1 Introduction

The Lombardy region is highly sensitive to natural instability processes: it's the Italian region with the highest number of municipalities subject to landslide risk, mostly in mountain areas, covering more of the 44% of the total surface and including more than 1.2 mln of people. Many serious and widespread hydrogeological phenomena occurred in the last 25 years, causing damages to structures and people (Regione Lombardia-IReR, 2008, 2011).

In order to mitigate the damage and the risk even resulting from intense rainfall, a national decree (DPCM, 2004, February 27th) established the national alerting system, which identified an alerting procedure that allows the Civil Protection to adopt in advance a series of prediction and prevention actions. The national decree was incorporated into regional level through a regional decree (d.g.r. 8753/2008), that identifies the Functional Centre as the reference structure for the alerting system.

The regional Functional Centre (CFMR) is heavily involved to improve forecasting and prevention, thus it has the necessity to maintain a level of knowledge of the phenomena as current as possible, mainly regarding to those responsible for the major risks: in particular muddy-debris flows, that lead to serious damage next to the alluvial fans.

The state of knowledge of these phenomena has increased substantially over the last decades, but they remain difficult to predict: parameters for slope failures are numerous and include, among others, rainfall infiltration, soil characteristics and antecedent moisture conditions depending on the rainfall history (Wieczorek, 1987).

Recognizing rainfall as the main triggering factor, in the literature two approaches have been proposed to evaluate the dependence of landslide occurrence on rainfall measurements (Brunetti et al., 2010):

- the first approach uses process-based models (Montgomery, Dietrich, 1994; Wilson, Wieckzorek, 1995; Iverson, 2000; Papa et al., 2013), based upon physical laws controlling slope instability. Stability conditions are evaluated relying on static models, whose equilibrium is calculated along a potential slip surface (usually assumed as planar and parallel to the topographic surface, set at a fixed depth). The pore water pressure can be estimated through different infiltration models.
- the second approach uses empirical thresholds (Caine, 1980; Cancelli, Nova, 1985; Ceriani et al., 1992, 1994; Guzzetti et al., 2007, 2008; Regione Lombardia-IReR, 2011), that define the values of rainfall, soil moisture, or hydrological conditions that, when reached or exceeded, are likely to trigger landslides.

  Rainfall thresholds are defined through statistical analysis of past rainfall events that caused slope failures, and can be classified according to the geographical area (global, national, regional or local) to which they refer, and to the type of rainfall information used to establish the threshold itself (Guzzetti et al., 2007, 2008).

Even though the two approaches are conceptually different, often the resulting thresholds are comparable (Frattini et al., 2009): thus, also due to a broad literature on landslide rainfall thresholds, especially intensity–

duration equations (Caine, 1980; Ceriani et al., 1992, 1994; Guzzetti et al., 2007, 2008; Regione Lombardia-IReR, 2011), the latter are more easy to handle and they are now preferred for the hydrogeological hazard evaluations in Lombardy region.

In the present study we have been working within the second approach and, statistically processing morphological, hydrogeological and land use data from Medium-Low Valtellina (Fig. 0), we derived equations that define thresholds in function of local characteristics.

Moreover, since it is now well established that antecedent rainfall must be taken into account in landslide forecasting, we chose to process observed and forecasted rainfall data by integrating them with the soil characteristics: starting from a modified version (Singh, 1982; Mishra et al., 2004, 2006) of the *Curve Number CN* method (USDA, 1986, 2004), we obtained equations that return the “equivalent rainfall” values.

Comparing this latter quantity with the above thresholds, we developed an early warning system useful within the alerting procedure: in the following paper, in order to obtain clear examples, we have chosen to make the approximation to extend the results obtained on the study area to the whole alpine and prealpine areas of the region.

2 Study area

The Lombardy region, with a total surface of 23856 km², is characterized by a wide plain area (46.9%), a hilly prealpine area (12.5%) and a mountain area (40.6%).

The northern Alpine region has a significantly complex and detailed geomorphological pattern. The geology of Alps is rather complex (Regione Lombardia-IRer, 2008, 2011), but the tectonic structure is similar to other continental collision chains. A geological subdivision of the Alps can be defined considering the location of the major structural elements with respect to the Insubric (or Periadriatic) suture/shear Line, the main regional tectonic lineation, with a prevailing west-est orientation, that represents the contact surface between the old Adria and Eurasia tectonic plates:

- south of the Line: the folded and overthrust units of the Southern Alps are predominant;
- north of the Line: we can recognize three major paleogeographic domains, characterized by different degree of metamorphism: Helvetic (with rocks from the European plate), Austroalpine (with rocks from the Apulian plate) and Pennidic (with rocks resulting from an old oceanic sedimentation basin, placed between the previous two areas).

Valtellina, valley of the River Adda and one of the main Alpine valleys, following the Insubric Line, is parallel to the alpine ridge. It has undergone an evident glacial erosion, which created wide and deep profiles, so that the altitude of the bottom of the valley itself is singularly limited: Sondrio, at the center of Valtellina, is only 293 m above the sea level. The entire valley is 120 km long and 66 km wide (Fig. 0).

The rainfall regime of Lombardy is moderately continental in the southern plain area, whereas the northern mountain area has a proper alpine climate.

In the plains the temperature presents an important annual excursion (+24° C in July, +1° C in January), with the maximum values towards the south-eastern part of the region. In the prealpine area, temperatures are influenced by the transition between the plain area and the Alps, except for the lake areas, where the mass of water plays a significant mitigating role (January averages are seldom below the +3/+4 °C). The climate is mild at the bottom of the main Alpine valleys; while in the mountains, with strong variations linked to altimetry, morphology and exposure, is rather cold (typical averages: -10° C in January, +7° C in July).

Rainfall precipitation is higher on the prealpine area, up to a maximum of about 2000 mm/year, more frequent in April-May and October-November (snowy periods are limited to 3-8 days per year); and decreases towards the south east of the region, where the minimum average values are observed (Mantua, 685 mm/year). In the mountains the rainfall is generally lower, mainly concentrated in July-August and characterized by frequent storms (high precipitation intensity and short time duration).

In the mountain areas, the two predominant types of rainfall events responsible in the triggering of muddy debris flows (Regione Lombardia-IRer, 2008, 2011) are:

- rainfall events distributed in more consecutive days: they are generally linked to west-est moving depressions and they take origin from the contrast of warm air masses of tropical origin with masses of cold air from the high latitudes. These cyclonic rains are more likely to hit the mountain basins, during the spring and autumn, and are uniformly spread (Barry et al., 1998; Greppi, 2005; Pinna, 1977).
- short and intense rainfall events: these storms, typical of the summer season, are often generated from the sliding of cold air layers over hot air layers, that (especially during the late afternoon) are next to the soil surface; this anomalous situation is soon reversed, because the heavier cold air tends to fall, reaching the ground and forcing the hot air to rise (even in a violent way) and creating perturbations, sometimes in the form of hail (Pinna, 1977; WMO, 2003). These intense events usually have effect on limited areas (sometimes only hundreds of m^2) and are often favored by local conditions (topography, contrast between sunny and shady slopes, etc).

Figure 0

Study area (Medium-Low Valtellina), evidenced in the national and regional context, with the positioning of the 52 studied landslide events.