Nat. Hazards Earth Syst. Sci., 15, 2461–2472, 2015
www.nat-hazards-earth-syst-sci.net/15/2461/2015/
doi:10.5194/nhess-15-2461-2015

Natural Hazards and Earth System Sciences
Open Access

Detailed and large-scale cost/benefit analyses of landslide prevention vs. post-event actions

G. Salbego, M. Floris, E. Busnardo, M. Toaldo, and R. Genevois

Dipartimento di Geoscienze, Università degli Studi di Padova, Via G. Gradenigo 6, 35100, Padova, Italia

Correspondence to: (mario.floris@unipd.it)

Received: 19 January 2015 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 12 February 2015
Revised: 8 October 2015 – Accepted: 18 October 2015 – Published: 6 November 2015

Abstract. The main aim of this paper is to test economic benefits of landslide prevention measures vs. post-event emergency actions. To this end, detailed- and large-scale analyses were performed in a training area located in the northeastern Italian pre-Alps that was hit by an exceptional rainfall event occurred in November 2010. On the detailed scale, a landslide reactivated after 2010 event was investigated. Numerical modeling demonstrated that remedial works carried out after the landslide – water-removal intervention such as a drainage trench – could have improved slope stability if applied before its occurrence. Then, a cost/benefit analysis was employed. It defined that prevention would have been economically convenient compared to a non-preventive and passive attitude, allowing a 30 % saving relative to total costs. On the large scale, one of the most affected areas after 2010 event was considered. A susceptibility analysis was performed using a simple probabilistic model, which allowed to highlight the main landslide conditioning factors and the most hazardous and vulnerable sectors. In particular, such low-cost analysis demonstrated that almost 50 % of landslides occurred after 2010 event could be foreseen and allowed to roughly quantify benefits from regional landslide prevention. However, a large-scale approach is insufficient to carry out a quantitative cost/benefit analysis, for which a detailed case-by-case risk assessment is needed. The here proposed approaches could be used as a means of preventive soil protection in not only the investigated case study but also all those hazardous areas where preventive measures are needed.

1 Introduction

Landslides are one of the most dramatic natural hazards along with earthquakes and floods. For this reason, hazard and risk assessment has been the main aim of a large number of scientific papers (Corominas et al., 2014 and reference therein), focusing on geomorphological (Baek and Kim, 2015; Cardinali et al., 2002; Devoto et al., 2014) and multidisciplinary or statistical approaches (Sterlacchini et al., 2007; Dai et al., 2002). The level of risk is generally defined as the intersection of hazard with the value of the elements at risk by way of their vulnerability (Crozier and Glade, 2006; Alexander, 2002). This assumption is generally based on a great number of variables; vulnerability of element at risk is closely related to the type of landslide, and frequency-based hazard assessment often relies on a few decades of knowledge of slope instabilities. Fortunately, previous years' measurements have been thoroughly collected thanks to GIS databases, web information sharing and a greater awareness of landslide risk. This attitude allowed some authors to calculate the costs of damages due to slope instabilities within many environments around the world: from 1972 to 2007, landslides and rockfalls cost EUR 520 million and caused 32 fatalities in Switzerland (Hilker et al., 2009), while in the United States a USD 1–2 billion expense in economic losses and about 25–50 deaths per year have been estimated (Schuster and Fleming, 1986), e.g., USD 9 million expense in only direct cost losses in Colorado during 2010 (Highland, 2013). Historical research indicates that more than 50 593 people died, went missing or were injured in 2580 landslides and floods in Italy, where 26.3 % of the 8102 municipalities have been hit by slope instabilities between 1279 and 2002 (Guzzetti et al., 2005b); economic loss related to the single destructive landslide at Ancona (Marche region) in 1982

Published by Copernicus Publications on behalf of the European Geosciences Union.

was estimated at USD 700 million (Alexander, 1989). On the global scale, 2620 landslides were recorded during the 7-year period of 2004–2010, causing a total of 32 322 fatalities (Petley, 2012). Besides these historical data, the need for landslide damage prediction is very strong if we want to implement preventive measures against slope instabilities, even at a large scale. Within a small test site of about 20 km^2 north of Lisbon (Portugal), cumulative risk expressed in direct costs for buildings and roads was calculated to be about EUR 5 million (Zêzere et al., 2008). In southern India, the triggering of many landslides hanging over 20 km long roads could cost from USD 90 840 to 779 500, with an average annual total loss estimated at USD 35 000 (Jaiswal et al., 2010). These expenses highlight how much people need protective measures against landslides and floods, which cause USD billions every year in damages and economic losses. This need can be summarized in the term “risk management”, referring to the full range of procedures and tasks that ultimately lead to the implementation of rational policies and appropriate measures for risk reduction (Crozier and Glade, 2006). One important task in risk management is the evaluation of benefits from preventive actions which can encourage authorities and population to invest money for preventing damage due to slope failures. To this end, the estimation of the most landslide-prone areas and of the effectiveness of possible preventive measures is needed.

Scientific literature offers a variety of different methods to assess risk and economic losses due to landslide events; both of these features represent the central topic when decision makers are called to act toward prevention, and thus an in-depth analysis is needed in order to obtain the best result with the least effort. The first problem to solve is the scale of analysis; many authors prefer a regional-scale approach, which necessarily leads to a qualitative or semi-quantitative analysis due to the impossibility of obtaining or considering data from every landslide (Von Ruette et al., 2011). In this kind of approach, the probability that a landslide could cause damage is accounted for through hazard or susceptibility maps, which are the start point of the analysis. These maps are next overlaid with information concerning elements at risk and their economic value, defined by maps of probability of direct monetary loss per year (Blahut et al., 2014) or by quantification of economic losses at municipal level (Pellicani et al., 2014). However, other authors focus on a slope-scale approach, in which information on landslide events and local features need to be wisely considered. Despite the fact that every event has to be evaluated one by one, this analysis usually allows quantitative assessment of landslide costs and losses; in this way, different alternatives can be thoughtfully weighted (Crosta et al., 2005) and local toolboxes for vulnerability assessment can be created (Papathoma-Köhle et al., 2015). The slope-scale approach can also help in the realization of a cost/benefit analysis, a topic rarely investigated in the scientific literature despite being of paramount importance, which consists of an economical comparison between the cost of prevention and the cost of the rebuilding what have been lost (Boonyanuphap, 2013; Crosta et al., 2005; Frattini and Crosta, 2006). Thus, given a specified landslide event which caused various damages, costs of rebuilding are well known, while costs related to a potential prevention plan depend on what type of preventive work is chosen and on what business company is selected. Every one of these last features has to be generally evaluated on a case-by-case basis.

In this work, we have considered the effects of an exceptional rainfall event that hit the Italian pre-Alps of the Vicenza province (NE Italy) in 2010 (Floris et al., 2012, 2013) to perform a cost/benefit analysis of landslide prevention vs. post-event actions. To achieve this goal, slope-scale (detailed) and large-scale (1 : 10 000) analyses (Lee and Min, 2001) were carried out. On the slope scale, numerical simulations and cost/benefit estimation were performed on a landslide reactivated by the 2010 rainfall event to define if preventive measures could avoid the reactivation of the instability and if they could effectively carry an economic benefit, as a result of an effective risk management methodology. On the large scale, a landslide susceptibility analysis was carried out in one of the most affected sectors (Marosticano Hills; Fig. 1) after the 2010 event to verify if instability phenomena could be foreseen and to estimate possible benefits from regional-scale prevention measures before the rainfall event.

2 Case study

In recent years, Italy has been hit by several exceptional rainfall events, causing damages to public and private buildings, infrastructures and activities. One of these events hit the province of Vicenza (Veneto Region) in 2010. This event lasted from 31 October to 2 November; the average of the rainfall measured by the 11 rain gauges located in the affected area was 336 mm and the maximum cumulative rainfall registered by one of the rain stations was 500 mm (Floris et al., 2012, 2013). In the following days, a great flood hit plain territories and 500 warnings of landslides, distributed over 20 municipalities, were received at the Soil Protection Division. Many of these slope failures affected the Marosticano area, a 110 km^2 territory located in the northeastern sector of the province (Fig. 1). Here, landslides were classified as rotational/translational slides and earth flows (following the classification proposed by Varnes, 1978). These failures involved mostly silty-clay soils, i.e., the weathering products of Late Paleocene–Early Miocene extrusive magmatic rocks. Weathering of basic bedrock led to the typical geological and geomorphological environment within Vicenza’s pre-Alps hilly belt, where basalt and tuffaceous rock outcrops are sporadic because a variable thickness of eluvial and colluvial deposits is present. The November 2010 event highlighted the partial lack of preventive and maintenance works, a soil defense attitude which has still to be acquired by authorities

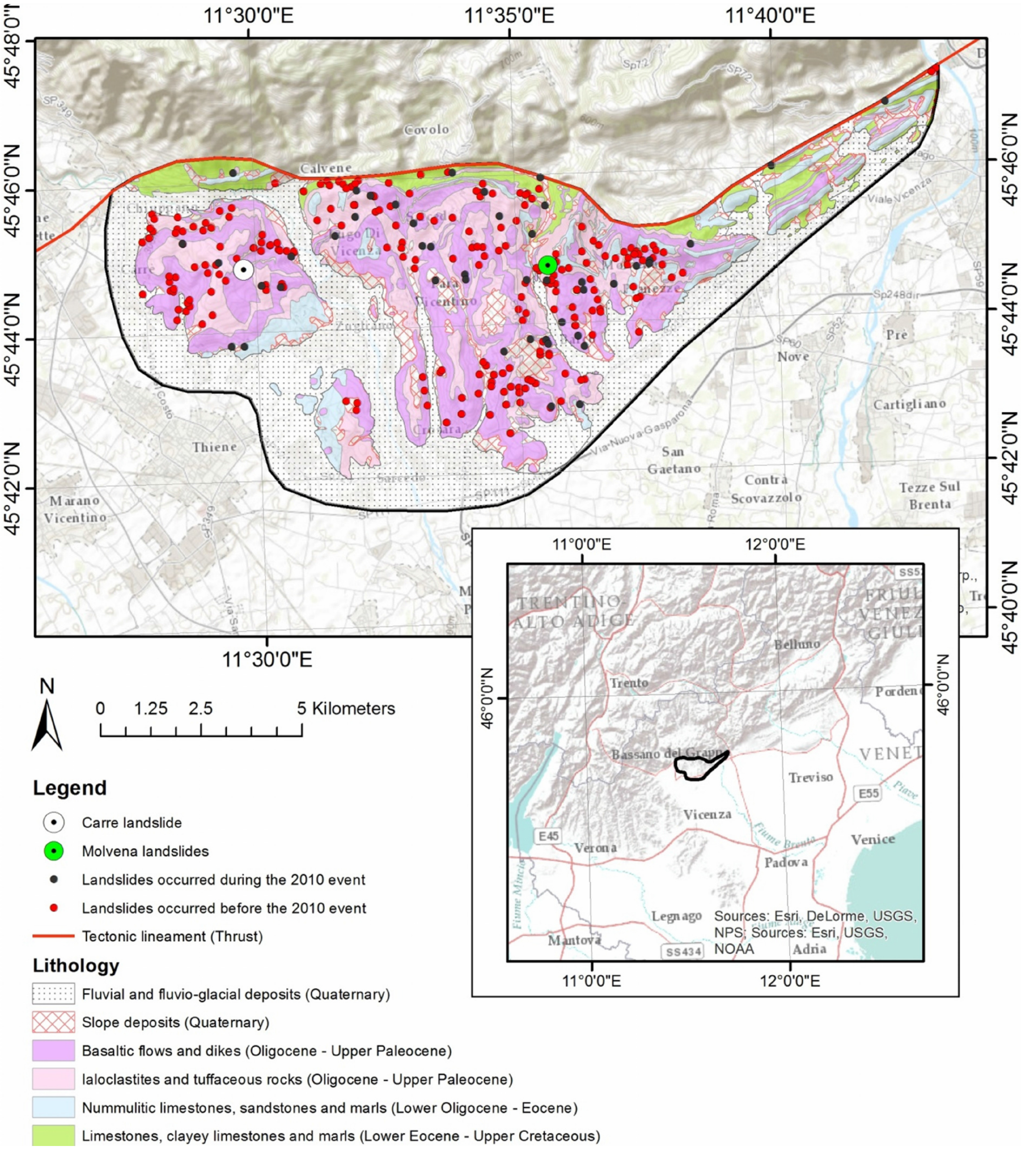

Figure 1. Lithological map of the study area with the location of landslides considered in the detailed cost/benefit analysis (Carrè and Molvena) and of landslide data sets used in the large-scale analysis.

and population at the present time but is more needed today than in the past, because the frequency of exceptional rainfall events in Italy has increased in the last decades (Floris et al., 2013), with one damaging event about every 20 years (Floris and Bozzano, 2008); thus, the November 2010 event represents only one element of this developing trend. As a result, without any kind of soil protection, Vicenza's administration had to face EUR 300 million of remediation works and about EUR 1 billion of infrastructure and building losses. In this paper, we tried to estimate possible benefits from preventive actions before 2010 in the Marosticano area, where the costs for post-landslide remediation works amounted to about EUR 20 million.

Figure 2. View of Carrè landslide.

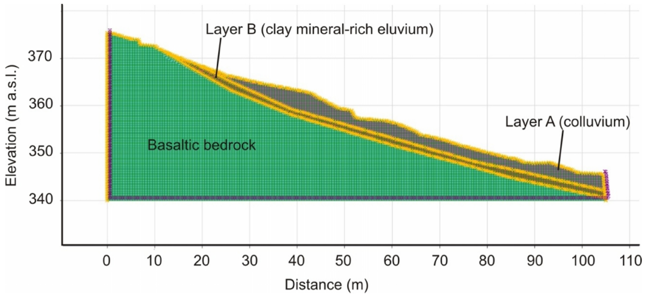

Figure 3. Carrè landslide cross section used in the numerical simulations.

On the slope scale, we chose to focus our attention on a roto-translational slide occurred in the Carrè municipality (Fig. 2); this landslide is located on an unstable slope which was affected by past and recent instabilities – including during the 2010 event – forcing authorities to demolish an old house and rebuild the main road, with a total direct cost of EUR 60 000. The landslide body lies above a basaltic bedrock and involves a few-meters-thick eluvium–colluvium layer. The landslide area covers about 5500 m^2 (100 m length × 65 m width), with a 1 m high main scarp. Field data resulted in a supposed shear surface located within the first shallower meters (inside layer B shown in Fig. 3), where a decrease of strength occurred in silty-clay soils due to pore pressure rising. On the large scale, the entire territory of Marosticano hills was investigated.

3 Methods

3.1 Detailed-scale analysis

Detailed-scale analysis aimed to define if a specific preventive work employed before the 2010 event could have either avoided landslide or not. A numerical model was implemented in order to study slope stability along with remedial measure which was actually realized after the slide: a drainage trench, whose planned task was to reduce the water table by 2 m from the surface and get rid of the most important landslide triggering factor (Roggia, 2014). The analysis was performed with Itasca's FLAC® 7, a finite-difference software for numerical modeling of 2-D continua (ITASCA, 2011). It is a commonly used code in geosciences because of the numerous constitutive models implemented which allow the study of deformation and yield in every node of the grid; each one of these nodes follow a linear or non-linear tension-deformation rule in response to forces or boundary conditions. The analysis began with a well-defined conceptual model built on the whole available geological and geotechnical knowledge. Slope was represented by three different lithotypes: a basaltic bedrock at the bottom, a clay-mineral rich eluvium interface "B" in the middle and a colluvium horizon "A" at the top (Fig. 3). This geotechnical setting was deducted from field observations and laboratory tests, along with other technical and geophysical surveys performed by local authorities. Slope conditions were then modeled using back analysis: we had at our disposal ranges of strength parameters from professional reports (Massagrande, 2012; Naldi, 2014) and FLAC user manuals (ITASCA, 2011), and we also knew approximately where slip surface was localized; in this analysis we set the water table at the ground surface because it was assumed as the conceivable limit condition for the slope during the 2010 event. Back analysis allowed us to calibrate strength parameters, which have been used to simulate the effects of the drainage trench.

After we proved that a drainage trench could have effectively avoided landslide occurrence during the 2010 event, the next step was to understand if this kind of preventive work could have been also economically convenient. Thus, drainage trench costs were compared with the total cost of all remedial measures (which included the reshaping of the slope and the drainage trench itself) applied after the landslide occurrence. The so-called cost/benefit analysis was used to compare landslide prevention costs with the total cost of landslide remediation works. Such an approach is generally employed in economics and aims to compare the economic efficiency of various alternatives used to reach a specific objective. This method verifies whether benefits brought by one alternative are greater than the related costs (Momigliano and Nuti, 2001). Cost/benefit methodology permits a multi-year analysis, and for this reason every monetary resource has to be carried back to the first time of policy implementation. In order to get all amounts fully comparable throughout the years, it is necessary to apply a discount rate. Equation (1) is employed to determine the value (present value, PV) of a X monetary resource available at future time t, assuming a r discount rate:

$$\mathrm{PV}(X) = \frac{1}{(1+r)^{\mathrm{t}}} X. \tag{1}$$

Considering the flow of C_{t} costs and B_{t} benefits, the real expense comparison is expressed by NPV (net present value), defined as the difference between the benefits and costs throughout the years, as in Eq. (2) (Frattini and Crosta, 2006):

$$\mathrm{NPV} = \sum_{\mathrm{t}=0}^{\mathrm{T}} \frac{B_{\mathrm{t}}}{(1+r)^{\mathrm{t}}} - \sum_{\mathrm{t}=0}^{\mathrm{T}} \frac{C_{\mathrm{t}}}{(1+r)^{\mathrm{t}}}. \tag{2}$$

Thus, the cost/benefit analysis allowed us to compare the preventive costs with the total remedial costs of the Carrè landslide. In a process like this, the definition of all amounts has been a critical point: C_{t} costs were set to preventive drainage trench expenses, obtained from remedial work projects (Roggia, 2014) which include the costs of the analysis on the stability of the slope; however, due to the impossibility to calculate the indirect costs of losses, we set B_{t} benefits to the total amount of remedial works. We have calculated NPV for 20 years because it is the return period of exceptional rainfall events related to the triggering of landslides (Floris et al., 2012, 2013). Furthermore, 20 years is the limit for a cost/benefit analysis because of the possible changes in the inflation rate and in the discount rate. Hence, a return period of 20 years could represent a good choice to have an overview of the benefits from prevention measures in the study area. Cost/benefit analysis permitted us to consider the annual maintenance cost, too: protective measures management generally reveals to be as fundamental as prevention itself, because the lack of surveillance can be considered as much as a preparatory factor. This amount was set to EUR 400 per year, because many inspections could be realized by sight or with basic instrumentations. Here, a discount rate of 1.6 % was applied, obtained from the website of Italian Economy and Finance Department and referred to 15 years Euro-BTP *i* notes (15 years represent the nearest interval to our 20 years preventive policy).

3.2 Large-scale analysis

In order to understand whether landslides that occurred in 2010 could have been foreseen and to quantify possible benefits from pre-event measures before the rainfall event, a spatial analysis over the Marosticano area was performed. This represents a crucial step toward landslide prevention, because it would have been impossible to decide where to intervene without a clear overview on landslide susceptibility and on more hazardous areas. Statistical analysis was employed assuming that landslide occurrence is generally determined by landslide-related factors and that future landslides will occur under the same conditions as past landslides (Chung et al., 1995; Lee and Pradhan, 2006). A very common bivariate analysis known as "frequency ratio" was adopted: spatial landslide predictability was calculated from the analysis of the relation between landslides and most important landslide conditioning factors (Lee and Pradhan, 2007; Zhu and Huang, 2006). In order to achieve the final map, the landslide inventory data set and environmental factor data layers were collected from the Spatial Data Infrastructure of the Veneto Region (http://idt.regione.veneto.it/). Morphometric (elevation, slope, curvature, aspect) and non-morphometric (river distance, road distance, lithology and land use) environmental factors were considered. As in the majority of probabilistic spatial analyses, every single factor needed to be reclassified and divided in sub-categories of values (see Table 3 of Sect. 4.2); because this is a crucial initial step of the analysis, we tested numerous classifications, taking into account natural breaks in the distribution of continuous data, geomorphic and geological features of the study area and the distribution and size of landslides (Floris et al., 2011). Then, a table for each landslide-related factor was created and compiled with the following values: $N^{\mathrm{L}}_{\mathrm{pix}}(X_i)$, the number of pixels where landslide occurred within class i of factor X; $\sum_{i=1^n} N^{\mathrm{L}}_{\mathrm{pix}}$, the total pixels where landslide occurred within the entire area; $N_{\mathrm{pix}}(X_i)$, the number of pixels where landslide did not occur within class i of factor X; $\sum_{i=1}^{n} N_{\mathrm{pix}}$, the total pixels where landslide did not occur within the entire area; and n, the number of factors in the study area.

Frequency ratio index (FRI) represents the ratio of the landslide occurrence probabilities to the non-occurrence probabilities for a given class within a factor. FRI is calculated using Eq. (3) (Jaafari et al., 2014; Lee and Min, 2001; Lee and Pradhan, 2007):

$$\mathrm{FRI}_n = \frac{\frac{N^{\mathrm{L}}_{\mathrm{pix}}(X_i)}{\sum_{i=1}^{n} N^{\mathrm{L}}_{\mathrm{pix}}}}{\frac{N_{\mathrm{pix}}(X_i)}{\sum_{i=1}^{n} \mathrm{N}_{\mathrm{pix}}}}. \qquad (3)$$

The larger the ratio is, the stronger the relationship between landslide occurrence and the given factor attribute (Jaafari et al., 2014). A value of 1 represents an average value, but a value > 1 means that the percentage of the landslide is higher than the area without landslide and refers to a higher correlation with conditioning factors; a value < 1 means lower correlation. In the case under investigation we set 1.6 as the lower limit to infer a correlation between landslide and conditioning factors. The landslide susceptibility index (LSI) is then obtained summing all factor index contributions, as in Eq. (4) (Yalcin et al., 2011):

$$\mathrm{LSI} = \mathrm{FRI}_1 + \mathrm{FRI}_2 + \mathrm{FRI}_3 + \ldots + \mathrm{FRI}_n. \qquad (4)$$

Thus, LSI allows creating a susceptibility map and defining which areas are more prone to landslide, given a specific geological, geomorphological and anthropic environment and landslide type.

To test the good of fitness and the forecasting power of the adopted model, success and predictive rate curves were calculated (Chung and Fabbri, 2003). The success rate curve helped to quantify how the prediction image (i.e., susceptibility map) fits the landslides occurred in the study area, comparing LSI values with the entire data set of instability phenomena before 2010. The predictive rate curve was calculated comparing LSI values and landslides occurred after the 2010 rainfall event; this curve helped in the classification of susceptibility levels and in the evaluation of the percentage of 2010 landslides which could be foreseen.

Finally, on the basis of results from detailed-scale analysis (i.e., percentage of benefits from prevention measures), we roughly evaluated possible savings from large-scale pre-event actions by subtracting the possible costs of prevention in the predictable unstable areas from the total costs of post-event actions.

4 Results

4.1 Detailed-scale analysis

In the back analysis, after numerous numerical simulations with different soil properties, a fully saturated slope col-

Table 1. Soil properties which lead to slope failure under fully saturated conditions.

	Layer A	Layer B	Bedrock
Model	Mohr–Coulomb	Mohr–Coulomb	Mohr–Coulomb
Density [kg m^{-1}]	1900	1900	2700
Bulk modulus [Pa]	5×10^6	1×10^6	3×10^{10}
Shear modulus [Pa]	2×10^6	5×10^5	1×10^{10}
Cohesion [Pa]	1×10^4	6×10^3	6×10^7
Tension [Pa]	1×10^4	6×10^3	1×10^7
Friction angle [°]	23	15	31

Table 2. Cost/benefit analysis for the Carrè landslide: total remedial costs of EUR 57 000 were considered a benefit which had to be reduced by the prevention and maintenance costs. The final saving was obtained by summing all years' savings.

			Discounted amounts		
Year	Cost	Benefit	Cost	Benefit	Net present value
1	EUR 17 652.00	EUR 0.00	EUR 17 363.76	EUR 0.00	EUR −17 363.76
2	EUR 400.00	EUR 0.00	EUR 387.04	EUR 0.00	EUR −387.04
3	EUR 400.00	EUR 0.00	EUR 380.72	EUR 0.00	EUR −380.72
4	EUR 400.00	EUR 0.00	EUR 374.51	EUR 0.00	EUR −374.51
5	EUR 400.00	EUR 0.00	EUR 368.39	EUR 0.00	EUR −368.39
6	EUR 400.00	EUR 0.00	EUR 362.38	EUR 0.00	EUR −362.38
7	EUR 400.00	EUR 0.00	EUR 356.46	EUR 0.00	EUR −356.46
8	EUR 400.00	EUR 0.00	EUR 350.64	EUR 0.00	EUR −350.64
9	EUR 400.00	EUR 0.00	EUR 344.91	EUR 0.00	EUR −344.91
10	EUR 400.00	EUR 0.00	EUR 339.28	EUR 0.00	EUR −339.28
11	EUR 400.00	EUR 0.00	EUR 333.74	EUR 0.00	EUR −333.74
12	EUR 400.00	EUR 0.00	EUR 328.29	EUR 0.00	EUR −328.29
13	EUR 400.00	EUR 0.00	EUR 322.93	EUR 0.00	EUR −322.93
14	EUR 400.00	EUR 0.00	EUR 317.66	EUR 0.00	EUR −317.66
15	EUR 400.00	EUR 0.00	EUR 312.47	EUR 0.00	EUR −312.47
16	EUR 400.00	EUR 0.00	EUR 307.37	EUR 0.00	EUR −307.37
17	EUR 400.00	EUR 0.00	EUR 302.35	EUR 0.00	EUR −302.35
18	EUR 400.00	EUR 0.00	EUR 297.41	EUR 0.00	EUR −297.41
19	EUR 400.00	EUR 0.00	EUR 292.56	EUR 0.00	EUR −292.56
20	EUR 400.00	EUR 57 000.00	EUR 287.78	EUR 41 008.39	EUR 40,720.61
Discount rate		1.60 %	Σ net present value		EUR 17 277.75

lapsed with parameters in Table 1. Slope was unstable only if the eluvium layer "B" was set with low-strength parameters: this assumption was quite consistent with the presence of a clay mineral-rich layer (Toaldo, 2014). Plasticity zones were concentrated in this thin layer where soil did not have sufficient shear strength, so movement was allowed (Fig. 4). This result was considered acceptable, since we obtained a shear surface and a morphological setting comparable to field surveys and observations. Instability was also confirmed by the calculated factor of safety (FoS) < 1. The FoS was calculated with the shear strength reduction method (Dawson et al., 1999; Matsui and San, 1992) implemented in FLAC, which is a method widely used for analyzing stability of rock and soil slopes (Dawson and Roth, 1999; Soren et al., 2014; Zettler et al., 1999). The same parameters were reutilized in the second model, where the water table was reduced by 2 m for a 30 m distance, simulating the planned drainage trench and its activation. This securing measure stabilized the slope, with a FoS > 1. Thus, if the Carrè administration had created the drainage trench before the landslide event and not after it, this preventive work could have avoided the landslide itself. A part of those EUR 60 000 could have been saved, along with other tens of thousands of Euros spent in incalculable indirect costs (emergency actions, social cost due to inaccessibility of the road).

Table 2 shows the results obtained from the cost/benefit analysis applied to the Carrè landslide: local administration spent EUR 57 000 in remediation costs, while the preventive works amount would have cost EUR 17 652. Thus, considering a 20-year policy and 400 Euros per year in mainte-

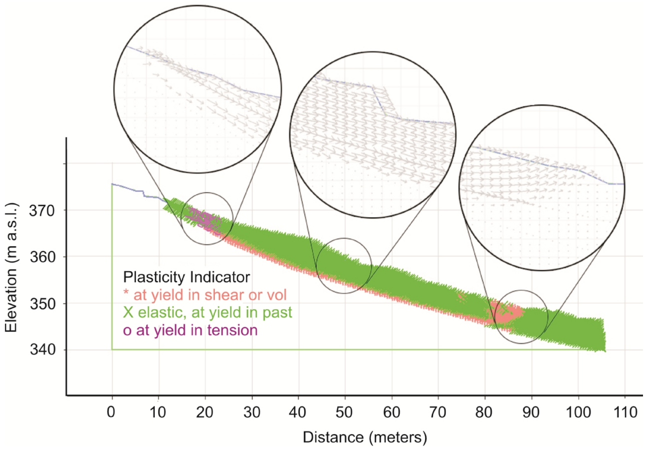

Figure 4. Distribution of plasticity zones during Carrè landslide in the case of the water table at the ground surface. Insets show the direction of displacement vectors in different parts of the landslide body.

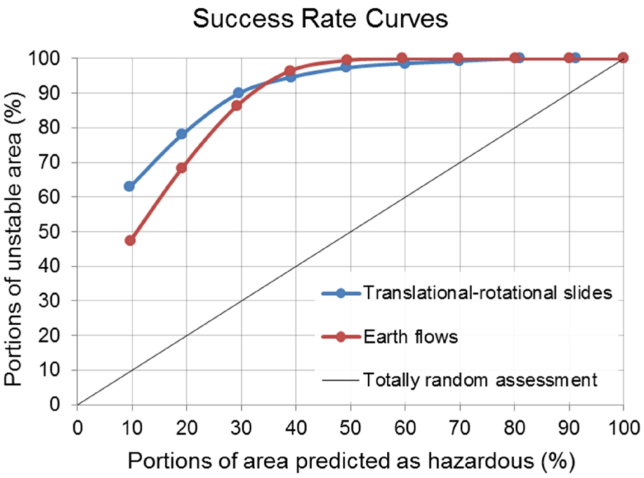

Figure 5. Success rate curves showing how the adopted model fits the instability conditions of the study area.

nance expenses, a total amount of EUR 17 277 would have been saved (30 % of the total remediation costs). This amount must be kept under advisement especially by local administrations, which could have allocated these funds to other activities, soil protection plans or possibly other preventive works. We supposed that geological, geomorphological and geotechnical considerations could be even valid for other landslides, which happened within the same background and environment conditions of Carrè (similar lithology, slope angle, land use, road distance and rainfall intensity); thus, the cost/benefit methodology was employed at three landslide sites in the Molvena municipality, located a few kilometers from Carrè. Drainage intervention was assumed, and the economic study proved that of the total EUR 130 000 spent in remediation works, about 40 % would have been saved with a preventive policy (Salbego, 2014).

4.2 Large-scale analysis

FRI was calculated for each class belonging to eight landslide-related factors. For morphometric factors, every class was carefully chosen after repeated analysis, performed to isolate the best landslide pre-conditioning range of values. In this particular case, a temporal validation was chosen (Chung and Fabbri, 2003): the model was built with an input data set of landslides which occurred before the November 2010 event, and then predictability and validation assessments were made using a test data set of landslides occurred during the same event. First, the input data set was obtained after a search for landslide perimeter data and triggering areas (Trigila, 2014), scanning every available source (field surveys, orthophotos and GIS shading capabilities). The only available data for the test data set were point features, so a buffer of 10 m around each element was applied (Adami et al., 2012). Table 3 shows that earth flows are predisposed by altered massive (basaltic) rocks, slope angle between 13 and 23° and elevation from 245 m to 420 m a.s.l. Higher and steeper slopes are more susceptible to translational or rotational slides, which usually occur on altered stratified (tuffaceous) bedrock. The success rate curve (Fig. 5) shows what part of the assessed landslide susceptible area is actually an unstable area. It represents the cumulative percentage (fraction; y axis) of landslides in the input data set with respect to susceptibility classes (expressed as the portion of the study area with susceptibility above a given value; from greater to lower; x axis): a hypothetical curve coinciding with a diagonal from 0 to 100 % would be equivalent to a totally random assessment, so the further up away the success rate curve is from that diagonal the better the model has been created (Remondo et al., 2003). Curves for slides and earth flows are both far up from the diagonal, so the result is quite convincing. Then, we used the November 2010 landslides to test the forecasting power of this model by calculating predictive rate curves. Figure 6 shows that the validation data set did not perform as well as the first one, but both curves are higher than the random diagonal, so results are acceptable even in this case. The susceptibility map confirmed the results of statistical analysis, as shown in Fig. 7: most susceptible areas for translational/rotational slides are located at greater elevation and slope, nearer to the roads than earth flows, which occur at lower elevation and slope. Analysis confirmed what occurred during the November 2010 event: heavy rainfall caused instabilities mainly along roads (90 % of the total damage), so they need to be kept under control and be protected with preventive works.

Table 4 shows FRI ranges of susceptibility levels used for classifying prediction maps of Fig. 7. The area was classified as having high, medium, low or very low susceptibility on the basis of the shape of predictive rate curves (Chung and Fab-

Table 3. Frequency ratio index (FRI) for each category of input factors. Values from medium to high susceptibility are shown in bold.

Morphometric factors		
Elevation (m a.s.l.)	Slides	Flows
Classes	FRI	FRI
80–145	0.0	0.0
> 145–245	0.5	1.5
> 245–314	**1.7**	**1.7**
> 314–420	**3.3**	**1.7**
> 420–577	**12.2**	1.0
Slope (°)	Slides	Flows
Classes	FRI	FRI
0–13	0.4	0.6
> 13–23	**2.0**	**1.9**
> 23–33	**2.3**	**1.7**
> 33–74	1.5	0.8
Curvature	Slides	Flows
Classes	FRI	FRI
Very concave	1.5	1.0
Concave	**1.6**	1.4
Flat	0.7	0.7
Convex	1.3	1.4
Very convex	**1.7**	0.6
Aspect	Slides	Flows
Classes	FRI	FRI
North	1.2	0.7
East	0.7	0.9
South	1.4	1.1
West	0.5	0.9
Non-morphometric factors		
Road distance (m)	Slides	Flows
Classes	FRI	FRI
0–25	1.3	0.5
> 25–50	**1.6**	0.6
> 50–75	1.4	1.0
> 75–100	1.3	**1.6**
> 100–200	0.6	0.8
> 200	0.8	1.2
River distance (m)	Slides	Flows
Classes	FRI	FRI
> 0–100	0.5	0.4
> 100–200	1.5	1.7
> 200–300	**2.0**	1.5
> 300–400	1.1	**1.8**
> 500–1000	0.2	0.2
> 1000	0.2	0.0
Lithology	Slides	Flows
Classes	FRI	FRI
Weathered massive bedrock	1.2	**2.5**
Stratified rocks	1.1	0.0
Weathered stratified bedrock	**2.7**	**1.7**
Layered rocks	1.1	0.0
Fluvial deposits	0.0	0.0
Alluvial deposits	0.0	0.0
Eluvial/colluvial	0.0	0.0
Land use	Slides	Flows
Classes	FRI	FRI
Urban	0.8	0.6
Industrial	0.0	0.0
Extractive	0.0	0.0
Green areas	0.0	0.0
Arable	0.0	0.0
Seasonal cultivation	0.1	1.0
Permanent cultivation	0.2	0.3
Woody	0.3	0.7
Grassland	1.6	1.1
Shrubby	1.1	1.6
Sparse vegetation	**6.2**	**2.2**
Water body	0.0	0.0

Table 3. Continued.

bri, 2003; Floris et al., 2011). About 50 % of 2010 landslides fall in high and very high susceptibility levels, it means that such instabilities could be foreseen before the 2010 rainfall event. Consequently, a part of the EUR 20 million expended for post-event actions in the Marosticano area could be saved: taking into account results from detailed analysis, 30 % of about EUR 10 million.

5 Discussion and conclusions

In this paper, we dealt with detailed and large-scale analyses aimed to quantify possible benefits from landslide prevention: to this end we have considered the 2010 exceptional rainfall event that hit the pre-Alps sectors of the Vicenza province (NE Italy), triggering hundreds of instabilities.

On a detailed scale, we have considered the reactivation of the Carrè landslide after the 2010 event: it moved frequently in the past, destroying an old house and the provincial road. Numerical modeling demonstrated that a drainage trench, which was included in the project of post-event remediation works, could have been a good preventive measure to improve slope stability if applied before the landslide itself. Prevention costs were compared to those relative to remedial works, usually applied after the landslide occurrence. It was possible to define a saving of 30 % on the total amount

Table 4. Levels of susceptibility assigned on the basis of the degree of prediction of different landslide index ranges.

Slides			
FRI	Area (%)	Nov. 2010 Lds. (%)	Level of susc.
12–30	10	20	Very high
10–12	20	34	High
9–10	20	30	Medium
6–9	30	16	Low
3–6	20	0	Very low
Flows			
FRI	Area (%)	Nov. 2010 Lds. (%)	Level of susc.
11–14	10	22	Very high
10–11	20	36	High
8–10	20	27	Medium
5–8	30	13	Low
3–5	20	2	Very low

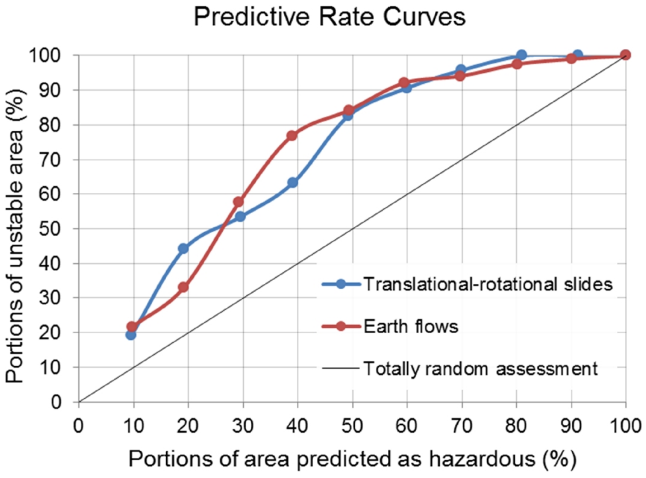

Figure 6. Predictive rate curves showing how the adopted model fits the instabilities triggered by the November 2010 rainfall event.

(about EUR 60 000), surely a great economic improvement for local administrations (confirmed by cost/benefit analyses performed within the environment of Molvena and not included in this paper). It is important to note that in the analysis we did not include the tens of thousands of Euros spent on incalculable indirect costs, such as emergency actions and social costs due to inaccessibility of the road. Thus, if the municipalities of the Vicenza province had acted before the 2010 event, an important amount of money would have been saved and possibly reutilized for other purposes.

On a large scale, we performed a susceptibility analysis in the Marosticano hills, which were one of the most affected areas after the 2010 event; this analysis considered landslides occurring before 2010 along with the natural variability of geological, geomorphological and geotechnical features of soils involved in slope failures. This method allowed us to understand which factors are related to landslides occurrence and to point out the most susceptible sectors of the study area. The key index of this approach, called the “frequency ratio index”, provided classes of values within each factor which are more inclined to cause landslide events. The definition of slide and flow susceptibility maps, along with the obtained indexes, allowed us to give a solid basis to the observations related to the 2010 rainfall event: spatial analysis defined that areas near the roads and placed over basaltic and tuffaceous weathered bedrock were generally the territories more frequently hit by landslides, as effectively occurred during the November 2010 event. Comparing the results from susceptibility analysis with the spatial distribution of landslides triggered by 2010 rainfall event, we found that 50 % of the instabilities (including the Carrè and Molvena landslides) fall in areas classified as highly and very highly susceptible; hence such instabilities could be foreseen. Therefore, a part of the EUR 20 million expended for post-event actions in the Marosticano hills could be preserved by prevention measures. We could not get enough data on the cost of post-event actions for the foreseeable landslides; because magnitude of instabilities and damages were very similar all over the area (Floris et al., 2012) we can reasonably suppose that such costs can reach the 50 % of the total (about EUR 10 million). Taking into account results from slope-scale analysis, where we estimated a saving potential of 30 % from pre-event actions, up to EUR 3 million could be saved by regional landslide-hazard assessment.

Even if large-scale analysis helped us to roughly estimate possible benefits from landslide prevention in the study area, such approach cannot define where to act with preventive works; indeed, results of spatial analysis showed that the majority of the study area would need to be defended – regardless of money and time – in order to take care for all the most susceptible environments. Therefore, preventive works must be planned on a detailed scale with regards to those specific slopes which show instabilities occurred in the past. This is an important factor because landslides are frequently consequent upon partial or complete reactivation of existing landslide bodies, often triggered by rainfall (Floris and Bozzano, 2008, and references therein). Despite the limits of large-scale analyses, they are very low-cost investigations which can be easily performed by technicians of local and regional authorities and can be used as preliminary study to identify the most hazardous areas where to perform detailed surveys, supporting decision making and land use planning (Akgun, 2012).

In this work we performed quite simple analyses, which considered landslides occurred in the past (before and during the 2010 rainfall event), to point out possible benefits from landslide prevention on different scales. In order to perform forecasting analyses, a complete risk assessment has to be carried out to evaluate cost/benefit ratio of pre-event actions; more refined models recently proposed by some authors (Bordoni et al., 2015; Gioia et al., 2015) would be

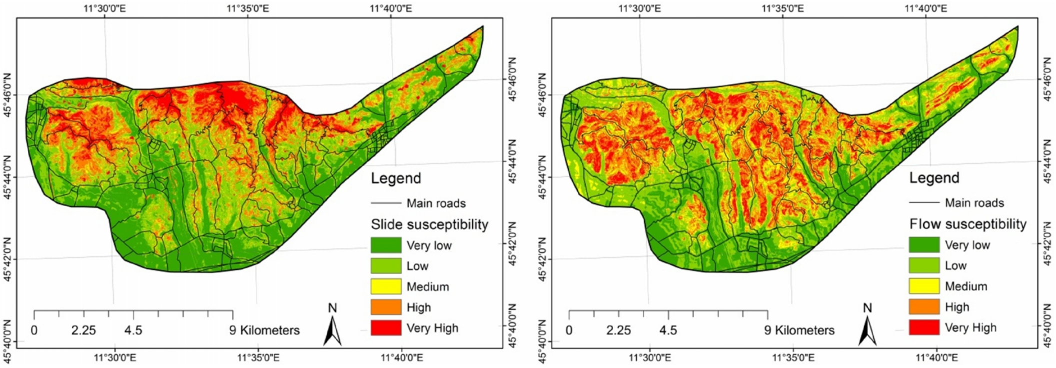

Figure 7. Translational/rotational slide and earth flow susceptibility maps. The classification of susceptibility is based on the results of the validation, interpreting predictive rate curves of Fig. 6.

recommended to improve both spatial and temporal prediction of landslides and induced damages on slope and large scales. However, the adoption of more refined tools could affect the costs of landslide prevention assessment; therefore, a cost/benefit analysis is always a primary crucial step before choosing between the numerous investigation methods proposed in the scientific literature (Dai et al., 2002, and references therein; Guzzetti et al., 2005a), which often lead to very similar results (Othman et al., 2015) depending mainly on site characteristics and available data (Lagomarsino et al., 2015).

The case study we dealt with in this paper can effectively contribute to improve our awareness and knowledge on prevention benefits. It is real evidence which proves that avoiding landslide occurrence represents a sustainable policy to deal with the social side of risk mitigation. This methodology can also provide an economic point of view for the global landslide issue, giving authorities the appropriate tool to face this ever-growing problem. To this end, new-generation early warning systems should be developed for monitoring and preventing instabilities on local and regional scales (Manconi et al., 2015; Segoni et al., 2015); thanks to the new availability of free data from spaceborne sensors and of WebGIS low-cost solutions, such systems represent reliable and cost-efficient tools to reduce landslide risk (Stähli et al., 2015). Afterwards, prevention is effectively possible from the economic point of view to the architectural one and could represent an efficient way to defend every defenseless territory.

Acknowledgements. This research was financially supported by the Italian Ministry of Education, University and Research: national research project (PRIN 2010-11) (principal investigator: Rinaldo Genevois, Department of Geosciences).

Edited by: F. Guzzetti
Reviewed by: D. Calcaterra and two anonymous referees

References

Adami, S., Bresolin, M., Carraretto, M., Castelletti, P., Corò, D., Di Mario, F., Fiaschi, S., Frasson, T., Gandolfo, L., and Mazzalai, L.: An unconventional GIS-based method to assess landslide susceptibility using point data features, Geophys. Res. Abstr., vol. 14, ISSN: 1607-7962, 2012.

Akgun, A.: A comparison of landslide susceptibility maps produced by logistic regression, multi-criteria decision, and likelihood ratio methods: a case study at Izmir, Turkey, Landslides, 9, 93–106, doi:10.1007/s10346-011-0283-7, 2012.

Alexander, D.: Urban landslides, Progr. Phys. Geogr., 13, 157–189, 1989.

Alexander, D. E.: Principles of emergency planning and management, Oxford University Press New York, 340 pp., 2002.

Baek, M. H. and Kim, T. H.: A study on the use of planarity for quick identification of potential landslide hazard, Nat. Hazards Earth Syst. Sci., 15, 997–1009, doi:10.5194/nhess-15-997-2015, 2015.

Blahut, J., Glade, T., and Sterlacchini, S.: Debris flows risk analysis and direct loss estimation: the case study of Valtellina di Tirano, Italy, J. Mt. Sci., 11, 288–307, doi:10.1007/s11629-013-2806-2, 2014.

Boonyanuphap, J.: Cost-benefit analysis of vetiver system-based rehabilitation measures for landslide-damaged mountainous agricultural lands in the lower Northern Thailand, Natural Haz., 69, 599–629, doi:10.1007/s11069-013-0730-y, 2013.

Bordoni, M., Meisina, C., Valentino, R., Bittelli, M., and Chersich, S.: Site-specific to local-scale shallow landslides triggering zones assessment using TRIGRS, Nat. Hazards Earth Syst. Sci., 15, 1025–1050, doi:10.5194/nhess-15-1025-2015, 2015.

Cardinali, M., Reichenbach, P., Guzzetti, F., Ardizzone, F., Antonini, G., Galli, M., Cacciano, M., Castellani, M., and Salvati, P.: A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy, Nat. Hazards Earth Syst. Sci., 2, 57–72, doi:10.5194/nhess-2-57-2002, 2002.

Chung, C. F. and Fabbri, A. G.: Validation of spatial prediction models for landslide hazard mapping, Natural Haz., 30, 451–472, 2003.

Chung, C. F., Fabbri, A. G., and Van Westen, C. J.: Multivariate regression analysis for landslide hazard zonation, in: Geographical information systems in assessing natural hazards, Springer, the Netherlands, 107–133, 1995.

Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., and Agliardi, F.: Recommendations for the quantitative analysis of landslide risk, Bull. Eng. Geol. Environ., 73, 209–263, 2014.

Crosta, G. B., Frattini, P., Fugazza, F., and Caluzzi, L.: Cost-benefit analysis for debris avalanche risk management, edited by: Hungr, O., Fell, R., Couture, R. and Eberhardt, E., in: Landslide Risk Management, A.A. Balkema Publishers, 517–524, 2005.

Crozier, M. J. and Glade, T.: Landslide hazard and risk: issues, concepts and approach, Landslide hazard and risk, Wiley, West Sussex, 1–40, 2006.

Dai, F. C., Lee, C. F., and Ngai, Y. Y.: Landslide risk assessment and management: an overview, Eng. Geol., 64, 65–87, 2002.

Dawson, E. M. and Roth, W. H.: Slope stability analysis with FLAC, in: FLAC and Numerical Modeling in Geomechanics, edited by: Detournay, C., and Hart, R., Rotterdam, Balkema, 3–9, 1999.

Dawson, E. M., Roth, W. H., and Drescher, A.: Slope stability analysis by strength reduction, Geotechnique, 49, 835–840, 1999.

Devoto, S., Boccali, C., and Podda, F.: Geomorphological surveys and software simulations for rock fall hazard assessment: a case study in the Italian Alps, Nat. Hazards Earth Syst. Sci. Discuss., 2, 7329–7365, doi:10.5194/nhessd-2-7329-2014, 2014.

Floris, M. and Bozzano, F.: Evaluation of landslide reactivation: a modified rainfall threshold model based on historical records of rainfall and landslides, Geomorphology, 94, 40–57, 2008.

Floris, M., Iafelice, M., Squarzoni, C., Zorzi, L., De Agostini, A., and Genevois, R.: Using online databases for landslide susceptibility assessment: an example from the Veneto Region (northeastern Italy), Nat. Hazards Earth Syst. Sci., 11, 1915–1925, doi:10.5194/nhess-11-1915-2011, 2011.

Floris, M., D'Alpaos, A., De Agostini, A., Stevan, G., Tessari, G., and Genevois, R.: A process-based model for the definition of hydrological alert systems in landslide risk mitigation, Natural Hazards and Earth System Science, 12, 3343–3357, doi:10.5194/nhess-12-3343-2012, 2012.

Floris, M., D'Alpaos, A., De Agostini, A., Tessari, G., Stevan, G., and Genevois, R.: Variation in the Occurrence of Rainfall Events Triggering Landslides, in: Landslide Science and Practice, edited by: Margottini, C., Canuti, P., and Sassa, K., Springer Berlin Heidelberg, 131–138, 2013.

Frattini, P. and Crosta, G. B.: Valutazione dell'accettabilità del rischio da frana e analisi costi-benefici, Giornale di Geologia Applicata, 4, 49–56, 2006.

Gioia, E., Carone, T., and Marincioni, F.: Rainfall and land use empirically coupled to forecast landslides in the Esino river basin, central Italy, Nat. Hazards Earth Syst. Sci., 15, 1289–1295, doi:10.5194/nhess-15-1289-2015, 2015.

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., and Ardizzone, F.: Probabilistic landslide hazard assessment at the basin scale, Geomorphology, 72, 272–299, 2005a.

Guzzetti, F., Stark, C. P., and Salvati, P.: Evaluation of flood and landslide risk to the population of Italy, Environ. Manage., 36, 15–36, 2005b.

ITASCA Consulting Group: Inc FLAC-2D (Fast Lagrangion Analysis of Continual in 2Demensions) Version 7.0, User's Manual, USA, 2011.

Highland, L. M.: Landslides in Colorado, Usa: Impacts and Loss Estimation for the Year 2010, BiblioGov, 2013.

Hilker, N., Badoux, A., and Hegg, C.: The Swiss flood and landslide damage database 1972–2007, Nat. Hazards Earth Syst. Sci., 9, 913–925, doi:10.5194/nhess-9-913-2009, 2009.

Jaafari, A., Najafi, A., Pourghasemi, H. R., Rezaeian, J., and Sattarian, A.: GIS-based frequency ratio and index of entropy models for landslide susceptibility assessment in the Caspian forest, northern Iran, Int. J. Environ. Sci. Technol., 11, 909–926, 2014.

Jaiswal, P., Van Westen, C., and Jetten, V.: Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India, Nat. Hazards Earth Syst. Sci., 10, 1253–1267, doi:10.5194/nhess-10-1253-2010, 2010.

Lagomarsino, D., Segoni, S., Rosi, A., Rossi, G., Battistini, A., Catani, F., and Casagli, N.: Quantitative comparison between two different methodologies to define rainfall thresholds for landslide forecasting, Nat. Hazards Earth Syst. Sci., 15, 2413–2423, doi:10.5194/nhess-15-2413-2015, 2015.

Lee, S. and Min, K.: Statistical analysis of landslide susceptibility at Yongin, Korea, Environ. Geol., 40, 1095–1113, 2001.

Lee, S. and Pradhan, B.: Probabilistic landslide hazards and risk mapping on Penang Island, Malaysia, J. Earth Syst. Sci., 115, 661–672, 2006.

Lee, S. and Pradhan, B.: Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models, Landslides, 4, 33–41, 2007.

Manconi, A. and Giordan, D.: Landslide early warning based on failure forecast models: the example of the Mt. de La Saxe rockslide, northern Italy, Nat. Hazards Earth Syst. Sci., 15, 1639–1644, doi:10.5194/nhess-15-1639-2015, 2015.

Massagrande, A.: Indagini geognostiche finalizzate alla caratterizzazione litologico-stratigrafica e fisico-meccanica dei terreni (Geognostic surveys for lithological, physical and mechanical characterization of deposits involved in the Carrè landslide), professional report, Carrè Municipality (Italy), 2012.

Matsui, T. and San, K. C.: Finite element slope stability analysis by shear strength reduction technique, Soils Found., 32, 59–70, 1992.

Momigliano, S. and Nuti, F. G.: La valutazione dei costi e dei benefici nell'analisi dell'impatto della regolazione, Rubbettino Editore, 2001.

Naldi, M.: Indagini geofisiche e valutazioni idrogeologiche finalizzate alla verifica del movimento franoso verificatosi a valle del sostegno P95 (Geophysical and hydrogeological surveys of the Carrè landslide), professional report, Carrè Municipality (Italy), 2014.

Othman, A. A., Gloaguen, R., Andreani, L., and Rahnama, M.: Landslide susceptibility mapping in Mawat area, Kurdistan Region, NE Iraq: a comparison of different statistical models, Nat. Hazards Earth Syst. Sci. Discuss., 3, 1789–1833, doi:10.5194/nhessd-3-1789-2015, 2015.

Papathoma-Köhle, M., Zischg, A., Fuchs, S., Glade, T., and Keiler, M.: Loss estimation for landslides in mountain areas – An integrated toolbox for vulnerability assessment and damage documentation, Environ. Model. Softw., 63, 156–169, doi:10.1016/j.envsoft.2014.10.003, 2015.

Pellicani, R., Van Westen, C. J., and Spilotro, G.: Assessing landslide exposure in areas with limited landslide information, Landslides, 11, 463–480, 2014.

Petley, D.: Global patterns of loss of life from landslides, Geology, 40, 927–930, 2012.

Remondo, J., González, A., De Terán, J. R. D., Cendrero, A., Fabbri, A., and Chung, C.-J. F.: Validation of landslide susceptibility maps; examples and applications from a case study in Northern Spain, Natural Haz., 30, 437–449, 2003.

Roggia, F.: Intervento di sistemazione del dissesto franoso di Via Valdaro in Comune di Carrè (VI) (Remediation works of landslide which affect Valdaro Street in the municipality of Carrè, Vicenza Province), professional report, Carrè Municipality (Italy), 2014.

Salbego, G.: Studio sulla previsione dei fenomeni franosi nell'area del Marosticano (Provincia di Vicenza) per un'efficace analisi costi/benefici degli interventi di prevenzione (A study on landslides forecasting in the Marosticano area (Vicenza Province) aimed to an effective cost-benefit analysis on preventive actions), Master's thesis in Geology and Technical Geology, Dept. of Geosciences, Padua, Italy, 2014.

Schuster, R. L. and Fleming, R. W.: Economic losses and fatalities due to landslides, Bull. Ass. Eng. Geol., 23, 11–28, 1986.

Segoni, S., Battistini, A., Rossi, G., Rosi, A., Lagomarsino, D., Catani, F., Moretti, S., and Casagli, N.: Technical Note: An operational landslide early warning system at regional scale based on space–time-variable rainfall thresholds, Nat. Hazards Earth Syst. Sci., 15, 853–861, doi:10.5194/nhess-15-853-2015, 2015.

Soren, K., Budi, G., and Sen, P.: Stability analysis of open pit slope by finite difference method, Int. J. Res. Eng. Technol., 3, 326–334, 2014.

Stähli, M., Sättele, M., Huggel, C., McArdell, B. W., Lehmann, P., Van Herwijnen, A., Berne, A., Schleiss, M., Ferrari, A., Kos, A., Or, D., and Springman, S. M.: Monitoring and prediction in early warning systems for rapid mass movements, Nat. Hazards Earth Syst. Sci., 15, 905–917, doi:10.5194/nhess-15-905-2015, 2015.

Sterlacchini, S., Frigerio, S., Giacomelli, P., and Brambilla, M.: Landslide risk analysis: a multi-disciplinary methodological approach, Nat. Hazards Earth Syst. Sci.,, 7, 657–675, 2007.

Toaldo, M.: Caratterizzazione Geotecnica e mineralogica di depositi vulcanici alterati soggetti a fenomeni di scivolamento nell'area pedemontana della provincia di Vicenza (Geotechnical and mineralogical characterization of weathered volcanic deposits prone to slide in the Vicenza foothills), Master's thesis in Geology and Technical Geology, Dept. of Geosciences, Padua, Italy, 2014.

Trigila, A.: Sviluppo di metodologie e modelli per la valutazione della suscettibilità all'innesco di frane superficiali rapide in un'area della Sicilia nord-orientale (Methods and models for the evaluation of shallow landslides triggering in NE Sicily), PhD's thesis in Geological Sciences, University of Rome "Sapienza", 2014.

Varnes, D. J.: Slope movement types and processes, edited by: Schuster, R. L., and Krizek, R. J., Landslides-Analysis and control: National Research Council, Washington, D.C., Transportation Research Board, Special Report 176, 11–33, 1978.

Von Ruette, J., Papritz, A., Lehmann, P., Rickli, C., and Or, D.: Spatial statistical modeling of shallow landslides – Validating predictions for different landslide inventories and rainfall events, Geomorphology, 133, 11–22, 2011.

Yalcin, A., Reis, S., Aydinoglu, A. C., and Yomralioglu, T.: A GIS-based comparative study of frequency ratio, analytical hierarchy process, bivariate statistics and logistics regression methods for landslide susceptibility mapping in Trabzon, NE Turkey, Catena, 85, 274–287, 2011.

Zettler, A. H., Poisel, R., Roth, W., and Preh, A.: Slope stability based on the shear reduction technique in 3D, in: FLAC and Numerical Modeling in Geomechanics, edited by: Detournay, C., and Hart, R., Rotterdam, Balkema, 11–16, 1999.

Zêzere, J. L., Garcia, R. A. C., Oliveira, S. C., and Reis, E.: Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal), Geomorphology, 94, 467–495, 2008.

Zhu, L. and Huang, J.-F.: GIS-based logistic regression method for landslide susceptibility mapping in regional scale, Journal of Zhejiang University Science A, 7, 2007–2017, 2006.