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The RES approach for debris flow susceptibility analysis: a case study

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Abstract. Climate change has increased the occurrence and magnitude of debris flow events, especially in mountain areas. Moreover, their unpredictability requires to develop reliable methodologies for the evaluation of debris flow susceptibility, which is the starting point for risk assessment and management. In this paper, a modified version of the Debris flow Propensity Index (DfPI) is developed for the debris flow susceptibility estimation at basin scale. Bedrock lithology, fracture network, quaternary deposits, slope angle, channel network, and land use were identified as debris flow predisposing factors and were indexed by using open-access data and geodatabases. The objective of the proposed study is to develop a simple and economic procedure for the susceptibility estimation, easily to implement in GIS-based software for further analyses, such as propagation simulations or hazard scenarios, useful for planning mitigation strategies. The Canè Valley, a small valley located in the more famous Camonica Valley, (Lombardia Region, Northern Italy), was used as a case study for developing and testing the proposed approach.

1 Introduction

Debris flows are rapid to extremely rapid phenomena able to mobilize a large amount of soil, sediments or debris, usually following the path of a pre-existing channel. Due to these aspects and their unpredictability, these phenomena are generally deemed as highly dangerous [1]. Mountain regions are heavily affected by these events: the permafrost degradation and the glacier retreat, in addition to the increasing frequency of extreme rainfall events require to undertake mitigation strategies for managing the debris flow risk. The starting point of risk analysis is the detection of the most susceptible areas and the possible propagation scenarios.

A correct risk assessment requires a quantitative approach through “Quantitative Risk Analysis (QRA)” [2,3] routines, based on a multi-level characterization of the study area starting from the definition of susceptibility maps. Many methodologies have been developed for the susceptibility mapping: inventory-based, heuristic, statistical or deterministic methods [4]. The main limitation of the proposed methods [5-7] is related to data availability, which usually appears to be a complex problem.

Bonetto et al. [8] applied the matrix approach suggested by the Rock Engineering System (RES) [9] method for the evaluation of the debris flow susceptibility at regional scale in a rapid and economical way. The authors identified five predisposing factors for the evaluation of the Debris flow Propensity Index (DfPI) at the basin scale: (i) bedrock lithology, (ii) fracture network, (iii) quaternary deposits, (iv) slope angle, and (v) channel network.

In this research, starting from the innovative approach developed by [8], a modified version of the DfPI was proposed by introducing the land use as a predisposing factor, given that it plays an important role in controlling the interaction between surface runoff and soil or sediment deposits. The methodology was applied to the Canè Valley, located in the Central Alps (Northern Italy). The obtained DfPI was validated by comparing the occurred phenomena recorded in the study area. Strong points, limitations and future developments of the proposed approach will be also discussed.

2 Study area

The Canè Valley (Figure 1) is a glacial valley located in the northern sector of Camonica Valley (Central Alps, Lombardia Region, Italy) and covers an area of approximately 14 km^2.

The geology of the area is well described by the Italian Geological Cartography at 1:50.000 scale [10]: the bedrock is composed by rocks of the Austroalpine Domain, belonging to the Peio Unit, which is composed by metamorphic rocks (mainly micaschists and paragneisses, with local bodies of metapegmatites, anphibolites, marbles and quarzites) and igneous intrusions located in the northern portion of the valley.

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The bedrock is covered by discontinuous quaternary deposits, mostly associated with gravitational phenomena involving the steep slopes or with glacial processes active in the past, which have shaped the valley. The lower sector of the valley is covered by alluvial deposits and mixed-origin fans, mainly generated by debris flow phenomena.

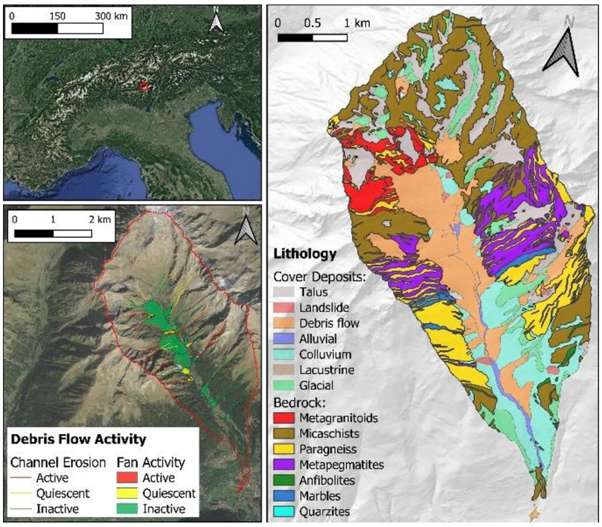

Fig. 1. Location, debris flow activity map and geological sketch of the Canè Valley.

3 Methodology

The methodology proposed in [8] was modified by adding the land use to the five predisposing factors (lithology, fracture network, Quaternary deposit, slope angle and channel network). These factors, considered as independent parameters, have a significant influence on the triggering processes of debris flow phenomena. Their spatial distribution allows to perform a widespread analysis throughout the territory. Moreover, in debris flow analysis the land use is important in the control of slope behaviour during rainfall and it reflects the different soil conditions related to erodibility or resilience to the impact of rainfall and surface runoff.

Figure 2 shows the new proposed matrix: on the main diagonal there are the predisposing factors, while the off-diagonal terms represent the mutual interactions, scored using the Expert Semi-Quantitative approach (ESQ), which assigns a value ranging between 0 (minimum interaction) and 4 (maximum interaction).

The a_i values represent the weight of each parameter on the susceptibility of the phenomenon and how the parameter influences the system. It can be obtained by the following equation:

$$a_i = \frac{1}{\max(I_{ijth})} \times \left(\frac{C+E}{\sum C+\sum E} \times 100\right) \tag{1}$$

where C is the sum of all cells on the same row and describes the effects of the system on the parameter (Causes), E is the sum of all cells on the same column and quantifies the effects that the parameter has on the system (Effects), $max(I_{ijth})$ is the maximum possible value for a cell of the interaction matrix (in this case is equal to 4 according ESQ approach).

For each parameter of the diagonal matrix, a specific index P_{ik} was defined. These indexes describe the influence of each predisposing factor to generate debris flow events. In particular, they were calculated by dividing into homogeneous classes the values of the considered predisposing factor, assigning a representative value and evaluating the percentage of its areal distribution into the whole basin. The P_{ik}s were defined by using open access data available on geodatabases [10-13].

A detailed description of the considered indexes and their evaluating procedure is provided in [8]. As stated in the Introduction, the land use has been addressed for the DfPI evaluation. Land use plays a relevant role in the erosion control, since the presence and type of vegetation influences the mechanical behaviour of the cover deposits and soils. By using the land use map provided by the regional administration [12], land covers were grouped into 4 classes: i) rock and deposit, ii) grassland, iii) vegetated areas (mainly forests), iv) lakes or dams, v) urbanized areas. For each class, the qualitative rating S_{Ui} was assigned based on the propensity to generate debris flow. S_{Ui} can assume values from 0 to 4, and allows the evaluation of the S_{UBi} index, which provide the weight of each land use class within the basin and it was defined as follows:

$$S_{UBi} = \frac{A_{UI}}{A_b} \cdot S_{Ui} \tag{2}$$

where A_{Ui} is the area associated with the ith class, A_b the area of the basin and to that class. The sum of all the contributions given by each class defines the global index, i_U:

$$i_U = \sum S_{UBi} \tag{3}$$

The susceptibility is finally quantified using the Debris flow Propensity Index (DfPI), ranging from 0 to 100:

$$DfPI = \sum(a_i \times P_{ik}) \tag{4}$$

The evaluation of the level of susceptibility associated with the studied area can by qualitatively expressed using the following Table 1, derived from [8].

Table 1. DfPI index values and related susceptibility classes; form [8].

CLASS	DfPI	Susceptibility
I	0 - 1	None
II	2 - 8	Very Low
III	9 - 25	Low
IV	26 - 42	Medium
V	43 - 53	High
VI	54 - 70	Very High
VII	71 - 100	Extremely High

Bedrock lithology	The type of substrate in relation to its mineral-petrographical composition and strength conditions, considering the same stress state, will affect the degree of fracturing.	The composition of the substrate affects the alterability of the rock and therefore the susceptibility to generate debris, which can be easily mobilized.	The slope is the morphological expression of rock weathering. Strength, fabric and rock texture affect slope morphology.	Compositional and textural features affect the erodibility of the stream. For this reason the hydrographical network is influenced.	The type of substrate influence the type of land cover
Faulting and structural elemnts can cotrol juxtaposition of different types of rock.	**Fracture network**	Brittle deformation influences the rock fracturing, increasing the rock weathering. These processes increase the availability of loose material that change the magnitude of the deposit.	Higly fractured substrates are subject to alteration, erosion and decrease of mechanical properties (friction angle and cohesion) with consequent influence on slopes (minor slopes).	The presence of brittle deformation affects the erodibility and alterability of the substrate, increasing the erosive power of streams. Moreover, fault zones may allow the formation of new stream.	The presence of fractures influences the erodibility and the water circulation
Quaternary deposits define areal distribution of bedrock at surface.	No direct conditioning on the development and localization of fragile structures. They protect the fractured substrate from the action of atmospheric agents, limiting the weathering and decay of the resistance parameters	**Quaternary deposits**	Slopes on deposits have different acclivity depending on the types, thickness and textural characteristics of the loose deposits that characterize them	Type, thickness and textural characteristics of the deposits influence the morphology around the stream.	The type of depositis and their thicknesses influence the land use
No influence	No influence	The slope affects the presence, stability and thickness of any deposits	**Slope**	The slope affects the energy of the watercourse and the erosive power	The slope influence the land use
No influence	No influence	The channel can determine the accumulation or movement of the deposits by changing the distribution and textural characteristics of deposits.	Depending on the energy of the watercourse and its erosive capacity, the hydrographic network can reshape the slope	**Hydrographic network**	Hydrografic network has a great influence on the land use
No influence	No influence	Land cover influences distribution and characteristics of the deposit	Land cover influences the slope stability	No influence	**Land Use**

Fig. 2. Interaction matrix defined for the case study here presented.

4 Results and Discussion

The encoded 6x6 matrix (Figure 3) shows the ESQ values used for off-diagonal terms and the a_i x P_{ik} results for each predisposing factor. The proposed matrix is a useful standardized tool, universally applicable, since it is independent of type and characteristic of the basin.

The results highlighted that the Canè Valley has a very high susceptibility to debris flow events since the DfPI obtained with the proposed methodology is equal to 64.72. This mirrors the data available in the landslide inventory [14, 15] where 30 debris flow-like phenomena were recorded in the last 50 years. Moreover, by analysing the regional orthophotos and satellite images, the morphological effects of about 10 past events are still visible (Figure 4). Consequently, for the Cané Valley (14 km^2) it is possible to estimate a debris flow density of 2.71 events per km^2. Actually, this spatial distribution is mainly concentrated in the middle sector of the valley, where most of the active fans are located (Figure 4).

							CAUSE [C]	C_i+E_i	Parameter	P_{ik}	a_i	$DfPI_i$
	P1	1	4	2	3	1	11	15	**Bedrock Lithology [P1]**	0.84	3.41	2.86
	3	**P2**	3	4	4	1	15	16	**Fracture Network [P2]**	4	3.64	14.55
	0	0	**P3**	2	2	1	5	20	**Quaternary Deposit [P3]**	1.34	4.55	6.09
	0	0	4	**P4**	4	3	11	23	**Slope Angle [P4]**	3.14	5.23	16.41
	0	0	3	3	**P5**	2	8	23	**Channel Network [P5]**	4	5.23	20.91
	1	0	1	1	2	**P6**	5	13	**Land Use [P6]**	1.32	2.95	3.90
EFFECT [E]	4	1	15	12	15	8	110					**64.72**

Fig. 3. Interaction matrix after coding using the indexes for the six parameters and their interactions.

The results confirm the reliability of the GIS-based approach proposed for the quantitative estimation of the debris flow susceptibility into a basin by using available and easy-to-access data.

The main limitation of this approach is the use of a single value for quantifying the whole basin susceptibility. This can be useful for a rough preliminary estimation and for a hierarchical risk management at regional scale (i.e. in defining areas of interest for future defensive works). However, no information is provided on the spatial distribution inside the basin, which could be useful for further risk assessment steps, such as hazard areas identification.

5 Conclusions

The approach presented in this study is easily applicable and it requires input data which can be found on open access geodatabases.

For the considered case study, the RES method yielded a numerical value of DfPI index corresponding to a very high susceptibility class. This outcome is confirmed by the current distribution of debris flow phenomena in the study area.

At regional scale or when we analyse large portion of the territory, if the susceptibility analysis is carried out to focus the attention on critical area detected by the model, it is then possible to model the runout of possible events.

This approach has still quite visible limits, considering that it provides a simple numerical value that describe a whole basin without considering the effective spatial distribution. In the present form, global DfPI has been validated using existing landslide inventory and satellite or aerial images, but the natural next step will be the mapping of the potential source distribution inside the considered basin.

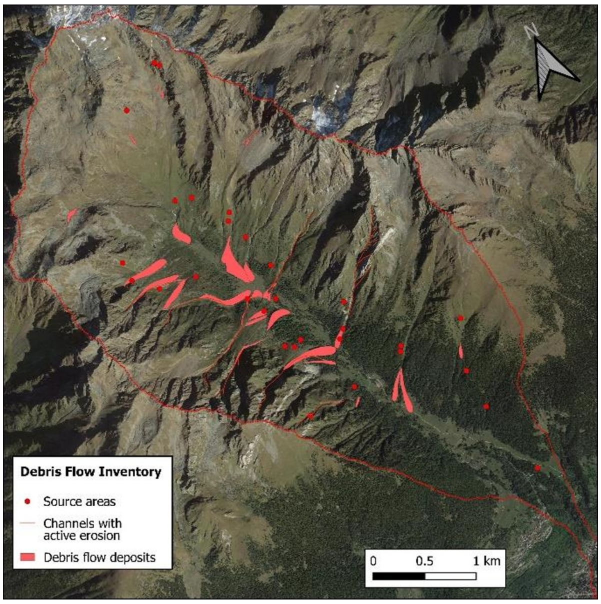

Fig. 4. Debris flow inventory of the Canè Valley.

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