# *Assessing landslide exposure in areas with limited landslide information*

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# Assessing landslide exposure in areas with limited landslide information

**Abstract** Landslide risk assessment is often a difficult task due to the lack of temporal data on landslides and triggering events (frequency), run-out distance, landslide magnitude and vulnerability. The probability of occurrence of landslides is often very difficult to predict, as well as the expected magnitude of events, due to the limited data availability on past landslide activity. In this paper, a qualitative procedure for assessing the exposure of elements at risk is presented for an area of the Apulia region (Italy) where no temporal information on landslide occurrence is available. Given these limitations in data availability, it was not possible to produce a reliable landslide hazard map and, consequently, a risk map. The qualitative analysis was carried out using the spatial multi-criteria evaluation method in a global information system. A landslide susceptibility composite index map and four asset index maps (physical, social, economic and environmental) were generated separately through a hierarchical procedure of standardising and weighting. The four asset index maps were combined in order to obtain a qualitative weighted assets map, which, combined with the landslide susceptibility composite index map, has provided the final qualitative landslide exposure map. The resulting map represents the spatial distribution of the exposure level in the study area; this information could be used in a preliminary stage of regional planning. In order to demonstrate how such an exposure map could be used in a basic risk assessment, a quantification of the economic losses at municipal level was carried out, and the temporal probability of landslides was estimated, on the basis of the expert knowledge. Although the proposed methodology for the exposure assessment did not consider the landslide run-out and vulnerability quantification, the results obtained allow to rank the municipalities in terms of increasing exposure and risk level and, consequently, to identify the priorities for designing appropriate landslide risk mitigation plans.

**Keywords** Spatial multi-criteria evaluation · Susceptibility · Elements at risk · Exposure · Landslide risk

## Introduction

The evaluation, in mathematical terms, of landslide risk can be very complicated, due to several aspects, related to the complexity in assessing landslide hazard and vulnerability (Glade 2003; Uzielli et al. 2008).

For a given category of elements at risk, the specific risk can be quantified as the product of vulnerability, amount of elements at risk and the probability of occurrence of a specific hazard scenario with a given return period in a given area (Van Westen et al. 2006). In order to compute the total risk, all the specific risks for all types of elements at risk, and for a number of hazard scenarios with different return periods, are integrated (Glade et al. 2005).

A correct evaluation of the landslide hazard requires the analysis of the probability of occurrence of a specific type of landslide with a given intensity at a specific location, within a certain time period (Van Westen et al. 2006). However, often, there are not enough data to make a reliable assessment of the temporal probability of occurrence. This probability may be assessed either by computing the probability of failure of a slope (or the reactivation of existing landslides), or through the frequency analysis of past landslide events. In the latter case, the temporal frequency of landslides may be determined, directly, by using records of landslides, or, indirectly, from the recurrence of the landslide triggering events (Corominas and Moya 2008). In many cases the absence or incompleteness of landslide records makes it impossible to establish a quantitative relationship between the occurrence of landslides and the most important triggering events. Because of these difficulties in determining temporal probability, many landslide studies are only focusing on the evaluation of susceptibility (Van Westen et al. 2006), by analysing the relationship between the spatial distribution of instability factors, i.e. the environmental factors that are correlated with slope instability, and the distribution of past landslide events (Fell et al. 2008).

Another difficult task is to evaluate the vulnerability of the elements at risk, through the quantification of the degree of damage of the elements at risk resulting from the occurrence of a landslide of a given intensity (Glade 2003). The vulnerability depends on a series of factors which are difficult to assess, such as the type of landslide, the magnitude and intensity of the landslide and the capacity of the element at risk to withstand the landslide impact (Fuchs et al. 2007). Furthermore, elements at risk vary in space and time, and therefore, the vulnerability varies as well. In this case, the vulnerability should be regarded as depending on the proportion of time that an element at risk is exposed to the hazard, especially when dealing with persons (Lee and Jones 2004). So, for the determination of the temporal vulnerability of the elements at risk, it is important to consider the probability that the element is present at the time of impact (Jaiswal et al. 2010).

The spatial overlay of a set of elements at risk with landslide susceptibility zones is defined as exposure. Generally, the exposure identifies which elements at risk might experience some degree of damage. Lee and Jones (2004) evaluate the exposure as the proportion of total value of the element at risk likely to be present and thereby susceptible to being adversely impacted by the landslide, while the vulnerability is defined as the proportion of the total value of the element at risk likely to be affected detrimentally by a given magnitude of landslide. Assessing the exposure of elements at risk means evaluating the proportion of the assets that are located in the hazardous areas. Exposure analysis is an intermediate stage of risk assessment, which links the susceptibility and hazard assessment with the value of elements at risk. In literature, relatively few studies are focused on procedures for the assessment of landslide exposure; generally, the landslide exposure is considered as a part of the landslide risk assessment (Lee and Jones 2004; Sassa et al. 2005). The exposure analysis is widely carried out in other fields, for example, in studies related to rainstorms or earthquakes (OSFI 1998; UNDP 2011; Quan et al. 2011) or in those related to the urban systems (Masure and Lutoff 2008).



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Generally, landslide risk assessment and management consist in estimating the level of risk, evaluating whether it is acceptable and adopting appropriate control measures for the mitigation of the risk when the level of risk cannot be accepted (Aleotti and Chowdhury 1999; Dai et al. 2002; Crosta et al. 2005; Sassa et al. 2005; Fell et al. 2008). Several methods can be used according to the scale of the study, the data availability and the aims of the hazard and risk analysis (Lee and Jones 2004; Glade et al. 2005; Van Westen et al. 2006), which can be grouped in qualitative, semi-quantitative and quantitative methods. In the quantitative methods, the total risk can be represented by means of a risk curve, expressing the relation between all hazard scenarios with different temporal probabilities and the corresponding expected losses (Van Westen et al. 2010). Whatever the method for landslide risk assessment is, the main sources of uncertainties stem from the estimation of the temporal probability of a specific landslide event with given intensity, the analysis of the physical vulnerability and the evaluation of expected losses.

In order to make a reliable map that predicts the landslide hazard and risk in a certain area, it is crucial to have an insight into the spatial and temporal frequency of landslides, run-out distance and landslide magnitude (Remondo et al. 2005); therefore, each landslide hazard or risk study should start by making a landslide inventory that is as complete as possible in both space and time (Ibsen and Brundsen 1996; Lang et al. 1999; Glade 2001; Van Westen et al. 2008). A landslide inventory map should give an insight into the location of landslide phenomena, the types, failure mechanisms, causal factors, frequency of occurrence, volumes and the damage that has been caused (Fell et al. 2008). Furthermore, it should include information on landslide activity, useful to define the temporal frequency of landslides (Guzzetti et al. 2006; Van Westen et al. 2008).

In this paper, a qualitative method for assessing the exposure is presented for an area where no temporal information on landslide occurrence is available. This is quite a common situation in many countries. Landslide inventories may be available, but they often lack sufficient information on dates of landslide occurrence in order to be able to estimate temporal probabilities of landslide occurrence, as well as the expected magnitude of events. Given these limitations in data availability and details, a qualitative exposure map has been produced from the combination of a landslide susceptibility map and a weighted assets map, both generated using a spatial multi-criteria evaluation (SMCE) procedure in a global information system (GIS) environment. Subsequently, a quantitative assessment of exposure was carried out by evaluating, for each municipality in the study area, located in the South of Italy, the exposed assets (or consequences) in monetary terms. After calculating the economic value, an estimation of the total risk at municipal level was evaluated, by assigning temporal probability values to the various classes and plotting these against the quantified exposure in risk curves (Van Westen et al. 2010).

## Study area

The study area extends for 1,282 km$^2$ in the western part of the Apulia region, in Southern Italy (Fig. 1). This area represents the geographical region called Daunia, including 25 municipalities in Foggia province. Daunia is bordered, in the North by the Fortore river, in the East by the Apulian Foreland, in the West by the Southern Apennines and in the South by the upper drainage basin of Ofanto River.

Elevation in the area ranges from about 50 masl at Fortore River to 1,152 masl at Mt. Cornacchia. Due to this large altitude range, the climatic conditions are quite variable and characterised by cold winters and mild summers. Rainfall is abundant especially from November to February. The total annual rainfall average is 800 mm. The annual average temperature is around 12 °C, and monthly means range from 2 °C to 21 °C.

The geological setting of Daunia is closely related to the geological history of the Southern Italian Apennines. The Apulian sector of the Southern Apennines is an allochthonous unit overlaying the terrigenous successions of the Bradanic Trough, which in their turn override the Apulian Foreland units. In the study area, two different stratigraphic successions have been recognised. These are the Daunia Unit, in the East, and the Fortore Unit, in the West (Dazzaro and Rapisardi 1996). The Daunia Unit is formed by an Oligocene–Miocene succession of clayey and calcareous strata (Red Flysch and Numidic Flysch Formations), a calcareous-marly turbidite succession (Faeto Flysch Formation), and clay and marly-clay formation (Toppo Capuana Formation). The Fortore Unit consists of Red Flysch and Numidic Flysch Formations, superimposed by pseudotransgressive terrigenous Miocene deposits (San Bartolomeo Flysch and Toppo Capuana Formations) (Dazzaro et al. 1988). The Faeto Flysch Formation consists of a lower clayey-marly member and an upper marly-calcareous one.

The geological–structural setting of the area is characterised by a wide variety of formations with very different mechanical properties (rocky successions versus clays), interacting with each other and often heavily folded and faulted due to the intense tectonic actions occurred during the Apenninic orogeny (Mostardini and Merlini 1986; Patacca and Scandone 2007).

The Red Flysch, in the lower part, is made up of calcareous turbidites, interbedded with red and green clays and marly clays, while in the upper part it is formed by marly clays and scaly clays, grey-green to red in colour. At the top of the Red Flysch, there are strata of bentonite clays. In both scaly clays part of the Red Flysch and bentonite clays, the fissuring and the very poor strength properties control the mechanical behaviour of the soil (Cotecchia et al. 2006).

As a result, the landscape is characterised mainly by clayey slopes with medium steepness (around 12°), which locally increases (until 45°) in the presence of rocky strata. The lower slopes up to 300–400 masl are covered by arable crops and olive groves, while the slopes at higher altitudes are occupied by deciduous forests and areas with herbaceous vegetation used as pasture.

Due to the lithological, structural, geomorphological and climatic characteristics of the area, landslides are frequent in the Daunia region and cover about 12 % of the territory. In this portion of the Apennines, meteoric events and earthquakes represent the main triggering factors of landslides. A peculiar aspect of the landslides occurring in the Daunia region is the wide variety of the soils involved, mainly consisting of rock-like to soil-like strata interacting with each other and often heavily fractured. Mass movements consist of composite and complex

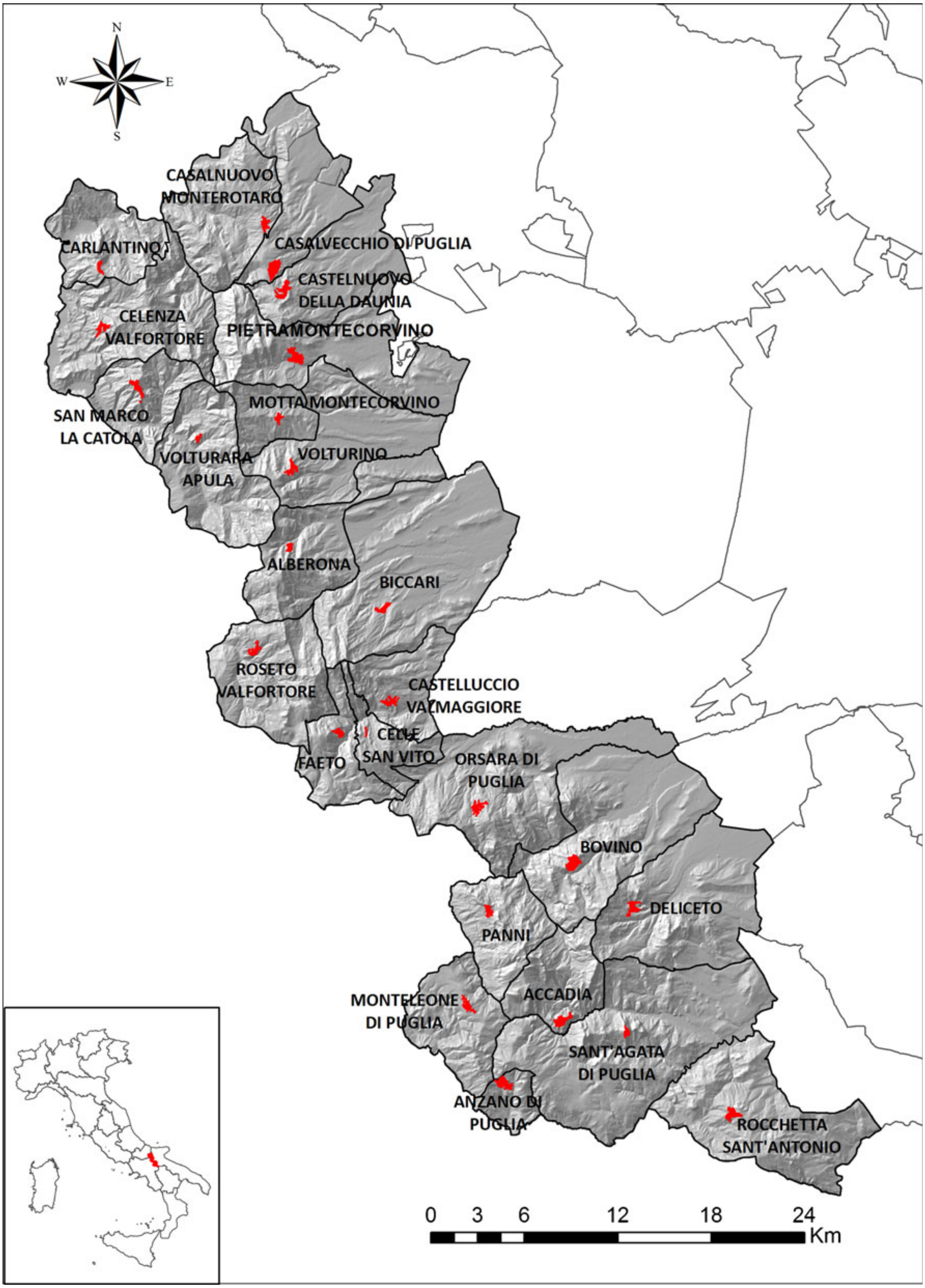


**Fig. 1** Daunia region composed by 25 municipalities with the localisation of the urban areas

landslides (Cruden and Varnes 1996) that range in type, volume and velocity from deep slow rotational and translational slides to shallow moderately fast earthflows. These landslides are triggered in the lower part of the slopes, where the clayey successions outcrop, and due to their retrogressive evolution, affect the rocky slabs on which the urban centers are located.

Therefore, landslides are a major source of damage to properties in the urban centers of the area, involving especially the transportation system and the stability of building's foundations. In the last 50 years, the growing demand for physical development of these mountain centers has produced a very rapid expansion of built-up areas, often with poor planning of urban and territorial infrastructure, and invasion of the agricultural areas. Because of this development of new constructions on unstable hillslope areas, human activities such as deforestation or excavation of slopes for road cuts and building sites, etc., have become other important triggers for landslide occurrence.

## Methods and data

### Available data and limitations

The landslide inventory map used in this study was produced by the Basin Authority of Apulia region (POR PUGLIA 2009), through stereoscopic aerial-photo-interpretation, using black and white aerial photographs at scale 1:33,000, flown in 2003 by the Italian Military Geographical Institute. The polygons representing landslide areas were digitised in GIS on georeferenced orthophotos at scale 1:5,000. About 1,320 landslides were detected, mapped and classified according to movement typology. Five landslide typologies were recognised (Fig. 2a): rotational slides (2 %), translational slides (5 %), earthflows (27 %), complex movements (24 %) and areas with many undifferentiated mass movements (20 %). The first four types are in accordance with the classification defined by Varnes (1984), while the last category was introduced to indicate areas characterised by the coalescence of different landslides not individually classifiable or by shallow landslides with poorly defined boundaries. The typology of movement has been attributed to each landslide polygon through the image analysis of diagnostic features (morphological, vegetation and drainage characteristics that allow an image interpreter to classify the identified landslide phenomena). For 22 % of the landslides, the movement typology could not be determined, due to the absence of clear diagnostic features or their alteration by external factors (e.g. ploughing, revegetation). The main limitation of the landslide inventory map is the absence of information on the occurrence date and the landslide activity, since the landslides were not detected in different years for the lack of a multi-temporal dataset.

The landslide inventory map and all other thematic information layers were stored and managed in a GIS spatial database using both vector and raster (cell size of 10 m) formats. A digital elevation model (DEM) was generated through an interpolation algorithm, using contour lines with a 5-m interval and elevation points, which were extracted

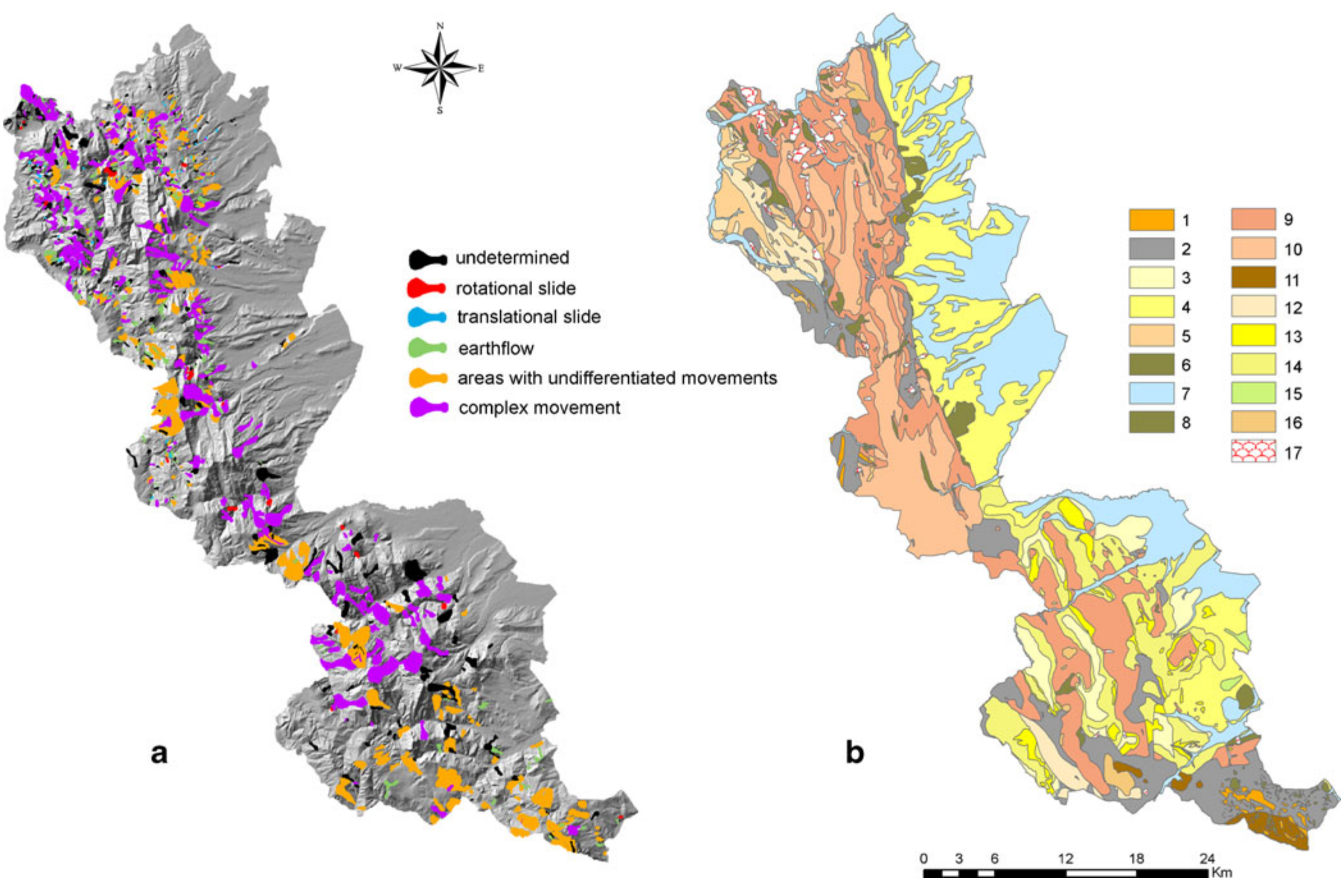


**Fig. 2** **a** Landslide inventory map with indication of movement typology; **b** lithological map at 1:100,000 scale (Legend: *1* quarzitic sandstone, sand and clayey sand; *2* varicoloured clay; *3* clay and sandy clay; *4* blue-grey clay; *5* Toppo Capuana marly clay; *6* breccia; *7* polygenetic gravel of different size; *8* debris deposits; *9* clayey-marly facies of Faeto Flysch; *10* calcareous-marly facies of Faeto Flysch; *11* marl, silty clay, calcareous marl; *12* San Bartolomeo Flysch; *13* puddingstone; *14* sand and sandstone; *15* sands with clayey intercalations; *16* yellow-gray sands; *17* landslide deposits)

from the Apulia Regional Technical Map, at scale 1:5,000. From the DEM, standard morphometric information layers were obtained, i.e. the slope and aspect maps.

The lithological map was produced by integrating the original Geological Map of Italy at 1:100,000 scale with historical geological sheets at 1:25,000 scale. More detailed geological sheets were available only for small areas; consequently, the information was discontinuous, inhomogeneous and negligible compared with the analysis scale. The lithological thematic map, shown in Fig. 2b, includes 16 lithological units. The land use map at 1:5,000 scale, obtained from the SIT (Sistema Informativo Territoriale) of the Apulia Region, was simplified, and the 58 land use types were merged into six classes: urban area, crops, pasture, shrubs, forests, bare and water bodies (rivers and lakes).

### Spatial multi-criteria evaluation

Because of the main limitations concerning the availability of temporal data on landslides and triggering events, a qualitative method was used in generating the landslide susceptibility map, which was combined with the elements (or assets) at risk to produce an exposure map, through a SMCE method in a Geographic Information System (ILWIS-GIS). Spatial multi-criteria evaluation is a technique for decision making, which uses spatial criteria, which are standardised, combined and weighted with respect to a main goal (Van Westen et al. 2010), in this case, the landslide susceptibility map and the asset maps. The analysis was implemented by using the SMCE module of ILWIS-GIS (Integrated Land and Water Information System), in which the input consists of a set of indicator maps, considered as the spatial representation of the criteria, which are grouped, standardised and weighted in a "criteria tree"(ITC 2001). The output is represented by a "composite index map", which indicated the spatial representation of the main goal.

The theoretical background for the multi-criteria evaluation is based on the analytic hierarchy process (AHP), developed by Saaty (1980) (Van Westen et al. 2010). The use of AHP in GIS-based multi-criteria decision-making approaches is widely used in urban planning, especially in relation to land use allocation problems (Ceballos-Silva and Lòpez-Blanco 2003; Svoray et al. 2005; Hossain et al. 2007). It is also used in studies related to forest conservation planning at a landscape scale (Phua and Minowa 2005; Greene et al. 2010) and to site selection for nuclear waste facilities (Carver 1991; Malczewski 1996; Sharifi and Retsios 2003). The technique has been applied to landslide susceptibility and risk assessment, although in a few cases only. Yoshimatsu and Abe (2006) applied the AHP method for identifying areas susceptible to landsliding in Japan, assigning scores to each factor of micro-topography of landslide-prone areas. Castellanos and Van Westen (2007) developed a procedure for the generation of a landslide risk index map at national level in Cuba, using a SMCE. Finally, Gorsevski and Jankowski (2010), for the landslide susceptibility assessment, used the fuzzy membership functions to standardise terrain attributes and develop criteria, while the aggregation of the criteria was achieved by the use of SMCE techniques.

The use of a procedure based on an expert-based SMCE method allows obtaining of a qualitative evaluation of the susceptibility and exposure at regional scale, also in absence of temporal information about input data and, therefore, when it is not possible to use probabilistic methods for assessing landslide hazard and vulnerability.

In general, the AHP technique allows decomposing of a specific problem into a hierarchy of criteria so that decisions can be made by using the relative importance of the criteria, by weighting the factors and criteria at each level of hierarchy.

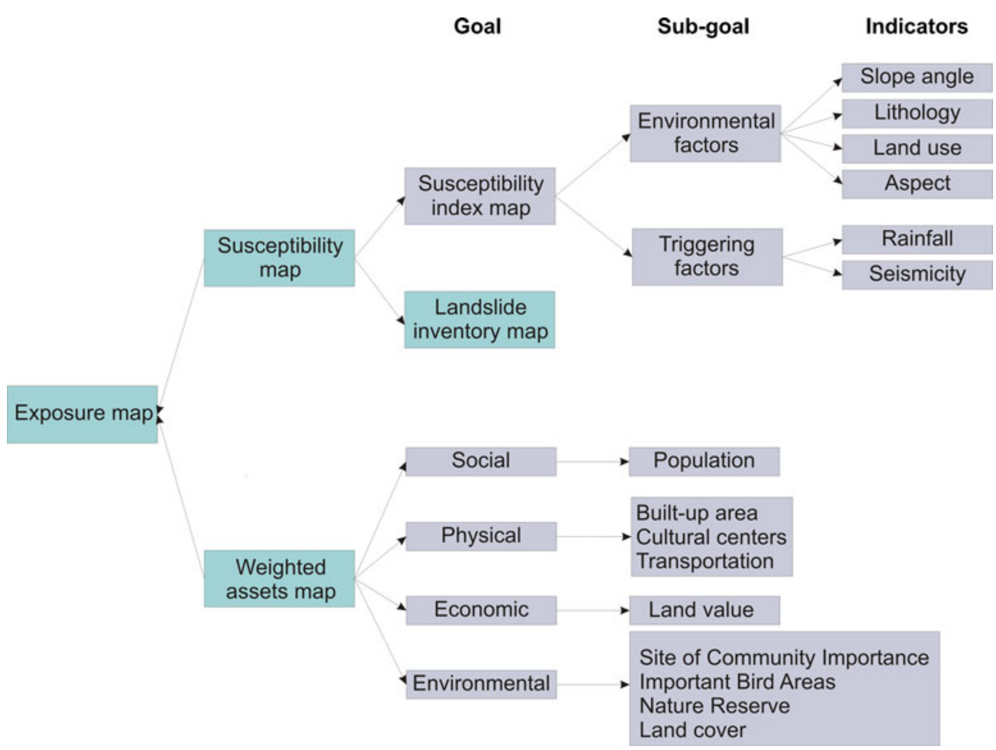


**Fig. 3** Model for the qualitative assessment of landslide exposure in Daunia region

The procedure to generate both the landslide susceptibility map and the weighted assets map (see Fig. 3), by using SMCE technique, is composed by the following general steps: (1) definition of the problem, selecting the criteria and structuring of the problem into a criteria tree, with several branches or groups, and a number of factors and/or constraints; the "factors" are the criteria that contribute in different way to the goal; they can be grouped into several "group of factors", which in turn can be grouped into several "sub-goals"; the "constraints" are criteria used to mask out the area where the goal cannot be reached (Van Westen et al. 2010); each factor is represented by an "indicator map"; (2) standardisation of the factors, which may be in different format (nominal, ordinal, interval, etc.) and normalisation to a range of 0–1, through the following methods: maximum linear, interval linear, goal linear, convex and concave curves (Van Westen et al. 2010); (3) weighting of the factors (criteria) within each group, by means of three main methods: direct method, pairwise comparison and rank ordering; (4) weighting of the groups (intermediate result), in order to come to an overall weight value; (5) classification of the results. After selecting the appropriate indicator maps, defining their standardisation and the hierarchical structure, it is necessary to classify each indicator as favourable (benefit) or unfavourable (cost) in relation to the intermediate objective or to the main goal. Another significant aspect to be considered in the model structuring is defining one or more constrain indicators. Constrain indicators consist of input maps containing areas that do not satisfy a particular binding condition and assign zero values to the resulting composite index map.

In this study, the exposure map is not obtained as main goal in SMCE module. The input maps (susceptibility and weighted assets) are generated separately as main goals of different criteria trees, subdivided into classes and afterward combined in a two-dimensional table or matrix. The landslide susceptibility index map consists of environmental conditional factors influencing the slope stability and triggering factors related to the occurrence of landslides. Four types of assets are combined in the weighted assets map: (1) physical (buildings, cultural buildings and transportation networks), (2) social (population), (3) economic (land value) and (4) environmental (land cover and protected areas). Therefore, these categories represent more the relative importance of the assets than an actual measure of their amount. As previously mentioned, the susceptibility composite index map is divided into three classes (low, medium and high susceptibility level), and the existing landslides are added in the final susceptibility map in order to indicate a very high susceptibility level, as in the study area, reactivation phenomena are very common. The four asset maps are computed separately, subdivided into two classes (low and high) according to their histograms and combined in order to obtain the final weighted assets map, representing different levels of relative importance of the assets in the area. The exposure map is generated combining in a two-dimensional table, the susceptibility map and the final weighted assets map. Then, the exposure map could be converted into a qualitative risk map by assuming values for temporal and spatial probability of occurrence of landslides in each of the susceptibility classes.

#### Method for susceptibility assessment

The first step in the generation of the landslide susceptibility index map was the selection of indicator maps and the definition of the structure of the criteria tree, followed by the standardisation and weighting of indicator maps. In this study, the susceptibility index map was obtained by combining two intermediate maps corresponding to two main groups of indicators: environmental factors and triggering factors.

The environmental and triggering factors consist of a set of thematic layers that are considered to have an influence on the occurrence of landslides and can be utilised as causal factors in the prediction of future landslides. The selection of causal factors differs depending on the scale of analysis, the characteristics of the study area, the landslide type and the failure mechanisms (Guzzetti et al. 1999; Van Westen et al. 2008). In this study, due to the lack in temporal data availability, only the spatial variation of triggering agents over the study area has been considered. After an analysis of the relationship between a number of factors, using bivariate statistical analysis, the following predisposing factors were selected as they had the largest relevance for landslide initiation: slope angle, aspect, land use and lithology, while rainfall and seismicity were taken into account as triggering factors.

The slope angle and aspect maps were generated in ArcGIS from the DEM with a 10 m spatial resolution. The Slope angle map was obtained through an algorithm that calculates automatically the maximum rate of change between each cell and its neighbours in the steepest downhill direction. The maximum slope angle obtained was 45°, with a mean value of 9.5°. From the analysis of the slope angle histogram, we found that the 43.8 % of the study area has a slope angle between 0° and 8°. The frequency distribution of slope angles in areas affected by landslides revealed that hillslopes with slope angle lower than 6° are not affected by landslides, while most of unstable areas (30 %) had a slope angle between 10° and 12°. Based on these results, areas with slope angle between 0° and 6° were selected as constraints, indicating areas with no landslide susceptibility. For normalising the slope angle indicator, a direct method was used. The slope angle map was divided into 23 classes, each one of 2°. Increasing values, between 0 and 1, were assigned to classes with slope angle between 7° and 28°, while unit value was given for slope angles ranging from 29° to 45°.

Also, the Aspect map was generated from the DEM, by using an algorithm that identifies the downslope direction of the maximum rate of change in value from each cell to its neighbours. The aspect map was divided into eight classes, each of which is 45° wide. About 37 % of the study area is facing N–NE; however, the most unstable hillslopes are those facing south-east and, secondly, south-west while there are very few landslides located on slopes facing north. This is due to the winds from SE that cause a strong rise in temperature and simultaneously a marked affect of soil drying, which makes it more vulnerable to erosion. The ranking method with an expected value option was used to normalise the aspect classes. Through this method, the higher normalised values were assigned to the classes more prone to landsliding.

The land use map with six legend classes was normalised using the direct method. To assign weights, the relative importance of the land use classes were determined by analysing their relationship with the past landslide events through a bivariate statistical analysis. This analysis has showed that land uses where the soil could be more exposed to erosional processes, such as bare, crops and pasture areas, are those mostly affected by landslides. Water bodies (rivers and lakes) were considered constraint factors, such as flat areas.

The lithology indicator map was composed by 16 lithological units. The spatial correlations between lithologies and existing landslides were evaluated, in order to define the highest landslide-prone units. It was found that the lithologies more susceptible to landsliding are those tectonically disturbed and remolded, with poor strength properties, such as old landslide deposits, varicoloured clays (Red Flysch), marly-clayey facies of Faeto Flysch and debris deposits. Weights ranging between 0 and 1 were assigned to the 16 units using the rank-ordering method.

The two triggering factors taken into account in this study were rainfall and seismicity. Rainfall is the main triggering factor in this area. Annual total rainfall data were obtained from 24 meteorological stations located inside the study area or in the direct vicinity. The spatial variation over the study area was calculated by interpolating the point data from 1920 up to 2005, published by Civil Protection Authority of Apulia Region. The values range from 551.3, at low elevation areas in the eastern part of the study area, to 907.6 mm in the mountainous zones. To standardise the rainfall values, the maximum linear method was used. In this way, the input values were divided by the maximum value possible (Castellanos and Van Westen 2007), 907.6 mm in this case.

Although earthquakes are less frequent than rainfall events in the study area, there is a strong correlation between landslides and seismicity. Historical sources revealed that, from the fourth century, seismic events with intensity greater than VIII degree of Mercalli scale occurred (Boschi et al. 1995, 2000). The epicenters of both the historical and recent earthquakes are lined up along a strip, oriented NW–SE, which coincides with the axis of the chain. Maximum peak ground acceleration (PGA) data were used from the seismic hazard map of Italy made by the National Institute of Geophysics and Volcanology (INGV 2004). The PGA values range between 0.14 and 0.23 g with a mean of 0.18 g. The highest values are localised on the south-western border of the study area, near the Apennine Chain. The standardisation of PGA value was made using the maximum linear method.

After generating the hierarchical structure, selecting and standardising the indicators, weights were assigned to each indicator and intermediate map. The four environmental factors were weighted using the direct method, considering lithology and slope angle indicators as the most important. The weights for the triggering factors were evaluated through a pairwise comparison. The standardisation and weighting methods are summarised in Table 1.

#### Method for generation of the weighted assets map

Considering the limitations in the input data, a qualitative assessment of the importance of the assets was carried out. Subsequently, the information on the assets was used for the exposure analysis and later also for estimating landslide risk.

**Table 1** Summary of indicators, intermediate maps or subgoals, with their corresponding weight values, and indication of the weighting and standardization methods

| Qualitative index map | | | | Weighting | Standardization |
|---|---|---|---|---|---|
| Susceptibility | | | | | |
| | 0.75 | *Environmental factors* | | Direct | |
| | | 0.40 | Slope | | Direct |
| | | 0.40 | Lithology | | Ranking |
| | | 0.15 | Land use | | Direct |
| | | 0.05 | Aspect | | Ranking |
| | 0.25 | *Triggering factors* | | Pairwise | |
| | | 0.88 | Rainfall | | Maximum |
| | | 0.12 | Seismicity | | Maximum |
| Assets | | | | | |
| *Social* | | | | | |
| | 1.00 | *Population* | | | Concave |
| *Physical* | | | | Pairwise | |
| | 0.73 | *Built-up area* | | | Concave |
| | 0.19 | *Cultural centre* | | | Concave |
| | 0.08 | *Transportation* | | | Ranking |
| *Economic* | | | | | |
| | 1.00 | *Land value* | | | Direct |
| *Environmental* | | | | Rank. Expected Value | |
| | 0.31 | *Sites of Community Importance* | | | Direct |
| | 0.31 | *Important Bird Areas* | | | Direct |
| | 0.31 | *Natural Reserve* | | | Direct |
| | 0.07 | *Land cover* | | | Direct |

Note that in this study we did not consider vulnerability separately, as we lacked information on expected intensities of landslides.

The identification and mapping of asset indicators were made considering the main known effects of landsliding in the study area (Cotecchia 1963; Spilotro et al. 1992; Guzzetti et al. 1994; Zezza et al. 1994; Spilotro et al. 2000; Puglisi et al. 2005; Pennetta 2006). Most of the assets affected by landslides are the buildings and the transportation networks, followed by agricultural lands, service infrastructures and public service structures. Damages to public and private buildings and to transportation network result in indirect damages to the population, in the form of temporary homelessness, permanent or temporary unavailability of agriculture and farming structures, disruption of services, longer travel times and so on (Galli and Guzzetti 2007).

For the qualitative assessment of the relative importance, the assets were divided into four different types, i.e. physical, social, economic and environmental (UNPD 2004). A total of nine indicators were considered: built-up area, cultural centers and transportation (physical indicators), population (social indicators), land value (economic indicators), sites of community importance, important bird areas, nature reserve and land cover (environmental indicators).

The first two physical indicators were generated using the information obtained from the Regional Technical Map of Apulia (at 1:5,000 scale), which contains information about the size and typology of buildings, subdivided into buildings (private and public), sheds, castles and churches. Additional information about the number of people in each municipality was inserted in the map. The built-up area indicator represents the number of buildings per hectare (building density) within each of the 25 urban centers. It was defined by dividing the number of buildings, in each urban centre, by the total area (hectares) of the urban centre. The building density in an urban centre was considered more relevant than the total number of buildings per centre as the last one does not consider the area of the centre. For the same reason, the population density was used instead of the total population per administrative unit.

Population data were obtained from the annual demographic balance made by ISTAT (National Institute of Statistics). Most urban centers have a building density ranging from 10 to 25 buildings/ha and a population density ranging from 15 to 50 persons/ha. The maximum values of building and population density respectively 50 buildings/ha and 700 persons/ha are related to Anzano di Puglia municipality in the southern part of Daunia region. To avoid a disproportionately distribution of buildings and population on the study area, a concave curve-standardising method was used for both the indicators, with an inflection point at 36 buildings/ha for the built-up indicator and at 80 persons/ha for the population indicator.

The cultural centres indicator is given by the number of cultural buildings (only castles and churches) in each municipality. Especially the municipalities located in the central part of Daunia, such as Faeto, Celle San Vito and Bovino, have a rich cultural, historical and artistic heritage. Each of these localities, as crossed by an important Roman road, Via Appia Traiana, has between seven and ten cultural buildings. For the other municipalities, these values range from two to four. The standardisation was done using the concave method with an inflection point at 5.

The transportation indicator represents the distribution of the road system in the study area. The road network was extracted from the Regional Technical Map of Apulia and was subdivided into four categories: motorway, paved road, unpaved road and bridges. The latter are located mainly along paved roads at river crossings. To standardise the classes of transportation indicator, the ranking method with an expected value option was used. The motorway was considered the first priority, secondly, paved roads and bridges, and finally, unpaved roads.

The land use map was used as indicator for both the economic (land value indicator) and environmental (land cover indicator) maps. In the first case, the 32 land use classes were classified according to their importance for the regional production. Therefore, industrial areas, commercial areas, sites for production and distribution of energy and new urbanisation sites were considered the most important elements. For the environmental exposure, the same elements were evaluated in terms of their environmental value. The highest value has been assigned to deciduous and conifer forests and to reforestation areas. A slightly lower value has been given to olive groves, vineyards and orchards, because they represent an important resource for the regional rural environment. To standardise both the indicators, weights ranging between 0 and 1 were assigned to the land use classes using the direct method.

Besides the land cover indicator, the protected areas were used as indicators for the environmental index map. From the Italian National Geoportal, three indicators were selected: sites of community importance (SCI), important bird areas (IBA) and nature reserve. SCI are defined in the European Commission Habitats Directive as sites which, in a biogeographical region, contribute significantly to the maintenance of biological diversity and to the maintenance or restoration at a favourable conservation status of a natural habitat type or of a species. In Daunia region, there are six SCI units with a total area of about 400 km$^2$, which is 31 % of the study area. The important bird areas aim at the conservation of specific bird species and other biodiversity. There is only one IBA, Daunia Mountains, in the northern part of the study area, with an area of 750 km$^2$, which includes three of the six SIC. Finally, a limited area of the Regional Nature Park of Ofanto River is included in the most southern part of Daunia region. These three environmental indicators were considered equally important, so a unit standardised value was assigned to them.

After the selection of the indicators and their normalisation, the definition of indicator weights was carried out. Table 1 gives an overview of the indicators, standardisation and weighting methods, and the resulting weights. The economic and social index maps were composed only of one indicator. For the physical indicators, the weights were established through the pairwise comparison method, considering the built-up areas more important than cultural sites and transportation network. Finally, the environmental indicators were weighted using the ranking method with the expected value option, through which the three protected areas were considered the same way with weights greater than that relating to the land cover indicator. A representation of the model used for the qualitative assessment of exposure is given in Fig. 3.

### Method for exposure assessment

A quantitative assessment of the exposure of assets was carried out for each municipality. The quantification of the amount of the elements at risk could be done in terms of monetary values (i.e. value of buildings, forest or crops) or by expressing the number of buildings, persons, etc.

As the population is a mobile asset (Lee and Jones 2004), the evaluation of exposure of persons in building requires the calculation of conditional probability of persons being present in building, given the time of the day that the landslide might occur (Van Westen et al. 2006). Due to the difficulties both in assessing the temporal and spatial distribution of people in an urban centre and the ethical dilemma in quantifying the economic value associated to injuries or deaths, we decided to remove the number of people in buildings from the list of assets that would be represented in monetary values.

With regard to cultural buildings, they are located in the oldest part of urban centres that is the most stable. For this reason and also because the economical quantification of damage to castles and churches needs the evaluation of restoration costs, we have not considered this asset in the quantitative analysis.

Finally, the quantitative assessment of exposure was carried out for 25 types of assets, obtained from the four previous mentioned asset maps, which are: residential buildings, commercial buildings, arable crops, orchards, olive groves, pastures, shrubs, vineyards, crops, conifer forests, deciduous forests, mixed forests, building sites, cemeteries, landfills, farms, hospitals, industrial areas, energy areas, sport areas, motorways, paved roads, unpaved roads and wind turbine generators. The quantification, in terms of areal extent (squared meters and hectares), of assets has been done for each municipality. The information on the amount of assets was combined with the landslide susceptibility index map.

Therefore, in order to evaluate the economic exposure at municipal level associated to the different susceptibility classes, the unit market values or unit construction costs have been taken into account for each asset class. As far as residential and commercial buildings are concerned, the unit market value (Euros per square meter) relative to 2010 was obtained from the Observatory of Real Estate Market instituted by the National Territorial Agency. For each municipality, the maximum, minimum and medium values were used. The minimum value has been assumed as unit construction costs (Euros per square meter) for the building sites. For industrial areas, hospitals, cemeteries, sports areas, landfills and farms, the unit construction costs were calculated from fixed values for the entire region, defined in 1988 by the National Territorial Agency. Subsequently, these values were updated, by calculating the inflation rate using data of ISTAT (National Institute of Statistics). Also, the unit agricultural values (Euros per hectare) for the year 2008 were obtained from the National Territorial Agency. For the three types of road, unit construction costs obtained from the Regional Price List of Apulia for 2010 were used. Finally, the economic value of wind farms was evaluated. The location of each wind generator was mapped from orthophotos for the entire study area. As a result, a map with 460 wind mills was obtained, of which about 240 were installed in the area between 2007 and 2010. The economic value of a wind farm was based on the following main parameters: investment costs, operating and

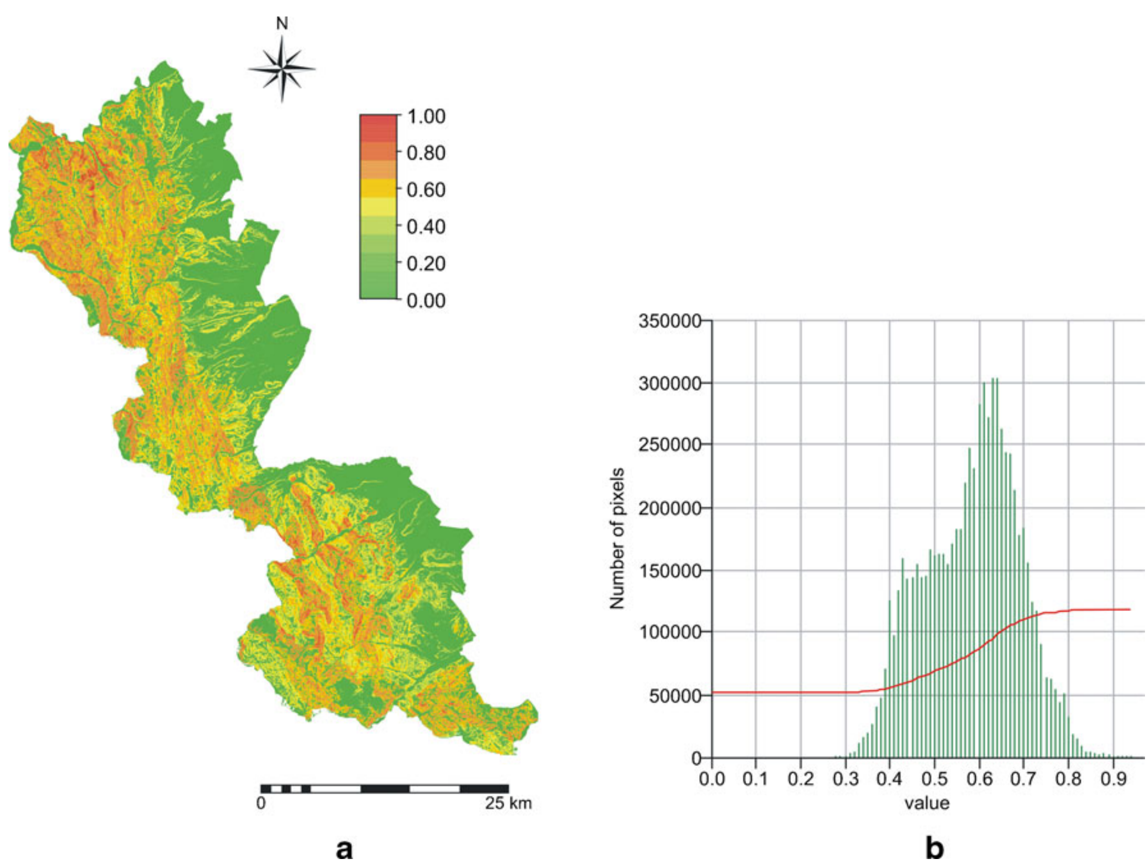


**Fig. 4** **a** Landslide susceptibility composite index map standardised to 0–1 range; **b** histogram and cumulative curve of landslide susceptibility index map

**Table 2** Summary statistics of the landslide susceptibility index map and the asset maps, with indication of their threshold values

| Maps | Summary statistics | | | | | | |
|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | Median | Predominant | SD | Threshold |
| Environmental factors | 0.04 | 0.96 | 0.40 | 0.40 | 0.14 | 0.18 | |
| Triggering factors | 0.62 | 0.96 | 0.80 | 0.82 | 0.88 | 0.09 | |
| **Susceptibility** | 0.00 (0.28) | 0.93 | 0.32 | 0.43 | 0.00 | 0.3 | |
| Physical indicators | 0.01 | 0.75 | 0.01 | 0.01 | 0.01 | 0.04 | 0.04 |
| Social indicators | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.13 |
| Economic indicators | 0.01 | 1.00 | 0.66 | 0.65 | 0.70 | 0.09 | 0.65 |
| Environmental indicators | 0.07 | 0.73 | 0.29 | 0.13 | 0.11 | 0.21 | 0.13 |
| **Weighted assets map** | 0.03 | 0.91 | 0.13 | 0.12 | 0.12 | 0.04 | |

maintenance costs, annual production of energy and life of the turbine (Graniglia 2010). Considering these aspects, a total cost of 1,200 € for kilowatts installed (Euros per kilowatt) was calculated.

After the definition of the monetary value of the 25 asset classes for each municipality, a quantitative analysis of their exposure has been carried out. Therefore, the exposed values associated to each susceptibility class, at municipal level, were quantified by multiplying the number of the individual exposed assets (squared meters, hectares and number) with their unit economic value, for each susceptibility class.

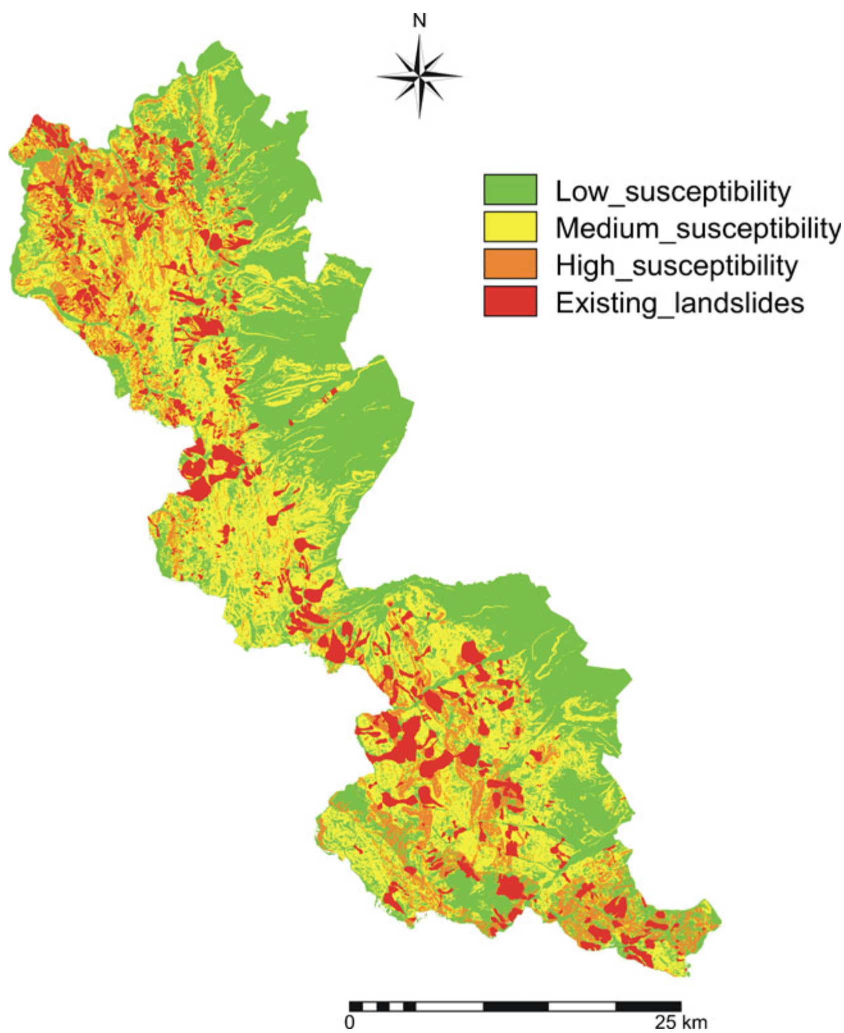


**Fig. 5** Landslide susceptibility map for Daunia region

## Results

The susceptibility composite index map is presented in Fig. 4a. This map is characterised by a large number of pixels with zero values, which are 44.18 % of the total area of the composite index map. These pixels correspond to the before selected constraint areas, i.e. flat areas and water bodies. The susceptibility index values range between 0.00 (0.28 excluding the zeros) and 0.93 with a mean of 0.32 (see Table 2).

The cumulative curve shown in Fig. 4b represents the summation of the number of pixels with a given susceptibility index

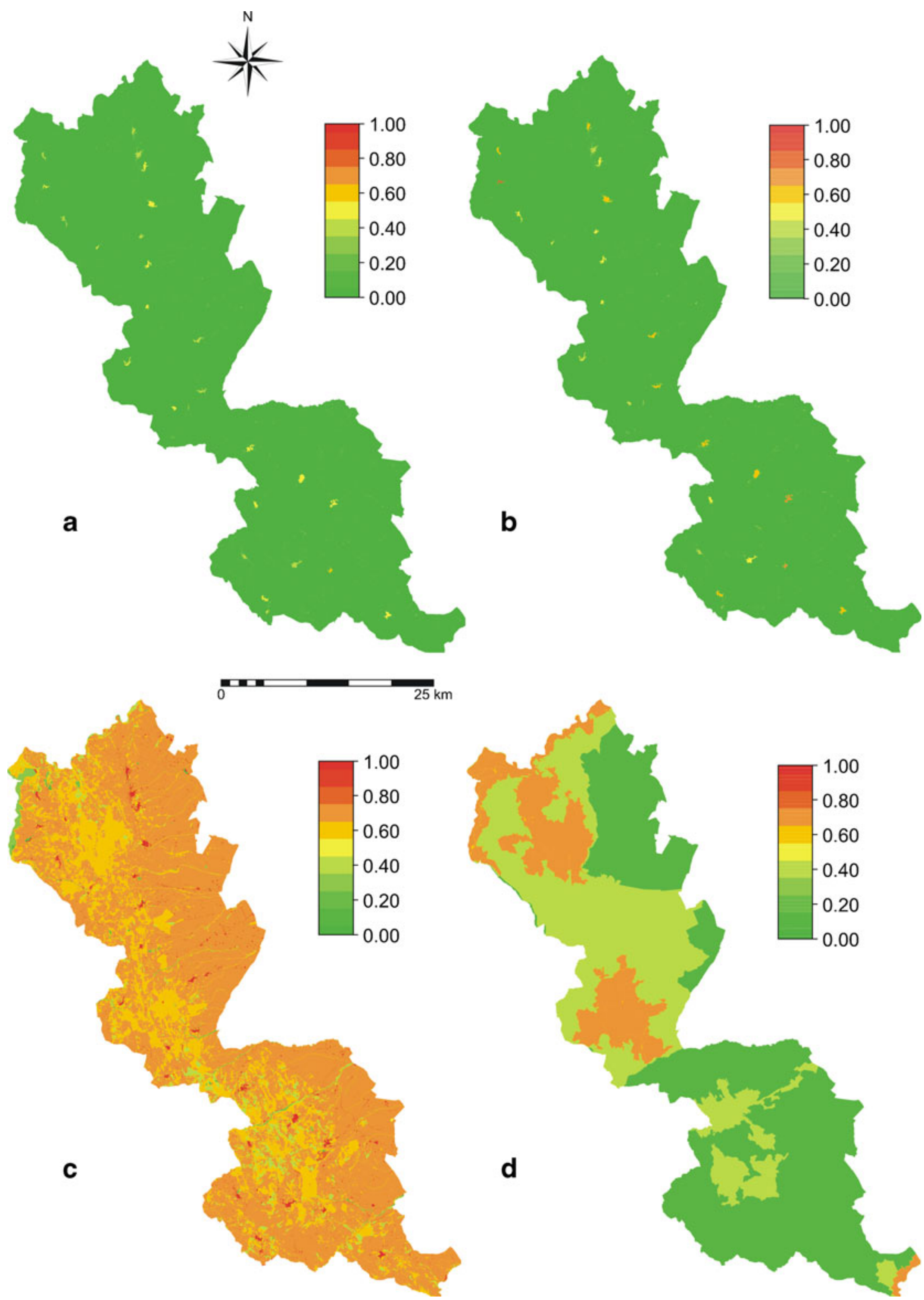


**Fig. 6** The asset maps standardised between 0 and 1 used for production the qualitative weighted assets map. **a** Physical asset index map, **b** social asset index map, **c** economic asset index map, **d** environmental asset index map

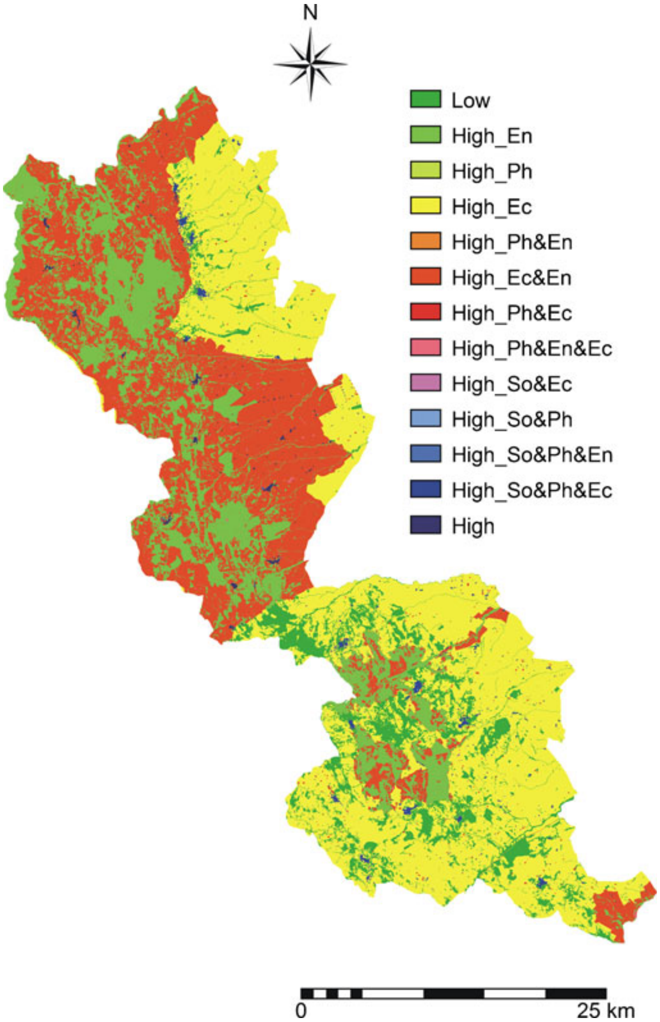


**Fig. 7** Final qualitative weighted assets map with 13 different classes obtained by combining the classes of asset index maps

value, ranging between 0 and 1. In order to interpret the map better, the susceptibility composite index map was subdivided into three susceptibility classes: low susceptibility (for index values smaller than 0.35), medium susceptibility (for index values between 0.35 and 0.65) and high susceptibility (for index values larger than 0.65). These threshold values were evaluated in an interactive way, by considering different thresholds, deriving for each one the areas belonging to susceptibility classes and comparing these with the known landslides.

In the landslide susceptibility index map, the highly susceptible areas coincide with the most landslide-prone lithological units, such as landslide deposits, Red Flysch, clayey-marly facies of Faeto Flysch and San Bartolomeo Flysch, and with high values of slope angle. In particular, two ranges of slope angle values characterise the high susceptibility areas: values between 10° and 16°, relative to the slopes with outcropping clayey and debris deposits, and values between 22° and 30°, corresponding to the slopes with flysch soils.

After splitting the landslide susceptibility index map into three classes, by using the landslide inventory for defining the best class boundaries, the landslides contained in the inventory map were added, and a fourth susceptibility class was created, consisting of old and recent existing landslides, because in the study area the reactivation of pre-existing landslides is very frequent.

Finally, the landslide susceptibility map (Fig. 5) shows the spatial distribution of the areas with different susceptibility level for the Daunia region. This map represents the basis for a more detailed study on exposure, in qualitative and quantitative terms.

The asset maps show the spatial distribution and relative importance of physical, social, economic and environmental indicators (Fig. 6). The physical index values range between 0.01 and 0.75, with a mean, a median and a predominant value of 0.01 (Table 2). The large number of pixels with 0.01 values is due to the multiplication of the intermediate maps of Built-up area, Cultural centers and Transportation, which present the highest values within the urban centres and along the road network. The social index map is characterised by values ranging from 0 to 1 (Table 2).

**Table 3** Definition of qualitative importance classes by combining the classes of the four asset maps

| Asset_class | Economic | Environmental | Physical | Social |
|---|---|---|---|---|
| Low | Low | Low | Low | Low |
| High_So&Ph | Low | Low | High | High |
| High_Ph | Low | Low | High | Low |
| High_En | Low | High | Low | Low |
| High_So&Ph&En | Low | High | High | High |
| High_Ph&En | Low | High | High | Low |
| High_Ec&En | High | High | Low | Low |
| High | High | High | High | High |
| High_Ph&En&Ec | High | High | High | Low |
| High_Ec | High | Low | Low | Low |
| High_So&Ph&Ec | High | Low | High | High |
| High_Ph&Ec | High | Low | High | Low |
| High_So&Ec | High | Low | Low | High |

**Table 4** Two-dimensional table used for deriving the qualitative landslide exposure classes from the combination of the susceptibility and asset classes

| Asset_class | Low_susceptibility | Medium_susceptibility | High_susceptibility | Existing_landslide |
|---|---|---|---|---|
| Low | No_exposure | Low_exposure | Low_exposure | Low_exposure |
| High_En | Low_exposure | Low_exposure | Medium_exposure | Medium_exposure |
| High_Ph | Low_exposure | Low_exposure | Medium_exposure | Medium_exposure |
| High_Ec | Low_exposure | Low_exposure | Medium_exposure | Medium_exposure |
| High_Ph&En | Low_exposure | Medium_exposure | High_exposure | High_exposure |
| High_Ec&En | Low_exposure | Medium_exposure | High_exposure | High_exposure |
| High_Ph&Ec | Low_exposure | Medium_exposure | High_exposure | High_exposure |
| High_Ph&En&Ec | Low_exposure | Medium_exposure | High_exposure | High_exposure |
| High_So&Ph | Low_exposure | Medium_exposure | High_exposure | Very_high_exposure |
| High_So&Ec | Low_exposure | Medium_exposure | High_exposure | Very_high_exposure |
| High_So&Ph&En | Low_exposure | Medium_exposure | High_exposure | Very_high_exposure |
| High_So&Ph&Ec | Low_exposure | Medium_exposure | High_exposure | Very_high_exposure |
| High | Low_exposure | High_exposure | Very_high_exposure | Very_high_exposure |

Initially, the four index maps were combined in a "criteria tree", as intermediate maps, in order to obtain, by using the SMCE method, a weighted assets map. All the maps were standardised between 0 and 1 through the same method, i.e. the maximum linear method. For the weight assignation, the ranking method (expected value) was used. Through this method, the relative ranking of the factors was indicated, and the software has converted these in quantitative weights; in this case, the weights were assigned considering the social index as the most important factor (0.52), followed by the physical (0.27), economic (0.15) and environmental (0.06) indices. The resulting weighted index map is characterised by index values ranging between 0.03 and 0.91, with a mean of 0.13, a median of 0.12 and a predominant value of 0.12 (Table 2). The higher index values were concentrated in the urban centres. In order to avoid this problem, the qualitative analysis was carried out through a different procedure. The four index maps, after being computed separately, were subdivided into two classes (low and high importance) according to their histograms. The respective threshold values were evaluated in an interactive way (see Table 2). Subsequently, the reclassified asset maps were overlain in order to obtain a unique map (Fig. 7). This final qualitative weighted assets map consists of 13 classes, which represent the combinations of the eight classes of importance (Table 3).

Finally, the assessment of landslide exposure was carried out by combining in a two-dimensional table the susceptibility map and the weighted assets map with relative classes (Table 4). The combinations between the four susceptibility classes and the 13 asset classes were classified into five exposure classes: no, low, medium, high and very high exposure (Fig. 8). In Table 5, the percentage of territory for the different levels of landslide exposure for each municipality are summarised.

The procedure used for the quantitative assessment of the exposure of elements at risk consisted in the overlay of the assets with the landslide susceptibility map, evaluating the amount of assets in each susceptibility class and quantifying for each municipality the economic values for the various susceptibility levels. The analysis at municipal level allows categorising the 25 municipalities in order of

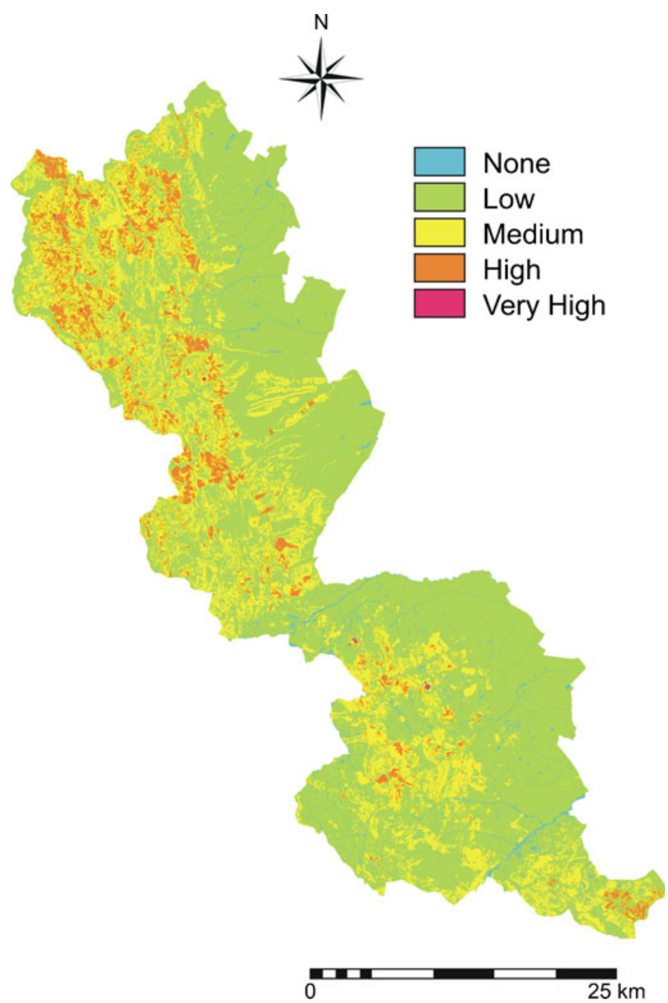


**Fig. 8** Qualitative landslide exposure map subdivided into five classes obtained by combining the four susceptibility classes and the 13 weighted asset classes

**Table 5** Percentage of each municipality with no, low, medium, high and very high exposure

| Municipality | No exposure (%) | Low (%) | Medium (%) | High (%) | Very high (%) |
|---|---|---|---|---|---|
| Accadia | 0.5 | 43.1 | 47.9 | 8.4 | 0.0 |
| Alberona | 0.0 | 48.8 | 34.8 | 16.2 | 0.1 |
| Anzano di Puglia | 2.9 | 72.0 | 23.4 | 1.2 | 0.4 |
| Biccaril | 0.5 | 79.6 | 17.9 | 2.0 | 0.0 |
| Bovino | 1.6 | 80.6 | 15.4 | 2.1 | 0.2 |
| Carlantino | 0.0 | 29.6 | 42.6 | 27.7 | 0.1 |
| Casalnuovo Monterotaro | 0.2 | 40.8 | 38.6 | 20.3 | 0.0 |
| Casalvecchio di Puglia | 1.3 | 83.4 | 13.6 | 1.7 | 0.0 |
| Castelluccio Valmaggiore | 0.0 | 53.4 | 39.5 | 6.9 | 0.2 |
| Castelnuovo della Daunia | 2.6 | 86.3 | 7.8 | 3.3 | 0.0 |
| Celenza Valfortore | 0.0 | 38.5 | 45.3 | 16.2 | 0.0 |
| Celle San Vito | 2.1 | 64.7 | 26.8 | 6.3 | 0.1 |
| Deliceto | 2.5 | 92.4 | 4.4 | 0.7 | 0.0 |
| Faeto | 1.1 | 62.4 | 34.6 | 1.8 | 0.1 |
| Monteleone di Puglia | 2.9 | 85.1 | 11.7 | 0.3 | 0.0 |
| Motta Montecorvino | 0.7 | 50.6 | 31.7 | 17.0 | 0.1 |
| Orsara di Puglia | 3.4 | 80.0 | 15.0 | 1.4 | 0.2 |
| Panni | 2.1 | 56.5 | 38.2 | 3.2 | 0.1 |
| Pietramontecorvino | 1.3 | 79.8 | 16.3 | 2.5 | 0.0 |
| Rocchetta Sant'Antonio | 2.9 | 60.5 | 31.3 | 5.2 | 0.0 |
| Roseto Valfortore | 0.0 | 56.1 | 37.7 | 6.3 | 0.0 |
| San Marco La Catola | 0.0 | 31.1 | 42.6 | 25.9 | 0.3 |
| Sant' Agata di Puglia | 2.3 | 77.5 | 19.9 | 0.3 | 0.0 |
| Volturara Appula | 0.0 | 45.0 | 42.9 | 12.1 | 0.0 |
| Volturino | 1.1 | 78.8 | 16.1 | 3.8 | 0.1 |

economic exposed values. Table 6 provides, for each municipality, the economic value of the assets exposed to different landslide susceptibility classes.

As no information is available on the temporal and spatial probability of landslide events, it is not possible to generate landslide risk map based on historical information. In order to demonstrate how the exposure map could be used to obtain an estimation of the expected losses, a number of assumptions were made. Four hazard scenarios were assumed with a return period of 10, 25, 50 and 100 years, respectively. For each hazard scenario, the percentage of area, covered by the four susceptibility classes that will be affected by landslides was estimated, on the basis of expert knowledge of the authors on landslide mechanisms of the area (Table 7). The consequences of a specific hazard scenario were obtained by multiplying the exposed value of assets, shown in Table 6, by the spatial probability of occurrence of landslides, indicated as the fraction of the area of each susceptibility class likely to be affected. Note that we did not include an estimation of the vulnerability as we have no information on the expected size-frequency distribution and considered $V=1$. The sum of the consequence of the four hazard scenarios was calculated. In Fig. 9, the risk curves of the 25 municipalities were plotted, with the temporal probability against the total expected losses.

Finally, the total landslide risk in monetary terms was evaluated for each municipality by calculating the area under the curves (Table 8).

## Discussion

The analysis provides the spatial distribution of the exposure level in the study area. The resulting exposure map (Fig. 8) and the two-dimensional table containing the exposure classes (Table 4) show that the areas with low susceptibility level and low asset importance are not exposed areas. A low susceptibility involves a low exposure for all types of assets. The area with high exposure is located, on the contrary, where the susceptibility is high, and the importance of almost two types of elements at risk is high. A very high exposure characterises areas where existing landslide are present, and the social importance of assets is high. The higher level of exposure ("very high" exposure class) is localised in urban areas where the importance of social, physical and economical

**Table 6** Definition for each municipality of amount in monetary terms of exposed assets for the four susceptibility classes

| | Amount (€), exposure of elements at risks | | | |
|---|---|---|---|---|
| Municipality | Existing landslides | High susceptibility | Medium susceptibility | Low susceptibility |
| Accadia | € 6,813,801 | € 19,665,488 | € 62,509,919 | € 76,502,237 |
| Alberona | € 33,799,703 | € 8,529,074 | € 70,317,745 | € 114,001,176 |
| Anzano di Puglia | € 15,929,285 | € 18,547,065 | € 29,375,272 | € 35,392,987 |
| Biccari | € 3,447,355 | € 2,607,783 | € 78,964,722 | € 409,452,354 |
| Bovino | € 64,189,500 | € 21,492,251 | € 97,135,181 | € 190,165,504 |
| Carlantino | € 14,945,873 | € 18,014,178 | € 16,331,414 | € 15,037,893 |
| Casalnuovo Monterotaro | € 6,419,824 | € 11,611,031 | € 29,921,284 | € 144,185,248 |
| Casalvecchio di Puglia | € 472,057 | € 3,550,419 | € 18,541,713 | € 247,572,787 |
| Castelluccio Valmaggiore | € 12,347,623 | € 10,851,746 | € 39,033,297 | € 22,730,199 |
| Castelnuovo della Daunia | € 4,558,383 | € 4,930,715 | € 65,296,344 | € 166,733,056 |
| Celenza Valfortore | € 12,582,339 | € 28,537,297 | € 49,759,713 | € 62,314,998 |
| Celle San Vito | € 5,928,560 | € 841,331 | € 18,475,508 | € 19,017,756 |
| Deliceto | € 11,287,393 | € 33,778,758 | € 102,918,608 | € 227,548,238 |
| Faeto | € 5,438,994 | € 1,921,718 | € 56,533,231 | € 87,833,846 |
| Monteleone di Puglia | € 1,465,292 | € 20,155,777 | € 42,186,739 | € 113,654,203 |
| Motta Montecorvino | € 12,128,215 | € 2,770,547 | € 32,640,773 | € 45,790,671 |
| Orsara di Puglia | € 63,465,896 | € 13,061,142 | € 86,284,543 | € 196,352,348 |
| Panni | € 33,088,496 | € 8,600,603 | € 60,462,482 | € 31,656,575 |
| Pietramontecorvino | € 11,130,685 | € 25,254,242 | € 63,368,287 | € 225,151,639 |
| Rocchetta Sant'Antonio | € 11,580,089 | € 88,173,248 | € 21,880,984 | € 120,989,896 |
| Roseto Valfortore | € 4,313,940 | € 4,627,946 | € 64,372,459 | € 73,370,788 |
| San Marco La Catola | € 35,603,600 | € 18,185,864 | € 36,647,844 | € 22,136,828 |
| Sant' Agata di Puglia | € 25,023,262 | € 46,392,945 | € 111,580,805 | € 319,997,314 |
| Volturara Appula | € 8,544,582 | € 23,055,078 | € 56,045,156 | € 74,006,023 |
| Volturino | € 36,731,047 | € 8,432,386 | € 82,406,076 | € 154,373,073 |

assets is greater. The following class ("high" exposure) covers areas with existing landslides and with important environmental assets, such as natural reserve, important bird areas and sites of community importance.

As can be observed from Table 5, the percentage of territory exposed to landsliding in Daunia is higher in the following six municipalities: Carlantino, San Marco La Catola, Casalnuovo Monterotaro, Motta Montecorvino, Celenza Valfortore and Alberona. They are characterised by both existing landslides and very high susceptibility values due to steep slope angles, varicoloured clay and flyschoid formations highly susceptible to landslides combined with a high concentration of rainfall. The importance of assets is high for these areas, especially in terms of environmental value. The percentage of "very high" exposure class is negligible, as the area with very high exposure is too small compared with the total area of each municipality. This qualitative

**Table 7** Definition of four hazard scenarios with return periods of 10, 25, 50 and 100 years and the corresponding estimated fraction of the area expected to be affected by landslides for the four susceptibility classes

| | Return period | | | |
|---|---|---|---|---|
| | 10 | 25 | 50 | 100 |
| Existing_landslides | 0.1 | 0.15 | 0.25 | 0.5 |
| High_susceptibility | 0.05 | 0.1 | 0.15 | 0.25 |
| Medium_susceptibility | 0.01 | 0.015 | 0.025 | 0.05 |
| Low_susceptibility | 0.001 | 0.0015 | 0.0025 | 0.005 |

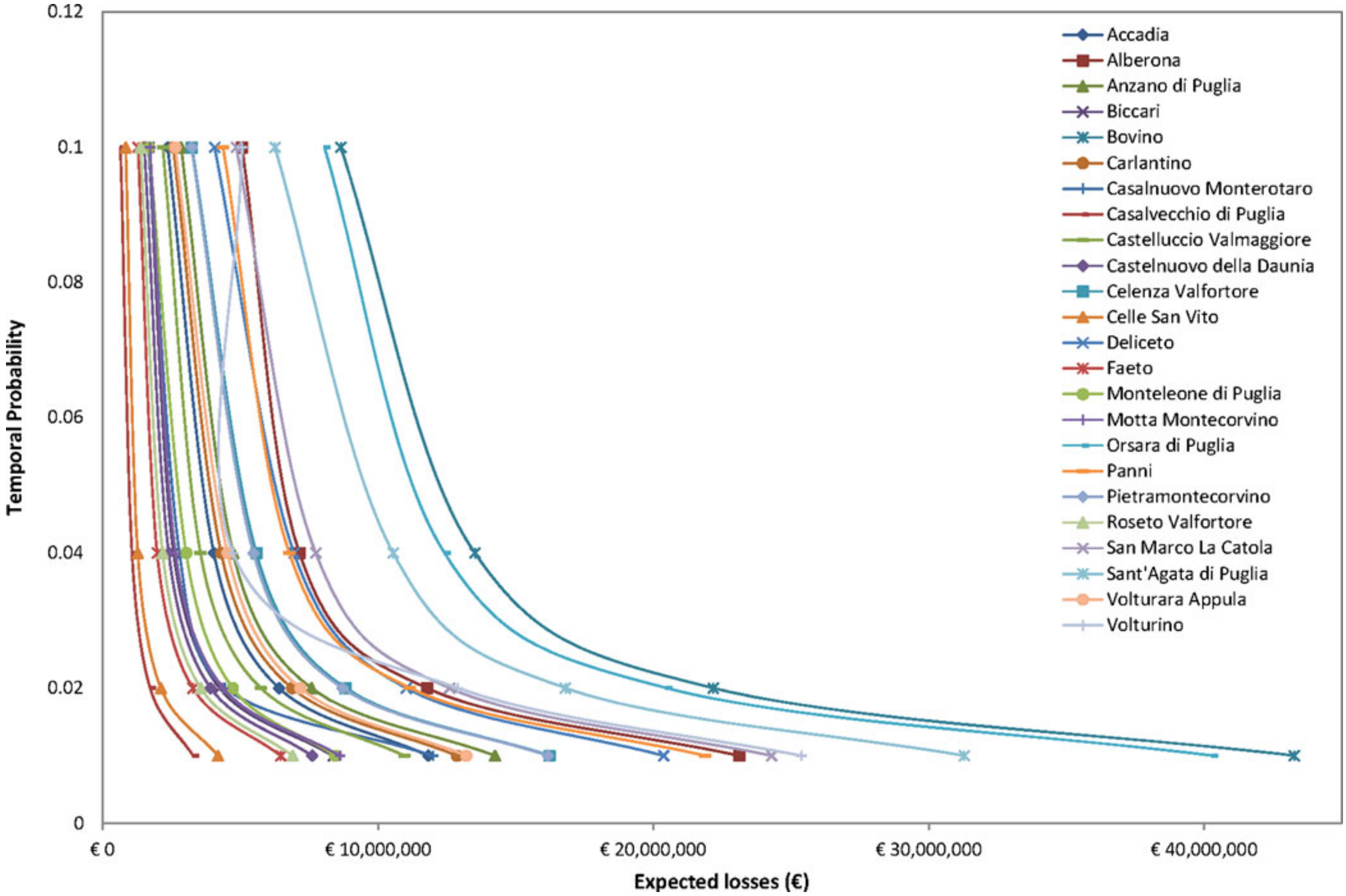


**Fig. 9** Risk curves calculated for the 25 municipalities of Daunia region

procedure for evaluating the landslide exposure in Daunia does not intend to quantify the risk but to provide information for risk assessment, useful in a preliminary stage of regional planning or for more detailed studies on the high-exposure areas.

In order to perform a general estimation of the risk level in Daunia territory, an estimation of the temporal and spatial probabilities of landslides was made based on expert opinion. This conversion from exposure to risk is the most uncertain step in the analysis, as unfortunately there is no database available with dates of landslide occurrence. This could be improved considerably if a multi-temporal landslide inventory would be carried out, using aerial photographs and satellite images from different decades. Also, archive studies could be used to get a better idea on the history of landslide processes in the past. However, this is rather time-consuming, and in Italy, there have been several projects aiming for this (e.g. AVI project, IFFI project). Unfortunately, up to now, this has not resulted in a sufficiently large dataset of landslides with known dates of occurrence. Therefore, the method proposed in this study can be carried out in the absence of such data in order to quantify the exposure, which is a basic input in spatial planning and risk reduction planning. The landslide risk values, obtained, in monetary terms, as the integration of all specific consequences over all probabilities, allowed the ranking of the municipalities in order of increasing landslide risk. In Table 8, it can be observed that the first six municipalities with higher values of risk are: Bovino, Orsara di Puglia, Sant'Agata di Puglia, Rocchetta Sant'Antonio, San Marco La Catola and Deliceto. They are all located, except San Marco La Catola, in the southern part of Daunia. By comparing these results with those of the qualitative analysis of exposure, it can be noted that high values of risk (Table 8) correspond to low levels of exposure (Table 5). This is due to the fact that, in the qualitative analysis, the spatial distribution of exposure is affected by the geometrical representation (size) of elements at risk and susceptibility indicators. Although the social and physical assets have more importance than the economic and environmental ones, their size is smaller, and consequently, they produce small areas with high exposure values. These areas compared with the whole municipal territory generate a low percentage of exposure. The results of quantitative analysis of landslide risk show that the higher risk values are distributed in the southern municipalities, which are characterised by lower altitude and, consequently, by a major distribution of elements at risk on territory.

It is important to mention that, as the temporal probabilities of landslides were assumed, the landslide risk values are not absolute, but relative and allow making of a significant the comparison between the municipalities.

A method which allows quantifying of the landslide risk, even with limited hazard and vulnerability data, through the quantification of the expected losses, in monetary terms, allows also to establish the changes of risk in future with urban development and inflation.

**Table 8** Total risk values in monetary terms for each municipality, derived by c-alculating the area under the risk curves

| Municipality | Total risk |
|---|---|
| Bovino | € 570,494 |
| Orsara di Puglia | € 521,637 |
| Sant' Agata di Puglia | € 454,901 |
| Rocchetta Sant'Antonio | € 370,832 |
| San Marco La Catola | € 328,647 |
| Deliceto | € 301,097 |
| Panni | € 285,273 |
| Alberona | € 274,228 |
| Celenza Valfortore | € 242,052 |
| Pietramontecorvino | € 236,888 |
| Volturino | € 205,358 |
| Anzano di Puglia | € 203,591 |
| Volturara Appula | € 196,805 |
| Carlantino | € 185,623 |
| Accadia | € 174,931 |
| Castelluccio Valmaggiore | € 151,822 |
| Casalnuovo Monterotaro | € 138,396 |
| Monteleone di Puglia | € 133,329 |
| Motta Montecorvino | € 111,531 |
| Biccari | € 108,225 |
| Castelnuovo della Daunia | € 101,909 |
| Roseto Valfortore | € 92,606 |
| Faeto | € 83,464 |
| Celle San Vito | € 53,575 |
| Casalvecchio di Puglia | € 45,989 |

## Conclusions

Although the studies on landslide risk assessment presented in literature are increasing, the elaboration of quantitative risk zonation maps, expressing the expected monetary losses as the product of probability (of occurrence of a landslide with a given magnitude), costs (of elements at risk) and vulnerability (the degree of damage of the elements at risk due to the occurrence of a landslide with a given magnitude) is often hampered by too limited information on temporal and spatial probability of events.

In this paper, a procedure for assessing the exposure at regional scale is presented for an area where no temporal information on landslide occurrence is available. A qualitative exposure map has been produced from the combination of a landslide susceptibility map and a weighted assets map, both generated using an expert-based SMCE procedure, and subsequently, a quantitative assessment of exposure was carried out by evaluating, for each municipality in the study area, the exposed assets in monetary terms. After calculating the economic value, the total risk at municipal level was evaluated, by assigning temporal probability values. In this study, we did not consider vulnerability separately, as we lacked information on expected intensities of landslides.

The aim of the qualitative analysis is to produce a reliable landslide exposure map (given the scale and the limitations of input data), which allows zooming in the high-exposure areas for more detailed risk analyses. Moreover, a procedure, which allows evaluation of exposure through the selection, weighting and standardisation of both the most relevant environmental and triggering indicators for the susceptibility assessment and the most relevant social, physical, economic and environmental indicators for evaluating the importance of assets could be improved and updated according to the user needs. A validation of the procedure, by comparing the estimated consequences and the recorded losses, in monetary terms, related to past landslide events, could be extremely useful. It was not possible to validate the proposed methodology, due to the difficulty, at regional scale, in obtaining damage data.

The analysis of the risk curves related to the 25 municipalities has showed that the total risk values, expressed in monetary terms, is higher for the bigger municipal areas located in the southern part of the study area where the elevation is lower (Bovino, Orsara di Puglia, Sant'Agata di Puglia, Rocchetta Sant'Antonio), as the elements at risk distributed on the municipal territory are more numerous.

The results of the risk analysis are useful for ranking the municipalities in order of increasing risk and for supporting decision makers in prioritising funding for risk mitigation measures at municipal levels.

Finally, this study displays an approach that can be applied for the landslide exposure assessment in absence of reliable temporal data and represents a valid tool for the risk landslide management, especially because it allows establishing of the changes in risk in the future with urban development and inflation.

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