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Quick multiparametric hazard analysis for shallow landslides / Berbero, Monica; Napoli, Maria Lia; Adorno, Giuseppe; Vizia, Silvia. - In: GEAM. GEOINGEGNERIA AMBIENTALE E MINERARIA. - ISSN 1121-9041. - STAMPA. - 160:2(2020), pp. 17-23. [10.19199/2020.160.1121-9041.017]

DX.DOI.ORG/10.19199/2020.2.1121-9041.017

Quick multiparametric hazard analysis for shallow landslides

Monica Barbero*
Maria Lia Napoli*
Giuseppe Adorno**
Silvia Vizia***

* Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Italy
** Regione Piemonte – Direction of Public Works, Land Protection, Civil Protection, Transports and Logistics – Regional Technical Field – Biella and Vercelli
*** RFI – Direzione Commerciale – Sviluppo e Commercializzazione Territoriale Nord Ovest, Milano

Corresponding author: Monica Barbero

This paper presents a quick and multiparametric method for shallow landslides susceptibility and hazard zoning, based on the principles of the Rock Engineering System (RES). The implementation of this methodology is achieved through the identification of the most sensitive triggering parameters and the study of their interrelationships. An interaction matrix is used to define a susceptibility index. The Geographical Information System is used for spatial data management so as to draw landslide susceptibility and hazard maps. The proposed approach is applied to the Municipality of Cellio (VC) located in the Valsesia area (northern Italy) using data updated to 2012. In order to validate the method, the hazard map obtained is compared with known landslides occurred in the last 7 years and with a deterministic method, the Stability Index Mapping (SINMAP). The results are found to be in good agreement. With respect to other hazard assessment approaches, the proposed method has the great advantage of providing reliable susceptibility and hazard maps at small scales in a short time and without requiring a high number of parameters. Therefore, it can be easily applied for preliminary hazard assessment, monitoring and territorial planning activities.

Keywords: *Shallow landslides, landslide susceptibility maps, landslide hazard maps, Rock Engineering System, quick method.*

Il presente articolo presenta un metodo speditivo e multiparametrico per la realizzazione di carte di suscettibilità e pericolosità da frane superficiali, basato sul Rock Engineering System (RES). Per poter implementare il suddetto metodo, è richiesta l'identificazione dei principali e più critici fattori di innesco. Lo studio delle loro interazioni e la costruzione di una matrice di interazione consente di definire un indice di suscettibilità. L'elaborazione dei dati territoriali in ambito GIS consente, infine, di realizzare le mappe di suscettibilità e di pericolosità. L'approccio speditivo illustrato nel presente articolo è stato applicato al Comune di Cellio (VC), in Valsesia (Nord Italia), utilizzando dati aggiornati al 2012. Per dimostrare la validità del metodo proposto, la mappa di pericolosità ottenuta è stata confrontata con l'ubicazione delle frane registrate dal 2012 al 2019 e con il risultato fornito dal metodo deterministico SINMAP (Stability Index Mapping). Rispetto ad altri approcci disponibili in letteratura per la stima della pericolosità da frana, il metodo proposto in questa sede presenta il notevole vantaggio di fornire mappe di suscettibilità e pericolosità a piccola scala in breve tempo e senza richiedere necessariamente la conoscenza di un elevato numero di parametri. Pertanto, il metodo proposto può essere facilmente applicato nell'ambito di valutazioni preliminari della pericolosità da frane superficiali, per pianificazioni territoriali e studi di monitoraggio.

Parole Chiave: *Frane superficiali, mappe di suscettibilità, mappe di pericolosità, Rock Engineering System, approccio speditivo.*

1. Introduction

The methods proposed in the literature for the susceptibility and hazard assessment evaluate the propensity of a region to natural disasters (susceptibility) and the probability that a potentially dangerous event of a given magnitude can occur in a certain location within a given period of time (hazard) (Corominas and Moya, 2008; Scavia *et al.*, 2020). As well known, susceptibility and hazard methods can be divided into qualitative and quantitative methods (Ko Ko *et al.*, 2004; Fell *et al.*, 2008; Corominas and Moya, 2008). The former are subjective and produce a descriptive zonation, the latter are based on objective criteria and produce a quantitative estimation of the occurrence probability of a natural event.

Susceptibility refers to the likelihood of a landslide occurring in an area on the basis of local terrain conditions (National Research Council, 2004). In that sense, susceptibility maps are a very useful tool for territorial planning. Some of the most commonly used methods for determining susceptibility are empirical (Amadesi and Vianello, 1978; Hudson, 1992), landslides inventory and geomorphological (Gee, 1991), statistical (Baeza and Corominas, 2001; Fell *et al.*, 2008; Bovolenta *et al.*, 2017) and deterministic methods (Montgomery and Dietrich, 1994; Pack *et al.* 1998). The discriminant between susceptibility and hazard is the factor "time", i.e. return period, which is related to triggering factors (Dai and Lee, 2002). For shallow landslides triggering factors are mainly climatic conditions and precipitation of medium-strong intensity. The critical rainfall threshold, responsible for the activation of a landslide, must therefore be quantitatively determined. Many empirical thresholds are available in the literature (Govi *et al.*, 1985; Crosta and Frattini, 2001; Aleotti, 2004; Guzzetti *et al.*, 2007). They differ according to the rainfall variables used, for example the rainfall intensity (amount of rain accumulated over a given time interval, usually expressed in millimeters per hour or day).

According to the literature (Hudson, 1992; Rozos *et al.*, 2006; Rozos *et al.*, 2008; Mousavi *et al.*, 2011; Hudson and Feng, 2015; Bovolenta *et al.* 2017), this paper reports on a hazard method for shallow landslides. The method was developed with the aim to define a "modus operandi" of general validity, to be applied at small scales. The major goal was to introduce a simple and quick method for the production of landslide susceptibility and hazard maps in a GIS (Geographic Information System) environment, that could be used by both specialized practitioners and technicians for land use planning and possible allocation of funds for monitoring and safety measures of potentially unstable areas. For these reasons, an empirical approach was chosen, which evaluates the susceptibility on the basis of the most important landslide triggering parameters. Specifically, to evaluate the susceptibility a heuristic method was used, which requires an index (i.e., a weight) to be assigned to each sensitive parameter. In order to minimize the subjective attribution of weights to each trigger, the semi-quantitative method proposed by Hudson in the early 90's (Hudson, 1992), the Rockfall Engineering System (RES), was considered. The RES methodology provides an analytic approach to study the main parameters governing a specific circumstance and their interactions, in order to compute an instability index (Hudson and Feng, 2015). Moreover, an empirical relationship was used to determine the rainfall intensity threshold responsible for the landslide triggering.

The procedure developed in this paper was applied to the municipality of Cellio in the Valsesia area, in northern Italy, using data updated to 2012. In this way, the landslides occurred in the following 7 years were used to validate the proposed approach. Moreover, a comparison with the deterministic method SINMAP (Stability Index Mapping), developed by Pack *et al.* (1998), was made.

2. Proposed hazard analysis procedure

A quick method to map shallow landslides hazard has been developed with the aim to define a "modus operandi" of general validity to be applied at small scales. For brevity's sake, the proposed method will be called QHM (Quick Hazard Method) in what follows. Through the use of GIS the QHM provides susceptibility and hazard maps. To evaluate landslide susceptibility, the empirical method of indexing causes was used. In order to reduce the subjective determination of the weights to be assigned to the factors identified as major causes of slope instability, the semi-quantitative RES approach was chosen. This methodology, proposed by Hudson for rock engineering problems in 1992 (Hudson, 1992), has also been used for a variety of other engineering issues, including blast fragmentation problems, debris flows phenomena and stability of natural and artificial slopes (Sanchidrián and Singh, 2013). The RES method provides a systematic approach to study the primary variables governing a particular circumstance, their interactions and hence the engineering options as related to risk (Hudson and Feng, 2015). To do this, an interaction matrix is used (Figure 1). Once the main parameters (P_i) affecting the system are established, they are placed along the leading diagonal of the matrix. The effects of each factor on the others, called 'interactions', are located on the off – diagonal cells.

Each sensitive parameter P_i has to be divided into several categories, representing specific conditions causing the slope failure, and a score has to be assigned to each one. The lower the category (and the score), the more stable the conditions. Binary interactions between parameters are denoted by numerical values, using the Expert Semi-Quantitative (ESQ) method (Hudson, 1992). Again, the lower the value, the less the interaction.

Each row C_i of the matrix represents the influence of the P_i parameter on the others (cause, C), while each column E_i represents the effects of the other parameters on P_i (effect, E). The sum of the C_i and E_i values represents an indicator of the i-parameter's significance in the system. A weighting coefficient, a_i, can be calculated as shown in Eq. (1), where r is the maximum rating assigned to the categories and k is the number of the sensitive parameters considered.

$$a_i = \frac{1}{r}\frac{\left(C_i + E_i\right)}{\sum_{i=1}^{k}\left(C_i + E_i\right)}100 \tag{1}$$

Finally, the susceptibility index (SI) can be determined for the system as shown in Eq. (2):

$$SI = \sum_i a_i P_i \tag{2}$$

$$\begin{bmatrix} P_1 & 1,2 & \dots & 1,k & 1,n \\ 2,1 & P_2 & \dots & 2,k & 2,n \\ \dots & \dots & \dots & \dots & \dots \\ k,1 & k,2 & \dots & P_k & k,n \\ n,1 & n,2 & \dots & n,k & P_n \end{bmatrix}$$

Fig. 1. Interaction matrix. The main parameters P_i are placed on the leading diagonal. Their interactions are located in the off-diagonal boxes.

Matrice di interazione. I parametri principali P_i sono elencati lungo la diagonale principale. Le interazioni tra i parametri sono elencati nelle celle non diagonali.

Tab. 1. Slope gradient, slope curvature, flow area and shallow landslide classes, and related scores.
Classi di pendenza, di curvatura, di aree di flusso e di precedenti dissesti, e relativi punteggi.

Classes of slope gradient [°]	Score	Classes of curvature	Score	Classes of flow area [m^2]	Score	Classes of landslide	Score
< 16	1	< 0 (concavity)	3	> 1600	3	active	3
25÷35	3	> 0 (convexity)	2	800÷1600	2	dormant	2
16÷25 and 35÷45	2	= 0 (flat surface)	1	< 800	1	stabilized	1
> 45	0						

SI can be easily determined and graphically represented using the GIS techniques. This parameter represents the inherent potential instability of each grid cell of the landslide susceptibility map. The choice of the sensitive parameters (Pi) is strictly related to the characteristics of the study area and available data (Guzzetti *et al.*, 1999; Jebur, 2014; Kavzoglu *et al.*, 2015; Rozos *et al.*, 2008). For shallow landslides slope gradient, orientation of soil layers, lithology, surficial soil layer thickness, vegetation, curvature of the slope, flow area, previous landslides, land use and land cover are some of the main predisposing and triggering causes usually considered in the literature (Bartolomei *et al.*, 2006; Campus *et al.*, 2005; Mousavi *et al.*, 2011). Once susceptibility has been evaluated, to assess landslide hazard the time recurrence must be evaluated. To do this, as described in Section 3.2, an empirical rainfall threshold available in the literature for the study area was used.

3. Application of the proposed method

The QHM proposed in this paper was applied to a case study, the former Municipality of Cellio (VC), which at present is Cellio-Breia Municipality, in Sesia Valley, north-western Italy. It is a mainly mountainous area subjected to heavy rainfalls, which induce channelled water and washing out on the slope. These features often cause the triggering of instability of surface soil layers.

3.1. Susceptibility analysis

To perform a susceptibility analysis in the QHM an interaction matrix was constructed. First, the main variables for the leading diagonal terms (P_i) were established. Then, the interactions for the off-diagonal boxes were evaluated.

On the basis of the data and thematic maps available for the area of interest, it was not possible to evaluate some of the causative factors of landslides, such as orientation of the soil layers, lithology, surficial soil layer thickness, vegetation and land cover. Thus, only the following four sensitive parameters were taken into account in the analysis: slope gradient (P_1), curvature (P_2), flow area (P_3) and previous landslides (P_4).

Therefore, the first step was to draw the spatial variation maps for these parameters using a GIS environment. To this aim, a DTM with a grid pitch of 20 meters was used. Each of the four P_i parameters was divided into different categories. A score ranging from 0 to 3 (least severe to most severe conditions, respectively) was assigned to each one, as shown in Table 1:

1. Slope gradient: a map of slope gradient was created from the DTM, using a specific ArcGis tool. To define the slope gradient classes, previous findings from the literature were considered. These studies have indicated that the shallow landslides mainly occur in slopes with a dip from 16° to 45°, with a frequency peak between 25° and 35° (Campus *et al.*, 2005; Govi *et al.*, 1985).
2. Slope curvature: based on the DTM and by means of a specific GIS tool, a map of curvatures was obtained. A distinction between negative (upwardly concave), positive (upwardly convex) and straight curvature (flat surface) was also made (Bartolomei *et al.*, 2006; Mousavi *et al.*, 2011).
3. Flow area: this parameter was obtained from the DTM, by means of the GIS technology (Bartolomei *et al.*, 2006). The scores increase as the accumulated water flow increases (leading to the soil saturation).
4. Previous landslides: landsides map provided by the Cellio Municipality was used with regard to soil slips, the most common instability type. The scores reported in Table 1 were associated to three classes of landslides: active, dormant and stabilized.

The scores chosen for the off-diagonal terms of the interaction matrix, considering the influence of parameter A on parameter B, are listed in Table 2.

As mentioned above, the off-diagonal terms represent binary interactions between the sensitive parameters. They were given numerical values ranging from 0 to 2, where 2 means "critical", 1 "medium" and 0 "no interaction". The adopted range (0-2) is smaller

Table 2. Scores for the interaction between different parameters for the Cellio Municipality.
Punteggi attribuiti a coppie di parametri in funzione delle loro reciproche interazioni per il caso studio del Comune di Cellio.

Couple of parameters	Parameter A	Parameter B	Score
1,2	Slope gradient	Slope curvature	2
2,1	Slope curvature	Slope gradient	1
1,3	Slope gradient	Flow area	2
3,1	Flow area	Slope gradient	0
1,4	Slope gradient	Previous landslides	2
4,1	Previous landslides	Slope gradient	1
2,3	Slope curvature	Flow area	2
3,2	Flow area	Flow area	0
2,4	Slope curvature	Previous landslides	1
4,2	Previous landslides	Slope curvature	1
3,4	Flow area	Previous landslides	1
4,3	Previous landslides	Flow area	1
1,n	Slope gradient	Susceptibility	2
2,n	Slope curvature	Susceptibility	1
3,n	Flow area	Susceptibility	1
4,n	Previous landslides	Susceptibility	2
n,1	Susceptibility	Slope gradient	0
n,2	Susceptibility	Slope curvature	0
n,3	Susceptibility	Flow area	0
n,4	Susceptibility	Previous landslides	1

than usual ones because it would have made no sense to consider a wider classification without much information available. Although this lack of information constitutes a limitation in the analysis, it can be accepted in favour of the quickness of this procedure.

Finally, the interaction matrix was compiled (Figure 2). Along the leading diagonal were located the four sensitive parameters available for the case study and the susceptibility, P_n. On the off-diagonal cells were placed the effects of each principal parameter P_i on the others (i.e., interactions).

$$\begin{bmatrix} P_1 & 2 & 2 & 2 & 2 \\ 1 & P_2 & 2 & 1 & 1 \\ 0 & 0 & P_3 & 1 & 1 \\ 1 & 1 & 1 & P_4 & 2 \\ 0 & 0 & 0 & 1 & P_n \end{bmatrix}$$

Fig. 2. Interaction matrix for the case study.
Matrice di interazione relativa al caso studio.

The interactive intensity value of each parameter, which is denoted as the sum of the C_i and E_i scores (cause + effect), is: P_1: $C_1 + E_1 = 10$; P_2: $C_2 + E_2 = 8$; P_2: $C_3 + E_3 = 7$; P_4: $C_4 + E_4 = 10$.

An interaction percentage value for each (i-th) parameter can be determined from Eq. (3):

$$\left(C_i+E_i\right)_\% = \frac{\left(C_i+E_i\right)}{\sum_{i=1}^{k}\left(C_i+E_i\right)} 100 \qquad (3)$$

obtaining the cause+effect percentage vector constituted by the four interaction percentage values: $(C + E)_\% = (28.57;\ 22.86;\ 20.00;\ 28.57)\%$. These values represent the relative attitude of each parameter P_i to induce a landslide. In this case study, slope gradient and previous landslides are the most influent factors. Then, it was possible to calculate the weighting coefficient, a_i, for each parameter P_i using Eq. (1) or, similarly, as the ratio between the cause+effect percentage and the maximum score, r, assigned to the classes, that is 3: $a_i = (9.52;7.62;6.67;9.52)$. The a_i values are then introduced in the susceptibility index formula of Eq. (2): $SI = \sum_i a_i P_i = 9.52P_1 + 7.62P_2 + 6.67P_3 + 9.52P_4$, being P_i the scores chosen for the main parameters.

Using the ArcGIS software a susceptibility map was constructed, having identified three classes of susceptibility: S1, very low; S2, low/moderate (i.e. there are no evidences that the area is prone to landslide, but there are some unfavourable factors that make the triggering of a landslide conceivable); S3, high. The susceptibility map obtained is shown in Figure 3.

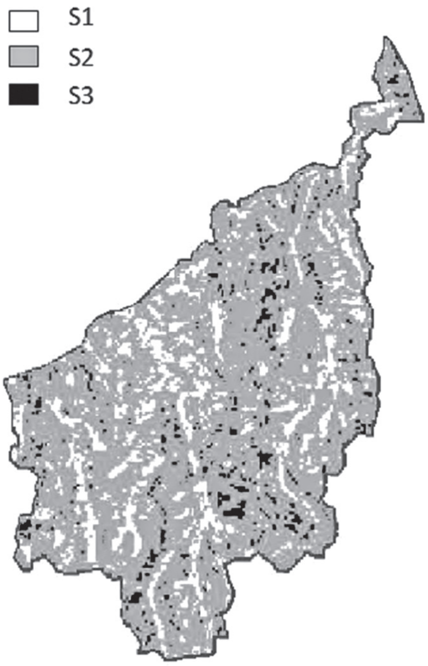

Fig. 3. Map of susceptibility to shallow landslides for the Cellio Municipality (VC). Classes of susceptibility: very low (S1), low/moderate (S2) and high (S3)
Mappa di suscettibilità da frane superficiali per il Comune di Cellio (VC). Classi di suscettibilità: molto bassa (S1), bassa/media (S2) e elevata (S3).

This map shows that the most part of the territory (about 80%) is characterized by a low/moderate susceptibility and that high susceptibility areas are just 4% of it.

3.2. Hazard analysis

In order to define the landslide temporal probability, three empirical equations for the critical rainfall thresholds were considered: local threshold for Valsesia region equal to 2.65 mm/h, regional threshold for Piemonte Region equal to 3.88 mm/h (Aleotti, 2004) and pragmatic threshold for mountain environment equal to 5.07 mm/h (Tiranti and Rabuffetti, 2010). According to the literature suggestions, the critical duration was set at 24 hours, as it is reasonable to assume that after that period the water flow in the soil stops and stationary conditions are reached. With the aim to choose the more realistic rainfall threshold, these values were compared with the intensity provided by the pluviometric station closest to the study area, in order to calculate the number of the threshold exceedances and compare them with the available historical data. With reference to available pluviometric data, a period of 11 years was considered. Finally, the regional threshold was chosen, as it provided a number of exceedances closest to historical data. This value was exceeded 22 times in the reference period, that is 2 exceedances in a year. As each exceedance can be considered as a landslide triggering, a return period, T, of 6 months was used to estimate the hazard in the Cellio Municipality. Since the whole study area is characterized by the same T, the hazard map shown in Figure 5b matches up well with the susceptibility map of Figure 3.

4. Validation of the QHM

4.1. Comparison with landslide events registered after 2012

In order to validate the approach proposed in this paper, the location of the shallow landslides occurred since 2012 in the former Cellio Municipality was superimposed on the hazard map provided by the QHM method. As shown in Figure 4, 25 landslides were registered and their location is highlighted with circles (Adorno personal communication, 2020). All the landslides are located in moderate or high hazard areas, confirming the validity of the predicted map and, hence, the reliability of the proposed method.

4.2. Comparison with a deterministic method

To verify the reliability of the QHM, the results were also compared with those obtained from a deterministic method, the Stability Index MAPping – SINMAP (Pack *et al.*, 1998). SINMAP, based on the infinite slope stability model, is implemented in a routine of ArcGIS and provides a stability index SI, which is defined as the probability that the safety factor, SF, is greater than one. For the case study, the topographic variables were taken directly from the DTM with a grid pitch of 20 meters, while the other parameters were introduced in the analysis as variables between their upper and lower limits, assuming a uniform probabilistic distribution. Specifically, the detachment areas were chosen by observing the landslides inventory maps, the transmissivity was calculated on the basis of a mean permeability value, k, equal to $4{,}4 \cdot 10^{-5}$ m/s (Campus *et al.*, 2005) and the soil mechanical parameters were taken from the literature and a back analysis (unit weight: 16 kN/m^3; friction angle: 25°÷30°; cohesion: 3 kPa).

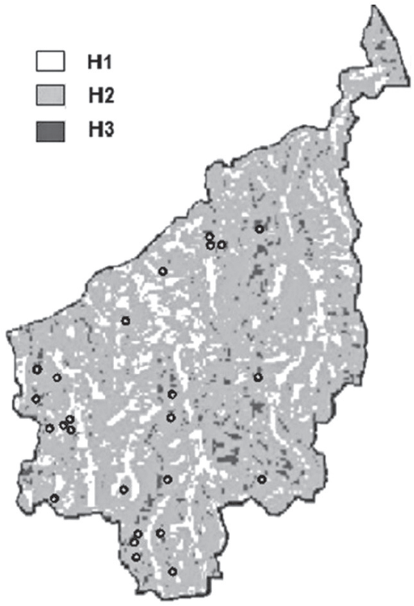

Fig. 4. QHM hazard map for the Cellio Municipality (VC) with the indication of the landslides occurred from 2012 to 2019, highlighted with the black and white circles.
Mappa di pericolosità ottenuta con il metodo QHM per il Comune di Cellio (VC) con l'indicazione delle frane registrate dal 2012 al 2019 ed indicate con i cerchi bianchi e neri.

A stability index map was generated using the same classes of the QHM susceptibility map. The hazard maps obtained with QHM and SINMAP were then compared. As shown in Figure 5, in the SINMAP map the area belonging to the lowest hazard class (H1) is a bit wider (around 14%) than that shown in the QHM map, while the opposite occurs for the low/moderate hazard class (H2). The area with the highest level of hazard (H3) is instead comparable. Therefore, the QHM results appear broadly a bit more conservative.

6. Conclusions

The multiparametric methodology proposed in this paper enables to define, at small scale and in short time, the areas most affected by shallow landslide acti-

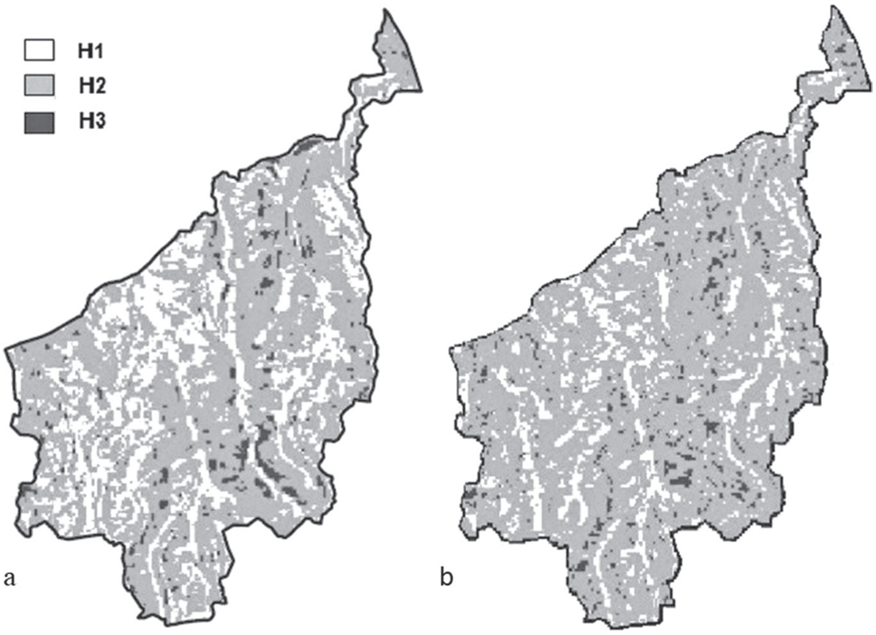

Fig. 5. Comparison between the SINMAP (a) and the QHM (b) hazard maps. Classes of hazard: very low (H1), low/moderate (H2) and high (H3).
Mappa di pericolosità da frane superficiali per il Comune di Cellio (VC) ottenute con SINMAP (a) e QHM (b). Classi di pericolosità: molto bassa (H1), bassa/media (H2) e elevata (H3).

vities, providing susceptibility and hazard maps of clear and simple interpretation. This represents the basic requirements for planners, local administrations and decision makers for monitoring and territorial planning activities. Despite rigorous methods, which require a high number of parameters (often very difficult to determine) for their application, the great advantage of the QHM method is that it can be applied at various scales and requires the knowledge of relatively few parameters.

The result is even more satisfactory if one takes into account that for the proposed case study the available information was very limited (i.e. half of the parameters generally required for rigorous methods to be applied). The reliability of the empirical QHM was tested comparing the hazard map (obtained using the DTM and other data updated to 2012) with the landslides occurred in the last 7 years in that area. This comparison showed a good agreement between the predicted higher hazard zones and the location of the landslides. Moreover, the QHM hazard map was also compared with that provided by the deterministic SINMAP method. The two hazard maps were found to be in good agreement, as well. In particular, almost all of the highest hazard areas of the QHM map corresponded to those of the SINMAP map. Moreover, the vast majority of DTM's cells (around 73,2%) were found to belong to the same hazard class, while around 26,6% differed from each other one class maximum on the safety side.

An interesting future work would be to apply these methodologies to other case studies and to compare the results with the aim of checking if the differences highlighted in this paper still remain, with particular reference to the estimation of the medium-hazard landslide areas.

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Acknowledgements

The authors would like to thank the Regione Piemonte – Direction of Public Works, Mountains, Land Protection, Forests, Civil Protection, Transports and Logistics – Regional Technical Field – Biella and Vercelli, for providing access to geological, topographic and geomechanical data.