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The Territorial Debris Flow Early Warning System of Piemonte (North-western Italy)

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Abstract. Debris flows are one of the most frequent and dangerous phenomena affecting the Alpine environment; they are responsible of 36% of casualties due to gravitational phenomena in the Italian Alps during the last century. In the Western Italian Alps (Piemonte, Italy) a Territorial Debris Flow Early Warning System (Te-DFEWS) aimed to forecast and predict the occurrence of sediment mass-transport has been developed, based on the characterization of small Alpine catchments (< 50 km^2) and the processes that take place in these. The Te-DFWES is based on the identification of predisposing and triggering factors that determinate debris flow occurrence. The Te-DFEWS operates from 2010 in present-time and nowcasting using weather radar observations as input data. Recently (2021), the Te-DFEWS has been improved extending the forecasting window (up to 48h from simulation) by the introduction of Quantitative Precipitation Estimate/Forecast (QPE/QPF) input from COSMO-2I and ICON-IT, local high-resolution weather models. The Te-DFEWS, named DEFENSE (DEbris Flows triggEred by storms - Nowcasting SystEm) and the related warning procedures are presented as an operational tool integrated in the Regional Warning System for Geo-hydrological and Hydraulic Risk at the Functional Centre of Piemonte, managed by the Regional Agency for Environmental Protection of Piemonte (Arpa Piemonte).

1 INTRODUCTION

Channelized debris flows affect Alpine valleys, causing 36% of casualties by gravitational phenomena in the Italian Alps during the last century and economic losses. In Piemonte (Western Italian Alps) a Te-DFEWS [1] has been developed in 2010 starting from an innovative classification of Alpine catchments and using the precipitation estimates from weather radar as model input to identify the triggering rainfall amount and distribution. In 2021, weather radar rainfall estimates, which provide input for the present-time observation and the nowcasting (rainfall intensity and distribution expected within the next hour), has been completed with the integration of the Quantitative Precipitation Estimate/Forecast (QPE/QPF) from COSMO-2I (the Italian version of the COSMO-MODEL) and ICON-IT (ICOsahedral Nonhydrostatic) high-resolution models to lengthen the forecasting window (next 48h).

The Te-DFEWS is focused on 2100 Alpine catchments classified by the Clay Weathering Index (CWI) based on the propensity of lithologies to produce different quantity of clay or clay-like minerals as loose material that directly affect the behaviour of debris flows (Fig. 1).

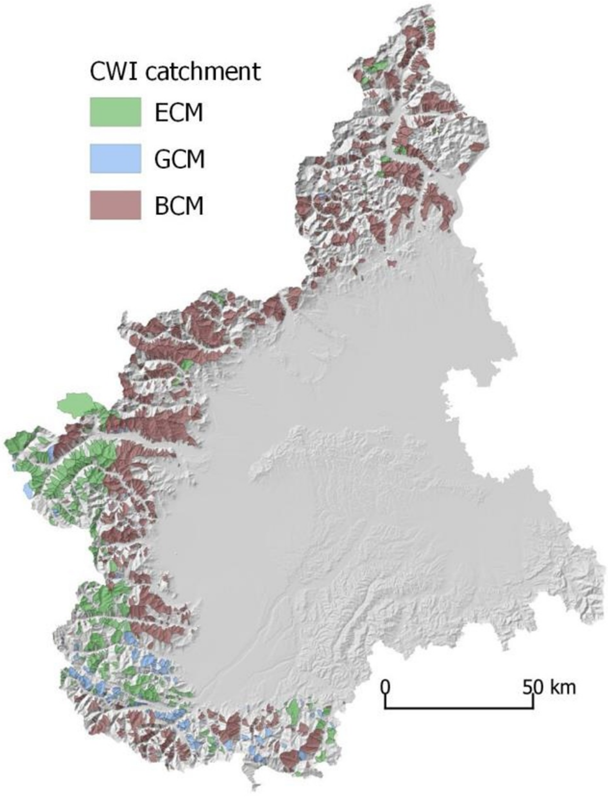

Fig. 1. The 2100 Alpine catchments classified by CWI.

2 The DEFENSE Te-DFEWS

The DEFENSE Te-DFEWS is based on the classification of catchments using the CWI [2], an index used to define the propensity of lithotypes which forming the bedrock of a catchment to produce clay or

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other fine minerals with clay-like rheological behaviour (e.g., phyllosilicates in general). This was based on evidence of the role played by the amount of fine particles in the loose material in the initiation and evolution of debris flows. Through the CWI three types of catchments are distinguished based on the prevailing lithology that forms the catchments' bedrock:

a. Excellent Clay-Maker (ECM) catchments formed mainly by rocks with an excellent propensity to produce clay as loose material, such as thin foliated and/or fine-grained metamorphic rocks or clayey sedimentary rocks.
b. Good Clay-Maker (GCM) catchments formed mainly by rocks with a good propensity to produce clayey silt as loose material, such as massive limestone or dolostones.
c. Bad Clay-Maker (BCM) catchments formed mainly by rocks with a bad propensity to produce clay or clay-like minerals as loose material, such as intrusive igneous rocks or massive and coarse-grained metamorphic rocks.

The three catchment classes show markedly different characteristics in debris flow behaviour and are clearly distinguishable by the sedimentological and morphological characteristics of debris flow deposits and alluvial fans, as shown in Tab. 1 and 2.

Table 1. CWI catchments' behaviour.

CWI class	Dominant rheology - depositional style	Mean triggering occurrence [years]	Rainfall threshold	Main occurrence season
ECM	Cohesive debris flow (viscoplastic) - steep-asymmetrical levee and flat lobe with clay matrix	2	storm of moderate intensity (≥ 20 mm/h)	summer
GCM	Cohesive debris flow (viscoplastic) - flat-symmetrical levee and flat lobe with clayey silt matrix	5	storm of high intensity (≥ 30 mm/h)	late spring-early fall
BCM	Non-cohesive debris flow (frictional/collisional) - levee-like boulder train and fan-lobe with gravel-sand and silty matrix	20	storm of very high intensity (≥ 50 mm/h)	fall and spring (rarely in summer)

Table 2. CWI catchments' alluvial fans characteristics.

CWI class	Alluvial fan/Catchment area ratio [%]	Alluvial fan shape	Alluvial fan surface slope	Alluvial fan grain-size distribution
ECM	5	Strongly irregular	Gentle with irregular distribution of local slope gradients	Regular
GCM	20	Regular fan-shaped	Very gentle with regular distribution of local slope gradients	Regular
BCM	5	Regular lobe-shaped	Very irregular with steep slope in apex zone and flat slope in toe zone	Strongly irregular: grain-size decrease from apex to toe. Grain-size changes are highlighted by morphological steps in longitudinal section.

Moreover, according to [3] they have been divided into catchments capable of generating debris flow or not based on the area ratio of outcropping bedrock vs. plant cover, according to the Fig. 2.

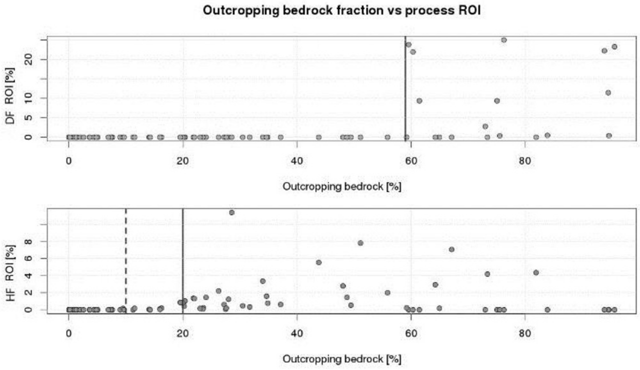

Fig. 2. Outcropping bedrock thresholds for torrential process type. Where: ROI is the Relative Occurrence Index, DF is Debris Flow and HF is Hyperconcentrated Flow (modified from [3]).

It has been demonstrated that the area ratio of outcropping bedrock vs. plant cover, and consequently the capacity of a catchment to generate debris flow, is strongly influenced by the occurrence of wildfires that largely involve a given catchment [4]. In that case, the debris flows' triggering thresholds should be lowered from 20% to 60% compared with the standard values in Tab. 2.

Traditional DFEWSs (Territorial and Local) are usually based on rainfall rate thresholds derived by recording of rain gauges, but rain gauge networks are often inadequate to properly detect rain field in mountain areas [5], especially if thunderstorms happen, even of small size (around 1 km in diameter) and very localized. Operational polarimetric C-band weather radar can provide reliable real-time rainfall estimation with high spatial and temporal resolution. Arpa Piemonte implemented an algorithm for storm identification and tracking using the Tracking Radar Echoes by Correlation (TREC) technique [6]. In this pattern recognition procedure, radar-echo data are stored in arrays, and, on each iteration an array is compared to all other arrays of same size for the subsequent time step to determine which array exhibits the highest correlation with the previous array [7]. In this way, storm cells are localized, classified (e.g., maxima echo, storm area, Vertical Integrated Liquid - VIL) and tracked. Considering the overall path of the storm is possible to forecast the next position of the storm with nowcasting techniques (withing one hour).

Arpa Piemonte has developed since 2005 a WebGIS-based system to disseminate real-time weather radar and weather stations data both for stakeholders and citizens. This application is primarily focused on visualizing meteorological and hydrological data for decision support and situational awareness [8].

Arpa Piemonte moved to a new approach, oriented to real-time analysis and nowcasting derived products, using full GIS functionality by the choice of Linux platform and GFOSS tools. The PostGIS extension allows for the native storage of geometries in the database and allows for various GIS queries to be made between data, including unions, area calculations, and features within. Geometry features can then be displayed by various GIS servers and client applications, allowing the database to act as a backend GeoSpatial database for GIS servers.

Storms, represented by ellipses that reproduces their real size, with their parameters e.g., area, VIL, mean and maximum reflectivity, cloud top, lifetime) and paths are stored in the PostgreSQL/PostGIS database, where catchments polygons are also stored, using Python scripts. Storm cells, with enough intensity to exceed the debris flows trigger thresholds, that are intersecting or will intersect the polygons representing the catchments in the next 60 minutes, are identified and a warning is automatically displayed on the WebGIS interface (Fig. 3) and issued by e-mail to the regional EWS operators and stakeholders.

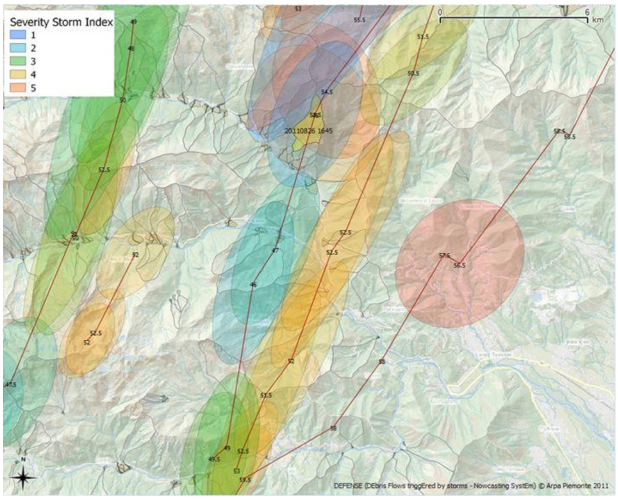

Fig. 3. DEFENSE WebGIS interface: storm cells are represented by coloured ellipses, according to their severity (instantaneous intensity), red lines are storms' paths, numbers at the ellipses' centroids are the reflectivity values (dBZ) estimate by weather radar; catchments delimitation are represented in black, alluvial fans as beige polygons.

Regarding the shorth-medium forecast (from 2 to 48 hours), recently (2021) the Te-DFEWS DEFENSE has been improved with a new input module for QPE and QPF, deriving from COSMO-2I high-resolution meteorological model (00 UTC run) interpolated over the catchments' areas. The model itself is experimenting a transition toward ICON-IT model and will further migrate under the new framework.

Some verifications have been done over significant case studies, showing a discreet predicting potential of the technique; verifications were mainly carried out using fuzzy verification strategies [9] and plotting general scores like FSS (Fraction Skill Score) [10].

CWI catchments have been inscribed in larger areas (Macrobasins) where the quantitative rainfall forecast is interpolated. For each Macrobasin a set of thresholds are assigned, depending on the CWI catchments classes included in the Macrobasin (Fig. 4).

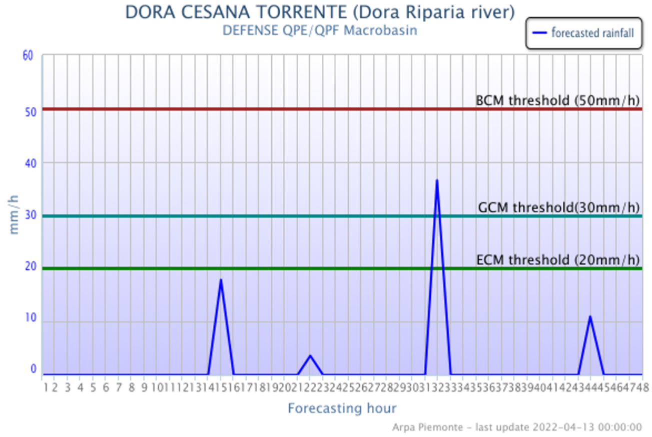

Fig. 4. Example of CWI triggering thresholds within a Macrobasin.

When one or more thresholds are exceeded in one or more Macrobasins a warning is issued in the same way previously described. Grouping of individual catchments into Macrobasins was adopted to meet the spatial resolution of the COSMO-2I and ICON-IT models, which is lower than that obtained from weather radar estimates, and to better synthesise and visualize the warning scenarios by an interactive bulletin on the Arpa Piemonte's institutional website.

3 Conclusions

The DEFENSE Te-DFEWS has been described as an example of regional EWS that tries to integrate in the most comprehensive way all the predisposing and triggering factors for debris flow occurrence in small Alpine catchments. The presented methodology, adopted to forecast and predict the debris flows triggering considering the characteristics of each catchment and related processes that in these take place, has demonstrated that the prediction of debris flows is not linked to the identification of rainfall thresholds with generic value effective for all the catchments. On the contrary, the triggering thresholds must be determined taking into consideration the greater number of aspects that distinguish a given catchment, which *de facto* represent the set of predisposing factors that drive the occurrence of debris flows and their features. In this paper it was also pointed out that it is extremely important to choose the most suitable tool to observe and forecast the initiating causes (rainfall, in this specific case) and understanding which types of rainfall are most effective in determining the critical conditions for the triggering of such phenomena. On the conceptual model, an operational Te-DFEWS has been developed aimed to predict the likely occurrence of a debris flow at different time scales (present-time, nowcasting and short-medium forecast period) using diversified approaches and input sources for each time scale to ensure the best system performance. The Te-DFEWS has been realized to be upgradable, easy to check through a user-friendly WebGIS interface accessible at any time and from any device (smartphones, tablets and computers with every operating system and web browser). The automatic warnings issued when thresholds are exceeded, via the WebGIS interface, via e-mail and through an interactive bulletin published on the institutional site, also contribute to make this EWS an effective and indispensable tool for the mitigation of the hazard and risk induced by debris flows at regional scale. An exhaustive evaluation of the Te-DFEWS performance (missed and false alarms quantification) is still under analysis, considering the youth of this EWS in its last updated version (2021).

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