# Quantitative Landslide Risk Assessment at the River Basin Scale

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**Abtsract.** Landslides and mass movements in general are very common in Italy, especially along the main mountain chains such as the Alps and the Apennines. The study area is no exception to this rule, as it is strongly subjected to mass movements.

The study area is the Arno river basin, which is located in northern Apennines, Italy, and has an extension of 9116 km$^2$. A new landslide inventory of the whole area was carried out using conventional (aerial-photo interpretation and field surveys) and non-conventional methods such as remote sensing techniques including DInSAR and PS-InSAR, (Farina et al. 2006). The great majority of the mapped mass movements are rotational slides (75%), solifluctions and other shallow slow movements (17%) and flows (5%), while rapid flows and falls seem less frequent everywhere within the basin.

This research is aimed at assessing landslide hazard and risk at basin scale. The final goal is to create a dynamic tool, managed in a GIS environment, useful for landslide risk pre-disaster planning and management.

The assessment of landslide hazard in terms of probability of occurrence in a given time, based for mapped landslides on direct and indirect observations of the state of activity and recurrence time, has been extended to landslide-free areas through the application of statistical methods implemented in an artificial neural network (ANN). On the basis of the more common landslides in the Arno river basin and the results of the univariate statistical analysis five preparatory factors were selected: slope angle, lithology, profile curvature, land cover and upslope contributing area.

The definition of position, typology and characteristics of the elements at risk has been carried out with two different methodologies: i) buildings and infrastructures were directly extracted from digital terrain cartography at the 1:10,000 scale, whilst ii) non-urban land use was identified and mapped based on an updated and improved CORINE land cover map at the 1:50,000 scale.

The definition of the exposure for each type of element at risk was based on their presumed asset and income values. Landslide vulnerability, defined as the degree of lost of elements at risk due to a landslide of a settled intensity, usually expressed as a value ranging from 0 to 1, was estimated on the basis of the typology and economic and social relevance of the elements at risk. Landslide intensity, usually defined as proportional to kinetic energy, was obtained considering landslide typology as a proxy for expected velocity.

The landslide risk was assessed both in a qualitative and quantitative way. In the former case contingency matrices were used to intersect hazard classes with vulnerability and exposure classes, while in the second case quantitative assessment of risk was carried out through the application of the risk equation, therefore applying the product of the numerical values of hazard, vulnerability and exposure (Cruden and Fell 1997).

**Keywords.** hazard analysis, risk analysis, Arno river basin, Artificial Neural Networks

**1. Study area and landslide inventory map**

The study area is strongly subjected to mass movements that have accumulated a large number of recorded cases (more than 27,500) and a huge total damage, both in properties and life losses.

The Arno River basin extends for about 9100 km$^2$ across the Northern Apennine chain in Central Italy.

This orogen is a complex thrust-belt system made up by the juxtaposition of several tectonic units, built up during the Tertiary under a compressive regime that was followed by extensional tectonics from the Upper Tortonian (Catani et al. 2005).

The extensional phase produced a sequence of horst-graben structures with a NW-SE alignment which have been filled with marine (to the West) and fluvio-lacustrine (to the East) sediments (Martini and Vai 2001) set down from Upper Tortonian to Quaternary.

From a geomorphological point of view the Arno river basin is mainly hilly, with four chains: Monti Pisani-Montagnola Senese, Monte Albano-Chianti, Calvana-Monte Morello and Pratomagno, Monte Falterona-Mandrioli-Alpe di Catenaia, which are mainly made of flysch rocks. Cohesive and granular fluvio-lacustrine sediments outcrop in the plains.

The area is characterized by a temperate climate with a dry summer. The general annual rainfall pattern is characterised by a summer minimum in July, and two maxima, one in November and the other at the end of the winter. Mean values of yearly rainfall vary in relation to relief and location, ranging from 800 mm on the Chiana valley to about 1800 mm on the Apenninic ridges.

It is widely known and agreed that slides affecting the Arno River basin and generally the Northern Apennines mainly move by reactivation of dormant slides, which were probably initiated during the early phases of the Holocene as a consequence of ice retreat at the end of the last glaciation (Bertolini et al. 2001).

The landslide inventory of the Arno river basin, carried out between 2003 and 2005, counts more than 27,500 events. The inventory has been organized following the approach proposed by Soeters and van Westen (1996) which consists in i) Acquisition of literature and ancillary data such as existent inventories, ii) mapping from aerial photographs at 1:13,000 and 1:33,000 scale (years from 1993 to 2000), iii) field survey and validation, which represented a key source especially for assessment of state of activity and validation of hazard. The inventory was then updated with the Persistent Scatterers technique which allowed to redefine the state of activity and the perimeter of the former landslides, and detect new movements (Farina et al. 2006).

For each landslide, information regarding the typology, state of activity, perimeter and area has been recorded. Detachment and deposition zones were mapped together.

Statistics on landslide types show that the most represented surface processes are slides (74.8%) and solifluctions (17.4%), followed by shallow landslides (6,6% ) and flows (4.5%). Regarding the state of activity 60% of the phenomena are in a dormant state, 38% in an active state and just 2% are in inactive, stabilized state (Fig. 1). The single landslide surface area ranges from 100 $m^2$ to 5 $10^6$ $m^2$.

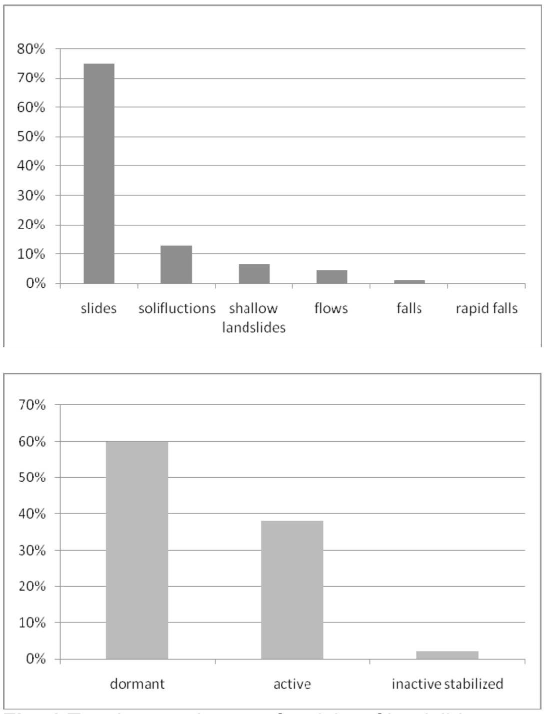


**Fig. 1** Typology and state of activity of landslides mapped in the Arno river basin.

**2. Hazard analysis**

The method adopted for the susceptibility analysis in the study area has been the setting up of suitable statistical estimators defined with the help of a set of artificial neural networks (ANN). Neural networks were chosen because they require loose hypotheses on the variable distribution and allow for the use of mixed-type parameters (e.g. categorical and cardinal units) (Ermini et al. 2005; Gomez and Kavzoglu 2005). The computation was carried out through a discrete pixel basis analysis followed by the definition of unique condition units (Bonham-Carter 1994; Chung et al. 1995) for the application of statistical analysis within a GIS environment.

On the basis of the most common landslides in the Arno river basin and the results of the univariate statistical analysis five preparatory factors were selected: slope angle, lithology, profile curvature, land cover and upslope contributing area. All the morphometrical parameters have been derived from a DTM of the Arno basin, produced by the cartographic service of the Tuscany Region Administration and released in 2002, with a resolution of 10 m × 10 m.

Temporal prediction was obtained through the combination of the model results with the information regarding the state of activity for the mapped landslides.

The state of activity has been used to assign average recurrence intervals to the susceptibility classes and to active landslides. In such a way, five classes of recurrence time were selected and associated to five classes of temporal hazard (10,000 years for H0; 1000 years for H1; 100 years for H2; 10 years for H3 and 1 year for H4), the latter directly assigned only to active mapped mass movements (Catani et al. 2005). Recurrence time was then translated into probability by the computation of the absolute hazard H(N) in a given time span N using the binomial distribution so that $H(N) = 1 - (1 - 1/T)N$ (see e.g. Canuti and Casagli 1996). Computations were carried out for N=2, 5, 10, 20 and 30 years, respectively. Absolute hazard is thus characterized by five classes (from H0 to H4) with probabilities ranging from 0 (class H0) to 1 (class H4) for each time span.

**3. Risk analysis**

Risk was computed on the basis of the combination of hazard, vulnerability and exposure as suggested by Varnes and IAEG (1984):

$$R = H\ V\ E$$

Where R is risk, H is hazard, V is vulnerability and E is exposure.

Vulnerability is a function of intensity, which can be defined as a measure of the severity of the phenomenon in terms of potential destructive power. Intensity is essentially considered as depending upon kinetic energy, hence, mass and velocity (Hungr 1995).

In the case of the Arno River basin the definition of intensity and run-out is influenced by the fact that mass movements are deep-seated reactivated slides sometimes evolving into flows. Restricting the analysis to this type of movement introduces a notable simplification, since a limited range of velocities can be adopted for the intensity computation and the expected mobilized volume can be reasonably deemed as equal to the present estimated landslide volume (Catani et al. 2005; DRM 1990; Cruden and Varnes 1996). Two main cases were thus considered: deep-seated rotational slides and shallow flows or planar slides with virtually constant depth. In the latter case, intensity as a function of volume was set proportional to the area of the mapped phenomenon. In the former case, a geometric model was used to compute the volumes. The volumes range from $10^2$ $m^3$ to $10^8$ $m^3$. Four classes of intensity have been defined on the basis of the statistical distribution and literature values (Fell 1994).

The vulnerability is usually considered as a function of a given intensity and it is defined as the expected degree of loss for an element at risk as a consequence of a certain event (Varnes and IAEG 1984; Fell 1994). The vulnerability value ranges generally between 0 (no damage) to 1 (complete destruction). Exposure, defined as the number of lives or the value of properties exposed at risk, is often strictly connected to vulnerability in its practical assessment (Schuster and Fleming 1986; Turner and Schuster 1996).

The assessment of vulnerability and exposure is based on the selection of the relevant information present in digital topographic maps at the scale of 1:10,000 as well as in the updated land cover map at the 1:50,000 scale. For every single object a value of vulnerability and exposure has been given on the basis of typology and main utilization. Vulnerability values are given in percentage of loss for each different class of intensity and for each type of element at risk, while exposure has been given in euro/m$^2$ and estimated on the basis of the presumed asset and income values.

The landslide risk was assessed both in a qualitative and quantitative way. In the former case contingency matrices were used to intersect hazard classes with vulnerability and exposure classes, thereby classifying the territory of the Arno river basin in five classes of landslide risk (R0, R1, R2, R3, R4).

The quantitative assessment of risk was carried out through the application of the risk equation, therefore applying the product of the numerical values of hazard, vulnerability and exposure (Cruden and Fell 1997). The procedure lead to the definition of risk values expressed as economic losses for each terrain units and for different periods of time in the future (2, 5, 10, 20 and 30 years) (Fig. 2).

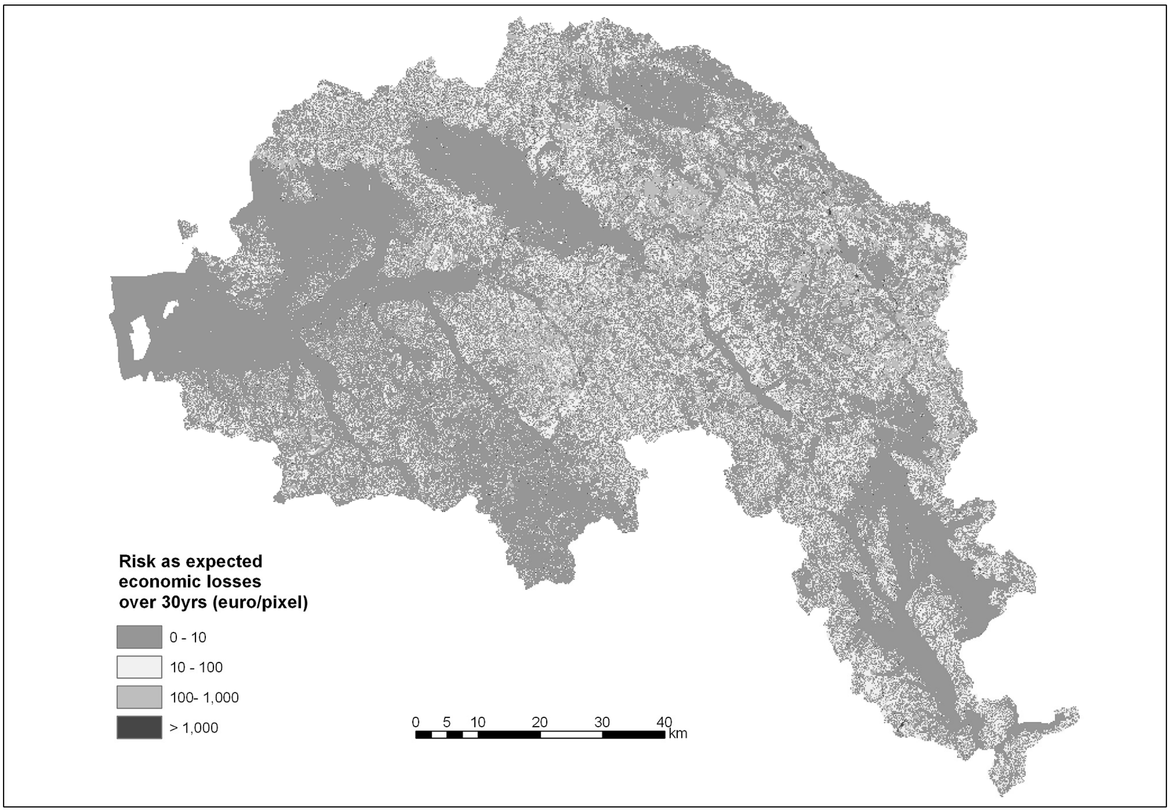


**Fig. 2** Landslide risk map of the Arno river basin over a period of 30 years. The risk is expressed as economic losses due to landslides for each terrain unit (from Catani et al. 2005)

**4. Results and conclusions**

In this research an analysis of landslide risk at the basin scale has been carried out. The study area is the Arno river basin, located in the northern Apennines.

For the landslide susceptibility assessment a statistical approach, through the implementation of artificial neural networks, has been used. The Arno river basin has been classified in four classes of susceptibility: S0, S1, S2 and S3. The results show that the 41.6 % of the territory is in the lower class of susceptibility S0, 25.5% in S1, 20.3% in S2 and 12.6% in S3.

Model validation, carried out comparing susceptibility statistics with mapped landslides, confirms that prediction results are very good, with an average percentage of correctly recognized mass movements of about 90%. The analysis also revealed the existence of a large number of unmapped mass movements, thus contributing to the completeness of the final inventory.

The qualitative landslide risk assessment carried out by means of contingency matrices allowed to classify the whole territory of the basin into five classes of risk. The results show that just 0.1% (about 9.17 $km^2$) of the territory is classified in higher class of risk (R4). The most risky areas are located in the SE portion of the basin, where particular geological conditions cause many landslides and pose high risk to buildings and infrastructures.

The quantitative risk has been computed through the direct application of the risk equation, therefore applying the product of the numerical values of hazard, vulnerability and exposure (Cruden and Fell 1997). The procedure lead to the definition of risk values expressed as economic losses for each terrain unit and for different periods of time in the future (2, 5, 10, 20 and 30 years). It is worth noting that these figures represent the cost of direct and indirect damages due to landslides in absence of mitigation measures (Table 1).

In the next five years, around 2.5 billion of euros should be expected as economic losses due to landslides. This value agrees with the data regarding the costs for landslide mitigation measures spent in the Arno river basin in the last five years.

**Table 1** Risk values computed as expected economic losses cumulated for five time intervals

| Cumulated time (years) | Expected economic losses (euro) |
|---|---|
| 2 | € 1,497,099,000 |
| 5 | € 2,498,767,000 |
| 10 | € 3,662,134,000 |
| 20 | € 4,930,778,000 |
| 30 | € 5,586,896,000 |

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**References**

Bertolini G, Pellegrini M, Tosatti G (eds) (2001) Le frane della regione Emilia-Romagna, oggetto di interventi di protezione civile nel periodo 1994–1999. Quad Geol Appl 8(1–2) (in Italian)

Bonham-Carter GF (1994) Geographic information systems for geoscientists: modeling with GIS. Pergamon, Ottawa, Canada, 198 pp

Canuti P, Casagli N (1996) Considerazioni sulla valutazione del rischio di frana. CNR-GNDCI Publication 846, 57 p (in Italian)

Catani F, Casagli N, Ermini L, Righini G, Menduni G (2005) Landslide hazard and risk mapping at catchment scale in the Arno River basin. Landslides 2:329-342

Chung CF, Fabbri AG, van Western CJ (1995) Multivariate regression analysis for landslide hazard zonation. In: Carrara A, Guzzetti F (eds) Geographical information system in assessing natural hazards. Kluwer, Dordrecht, The Netherlands, pp 107–142

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides investigation and mitigation, Special Report 247. Transportation Research Board, National Research Council, Washington, DC, pp 36–75

Cruden DM, Fell R (1997) Landslide risk assessment. In: Proceedings of the Workshop on Landslide Risk Assessment, Honolulu, Hawaii. Balkema, Rotterdam, The Netherlands, 384 p

DRM – Délégation aux Risques Majeurs (1990) Les études préliminaries à la cartographie réglementaire des risques naturels majeurs. Secrétariat d'Etat auprès du Premier Ministre chargé de l'Environment et de la Prévention des Risques tecnologiques et naturels majeurs. La Documentation Française. 143 p

Ermini L, Catani F, Casagli N (2005) Artificial neural networks applied to landslide susceptibility assessment. Geomorphology 66:327–343

Farina P, Colombo D, Fumagalli A, Marks F, Moretti S (2006) Permanent Scatterers for landslide investigations: outcomes from the ESA-SLAM project. Engineering Geology 88 (3-4): 200-217

Fell R (1994) Landslide risk assessment and acceptable risk. Canadian Geotechnical Journal 31(2): 261-272

Gomez H, Kavzoglu T (2005) Assessment of shallow landslide susceptibility using artificial neural networks in Jabanosa River basin, Venezuela. Engineering Geology 78:11–27

Hungr O (1995) A model for the runout analysis of rapid flow slides, debris flows and avalanches. Canadian Geotechnical Journal 32:610–623

Martini IP, Vai GB (eds) (2001) Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins. Kluwer Academic, Dordrecht, The Netherlands, 632 p

Soeters R, van Westen CJ (1996) Slope instability recognition, analysis and zonation. In Turner AK, Schuster RL (eds) Landslides: investigation and mitigation. Transportation Research Board, National Research Council Special Report 247, pp 129-177

Schuster RL, Fleming RW (1986) Economic losses and fatalities due to landslides. Bull Am Assoc Eng Geol 23(1):11–28

Turner AK, Schuster RL (eds) (1996) Landslides: investigation and mitigation. Transportation Research Board, National Research Council Special Report 247

Varnes DJ, IAEG Commission on Landslides (1984) Landslide hazard zonation—a review of principles and practice. UNESCO, Paris, 63 p