Landslide risk modeling: an experience in northern Spain

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ABSTRACT: This work presents a quantitative procedure for landslide risk analysis and zoning developed in northern Spain. The proposed method provides the means to obtain landslide risk models expressing the expected damage due to landslides on material elements and economic activities in monetary terms, according to different scenarios and periods. The underlying hypothesis is that reliable predictions about hazard and risk can be made using models based on a detailed analysis of past landslide occurrences in connection with conditioning factors and data on past damage. Landslide risk models obtained are useful to identify areas where mitigation efforts will be most cost-effective. They allow identifying priority areas for the implementation of actions to reduce vulnerability (elements) or hazard (processes). The procedure can also be used as a preventive tool, through its application to Strategic Environmental Impact Assessment (SEIA) of land use plans. Results show that the proposed approach and the formulated hypothesis are basically correct, providing estimates of the order of magnitude of expected losses for a given period.

1 INTRODUCTION

This contribution is a synthesis of the work carried out during the last decade by the authors and builds on former papers focused essentially on susceptibility and hazard modeling (Remondo et al. 2005, Remondo 2001) and risk assessment (Remondo et al. 2008, Bonachea 2006). Some of the limitations, uncertainties and strengths found during the elaboration of landslide risk models have been addressed. In particular, new and better data have been incorporated (longer landslide time series; better quality or higher resolution variables) which made it possible to obtain better models, with higher prediction capability. A more refined approach to assess indirect risk has also been applied. Frequency scenarios for short and long-term predictions have been formulated. The overall aim of the contribution is to improve hazard and risk prediction capabilities.

2 STUDY AREA AND LANDSLIDES

The proposed approach has been applied in a study area (140 km^2) placed in the Deba Valley (Guipúzcoa province, Spain). The area (Fig. 1), located in the Pyrenean Alpine orogen, is underlain by Cretaceous and Paleogene sedimentary rocks (limestone, marl, claystone, sandstone, flysch) and some volcanics. These formations are moderately folded and faulted following a prevalent WNW-ESE structural trend. Average slope gradient is 22º, regolith thickness ranges between 0.5 and 3 m. Several types of slope movements have been identified in the area, but shallow translational slides (Cruden & Varnes 1996) are by far the most frequent (Fig. 2), normally triggered by intense rainfall events.

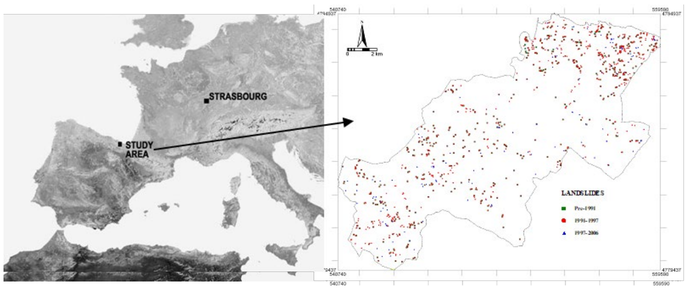

Figure 1. Location of the study area and distribution of landslides occurred up to 2001.

For the elaboration of landslide risk zoning maps, data about past landslides, terrain parameters related to instability (conditioning or causal factors), exposed elements and damage due to landsliding need to be obtained.

This analysis only considers one type of movement (representing over 85% of the landslides occurred in the area since 1954), but it does not seem that the incorporation of other landslide types with larger volumes (for which susceptibility or hazard models have not yet been elaborated) would significantly change the picture, due to their low probability of occurrence.

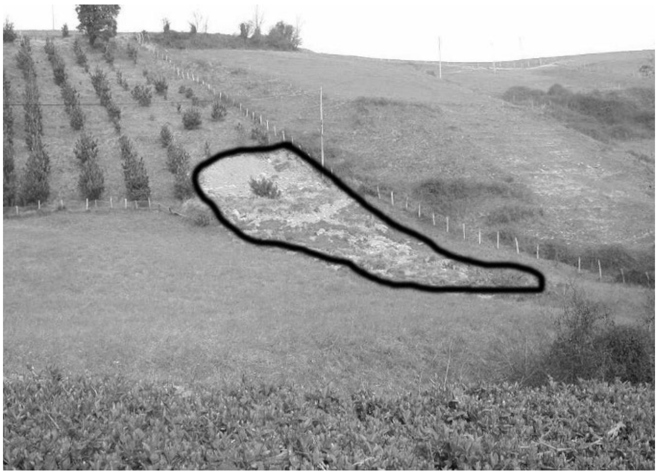

Figure 2. Shallow debris slide affecting a reforested and cultivated area; this is the type of movement used for modeling.

3 METHODOLOGY

3.1 *Susceptibility*

A rupture model for the type of movement considered was defined and, accordingly, conditioning variables identified. A landslide susceptibility model (susceptibility zoning map) was constructed by means of Favorability Functions (Chung & Fabbri 1993) analyzing the statistical relationships between past movements and the available information on conditioning factors. Some methodological modifications were introduced for the elaboration of models with respect to previous works: (1) continuous variables were used instead of categorical ones; (2) more accurate Digital Elevation Models (DEM) and therefore more precise derived models were adopted; (3) fuzzy boundaries for thematic variables were considered. This resulted in an improvement of the prediction capability of susceptibility models by about 5% with respect to the results presented in other works (Remondo 2001, Remondo et al. 2005). These authors showed, for instance, that about 58% of landslides in the validation sample fell on pixels corresponding to the 20% of the study area with the highest susceptibility. With the improvements indicated we have predicted about 63% of future landslides in the 20% most susceptible part of the study area.

3.2 *Hazard*

Transformation of susceptibility into hazard models requires temporal data on landslide occurrence. Alternatively, this transformation can be performed establishing a cause-effect correlation between landslides and their triggering factors if the frequency of the latter is known and the correlation well defined. In order to determine landslide frequency in the past and make extrapolations of future frequency, different scenarios of future behavior were formulated (Remondo et al. 2008) (Fig. 3) on the basis of trends derived from the time intervals analyzed (eight intervals, between 1954 and 2006).

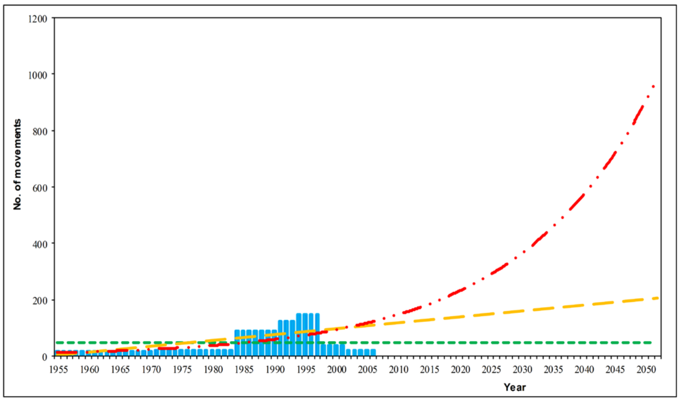

Figure 3. Frequency scenarios derived from past landslide occurrence in the study area. a. Total No. of landslides in the future equal to past 50 years; b. Future landslides increasing according to a linear trend; c. Future landslides increasing according to past (exponential) trend.

3.3 *Vulnerability*

The analysis of damage produced by past landslides of the type considered (low magnitude, shallow translational movements) on the exposed elements (only linear infrastructure, land use, buildings and socioeconomic activities, have been affected in the past) prone to be affected by future events, was used to estimate vulnerability for the type of movement analyzed. This was expressed as the damage/cost of the element ratio (Remondo et al. 2008). Of course, uncertainty on vulnerability estimates is immediately translated into risk estimates (equation 1).

Vulnerability is expressed here as the ratio between losses experienced by an exposed element when affected by an event, and its value. Estimates of indirect losses are more complex due to the scarcity of data. Therefore, assumptions concerning potential indirect losses must be made and scenarios defined.

3.4 *Risk*

The well known expression (Varnes 1984) was used to compute risk:

$$R = H \bullet E \bullet V \quad (1)$$

where,

R = risk or expected economic losses per year (Euros•a^{-1})
H = hazard or annual probability of occurrence (0-1•a^{-1})
E = exposure or value of the exposed element (Euros)
V = vulnerability or fraction of the value that would be damaged (0-1)

As vulnerability is equal to "potential loss" divided by "value of the exposed element (E)", risk can be expressed as:

$$R = H \bullet Potential\ loss \qquad (2)$$

For each type of element (roads, buildings, land-use) and for each hazard scenario defined (magnitude of the movement, which determines vulnerability and probability of occurrence) a specific risk model can be obtained. For each scenario there will be only one probability (hazard) and one vulnerability value for each type of element. Direct risk can thus be expressed as the sum of the specific risks estimated for each element present. The total risk would be the sum of direct and indirect (losses on economic activities) risk values.

The meaning of indirect risk and the procedure to estimate it are quite different. Landslides often affect roads and railways (or lifelines). This implies the interruption of traffic, loss of working hours and/or increase in transport distance. Indirect risk for that type of interruption can be expressed as:

$$IR = H \bullet Potential\ indirect\ loss \qquad (3)$$

To assess this risk sectors of roads or railways between junctions have been identified. An interruption at any point of one sector would stop traffic between its two extremes or junctions. Hazard is expressed as probability of occurrence of a landslide in each pixel that contains a road. Potential loss is estimated on the basis of the number of vehicles travelling through the road section (per hour, per day), average number of passengers, percentage of population economically active in the area, average value of the working hour and number of hours the road is likely to be interrupted by a landslide of a given type and size. The latter, will depend on the type of road. For each sector the additional distance that should be covered by each vehicle to take the shortest alternative route (or the cost of the alternative transport in the case of railway track interruption) was determined. That is, indirect losses considered here include two cost components: value of working hours lost and extra transport costs.

Indirect losses due to traffic suspension are generated at a specific point but are distributed over a wide area and have a diffuse character. In the case of direct risk, the loss takes place in the points (pixels) where it is generated.

Total risk can therefore be computed as:

$$TR = \Sigma\ (H \bullet P\ loss_{\ (Infrastructure,\ Buildings,\ Land\text{-}use,\ Activities)}) \qquad (4)$$

4 RESULTS

Specific risk models have been obtained for each type of exposed element and for two prediction time spans (10 and 50 years). Three scenarios of landslide frequency have been considered and used to obtain models of direct risk. Indirect risk models have also been generated combining hazard models and indirect potential losses (only losses on economic activities have been considered). Finally, total risk models have been produced by addition of direct and indirect risk models.

The spatial meaning of direct risk (losses produced in a precise location) and indirect risk (losses originated at a specific location but suffered in a larger and even external area) is different. However, total risk models obtained, by addition of both, provide landslide risk zonings that show where higher losses are expected to be generated in the future. This indicates where efforts should be focused or mitigation measures directed to obtain the best investment/loss reduction ratio.

Numerical results in monetary terms, for the different landslide risk models generated, are summarized in table I. The graphic representation of direct and indirect risk models is shown in Figures 4 and 5.

4.1 *Direct risk analysis*

4.1.1 *Specific risk for Infrastructure*

Depending on the future hazard scenario considered (Fig. 3), specific economic losses expected from damage on infrastructure in the next 50 years vary between 5,596,818 and 37,131,262 Euros (Table I). These models show that the main losses are likely to occur in local roads and in the railway. Obviously, the differences between risk estimates for the different scenarios are reduced if a shorter period (10 years) is considered (1,132,550 to 3,323,065 Euros).

The expected average annual loss increases with time in the case of scenarios B and C, especially the latter (exponential hazard increase), and so does uncertainty. Taking into account the more than likely increase in exposure (infrastructure, buildings, etc) with time, the cumulative damage at the end of the period considered should be even greater, although there is considerable uncertainty regarding this increase.

4.1.2 *Specific risk for Buildings*

The specific risk for buildings is very low due to the type of landslides that occur in the study area. Depending on the hazard scenario, the expected losses in the next 50 years could vary between 7,851 and 52,809 Euros. These figures are insignificant compared with those related to damage on other types of human elements (Table I). Although the expected losses are very low, due mainly to the small vulnerability of these elements, about 20% of the buildings could be affected by landslides during the longer period considered, since many of them are located in landslide-prone areas.

4.1.3 *Specific risk for Land use*

Depending on the hazard scenario, the specific risk obtained for land use and for a 50 year-period varies between 256,494 and 1,906,750 Euros. This is much lower than for infrastructure but higher than for buildings (Table I). The highest losses per unit area are expected to occur in cultivated areas, followed by grasslands and reforested zones. However, when total expected losses are considered, the higher values correspond to grasslands, which cover a much larger area than the other two types of land use.

Table I. Risk values (Euros) obtained for a 50-year period according to the scenarios proposed.

Element	Sce. A (x 10^3)	%	Sce. B (x 10^3)	%	Sce. C (x 10^3)	%
Railway	133	1.92	387	1.87	835	0.18
Motorway	41	0.59	126	0.61	296	0.64
National road	268	3.85	784	3.79	1,718	3.72
Regional road	244	3.50	733	3.54	1,694	3.67
Local road	4,907	70.18	14,498	70.05	32,586	70.54
INFRASTRUCTURE	**5,596**	**80.04**	**16,530**	**79.86**	**37,131**	**80.38**
Land use	256	3.67	862	4.17	1,906	4.13
Buildings	7	0.11	23	0.11	52	0.11
TOTAL DIRECT	**5,861**	**83.82**	**17,416**	**84.15**	**39,090**	**84.62**
Railway	1,020	14.59	2,952	14.26	6,363	13.78
Motorway	19	0.27	58	0.28	136	0.03
National road	69	0.99	203	0.01	451	0.98
Regional road	9	0.14	29	0.14	69	0.01
Local road	12	0.18	37	0.18	85	0.19
TOTAL INDIRECT	**1,131**	**16.18**	**3,281**	**15.85**	**7,106**	**15.38**
TOTAL RISK	**6,992**	**100.0**	**20,698**	**100.0**	**46,197**	**100.0**

4.1.4 *Total direct risk*

Total direct risk models have been produced by simple addition of the specific risk models for each type of exposed element (Table I). Values obtained for 50- and 10-year-long periods range between 5,861,163 and 39,090,821 Euros and 1,193,981 and 3,502,652 Euros, respectively, depending on the hazard scenario. Damage on infrastructure, especially local roads, accounts for most of the total direct risk. This is largely due to the presence of a dense network of (poorly-protected) local roads, many of which cross landslide-prone areas.

This analysis shows that, even in the case of the most pessimistic scenario (Scenario C, Fig. 3) the total expected losses are relatively low. They would exceed 10^6 Euros/year in the whole area (taking into account price values at year 2000) towards the end of the 50 year period considered. For comparison, this is roughly 0.01% of the total value (year 2000) of the elements analyzed in the study area. It thus appears that the application of post-damage corrective measures would be the most cost-effective approach. That is, the advisable strategy is repairing damage *"a posteriori"*, since according to past records no losses of human lives or injuries are likely to occur and the expected level of losses can easily be afforded by local administrations.

Figure 4. Graphic representation of a direct risk model for a subzone according to scenario C. Pixel size: 10 x10 m.

4.2 *Indirect risk*

Indirect risk for each point (sector) of the road and railway network was obtained multiplying hazard (probability) by the expected losses caused by a traffic interruption (Remondo et al. 2008). These were obtained from data on vehicle and passenger flows, average duration of the interruption, number of work hours lost, average value of work hour, plus the additional transportation cost (alternative route). These must be considered as minimum indirect losses, because other cost components are not included in the analysis. Potential indirect risk values were calculated for each road section and time span considering the three hazard scenarios.

Activity ratio of the population in the area, according to public statistics, is 45.5% (Eustat 2006). The average number of passengers per vehicle is 1.55 (Eustat 2006) and the average cost of the working hour around 10 Euros (Eustat 2006). Traffic intensity (flow) varies between 500 vehicles/hour (on a stretch of a national road) and 2 vehicles/hour (on small country roads). Additional travel distance in the case of road interruption varies between 1 and 5 km. On the basis of these data, indirect losses were calculated for all road and railway sections. As shown in Table I, the greatest expected losses correspond to interruptions in the serviceability of the railway. Indirect losses due to traffic interruption on roads are much smaller. The figures obtained for the next 50 years considering the different hazard scenarios (1,131,660 to 7,106,430 Euros) are relatively small. As in the case of direct risk, a corrective rather than preventive mitigation strategy seems to be the most cost-effective.

Comparison between direct risk for infrastructure and indirect risk due to traffic interruptions shows that (Table I):

The calculated indirect risk values are about 20% of those of direct risk. This, nevertheless, is a bit misleading because only part of the indirect losses is included in the present analysis. If all cost components were contemplated (delays in the arrival of supplies to factories, interruption of life-lines linked to roads, etc.) the picture might change.

The situation is different in the case of the railway. Direct damage to the railway caused by landslides is likely to be quite high, but indirect losses are much higher due to the number of people affected and the cost of the alternative transport, that considerably increase losses.

In the case of national and regional roads, direct risk is greater than indirect risk. Indirect losses are not very important, since the delays would not be very significant given the facility to take alternative routes.

Local roads present the greatest specific risk values. This is due to the high density of the local road network, a significant part of which goes through mountainous landslide-prone areas. Conversely, indirect risk is small, due to limited traffic flow and the facility to take alternative routes.

Figure 5. Graphic representation of an indirect risk model for a subzone according to scenario C. Pixel size: 10 x10 m.

5 DISCUSSION

The procedure presented makes it possible to produce risk models that express expected damage on material elements and economic activities in monetary terms considering different hazard scenarios based on past landslide frequency. These models allow to identify the locations where landslide activity is expected to cause the highest damage and where the application of mitigation measures should be a priority. Consequently, the maps provide a useful basis for incorporating better landslide risk management policies and practices into land-use planning.

The results obtained in the area analyzed show that, even in the most pessimistic scenario, the expectable total monetary losses due to landsliding are not very high (if compared with the value of the exposed human elements). In this particular area, corrective strategies, based on repairing or compensating the damage, would be more cost-effective than preventive measures. Obviously, this reasoning may not be applicable to other areas.

Risk assessment has several uncertainties, in part due to limitations of the methodology, but mostly to the scarcity or quality of data. Independent evaluation of the susceptibility and hazard models indicates that they provide reasonably good predictions. However, unless good time series on landslides are available (and in most cases they are not) susceptibility models cannot be transformed into hazard models that reliably express the spatial-temporal probability of landslide occurrence in quantitative terms.

Ideally, the evaluation of risk predictions should be performed through comparison with damage caused by landslides occurred after the period of analysis used to construct a model, but the possibility to obtain enough data is very limited (or requires waiting for a long period).

The landslide risk analysis described, despite its uncertainties and limitations, can be of considerable value for decision making concerning risk prevention and management. Risk quantification provides, first of all, a basis for deciding whether it is advisable to plan a preventive or a corrective (as is the case in our study area) strategy. Secondly, it enables the identification of high-risk areas, including data on hazard, exposure and vulnerability. This quantitative analysis should help to determine priority areas for mitigation and the type of action to be carried out, either reducing the vulnerability of the elements or the potential activity of the hazardous process.

One of the limitations of the method, as formerly discussed, is the uncertainty with respect to future exposure and, therefore, risk. However, this can be "turned round" and converted into a potential. Distribution of new elements on a territory is normally established through land-use plans. These plans propose locations for land use in general. Using the distribution proposed by a plan, it is possible to assess risk. Different land-use proposals (exposure scenarios) can thus be compared in terms of landslide risk and the landslide risk analysis procedure presented here can be used as a tool for the Strategic Environment Impact Analysis (SEIA) of land-use plans.

The method proposed provides the means to express risk in, at least, semi-quantitative terms and also analyze land-use proposals from the point of view of future risk.

6 PERSPECTIVES

Certain lines of research that would help to improve both the procedures and results presented have being considered. One of the lines to follow is to look into the possibility of obtaining very high resolution Digital Elevation Models, since it seems very clear that the higher the resolution of these maps, the greater the susceptibility model's prediction capability. The use of different techniques (photogrammetry, LIDAR, GPS, total stations, etc), allows a large number of points to be captured, and these serve to generate high resolution and high quality DEMs.

It is essential to continue carrying out systematic inventories of events in order to improve the susceptibility analyses. Better data on past occurrence would also help to formulate more realistic scenarios of future frequency.

The continuous updating of non-static variables such as land use, new infrastructure, buildings, town planning, etc, would help to generate vulnerability models and risk models more in accordance with the new situations that can arise. The formulation of different land-use scenarios, based on different planning proposals, would allow the generation of risk models that could be used as tools for planning or for strategic EIA.

It would be convenient to carry out systematic cost/benefit analyses to compare potential damage under different scenarios with the cost of implementing mitigation measures or strategies, to determine to what extent the latter are justified.

The evaluation process for risk models needs to be improved by means of methods or strategies that are comparable to those used for susceptibility model evaluation. Efforts should be devoted to the gathering of data on damage caused by landslides in order to better test the quality of the risk predictions obtained.

Finally, it would be worth exploring the usefulness of the approach and methods described here to other geomorphic hazards. Initial application to the case of sinkhole collapse has produced promising results (Galve et al. 2008).

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