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GIS tools for preliminary debris-flow assessment at regional scale

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Abstract: The assessment of the areas endangered by debris flows is a major issue in the context of mountain watershed management. Depending on the scale of analysis, different methods are required for the assessment of the areas exposed to debris flows. While 2-D numerical models are advised for detailed mapping of inundation areas on individual alluvial fans, preliminary recognition of hazard areas at the regional scale can be adequately performed by less data-demanding methods, which enable priority ranking of channels and alluvial fans at risk by debris flows. This contribution focuses on a simple and fast procedure that has been implemented for regional-scale identification of debris-flow prone channels and prioritization of the related alluvial fans. The methodology is based on the analysis of morphometric parameters derived from Digital Elevation Models (DEMs). Potential initiation sites of debris flows are identified as the DEM cells that exceed a threshold of slope-dependent contributing area. Channel reaches corresponding to debris flows propagation, deceleration and stopping conditions are derived from thresholds of local slope. An analysis of longitudinal profiles is used for the computation of the runout distance of debris flows. Information on erosion-resistant bedrock channels and sediment availability surveyed in the field are taken into account in the applications. A set of software tools was developed and made available (https://github.com/HydrogeomorphologyTools) to facilitate the application of the procedure. This approach, which has been extensively validated by means of field checks, has been extensively applied in the eastern Italian Alps. This contribution discusses potential and limitations of the method in the frame of the management of small mountain watersheds.

Keywords: Debris flow; Geographic information system; Digital elevation models; Runout; Alluvial fan; Watershed management; Geomorphometry

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Introduction

Debris flows are widespread in small steep headwater watersheds under different climates and are responsible for major damage when they encroach transport routes or urban areas. The hazards related to debris flows are thus a major concern for the safety of settlements, roads, and railways in mountainous regions. A wide range of methods for recognizing the possible occurrence of debris flows and mapping the areas at risk have been developed as a prerequisite for the implementation of structural and non-structural control measures.

The identification of the catchments and alluvial fans prone to debris-flow occurrence can be performed on the basis of data from historical archives (Barnikel and Becht 2003; Marchi and Cavalli 2007; D'Agostino 2013), dendrogeochronological methods, which enable also the evaluation of event frequency (Strunk 1989; Bollschweiler et al. 2007; Stoffel 2010), morphometric settings (Bertrand et al. 2013, and references therein), and combined methods (Jomelli et al. 2003).

A further step toward hazard assessment is the rating and ranking of the areas at risk by floods with intense bedload and debris flows on alluvial fans at the outlet of mountain streams. Amongst the first methods aimed at this task, we remind the method by Aulitzky (1972, 1994), based on a check list of queries related to fan slope, topographic settings of the channel, the particle size of transported sediment, and land use. The inquiry of field conditions is still valuable for preliminary recognition of expected flow processes on alluvial fans under paroxysmal conditions, especially with regard to the basic differentiation between bedload and debris flow. However, this approach is increasingly being coupled or even replaced by numerical methods, of different complexity, which simulate the triggering, propagation, and deposition of debris flows.

These methods range from simple topography-based indices to sophisticated, physically-based numerical models (Hungr 1995; Rosatti and Begnudelli 2013; Mergili et al. 2017) capable of simulating the dynamics of debris flows, including sediment entrainment, which is of utmost importance, especially if the simulation involves erodible channel reaches upstream of the distal deposition areas. Simplified GIS-based conceptual models (Gruber et al. 2009; Horton et al. 2013; Huggel et al. 2003; Mergili et al. 2015) lie between the two end terms of topography-based indices and physically-based models. The choice of the methods depends on the spatial scale of the analysis and on the objectives of the assessment, the two aspects being often linked. Typically, physically based models are preferred for detailed analysis of specific cases, when the required information for input parametrization is available. Given the process complexity and the uncertainty affecting the input parameters, GIS-based simplified conceptual models may be preferred to identify potential impact areas at large and regional scale. Huggel et al. (2003) developed two regional-scale GIS-models, Modified Single Flow (MSF) and Multiple Flow (MF), based on single- and multiple-flow direction approaches, respectively, to simulate the debris flows from lake outburst. Debris-flow propagation is expressed with relative probability values indicating the hazard potential at a certain location. More recently, Horton et al. (2013) developed Flow-R, a distributed empirical model for regional debris-flow susceptibility assessment. Flow-R requires essentially a Digital Elevation Model (DEM) and implements several algorithms for the automatic delineation of source areas and for the estimation of affected areas. Constrained random walks for routing mass points through a DEM until reaching the selected stopping criterion are implemented in GRASS GIS by Mergili et al. (2015).

The present study develops a GIS-based procedure implemented in a set of tools for the identification of mountain channels potentially affected by debris flows and for the evaluation of the priority of analysis of alluvial fans. The procedure has limited data requirements and is aimed at the fast application at the regional scale. Differently from the conceptually similar GIS-based models mentioned above, the proposed procedure does not provide information on the potential inundation area but enables the characterization of mountain channels with regard to debris-flow dynamics. The methodology can be easily integrated with other informative layers related to geolithological settings and land use to overcome the limitations related to the topography-based approach.

1 Methods

1.1 Procedure

The developed procedure starts with three steps based on the exploitation of a DEM: i) derivation of the channel network, ii) identification of debris-flow initiation areas, iii) assessment of channel reaches prone to the propagation, deceleration, and stopping of a potential debris flow. The overall workflow is shown in Figure 1. The only required input is the DEM, and thus the proposed workflow must be considered as a purely morphometric approach intended to provide a fast characterization of the topographic controls on the debris-flow process.

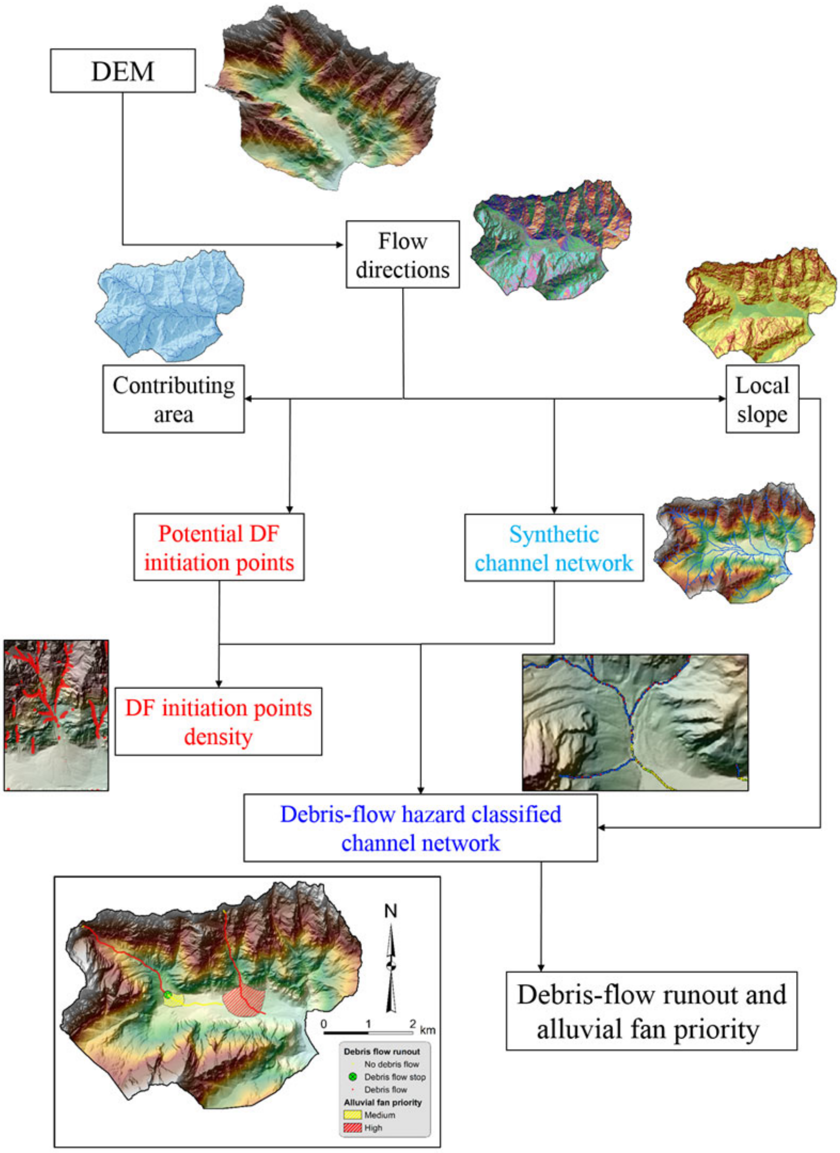

Figure 1 Workflow of the GIS procedure (DEM, Digital Elevation Model; DF, Debris flow).

Different algorithms for channel network derivation have been developed and are available in both commercial and open source GIS software. They can be grouped into three main approaches: drainage area constant threshold (O'Callaghan and Mark 1984), slope-area threshold (Montgomery and Dietrich 1992; Montgomery and Foufoula-Georgiou 1993; Desmet et al. 1999) and curvature based (Tarboton and Ames 2001; Sofia et al. 2011; Cavalli et al. 2013). In the developed workflow a slope-area approach based on the Stream Power Index (*SPI*), proposed by Marchi and Dalla Fontana (2005), is chosen in order to derive the synthetic channel network from the DEM of the area under study, *SPI* is computed as:

$$SPI = A^{0.5}\,S \qquad (1)$$

where A is the drainage area (m^2), computed on the basis of flow directions derived with the D8 single flow algorithm (O'Callaghan and Mark 1984) from the hydrologically correct DEM, and S (m/m) the local slope, calculated as the ratio between the difference in elevation and the distance between the given cell and the cell in the direction of steepest descent (Vianello et al. 2009). Potential channel heads are identified as raster cells falling within areas of topographic convergence and having an *SPI* exceeding a threshold value that should be determined based on field observations and visual comparison with the real drainage network density. *SPI* represents a sound indicator of the topographic control on the potential intensity of erosional and sediment transport processes and, for this reason, it was preferred to other methods for channel network extraction.

The potential debris-flow source areas are also identified by means of a slope-dependent threshold of contributing area. To this end, similarly to the models proposed by Wichmann and Becht (2005) and Horton et al. (2013), an empirical relationship between drainage area and slope derived by Zimmermann et al. (1987) based on several debris-flow events occurred in Switzerland is applied:

$$S = 0.32\,A^{-0.2} \tag{2}$$

where A is the drainage area (m^2) and S the slope (m/m) calculated for each DEM cells following the same methodologies used in Eq. (1). A study by Kaless (2006) compared the area-slope threshold defined by Eq. (2) with a relationship derived using drainage area and slope values of debris-flow triggering areas in several catchments of the Autonomous Province of Trento (northern Italy). The results of this study confirm the validity of Eq. (2) also for the morphoclimatic contexts of the eastern Italian Alps. Cells of the DEM with a slope exceeding the values identified by Eq.(2) are classified as potential debris-flow initiation sites. Furthermore, an upper threshold of the local slope is set to 38°, the approximate value of the angle of internal friction of the material usually present at the sources of debris flow in alpine environments. This assumption is intended to filter out potential initiation cells falling in very steep areas where sediment availability is most likely low or negligible. An upper drainage area threshold of 10 km^2 was set based on observations on a number of debris-flow catchments of eastern Italian Alps (Marchi and D'Agostino 2004). This drainage area threshold aims to remove spurious debris-flow initiation points from channels that are actually characterized by bedload and suspended sediment transport. Since this morphometric approach mainly leads to identify the initiation cells presenting the topographic condition to trigger debris flows without taking into account for sediment availability, some geomorphological or geological dataset should be used to further remove inaccurate source cells. In the applications carried out in the eastern Italian Alps, information on bedrock channel and sediment availability surveyed in the field were used to filter the initiation cells identified by means of the area-slope threshold (Eq. 2).

Since debris flows may occur with variable intensity, especially with regard to kinematic aspects, along the various parts of the channel network, it is important to identify the channel reaches prone to debris-flow propagation, deceleration, and stopping. It has been reported in the literature that a debris flow can start depositing the transported material on slopes of about 6°-10° and usually stopping at values around 3°-5° (Burton and Bathurst 1998; Benda 1985; Vandre 1985). Accordingly, following a cautionary approach, the proposed procedure classifies the raster cells in the slope range of 3°- 8° and below 3° as deceleration and stopping, respectively. The raster cells of the channel network not classified as the potential initiation, deceleration and stopping belong to the propagation category.

The classified channel network obtained according to the method described above represents a simple and fast approach to identify at regional scale potential debris-flow prone streams. Nevertheless, given the simplicity of this approach, the classified channel network is not able to fully describe debris-flow phenomenology along all the streams analyzed. The interpretation of streams with a complex longitudinal pattern, characterized by an alternation of initiation, propagation, deceleration and stopping reaches is not straightforward. To address this issue, the developed procedure implements an analysis of longitudinal profiles aimed to evaluate the runout distance of a potential debris flow. The runout distance (W) calculation relies on the empirical relationship by Vandre (1985):

$$W = \alpha\,\Delta h \tag{3}$$

where Δh is the difference between the debris-flow starting point and the point at which deceleration begins and α is an empirically derived coefficient, set to 0.4 according to the data by Vandre (1985).

Based on this relationship, Burton and Bathurst (1998) developed a rule-based debris-flow transport model, applying the following rules to govern debris flow transport and deposition:

i) Downstream the initiation point, slopes greater than 10° allows the debris flow to continue unconditionally;

ii) In case of slopes between 4° and 10°, the debris flow stops either over the runout distance (Eq. 3) or on reaching the 4° slope, whichever condition is first satisfied;

iii) Slopes lower than 4° lead to an

unconditionally halt of the debris flow.

We chose threshold values slightly different from those originally proposed by Burton and Buthurst (1998) considering the criteria established for deriving the classified channel network. Accordingly, a debris flow starts at the initiation points identified by Eq.(2) and the deceleration of debris flow begins on slopes lower than 8°. Furthermore, following a cautionary approach, we do not consider unconditionally slope-based stopping conditions (i.e., at slopes < 3°). Hence, debris flows halt once:

$$\begin{pmatrix}\text{Distance travelled}\\ \text{on slopes} < 8°\end{pmatrix} > 0.4 \cdot \begin{pmatrix}\text{Elevation lost}\\ \text{on slopes} > 8°\end{pmatrix} \quad (4)$$

where the travel distances are measured along a longitudinal profile of the investigated stream. In the case of multiple initiation points, the choice of the most upstream point is recommended. The runout distance calculation takes into account the possibility of a new debris-flow triggering after an upstream stop of the debris flow.

It is worth noting that the identification of debris inundation areas is not possible using the runout distance calculation previously described. However, the results of runout distance along a longitudinal profile can be overlaid to the alluvial fans of the investigated streams (see the Applications section).

1.2 Tools

In order to facilitate the application of the proposed procedure, a set of software tools were developed.

The first tool is a model builder script available in a Toolbox for ArcGIS 10.3. The required inputs are the DEM, which should be hydrologically corrected, the *SPI* threshold value for channel network derivation (Eq. 1) and the resolution of the input DEM. This tool produces three outputs: i) the classified channel network (raster format), ii) a map of initiation point density, and ii) the channel network in 3D shapefile format. The output of the classified channel network is an integer raster with a numerical code for the cells of debris-flow triggering (2), propagation (1), deceleration (3) and stopping (4). In order to enrich the information provided by the cells classified as potential debris-flow initiation point and to identify the zones of the study area where the concentration of potential triggering points is greater, a map of density is also provided as an output. The initiation point density map is calculated through the Kernel Density tool available in ArcGIS by setting 50 m as the default value for the searching radius and the resulting values are expressed in points/hectare. This map can be classified by means of natural breaks algorithm, excluding zero values, into two classes. The class with higher values of density can be used to detect the most hazardous situations on the slopes and along the streams, since in the density calculation, both debris-flow initiation points used to classified the channel network and the ones on the hillslope are considered. The last output of the tool is the 3D shapefile of the channel network on which the user can select and extract the channel reaches to be analyzed in the following step of the procedure (i.e., runout distance calculation).

The second tool, an ArcGIS model builder script is needed to prepare the input for the tool devised for runout distance calculation, which requires a point shapefile including the information related to the elevation and the class of the classified channel network.

The third and last tool of the procedure is devoted to the runout distance calculation. It is developed in Matlab and implements the steps illustrated in the previous section (Eq. 4). It requires as input the point shapefile of the reaches to be investigated, i.e., the output of the "Procedura2PointProfile" tool. The results is a point shapefile with every point classified as "*no debris flow*" in case the reach has no initiation point upstream or is downstream of a debris-flow halt, "*debris-flow halt*" in the case of occurrence of stopping conditions, and "*debris flow*" in all the remaining cases.

The developed tools are freely available for download at: https://github.com/HydrogeomorphologyTools.

2 Applications

The procedure for debris-flow assessment described in the previous section was applied in several mountainous regions. The most systematic application involved the whole territory of the Autonomous Province of Trento (northern Italy). This region (Figure 2) covers 6210 km² with about

70% of the total area lying above 1000 m a.s.l. and a mean elevation of 1400 m a.s.l. The region is characterized by complex geostructural settings marked by high lithological heterogeneity, including magmatic, metamorphic and sedimentary rocks, and the presence of relevant structural lineaments and deformation structures (Castellarin et al. 2005). Quaternary deposits are widespread in the area, including glacial deposits and talus slopes at the highest elevations and alluvial deposits in the valley floors. The climate is alpine; precipitation exhibits a bimodal regime, with maxima in spring-early summer and in autumn, which generally receives the most abundant precipitation. Typically, the precipitation during cold months (October–April) occurs as snowfall. Forests (especially conifer stands) cover around 70% of the total area, rocky outcrops, bare debris, and grassland are widespread at the highest elevations; agricultural and urban areas are mostly located on alluvial fans and in valley floors.

A DEM derived from airborne LiDAR data (2006-2007) is available for the whole territory of the Province at a resolution of 1 m (0.15 m vertical accuracy) for the main valley and urbanized area, and 2 m (0.3 m vertical accuracy) for the remaining areas. Most of the application of the procedure to the Autonomous Province of Trento was based on the LiDAR DEM, with a resampled resolution of 10 m; only in two sectors, covering an area of 632 km^2, a 10-m resolution DEM derived from photogrammetry-based map was used for the analysis. The application of the procedure was carried out by subdividing the territory in 18 catchments ranging in area from 26 to 937 km^2, with an average area of 351 km^2. The processing of different areas was necessary to identify an appropriate threshold for synthetic network derivation and to facilitate data elaborations avoiding large datasets. The study also required the individuation and digitalization of the alluvial fans for the whole studied region; a total of 2481 alluvial fans have been digitized by means of analysis of aerial photography, LiDAR DEM derivatives and field surveys.

The main results of the first step of the procedure are the identification of potential initiation sites and the classified channel network

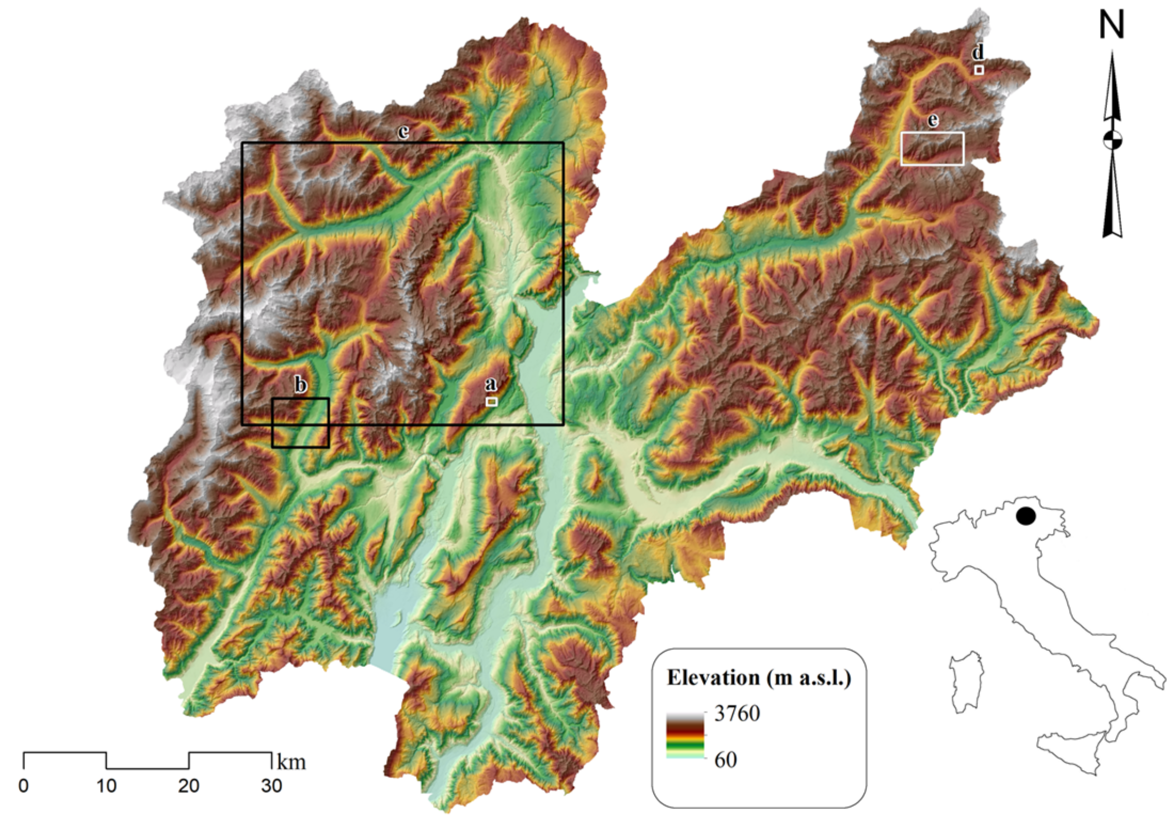

Figure 2 Location map of the Autonomous Province of Trento (Italy). Black rectangles indicate the location and extent of the areas shown in Figure 4 (a), Figure 6 (c), Figure 7 (b), Figure 8 (d), and Figure 9 (e).

(Figure 3). The identified potential debris-flow initiation cells were used for the kernel density analysis in order to detect the most hazardous areas in terms of erosion potential. The analyses led to thresholds for the identification of the class with higher values of density ranging from about 6 to 8 points/hectare in the different catchments. The results of the density analysis (Figure 4) underwent field checking and validation. The field surveys revealed the effectiveness of density maps for the identification of sites that could deserve further investigation. Since the potential debris-flow initiation sites are not restricted to the channel network but they have been identified also on the hillslopes, a density map can be of help also for vegetation management.

In the application to the Autonomous Province of Trento, the classified channel network was systematically intersected with layers of vulnerable elements such as road infrastructure, forest road, and urbanized areas to derive a simplified risk-based zoning. This information along with potential initiation sites and instability areas maps was also exploited to derive indices aimed to compare third order catchments in terms of propensity to debris-flow processes and presence of urban areas potentially at risk. In this study, two indices were developed to compare third order catchments in terms of i) presence of instability phenomena in areas with a high topographic propensity to debris-flow triggering (*sediment supply index* - I_{ss}), and ii) presence of urban areas exposed to the debris-flow hazard (*urbanization index* - I_u). I_{ss} is based on the intersection between the potential debris-flow initiation points and a map of the unstable areas:

$$I_{ss} = \frac{DI \cap IA}{A} \tag{5}$$

where DI is the number of debris-flow initiation points, IA the areas affected by instability phenomena and A the catchment area (km^2). This index permits to highlight those initiation points that, since they fall within areas affected by instability with a large sediment availability, require priority attention in view of the execution of detailed investigations and of possible control measures. I_u is a metric of the interaction between urban development and the presence of potentially hazardous streams:

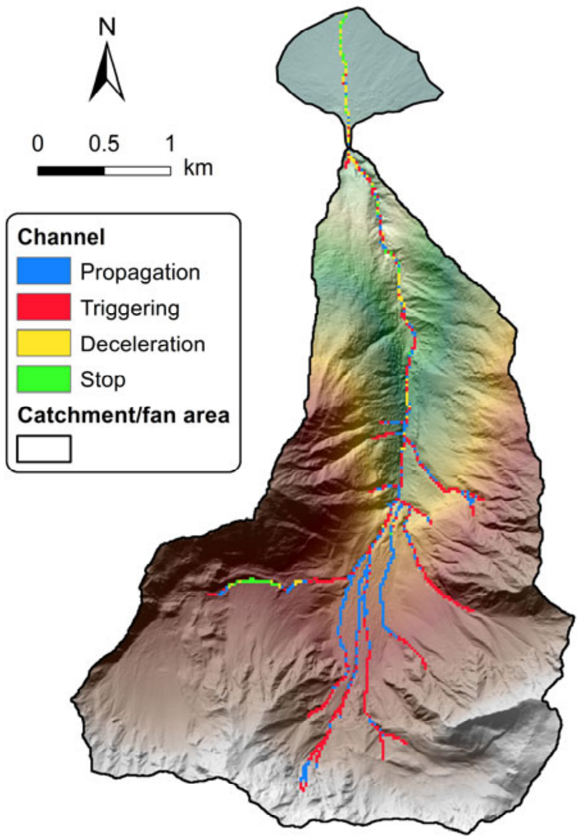

Figure 3 Example of the classified channel network.

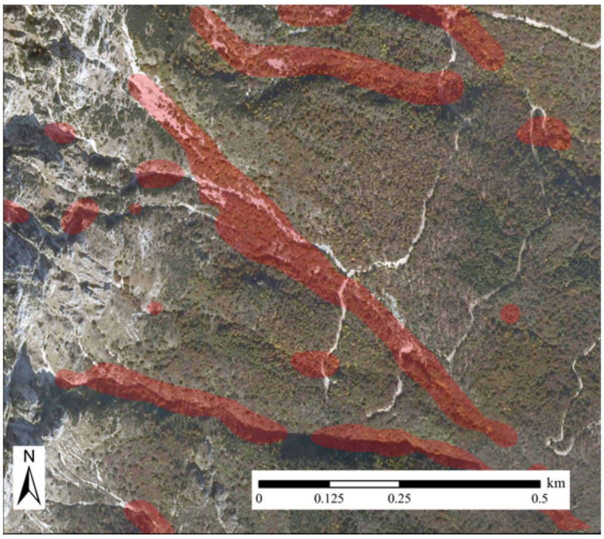

Figure 4 Example of high debris-flow initiation point density (Red). Some of the mapped areas are in correspondence of instability areas threatening a forest road.

$$I_u = \frac{CH \cap UA}{A} \tag{6}$$

where CH is the number of raster cells of the channel network, UA the urbanized areas (e.g., buildings, roads) and *A* the catchment area (km^2).

The combined analysis of sediment supply and urbanization indices provides information that may be helpful for watershed management. Figure 5 shows the values of the two indices for 20 third-order catchments in a selected portion of the study area; the red lines that identify four quadrants correspond to the mean values of the indices. Quadrant I contains the basins which, having higher average values for both indices, present more critical situations in the analyzed area. An opposite situation can be observed in quadrant III, while quadrants II and IV identify intermediate situations. This analysis can contribute, together with the other tools proposed in the present study, to the prioritization of areas concerning debris-flow hazard.

The computation of the runout distance along the classified channel network represents a pivotal step in the procedure since it permits to classify the alluvial fans according to priority levels (Table 1). The same level is ascribed to the whole fan surface (Figure 6): the coding of alluvial fans is functional to prioritize further studies aimed at the assessment of debris-flow inundation areas. The mapping of inundation areas according to proper debris-flow scenarios can be achieved by means of 2D numerical models and is outside the scope of the GIS tools presented in this paper. The effect due to the presence of sediment retention basins was also considered: if a retention basin is present, the priority resulting from runout computation is lowered by one level. The classification of 2481 alluvial fans mapped in the studied territory resulted in 1903 “High”, 111 “Medium” and 467 “Low”. In general, the alluvial fans classified as high are relatively small, located in elevated

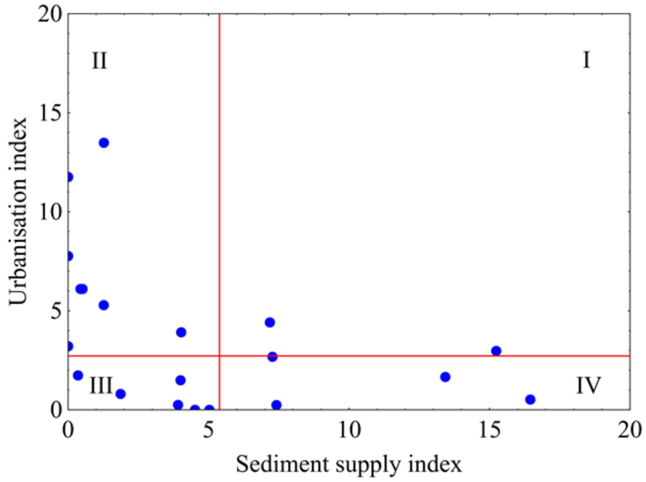

Figure 5 Relationship between the values of indices of sediment supply and urbanization for third-order catchments (blue dots) in a sector of the study area. The red lines, which divide the scatterplot into quadrants, correspond to the mean values of the indicators.

Table 1 Criteria based on runout distance computation used to assign priority for further analysis to alluvial fans

Priority	Criteria
High	• No debris flow halt • Debris flow halts beyond the first third of the fan
Medium	• Debris flow halts within the first third of the fan
Low	• Debris flow halts upstream the fan • No debris-flow initiation sites upstream the fan

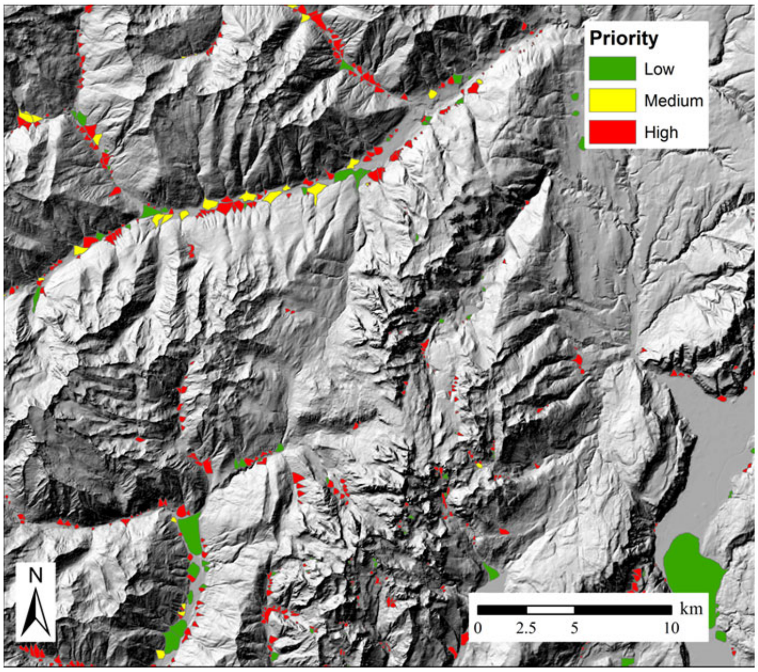

Figure 6 Prioritization of alluvial fans based on the classification criterion shown in Table 1.

areas and with high slopes. Figure 7 shows the classified channel network and alluvial fans in one selected sector of the study area. This combined map provides useful information both on the local propensity to debris flow along the channel network and on the priority of alluvial fans.

Recently, the overall procedure was applied also to three pilot areas of another region in northern Italy (Veneto region) covering a total area of 573.4 km². The application to Veneto region allowed the characterization of 149 alluvial fans and put the basis for a more systematic application to the whole regional territory.

The proposed methodology has been extensively tested in collaboration with the Watershed Management Office (*Servizio Bacini montani*) of the Autonomous Province of Trento following a two-step validation approach. The first validation step was based on the extensive visual analysis of aerial imagery, high-resolution orthophotos and high-resolution DEM derivatives, such as shaded relief, residual relief, openness, and slope (Cavalli et al. 2013). The first objective of this validation step was to assess the coherence of DEM-derived channel network; a further target was to detect evid ence of erosion processes in areas with high density of debris-flow initiation points (Figure 8). The second validation step consisted in field surveys over specific validation sites, interesting almost 100 streams and related alluvial fans. For these sites field campaigns aimed at the geomorphological interpretation of torrential processes characteristics. A mobile GIS with GPS capability has been used during the field surveys to perform the direct comparison between model results and reality. The objectives of the surveys were manifold: i) validation of location and extent of DEM-derived channel network, ii) survey of areas with high density of initiation points, to evaluate the presence of extensive erosional processes and availability of sediment, iii) geomorphological observations along the stream channels to evaluate the characteristics of channel reaches and validate the automatic classification with respect to debris-flow susceptibility, iv)

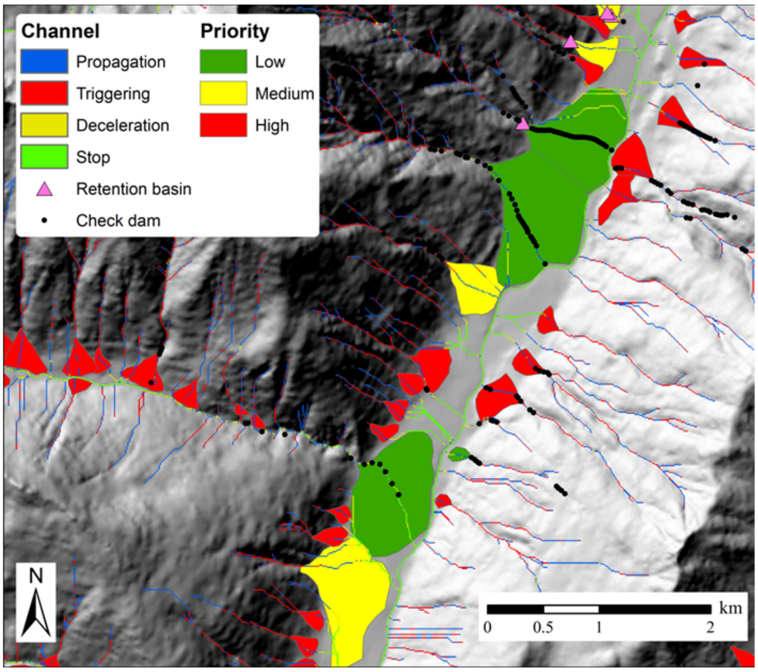

Figure 7 Classified channel network and alluvial fans in a sector of the study area.

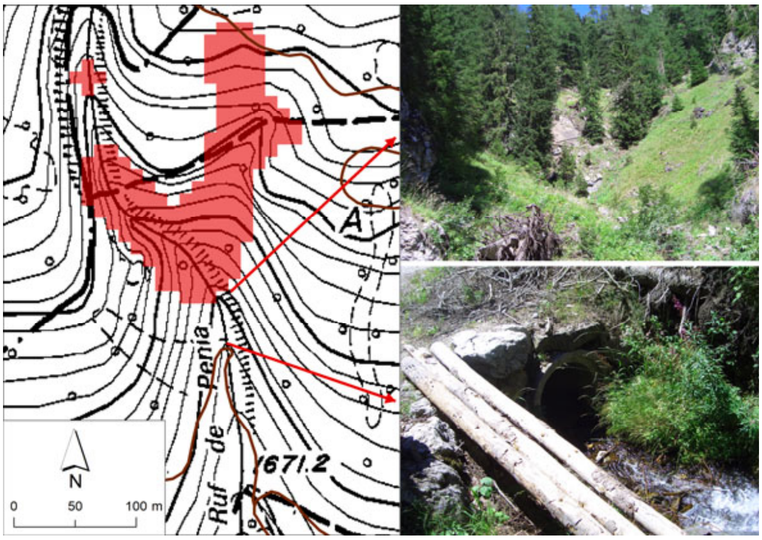

Figure 8 Field survey of an area with high density of debris-flow initiation points (red) just upstream of a small culvert on a forest road (brown line). Problems for the safety of the road and downstream areas may arise from the combination of high debris-flow susceptibility and small culvert size.

analysis of the alluvial fan area to recognize, through a geomorphological approach, the processes affecting the fan. In recent years, some of the alluvial fans classified with high priority have been affected by debris flows and field observations provided evidence that the classified channel network and the identified potential initiation areas well represented the dynamic of debris flow in the upstream catchment (Figure 9).

The overall validation procedure showed that the proposed methodology produces reliable results in most situations. We observed that the failures of the method are usually related to the rare situations where the channel network is not correctly represented, as in the urbanized areas. It is worth stressing that a quantitative calibration of the proposed methodology is not possible since it does not aim at the assessment of potential inundation areas, as several already available numerical models do. The presented methodology is rather a GIS-based procedure based on some simplifications (discussed in the following section), which enables mapping debris-flow susceptibility for management purposes over large areas. A satisfactory confirmation of this outcome is given by the fact that the results of the systematic application of this method to the Province of Trento are currently used for the implementation of watershed management practices.

3 Discussion

The assessment of debris-flow susceptibility at the regional scale is increasing in interest and recently has been the object of several studies using different approaches (Blahut et al. 2010; Bertrand et al. 2013; Bregoli et al. 2015; Berenguer et al. 2015; Pastorello et al. 2017). The application of physically-based models at the regional scale is prone to significant uncertainty related to the complex inputs required and boundary conditions (Borga et al. 2002; Bregoli et al. 2015). For example, detailed and accurate information on hydraulic and mechanical characteristics of soils and debris-flow rheology is difficult to be obtained

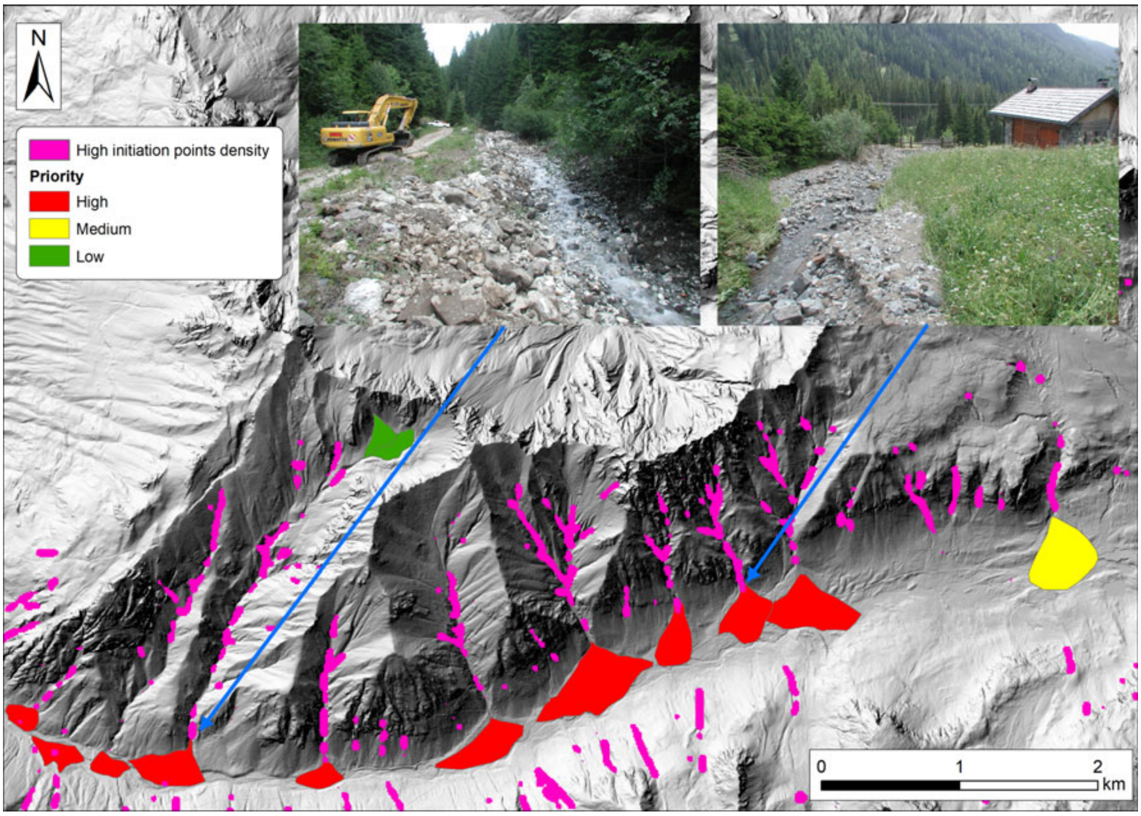

Figure 9 Field check of the developed GIS-based procedure: two debris flows affected catchments characterized by widespread areas of potential triggering and whose alluvial fans were classified as high-priority.

at the regional scale. These considerations are in favor of the use of simplified and fast approaches, mainly based on DEM-derived morphometric parameters that can be easily calculated also at wide scales.

Topography-based models like MSF and MF (Huggel et al. 2003; Gruber et al. 2009), Flow-R (Horton et al. 2013) and Random Walk (Mergili et al. 2015) are suitable for the assessment of possible inundation areas in terms of hazard probability. Differently, the GIS procedure presented in this paper, based on the integration of different morphometric indices, is mainly focused on individual confined channels, represented by the DEM cells with the highest flow concentration, and achieves a classification of channel reaches according to initiation, propagation, deceleration, and stopping of debris flows. The proposed GIS-procedure introduces strong simplifications (it is worth reminding that debris-flow volume is not taken into account) to reduce the complexity of the analysis, thus facilitating application on wide areas and overcoming the problems due to the lack of detailed information at these scales. The main limitations are related to the empirical nature of these indices that are mostly based on the morphological characteristics of the area under analysis and do not consider specific variables as rainfall intensity, flow velocity and rheological characteristics of debris flows.

Despite the strong simplifications underlying this approach, the applications conducted in different mountainous areas have demonstrated its effectiveness for a preliminary and expeditious classification of channels and alluvial fans, which provides information directly suitable for practitioners involved in the management of mountain catchments. The main advantage is that, given the purely morphometric approach, the procedure does require a limited number of parameters in input (i.e., a hydrologically corrected DEM and an *SPI* threshold for channel network derivation). The choice of this approach relies also on the fact that debris-flow triggering factors are largely spatially variable and thus, for analyses at the regional scale, a generic approach based on few inputs is recommended (Pastorello et al. 2017).

Recognition of the topographic control on triggering, propagation and deposition of debris flows provides information directly suitable for the implementation measures or for identifying sites that need further studies. An example of the application of the proposed GIS tools to the implementation of control measures is the installation of sediment traps in channels where topography-based indices indicate debris-flow deposition: the effectiveness of artificial sediment retention structures is enhanced by the natural tendency of debris flows to deposition. The maps of initiation points density can provide useful information on debris flow triggering sites where a careful vegetation management can be addressed and appropriate stabilization works can be planned both along the channels and on the hillslopes. Rating and ranking alluvial fans according to debris-flow runout (and presence of elements at risk) provides another example of the use of the developed procedure: the most critical situations can be selected for detailed analysis by means of more sophisticated (and more data-demanding) physically-based models, whereas the summary evaluation of debris flows by means of the topography-based indices can be deemed sufficient for other cases, such as natural alluvial fans.

Some limitations of the proposed method can be overcome by combining the topography-based indices with data on other factors that influence debris-flow formation and propagation. As an example, maps of landslides, active sediment sources or geomorphological maps indicating the presence of thick erodible debris can be overlaid with the map of the density of debris-flow initiation points, thus permitting to identify sites in which both debris availability and topographic conditions favor debris flow occurrence. The same approach permits filtering potential debris-flow initiation points corresponding to outcropping bedrock or to channels where grade control dams make the bed not erodible. Other limitations are intrinsic to the topography-based approach, which implies drastic simplifications of complex physical processes and neglects the representation of different event scenarios. We recall here that topography-based indicators are not intended to replace the numerical models of debris flows, while they aim at integrating knowledge resulting from historical records on flood and debris-flow disasters with the recognition of flow processes based on topographic control of occurrence and propagation of debris flows.

Open source and freely available tools have been developed to facilitate the application of the presented methodologies. The way the tools are proposed implies an expert intervention (for example in order to select the proper channel network to consider when characterizing debris-flow initiation, propagation, deceleration and stopping conditions). On the one hand, this could be regarded as a partial limitation requiring external inputs but, on the other hand, it removes the risk of carrying out "one-click" applications without grasping the whole complexity of the analysis. The expert intervention could be regarded as a positive checkpoint in the workflow in order to carry out a sound analysis that cannot exempt from a detailed, field-based knowledge of the study area.

Finally, it is worth stressing that the limitations of the GIS procedure proposed in this paper imply that more testing is needed to validate its applicability to contexts different from the alpine basins.

4 Concluding Remarks

The procedure presented in this paper aims at providing a preliminary characterization of the streams prone to debris flow, including the assessment of the runout distance on alluvial fans. The tools developed can also be used to support the application of other methods, e.g. by identifying the initiation areas of debris flows, that can be chosen to represent the upstream end of the computation domain for 2-D debris-flow models.

The main features of the topography-based procedure developed for the preliminary assessment of debris flow are summarized below:

(1) Potential debris-flow initiation points are identified by means of a slope-dependent threshold of the upslope area (Eq. 2); a kernel density map permits to detect the areas with high density of debris-flow initiation points.

(2) Channel network, derived by means of Eq. (1), is classified into reaches susceptible to debris-flow initiation, propagation, deceleration, and stopping.

(3) A simplified empirical model, based on thresholds of slope and traveled distance (Eq. 4), is applied for runout assessment.

(4) Alluvial fans are classified into priority classes according to the runout distance.

The application to the territory of the Autonomous Province of Trento (northern Italy) in the frame of the development of a region-wide map of natural hazards has confirmed the usefulness of this empirical procedure as a tool for the preliminary identification of debris flows. All the steps of the procedure are implemented into a set of freeware software tools to support the personnel involved in landscape management in its application and to offer the opportunity to test the methodology in other contexts.

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