Debris-flow hazard assessment related to geomorphological and geological setting and to shallow-landslides occurrence.

D. Fontan & D. Murgese
SEA Consulting S.r.l., via Cernaia 27, 10121 Turin, Italy.

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ABSTRACT: Debris-flows hazard assessment related to shallow landslides occurrence is evaluated by means of AFHE (Alluvial Fan Hazard Evaluation) and SLHA (Shallow Landslides Hazard Assessment) methods. Both methodologies are based on the combination of weighted thematic maps, whose weights are calculated following the system theory approach. Results are obtained by means of GIS analysis. The AFHE method allows the calculation of the catchment hazard index and the production of the alluvial-fan hazard maps. The catchment hazard index describes the hill-slope proneness to deliver sediment towards the channels and the capability of the latter to transfer this sediment to the apex of the alluvial fan. The alluvial-fan hazard-map is a raster map, where the alluvial fan is partitioned into square cells, each one characterised by specific coefficients, ranging from 0 (very low hazard) to 1 (very high hazard). Values are given based on process energy, event frequency, prevailing geomorphological processes and hydraulic studies. The SLHA method allows the identification of potential sediment sources for debris-flows. This procedure is applied to obtain the shallow-landslide susceptibility for the catchment area by combining weighted thematic maps. Maps are related to the factors that control the occurrence of shallow landslide: geomorphology (slope, landslides presence), soil geotechnical properties, land cover, land use, soil permeability etc. The coupled methods were applied in a mountain area of the western Italian Alps. The proposed procedures are effective both at regional and at local scale, allowing a simple and quick preliminary hazard assessment.

1 INTRODUCTION

Debris-flows represent one of the major threats for human communities in the Alpine regions. This is due to the fact that past urban expansion occurred mainly on alluvial-fans increasing the risk related to this phenomenon and exposing an increasing number of people and facilities to this danger. An important task in natural hazard assessment, when dealing with alluvial-fan hazard zoning, is the identification of all those sectors which in case of intense rainfall may be affected by the debris flows. Another important task is the estimation of the magnitude of these events. This information is particularly useful in urban planning and when developing new mitigation structures.

This work introduces the combined use of two techniques developed by S.E.A. consultants: Shallow Landslides Hazard Assessment (SLHA) and Alluvial Fan Hazard Evaluation (AFHE). The first method provides information about the occurrence of shallow-landslide for the catchment area, thus about the debris flow material sources. The second method allows the calculation of indexes which give an idea about the percentage of sediment which can be transported from the slopes to the alluvial-fan apex by the drainage network; based on this information alluvial-fan zoning is performed. Considering different hazard levels and initial debris-flow magnitude, different urban planning policies and mitigation structures can be devised.

2 THEORETICAL FRAMEWORK: THE SYSTEM THEORY IN BRIEF

The weight of each factor influencing shallow-landslide occurrence or the alluvial-fan hazard index is calculated following the fully coupled model (FCM) proposed by Jiao and Hudson (1995). The basic tool for analysing the interactions between the factors controlling the evolution of the studied process (in this case the occurrence of shallow landslides) is a squared matrix: the Binary Interaction Matrix (BIM). Factors are placed in the leading diagonal boxes of the matrix (the leading diagonal is the one from top left to bottom right). Using a clockwise convention, we consider the influence of factor A on factor B in one off-diagonal box and the influence of factor B on factor A in another off-diagonal box (Fig. 1a). Interactions between the factors are quantified following an expert semi-quantitative method (Jiao and Hudson, 1995): 0 no interaction, ±1 weak interaction, ±2 medium interaction, ±3 strong interaction, ±4 "critical" interaction. Positive values indicate a positive correlation between the two considered factors, whereas a negative value is assigned in case of negative correlation. Taking into account that the BIM considers only interactions between single pairs of factors at a time, the value given to each box of the leading diagonal is 0 (i.e. factor A does not influence itself). When all the binary interactions are defined, the BIM is then used for examining the complete interaction network existing between all the variables of the model. Figure 1b shows a possible mechanism where factor A influences factor D, which in turn influences factor E, which influences factor B, which influences factor C, which influences factor A. This means that the interaction between A and D in a "fully" coupled model does not depend only on the relationship between the two factors, but it also depends on the binary relationships (i.e. D on E or B on C) in the pathway (loop) from A to A. The complete set of pathways displayed by the interaction matrix can be portrayed by means of graph theory (Fig. 1c) (Diestel, 2005). The leading diagonal boxes become the nodes of the graph and the arcs connecting the nodes represent the binary interactions defined by means of the initial BIM (Fig. b). The path displayed by the arcs indicates that, when the model is considered as whole (fully coupled), a single factor does influence itself (loop from factor A back to factor A). In order to evaluate this feedback process together with all the relations formerly outlined by the BIM, the Jordan recursion algorithm is applied. This algorithm converts the BIM into a Global Interaction Matrix (GIM), where all the relations between factors and feedback processes are considered together. Since one factor can influence itself in the GIM, the values of the leading diagonal boxes will differ from 0. The GIM provides the weights of each factor.

For a given situation, the model output will be the weighted sum of the factors value time factors weights:

$$\text{Model output} = k_1 \cdot F_1 + \dots\dots\dots + k_n \cdot F_n \tag{1}$$

where k_i is the weight of factor i and F_i is the factor value.

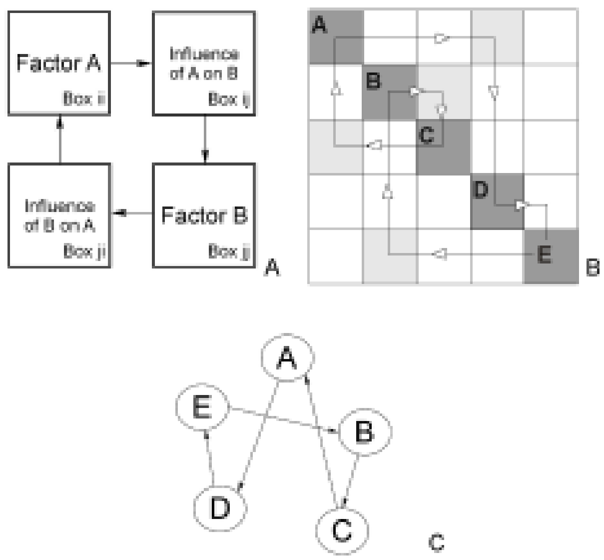

Figure 1. Example of a Binary interaction matrix (BIM) and hypothetical pathway for a 5-factor BIM; after Jiao and Hudson (1995).
A) Factors controlling the examined phenomenon are placed on leading diagonal boxes of the squared matrix. Interactions between factor A and factor B are placed in the two off-diagonal boxes.
B) Hypothetical pathway for a five-factor binary interaction matrix (BIM). Grey: factors A, B, C, D, and E; pale grey: interactions between factors. Arrows indicate the path of interactions.
C) Mechanism network obtained from the five-factor BIM of figure 1a.

3 ALLUVIAL FAN HAZARD EVALUATION

Hazard levels for alluvial-fans (HI_{AF}) were calculated following the Fontan et al. (2004) procedure. Alluvial-fan hazard is calculated considering the contribution to alluvial-fan activity from upstream catchments (
Figure **2**).

According to this procedure a two-step analysis is conducted.

- The first phase requires the calculation of total upstream catchment hazard index (HI_{CB}). This value provides an indication about catchment sediment-delivery proneness (likelihood) and the amount of sediment potentially delivered (magnitude). HI_{CB} is calculated as the sum of two indexes: the catchment tendency to transfer slope sediment to the drainage network (PI_{slo}), and the catchment sediment-transport proneness (PI_{ch}) (Table 1).These two terms are calculated following the system theory approach (Jiao and Hudson, 1995). PI_{slo} and PI_{ch} are the weighted sums of factors involved in slope failure process and downstream transportation (for variable codes refer to Table 2).

$$PI_{slo} = RE \cdot V\mathit{re} + SE \cdot V\mathit{se} + SLO \cdot V\mathit{slo} + CLI \cdot V\mathit{cli} + GEOT \cdot V\mathit{geot} + I \cdot V\mathit{i} + V \cdot V\mathit{v} \qquad (2)$$

$$PI_{ch} = SLO \cdot V\mathit{slo} + CLI \cdot V\mathit{cli} + GEOT \cdot V\mathit{geot} + HF \cdot V\mathit{hf} \qquad (3)$$

where Vi is the variable associated to the factor Fi. For further details about variables calculation see Fontan et al. (2004).

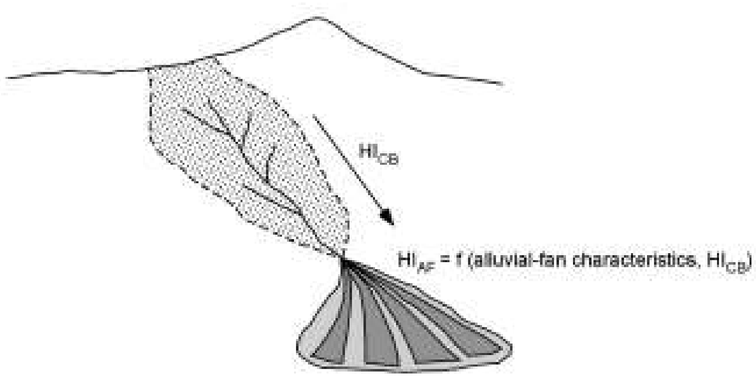

Figure 2. Alluvial-Fan Hazard evaluation: hazard level is calculated considering both alluvial-fan features and upstream catchment proneness to deliver sediment to downstream areas.

Table 1. PI_{slo} and PI_{ch} values.

Value	PI_{slo}	PI_{ch}
0	Sediments related to slope erosional processes do not reach the drainage network	Sediments are not transported downstream by the drainage network
1	Sediments related to erosional processes are entirely delivered to the rivers	All the sediment coming from the slope is transported downstream by rivers

When the two terms are calculated HI_{CB} is given by the following formula:

$$HI_{CB} = \left(\frac{PI_{slo} + PI_{ch}}{2} \right) \cdot \left(\frac{M_m}{M_{max}} \right) \tag{4}$$

where M_m is the average shallow-cover thickness and M_{max} is the assumed maximum thickness (10 m). HI_{CB} values range between 0 and 1.

Table 2 – Factors involved in HICB calculation

Factor	Code	Description	Data source
Quaternary deposits	SE GEOT I	Erodibility for slope deposits Geotechnical proprieties Infiltration proneness	Geological map
Slope	SLO	Tan (slope angle°)	Digital Terrain Model
Outcrops	RE	Bedrock erodibility	Geological map
Land cover	V	Vegetal cover values f(type and density)	Land cover map
Landslides (landslides reported for the study area)	I	Contribution to infiltration due to landslide presence	Geomorphological map
Human-made mitigation structures	HF	Contribution to slope stability due to slope engineering	Field observation
Climate	CLI	Rainfall Contribution to slopes instability	Piedmont Region Meteorological Database

- The second phase is related only to the alluvial-fan system areas. Hazard index calculation involves the sum of factors related to alluvial-fan features, represented in the form of vector data. These features are gathered by means of historical geomorphological and geological analyses focused on the alluvial-fan. For each vector layer, geographic objects are given a value based on the feature represented and the situation observed on the field or obtained from bibliographic information. Data used in this phase are related to:
  - $HI_{CB,}$ expressed as an homogeneous value for the entire alluvial fan;
  - Alluvial-fan Channels classified based on activity state (based on field observation and data from hydraulic studies);
  - Depressions or hummocks;
  - Historical analysis, which allows the identification of areas already affected by debris-flows in the past;
  - Presence of debris related to former alluvial-fan activity;
  - Vegetal cover;
  - Average slope. Slope classes are 0°-4° (areas, whose inclination does not allow flow propagation), 4°-11° (areas whose inclination allows sediment transportation), >11° (areas potentially subject to erosion) (Takahashi, 1981);

- Sediment grain-size;
- Stream-flow conditions. A distinction between floodable and non-floodable areas;
- Alluvial-fan activity. Active and inactive alluvial-fan sectors.

Based on field observations, these attributes are given values between 0 and 1 (0 not critical condition, 1 critical condition). Each one of the ten factors is represented as a thematic layer. Using the combination-maps technique, HI_{AF} is calculated as the sum of the factor values divided by 10 (number of factors).

4 SHALLOW LANDSLIDE HAZARD ASSESSMENT

Shallow landslides hazard was assessed according to the methodology proposed by (Fontan et al., in prep.). Shallow Landslides Hazard Assessment (SLHA) calculates landslides susceptibility-levels for specific areas based on the combination of weighted thematic maps (factors involved in the SLHA model). According to this method, shallow landslides hazard index (SLHI) is calculated as follows:

$$SLHI = a_1 \cdot x_1 + a_2 \cdot x_2 + a_3 \cdot x_3 + a_4 \cdot x_4 + \ldots + a_n \cdot x_n \qquad 5$$

where x_i are the values of parameters influencing landslide occurrence, and a_i are weights measuring the relevance of each parameter. Weights are determined according to the system theory (Jiao and Hudson, 1995).

Factors considered by SLHA model are given in Table 3. Variables assume values between 0 and 1 according to the classification system of Fontan et al., (in prep.).

5 HAZARD ASSESSMENT

Debris-flows hazard assessment involves the identification of the potential sediment source areas (sectors characterised by high shallow landslide susceptibility) and the analysis of the mechanisms favouring down-slope sediment transport. The first goal is achieved by the application of SHLA, whereas the second objective is achieved by means of AFHE.

Table 3. Factor involved in shallow landslide hazard calculation.

Factor	Code	Data source
tan(slope angle)	(SLO)	Digital Terrain Model
Cohesion	(C)	Geological map
Inner friction angle	(PHI)	Geological map
Permeability	(K)	Geological map
Specific Weight	(G)	Geological map
Landslides (presence of a landslide)	(L)	Geomorphological map
Quaternary deposits thickness	(M)	Geological map
Vegetal cover	(CV)	Land cover map
Water saturation	(H)	Digital Terrain Model
Infiltration (1-SLO)	(W)	Digital Terrain Model
Duration of rain event	(t)	Piedmont Region Meteorological Database
Rainfall level	(PIO)	Piedmont Region Meteorological Database

6 CASE STUDY: BRUZOLO MUNICIPALITY AREA

The study area corresponds to the municipality of Bruzolo (30 km west of Turin – Susa Valley – Piedmont Region- -NW Italy). Forested and scarcely urbanized hill-slopes represent 80% of the Bruzolo territory, whereas the remaining areas lie over the Dora Riparia River flood-plain. This populated area is characterised by residential sectors, farmlands and factories. The Pissaglio River is the most important drainage. Most of the residential and socially relevant areas are all located on the alluvial fan, whereas agriculture and industries are mainly located on the Dora Riparia River flood-plain.

The geological units outcropping in the study area belong to the tectonic units forming the Alpine belt. The slope area is characterized by the presence of rocks belonging to the Dora-Maira unit (marbles, micaschists, gneiss) and to the Piedmont unit (calc-schists and metamorphosed ophiolitic rocks). Quaternary deposits are represented by colluvial and glacial deposits. Lowland sectors are characterized by alluvial-fan and flood-plain deposits. The average thickness of the colluvial deposits is 5 m.

6.1 *Past events*

During the last 150 years the lower Susa Valley has been affected by one hundred floods. Seventy of these events, caused damages over wide areas. These events had an average recurrence interval of two years.

Floods occurred mainly during the time of the year characterized by high rainfall level: May (14% of the events), June (37% of the events) and September (11% of the events). More than half of the events which affected wide areas occurred toward the end of spring; about 60% of the episodes characterised also by the occurrence of debris-flows, caused damages to the urban areas. In eight cases, floods and/or debris-flows caused a total of forty victims among the population. According to local public archives, the most severe events occurred in October 1685, May 1728, July 1885, June 1891 and 1957, May 1977 and October 2000 (tab. 4).

During the last three hundred years, twenty floods have been recorded for the Pissaglio river, affecting urban areas in six cases. In October 1846, 12 people died and several buildings were damaged. In June 1875, one person died, due to a house collapsing. In 1957, the area in the vicinity of the cemetery was flooded. Since the 19th century, the inhabitants of Bruzolo have built river engineering structures in the upper and middle section of the alluvial fan, to prevent damages and victims in case of floods. The first structure to be realized was the embankment named “la Mura”, which was built on the left riverbank of the Pissaglio river (fig.). The most recent structures (riverbank reinforcements and check dams along the Pissaglio river) were built in 1957 and 2000.

Table 4 Events (folds, debris-flows) recorded for Bruzolo municipality .

Year	Damages
1710	NA
1728	NA
1798	Campobellino and Gerbido regions damaged. Cotti R. Toassone region damaged
1811	NA
1842	NA
1846	Barboj houses destroyed 12 people died River bank damaged
1860	NA
1875	NA
1900	NA
1900	NA
1900	River engineering structures damaged
1919	River engineering structures damaged
1927	NA
1937	NA
1945	NA
1947	NA
1947	NA
1955	NA
1957	Embankment built in 1845 destroyed
1964	NA
1968	NA
1972	Damages to the local roads
2000	-

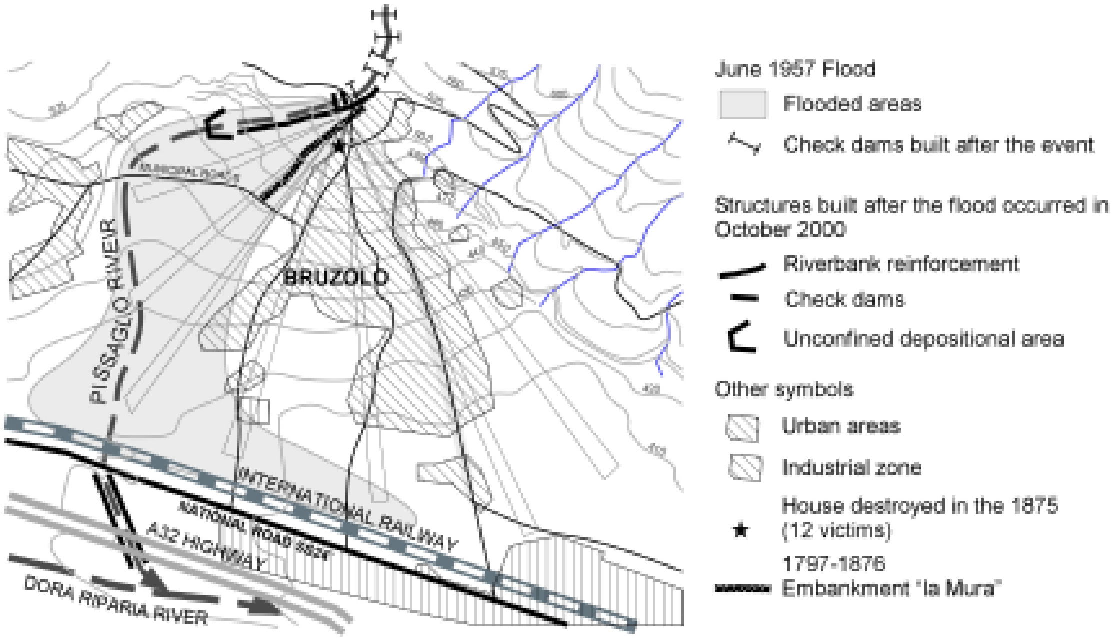

Figure 3. Maps showing the areas affected by June 1957 and October 2000 floods. River engineering structures built after these events are also displayed.

6.2 *SLHA application*

The data related to the factors involved in shallow landslide assessment were acquired from the Piedmont Region Meteorological Database, the Digital Terrain Model, the geological and the land-cover map for Bruzolo's municipality (Table 3).

According to the results shown in

Figure 4, 65% of the slope area is characterised by very high hazard level. Sectors presenting the highest shallow-landslides hazard level are located in the upper part of the study area, with grassland vegetation and/or slopes angle >25°. Another critical area is located just up-slope the alluvial-fan apex. For this sector the Pissaglio riverbanks display high shallow-landslide hazard levels. In case of heavy rain, these parts of the catchment could provide a high amount of sediment, which could easily reach the Pissaglio alluvial-fan.

6.3 *AFHE calculation*

AFHE calculation was performed considering the data related to the Pissaglio River catchment. Indexes values calculated for the first phase of the analysis (see par. 3) are shown in Table 4.

Table 4. HI_{CB}, PI_{slo} and PI_{cha} calculated for the Pissaglio River catchment.

Index	Value
HI_{CB}	0.36
PI_{slo}	0.56
PI_{cha}	0.89

HI_{CB} was calculated considering a shallow-cover average thickness of 5 m. Calculation was performed considering the worst meteorological conditions: the highest precipitation level recorded for the study area and rainfall event lasting 24 hours.

Only half (56%) of the total amount of shallow-landslide sediment reaches the drainage network (PI_{slo}). Rivers deliver down-valley about 89% (PI_{cha}) of the total amount of sediments which is transferred from the slopes. The total amount of sediments transferred to the alluvial-fan by the coupled slope-river system is about 36% (HI_{CB}) of the total volume of shallow-landslides which occurred on the hill-slope areas.

The HI_{CB} value was used during the second phase of the analysis: the alluvial-fan hazard assessment (Fig. 5).

High hazard levels are recorded for those sectors near the Pissaglio River characterised by the presence of abandoned channels. These areas are also characterised by the presence of debris-flow lobes. Bruzolo's urban expansion is restricted to those sectors characterised by low hazard level.

7 CONCLUSIONS

The combined application of Shallow Landslides Hazard Assessment and Alluvial Fan Hazard Evaluation represents a useful tool for local communities. Shallow-landslide hazard assessment allows the systematic identification of sectors characterised by high shallow-landslide occurrence proneness. These sectors can be considered as the major source of sediment which can be delivered to the streams of the Pissaglio river catchment, which covers 55% of the study area. Main controlling factors for landslide triggering appear to be slope angle and vegetation cover. High shallow-landslide hazard levels are recorded for areas where the slope angle is >25° and vegetation cover is mainly grassland. When assessing the hazard related to the occurrence of debris-flow, which in turn could affect the Bruzolo urban area, the efficiency of the coupled slope-river system in transferring sediment from the hill-slope sectors to the alluvial fan was estimated by means of alluvial fan hazard evaluation. According to the analysis, only 36% of the total sediment volume involved in shallow-landslide is transferred downstream.

Geological, geomorphological and historical analysis allowed the alluvial-fan hazard zoning. Information acquired for this part of the study includes data related to past alluvial-fan activity and results from hydraulic studies. This interpretation provides useful information about the future potential evolution of the alluvial-fan system.

The methods proposed permit a first-order assessment of the potential sediment source-areas for debris-flows. Shallow-landside hazard assessment gives an indication for local authorities and risk managers about the areas where land management policies should focus in order to reduce shallow-landslides occurrence. Studies aimed at exactly evaluating the potential amount of sediment involved in landslides would provide information about the magnitude of debris-flows which could represent a threat for the inhabited areas on the alluvial fan. This information is in turn a key element when planning mitigation structures and urban expansion policies.

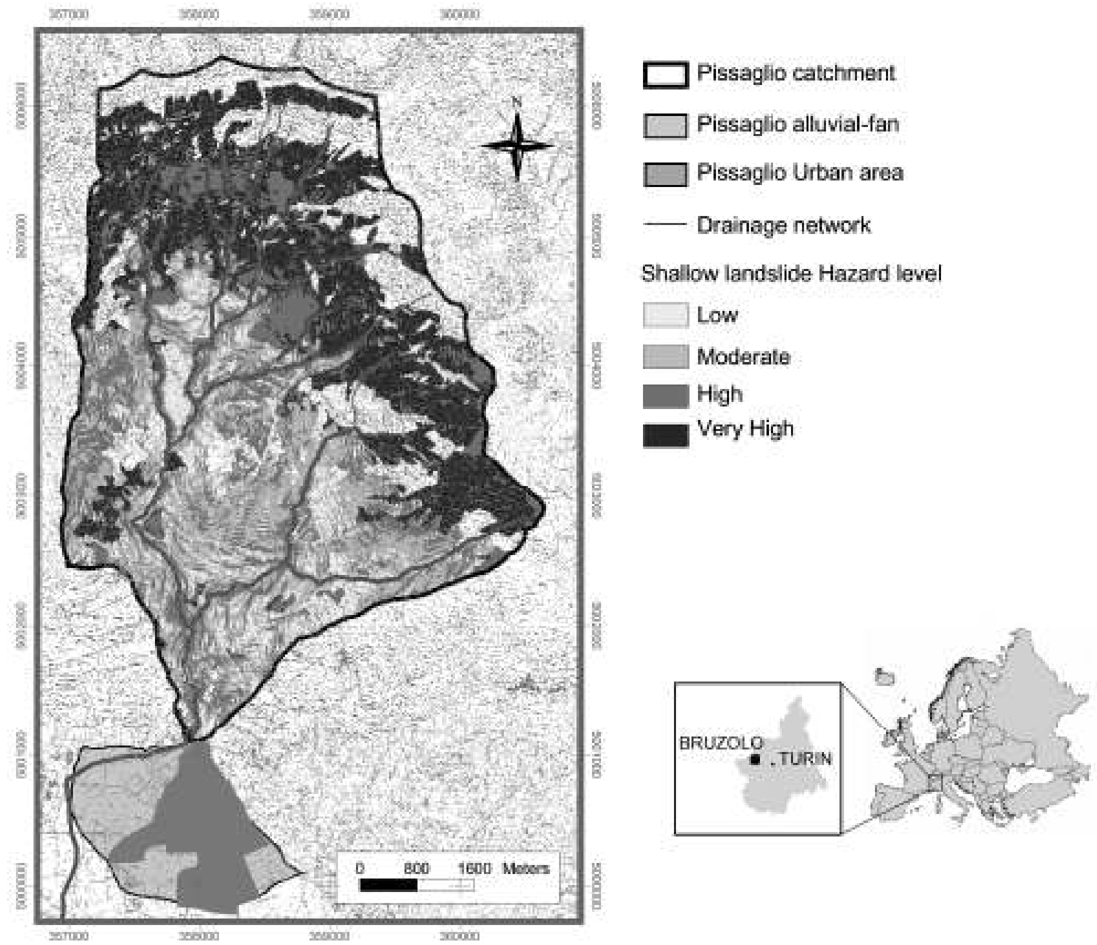

Figure 4 – Shallow landslide hazard assessment – Results. Potential sediments sources are represented by very dark and dark areas, where shallow-landslide hazard is high or very high. The analysis does not include outcrops.

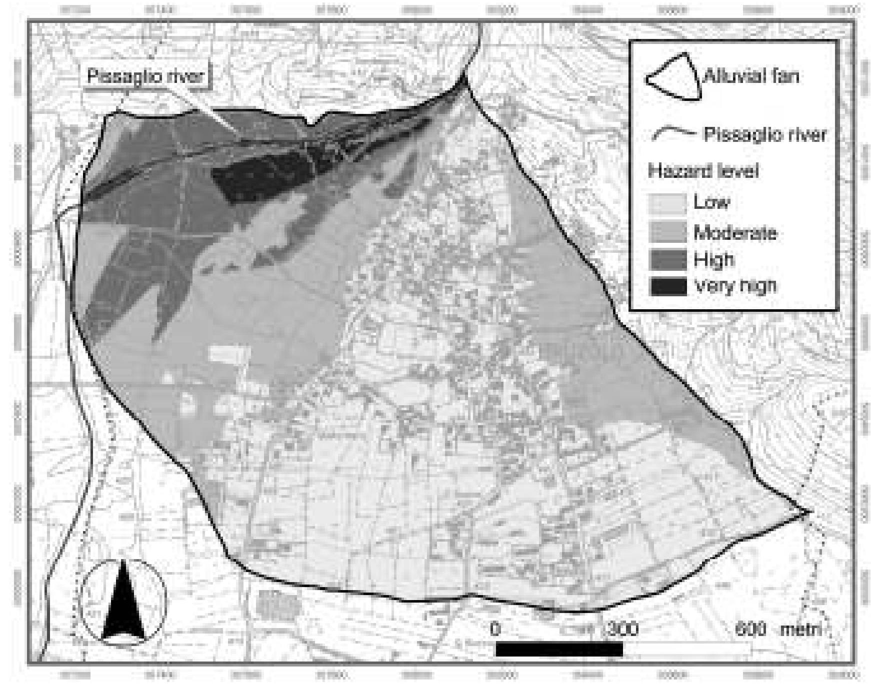

Figure 5. Bruzolo alluvial-fan hazard zonation. The Pissaglio river follows the path resulting from river engineering structures.

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