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The DEFENSE (debris Flows triggEred by storms – nowcasting system): An early warning system for torrential processes by radar storm tracking using a Geographic Information System (GIS)

Davide Tiranti [a,*], Roberto Cremonini [a,c], Federica Marco [b], Armando Riccardo Gaeta [a], Secondo Barbero [a]

[a] Regional Agency for Environmental Protection of Piemonte, Department of Forecasting Systems, Torino, Italy
[b] Regional Agency for Environmental Protection of Piemonte, Department of Geology and Geohazards, Torino, Italy
[c] Univeristy of Helsinki, Department of Physics, Helsinki, Finland

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ABSTRACT

Debris flows, responsible for economic losses and occasionally casualties in the alpine region, are mainly triggered by heavy rains characterized by hourly peaks of varying intensity, depending on the features of the basin under consideration. By integrating a recent classification of alpine basins with the radar storm tracking method, an innovative early warning system called DEFENSE (DEbris Flows triggEred by storms – Nowcasting SystEm) was developed using a Geographical Information System (GIS). Alpine catchments were classified into three main classes based on the weathering capacity of the bedrock into clay or clay-like minerals, the amount of which, in unconsolidated material, directly influences the debris flow rheology, and thus the sedimentary processes, the alluvial fan architecture, as well as the triggering frequency and seasonal occurrence probability of debris flows. Storms were identified and tracked by processing weather radar observations; subsequently, rainfall intensities and storm severity were estimated over each classified basin. Due to rainfall threshold values determined for each basin class, based on statistical analysis of historical records, an automatic corresponding warning could be issued to municipalities.

1. Introduction

Most geomorphic processes occurring in alpine catchments cause damage and can evolve into alluvial fans. Several studies on hazard and risk analyses associated with these processes in alpine environments have been carried out in the past decades (Govi and Sorzana, 1980; Tropeano et al., 1999; Tropeano and Turconi, 1999; Bardou et al., 2003, 2004; Tropeano et al. 2006; Marchi and D'Agostino, 2004; Bosco et al., 2007; Marchi et al., 2009). In the present study, a new multidisciplinary approach able to characterize the triggering causes of debris flows is proposed, according to previous investigations on characterization of alpine basins and related processes (Moscariello et al., 2002; Tiranti et al., 2008; Pirulli and Marco, 2010; Deangeli et al., 2013). A new basin classification methodology, based on the one by Tiranti et al. (2008), suggested a debris flow initiation in mountainous areas linked to the proper identification of basin characteristics, and in particular the main catchment lithology, in terms of dominant sedimentary processes, debris flow frequency and triggering rainfall characteristics. The initial study (Tiranti et al., 2008), which focused on 12 basins located in a limited area of the upper Susa Valley (Western Alps), proposed a lithological classification that was too schematic, or rather, the textural and compositional variations in each proposed lithological group (schists, carbonates and crystalline rocks) were not considered. For example, in the schist lithological group, the physical/chemical characteristics of a massive, carbonate calc-schist are very different from a phyllosilicatic and foliated calc-schist, despite both being products of clay or clay-like minerals, and the quantity and size of the derivative debris are also variable. Therefore, a new refined research was then applied over the whole Western Italian Alps, with heterogeneous geological and climate contexts; 2100 basins were characterized considering each lithotype of each lithological group; the sedimentological characteristics of debris flow deposits; the geomorphological settings of each basin, channel and alluvial fan; and climatic and historical data (triggering history and related climate conditions). The aim of such analysis was to classify torrential processes by statistical approaches through the understanding of the relationship between debris flow activities, linked to basin features (such as catchment lithology, the shallow deposits

* Corresponding author.
E-mail address: davide.tiranti@arpa.piemonte.it (D. Tiranti).

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distribution and the alluvial fans architecture), and debris flow events triggering rainfall intensity, frequency, sedimentological features and rheological behaviors. The regional application of this method allowed the identification of three basin distinct groups, characterized by different main dominant lithotypes, fan area/basin area (Fa/Ba) ratio, alluvial fan architecture, depositional style and hourly triggering rainfall intensity. Based on these aspects the three basin types are subject to produce debris flow events in response to different rainfall event typologies.

The typical tipping-bucket rain gauge measures rainfall impinging on its 30.5-cm-diameter funnel, in a near-point area of 0.073 m^2, and a sampling resolution of 0.254 mm (Wang and Wolff, 2010). Therefore, rain gauge networks are often inadequate for fully describing convective rainfalls. Several studies have been performed to evaluate the impact of rain gauge network density on modeling prediction (Duncan et al., 1993; Andréassian et al., 2001; Muttiah and Wurbs, 2002). Nowcasting convection in mountainous areas is challenging because of additional difficulties caused by complex orography. Nevertheless, the use of polarimetric weather radars (i.e. systems that transmit electromagnetic pulses simultaneously with vertical and horizontal polarization) can provide reliable real-time rainfall estimation with a high spatial and temporal resolution. An overview of the state-of-the-art on convective storm nowcasting can be found in Wilson et al. (1998, 2004). Nowcasting is defined as a very short-range forecasting (typically from 0 to 3 h ahead), and its achievement requires techniques including detailed analyses of the current meteorological conditions, made possible by fully utilizing all available observations (Browning, 1982). Nowcasting fills the gaps in the Numerical Weather Prediction models (NWP), specifically in the initial period, when their output is still unstable and their skill poor, due to spin-up errors. Arpa Piemonte created a storm nowcasting system based on the TREC technique (Tracking Radar Echoes by Correlation: Rinehart, 1979). The storm cells are localized, and characterized by several parameters derived from radar and satellite data (i.e. maximum echo, storm area, Vertical Integrated Liquid (VIL), cloud top temperature) and finally tracked (Davini et al., 2012). The storm positions and their interaction with alpine basins are then nowcasted by analyzing their previous positions. PostGIS is an extension of a PostgreSQL object-oriented database system that allows storage of Geographical Information System (GIS) objects in the database, and subsequent execution of many geographical operations, such as re-projections and intersections. Taking advantage of the PostGIS, basin- and radar-derived real-time information can be processed. By performing intersections between storm cells, either observed or nowcasted, as well as basins, statistical computations on rainfall field (average rainfall intensities, quantiles) can be derived for each basin. The innovative classification of alpine basins, the weather radar processing oriented to storm cells, and the GIS processing in the PostGIS process, form the original early warning system called DEFENSE (DEbris Flows triggEred by storms – Nowcasting SystEm). Observing and nowcasting heavy and localized rainfall in each basin, DEFENSE is able to predict the basin response to the precipitation and the impact of the resulting debris flow.

1.1. The study area

The territory of the Piemonte region is geomorphologically complex, and is composed of mountains, hills and alluvial plains, showing a concentric structure from the Alps and Apennines towards the Po valley. The Western Alps are characterized by an asymmetric transversal cross-section: the alpine Italian side (internal sector) is shorter and steeper than the external one. In the Piemonte region, the alpine front range shows a transition from plains (elevation range of 200–300 m asl) to mountain reliefs (elevation range of 1000 to 4800 m asl in the axial sector). Alpine valleys show a radial pattern from the western Po Plain, and the major valley systems are deeply incised in their bedrock.

Alpine lithologies record a geological history of about three hundred million years, and can be summarized as being composed of massive gneisses, gneisses and mica-schists, Hercinian and late-Alpine magmatic rocks, ophiolites, calc-schists, marbles, dolostones and limestones, often covered by glacial, alluvial and talus deposits.

The mountainous reliefs in the Piemonte region are subjected to rapid temperature and precipitation changes (Biancotti et al., 1998). There are bimodal annual precipitations with two maxima, in spring and in autumn, and two minima, in winter and in summer.

On the basis of the position of the main minimum, main maximum and secondary maximum, four types of rainfall regimes can be distinguished: three are typically continental, with the main minimum in winter, while the fourth is typically Mediterranean with the main minimum in summer (Biancotti and Bovo, 1998). Furthermore, the following precipitation regimes can be differentiated:

- Prealpine regime: with a main minimum in winter, a main maximum in spring and secondary maximum in autumn, it covers about 58% of the territory and includes the plains (except for the plain of Alessandria), most of the Monferrato hills (part of Tertiary Piemonte Basin – TPB), the plain of Cuneo and the Cottian Alps (except for the upper Susa Valley);
- Subcoastal regime: with a main minimum in summer, a main maximum in autumn and a secondary maximum in spring, it covers nearly 24% of the territory and includes the plain of Alessandria, the low Monferrato and Langhe hills (TPB), part of Maritime Alps and the upper Susa valley (Cottian Alps);
- Subalpine regime: with a main minimum in winter, a main maximum in autumn and a secondary maximum in spring, it covers about 13% of the territory and includes the northern plains and the Pennine and Lepontine Alps;
- Subcontinental regime: with a main minimum in winter, a main maximum in autumn and a secondary maximum in summer, it covers about 5% of the territory in the limited eastern sector of the Lepontine Alps, coinciding with the Lake Maggiore area.

2. Methods and results

In this section, two different approaches relative to a radar storm tracking system and a classification of alpine basins affected by debris flows, are presented. These two independent components have been integrated into an operative tool for the forecasting of debris flows.

2.1. Radar storm tracking

Rain gauge networks often miss localized and intense precipitation events (Duncan et al., 1993), while weather radars allow the monitoring of rainfall over large areas, with a high spatial and temporal resolution, if the radar echo exceeds the minimum detectable signal.

The regional radar network in Piemonte comprises two polarimetric C-band radars: the Bric della Croce radar, placed at 736 m asl, at the summit of the Torino Hill, and the Mt. Settepani radar, located at 1386 m asl, on the Ligurian Apennine.

The radar operational scan volume reaches a range of 170 (136) km for the Bric della Croce (Mt. Settepani) radar with a set of 11 elevations, ranging from -0.1° to 28.5° (0.3° to 28.5°) and