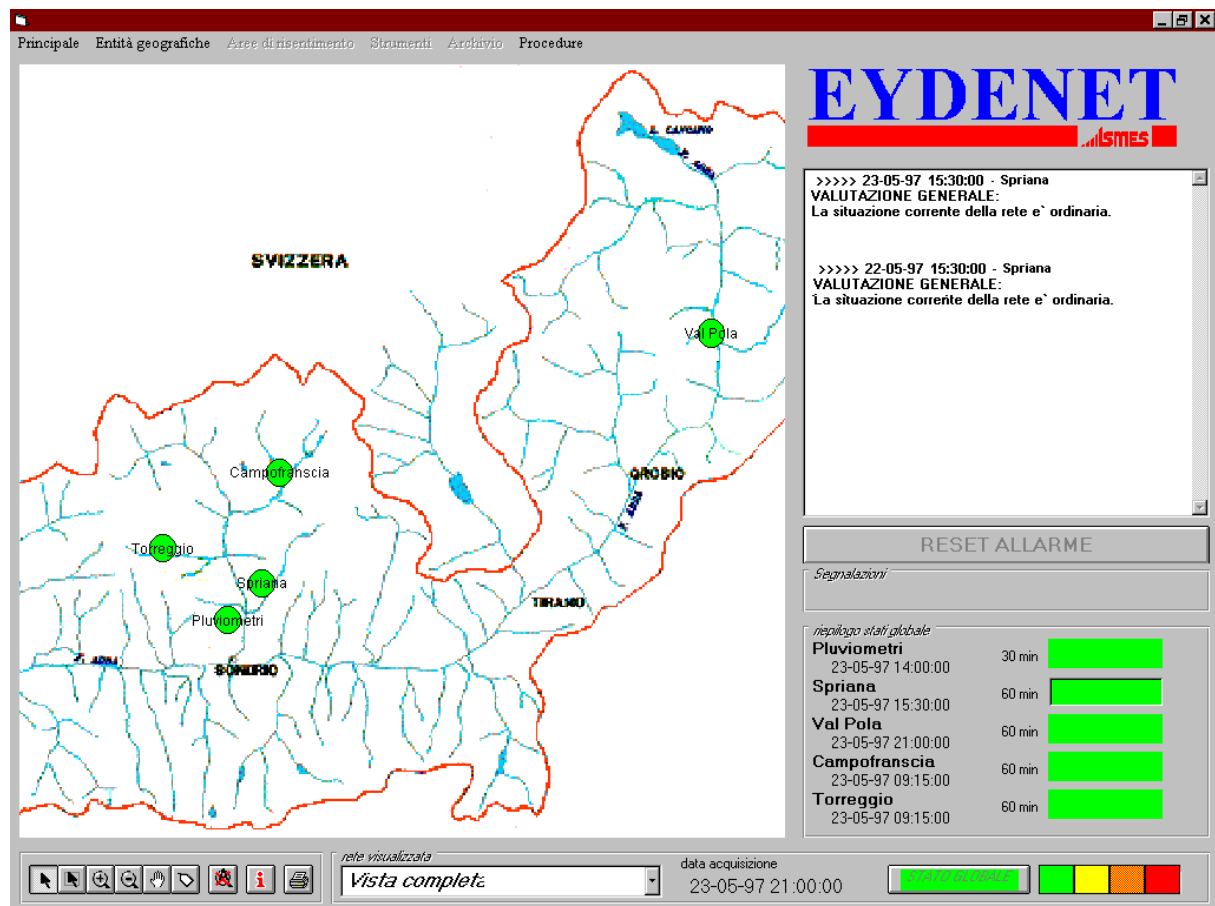F3: measures; indexes; explanations
F4: requests

Figure 3 - Eydenet: the window-based interface

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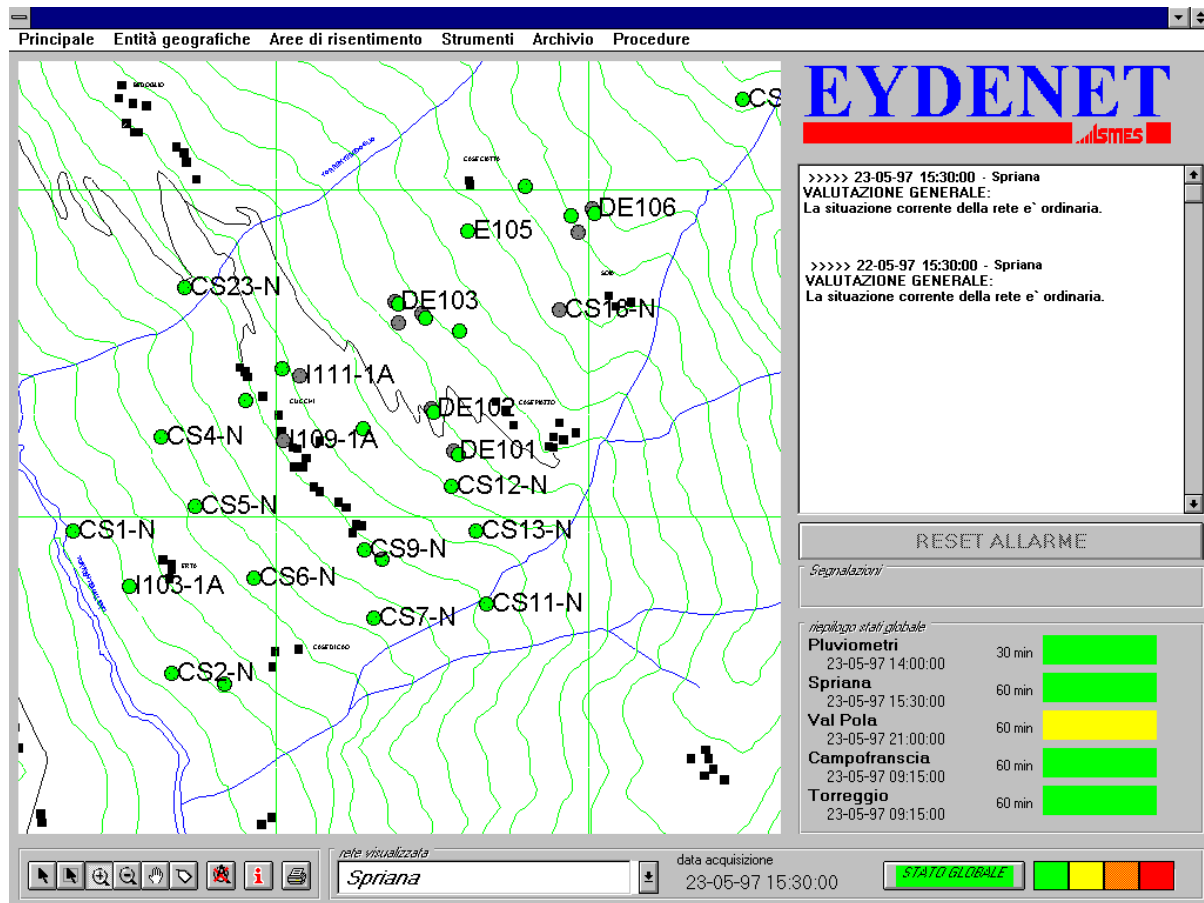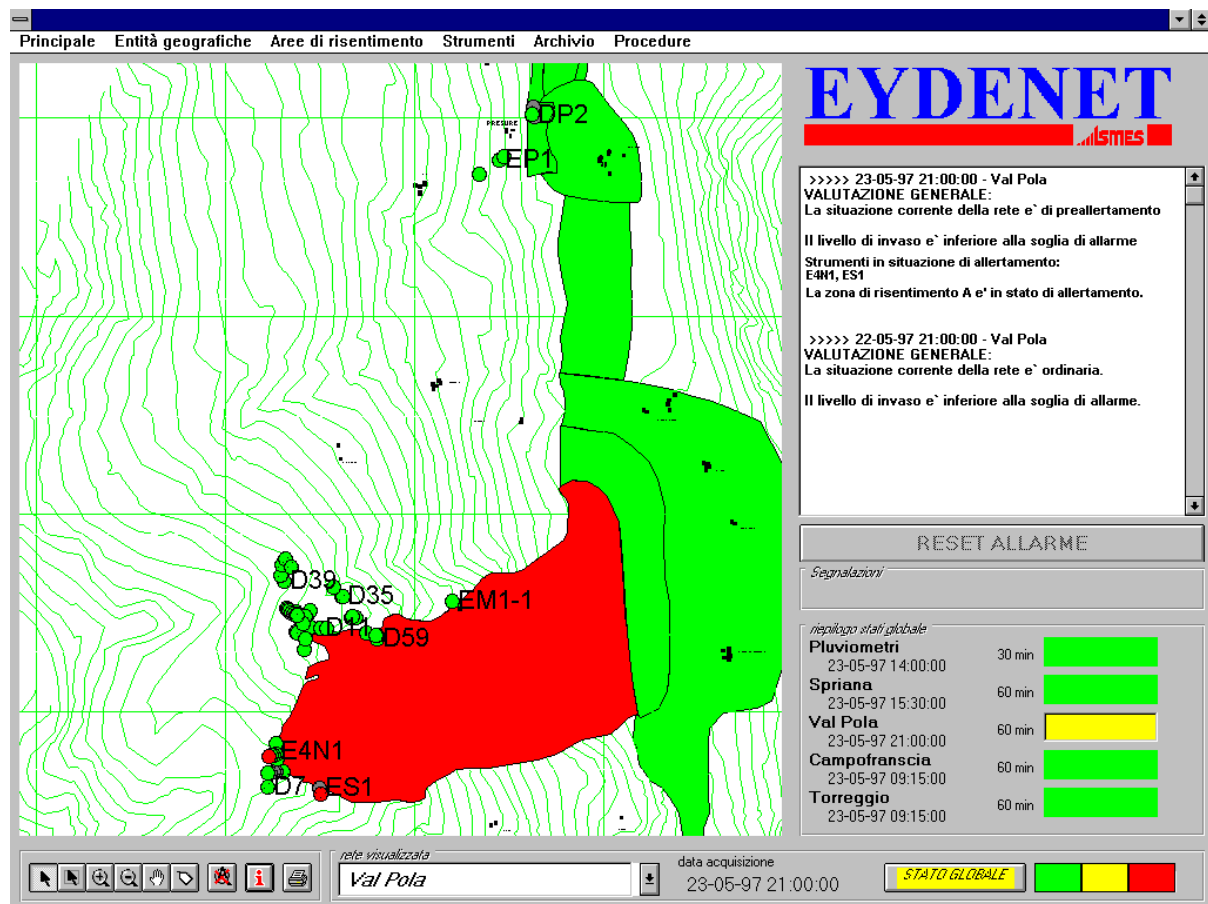
Figure 4 - Eydenet: assessing the state of a specific area

Figure 5 - Hazard level of zones