Predicting storm triggered debris flow events: application to the 2009 Ionian-Peloritan disaster (Sicily, Italy)

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Abstract

The main assumption on which landslide susceptibility assessment by means of stochastic modelling lays is that the past is the key to the future. As a consequence, a stochastic model able to classify past known landslide events should be able to predict a future unknown scenario as well. However, storm triggered multiple debris flows events in the Mediterranean region could pose some limits on the operative validity of such expectation, as they typically result by a randomness in time recurrence and magnitude and a great spatial variability even at the scale of small catchments. This is the case of the 2007/2009 couple of storm events, which recently hit north-eastern Sicily with a different intensity, resulting in largely different disaster scenarios.

The study area is the small catchment of the Itala torrent ($10 km^2$), which drains from the southern Peloritan Mountains eastward to the Ionian sea, in the province of the Messina territory (Sicily, Italy). Landslides have been mapped by integrating remote and field surveys, producing two event inventories which include 73 debris flows, activated in 2007, and 616 debris flows, triggered by the 2009 storm. Logistic regression was applied in order to obtain susceptibility models exploiting a set of predictors, which were derived from a 2m-cell digital elevation model and a 1:50,000 scale geologic map. The topic of the research was explored by performing two types of validation procedures: self-validation, based on the random partition of each event inventory and chrono-validation, based on the time partition of the landslide inventory. It was therefore possible to analyse and compare the performances both of the 2007-calibrated model in predicting the 2009 debris flows (forward chronovalidation) and vice versa of the 2009-calibrated model in predicting the 2007 debris flows (backward chronovalidation).

Both the two predictions resulted in largely acceptable performances in terms of fitting, skill and reliability. However, a loss of performance and differences in the selected predictors between the self-validated and the chrono-validated models arose. These are interpreted as effects of the non-linearity in the domain of the trigger intensity of the relationships between predictors and slope response, as well as in terms of the different spatial paths of the two triggering storms at the catchment scale.

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1. Introduction

Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of local terrain conditions (Brabb, 1984). This definition limits the task of the prediction procedures at estimating the spatial probability for future landslides. In fact, unlike hazard assessment, susceptibility studies are only aimed to determine "where" new landslides are more likely to occur, without considering any energy (magnitude) and temporal probability (time recurrence) estimation. In spite of its more limited predictive meaning, landslide susceptibility is actually the most largely pursued task in the field of regional geo-hydrological risk assessment, both for civil protection and land use planning. In fact, knowing where a landslide is more likely to occur allows the user to define mitigation planes for non-displaceable infrastructures (e.g., roads and buildings) or to modulate the territorial vulnerability with respect to the geomorphological threat scenarios in land management plans. Moreover, assessing landslide hazard with good precision and accuracy frequently requires time/money costs which are unreasonable and unbearable in regional or basin scale studies.

Landslide susceptibility assessment can be achieved by means of different methods, among which the stochastic approach has gained increasing importance in the last two decades in regional assessment applications. In fact, statistic models produce objective, quantitative and verifiable estimates of the spatial probability for new landslides in a given study area. Moreover, the stochastic approach is very easily implementable on Geographic Informative Systems (GIS) so to exploit the nowadays very diffused databases of physical-environmental attributes layers. These methods are based on some generally accepted assumptions, the basic one being *the past is the key to the future* (Carrara et al., 1995). Therefore, a susceptibility model trained in reproducing a past known landslide spatial distribution, will be able also to predict the future locations of the new failures. In particular, for a given study area, statistical techniques allow deriving and testing for significance the multivariate relationships between the spatial distributions of an inventory of landslides (the *known target pattern*) and a set of physical-environmental variables (the predictors), which are supposed, on the basis of a geomorphological model, to drive the slope failures acting as controlling factors. In the framework of the above recalled principle, the new landslides (the outcomes) will occur under the same conditions which explain the known landslide distribution. Thus, a calibrated predictive model optimises the functional relations between predictors and outcome, maximises its skill in fitting the known target pattern (the calibration dataset), and it is finally tested in correctly reproducing the unknown target pattern (the validation dataset). As the controlling factors are selected among the time-invariant preparatory causes, regardless the age of the landslide inventory exploited to train the model, as far as the basic assumption holds, any calibrated model will be able to predict any past or future unknown target pattern.

Unfortunately, very often, susceptibility assessment studies are affected by a lack of temporal information on the landslide inventory, which makes impossible to perform a pure temporal or chrono-validation.

Based on the scheme described above, in order to elude the lack of temporal information, strategies for the validation of the predictive models can be defined. In particular, when seasonal or event inventories (Guzzetti et al., 2012) are not available, a validation can be performed by following a *random time partition* procedure (Chung and Fabbri, 2003). In this case, the source inventory is split into a calibration and a validation subset to simulate the known and the unknown target patterns, respectively. In this work the above scheme is defined as a self-validation procedure to stress the circumstance that, under a morphodynamic perspective, calibration and validation patterns are actually two partial and complementary sides of the same event. Conversely, the term chrono-validation will be used when referring to pure temporal verification (Guzzetti et al., 2005), i.e. when the training and the test target patterns belong to two temporally separated datasets. A third scheme frequently adopted for model spatial transferability or exportation (e.g., Von Ruette et al., 2011; Costanzo et al., 2012a; Lombardo et al., 2014; Petschko et al., 2014), is based on the adoption of two different catchments or areas for calibration and validation (*spatial partition*).

It is evident how the whole scheme of the stochastic approaches is strictly dependent on the hold of the basic assumption. Any changes in the real relationships between preparatory causes and landslide activity will

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affect the prediction skill of the obtained susceptibility models. Extreme events produce those morphodynamic responses that can lie outside the general rule. In fact, due to intense triggering, such as a storm, the same area can result in an "out-of-range" slope response which could not be correctly predicted by a model skilled in fitting "normal" landslide scenarios. This could resides in the non-linearity of the relation between preparatory causes and landslides in the domain of the trigger intensity. Besides, the Mediterranean storms are typically affected by randomness in time recurrence and magnitude and a great spatial variability even at the scale of small catchments. It is therefore necessary to check for this kind of behaviour to find a strategy which maximises the ability of a susceptibility model to predict extreme events.

In spite of the wide diffusion of landslide susceptibility studies by means of statistical modelling, few cases are focused in detecting predictive limits when facing storm-triggered multiple debris flow events. In particular, the application of specific validation strategies to evaluate the effect of the trigger phenomenon in modifying the predictive performance of the models is very rare. A contribution to this topic is here given, exploiting a case study in north-eastern Sicily, where two recent storm events (2007 and 2009) hit with different intensities the Ionian side of the Peloritani Mountains (Fig. 1). In particular, the study area is the Itala catchment (nearly 10km^2), which is located in the southern sector of the Peloritan ridge.

In order to investigate our topic, the debris flows activated in the occasion of the two extreme events have been mapped by integrating remote and field surveys and a simple set of predictors prepared by exploiting a 1:50,000 scale geological map and a 2m-cell digital elevation model (DEM). Statistical models have been obtained by applying the stepwise (forward) binary logistic regression technique (Hosmer and Lemeshow, 2000), which has been largely adopted in landslide susceptibility studies (Atkinson et al., 1998; Olhmacher and Davis, 2003; Süzen and Doyuran, 2004; Brenning, 2005; Carrara et al., 2008; Costanzo et al., 2014; Lombardo et al., 2014; Heckmann et al., 2014) demonstrating suitability to the geomorphological task and producing high performances also in comparative studies (Guzzetti et al., 2006; Rossi et al., 2010). Exploiting multi-temporal high resolution images (provided by A.R.T.A.- Assessorato Regionale Territorio e Ambiente), two landslide event inventories (Guzzetti et al., 2012) have been prepared so to perform and validate two types of modelling procedure: self-validation, based on the random partition into a calibration and a validation subset of each event inventory and chrono-validation, based on the temporal partition into the 2007 and 2009 cases. The latter procedure was applied to analyse the performances both of the 2007-calibrated model in predicting the 2009 debris flows source areas (forward chrono-validation) and of the 2009-calibrated model in predicting the 2007 debris flow source areas (backward chrono-validation). By analysing and comparing the predictive performances of binary logistic regression for the four types of models, the role of the triggering rainfall intensities is outlined and discussed.

2. Background

Testing a susceptibility model against the future landslides is a quite hard task especially because it would require to "wait for the future to happen" (Guzzetti, 2005). Nevertheless, when a multitemporal landslide inventory is available, the validation can be performed using a temporal criterion to separate calibration and validation datasets. The effects of clustering landslides events on the basis of time intervals have already been analysed by several authors. Among others, Guzzetti et al. (2005) performed a "temporal verification procedure" which evaluates the effect of 5 landslide inventory updates on the performance of a susceptibility model. Similarly, other authors used a temporal criterion to validate the results of landslides susceptibility analysis at different scales (Zezere et al., 2004; Vergari et al., 2011; Wang et al., 2013), but none of them worked with storm triggered debris flows and split event inventories. Von Ruette et al. (2014) adopted a spatial partition scheme, limiting the temporal validation approach for predicting the landslides triggered by two rainfall events in two close but different catchments.

The Messina area (Fig. 1) and the debris flows event of 2009 have been the study case of several scientific articles centred on different topics. Several studies have been devoted to the implementation of remote and

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semiautomatic techniques for landslide recognition and mapping in a so relevant multiple occurring regional landslide event (Ardizzone et al., 2012; Mondini et al., 2011; Ciampalini et al., 2015). Del Ventisette et al. (2012) focused their research on the area of the Giampilieri village, analysing the triggering mechanism and estimating the volumes involved in the debris flows. They also applied a method based on the conditional analysis to obtain a susceptibility map. Goswami et al. (2011) and De Guidi and Scudero (2013) explored the relations between tectonic setting and landslide susceptibility, taking the Giampilieri and the Scaletta catchments as study areas. Reichenbach et al. (2014) evaluated the influence of land use changes in debris flow susceptibility for the Briga catchment. Stancanelli and Foti (2015) compared two different numerical models for simulating the 2009 debris flows event in the lower coastal sector of the stricken area. Aronica et al. (2012a) published a detailed description of the 2009 event, with an insight into the saturation conditions of the soils and an evaluation by difference of DEMs of the total volume of mobilised material for the Giampilieri catchment. Rainfall thresholds for the landslide activations have been investigated by Gariano et al. (2015), in the framework of a regional study, and Peres and Cancelliere (2014), with a specific study on the Ionian-Peloritan area, hit by the 2009 event. Lombardo et al. (2014) tested in the Briga and Giampilieri catchments spatial exportation techniques for logistic regression based susceptibility models.

As regards the 2007 event, Aronica et al. (2012b) applied a physically based modelling tool to simulate the debris flows affecting a very small catchment, located 5km south of the Itala stream.

Differently from the above mentioned researches, in this paper, exploiting two well split event inventories produced by two triggering events having different intensities, the relationships between trigger, controlling factors and morphodynamic response are faced and their effects on the predictive performance of stochastic susceptibility modelling verified. Moreover, until now no study has been published for the Itala catchment on the 2007 event, nor chronovalidated models and maps have been produced for the 2009 event.

3. General framework

3.1 Study area

The study area is located in the north-easternmost edge of Sicily (southern Italy), on the Ionian slopes of the Peloritan ridge, 20km southward from the town of Messina (Fig. 1a). In particular, the Itala catchment is located in the Itala municipality territory, stretching for $10km^2$ and draining south-eastward for near 6km from Mt. Scuderi (1,259m a.s.l.) to the Ionian Sea. Geologically, the area is situated between the Mandanici, Mela and Aspromonte structural units (Messina et al., 2004), which are separated by thrusts and further fractured by the neo-tectonic faults. These units are made of high to medium grade metamorphic rocks. In particular, the Mandanici unit is primarily characterised by the outcropping of phyllites, while Mela and Aspromonte units mainly consist of paragneiss and micashists (Fig. 1b).

According to the Köppen classification (Köppen, 1923), the climate in the region is classified as a Mediterranean (Csa) type, being therefore characterised by a dry season from April to September and a wet season from September to March, with an average yearly rainfall of nearly 900mm. Besides, due to the warm water of the Mediterranean Sea and the proximity of the ridge to the seacoast, storm events are frequent in the autumn season in this sector of Sicily.

Due to the limited length together with high steepness of the Ionian Peloritan torrents, although they are usually almost dry, under raining conditions, the discharge can rapidly increase determining floods which affect the infrastructures (especially roads) located in the proximity of the riverbanks. Moreover, under autumn storm events, the combination of their hydrologic regime and geomorphologic setting occasionally determines severe morphodynamic responses, including multiple debris flow and debris flood events, such as those occurred in 2007 and 2009. The potential occurrence of this kind of events makes the whole set of Ionian Peloritan catchments one of the most exposed zones to hydrogeological risk in Sicily.

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The inhabited areas of the Itala catchment are located in very dangerous sectors either at the base of very steep terraced slopes or near the outlet of the streams. With respect to the land use, the area can be divided in an eastern and a western sector. The former is highly terraced and mainly cultivated with citrus groves; the latter is characterised by chestnut forests and pastures. The study area is strongly affected by wildfires during the summer season; this influences the density of vegetation, the soil structure and the erosional processes acting on the slopes.

3.2 Historical records of rainfall events

The storm events of 2007 and 2009 have been analysed on the basis of two rain gauges belonging to the "Osservatorio delle Acque Sicilia", located in Briga and Messina Osservatorio (Fig. 1a). In particular, as the Peloritani area was historically hit by other storm events, a detailed analysis of antecedent rainfall conditions and historical record of debris flow events was carried out. The most important extreme meteorological events have been first selected and, on the basis of the historical archive of the two main local news papers ("Gazzetta del Sud" and "Giornale di Sicilia"), the associated landslide activity identified. However, the estimation of the severity of the slope responses to the triggering storms cannot be accurately assessed at a basin scale from this kind of historical data. Therefore, with the exception of the 2007 and 2009 inventories, the classification of the debris flow events was limited to a qualitative ordinal scale (no-landslides: N-L; tens of landslides: T-L; hundreds of landslides: H-L) based on the relevance and frequency of damages reported for the Itala catchment area.

By analysing the daily cumulated rain from 1975 to 2011 (with the exception of 6 years with no rainfall data: 1987, 1988, 1989, 2003, 2004, 2005), the 9 heaviest rainfall events have been detected on the basis of a 100mm threshold, which corresponds approximately to the rain quantity registered during the 2007 event. The Figure 2 shows the 1-, 3-, 7- and 20-days cumulated rainfall for the 9 events, together with the corresponding debris flow activity reported for the Itala catchment area (indicated with the red labels on the bar plot). Among the 9 selected events, only 5 caused important multiple occurrence of debris flows whose effects are reported on local newspaper. In fact, for the cases of 02/12/1996, 08/09/2000 and 20/01/2009, no landslides events were reported on local newspapers, which could indicate that either no landslides were activated or that they were not so relevant to produce damages to the villages. In these cases, the daily peak of rain was not anticipated by significant rain in the previous days. The more intense event of 01/03/2011 was responsible for the activation of tens of debris flows in a sector located about 5km south of Messina, but no landslides are reported for the Itala catchment.

Among the events which caused reported landslides, the 30/10/1985 and 04/10/1996 have very similar characteristics, as in both cases the main events were anticipated by important precipitations in the antecedent 72 hours. Differently, the event of the 24/11/1995 was recorded with a 123 mm/day and 155mm/week. Looking at the 3 days and 7 days before the main event, the quantity of rain does not seem so intense to lead to multiple debris flow occurrence, as it is very similar to the one recorded on 02/12/1996, which did not trigger landslides. Nevertheless, if a longer interval is considered (10days and 20days) the cumulative quantity of rain overcome the 300mm. This could justify the landslides activated in this occasion, which are reported in the journal "Gazzetta del Sud" of 26^{th} and 27^{th} of November.

The 26/10/2007 and the 01/10/2009 events are quite specific if compared to the others. In fact, on the one hand, the 2007 daily rainfall event was anticipated by 3 dry days and heavy rainfall condition in a week time; on the other hand, the severity of the 2009 rainfall event resides both on the daily (more than 200mm) and on the 10- and 20-days precipitations, which overcame 350 and 400mm, respectively. In particular, the Figure3a shows that on 2007 the main event (registered at Briga with 102mm of rain in 24 hours) was anticipated by longer and more extended raining periods, which lasted from the October 20^{th} to the 23^{rd} resulting in a cumulative weekly rainfall of 220.4mm. The storm triggered hundreds of debris flows in the whole area, but only 73 in the Itala catchment. The 2009 event (Fig. 3b) presented the highest daily rain (nearly 220mm); moreover, it followed two previous events: 16^{th} September: 49.2mm, in six hours; 23^{rd} – 24^{th} September:

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79.6mm, in ten hours, determining a cumulative rain quantity which overcame 412mm in 20 days. As a consequence, on 1st October 2009 in a less than 10 km^2 area, hundreds of debris flows and debris flood events produced large damages to buildings and main roads in the Itala catchment.

To give a view of the great spatial variability of rainfall storms in this area, it is worth to note that to the intense rainfall recorded at the Briga rain gauge (102mm/day and 220mm/day, respectively) corresponded low values for the Messina Osservatorio (3.6mm/day and no rain, respectively). This demonstrates that such extreme events are very localised, with rainfall conditions significantly changing in a range of only 15km distance. However, although the authors believe that the small-scale rainfall distribution is very important for the prediction of the debris flow locations, the rain gauge network is not dense enough to evaluate the variability of the rain conditions at the catchment scale. Therefore, this variable cannot be introduced in the susceptibility models.

3.2 The 2007 and 2009 debris flows

The typologies of the landslides that activated during the 2007 and 2009 events are mainly classified as channelized debris flows and debris avalanches or hillslope debris flows (Varnes, 1978; Hutchinson, 1988; Hungr et al., 2001; 2014), which involved the weathered mantle of the metamorphic bedrock on the very steep slopes of the Itala catchment (Fig. 4). However, as this paper aimed at studying the susceptibility for new activations or source areas prediction, the whole set of phenomena was processed as a single type, using in the following the general sense of the term *debris flow*. The very few cases of bedrock-landslides, such as falls and rotational slides, were deliberately excluded from the analysis, as they would have required a different approach both in terms of controlling factors and statistical methods.

In both the 2007 and 2009 cases, the main events were preceded by "fore-storm" rainfall events, which had been responsible for the saturation of the weathered mantle of the metamorphic bedrock (Aronica et al., 2012a). Therefore, when the main storms hit the area, the high water content rapidly reduced the shear strength of the regolithic layer determining the contemporaneous activation of multiple debris flows.

The difference in magnitude between the two phenomena, was not only related to the number of activated phenomena but also in the kinematic behaviour of the debris flows. In fact, on the 2007, the percentage of phenomena which reached the foot of the slope, or the main channel, was lower. This suggests that the quantity of water was enough to saturate the soil and trigger the shallow failures but not enough to determine a long distance transport. On the contrary, on the 1st October 2009 the slope conditions and the consequences were quite different, especially in terms of damages. The channelized debris flows (Fig. 4a) had energy enough to reach the main river network. In addition, being the discharge extremely high in volumes, the debris was transported for long distances to the coast forming a fan. The debris avalanches (Fig. 4b) were also characterised by high energy. Consequently, they reached the foot of the slopes causing damages to structures and roads.

4. Materials and methods

Among the large set of statistical methods, in the last two decades binary logistic regression (BLR) has become one of the most applied methods in landslide susceptibility studies. In fact, it does not require heavy constraints on the statistical distributions of the predictors and allows the user to include in the model both nominal and continuous variables. Furthermore, the structure of a BLR model (Hosmer and Lemeshow, 2000) is very simple and geomorphologically interpretable, being composed of single coefficients which describe the linear correlations between each predictors and the log-odds or logit function of the binary outcome (stable/unstable).

The application of BLR for landslide susceptibility assessment typically requires the following steps: the partition of the study area into mapping units, which are then characterised with respect to a set of potential predictors; the assignment to each mapping unit of its stability conditions, based on its spatial relation with a set of known landslides (e.g., inclusion or intersection); the extraction of a balanced (stable/unstable) dataset

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from the whole set of mapping units; the regression of the modelling function; the verification of the performance of the model in correctly predicting for each pixel its stability conditions, the latter defined on the basis of a set of unknown landslides.

This chapter describes the methods and the model building strategy which have been adopted to investigate the main topic of the research: exploring skills and limits in predicting the source areas of storm triggered debris flows.

4.1 Landslide inventory

Landslide recognition was performed by integrating a field survey, which was carried out soon after the 2009 disaster, and orthophoto analysis which allowed to visualise the slopes at different dates. In particular, the high resolution LiDAR (Light Detention And Ranging) data from two different acquisitions, respectively 2008 and 2009, were used. These data were provided by the Territory and Environment Department of the Sicilian Government (ATA2008 - Assessorato Regionale Territorio e Ambiente) and the National Civil Protection (PCN2009, Protezione Civile Nazionale). The ATA2008 data (taken in August) includes 0.25m pixel orthophotos and a DEM having 2 and 0.22m for horizontal and vertical resolution, respectively. The PCN2009 data were acquired six days after the 2009 event and includes 15cm pixel orthophotos, and a 1.1m cell DEM. Besides, multi-temporal (2005, 2006, 2010 and 2012) Google Earth™ (GE) images were analysed so to compare the 2007 and 2009 mapped phenomena with the previous and following slope conditions.

An event inventory (Guzzetti et al., 2012) has to report only those landslides which have been triggered by a single specific trigger occurrence, such as an earthquake, rainfall or snowmelt. To fit this constraint, a first landslide mapping was carried out on the 2008 and the 2009 images, obtaining a first version of the 2007 and 2009 inventories. However, the mapped landslides were supposed to be activated during the 26th October 2007 for the first inventory and the 1st October 2009 for the second. Therefore, the morphologies mapped on 2007 were also compared with the 2006 GE-images. By combining the data obtained from the three time frames, five different cases were obtained (Fig. 5): a) debris flows mapped on the 2007 orthophotos but activated before the 2007 event; b) debris flows activated during the 2007 event which did not reactivated or retreated during the 2009; c) debris flows activated during the 2007 that retreated or reactivated during the 2009; d) debris flows activated during the 2007 which have been completely eroded during the propagation phase of the 2009; e) debris flows which activated during the 2009 event in precedent stable areas.
The final event inventories (Fig. 6) contained 73 debris flows for the 2007, corresponding to cases b, c and d, and 616 for the 2009, corresponding to the case e. Each landslide inventory was stored into two separated vector layers: the first containing a polygon representing the source areas, the second containing the Landslide Identification Points, corresponding to the highest point along the crown of each mapped phenomenon (LIP, Costanzo et al., 2012a; Lombardo et al., 2014; Costanzo et al., 2014).

4.2 Binary logistic regression

Binary logistic regression (BLR) is a multivariate statistical technique, based on a frequentist approach, which is used to model the expected value of a response variable (the outcome) by a linear combination of either continuous and/or discrete predictor variables (Hosmer and Lemeshow, 2000). With respect to other frequentist methods (e.g., the discriminant analysis), it does not require any linearization or transformation to obtain normal distributed covariates. Moreover, the outcome of BLR is easily interpretable for applied scientists.
In binary logistic regression the response variable Y assumes one of the two mutually exclusive values of 0 (no landslide) or 1 (landslide) for stable mapping units or unstable mapping units, respectively.
The relationship between the predictors and the probability for the response variable to assume the value 1 is linearized by the logit function (Y), which corresponds to the following transformation:

$$logit(Y)= \ln[P(Y=1)/(1-P(Y=1))]=\alpha+\beta_1 x_1+\beta_2 x_2+\ldots+\beta_n x_n; \quad (1)$$

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where $P(Y=1)$ is the probability that the response variables assumes the value 1, α a constant term or intercept, the $x_1, x_2, \ldots x_n$ are the input predictor variables and the β_n their coefficients. Therefore, once the logit function is calculated, and the $\beta_1, \beta_2, \ldots \beta_n$ values are known, the probability can be back-calculated using the following formula:

$$P(Y=1)=e^{logit(Y)}/[1+e^{logit(Y)}]. \qquad (2)$$

This equation ensures that, for any given case, the probability $P(Y=1)$ will not be less than 0 or greater than 1 with *logit (Y)* ranging in the full ±∞ interval.

The odds ratios (OR), which are calculated by simply exponentiating the β_n, indicates how likely (or unlikely) it is for the outcome to be positive (unstable cell) when a unit change of an independent variable occurs (Hosmer and Lemeshow, 2000). Negatively correlated variables will produce negative β_n and OR limited between 0 and 1; positively correlated variables will result in positive β_n and OR greater than 1.

In order to estimate the best intercept and β_n coefficients, the logistic regression uses the maximum likelihood algorithm. This maximises the value of the log-likelihood function (LL), which indicates how likely is to obtain the observed value of Y, given the values of independent variables and coefficients (Menard, 2002). In particular, the global fitting of the regressed model on the data domain is usually expressed by the -2LL (negative log-likelihood) which is an estimator based on the maximum likelihood criterion. The differences in -2LL value between the model with only the intercept ($L_{INTERCEPT}$) and the full model (L_{MODEL}) have a χ^2 distribution, so that the significance of the regressed coefficients can be easily tested (Olmacher and Davis, 2003; Akgun and Turk, 2011). In other words, the -2LL test estimates the significance of the increase in model fitting produced by the introduction of the predictors.

In the present research, we applied BLR under a stepwise selection routine, which was already successfully adopted in landslides and debris flows susceptibility studies (Begueria, 2006; Meusburger and Alewell, 2009; Atkinson and Massari, 2011; Costanzo et al., 2014; Heckmann et al., 2014; Lombardo et al., 2014). The stepwise selection is an iterative procedure, which selects the best performing and most parsimonious set of predicting variables. It can be performed either in forward or in backward mode. In the first case the procedure starts from an “intercept only” model and consists in selecting and adding at each step, from the group of available variables, the one which results in the larger likelihood increase. On the contrary, the backward stepwise selection starts from a full model including all the variables and removes iteratively the variables until the model reaches the best fitting. In the forward stepwise selection, at every step the procedure introduces iteratively all the variables and selects the one that maximised the -2LL values. The first factor to be included is the one that produces the greatest change in the log-likelihood, with respect to the intercept. Exploiting the chi square distribution of the -2LL, the iterative calculation stops when the significance level of the increase produced by including a new predictor is lower than 1%. Thus, the final result is the restricted list of variables, each having its order of importance (i.e. the iteration in which it was picked up) that can be submitted to the final BLR.

All the statistical analyses which are hereafter discussed were performed by using an open source software (TANAGRA: Rakotomalala, 2005).

4.3 Covariates and outcome status assignment

The first step in modelling the debris flow susceptibility using a stochastic approach is to select those mapping units in which the study area has to be partitioned. Mapping units are the basic spatial elements in which the model will be able to produce a prediction. Two main types of mapping units are adopted in literature: hydro-geomorphological units and regular grids. The former allows the model to exploit the morphodynamic homogeneity of the area which is included into each single unit, corresponding to hydrological or slope units; the latter optimises the matching between the spatial resolution of the source layers of some important predictors, typically having the same grid structure of the DEM.

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In the present research a raster-based structure was adopted by partitioning the study area into a 8m square cells grid, which required also the rasterization of the spatial distribution of all the covariates.

Starting from a DEM and a geological map, the following eight potential predictors have been selected and their value assign to each cell in which the study area has been partitioned (Figs. 8 and 9): Outcropping lithology (GEO), Land use (USE), Aspect (ASP), Steepness (SLO), Topographic Wetness Index (TWI), Plan (PLAN) and Profile (PROF) curvatures and Distance from tectonic features (DFAULT).

Outcropping lithology and tectonic features are proxy variables expressing the mechanical properties of the bedrock and the weathered mantle. These variables were obtained from a 1:50,000 available geological map (Lentini et al., 2007), which was derived from 1:10,000 field surveys.

Land use allows the model to summarise those potential modifications of the natural structure of the regolithic mantle and the bedrock, which are related to anthropogenic activities. In order to express these properties, a land use map based on the analysis of the orthophotos ARTA2007/2008 and PCN2009 and field recognition was prepared. The final land use map contains 6 classes: i) medium-high vegetated terraces (MHVT); ii) low vegetated terraces (LVT); iii) chestnut forests (CF); iv) pastures (P); v) urbanised areas (UA); vi) river beds and beaches (RB).

Slope steepness, Plan and Profile curvatures are related with the energy of the relief. Steepness is commonly used as predictor in landslide susceptibility and very often it presents a very high importance. In fact, especially for debris flow analysis it is expected to be one of the most significant variables because it is directly linked to the shear strength acting onto the potential shallow failure surface. Moreover, for shallow failures presenting slide or flow mechanisms, the topographic surface and the rupture plane or zone can be considered as almost parallel. In this case, the slope steepness is a proxy for the real inclination of the potential failure surface. Steepness also controls the overland and subsurface flow velocity and runoff rate. At the same time, the topographic curvatures control the divergence and convergence, both of surface runoff and shallow gravitational stresses (Ohlmacher, 2007). Curvatures are expected to be the best proxy variables for convergent flow of water (plan curvature) and changes in flow velocity (profile curvature). In this study the *profile curvature* and the *plan curvature* were used, which correspond to the second derivatives of the slope steepness and the aspect, respectively.

Topographic Wetness Index is defined as $\ln(As/\tan\beta)$ where As is the local upslope area draining per contour unit length and β is the local slope angle. It describes the extension and distribution of the saturation zones assuming steady-state conditions and uniform soil properties. By comparing the field data, it has been demonstrated that TWI can be considered a proxy variable directly related with the properties of soil, in particular with the soil moisture, A horizon depth, Phosphorus content and organic matter (Moore et al., 1993).

Aspect controls the intensity at the earth surface of the solar insolation, and as a consequence, the evapotranspiration and flora and fauna distribution and abundance. Being the erosional processes related with the chemical physical weathering operated by water, temperature and vegetation, it is very important to consider this factor for the determination of landslide susceptibility. Besides, ASP frequently assumes a role of proxy variable for the attitude of the rock layers.

The source for the calculation of the topographic attributes was the DEM ARTA 2007/2008 subsequently resampled at 8m pixel size with the nearest neighbour approach. The resampling operation on the original DEM (2m pixel size) smoothed the effects of micro-topography and possible noise existing on the original data.

All the factors have been calculated using SAGA GIS (System for Automated Geoscientific Analysis, Conrad, 2007).

Once the 8m grid layers of the predictors were obtained, they were combined in a single multivariate one, which was crossed to the LIP vector layers, to set the stable/unstable status. Each cell hosting at least one LIP was set as unstable, so to calibrate the models in predicting the locations of future LIPs, which in our scheme correspond to debris flow initiation areas.

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4.4 Validation procedures and model building strategy

Model validation is a mandatory component of a susceptibility assessment studies (Carrara et al., 2003; Guzzetti et al., 2006; Frattini et al., 2010; Rossi et al., 2010). No matter the method adopted in modelling the susceptibility, rigorous and quantitative validation procedures furnish the only criterion for accepting or rejecting a predictive model.

The validation of a model requires the availability of a calibration and a validation set of landslides or outcomes. The training landslides are exploited to calibrate the maximum-likelihood fitting, so to optimise the regression coefficients; the predicted probability which is generated by the model is then compared to the actual unknown target pattern which is defined by the validation landslides set. The accuracy of a model is then evaluated by comparing the produced prediction image to the known (calibration) and unknown (validation) target patterns. In particular, the degree of fit expresses the ability of the model to classify the known cases, while the prediction skill is the ability to predict the unknown cases.

As proposed by Chung & Fabbri (2003), calibration and validation datasets can be obtained by time partition, random time partition or spatial partition. The first is possible when multi-temporal landslides inventories are available, the second is based on randomly partitioning single-epoch datasets and the third on sub-dividing the study area in two similar sub-sectors. Random time partition procedures can be applied either on the landslide inventory (Conoscenti et al., 2008a) or on the mapping units database (Conoscenti et al., 2008b), whilst spatial partition can also be performed also on not nested or adjacent areas such as in the study aimed at susceptibility model exportations (von Ruette et al., 2011; Costanzo et al., 2012b; Lombardo et al. 2014).

However, validating a model requires for testing its accuracy, precision, robustness and geomorphological adequacy or coherence, both in terms of predictive performance and inner structure of the model. The latter corresponds, in a stepwise BLR procedure, to the rank and the coefficients of the selected predictors (Frattini et al., 2010; Costanzo et al., 2014; Lombardo et al., 2014). Besides, as BLR requires for balanced (positive/negative cases) datasets, a single regressed dataset has to contain the positive cases (unstable cells) and an equal number of randomly selected negatives (Atkinson et al., 1998; Süzen and Doyuran, 2004; Nefeslioglu et al., 2008; Bai et al., 2009; Van Den Eeckhaut et al. 2009; Frattini et al., 2010; Costanzo et al., 2014), which could determine a low representativeness of the analysed cases. In particular, in this study, each pixel containing a LIP has been considered as diagnostic area (Rotigliano et al., 2011), while the negative cases have been randomly selected in the catchment, outside the landslide polygons. In order to obtain a better dispersion of points and to avoid autocorrelation of the spatial variables, the distance in the random selection was maximised. Therefore, every model was composed by 146 balanced cases (positive/negative), for 2007, and 1232 balanced cases, for 2009. This heavily reduces the number of actually analysed cases to a very small percentage of the cells in which the study area is partitioned, so that a need of testing the representativeness of the worked subset also arises. To control the possible effects introduced by this procedure, multi-extraction of negatives are to be performed and more than one dataset regressed. In particular, a multiple extraction produces *m* different balanced datasets, each composed by the union of the same positives and a different set of randomly extracted negatives; multi-fold cross validation procedures are then applied, by resampling *n* times the same dataset to perform *n* replicates of the regression procedure, finally obtaining *n*x*m* outcomes of the same performance indexes or model parameters.

In this research, two suites of ten dataset were extracted both for 2007- and 2009-models; to each dataset a 10-fold cross validation procedure was then applied, which gave for each mapping unit a total of one hundred probability estimates (10 replicates x 10 subsets), based on which accuracy and precision of the predictive performance were tested. Moreover, each of the one hundred replicates resulted in a set of ranked predictors and regression coefficients, the comparison of which allowed us to test the precision and the robustness of the model.

Once a cut-off for the estimated probability is fixed to split positive and negative predictions, the crossing with a target pattern results in the production of true positives (TP), true negatives (TN), false positives (FP: Type I errors) and false negatives (FN: Type II errors) cases. Contingency tables are used to summarise these

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data and to compute the model error rate, (TP+TN)/(TP+TN+FP+FN), sensitivity or true positive rate, (TP/(TP+FN)), and 1 – specificity or false positive rate, (FP/(TN+FP)). Moreover, in order to assess the prediction accuracy of the models the Hanssen and Kuipers (1965) skill score was also used. This index is defined as the difference between true positive and false positive. The HK maximum values measure of the ability of the forecast system to discriminate between events and non-events. Maximising this values means minimising the probability range where the user would be unsure of the forecast.

A cut-off independent technique for estimating the accuracy of a predictive model is represented by the Receiver Operating Characteristic (ROC) curves, which draws the trade-off between success and failures for decreasing probability threshold, in sensitivity versus 1-specificity plots. The Area Under the Curve (AUC) in the ROC plots is the most adopted metrics for the accuracy of the predictive models.

The precision and accuracy of the model can be also represented in spatial terms, by preparing prediction and error maps, in which for each mapping unit the mean susceptibility and the dispersion of its estimates are plotted and compared to the actual distribution of the unknown positives.

In order to investigate the main topic of this research, two kind of modelling procedures have been followed. A self-validation scheme was applied for each of the two event-inventories (2007 and 2009), by randomly splitting (90/10%) the 10 extracted balanced datasets of the two temporal suites in a calibration and a validation subset. For each dataset, the random splitting procedure was applied 10 times, resulting in one-hundred self-validated replicates.

A chrono-validation scheme was then applied, by calibrating the model with the whole event-inventory of each epoch and validating the performance in matching the event-inventories of the other. We hereafter refer to forward chrono-validation, if calibrating with 2007 and validating with 2009, and vice versa to backward chrono-validation, if calibrating with 2009 and validating with 2007. For each temporal model suite, we produced ten prediction images based on the ten datasets of the other suite, again having one hundred backward and one hundred forward chrono-validated replicates.

5. Results

The results of the cross-validation procedures for the 2009 and 2007 self-validated one-hundred models are presented in Tables 1 and 2. Generally, the 2009 models (Tab. 2) resulted in a better performing prediction with lower (0.336, for 2007; 0.219, for 2009) and more stable error rates. Similarly, the ROC-AUCs (Tab. 3) attested for the good quality of the models, with a higher performance for the 2009 model (2009-AUC = 0.85, 2007-AUC = 0.70) and no evidences of overfitting.

As regards the predictors, the 2007 model suite selected 5 variables (Fig. 9), four of which with a frequency of more than 5/10: West and South-West slope aspect, steepness and FDNb outcropping lithology resulted as the main causative factors for the 2007 debris flows. A larger set of variables (17) was included by BLR in the 2009 model suite (Fig. 10), 15 of which were selected more than 5 times. Among the topographic variables, the most important were: steepness, all the pixels without any northward aspect component, profile curvatures (both concave and convex) and plan convex curvature of slopes. Together with topographic variables, FDNb and MLEa lithologies, distance from tectonic elements (DFAULTS) and Chestnut forests (CF) and Pastures (P) land use classes were always selected with high and stable rankings. For what concerns the β-coefficients, only profile curvature concavity, the variables DFAULT and CF and P land uses showed negative values, indicating inverse correlations with the debris flow source areas.

Once the overall quality of the predictive performance of the 2007 and 2009 models was assessed, regressions were run for the ten full (without splitting into calibration and validation subsets) datasets of each event-inventory, so to maximise the fitting of the models. For both these full self-validated models (Fig. 11), the obtained ROC-AUCs are above the good performing threshold (>0.81, 2007; >0.87, for 2009), with average error rates of 0.26, for 2007, and 0.22, for 2009. The 2007 and the 2009 full models were then submitted to forward and backward chrono-validation, respectively, resulting in largely acceptable ROC-

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AUCs (>0.75) and error rates (<0.3), although a loss in the predictive performance of both the temporal predictions was observed. In particular, by comparing the self- and the chrono-validation performances, a decrease in AUC from 0.81 to 0.77, for 2007, and from 0.87 to 0.78, for 2009, arose. Besides, the mean error rate values increased from 0.26 to 0.30, for 2007, and from 0.20 to 0.28, for 2009. It is worth to note the strong decrease in performance affecting the 2009 model, which led the two chrono-validations to be almost equivalent. In Figure 12, the calculated mean (over 100 replicates) ROC curves are shown. Coherently, the HK mean scores are comparable between forward and backward validations, presenting a maximum of 0.433 and 0.446, respectively (Tab. 3).

A spatial view of the obtained prediction images for the 2007 and 2009 models is given in Figure 13. In particular, the susceptibility maps show the spatial distribution of the mean probabilities for the ten replicates, whilst the error maps describe the dispersion of the estimates, represented by a 2σ interval.

At a first glance, the two susceptibility maps appear quite different: the 2007 map shows a more diffused and graduated susceptibility, with the north-western and south-eastern sectors of the catchment hosting high susceptible areas. On the contrary, the 2009 map is characterised by a marked spatial separation between the north-eastern high susceptible sector and the remaining larger part of the catchment, which has a low susceptibility. In terms of error maps, the 2007 model is affected by a generally higher level of error, with the maximum values located in the central sector and minimum values along the stream network. The 2009 model, on the contrary, produced lower errors, with the exception of the stream network, which is characterised by quite higher values, and two single small areas, corresponding to the outcrops of poorly diffused lithologies (see Fig. 1).

To compare the two landslide susceptibility maps taking into consideration the distribution of the occurred debris flows, 2007 and 2009 LIPs were located onto a map of the residuals. This map represents the difference between the two (2007 and 2009) mean susceptibilities (Fig. 14). The residuals confirmed the dissimilarity between the two models in estimating the susceptibility of the catchment, with higher probabilities in the southern and north-western sectors, for the forward-, and in the north-eastern sector, for the backward-validated models, respectively.

By comparing the two susceptibility estimates in a dispersion density plot (Fig. 15), the above-described trend is verified. The two models linearly agreed in the higher range of susceptibility, whilst a larger dispersion existed in the lower and intermediate susceptibility range. In particular, for the stable areas (near the origin of the plot) the higher densities pixels are shifted toward a more than 45° steep linear trend, marking an overestimation for the 2007-calibrated model.

On a binarised perspective, by setting at 0.5 the cut-off value for stable/unstable discrimination, the final number of joint predictions (II, for TP, and IV, for FN sectors) was 77%, whilst disjoint predictions (I and III sectors of the plot) reached the 23%. The two chrono-validated models performed with different results in predicting the whole set of observed positives: the backward-calibrated model produced 46+3 (67%) true positives and 13+11 (33%) false negatives for the 2007-LIPs, while the forward-calibrated model produced 395+50 (72%) true positives and 90+81 (28%) false negatives for the 2009-LIPs.

6. Discussion

The analysis of the self-validated models pointed out that the 2009 model resulted in a higher predictive performance, with a higher number of selected variables. This could be interpreted as a direct consequence of the greater number of debris flows which compose the 2009 inventory (one order of magnitude more), so that a larger spectrum of multivariate conditions of the slopes was involved in failures and included in the datasets for the fitting of the models. However, the first four selected predictors for the 2009 model correspond to those composing the structure of the 2007 model: slope morphology (steepness, curvature and aspect), soil use and outcropping lithology.

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The comparison between the performances of the self- and the chrono-validated models has highlighted a loss in accuracy which is slightly more marked for the higher performing self-validated 2009 model. Therefore, although a large difference between the accuracy of the two self-validated models is observed, the comparison between the forward and backward chrono-validated models shows very smoothed differences in terms of ROC-AUC and error rates. This suggests that, in spite of the higher performance which the 2009 model obtained in classifying the same 2009 event, its skill in back-predicting the 2007 debris flow source areas, is the same showed by the 2007 in forth-predicting that of 2009.

On the one hand, the above-described results generally confirm the symmetry between forward and backward chrono-validations and the main assumption on which stochastically modelling is based. On the other hand, the loss in performance suffered from the 2009 model suggests that using self-validated models for temporal prediction can mislead the user in estimating the performance of the model. In fact, one would expect that the model calibrated with the largest landslide inventory would be the best performing in chrono-validation as it "includes" also the less extreme morphodynamic responses. However, in spite of the similar inner structure of the 2007 and 2009 models, the predictive performance of the 2009-backward model has lowered to the same ROC-AUC and error rates of the 2007-forward model. The reason for this behaviour could be connected to the different local characteristics of the two storm events, which differently hit the slopes even of a so small catchment. This would indicate, for this study case, that inside a 10km^2 area there are two different past and two different futures, depending on which of the two storm events are used for calibration.

At the same time, a non-linearity of the morphodynamic response of the slopes (different coefficients and/or predictors) could affect the performance in chrono-validation: a larger event does not produce a larger nested but rather a different response. The larger the difference between the triggering events, the greater the distinction in the response of the preparatory conditions.

In the domain of the predictors, this is highlighted by the different inner structures of the models. If compared to the 2007, the 2009 event has activated also eastern and south-eastern facing pixels, as well as high metamorphic grade (MLEa) lithologies and terraced deposits; topographic curvatures, distance from faults and soil use (the latter with negative coefficients) have also taken an important role in controlling the distribution of the debris flow source areas. However, this richer structure of the model does not increase its predictive power with respect to the 2007 debris flows distribution: the backward chrono-validation does not exploit this larger accuracy. This suggests that the 2007 debris flows were activated through different even if largely overlapping mechanisms.

In the domain of the geographical space, the map of the residuals provided a spatial view of the different behaviour of the two models, giving the interpreter clues for a possible role for the real path followed by the two storm fronts inside the Itala catchment. The 2009 model markedly overestimated the susceptibilities in the central-northern sector of the catchment, whilst the 2007 model produced higher susceptibilities than 2009 in the north-western inner mountain sector. Regardless of the different intensities, this spatial trend suggests that the 2009 storm path was limited to the coastal area, whilst the 2007 storm more homogeneously affected the whole catchment, activating also the slopes of the mountain sector. This interpretation is confirmed also by the different spatial distribution of the debris flows of the two event inventories.

However, from a risk perspective, the difference between the two models has not produced a relevant loss in prediction, as only a limited number of cases has resulted in a false positive prediction. This is why the mapped debris flows are largely located in the very susceptible pixels. However, the results of the present research have confirmed that the larger difference between the two models has been observed in the intermediate susceptibilities interval, which is the same region of the error plots where the self-validated models suffer for poor precision. This difference is also attested by the HK scores, which confirmed the good prediction skills, but having their maximum values proximal to 0.45. Under the considered triggering conditions, the multivariate relationship between debris flow activation and predictors is in fact linear, so that no single marked cut-off value for probability accurately discriminates positives from negatives.

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Nevertheless, it is worth highlighting the selection of a 0.5 cut-off value resulted in a higher performance for the temporal prediction of the positive cases (forward chrono-validation) of the 2007-calibrated model.

In general, the findings of previous studies (Zezere et al., 2004; Guzzetti et al., 2005; Vergari et al., 2011; Wang et al., 2013) regarding the effectiveness of temporal partition procedure to explain future landslides are here confirmed even in the case of debris flows triggered by an extreme rainfall event. However, it is worth to compare the results here obtained for chrono-validation (AUC=0.77/0.78), with the ones of Lombardo et al. (2014), which applied a spatial exportation scheme in two very close catchments. In facts, a higher performance (AUC=0.83) resulted for the prediction skill of the transferability procedure which was there adopted, by calibrating the model in the Briga catchment to predict the Giampilieri debris flows, using event inventories produced by the same 2009 storm triggering event. Sharing the triggering event allows for a higher predictive power, in spite of the circumstance that, in a spatial partition scheme, the calibrated model is totally blind with respect to the validation area, in terms of the spatial combination of the predictors and the target pattern (the unknown debris flows).

7. Conclusions

The main task of this research was to investigate those potential limits which could arise for stochastically based landslide susceptibility models, in case of multiple debris flows triggered by extreme events. To investigate this topic, chrono-validated models based on two different set of storm triggered debris flows (2007 and 2009 events) have been prepared for the same catchment: a forward model, calibrated on 2007 and validated on 2009, and a backward model, calibrated on 2009 and validated on 2007. Under the assumption that the past is the key to the future, the performances of the two types of chronological modelling should have been the same.

In light of the results of this research, the direct use of this basic assumption in case of extreme event must be critically accepted. In fact, even in the case of two storm events, the dissimilarities in the intensity and the real path followed by the two storm fronts, produced measurable differences in the behaviour of the two models, both in the domain of the predictors and in the spatial pattern of the susceptibility maps. Two main causes have been here recognised: on the one hand, the slopes did not linearly responded to the trigger intensity, so that different predictors and regressed coefficients were fitted by the two regressed models; on the other hand, effects produced by the non-homogeneity of the rain intensity for each single storm event, even at the scale of such a small catchment, have been detected.

In terms of the operative use of the susceptibility maps, the effects which have been identified in this study case attest for the risk either of over- or under- estimating the susceptibility, both for the 2009 and 2007 models. In particular, limits arise to the general perspective of using the most severe and available inventory for training the best performing model. In fact, in this research it was verified that this best performing self-validated model did not result in the most accurate one in chrono-validation, suffering also for susceptibility underestimation and false negative production.

In the present case, the differences between the two models basically reside in the intermediate susceptibility interval, so that a precautionary approach in reclassifying the susceptibility map could be adopted, accepting the precision limits in the intermediate probability classes. However, larger differences between the triggering storms to which calibration and validation event inventories are connected, would have resulted in larger predictive limits and more misleading susceptibility maps.

The strict relation between trigger intensity and slope response arises also from the comparison of this study to one made by applying spatial partition or transferability validation strategies in two adjacent catchments for the same 2009 trigger, obtaining a better predictive performance. In the opinion of the authors, this difference confirms limitations of the chrono-validation procedure when working with extreme rainfall events. For this reason, the application of transferability or chrono-validation should be evaluated from time to time on the basis of the availability of historical records of phenomena, information on the trigger event,

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and similarity with other areas where debris flow events already occurred. At the same time, the production of susceptibility maps such as those presented in this paper constitutes a basic starting point for modelling propagation, runout and magnitude associated to the predicted phenomena, so to achieve an estimation of the debris flow hazard within a given area.

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M. Cama, C. Conoscenti, L. Lombardo and E. Rotigliano have commonly shared all the part of the research as well as of the manuscript preparation. V. Agnesi has taken part to the final discussion of the data.
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Eliminato: ... [68]

Figures

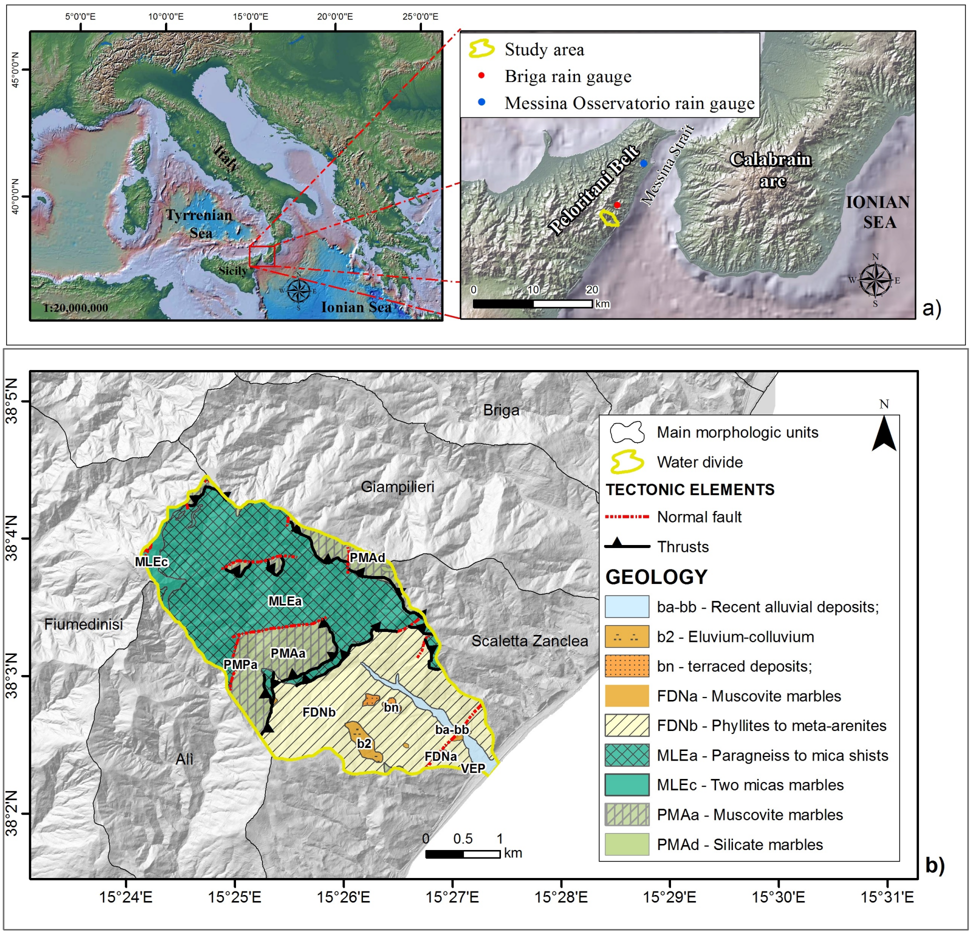

Fig. 1- *Setting of the Study area*

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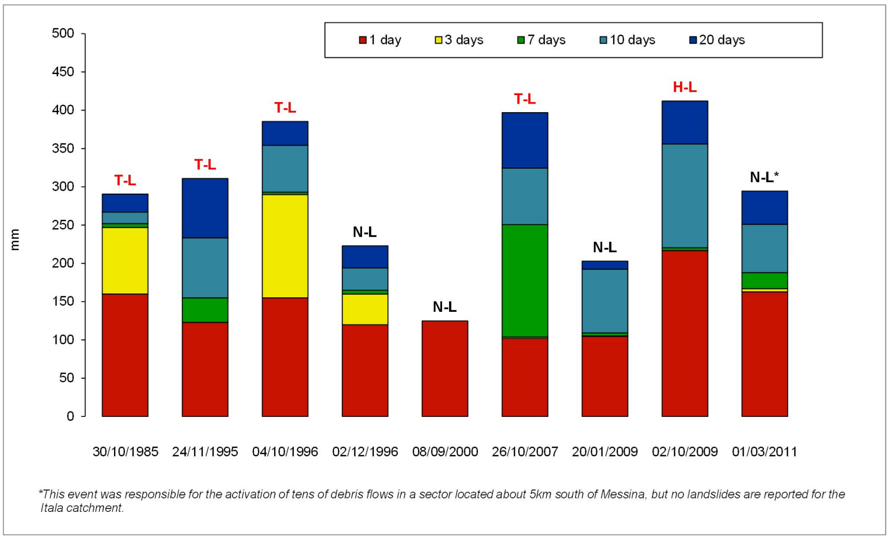

Fig. 2 *– Bar plot showing the cumulative rainfall in mm respectively for 1 day, 3, 7, 10 and 20 days.*

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Eliminato: ... [69]

Edoardo Rotigliano 6/10/y 11:12 AM
Eliminato: - *Hyetograph*

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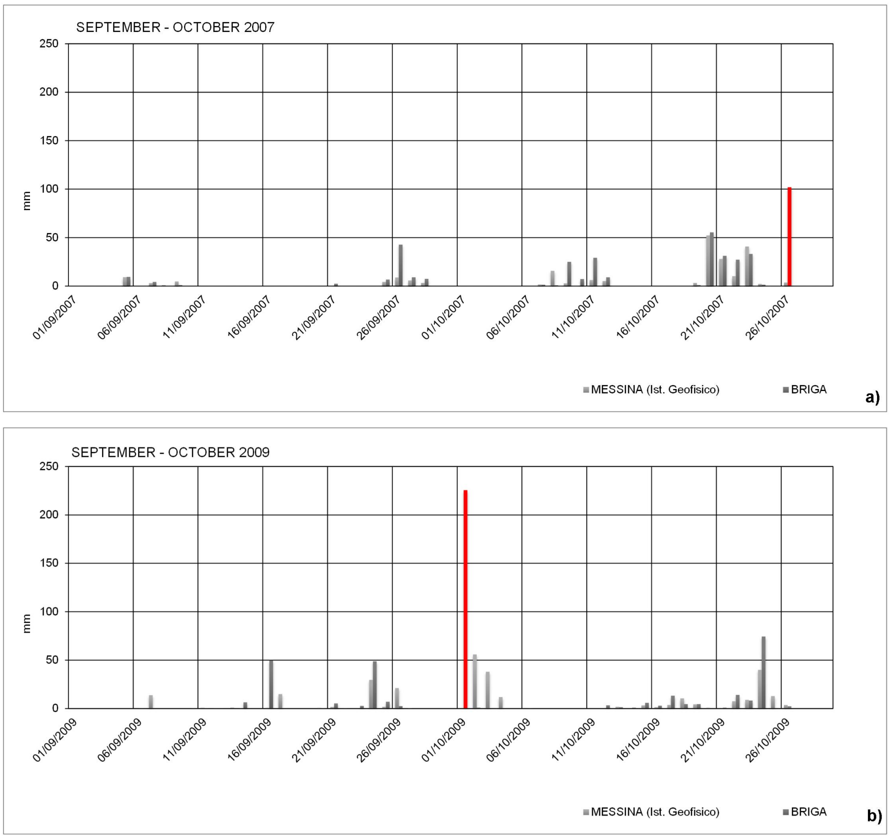

Fig. 3 – Time series of 2 months precipitations: a) October 2007*; b) October 2009.*

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Spostato (inserimento) [3]

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Eliminato: *daily precipitation during the month of*

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Eliminato: *. The 2007 event is clearly distinguishable on the 16th October registra* ... [70]

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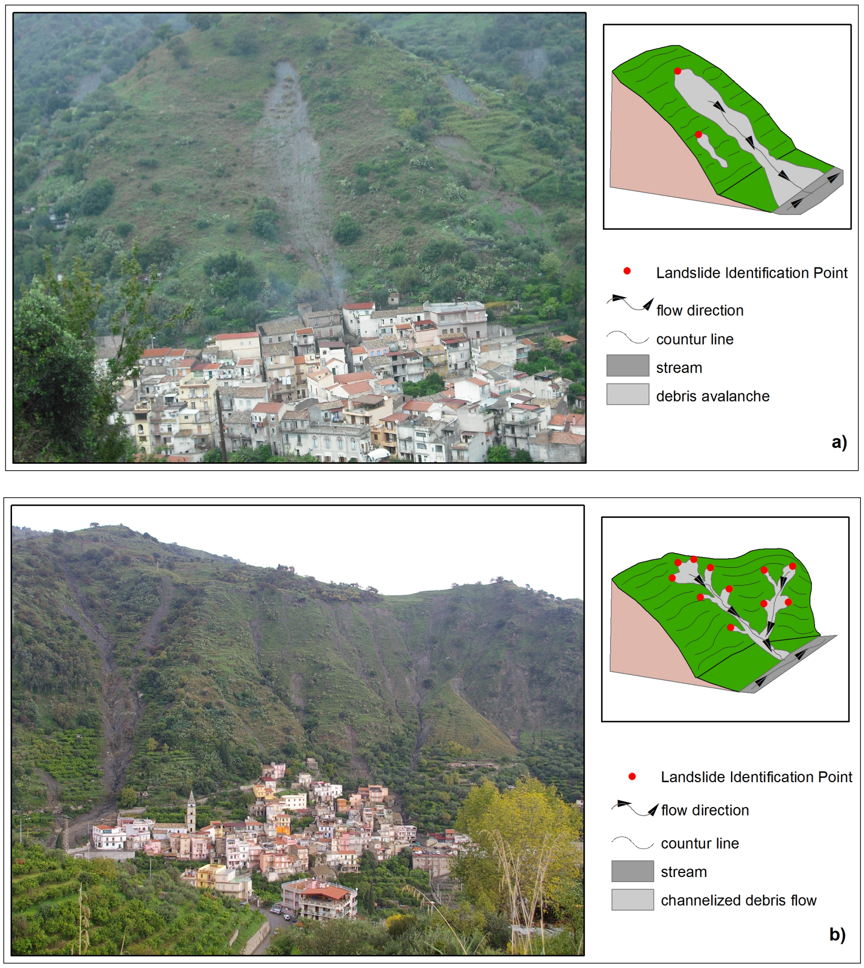

Fig. 4 - Overview of the area hit by the 2009 event: a) Guidomandri village: debris avalanches are observable on the triangular facets parallel to the coast; b) Itala village: channelized debris flows crossing the urbanized area.

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Spostato in su [3]: *Fig.*

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Eliminato: *3- Hyetograph showing the daily precipitation during the months of September and October 2009.* ... [71]

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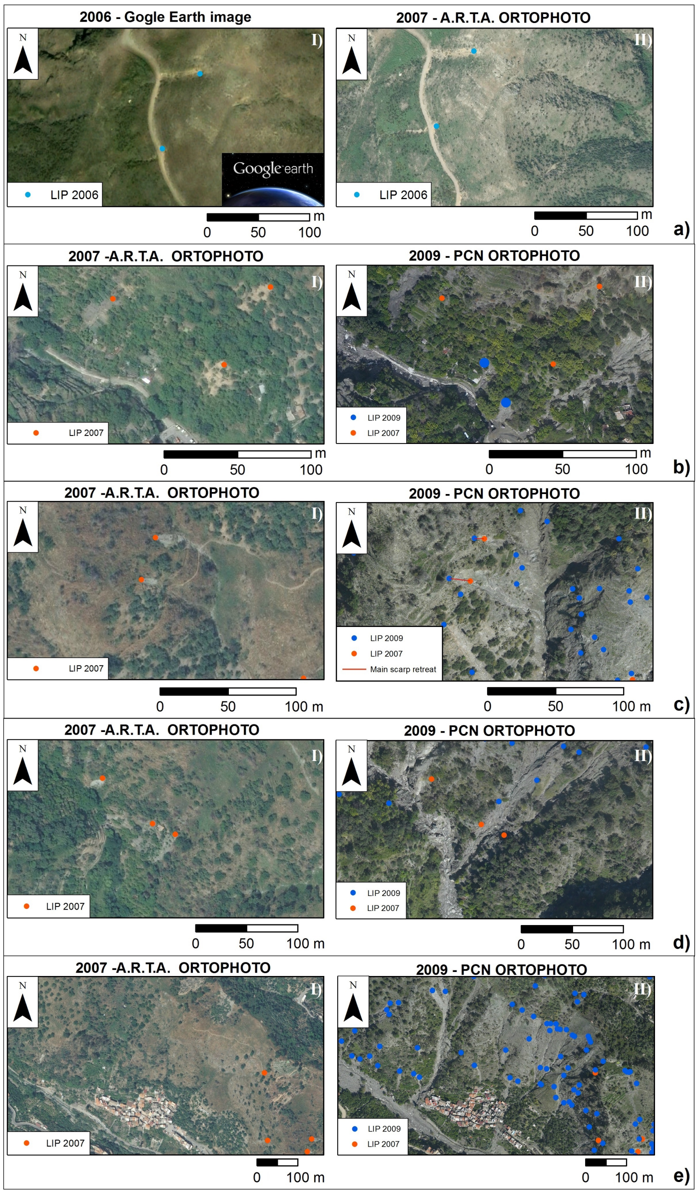
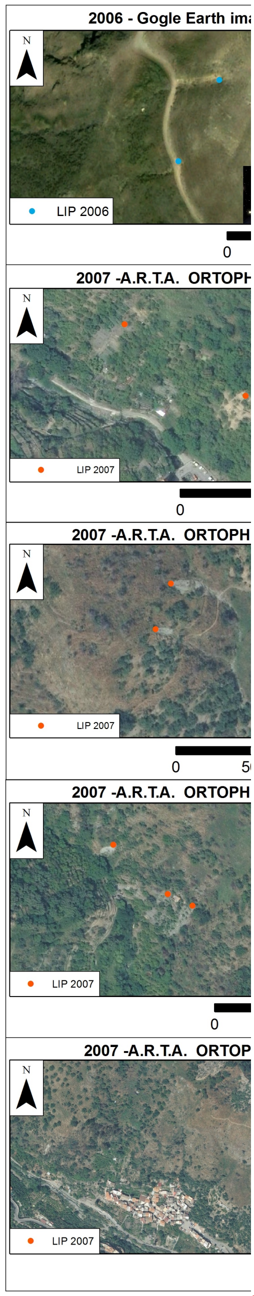


Fig. 5 - Comparison of morphologies between two different images resulting in five different cases: a) debris flows recognized on the 2007 orthophoto but activated before the 2007 event; b) debris flows activated in 2007 which did not reactivated or retreated in 2009; c) debris flows which activated in 2007 that retreated or reactivated in 2009; d) debris flows activated in 2007 which have been completely included in 2009; e) debris flows activated in 2009.



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Formattato: A sinistra

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Eliminato: *shallow landslides*

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Formattato ... [73]

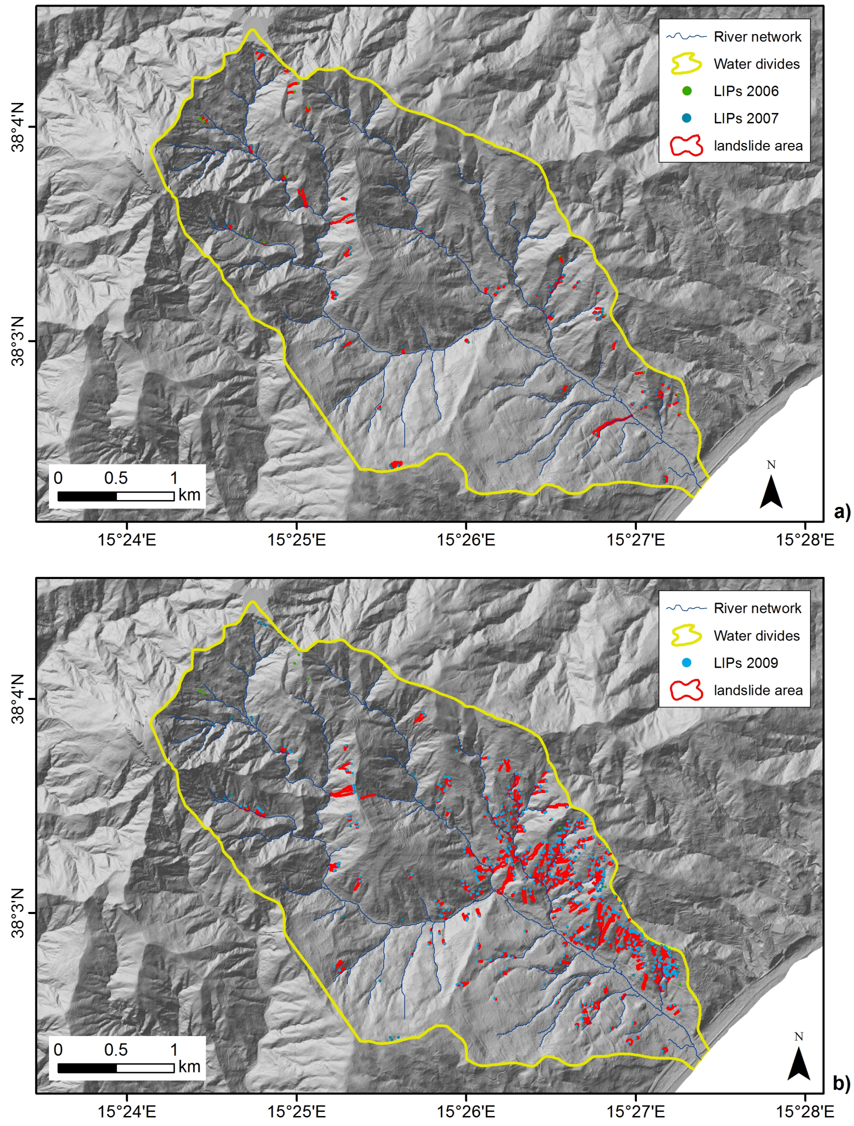

Fig. 6 *- Debris flow event inventories: a) 2007 inventory containing 73 debris flows; b)2009 event inventory containing 616 debris flows.*

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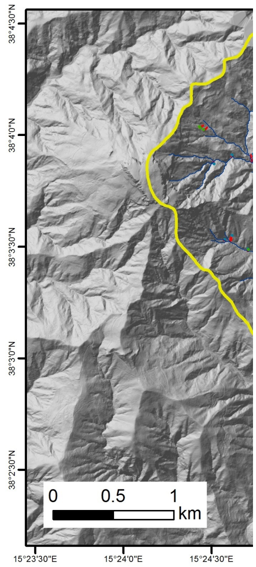

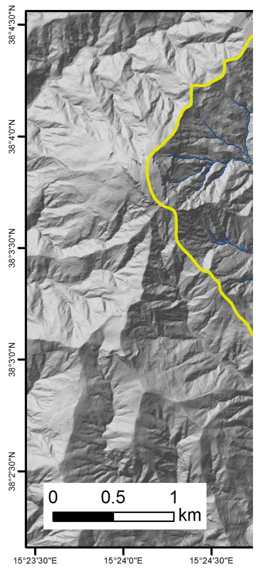

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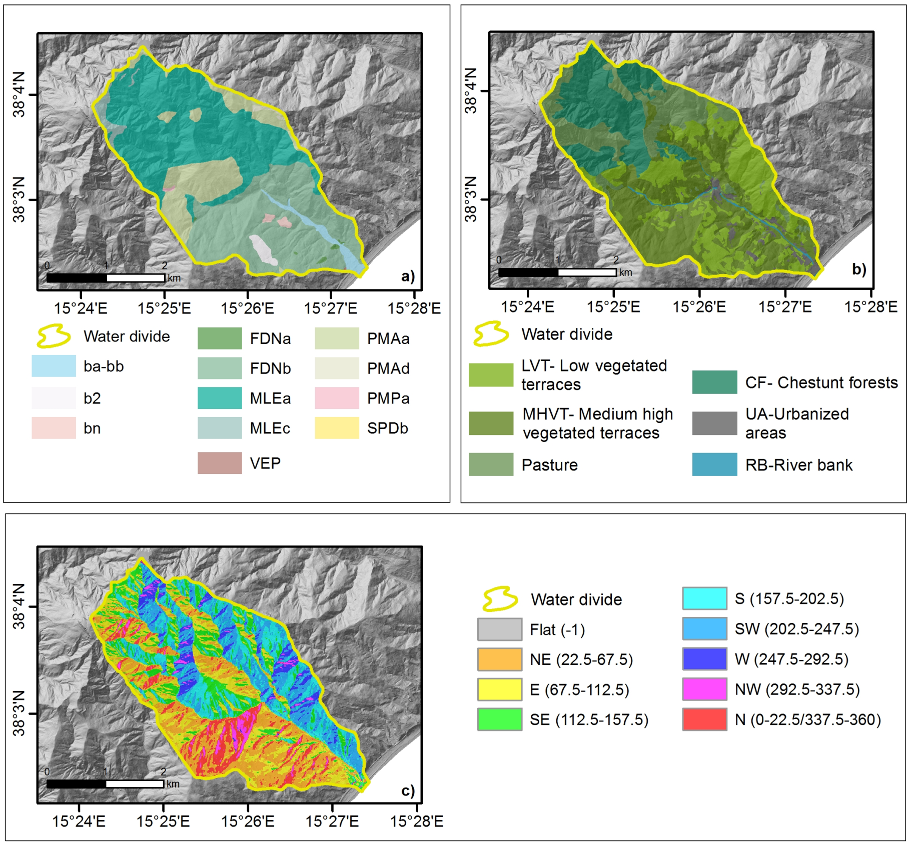

Fig. 7 *- Discrete variables: a) outcropping lithology (GEO; see Figure 1 for description); b) land use (USE); c)aspect (ASP).*

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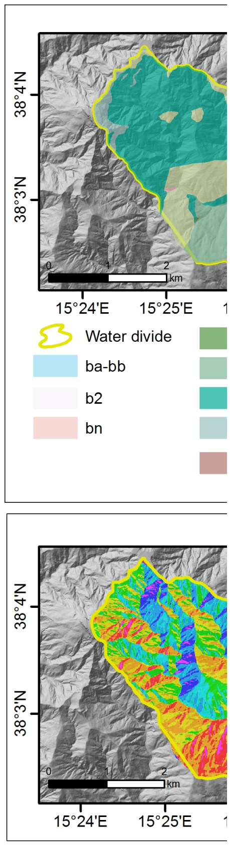

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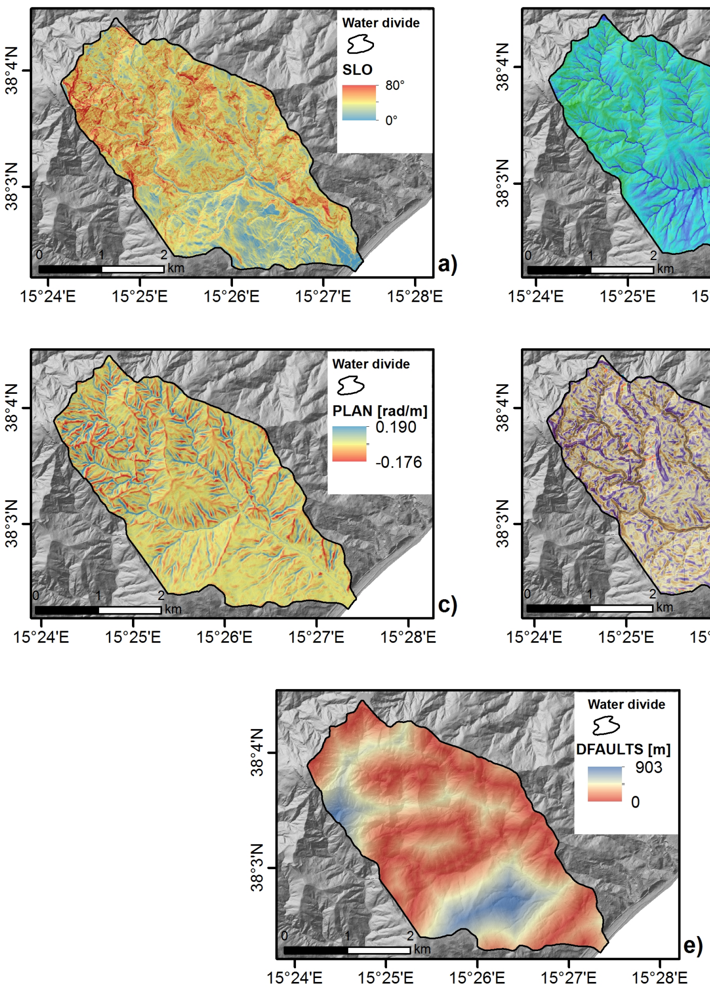

Fig. 8 *- Continuous variables: a) slope; b) topographic wetness index; c) plan curvature; d) profile curvature; distance from tectonic elements*

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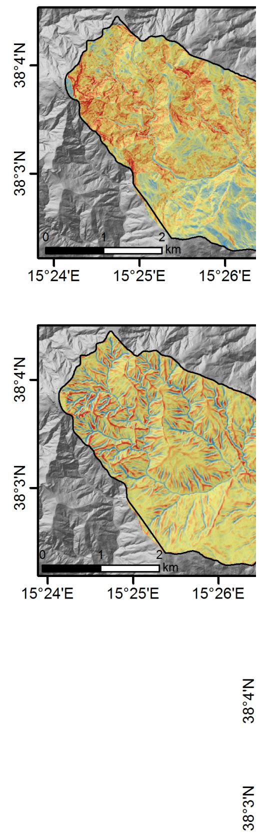

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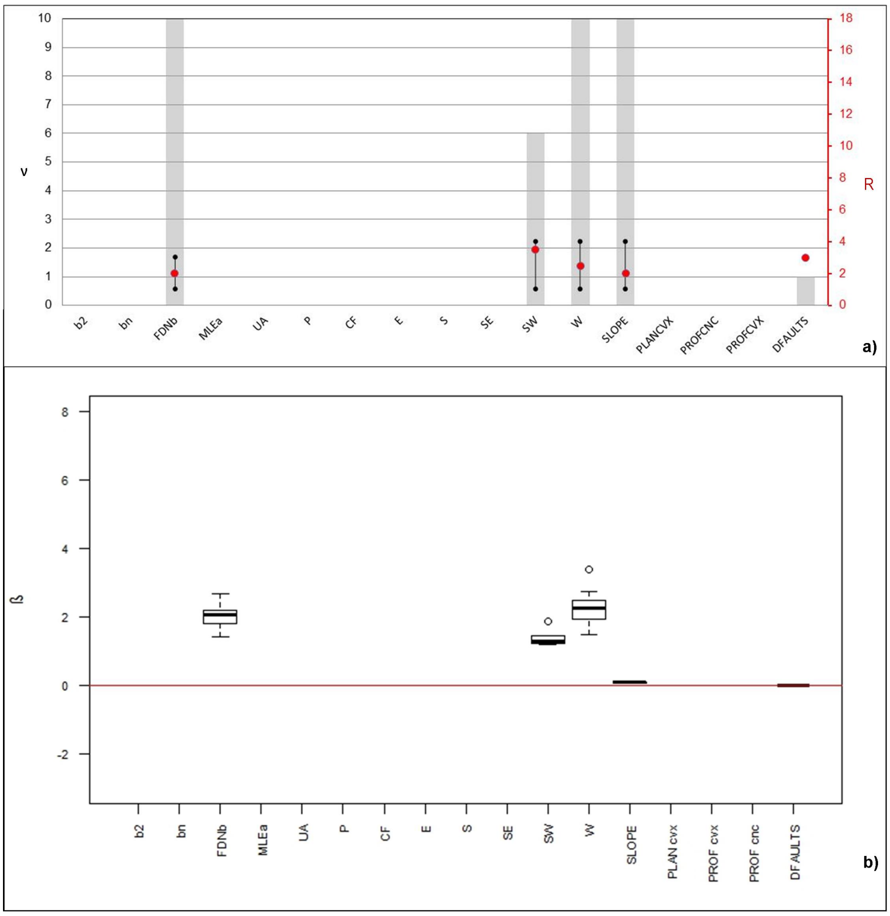

__Fig. 9__ - Selected variables for the 2007 suite of models: a) ranking and frequency; b) β values

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Eliminato: - *Error rate and AUC for self-validating (cross validation) 2007 and 2009* ... [75]

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Spostato in giù [4]: *Fig.*

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Eliminato: *suites*

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Eliminato: *(the β values of the curvatures is expressed in logarithm)*

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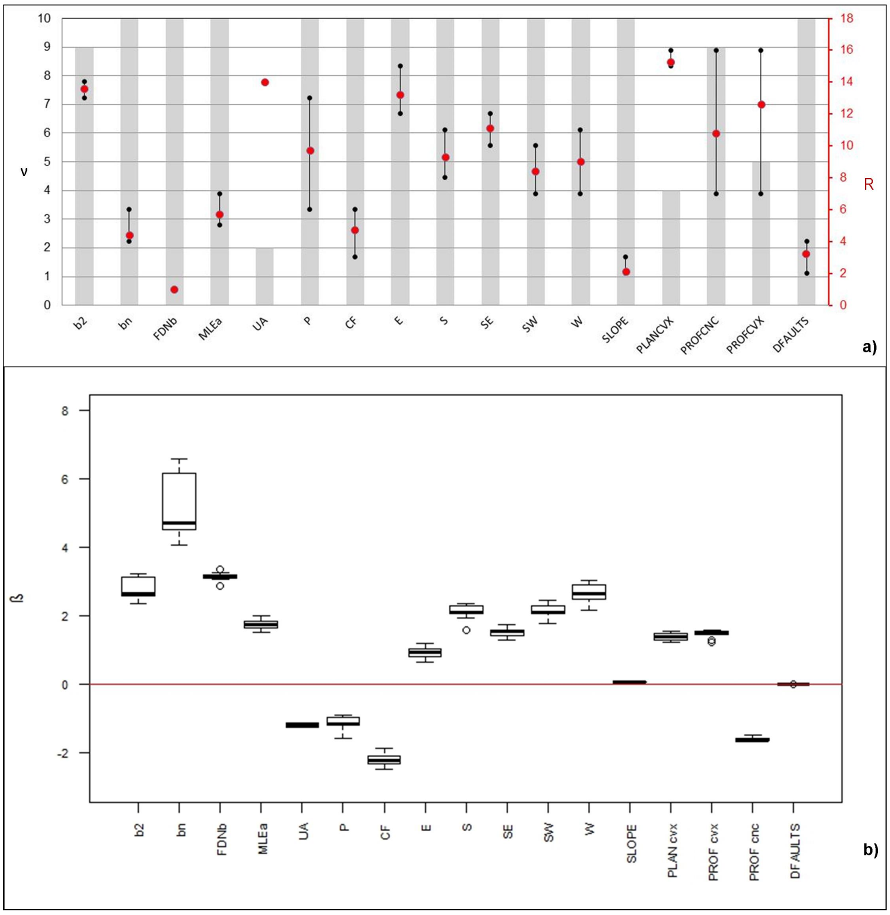

Fig. 10 - Selected variables for the 2009 suite of models: a) ranking and frequency; b) β values. For need of representation, the coefficients of the topographic curvatures are reported as logβ values.

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Spostato in giù [5]: *Fig.*

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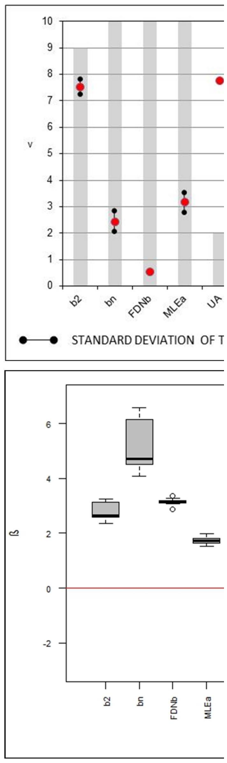

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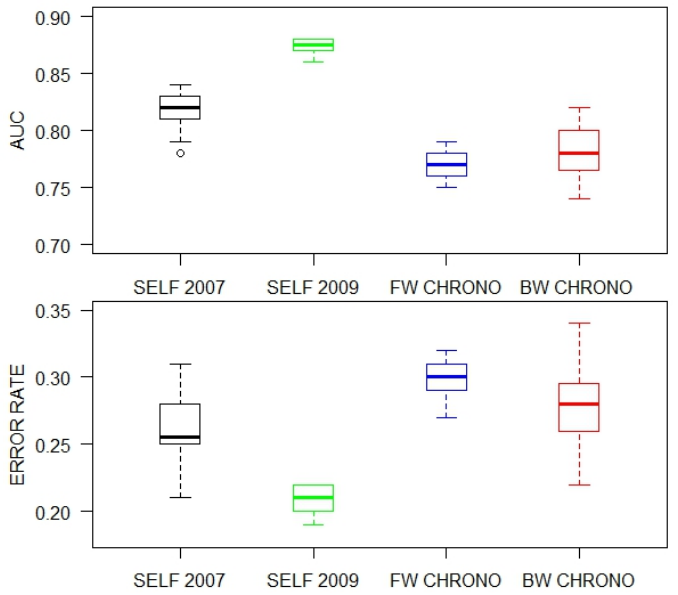

Fig. 11 - Distribution of the AUC and error rate values calculated on the 10 replicates for 2007 and 2009 modelling and 100 models during the chrono-validation process.

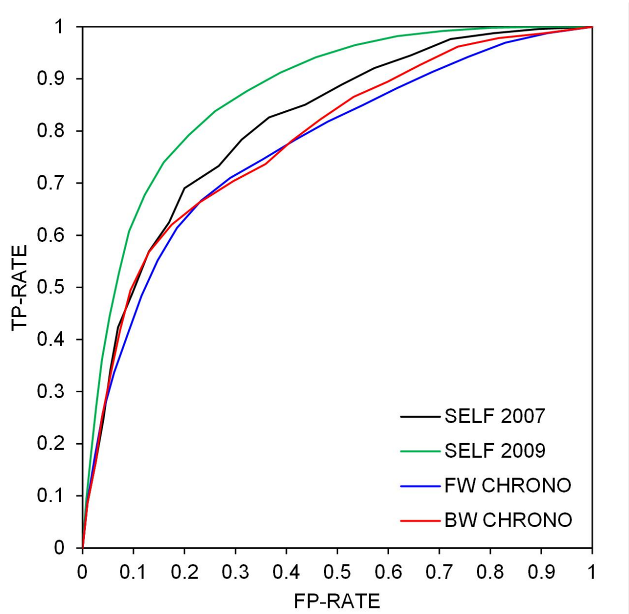

Fig. 12 *- Mean ROC curves.*

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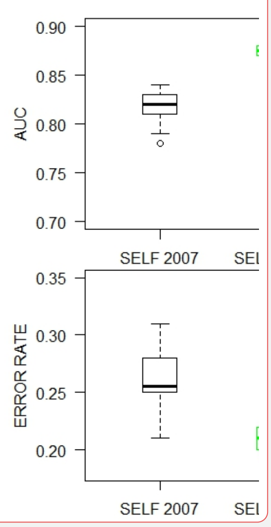

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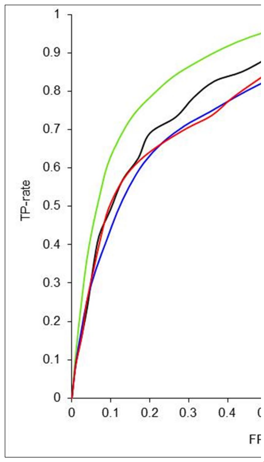

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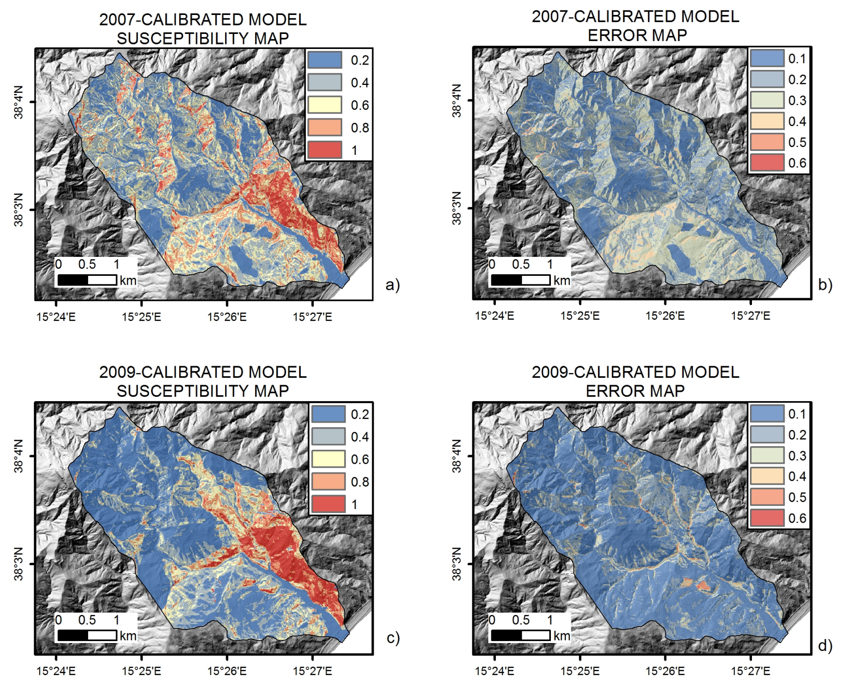

Fig. 13 - *Susceptibility and error maps for the 2007- and the 2009-calibrated models: a, c) mean susceptibility; b, d) error maps.*

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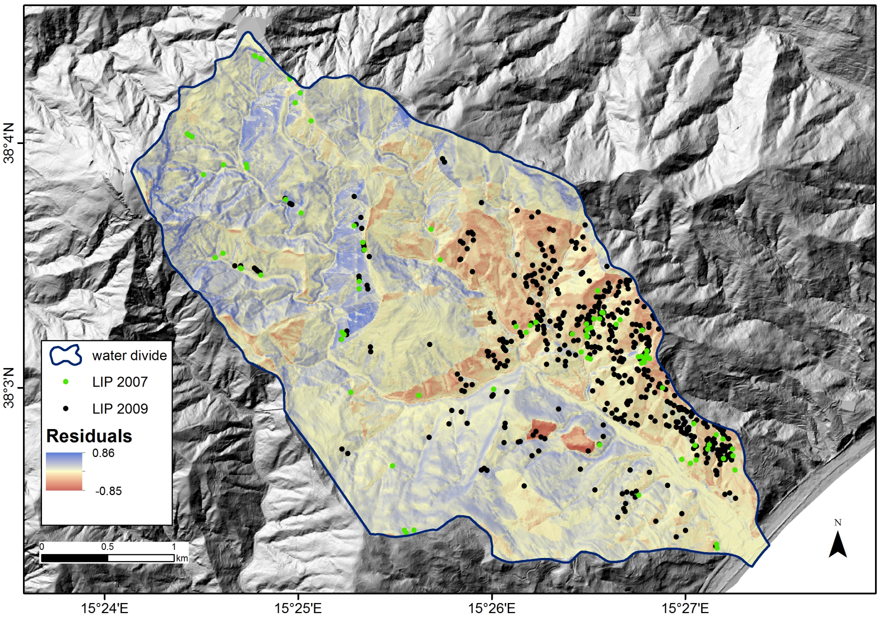

Fig. 14 *- Map of residuals calculated as percentage differences between the two (2007 and 2009) mean susceptibilities.*

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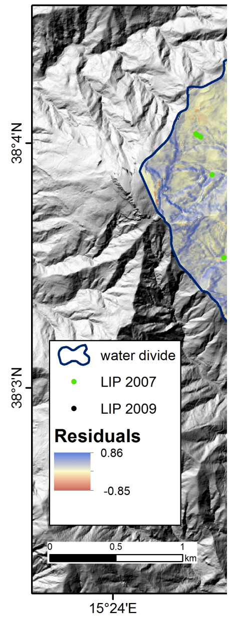

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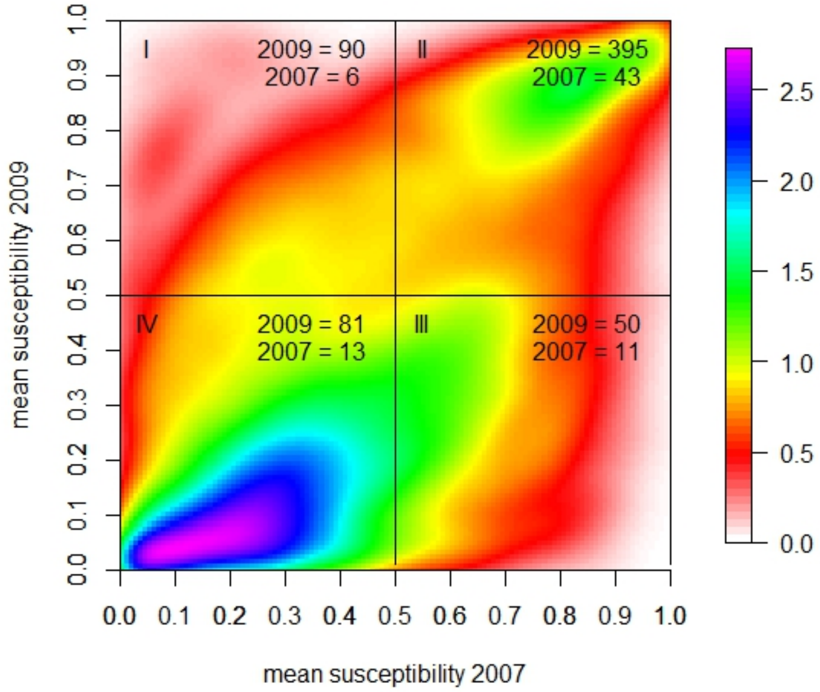

Fig. 15 - *Dispersion density plot calculated using 2d Binned Kernel Density algorithm (range for density calculation 0.045 xy). Positive cases for 0.5 cut-off values are reported for the two inventory events.*

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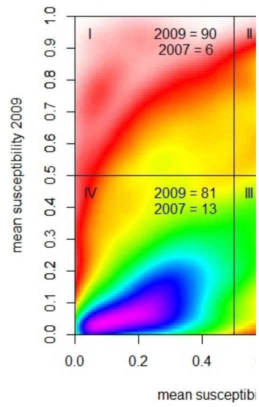

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Formattato: A sinistra

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Tables

Error rate			mean		0.336	dev.	0.028	
Values prediction			Confusion matrix					
					observed			
Value	Recall	1-Precision			YES	NO	Sum	
YES	0.645	0.331	predicted	YES	1348	668	2016	
NO	0.683	0.340	predicted	NO	742	1442	2184	
				Sum	2090	2110	4200	

Tab. 1 – Results of cross folded validation for the 2007 dataset.

Error rate			mean		0.219	dev.	0.011
Values prediction			Confusion matrix				
					observed		
Value	Recall	1-Precision			YES	NO	Sum
YES	0.777	0.216	predicted	YES	14335	3948	18283
NO	0.786	0.221	predicted	NO	4115	14502	18617
				Sum	18450	18450	36900

Tab. 2 - Results of cross folded validation for the 2009 dataset.

2007/2009				2009/2007			
Score	FP-Rate	TP-Rate	HK	Score	FP-Rate	TP-Rate	HK
0.990	0.000	0.000	0.000	0.970	0.000	0.000	0.000
0.941	0.010	0.089	0.080	0.925	0.010	0.086	0.076
0.898	0.024	0.175	0.151	0.890	0.026	0.166	0.139
0.862	0.040	0.259	0.219	0.860	0.038	0.250	0.212
0.815	0.062	0.337	0.275	0.820	0.057	0.340	0.283
0.764	0.089	0.411	0.322	0.778	0.074	0.419	0.345
0.723	0.116	0.484	0.368	0.729	0.094	0.495	0.400
0.681	0.147	0.552	0.404	0.646	0.131	0.568	0.438
0.635	0.185	0.614	0.429	0.558	0.174	0.620	**0.446**
0.581	0.233	0.666	**0.433**	0.481	0.228	0.662	0.434
0.518	0.290	0.710	0.420	0.394	0.296	0.704	0.408
0.457	0.354	0.746	0.392	0.323	0.359	0.737	0.378
0.402	0.416	0.783	0.366	0.265	0.410	0.781	0.371
0.350	0.482	0.818	0.336	0.219	0.466	0.822	0.356
0.304	0.549	0.850	0.300	0.176	0.532	0.865	0.334
0.263	0.617	0.882	0.266	0.143	0.598	0.895	0.296
0.224	0.686	0.913	0.227	0.113	0.662	0.927	0.265
0.183	0.757	0.942	0.186	0.081	0.737	0.962	0.225
0.138	0.829	0.970	0.140	0.055	0.816	0.978	0.162
0.087	0.912	0.987	0.076	0.030	0.903	0.987	0.084
0.014	1.000	1.000	0.000	0.007	1.000	1.000	0.000

Tab. 3 *– HK values for the 100-replicated chrono-validations*