RAINFALL INDUCED SHALLOW LANDSLIDE FORECASTING IN LARGE AREAS: APPLICATION OF THE TRIGRS MODEL OVER A BROAD AREA OF POST-OROGENIC QUATERNARY SEDIMENTS

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1. INTRODUCTION

We describe an approach for calibrating a deterministic model to assess shallow landslide susceptibility over a 550 km^2 area covered by Quaternary sediments.

We used the Transient Rainfall Infiltration and Grid-based Regional Slope-stability (TRIGRS) model (Baum et al., 2002; 2008; 2010) to compute infiltration-driven changes in factor of safety in a hilly part of the Marche Region in central Italy. This area of the Esino River basin covers and is characterized by post-orogenic Quaternary sediments prone to rainfall-induced shallow landslides. TRIGRS combines an infinite-slope stability analysis with a one-dimensional analytical solution for vertical infiltration under saturated or unsaturated initial conditions and finite basal boundary depth.

We ran the model for representative landslide-prone grid cells in each of the units for different rainfall scenarios. We compared modeled (pressure head, factor of safety) and observed (landslide occurrence) responses for sample cells of each map unit to examine the model's sensitivity to variations in material properties and to identify the most probable quartile. In order to apply the model over a digital landscape of the river basin we divided the study area into 4 property zones and used an empirical soil-thickness model to define the depth of each grid cell. Model output was then compared to a landslide inventory.

2. STUDY AREA

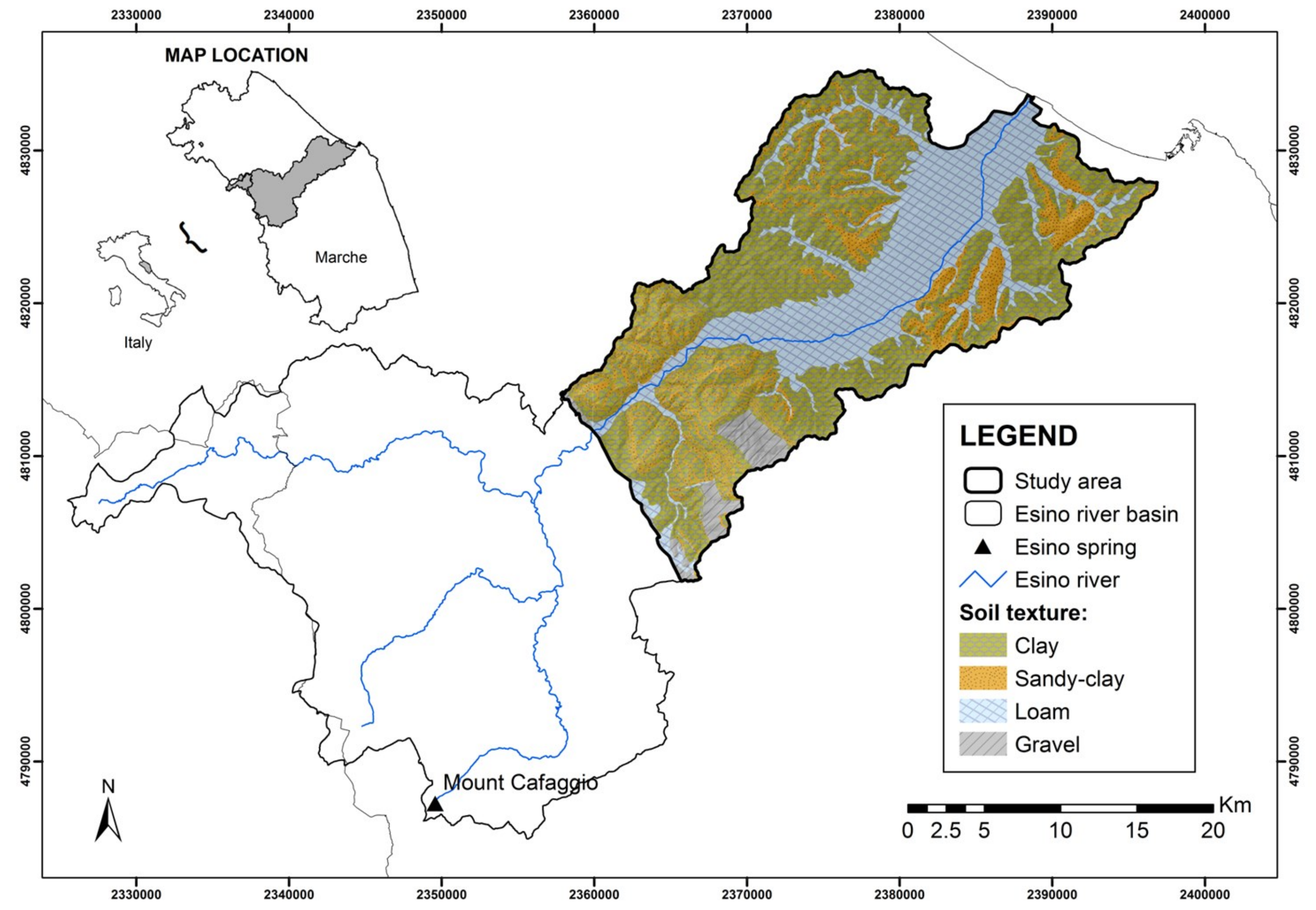


Figure 1. Map showing the study area. Highlighted are the soil texture classes that characterize the post-orogenic sediments of the Esino river basin.

3. DATA COLLECTION

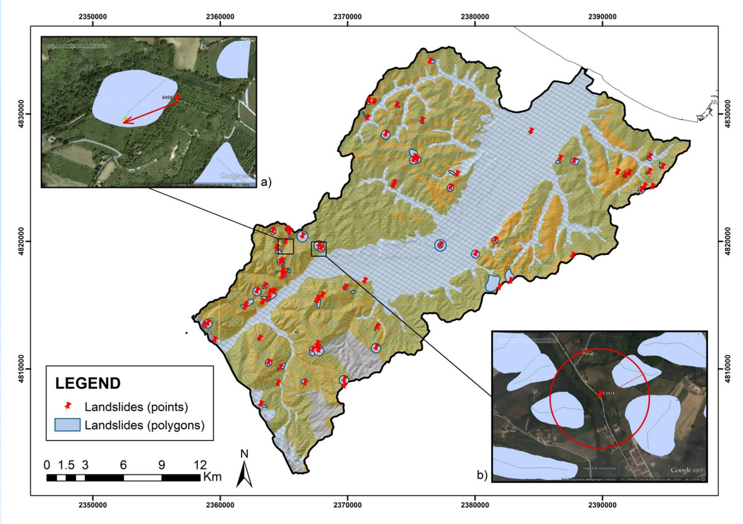
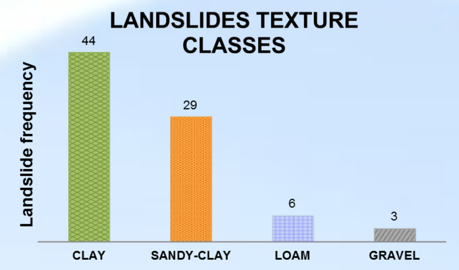
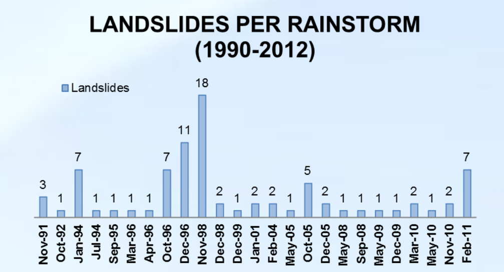


Figure 2 (LEFT). Landslide locations (82 points) mapped in the study area that occurred during the period 1990-2012. Each point was linked to an existing landslide polygon from the Italian landslides inventory (IFFI) (a), or to a buffer area when the connection with one specific polygon was uncertain (b).

Figure 3 (BELOW). Histograms showing the landslide frequency per texture class. Due to the low number of landslides and the lack of literature data for the material properties of the gravel, this class was not considered for the purpose of the study.





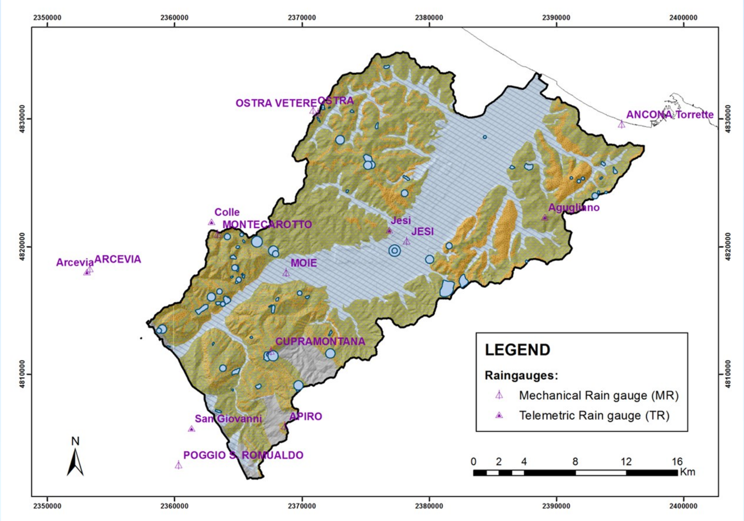
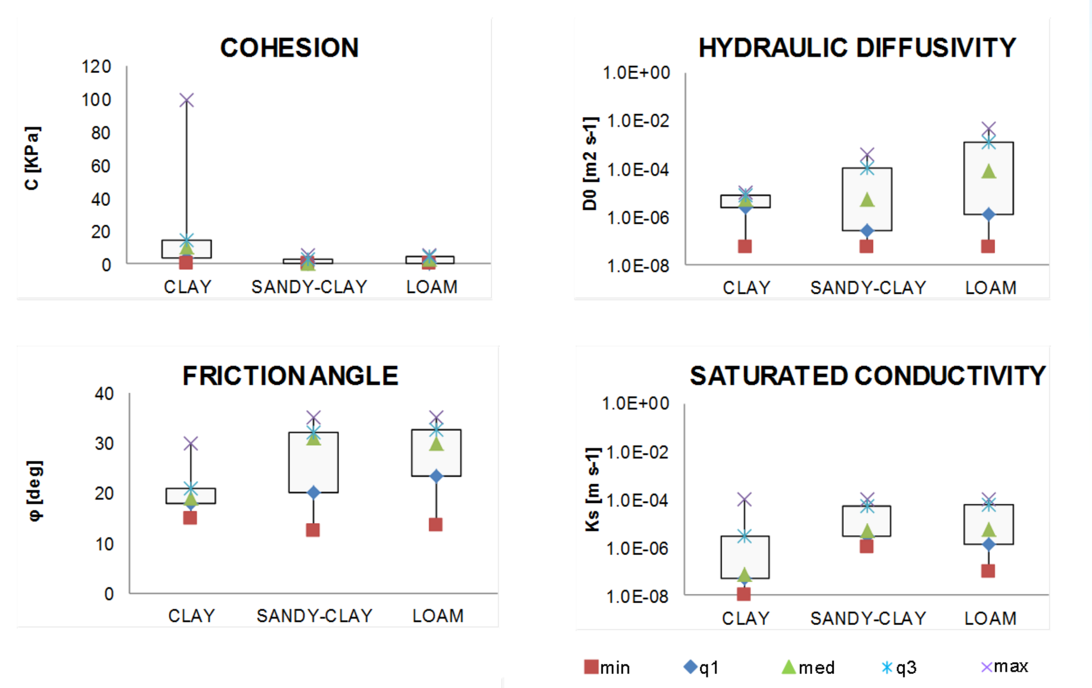


Figure 4 (RIGHT). Mechanical (MR) and Telemetric (TR) rain gauges used for the study. Every landslide was linked to the closest functional gauge.

Figure 5 (ABOVE). List of rainstorms that triggered landslides in the study area during the period 1990-2012. Histograms show the number of landslides initiated in each storm.



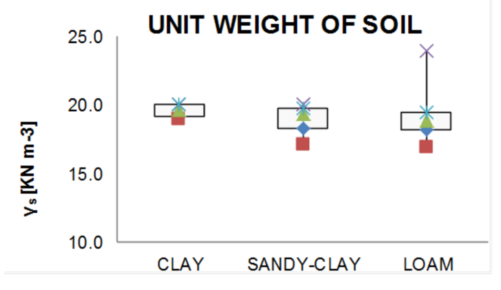


Figure 6. Box plot charts of central tendencies, such as the smallest observation (sample minimum), lower quartile (q1), median, upper quartile (q3), and largest observation (sample maximum), computed for each set of parameters required as input for TRIGRS: cohesion (c); angle of internal friction (φ); unit weight of soil (Y_s); hydraulic diffusivity (D_0); saturated hydraulic conductivity (K_s). Parameter values were obtained from published reports for nearby regions.

4. MODEL CALIBRATION

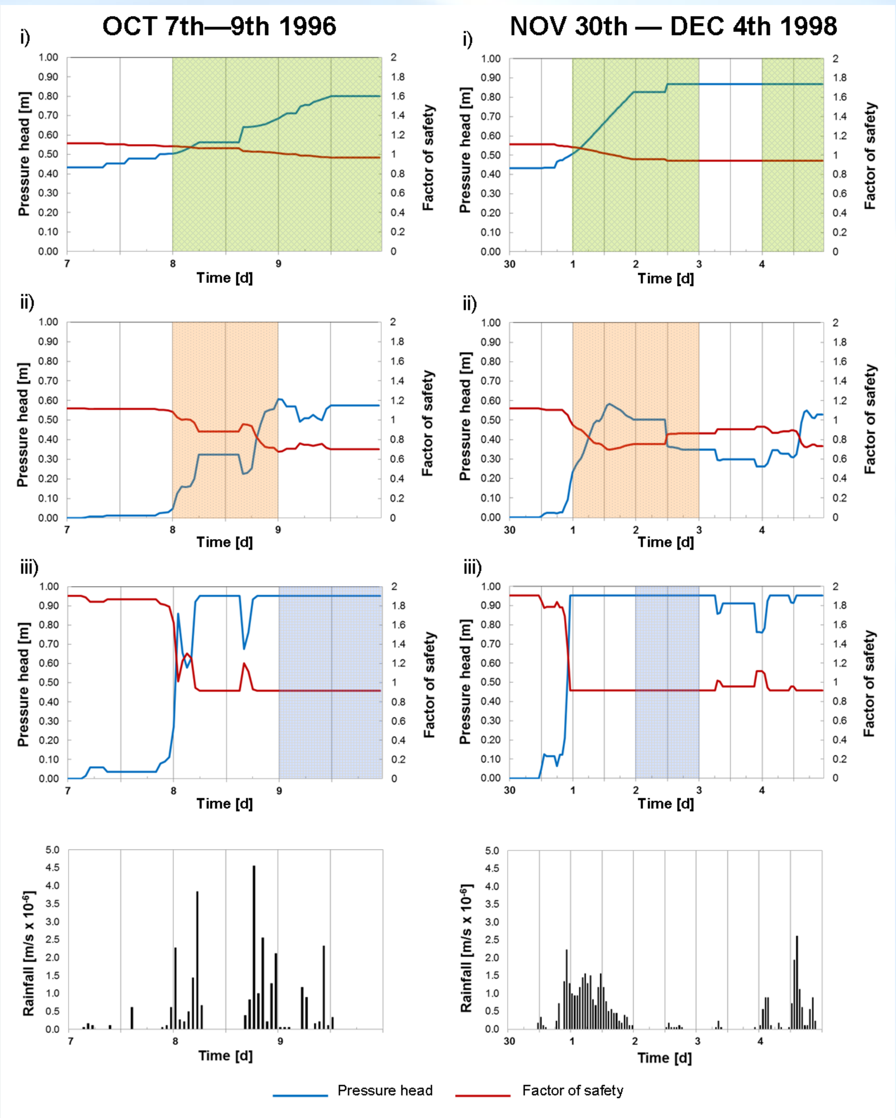


Figure 7. Calibration results for pressure head and Fs in a single cell, during the October 1996 and November 1998 storms. Highlighted is the period during which landslides were initiated in clay (i), sandy-clay (ii), and loam (iii).

We calibrated TRIGRS for a single cell using representative input values that yield a change in pore-water pressure such that factors of safety (Fs) were reduced to one in landslide locations.

Based on field observations and reports, average landslide depth was assumed to be 1m at the median slope angle for landslides in each soil type.

The storms chosen were those which triggered the largest number of landslides during the period 1990-2012; October 1996 and November 1998 with 7 and 18 landslides respectively.

The results of the calibration were constrained assuming the analyzed cell was stable at the beginning of the rainfall and unstable at the end of the storm (**Figure 7**).

Following the calibration on a single cell, we ran the model for the entire study area adopting the sequence of steps below.

STEP 1: Outline test cases, choose the rainfall event, select the rain gauge and the rainfall intervals (**Figure 8**);

STEP 2: Evaluate an "Antecedent Water Index" (**Figure 9**);

STEP 3: Construct input grids of slope from a 20m DEM, property zones, rainfall input, soil depth and water table depth (**Figure 10**).

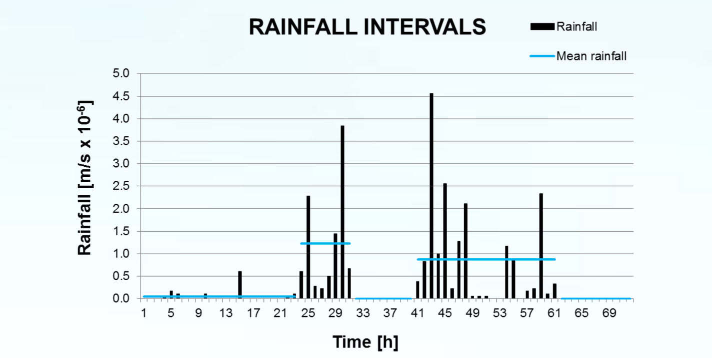
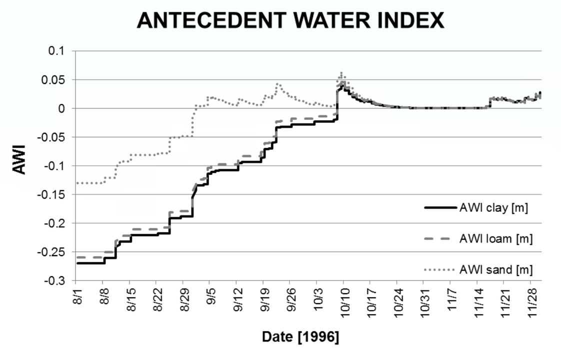


Figure 8 (ABOVE). We divided the storms into intervals (light blue lines) characterized by the mean rainfall of the period that they represent. The figure shows the rainfall intervals and intensities of the October 1996 storm as an example.

Figure 9 (BELOW). In order to estimate the initial water table depth, we computed an Antecedent Water Index (AWI) following Godt et al. (2006) for every rainfall event. We considered the wilting point condition as the beginning of the meteorological season or the beginning of consistent rainfall. If the AWI was approximately equal to or greater than 0 (field capacity) on the days prior to the landslide event, we ran TRIGRS with saturated conditions and an initial water table depth at: 0.5m for clay and 1m below the ground surface for sandy-clay and loam. If the AWI was less than 0 we proportionally decreased the level of the initial water table depth. The graph shows an example of the AWI trend for the period August 1st – November 30th 1996.



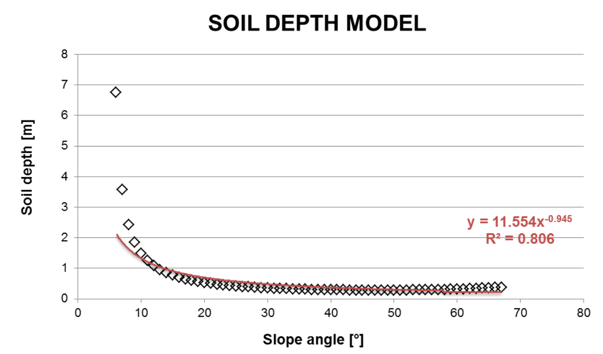
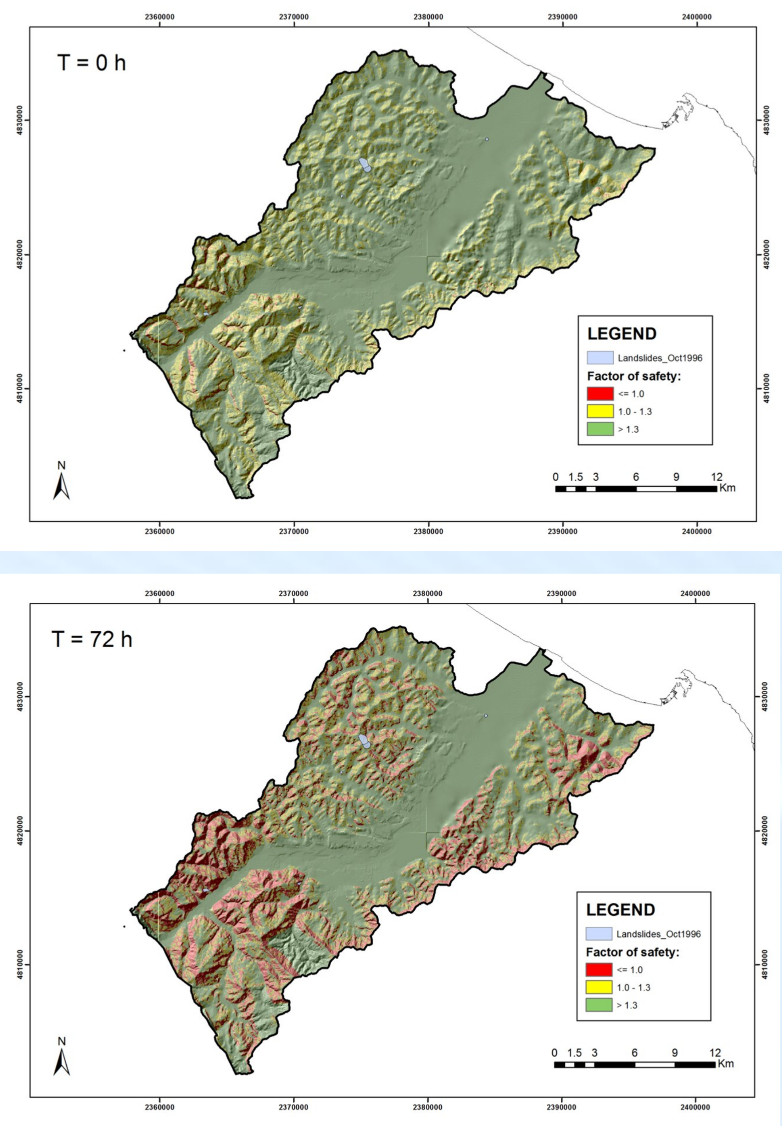


Figure 10 (LEFT). Relationship between soil depth and slope angle for clayey soils and power law ($y=ax^{-b}$) regression. The regolith depth was estimated assuming its correlation with the profile slope angle, so that the depth decreases with the increase of the slope (DeRose et al., 1991). Based on the strength properties values (friction angle, cohesion and unit weight of soil) gathered from the literature and calibrated in the above described tests we computed critical soil depth for Fs equal to 1.0. Using this approach, slope-dependent profiles of regolith depths (diamonds) have been developed for clayey, sandy-clay and loamy soils.

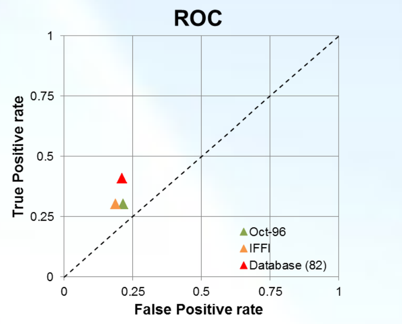
5. RESULTS

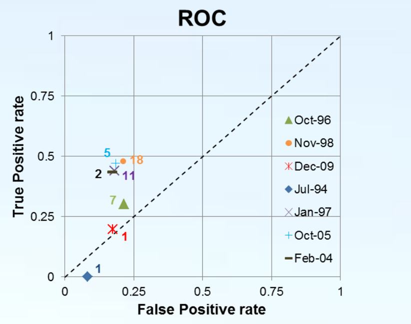


The output was visualized and compared spatially and temporally in a GIS software, showing that the Fs≤1 cells were minimized at the beginning of the storm and maximized at the end. These results indicate that the model was well calibrated (**Figure 11**).

The Receiver Operating Characteristics (ROC) technique has been used to assess the performance of TRIGRS as a landslide predictor for the study area. ROC curves for both the complete database and for particular rainfall events show that TRIGRS can be successfully used to build a susceptibility map and possibly be used to predict rainfall-induced landslides over large regions even where geotechnical and hydraulic properties data are not available (**Figure 12-13-14**).

Figure 11 (LEFT). Spatial and temporal distribution of Fs for the October 1996 event. The timing (0, 72 h) reflects the beginning and the end of the storm.





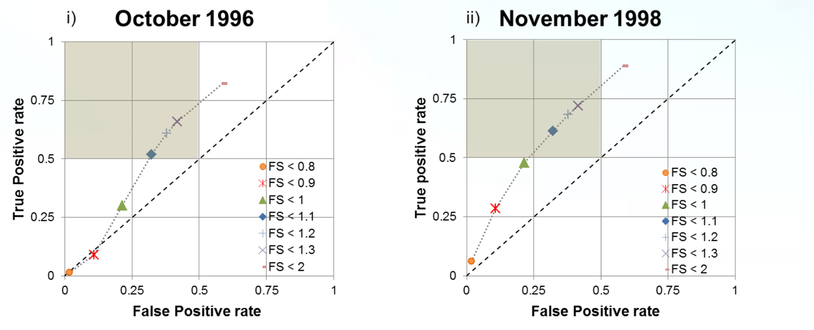


Figure 12 (UPPER LEFT). ROC analysis of results (Fs≤1) achieved for the October 1996 event, compared against the IFFI inventory and the 1990-2012 inventory. Better results are obtained using the inventory database of the period 1990 -2012.

Figure 13 (UPPER RIGHT). ROC analysis for different landslide scenarios (July 1994, October 1996, January 1997, November 1998, February 2004, October 2005 and January 2010). The data labels represent the number of landslides related to the rainfall event. The graph indicates that for the events that triggered a single landslide TRIGRS tends to over predict the extent of the landslide, but for scenarios with longer number of landslides results are improved.

Figure 14 (LOWER LEFT AND RIGHT). ROC curves for the events of October 1996 (i) and November 1998 (ii) plotted varying the range of Fs values considered to be unstable (True Positive). Acceptable predictions fall in the upper left quadrant of the graph (highlighted) so that TPR > 0.5 and FPR < 0.5. Based on these results, considering Fs = 1.1 - 1.3 as unstable maximizes the agreement between known and predicted landslides for both events.

6. REFERENCES

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