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Slope – catchment area relationship for debris-flow source area identification

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Abstract— **Classification of the source areas of debris flow, mud flows, debris avalanches is fundamental for the zonation of the territory susceptibility to the propagation of these type of landslide phenomena. Here we describe and discuss the data and the methods adopted to derive empirical equations useful to identify and to classify the possible source areas of fast moving landslides at regional and national scale in Italy. The empirical equations were derived based on a large catalogue of debris flows and the fitting of quantile regression curves. We used a 10m resolution DEM and an inventory of more than 4000 landslides distributed on three different Italian regions. Results highlight that differences exist between the equation parameters derived for confined and unconfined debris-flows.**

I. Introduction

In a recent review paper, [1] defines debris flow as a "*Very rapid to extremely rapid surging flow of saturated debris in a steep channel. Strong entrainment of material and water from the flow path*". Here, with the term debris flow we refer to the general class of flow-like landslides including also mud-flows and debris-avalanches.

Location of the debris flows initiation zones depends on multiple factors such as geomechanic characteristics of the potentially entrained material [2], erosion of the channel banks [3], wildfire occurrence [4], effect of forest harvesting [5] which are hard to collect at regional or national scale.

Many authors demonstrated a relationship between geomorphometric parameters and debris-flow source areas (e.g [6–10]) and in particular terrain slope and flow accumulation seem to play a relevant role in defining the possible initiation zone for the debris flows. Previous research has established also a distinction between channelized and hillslope (confined or unconfined) debris flows, i.e. between phenomena occurring within incised channels or on slopes made by unconsolidated sediments ([8,11–15].

In the framework of a project aimed at defining the areas prone to debris-flow propagation at national scale, we designed a preliminary procedure to identify and to classify the possible debris-flow source areas (initiation zones) only based on the analysis of geomorphometric information. Procedure is based on the analysis of the geomorphometric characteristic of the landslides source areas available for three large areas in the north, south and central Italy. Here, besides describing the research settings and the input data, we discuss the results.

II. Data

The research data used for this study are a Digital Elevation Model (DEM) and a debris-flow inventory map.

The used DEM is the Tinitaly DTM [16,17] with a ground resolution of 10 m × 10 m, and projection UTM WGS 84 zone 32N (EPSG:32632). It is the most detailed DEM available for the whole country. [16] describe the uncertainties and inhomogeneity present within the final product. The DEM was produced through the integration of all the topographic data available in Italy starting at least from the 1:25000 scale. Therefore, intuitively, the DEM reflects the quality and, above all, the spatial resolution of the input data used. In particular, it should be noted that where the available topographic cartography is made up of poorly detailed data, the listed points subsequently interpolated by triangulation are very scattered. Consequently, the triangle areas (TIN) resulting from the triangulation carried out in areas such as the one just described are significantly larger than the area of a final DEM cell (100 m^2). Arguably, topographic information in regions where the average value of the TIN area is significantly higher than the TINITALY cell area may be affected by locally important errors such as excessive generalizations and artifacts that can cause errors in the experiment. However [16] demonstrated that very high values of the triangle areas are expected in the flat (alluvial plains) areas, which are not interesting for the present study. Clearly, this problem remains where such excessive generalizations occur in non-flat areas.

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Debris-flow inventory maps, were carried out through geomorphological studies based on comparative analysis of stereoscopic aerial images taken in different years, associated with targeted or diffuse (depending on the working scale) field surveys.

Figure 1 shows the location of the debris-flow inventory maps produced by IRPI and used for the purpose of this work.

The inventory maps cover a total territory of 10,948 km^2, ~3% of the national territory and count 4004 polygons. We acknowledge that the original inventory was made of lines, which were buffered of 20 meters to account for small inaccuracies due to the mismatch between the debris-flow geometries and the DEM. Even if other inventories are available for the Italian territory (e.g. the Italian IFFI catalogue [18] or the Valle d'Aosta inventory [19]), only this inventory was used to perform the experiment, since for it we have full consciousness of the implementation techniques, methodologies and data used, and therefore of its limits and its potential.

III. METHODS

According to the literature, we considered the channelized and the hillslope debris-flows and we analyzed separately the three different areas in the north (Lombardy), south (Sicily) and center (Umbria) of Italy.

A. Hillslope and channelized debris flows

The classification of the inventory polygons into channelized and open slope debris-flow was based on the usage of a slope units maps available for the entire country [20]. Slope units are mapping units delimited by drainage and divide lines and are portions of terrain, defined by the general requirement of maximizing homogeneity within a single unit and heterogeneity between different ones [21]. The spatial intersection (∩) between vector

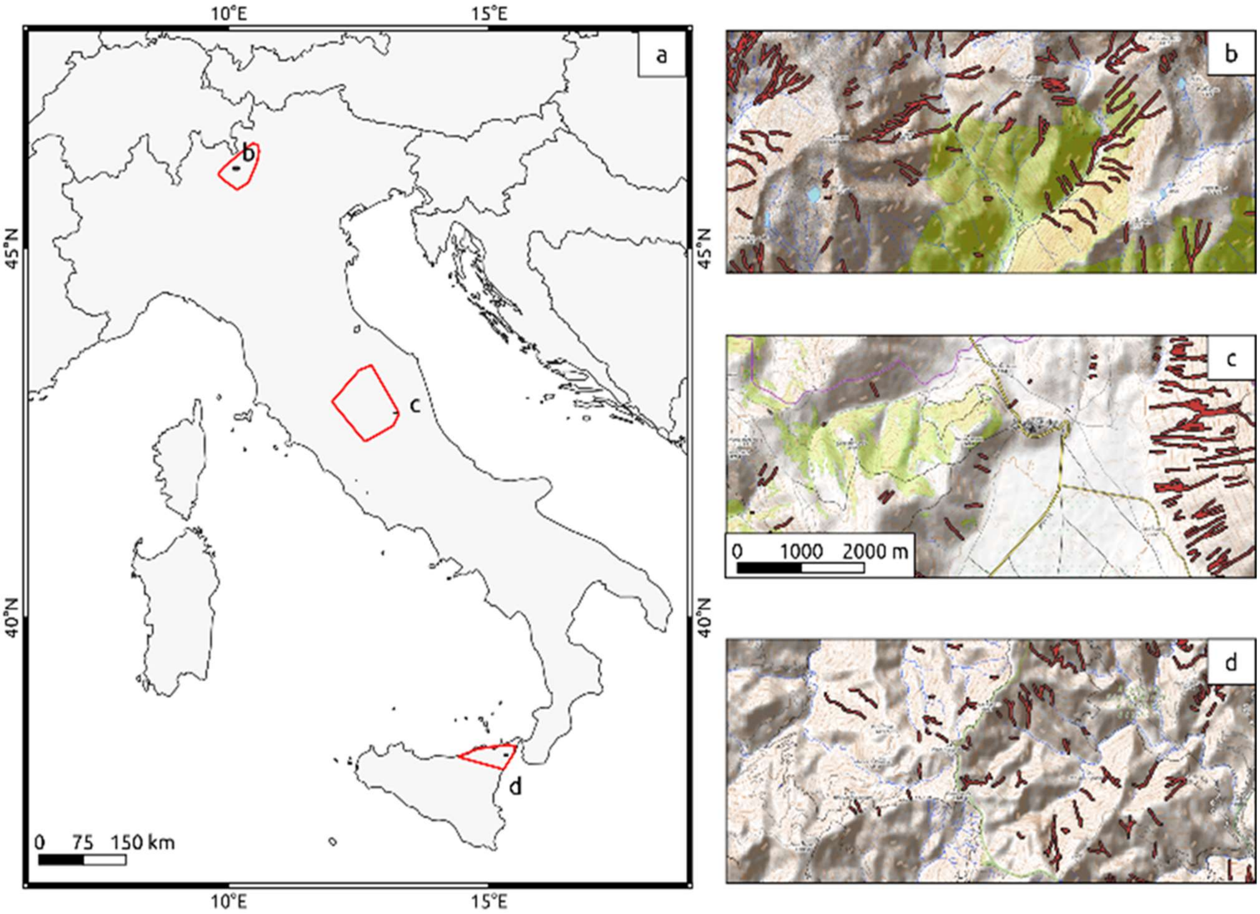

Figure 1. a) convex hull of the debris-flow inventory maps. b). c), d) insets showing details of the inventory

cartography of slope-units and landslide inventories produces a new cartography of vector polygons. Reason is due to the fact that, where the limits of the slope units (typically the drainage lines) intersect those of the polygons representing the debris flows, the latter are split. Landslides completely included inside the slope units, on the other hand, maintain their original geometry. The analysis of the ratio (A_{ratio}) between the areas of the polygons resulting from the aforementioned intersection and the areas of the corresponding landslide polygons in the original inventories, allows to identify polygons which are split by the intersection process and that, as a consequence, are located in the valleys delimiting the slope units. These original polygons are classified as channelized debris flows. More in detail it is assumed that a polygon corresponds to a channeled debris flow if the $A_{ratio} < 0.95$, otherwise it is assumed that it represents a hillslope debris flow.

B. Statistical model for the classification of the source areas of debris flows

The channelized and hillslope debris flow inventory is used to derive a statistical model aimed to assign, to each cell a value that expresses, in terms of probability, the propensity of that pixel (cell) to be a source area of debris flows.

The approach used is based on the assumption that the uppermost portion of the polygons representing the debris flows (in the inventories), can be considered their source areas. In particular, the procedure is based on the following steps: (i) identification of the uppermost portion of each polygon (cells where the elevation non-exceedance probability is larger than 90%), (ii) calculation of slope (β) and flow accumulation (*A*) for those cells, (iii) exclusion of cells having flow accumulation smaller than 500 m^2 (selecting only those cells that receive a given surface runoff), (iv) linear quantile regression in the bi-logarithmic scale log(tan(β)) and log(*A*), assuming a power law equation.

$$tan(\beta)=c*A^b$$

where c and b are the coefficient and the exponent of the power law, and are calibrated by a quantile regression. Six quantile regression lines were derived for the following percentiles: 5%, 10%, 25%, 75%, 90%, 95%. These linear functions are indicated as follows $\beta_{05}(A)$, $\beta_{10}(A)$, $\beta_{25}(A)$, $\beta_{75}(A)$, $\beta_{90}(A)$, $\beta_{95}(A)$ and shown in Figure 2 for the different study areas and the channelized and hillslope debris flows.

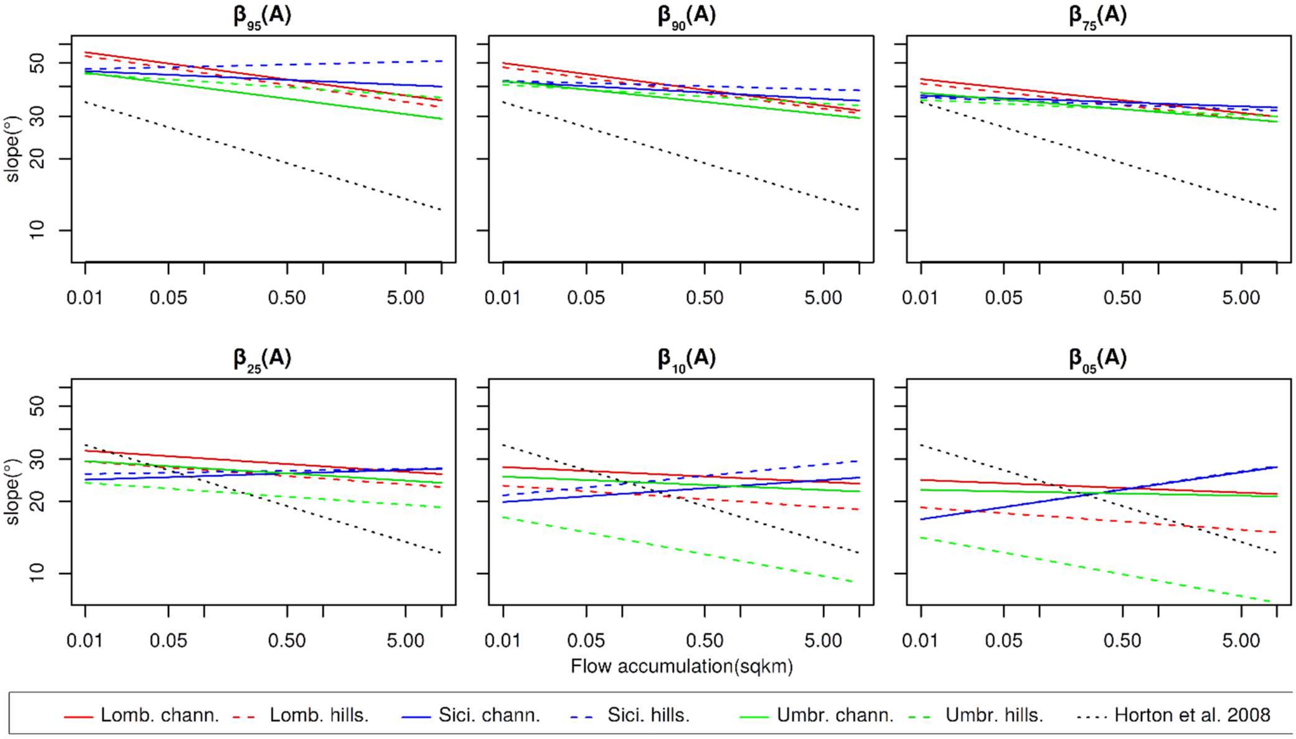

Figure 2. Quantile regression functions for the different study areas and the channelized and hillslope debris flows.

IV. RESULTS AND CONCLUSIONS

Figure 2 shows that the trend of the quantile linear functions derived for Lombardy and Umbria is similar to that observed by other authors [9,22]: debris flow source areas are located on steep areas when the flow accumulation area is small, while they may also be present in less sloping areas when the flow accumulation area is larger. The $\beta_{95}(A)$ and $\beta_{05}(A)$ functions shows that the source areas of debris flows tend to be absent on both low slope and high slope areas. Reasons for not observing source areas in flat zones is trivial. In very steep zones, instead, the cause of the scarce presence of initiation zones is (at least partly) imputable to the fact that debris flows mobilize unconsolidated materials that can hardly be found on steeply sloping areas.

Interestingly, we observe that for quantiles 75, 25, 10 and 5, the channelized functions always return higher values than those obtained for the hillslope functions. A possible explanation for this might be that channel sediments offer more resistance to be entrained, by drag force exerted by the flowing surface water, as opposed to the unconsolidated sediments lying on the slopes.

For the Sicilian inventory, a poorer correlation between slope and flow accumulation areas is observed. Here, the location of the debris flow source areas seems to be independent from the flow accumulation value.

Figure 2 also portrays, for reference, the equation, proposed by [9] and used by [22], which was derived as a lower limit boundary for the data collected by the authors. Even if the slope coefficient of this equation is markedly different from any of the functions derived in the present work, we observe that it only intersects the $\beta_{05}(A)$, $\beta_{10}(A)$, $\beta_{25}(A)$ functions which represent different realizations of the lower limit of the data used in the present work.

We acknowledge that not all the areas resulting by the application of the quantile functions can be considered as initiation zones since actually they also depend on other factors (see Section 1) which are not considered in the present study. However, this study provides results (functions) that can be used to conservatively identify and classify the portions of the territory which net of other factors, can be considered more prone to trigger rapid-moving landslides.

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