Landslides and Engineered Slopes: Protecting Society through Improved Understanding – Eberhardt et al. (eds)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-62123-6

SANF: National warning system for rainfall-induced landslides in Italy

M. Rossi, S. Peruccacci, M.T. Brunetti, I. Marchesini, S. Luciani, F. Ardizzone, V. Balducci, C. Bianchi, M. Cardinali, F. Fiorucci, A.C. Mondini, P. Reichenbach, P. Salvati, M. Santangelo, D. Bartolini, S.L. Gariano, M. Palladino, G. Vessia, A. Viero, L. Antronico, L. Borselli, A.M. Deganutti, G. Iovine, F. Luino, M. Parise, M. Polemio & F. Guzzetti
CNR, IRPI, Italy

S. Luciani, F. Fiorucci, A.C. Mondini & M. Santangelo
Università degli Studi di Perugia, Perugia, Italy

G. Tonelli
Gabriele Tonelli, Bologna, Italy

ABSTRACT: In Italy, rainfall-induced slope failures occur every year, claiming lives and causing severe economic damage. We have designed and implemented a landslide warning system, named SANF (an acronym for national early warning system for rainfall-induced landslides), to forecast the possible occurrence of rainfall-induced landslides in Italy. The system is based on: (i) rainfall thresholds for possible landslide occurrence, (ii) sub-hourly rainfall measurements obtained by a national network of 1950 rain gauges, and (iii) quantitative rainfall forecasts. Twice a day, the system compares the measured and the forecasted rainfall amounts against pre-defined ID thresholds, and assigns to each rain gauge a probability of landslide occurrence. This information is used to prepare synoptic-scale maps showing where rainfall-induced landslides are expected in the next 24 hours.

1 INTRODUCTION

Landslides are widespread phenomena that cause casualties and extensive damage. Landslide can be caused by different triggers, including rainfall, earthquakes, rapid snowmelt, and human activities. In Italy, intense or prolonged rainfall is the primary trigger of landslides. Damaging failures occur every year in this country, where they have caused more than 6300 casualties in the 60-year period, 1950–2009 (Salvati et al., 2010). In Italy, research to determine the amount of rainfall necessary to trigger landslides is of scientific and social interest. In this context, the Italian National Department for Civil Protection (DPC), an Office of the Prime Minister, asked the Research Institute for Geo-Hydrological Hazard Assessment (IRPI), of the Italian National Research Council (CNR), to design and implement an early-warning system to forecast the possible occurrence of rainfall-induced landslides in Italy. To respond to the request, we designed and developed SANF, an Italian acronym for National Early Warning System for Rainfall Induced Landslides.

SANF forecasts the possible occurrence of landslides by comparing rainfall measurements and forecasts with empirical rainfall thresholds for the possible occurrence of landslides. For the purpose, a national rain gauge network provides the rainfall measurements, and numerical weather models provide synoptic-scale quantitative rainfall forecasts. The landslide forecasts are based on rainfall thresholds of the mean Intensity-Duration (*ID*) type that are used to define critical levels for the possible occurrence of landslides, in five classes.

2 SYSTEM DESCRIPTION

The landslide early-warning system is based on the comparison between rainfall measurements and forecasts and empirical rainfall thresholds. Specifically, the system consists of three components (Fig. 1): (a) for rainfall and other data input and storage, (b) for data processing and analysis, and (c) for the production and delivery of the forecasts. The first component (a) consists of a set of procedures to import rainfall measurements and quantitative rainfall forecasts. The second component (b) consists of procedures to compare the measured and/or forecasted rainfall amount with a set of rainfall thresholds, and to determine the probability of possible landslide occurrence, in five classes or critical levels. Procedures to define and validate empirical rainfall thresholds for possible landslide occurrence through the analysis of past rainfall conditions that have resulted in slope failures are also included in this component. The third component (c) consists of procedures to generate and deliver synoptic-scale forecast maps showing critical levels for the possible occurrence of rainfall-induced landslides. The forecast maps are delivered as digital web maps through OGC (Open Geospatial Consortium) Web services. A summary report summarizing national and regional landslide forecasts is prepared and delivered daily to the DPC.

The system components exploit Open Source software and technologies, including:

- PostgreSQL (www.postgresql.org) with the PostGIS (postgis.refractions.net) spatial extension, for data management and storage;
- Mono (www.php.net), PHP (www.php.net/), and the R programming environment (R Development Core Team 2011), to design and execute modeling procedures and statistical analyses;
- GrADS (www.iges.org/grads/), wgrib (www.cpc.ncep.noaa.gov/products/wesley/wgrib.html), libsim, and DB.All.e, i.e., a set of libraries developed by the Hydro-Meteorological Service of the Emilia Romagna Region (www.arpa.emr.it/sim/) used to import the quantitative rainfall forecasts;
- GeoServer (geoserver.org/), used to generate output maps as OGC services;
- ExtJS (www.sencha.com/products/extjs/), GeoExt (geoext.org/) and OpenLayers (openlayers.org/) software libraries, for specific WebGIS interfaces;
- Apache (www.apache.org/) and Tomcat (tomcat.apache.org/), to provide HTTP webserver functionalities;
- WMware Server (www.vmware.com/), for OS virtualization; and
- Fedora (fedoraproject.org/) and Ubuntu (www.ubuntu.com/) GNU/Linux distributions.

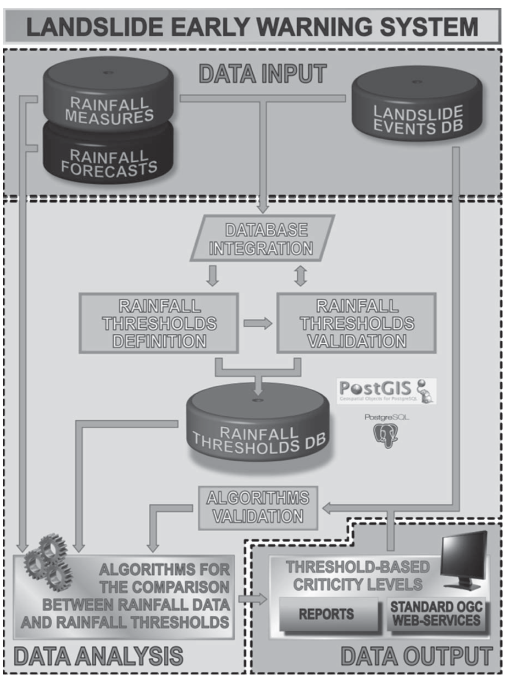

Figure 1. Logical framework adopted for the SANF early warning system for rainfall-induced landslides in Italy.

3 DATA INPUT AND STORAGE

Input data for SANF include: (i) rainfall measurements, (ii) quantitative rainfall forecasts, and (iii) information on past rainfall events that have resulted in landslides in Italy (Fig. 1). A network of 1950 rain gauges provides rainfall measurements in Italy (Fig. 2). Every six hours, rainfall measurements from this network are imported, validated, and stored in the system. Three-day quantitative rainfall forecasts (Fig. 3) are generated twice a day by DPC using the Italian Local Area Model (LAMI), and stored in the system. Information

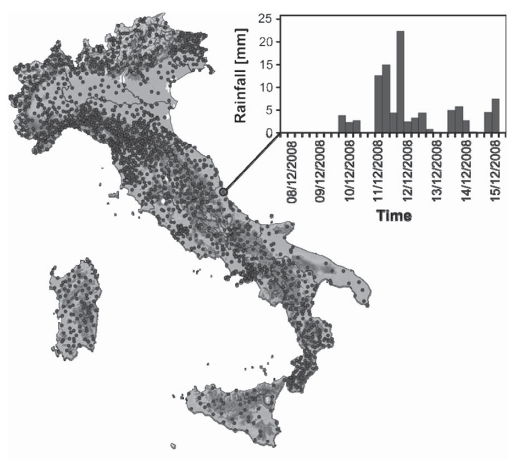

Figure 2. Geographical distribution of 1950 rain gauges of the network of the Italian national Department for Civil Protection. Inset shows a typical rainfall series used by the SANF system to forecast the possible occurrence of landslides.

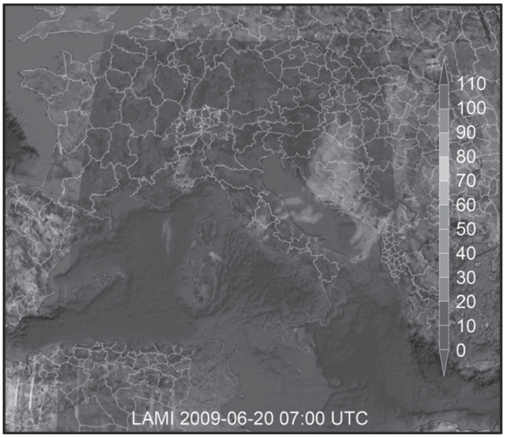

Figure 3. Map showing quantitative rainfall forecast produced by the Italian Local Area Model (LAMI) model.

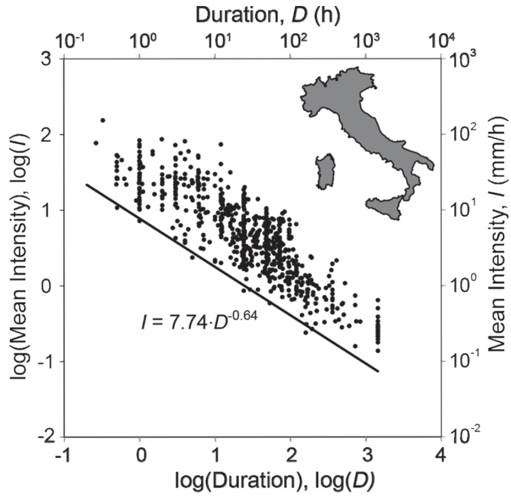

Figure 4. Intensity-duration conditions (dots) that resulted landslides in Italy. Black line is the rainfall threshold at 1% exceedance probability implemented in the SANF early warning system.

on past rainfall-induced landslides is used in the system to define empirical rainfall threshold for the possible occurrence of slope failures. For each rainfall event that has resulted in one or more failures, the information includes (i) the location and time/date of the landslide, and (ii) the rainfall conditions responsible for the failure, including the total event rainfall, the rainfall duration (*D*), and the mean rainfall intensity (*I*). A group of trained geologists and engineers compiled the database searching landslide information in newspapers, technical reports, and blogs. Procedures were established to harmonize the data collection phase, and to evaluate the collected information using pre-defined quality checks.

4 DATA PROCESSING AND ANALYSIS

The system data processing and analysis component (i) defines and validates the empirical rainfall thresholds for possible landslide occurrence, and (ii) matches the rainfall measurements and forecasts against the established thresholds.

4.1 *Definition if rainfall thresholds*

For rainfall-induced landslides, empirical thresholds for the possible initiation of failures may define the rainfall, soil moisture, or hydrological conditions that, when reached or exceeded, are likely to trigger landslides (Guzzetti et al., 2007, 2008, Brunetti et al., 2010). Empirical thresholds are obtained statistically from studying past rainfall events that have resulted in slope failures. SANF exploits mean intensity-duration (*ID*) rainfall thresholds defined adopting an objective statistical technique. For each landslide event in the database, the rainfall duration (*D*) and the rainfall mean intensity (*I*) that have resulted in the slope instability are established analyzing the rainfall record of the most representative rain gauge. Selection of the representative rain gauge depends on the geographic location and distance to the slope failure, and on the location of the rain gauge with respect to local topographical and morphological conditions. For most of the landslides, the representative rain gauge was the closest to the landslide.

To define reproducible, objective and reliable thresholds for possible landslide occurrence, IRPI has devised a specific method. The method assumes that the threshold curve is a power law, $I = \alpha \cdot D^{-\beta}$, where, *I,* is the mean rainfall intensity (in mm/h), *D* is the rainfall duration (in h), and α and β are positive coefficients. The ensemble of rainfall *ID* conditions that have resulted in landslides is fitted with a power law. For each rainfall event, the difference between the event intensity and the intensity of the fit is calculated. The probability density of the distribution of the differences is determined through Kernel Density Estimation, and the result fitted with a Gaussian function. Finally, thresholds corresponding to different exceedance probabilities are defined. Currently, the system uses a single threshold with 1% exceedance probability defined for the entire Italian territory (Fig. 4). Before its use in the early warning system, the rainfall threshold was successfully validated against independent rainfall conditions.

4.2 *Definition of critical levels*

To determine the probability of landslide occurrence, five critical levels are considered adopting a specific probabilistic scheme (Fig. 5). The scheme is based on four exceedance thresholds at 0.005%, 0.5%, 1.5% and 5%. In the scheme, the four thresholds separate five *ID* fields (shown by different tones of grey in Fig. 5). For any given rainfall duration, D, when the (measured or predicted) rainfall mean intensity, *I,* is lower than the 0.005% threshold, the rainfall condition is considered "well below the threshold" (level 1). Similarly, when the rainfall mean-intensity, *I,* is between the 0.005% and the 0.5% thresholds, the rainfall condition is considered "below the threshold" (level 2). When the rainfall mean intensity, *I,* is in the range between the 0.5% and the 1.5% thresholds or in the range between the 1.5% and the 5% thresholds, the rainfall condition is considered "on the threshold" (level 3) or "above the threshold" (level 4), respectively. Lastly, when the rainfall mean intensity, *I,* is equal to, or larger than, the upper 5% threshold, the rainfall condition is considered "well above the threshold" (level 5). In this area, landslides are typically expected, with a chance of false negatives of 5.0%, or more.

Every 12 hours, for each rain gauge, critical levels for the available rainfall measurements and rainfall forecasts are calculated. The critical levels for the rainfall measurements are calculated using the antecedent rainfall measured at durations of 24, 48, 72, and 96 hours (Fig. 6A). Levels obtained from the comparison of the measured rainfall (for each duration) and the corresponding values on the rainfall thresholds (L_{-24}, L_{-48}, L_{-72}, and L_{-96}) are combined to calculate the resulting critical level (*Ls*). If the level obtained for the antecedent 24-hour rainfall (L_{-24}) is larger than the other levels, then the L_{-24} is taken as the critical level. Else, the critical level is obtained through a weighted mean of the four levels:

$$L_S = \frac{W_{24}L_{-24} + W_{48}L_{-48} + W_{72}L_{-72} + W_{96}L_{-96}}{W_{24} + W_{48} + W_{72} + W_{96}} \quad (1)$$

In Equation (1), the weights (W_i) decrease linearly with the duration of the considered antecedent periods.

The rain gauge critical level for rainfall forecasts is obtained in a similar way, using the forecasted rainfall at 24 and 48 hours (Fig. 6B):

$$L_S = \frac{W_{48}L_{+24} + W_{24}L_{+48}}{W_{24} + W_{48}} \quad (2)$$

The National Department for Civil Protection (DPC) has subdivided the Italian territory in 129 alert zones. Critical levels of rain gauges belonging

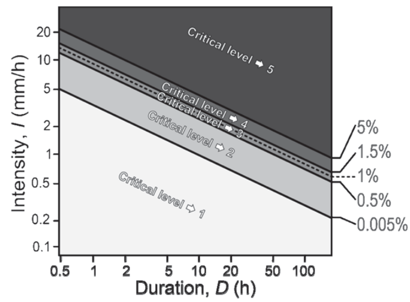

Figure 5. Intensity-Duration (*ID*) fields corresponding to five critical levels. *ID* fields are delimited by rainfall thresholds defined for different exceedance probabilities: 0.005%, 0.5%, 1.5% and 5% (solid lines). Dashed black line is the rainfall threshold at 1% exceedance probability.

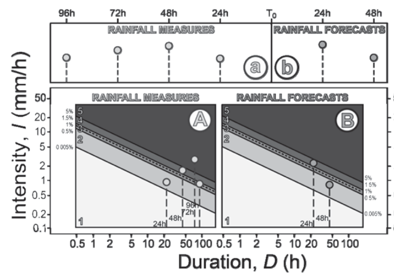

Figure 6. Example of rainfall intensity-duration conditions used for the calculation of rain gauges critical levels (*Ls*) using rainfall measures (A) and rainfall forecasts (B). (a) Periods considered for the calculation of *Ls* using rainfall measures. (b) Periods considered for the calculation of *Ls* using rainfall forecasts.

to the same ale rt zone are aggregated to define alert zone critical levels. The system uses two different aggregation criteria, based on the maximum and the modal values, respectively. Following the first criteria, the system assigns to the alert zone the highest level among those reached by rain gauges in the alert zone. Using the second criteria, the system assigns to the alert zone the most frequent (modal) level among those reached by rain gauges in the zone.

5 DELIVERY OF LANDSLIDE FORECASTS

The early warning system computes critical levels for each rain gauge and for each alert zone every 12 hours. When the critical levels are determined, the system generates synoptic-scale maps of critical levels for the possible occurrence of rainfall-induced landslides in Italy. Maps are prepared exploiting a specific spatial data infrastructure

Figure 7. The SANF early warning system main interface.

(SDI) as OGC vector (WFS) and raster (WMS) web services. The maps (i.e., the services) can be consulted using both open source and proprietary software (e.g., Quantum GIS, ESRI ArcMap). For convenience, the services were integrated in a dedicated WebGIS interface (Fig. 7) that provides tools for viewing, querying, and filtering the maps and data. The WebGIS interface allows for the visualization of landslide synoptic maps, including landslide inventory maps, landslide hazard maps, and landslide and flood risk maps.

Once a day, a specific procedure generates a summary report (in PDF format) containing, for both rainfall measurements and rainfall forecasts, a map showing the rain gauge critical levels, and two maps showing the alert zone critical levels (maximum and modal). The report is delivered via e-mail to the Italian National Department for Civil Protection.

6 DISCUSSION AND CONCLUSIONS

The SANF early warning system for the forecast of the possible occurrence of rainfall-induced landslides in Italy has been operational for two years (since October 2009). The system is based on the comparison between rainfall measurements and forecasts, and empirical rainfall thresholds. Twice a day, the system generates maps of landslide critical levels calculated for each rain gauge within a national network and for each alert zone in Italy. Forecast maps are generated as standard OGC web services and integrated in a dedicated Web GIS environment (Fig. 7). A daily bulletin summarizing national and regional information is prepared and delivered to the Civil Protection authorities.

Validation is a key part of the system, but is difficult to perform and the results remain uncertain. Further validation of the rainfall thresholds, and of the system algorithms is required. The rainfall ID threshold currently used in the system was validated using a reduced set of independent landslide information for a six-month period in the Abruzzo region. Activities for the collection of data on landslide spatial and temporal occurrence are in progress. The data will allow for a better validation of the system forecasts. The same data will also be used to define new regional and local empirical rainfall thresholds for possible landslide occurrence.

REFERENCES

Brunetti, M.T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D. & Guzzetti, F. 2010. Rainfall thresholds for the possible occurrence of landslides in Italy. *Natural Hazards and Earth System Sciences* 10: 447–458.

Guzzetti, F., Peruccacci, S., Rossi, M. & Stark, C.P. 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorology and Atmospheric Physics* 98: 239–267.

Guzzetti, F., Peruccacci, S., Rossi, M. & Stark, C.P. 2008. The rainfall intensity-duration control of shallow landslides and debris flows: an update. *Landslides* 5(1): 3–17.

Salvati, P., Bianchi, C., Rossi, M. & Guzzetti, F. 2010. Societal landslide and flood risk in Italy. *Natural Hazards and Earth System Sciences* 10: 465–483.