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Landslide susceptibility assessment by TRIGRS in a frequently affected shallow instability area / Ciurleo, M., Mandaglio, M.c., Moraci, N.. - In: LANDSLIDES. - ISSN 1612-510X. - 16:(2019), pp. 175-188. [10.1007/s10346-018-1072-3]

*Availability:*

This version is available at: <https://hdl.handle.net/20.500.12318/1109> since: 2021-02-03T19:16:35Z

*Published*

DOI: <http://doi.org/10.1007/s10346-018-1072-3>

The final published version is available online at: <https://link.springer.com/article/10.1007/s10346-018->

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Ciurleo, M., Mandaglio, M.C. & Moraci, N. Landslide susceptibility assessment by TRIGRS in a frequently affected shallow instability area. *Landslides* **16**, 175–188 (2019).

<https://doi.org/10.1007/s10346-018-1072-3>

which has been published in final version:

<https://link.springer.com/article/10.1007/s10346-018-1072-3>

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# Landslides

## LANDSLIDE SUSCEPTIBILITY ASSESSMENT BY TRIGRS IN A FREQUENTLY AFFECTED SHALLOW INSTABILITY AREA

--Manuscript Draft--

<b>Manuscript Number:</b>	LASL-D-18-00281R2
<b>Full Title:</b>	LANDSLIDE SUSCEPTIBILITY ASSESSMENT BY TRIGRS IN A FREQUENTLY AFFECTED SHALLOW INSTABILITY AREA
<b>Article Type:</b>	Technical Note
<b>Order of Authors:</b>	Mariantonietta Ciurleo Maria Clorinda Mandaglio NICOLA MORACI, Ph.D.
<b>Keywords:</b>	weathered gneiss, shallow landslides, susceptibility, TRIGRS
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<b>First Author Secondary Information:</b>	
<b>Order of Authors Secondary Information:</b>	
<b>Manuscript Region of Origin:</b>	ITALY
<b>Funding Information:</b>	

[Click here to view linked References](#)

## LANDSLIDE SUSCEPTIBILITY ASSESSMENT BY TRIGRS IN A FREQUENTLY AFFECTED SHALLOW INSTABILITY AREA

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### ABSTRACT

Landslide susceptibility assessment over large areas is considered a preliminary step for the planning or design of the most appropriate risk mitigation measures. The use of physically-based models is considered a useful tool for landslide susceptibility assessment. Sometimes, using the available geotechnical input data, physically-based models can be used to preliminarily assess landslide susceptibility to obtain a susceptibility map which allows the expert to identify areas where detailed in situ investigations and laboratory tests should be carried out.

In this context, the paper proposes a methodology based on the use of TRIGRS to preliminarily assess landslide susceptibility in an area of about 1 km<sup>2</sup> frequently affected by shallow phenomena in weathered gneiss. Owing to the fact that these materials are extremely complex to characterize from a mechanical and hydraulic point of view, the methodology starts with the collection and analysis of the geotechnical data available for weathered soils outcropping in the study area. The above-mentioned data are combined with the data provided by scientific literature on soils similar, for genesis and stress history, to those of the studied area. Through the application of TRIGRS, the data are combined in order to obtain the values of parameters that better analyze shallow landslide source areas. Subsequently, using the above-mentioned values, several susceptibility maps are obtained. Finally, the most representative shallow landslide susceptibility map for the area is chosen by means of the error index (EI), the true positive fraction (TPF) and the Forecasting Index (FI). The success of the best map is confirmed by the high value of the Area Under the receiver operator characteristic Curve (AUC) that demonstrates a good level of forecasting ability.

Keywords: weathered gneiss, shallow landslides, susceptibility, TRIGRS

### INTRODUCTION

Rainfall-induced shallow landslides are common on steep natural hillslopes mantled with a layer of colluvium or residual soil (Salciarini et al., 2006). They may evolve in flow-like landslides, presenting high velocities, and can cause loss of human life and severe socio-economic disasters (Hungar et al., 2014).

In weathered crystalline rocks, these phenomena present failure surfaces generally located along the contact between residual or colluvium soils and relatively less weathered rock. Due to their heterogeneity and the difficulty of undisturbed sampling, the geotechnical characterization is highly complex, and, as a consequence, experimental studies on naturally weathered rocks are limited (Gullà et al., 2005, 2006; Mandaglio et al., 2016a). In this context, shallow landslide susceptibility assessment in weathered rocks over large areas is also extremely complex. A preliminary susceptibility assessment of these phenomena can be carried out using the few available data and the data provided by scientific literature on soils similar for genesis and weathering grade. The relevance of shallow landslide consequences makes the susceptibility assessment fundamental, especially for the design of risk mitigation measures (Borrelli et al., 2018; Mandaglio et al. 2015, 2016b; Giofrè et al. 2017).

The best known definition of landslide susceptibility was proposed by Brabb (1984) who, starting from the principle that the past and present are keys to the future (Varnes, 1984), underlined the forecasting ability of susceptibility maps (Calvello et al., 2013). Later, Fell et al. (2008) defined landslide susceptibility as a quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of existing and potential landslides in a study area. This goal can be pursued by applying different zoning methods available in scientific literature. Soeters and van Westen (1996) classified these methods as heuristic, statistical and deterministic. Heuristic methods, able to process essentially topographic and geological input data, are considered basic methods for both analysing existing, and forecasting potential landslides (Cascini, 2008). When further details on input data are added and procedures based on statistical analysis are used, the methods are considered intermediate (Cascini, 2008). Finally, deterministic methods need hydrogeological and geotechnical data and are considered advanced methods (Cascini et al., 2008). According to these considerations, using advanced methods such as a physically-based model, able to reproduce the physical processes governing landslide triggering (e.g. Sorbino et al. 2010; Ciurleo et al. 2017; Moraci et al. 2017), the landslide susceptibility zoning of an area can be obtained.

One of the most widely used physically based models is the Transient Rainfall Infiltration and Grid-based Slope-Stability model TRIGRS (Baum et al. 2002; Savage et al. 2004). This model relies on the combination of an infiltration model, for pore water pressure analysis, with an infinite slope stability model for the computation of the Safety Factor (e.g., Baum et al. 2005; Montrasio et al. 2011; Salciarini et al., 2017). Despite the ability of the model to analyse shallow landslide

triggering over broad areas, it requires representative, spatially distributed geotechnical properties of soils; a correct initial water table location; soil thickness; topographic, geological and rainfall data.

The paper aims to assess the susceptibility of shallow landslide source areas in weathered gneiss by TRIGRS. The method is tested on a large scale (1:5000) in a study area located in southern Italy, periodically affected by shallow landslides, some of which evolve into debris flows. The paper preliminarily focuses on the identification of geotechnical and hydraulic properties of soils affected by shallow landslides thus allowing the identification of the input data. To carry this out, all the available geotechnical and geological information on weathered gneiss outcropping on the study area, and the data available in the surrounding zones or in other geographical contexts – characterised by soils similar from a geological and a geotechnical point of view – were summarised and used as input data for TRIGRS. Finally, several parametric analyses were performed by TRIGRS thus obtaining several susceptibility maps which are then compared and critically analysed in order to identify the best map.

## 2. STUDY AREA AND GEOTECHNICAL DATABASE

The study area (Fig. 1) is located between Bagnara Calabria and Scilla, along the SW coast of the Calabria region (Southern Italy). It is strictly linked to the geological context of the Messina Strait (Ferranti et al., 2008) and falls within the southern border of the Calabrian–Peloritani arc.

The study area, about 1 km<sup>2</sup>, is bordered at the top (630 m a.s.l.) by a flat surface of marine origin (Piano delle Aquile), and at the bottom (0 m a.s.l.) from a densely urbanized coastal plain, where the village of Favazzina is located (Fig. 2). The slopes are crossed by the A3 (SA-RC) highway, the railway and the SR 18 southern Tyrrhenian state road (Fig. 2). The slopes are characterised by a Paleozoic basement, made up of high-grade metamorphic rocks (para and ortho-gneiss), overlapped by Upper Pliocene to Holocene sedimentary deposits (Borrelli et al. 2012; Giofrè et al. 2016).

The Paleozoic crystalline basement shows intense and deeply weathered conditions (Fig. 2). Particularly, residual, colluvial and detrital soils (Class VI), classified according to Geotechnical Control Office (GCO, 1988), cover about 60% of the study area (e.g., Borrelli et al. 2012, 2014, 2015). Completely weathered rocks (Class V), classified according to GCO (1988), prevail in the upper portion of the slope, while highly and moderately weathered rocks classified according to GCO (1988) (respectively, Classes IV and III) crop out in the middle-lower portions of the slope.

The study area has been frequently affected by shallow landslides of flow type and, particularly in the last decade, shallow landslides have been triggered on class VI and during the run-out phase, severely affecting the urbanized area and transportation infrastructures located along the coastal plain (Fig. 2).

Among these, the most insidious phenomena occurred in 2001 and 2005. The first took place on 12<sup>th</sup> May 2001 and involved the methane pipeline, while the second occurred on the 31<sup>th</sup> of March 2005 on the slope overlooking the village of Favazzina (Fig. 2).

In both cases, these phenomena can be classified as very rapid to extremely rapid debris flows. They struck Favazzina, the SNAM (European gas utility public company) station of the methane pipeline, the SA-RC highway, the SR 18 state road, and the railway causing the derailment of the intercity trains Turin-Reggio Calabria (2001 event) and Reggio Calabria-Milan (2005 event).

These phenomena initially began as translational landslides located in the head of the channels, immediately below the secondary road, and affected the residual soils (Class VI) with a slip surface located at a depth generally less than 2 metres.

Data provided by Antronico et al. (2006) on the weathered gneiss of Class VI of Favazzina slopes were collected and combined with new in situ investigations and laboratory tests carried out in the study area. The overall available information consisted of: the stratigraphic conditions of the source areas; the grain size distribution, physical properties of soils and the mechanical properties of weathered gneiss in saturated conditions.

Referring to stratigraphic conditions, some information about the thickness of class VI was provided by three seismic refraction prospects and six continuous drilling boreholes (Fig. 3).

The in situ investigations showed the spatial variability of weathered soils thicknesses (Class VI) ranging from 1.4 m to 4.6 m depth (Fig. 3). Particularly, in the upper part of the slope (where shallow landslide source areas were located), the thickness of class VI assumes a value ranging from 1.5 m (Fig. 3, S2) to 2.0 m (Fig. 3, S1) while its value ranges from 1.4 m to 4.6 m, in the middle portion of the slope (Fig. 3, S3, S4, S5, S6). These values have been confirmed by seismic refraction prospects (ST1, ST2 and ST3) that show an average value of thickness ranging from 2 m to 5 m (Fig. 3).

In the study area, soils of class VI can be classified as silty sand (SM) with the following fractions; sand = 50.58%, gravel = 27.26%, silt = 19.05% and clay = 3.11% and as inorganic silt of medium compressibility with sand (ML) with fractions of Sand = 30 %, Silt = 45%, Clay = 25%, according to the Unified Soil Classification System (USCS). The plastic index and liquid limit of the sampled soil are 9.23 % and 33.27%, respectively. Regarding the physical properties of class VI, the natural unit weight values ( $\gamma$ ) range from 15 kN/m<sup>3</sup> to 20 kN/m<sup>3</sup>; the saturated unit weight ( $\gamma_{\text{sat}}$ ) varies from 19 kN/m<sup>3</sup> to 22 kN/m<sup>3</sup>; the dry unit weight ( $\gamma_d$ ) ranges between 12.5 kN/m<sup>3</sup> and 16 kN/m<sup>3</sup>; the void ratio ( $e$ ) is variable from a minimum of 0.65 to a maximum of 1.15; the values of soil porosity ( $n$ ) vary from 0.4 to 0.54 and the degree of saturation ( $S$ ) from 43% to 99% (Antronico et al. 2006).

The results of direct and triaxial shear tests carried out on these soils have shown that the shear strength envelope ranges from an upper limit, with a cohesion value of 0 kPa and a shear strength angle of 44°, to a lower limit characterized by a cohesion value of 0 kPa and a shear strength angle of 38°.

For rainfall data, the only available information can be gathered by the Scilla rain gauge of the Centro Funzionale Multirischi—ARPACAL (Calabria Region) (cod. 2510 — located near the study area), with reference to two shallow landslide triggering dates, 12 May 2001 and 31 March 2005. The rainfall data were, respectively, equal to 20 mm over two consecutive days on 12 May 2001 and 13.6 mm over two consecutive days on 31 March 2005.

### 3. METHODOLOGY

The methodology used for the susceptibility assessment of shallow landslide source areas in weathered gneiss can be divided into two stages. The first stage (stage I) is used for data base creation in order to identify the values of the input parameters to be applied in the second stage. The second stage (stage II) consists in the calibration of the physically based TRIGRS model for a preliminary assessment of the susceptibility to shallow landslide source areas.

Stage I was carried out by collecting all the available information on the soils affected by shallow landslides in the study area, i.e. weathered gneiss of class VI.

Since few in-situ investigations and laboratory tests are available for the soils of class VI of the studied area, a geotechnical data base was created combining the data provided by scientific literature on soils similar, for genesis and stress history, to those of the studied area with available data.

The main goals of this stage were to: i) identify and sum up ranges of variation of the main geotechnical properties of gneiss of class VI; ii) identify the thickness of class VI; and iii) localize the initial pore water pressure conditions.

In stage II, shallow landslide susceptibility maps by means of TRIGRS were obtained by varying the geotechnical input data in the ranges previously identified.

TRIGRS is a physically-based model widely used for computing the triggering areas of rainfall induced shallow landslides in different geo-environmental contexts (Godt et al. 2008; Schilirò et al. 2015; Sorbino et al. 2010). TRIGRS couples an infiltration model with an infinite slope stability model. The infiltration model in TRIGRS is based on the use of the linearized solution of the Richards equation proposed by Iverson (2000) and extended by Baum et al. (2002) to the case of an impermeable bedrock located at a finite depth.

TRIGRS predicts the pore-water pressure regime in saturated conditions using the following input parameters: slope, soil cover depth, depth of the initial steady-state water table, the steady (initial) surface flow and saturated hydraulic conductivity (Ks).

The original TRIGRS code, as developed by Baum et al. (2002) for fully saturated conditions, was later extended by Baum et al. (2008) to unsaturated soils (Salciarini et al., 2017). TRIGRS predicts pore-water pressure regime in unsaturated/saturated conditions, coupling the simple analytic solution for transient unsaturated infiltration proposed by Srivastava and Yeh (1991) to the original TRIGRS equation (Baum et al. 2008; Savage et al. 2004). This model is based on the fitting equation of soil water characteristic curve proposed by Gardner (1958) depending on four hydraulic parameters: saturated soil water content ( $\theta_s$ ), residual soil water content ( $\theta_r$ ), saturated hydraulic conductivity (Ks) and the Gardner parameter ( $\alpha$ ). The infiltrating water accumulates at the base of the unsaturated zone and then rises to the ground surface.

In both cases, the model approximates the infiltration process as a one-dimensional vertical flow and the obtained results are highly sensitive to the initial seepage condition.

The stability of an individual grid cell is analyzed by the one-dimensional infinite-slope model proposed by Taylor (1948) for the calculation of the safety factor in the unsaturated configuration, as follows:

$$F_s(Z, t) = \frac{\tan\phi'}{\tan\delta} + \frac{c' - \Psi(Z, t)\gamma_w \tan\phi'}{\gamma_s Z \sin\delta \cos\delta} \quad (1)$$

where:

$c'$  is soil cohesion for effective stress,  $\phi'$  is soil shear strength angle for effective stress,  $\delta$  is slope gradient,  $\Psi(Z, t)$  is the ground water pressure head ( $\Psi = u/\gamma_w$ ), depending on  $Z$  (vertical coordinate direction) and  $t$  (time),  $\gamma_w$  is unit weight of groundwater,  $\gamma_s$  is soil unit weight.

To compute the safety factor above the water table, the matric suction,  $\Psi(Z, t)\gamma_w$ , is multiplied by  $\chi$ , Bishop's (1959) effective stress parameter. According to Vanapalli and Fredlund (2000),  $\chi$  can be approximated as:

$$\chi = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad (2)$$

where:

$\theta$  is the volumetric water content,  $\theta_r$  is the residual water content, and  $\theta_s$  is the water content at saturation.

This analysis allows the calculation of the safety factor in each cell of the domain in which the study area is discretized. Moreover, the analysis is sensitive to some of the required input data, such as hydraulic properties of soils, initial steady-state groundwater conditions and soil depths (Godt et al. 2008; Salciarini et al. 2006; Sorbino et al. 2007, 2010).

TRIGRS, combined with a geographic information system (GIS), allows us to distinguish unstable ( $FS \leq 1$ ) from stable cells ( $FS > 1$ ).

In order to quantify TRIGRS results, in both saturated and unsaturated conditions, and to evaluate the performance of the model in the forecasting of shallow landslide source areas, the error index (EI) was used (Fig. 4). EI is defined, as follows:

$$EI (\%) = \frac{A_{TL} - A_{UTL}}{A_{TL}} = \frac{\sum Cells_{TL} - (\sum Cells_{TL} \cap \sum Cells_{FS \leq 1})}{\sum Cells_{TL}} \quad (3)$$

Where  $A_{TL}$  are the landslide source areas according to the landslide inventory (observed source areas),  $A_{UTL}$  areas computed as unstable located within the  $A_{TL}$  (observed source areas),  $\sum Cells_{TL}$  summation of cells actually affected by landslide source areas according to the landslide inventory,  $\sum Cells_{FS \leq 1}$  summation of cells computed as unstable by the model.

EI is the complementary of the true positive fraction of the model (TPF), also called *sensitivity*.

In order to evaluate the model forecasting capacity, the forecasting index (FI) was used (Fig. 4). FI is defined, as follows:

$$FI (\%) = \frac{A_{UN} - A_{UTL}}{A_{ST}} = \frac{\sum Cells_{FS \leq 1} - (\sum Cells_{TL} \cap \sum Cells_{FS \leq 1})}{\sum Cells_{ST}} \quad (4)$$

where:  $A_{UN}$  areas computed as unstable,  $A_{ST}$  the area of the basin not affected by triggering phenomena,  $\sum Cells_{ST}$  summation of cells not affected by landslides according to the landslide inventory.

Herein FI is considered a forecasting index in order to define the areas potentially affected by landsliding but unaffected by shallow landslide source areas until now. The equation 4 was originally defined “*false positive proportion/fraction (FPF or 1-Specificity)*” by Metz (1978) and Swets (1988), and actually used in statistical studies by several authors (e.g., Calvello et al., 2013; Fressard et al., 2014; Calvello and Ciurleo 2016; Ciurleo et al. 2016).

#### 4. ANALYSES OF THE RESULTS

Tables 1 and 2 summarize the geotechnical and hydraulic properties of class VI weathered gneiss. In particular, the saturated unit weight values ( $\gamma_s$ ) range from 19.22 kN/m<sup>3</sup> to 21.98 kN/m<sup>3</sup>; the cohesion value ranges from 0 kPa to 5 kPa and the shear strength angle from 30° to 44°, Table 1.

Regarding hydraulic properties, due to the lack of data for the study area, the values proposed by Gullà and Sorbino (1994); Cascini et al. (2006); Calvello et al. (2008) and Schilirò et al. (2015), obtained from laboratory (Richards pressure plate) and in situ tests (permeability tests) performed on gneiss similar for genesis and weathering grade (Class VI), were used in this study (Tab. 2). In particular, Gullà and Sorbino (1994), Calvello et al. (2008) and Cascini et al. (2006) identified for gneiss of class VI of the Unit of Sila (Calabria) saturated permeability values ( $K_s$ ) ranging from 1.27E-06 m/s to 3.50E-05 m/s; and Schilirò et al. (2015) identified, for gneiss of class VI of the Unity of Aspromonte (Sicily), saturated permeability values varying from 7.91E-06 m/s to 6.60E-05 m/s, the same authors also provided indications on the values of saturated volumetric water content  $\theta_s$ , ranging from 0.38 to 0.39, and of saturated hydraulic diffusivity coefficient  $D_0 = 1.55E-04$  m<sup>2</sup>/s – 3.84E-04 m<sup>2</sup>/s.

Regarding the initial pore water pressure condition, general information was provided by investigations and studies developed in weathered gneiss by Gullà and Sorbino (1996). The authors showed that at a depth of 1.45 m, the tensiometer measurements had values close to 0 in the months between February and May 1994 where shallow landslides of flow type occurred.

Referring to rainfall data, it was decided to consider the most intensive rainfall event - equal to 20 mm over two consecutive days on 12 May 2001 - in order to simulate the most critical conditions.

The overall data collected in stage I were used as input parameters of TRIGRS in stage II.

Other input data employed within TRIGRS are the following: digital elevation model (DEM), flow direction, cover depth, initial water table location. The spatial data are expressed in raster format using 5×5 m<sup>2</sup> square grid cells, and flow direction was directly derived by DEM.

Considering the presence of a thin layer of class VI over the parent material, a finite depth for the impermeable basal boundary was assumed. In this regard, a constant soil thickness equal to 1.5 m was considered. This assumption errs on the side of caution and is coherent with borehole logs S1 and S2 (Fig. 3) that underline a thickness of soil of class VI ranging from 1.5 m (S2) to 2.0 m (S1) in the upper part of the slopes where shallow landslides triggered in 2001. Furthermore, within the source areas of the shallow landslides triggered on 12 May 2001 and 31 March 2005, the geomorphological evidence shows 1.5 m slip surfaces located at the contact between the soil of class VI and the underlying bedrock.

With reference to the initial water table, different locations depending on the different cases of analysis were taken into consideration. The first was implemented locating the water table at the contact between the class VI and the parent rock in the whole study area. This assumption is coherent with the data provided by Gullà and Sorbino (1996) and summarized above. The second was implemented considering the influence of the secondary road in the upper part of the basin in the 2001 shallow landslides. To do this, a buffer zone constituted by three contour lines, each equal to 5 m, below the

secondary road and two different locations of the water table, respectively at 0 m and 0.5 m from the ground surface, were considered (Fig. 5).

The study area was analyzed by TRIGRS and parametric analyses were performed (Table 3) according to 36 different cases in saturated and unsaturated conditions. Table 3 summarizes the parameters used for the modelling, the first column reports a progressive identification number and the letter S, indicative of total saturation condition, or U for unsaturated conditions.

In all cases, a constant value of soil thickness equal to 1.5 m of depth from the ground surface, the average value of hydraulic data, an initial steady state water table located at the bedrock–soil interface, in the whole study area, except in the road buffer zone (zone “A” in Fig. 5) was assumed. In zone “A”, parametric analyses that consider a depth of water table located at 1.5 m, 0.5 m and 0 m from the ground surface were carried out in order to simulate the influence of the road on shallow landslide triggering. It is worth mentioning that in the cases where the water table in “zone A” is assumed equal to 0 m, TRIGRS in unsaturated conditions works equally to TRIGRS (i.e. the safety factor was evaluated considering  $\Psi = 0$  at the ground surface and  $\chi$  Bishop’s (1959) = 1). On the contrary, in the remaining study area (zone B, Figure 5) unsaturated TRIGRS considers different values of  $\Psi$  and  $\chi$  depending on the soil water content curves.

Finally, the saturated hydraulic diffusivity ( $D_0$ ) was calculated according to Grelle et al. (2014) and Schilirò et al. (2015) using the formula below:

$$D_0 = \frac{K_s H}{S_y} \quad (5)$$

where  $K_s$  is the saturated hydraulic conductivity,  $H$  the average soil thickness (assumed constant and equal to 1.5 m for the whole study area) and  $S_y$  the specific yield that can be assumed equal to 0.34 for the analyzed soils according to Johnson (1967), Loheide II et al. (2005) and Schilirò et al. (2015).  $H$  is considered equal to 1.5 m in coherence with the above-mentioned borehole logs and the constant soil thickness under study.

In particular, several parametric analyses in saturated and unsaturated conditions were performed using different combinations of shear strength data and locations of water table in the buffer zone, cases S and U in table 3.

For both saturated and unsaturated conditions, all cases were implemented considering the average values of hydraulic parameters. Particularly, in saturated condition,  $K_s=1.79E-05$  m/s,  $D_0=7.92E-05$  m<sup>2</sup>/s and  $\theta_s=0.39$  were assumed; in unsaturated condition, the same hydraulic parameters as saturated plus residual volumetric water content  $\theta_r=0.042$  and the parameter  $\alpha=11.7$  were considered in order to approximate the soil-water characteristic curve for wetting the unsaturated soil (Gardner, 1958).

With reference to shallow landslide inventory, it is worth highlighting that the multi-temporal shallow landslide map used for the evaluation of the performance of TRIGRS analyses was obtained by combining the information provided by Giofrè et al. 2016 (dated 2001 and 2005) with landslide inventories provided by the Calabria region (dated 2001 and 2016) and the sliding scarps identified by Bonavina et al. (2005) and Moraci et al. (2017).

Regarding the official landslide inventories of the Calabria region, in the inventory only phenomena classified as debris flows or complex shallow phenomena were considered, and the sliding scarps were transformed into circles starting from crowns, in GIS environment.

Tables 4 and 5 report a summary of obtained results, listed in crescent order of EI, and the values assumed by the two statistics true positive fraction (TPF) and forecasting index (FI).

In saturated conditions (table 4); TPF values range from 94.1% (Cases 17S and 15S) to 52.9% (case 1S) and FI ranges from 31.4% (Cases 17S and 15S) to 13% (case 1S). The values assumed by TPF are complementary to EI, while the values assumed by FI indicate that an area going from 31.4% to 13% (depending on cases of analysis), at present not affected by shallow landslides (following the available landslide inventory), might be susceptible to shallow landslide triggering in the future. In unsaturated conditions (table 5), the values of FI range from 26.5% (Case 17U) to 6.2% (Case 1U) showing the capability of TRIGRS to take into account the effect of suction on slope stability (reducing the areas considered susceptible to shallow landslides).

The overall parametric analyses were implemented considering: i) a constant value of soil thickness, equal to 1.5 m of depth from the ground surface; ii) the average value of hydraulic data; and iii) an initial steady state water table located at the bedrock–soil interface, in the whole study area, except in the road buffer zone (Zone A in figure 5). The best results, in terms of the smallest value of EI and the highest value of TPF, were obtained by the first group of analyses (cases 17, 15 and 13) in saturated as well as in unsaturated conditions. This group was carried out considering the average value of cohesion ( $c'=2.5$  kPa) and the minimum value of shear strength angle ( $\phi'=30^\circ$ ). The difference between the examined cases is due to the location of the initial water table in the road buffer zone (constituted by three contour lines, each equal to 5 m, from the secondary road) located at a depth of 0 m (case 17), 0.5 m (case 15) and 1.5 m (case 13), respectively. So doing, the first group of analyses shows values of  $EI < 8\%$  in saturated and  $EI < 13\%$  in unsaturated conditions.

In particular, cases 17S and 15S show  $EI=5.9\%$  and TPF values equal to 94.1%, thus proving the ability of the model to analyze more than 90% of the area affected by the phenomena which occurred from 2001 to 2016. FI values are, in both cases, equal to 31.4%, thus suggesting that 31.4 % of the study area, unaffected by landslides until now, could be susceptible to landslides in the future.

1 In unsaturated conditions, cases 17U and 15U show EI = 10.2% (case 17U) and EI=10.4% (case 15U), the TPF values  
2 are equal to 89.8% (case 17U) and 89.6% (case 15U). FI values change from 31.4% (in saturated condition) to 26.5% (in  
3 unsaturated condition), showing that 26.5 % of the study area could be susceptible to landslides in the future.

4 Case 13 in tables 4 and 5 shows values of EI ranging from 7.6% (in saturated condition) to 12.4 (unsaturated), TPF values  
5 are 92.4% (saturated) and 87.6% (unsaturated) and FI changes from 31.2% (saturated) to 26.3% (unsaturated).

6 The second group of analyses (cases 12S, 8S and 4S) (Tab. 4) was carried out considering saturated conditions, the  
7 minimum value of cohesion ( $c'=0$  kPa) and the average value of shear strength angle ( $\phi'=38^\circ$ ). The results show values  
8 of EI ranging from 11.5% to 13.8%. These values are higher than those obtained from the previously described cases  
9 (17S, 15S and 13S) but are lower than 15% thus proving the ability of the analyses to predict more than 85% of unstable  
10 areas, as reported by TPF results equal to 88.5% (case 12S), 88.3% (case 8S) and 86.2% (case 4S). In unsaturated  
11 conditions, cases 12U, 8U and 4U (Tab. 5) show values of EI ranging from 20.0% to 22.6%, far higher than those obtained  
12 from cases 17U and 15U.

13 The poorest analyses were in Cases 9, 5 and 1, carried out considering the average value of cohesion and shear strength  
14 angle ( $c'=2.5$  kPa,  $\phi'=38^\circ$ ). In saturated conditions, these results show values of EI equal to 43.6% (case 9S), 44.7% (case  
15 5S) and 47.1% (case 1S). In unsaturated conditions, EI values become 68.6% (case 9U), 70.1% (case 5U) and 73.9%  
16 (case 1U). These EI values are higher than those obtained for cases 17, 15 and 13 (both in saturated and unsaturated  
17 conditions).

18 The comparison of results shows that  $A_{UTL}$ , areas computed as unstable located within the  $A_{TL}$  (observed source areas),  
19 assumes, in saturated conditions, values greater than those obtained in unsaturated. Thus, EI (equation 3) decreases and,  
20 as a result, TPF increases.

21 In unsaturated conditions, for cases 10U, 6U, 2U, 9U, 5U, 1U implemented considering cohesion values equal to 2 kPa  
22 and 2.5 kPa and shear strength angle equal to  $38^\circ$ , TPF becomes less than 40% and EI is always equal or higher than 60%  
23 (Fig. 6c, d). However, for this study, it was decided that error index values above 20% (and then TPF > 80%) cannot be  
24 accepted because a well-calibrated susceptibility map should be capable of predicting at least 80% of the observed  
25 landslides. This value is far higher than the threshold of TPF=50% proposed by Fressard et al. (2014).

26 Focusing on the results obtained in saturated conditions, it is worth highlighting that cases 13S ( $c'=2.5$  kPa and  $\phi'=30^\circ$ )  
27 and 4S ( $c'=0$  kPa and  $\phi'=38^\circ$ ), implemented considering a water table located at a depth of 1.5 m from the ground surface,  
28 only partially analyze the landslides of 12th May 2001 (Fig. 7a). On the contrary, cases 17S and 12S, implemented  
29 considering the same geotechnical properties but a water table located at 0 m from the ground surface, can analyze the  
30 two landslide triggerings which took place on 2001 (Fig. 7b).

31 Therefore, Fig. 7 clearly highlights that if the water table located near the ground surface in the secondary road buffer  
32 zone (e.g., 0 m from the ground surface – case 17S and 12S, Fig. 7b) is not considered, one of the phenomena which  
33 occurred in 2001 cannot be analyzed by the model (Fig. 7a). This is due to the significant role played by the secondary  
34 road which, during the landslide event, channeled a greater quantity of water into the buffer zone, as already suggested  
35 by Antronico et al. (2006) and Bonavina et al. (2005).

36 According to principle that future landslides are likely to occur in the same geological, geomorphological and hydrological  
37 contexts that produced instability in the past up to the present, the map showing the lowest value of EI was considered  
38 the most representative susceptibility map for shallow landslides in the area (Fig. 8). Considering that two cases present  
39 the same value of EI, cases 17S and 15S, the overall accuracy of the best tests is evaluated by the ROC curves and the  
40 area under the ROC curves (AUC). ROC curves plot “sensitivity” on the Y axis versus “1-specificity” on the X axis (Metz  
41 1978; Swets 1988); an AUC of 1 represents a perfect test. According to Fressard et al. (2014), AUC values less than 0.7  
42 are indicative of a poor performance, values ranging from 0.7 to 0.8 represent a fair performance of the model, values  
43 between 0.8 and 0.9 reflect a good performance and over the threshold of 0.9, the predictive ability of the model can be  
44 considered excellent. In literature, few papers report AUC values higher than 0.80 (e.g., Schilirò et al. 2016; Ciurleo et  
45 al. 2017) for landslide susceptibility and hazard assessed by physically-based models. The obtained AUC values are  
46 86.32% (case 17S) and 86.16% (case 15S) thus demonstrating a good performance of the model.

47 Case 17S is considered the best map because it shows the lowest value of EI=5,9% and the highest value of AUC=86.32%  
48 (Fig. 8). It was obtained using: i) the average value of cohesion and the minimum value of shear strength angle, ii) the  
49 average value of hydraulic parameters and iii) a water table located at 0 m from the ground surface in the secondary road  
50 buffer zone and 1.5 m from the ground surface in the remaining study area.

51 Regarding the obtained FI value (31.4%) for case 17S, it is noted that 31.4% of the study area is susceptible to shallow  
52 landslide triggering events in the future.

## 54 5. CONCLUDING REMARKS

55 The obtained results show the ability of TRIGRS to predict shallow landslide source areas especially when few  
56 geotechnical input data are available. For the analyzed case study and on the basis of the available input data, the  
57 examination of saturated and unsaturated results shows that the saturated results seem to be more coherent with the  
58 shallow landslide source areas which occurred on the Favazzina slopes. Indeed, values of AUC higher than 80%  
59 demonstrate the good forecasting ability of the obtained shallow landslide susceptibility map. This result could be further  
60 improved with detailed in situ investigation and laboratory tests. These in-depth analyses will allow us to better  
61

1 characterize the mechanical and hydraulic properties of weathered gneiss, especially in unsaturated conditions, thus  
2 defining a more detailed geotechnical model of slopes. Once a detailed geotechnical slope model has been formulated,  
3 the ability of TRIGRS to take into account both the transient pore-water pressure regime and the unsaturated conditions  
4 (Savage et al. 2004; Baum et al. 2008) characterizing different soils should be tested in the study area in order to obtain  
5 more significant results.

6 The landslide susceptibility map can be considered a preliminary quantitative map which can select more limited zones  
7 where the above-mentioned in situ investigations and laboratory tests should be carried out in order to then rigorously  
8 characterize shallow landslide source areas (especially in terms of volume) and use the physically-based models correctly  
9 for the analysis of the propagation phase. This could provide a quantitative assessment of debris flow susceptibility and  
10 hazard to design the most appropriate countermeasures.

## 11 **Acknowledgments**

12 All authors have contributed in equally to the development of the research and to the extension of memory.

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## **LANDSLIDE SUSCEPTIBILITY ASSESSMENT BY TRIGRS IN A FREQUENTLY AFFECTED SHALLOW INSTABILITY AREA**

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Dear Editor,

the authors greatly appreciated the Editor and Reviewers' work and would like to thank you for the time you have devoted to reading and evaluating the manuscript.

According to your suggestions, a grammar and technical English checking process has been carried out and the aim of the paper has been reformulated.

The current version of the manuscript is now focused on the ability of a physically based model (TRIGRS) to simulate and forecast shallow landslide source areas. To this purpose, TRIGRS has been tested and calibrated, at large scale (1:5000), over an area in southern Italy affected by widespread shallow landslides that can evolve into debris flows. The obtained results highlight the ability of a skilled application of TRIGRS to assess the susceptibility of shallow landslide source areas in weathered gneiss when few geotechnical input data are available.

Kind regards

Nicola Moraci

<b>General comments for the Editor</b>	<b>Author's Answers</b>
<p>Title</p> <p>it is too broad. It should be adjusted according to the method applied and the study area.</p>	<p>According to your suggestion, the title has been changed.</p>
<p>Abstract</p> <p>it should be improved. Try to be more concise and straight to the point. And finally, there is not any remarkable conclusion at the end.</p>	<p>According to your suggestion, the abstract has been significantly improved.</p>
<p>Introduction</p> <p>It should be adjusted the structure. The research question is not clear and justified. The methodological approach described is very common in all this kind of studies. So, I think this is not the goal of the study. I propose to focus on the back analysis to establish the possible scenario that triggered the 2001 and 2005 landslides.</p>	<p>According to your suggestion, Introduction has been adjusted in the structure and the research question has been clarified. The goal of the study is the application of a physically based model (TRIGRS) to a study area (about 1 km<sup>2</sup>) frequently interested by shallow landslides to assess landslide susceptibility when few geotechnical data are available. Especially when few geotechnical data are available, TRIGRS must be calibrated through the comparison between the areas involved by landslides (landslide inventory map) and those computed as unstable by TRIGRS. According to principle that the past and present are keys to the future (Varnes, 1984), the future landslides are likely to occur in the same geological, geomorphological and hydrological processes that have led to instability in the past till the present. This means that after calibration, the map that better fit occurred landslides is able to forecast future landslides. In these conditions, the back analysis is not the goal of the paper but it is only used to calibrate the model.</p>
<p>Study area and geotechnical database</p> <p>References of the geomechanical database should be provided. And it is not clear for me, why to go 10 days ago of precipitation. There was no significant rainfall.</p>	<p>References of the geomechanical database have been added.</p> <p>According to your suggestion, the most intensive rainfall over two consecutive days (not 10) at 12 May 2001 has been considered.</p>

<p>Discussion and concluding remarks</p> <p>The whole discussion should be rewritten. It looks like a description of the results, and not a discussion properly. According to the content of the manuscript, the discussion should be focused on the use of TRIGRS for back analysis and try to understand the 2001 and 2005 triggering causes.</p>	<p>The whole discussion has been rewritten according to the goal of the manuscript and focusing on the application of TRIGRS (in saturated and unsaturated conditions) to assess susceptibility map of the case study. In particular, it has been highlighted that, when few geotechnical data are available, TRIGRS must be calibrated through the comparison between the areas involved by landslides (landslide inventory map) and those computed as unstable by TRIGRS. In these conditions, the back analysis of past events has been used to calibrate TRIGRS.</p>
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All the suggestions provided in the documentation attached to the decision letter have been carefully followed as shown in the document entitled "LASL-D-18-00281\_R1\_reply" where the answers to the comments are reported point by point.

[Click here to view linked References](#)SUSCEPTIBILITY ASSESSMENT OF SHALLOW LANDSLIDES BY A PHYSICALLY BASED APPROACH  11  
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Mariantonietta Ciarleo\*, Maria Clorinda Mandaglio\*, Nicola Moraci\*

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Corresponding author: Nicola Moraci (email: [nicola.moraci@unirc.it](mailto:nicola.moraci@unirc.it)). Department of Civil, Energy, Environment and Materials Engineering (DICEAM), Mediterranean University of Reggio Calabria, Reggio Calabria, Italy**ABSTRACT**

The present paper proposes a methodology based on two successive steps to simulate and forecast shallow landslides source areas especially when few geotechnical input data are available. The first step, aiming at collecting and combining the available geotechnical input data, ends with the identification of the main geotechnical properties of weathered soil covers. The second step is employed to assess the susceptibility of shallow landslide source areas using TRIGRS. Several parametric analyses have been carried out in an area of southern Italy using different combination of input data, and the results have been compared by the error index (EI) and the forecasting index (FI). EI is used in the choice of the best shallow landslide susceptibility map; FI is, herein, considered as a forecasting index instead of the "positive fraction". The best obtained map presents an Area Under the receiver operator characteristic Curve (AUC) of about 0.86 that can be considered satisfactory both in terms of location of triggering sources and forecasting of potentially unstable areas.

Keywords: weathered gneiss, shallow landslides, susceptibility, physically based approach

**INTRODUCTION**  3

Rainfall-induced shallow landslides are complex phenomena due to several mechanisms that can predispose triggering. They can evolve in flow-like landslides, presenting high velocities, and causing loss of human life and huge socio-economic disasters (Hungri et al., 2014).

In weathered crystalline rocks, these phenomena present failure surfaces located along the contact between residual soils and relatively less weathered rock. Due to the heterogeneity of these soils and the difficulty of undisturbed sample sampling, the geotechnical characterization is very complex, and as consequence experimental studies on naturally weathered rocks are limited (Gullà et al., 2005, 2006; Mandaglio et al. 2016a). When few geotechnical data are available, a preliminary analysis of these phenomena can be pursued using the data provided by scientific literature on soils similar for genesis and weathering grade. Moreover, the forecasting of shallow landslides in weathered soils over large area is extremely complex and the relevance of consequences makes landslide susceptibility assessment a fundamental issue especially for design of risk mitigation measures (Borrelli et al., 2018; Mandaglio et al. 2015, 2016b; Giofrè et al. 2017).

The landslide susceptibility assessment, intended as "a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in an area" can be performed by different methods, depending on scale of analysis and zoning purpose (Fell et al. 2008).

The choice of the most appropriate zoning method is linked to: landslide characteristics, expert judgment, quality and accuracy of available data (Fell et al. 2008; Ciarleo et al., 2016). An advanced level of zoning can be pursued by physically based models, able to reproduce the physical processes governing landslide triggering (e.g. Sorbino et al. 2010; Ciarleo et al. 2017; Moraci et al. 2017).

These models are based on the combination of an infiltration model, for pore water pressure analysis, with an infinite slope stability model for the computation of the Safety Factor (e.g., Baum et al. 2005; Montrasio et al. 2011; Salciarini et al., 2017). Despite the ability of these models to analyse shallow landslide triggering over broad areas, they need sufficient, spatially distributed geotechnical properties of soils, and a correct initial water table location. The results are sensitive also to topographic data and cover class, the rainfall data is also required.



















The paper aims to assess the susceptibility of shallow landslide source areas, in weathered gneiss, by means of physically based models. To pursue this aim, a methodological approach has been proposed and tested in a study area located in Southern Italy recurrently interested by shallow landslides, some of which evolve into debris flows. The approach consists of two stages: database creation (Stage I); shallow landslide susceptibility assessment (Stage II).

Stage I consists of collecting all the available geotechnical and geological information on residual soils outcropping on the study area, and combining them with the data eventually available in the surrounding zones or in other geographical contexts characterised by soils similar from a geological and a geotechnical point of view.

Stage II consists of the use of Transient Rainfall Infiltration and Gridbased Slope-Stability models TRIGRS (Baum et al. 2002) and TRIGRS unsaturated (Savage et al. 2004) able to pursue an advanced level of the susceptibility zoning to shallow landslide source areas at large scale (1:5000).

# Riepilogo dei commenti su LASL-D-18-00281\_R1\_reply.pdf

## Pagina: 7

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the title is to general. It should be adjusted considering the method applied and the local study area.
- R: Thanks, the title has been changed.
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This sentence related to EI and FI should be adjusted. It is not important to say in the abstract that FI was used instead of False positive fraction. I recommend to say something as "EI was used to assess the model performance and FI was considered to estimate the model forecasting capacity".
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the physically based models. Now the manuscript reads better.
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not all physical models use the Factor of safety. For example SHALSTAB.
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Commenti da pagina 7 continua a pagina successiva

[Click here to view linked References](#)SUSCEPTIBILITY ASSESSMENT OF SHALLOW LANDSLIDES BY A PHYSICALLY BASED APPROACH 

Mariantonietta Ciurleo\*, Maria Clorinda Mandaglio\*, Nicola Moraci\*

\*Department of Civil, Energy, Environmental and Materials Engineering, "Mediterranea" University of Reggio Calabria, Via Graziella - Loc. Feo di Vito - 89122 Reggio Calabria (RC)

Corresponding author: Nicola Moraci (email: [nicola.moraci@unirc.it](mailto:nicola.moraci@unirc.it)). Department of Civil, Energy, Environment and Materials Engineering (DICEAM), Mediterranean University of Reggio Calabria, Reggio Calabria, Italy**ABSTRACT**

The present paper proposes a methodology based on two successive steps to simulate and forecast shallow landslides source areas especially when few geotechnical input data are available. The first step, aiming at collecting and combining the available geotechnical input data, ends with the identification of the main geotechnical properties of weathered soil covers. The second step is employed to assess the susceptibility of shallow landslide source areas using TRIGRS. Several parametric analyses have been carried out in an area of southern Italy using different combination of input data, and the results have been compared by the error index (EI) and the forecasting index (FI). EI is used in the choice of the best shallow landslide susceptibility map; FI is, herein, considered as a forecasting index instead of "use positive fraction". The best obtained map presents an Area Under the receiver operator characteristic Curve (AUC) of about 0.86 that can be considered satisfactory both in terms of location of triggering sources and forecasting of potentially unstable areas.

Keywords: weathered gneiss, shallow landslides, susceptibility, physically based approach

**INTRODUCTION** 

Rainfall-induced shallow landslides are complex phenomena due to several mechanisms that can predispose triggering. They can evolve in flow-like landslides, presenting high velocities, and causing loss of human life and huge socio-economic disasters (Hungri et al., 2014).

In weathered crystalline rocks, these phenomena present failure surfaces located along the contact between residual soils and relatively less weathered rock. Due to the heterogeneity of these soils and the difficulty of undisturbed sample sampling, the geotechnical characterization is very complex, and as consequence experimental studies on naturally weathered rocks are limited (Gullà et al., 2005, 2006; Mandaglio et al. 2016a). When few geotechnical data are available, a preliminary analysis of these phenomena can be pursued using the data provided by scientific literature on soils similar for genesis and weathering grade. Moreover, the forecasting of shallow landslides in weathered soils over large area is extremely complex and the relevance of consequences makes landslide susceptibility assessment a fundamental issue especially for design of risk mitigation measures (Borrelli et al., 2018; Mandaglio et al. 2015, 2016b; Gioffrè et al. 2017).

The landslide susceptibility assessment, intended as "a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in an area" can be performed by different methods, depending on scale of analysis and zoning purpose (Fell et al. 2008).

The choice of the most appropriate zoning method is linked to: landslide characteristics, expert judgment, quality and accuracy of available data (Fell et al. 2008; Ciurleo et al., 2016). An advanced level of zoning can be pursued by physically based models, able to reproduce the physical processes governing landslide triggering (e.g. Sorbino et al. 2010; Ciurleo et al. 2017; Moraci et al. 2017).


These models rely on the combination of an infiltration model, for pore water pressure analysis, with an infinite slope stability model for the computation of the Safety Factor (e.g., Baum et al. 2005; Montrasio et al. 2011; Salciarini et al., 2017). Despite the ability of these models to analyse shallow landslide triggering over broad areas, they need sufficient, spatially distributed geotechnical properties of soils, and a correct initial water table location. The results are sensitive also to topographic data and cover thickness, the rainfall data is also required.

The paper aims to assess the susceptibility of shallow landslide source areas, in weathered gneiss, by means of physically based models. To pursue this aim, a methodological approach has been proposed and tested in a study area located in Southern Italy recurrently interested by shallow landslides, some of which evolve into debris flows. The approach consists of two stages: database creation (Stage I); shallow landslide susceptibility assessment (Stage II).


Stage I consists of collecting all the available geotechnical and geological information on residual soils outcropping on the study area, and combining them with the data eventually available in the surrounding zones or in other geographical contexts characterised by soils similar from a geological and a geotechnical point of view.

Stage II consists of the use of Transient Rainfall Infiltration and Gridbased Slope-Stability models TRIGRS (Baum et al. 2002) and TRIGRS unsaturated (Savage et al. 2004) able to pursue an advanced level of the susceptibility zoning to shallow landslide source areas at large scale (1:5000).


soil thickness?

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## 2. STUDY AREA AND GEOTECHNICAL DATABASE

1 The study area (Fig. 1) is located between Bagnara Calabria and Scilla, along the SW coast of the Calabria region  
2 (Southern Italy). It is strictly linked to the geological context of the Messina Strait (Ferranti et al., 2008) and it falls  
3 within the southern border of the Calabrian–Peloritani arc.

4 The study area, about 1 km<sup>2</sup>, is bordered at the top (630 m a.s.l.) by a flat surface of marine origin (Piano delle Aquile),  
5 and at the bottom (0 m a.s.l.) from a densely urbanized coastal plain, where the Favazzina village is located (Fig. 2).  
6 The slope is crossed by highway A3 (SA-RC), railway and SR 18 southern Tyrrhenian state road (Fig. 2).

7 The slope is characterised by a Paleozoic basement, constituted of high-grade metamorphic rocks (para and ortho-  
8 gneiss), overlapped by Upper Pliocene to Holocene sedimentary deposits (Borrelli et al. 2012; Giofrè et al. 2016).

9 The Paleozoic crystalline basement shows intense and deeply weathered conditions (Fig. 2). Particularly, residual,  
10 colluvial and detrital soils (Class VI) classified according to Geotechnical Control Office (GCO, 1988), which cover  
11 about 60% of the study area and represent the main predisposing factor for shallow landslide susceptibility, are  
12 widespread on the slope (e.g., Borrelli et al. 2012, 2014, 2015). Completely weathered rocks (Class V), classified  
13 according to GCO (1988), prevail in the upper portion of the slope, while highly and moderately weathered rocks  
14 classified according to GCO (1988) (respectively, Classes IV and III) crop out in the middle-lower portions of the slope.  
15 The study area has been frequently affected by shallow landslides of flow type and, particularly in the last decade, some  
16 shallow landslides severely affected the urbanized area and transportation infrastructures located along the coastal plain  
17 (Fig. 2).

18 Among these, the most incisive phenomena are dated 2001 and 2005. The first one occurred on the 12<sup>th</sup> of May 2001  
19 and involved the SNAM methane pipeline, and the second one occurred on the 31<sup>th</sup> of March 2005 on the slope  
20 overlooking the Favazzina village (Fig. 2).

21 In both cases, these phenomena can be classified as very rapid to extremely rapid debris flows. They hit the Favazzina  
22 village, the SNAM station of the methane pipeline, the highway SA-RC, the state road SR 18, and the railway causing  
23 the derailment of the intercity trains Turin-Reggio Calabria (2001 event) and Reggio Calabria-Milan (2005 event).

24 These phenomena initially started as translational landslides located in the head of the channels, immediately below the  
25 secondary road, and affected the residual soil covers (Class VI) with a slip surface located at a depth generally less than  
26 2 metres. In order to analyse and forecast shallow landslide source areas by means of geotechnical models, all the  
27 geotechnical data provided by several authors on weathered gneiss (Class VI) were collected and new in situ  
28 investigations and laboratory tests were carried out. Overall available information consisted on: the stratigraphic  
29 conditions of the source areas; the grain size distribution and index properties of covers. The mechanical properties  
30 of weathered gneiss in saturated conditions.

31 Referring to stratigraphic conditions, some information about the thickness of class VI has been provided by three  
32 seismic refraction prospects and six continuous drilling boreholes (Fig. 3).

33 These in situ investigations showed the spatial variability of covering thicknesses (Class VI) ranging from 1.4 m to 4.6  
34 m depth (Fig. 3). Particularly, in the upper part of the slope (where shallow landslide source areas were located), the  
35 thickness of class VI assumes a value ranging from 1.5 m (Fig. 3, S2) to 2.0 m (Fig. 3, S1) while its value ranges from  
36 1.4 m to 4.6 m, in the middle portion of the slope (Fig. 3, S3, S4, S5, S6). These values have been confirmed by seismic  
37 refraction prospects (ST1, ST2 and ST3) that show an average value of cover thickness ranging from 2 m to 5 m (Fig.  
38 3).

39 In the study area, soils of class VI can be classified as silty sand (SM) with the following fractions of sand = 50.58%,  
40 gravel = 27.26%, silt = 19.05% and clay = 3.11% and as inorganic silt of medium compressibility with sand (ML) with  
41 the following fractions of Sand = 30 %, Silt = 45%, Clay = 25% according to the Unified Soil Classification System  
42 (USCS). The plastic index and liquid limit of the sampled soil are 9.23 % and 33.27%, respectively. Referring to index  
43 properties of class VI, the natural unit weight values ( $\gamma$ ) range from 15 kN/m<sup>3</sup> to 20 kN/m<sup>3</sup>; the saturated unit weight  
44 ( $\gamma_{\text{sat}}$ ) varies from 19 kN/m<sup>3</sup> to 22 kN/m<sup>3</sup>; the dry unit weight ( $\gamma_d$ ) ranges between 12.5 kN/m<sup>3</sup> and 16 kN/m<sup>3</sup>; the void  
45 ratio ( $e$ ) is variable from a minimum of 0.65 to a maximum of 1.15; the values assumed soil porosity ( $n$ ) vary from  
46 0.4 to 0.54 and the degree of saturation ( $S$ ) from 43% to 99% (Antronico et al. 2006).

47 For these soils the results of direct and triaxial shear tests show that the shear strength envelope ranges from an upper  
48 limit, with a cohesion value of 0 kPa and a shear strength angle of 44°, to a lower limit characterized by a cohesion  
49 value of 0 kPa and a shear strength angle of 38°.

50 Referring to rainfall data, the only available information can be gathered by the Scilla rain gauge of the Centro  
51 Funzionale Multirischi—ARPACAL (Calabria Region) (cod. 2510 — located near the study area), with reference to  
52 two shallow landslide triggering dates, 12 May 2001 and 31 March 2005. From the data analysis, it is evident that the  
53 rainfall accumulated for 10 days before the event ranged from 26.8 mm (2001 event) to 13.8 mm (2005 event), and the  
54 rainfall accumulated during the event was equal, on average, to 20 mm over two consecutive days at 12 May 2001 and  
55 13.6 mm at 31 March 2005, Fig.4.

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SNAM is the name of methan pipeline. Now the text reads: the SNAM (European gas utility public company) station of the methane pipeline
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### 3. METHODOLOGY

The methodology used herein for the susceptibility assessment of shallow landslide source areas in weathered gneiss covers can be divided in two stages. The first stage (stage I) consists of data base creation in order to identify the input parameters to be used in the second stage. The second stage (stage II) employed to assess the susceptibility of shallow landslide source areas using physically based models.

Stage I has been pursued by collecting and combining all the available information for shallow landslides in weathered gneiss of class VI with in-situ investigations and laboratory tests specifically carried out in the study area. The main aim of this stage has been to identify and sum up the main geotechnical properties of class VI by comparing the results of in situ investigations and laboratory tests with the data available by scientific literature.

Stage II has been able to produce shallow landslide susceptibility maps by means of physically based models (TRIGRS and TRIGRS unsaturated) in order to choose which model better forecast the phenomena. These models have been used varying the geotechnical input data, on the basis of the results deriving from the previous stage of analysis, with the aim to define different shallow landslide-triggering scenarios in the study area.

TRIGRS is a physically based model widely used for computing the triggering areas of rainfall induced shallow landslides in different geo-environmental contexts (Godt et al. 2008; Schilirò et al. 2015; Sorbino et al. 2010). TRIGRS couples an infiltration model with an infinite slope stability model. The infiltration model in TRIGRS is based on the use of the linearized solution of Richards equation proposed by Iverson (2000) and extended by Baum et al. (2002) to the case of an impermeable bedrock located at a finite depth. Iverson's solution consists of a steady component and a transient component. TRIGRS predicts pore-water pressure regime in saturated conditions using the following input parameters: slope, soil cover depth, depth of the initial steady-state water table, the steady (initial) surface flow and saturated hydraulic conductivity ( $K_s$ ).

TRIGRS unsaturated predicts pore-water pressure regime in unsaturated/saturated conditions, coupling the simple analytic solution for transient unsaturated infiltration proposed by Srivastava and Yeh (1991) to the original TRIGRS' equation (Baum et al. 2008; Savage et al. 2004). This model is based on the fitting equation of soil water characteristic curve proposed by Gardner (1958) depending on four hydraulic parameters: saturated soil water content ( $\theta_s$ ), residual soil water content ( $\theta_r$ ), saturated hydraulic conductivity ( $K_s$ ) and the Gardner's parameter ( $\alpha$ ). The infiltrating water accumulates at the base of unsaturated zone and then rises up to the ground surface.

In both cases, the model approximates the infiltration process as a one-dimensional vertical flow and the obtained results are very sensitive to the initial seepage condition.

The stability of an individual grid cell is analyzed by the one-dimensional infinite-slope model proposed by Taylor (1948) for the calculation of the safety factor in the saturated configuration, as follows:

$$F_s(Z, t) = \frac{\tan\phi'}{\tan\delta} + \frac{c' - \Psi(Z, t)\gamma_w \tan\phi'}{\gamma_s Z \sin\delta \cos\delta} \quad (1)$$

where:

$c'$  is soil cohesion for effective stress,  $\phi'$  is soil shear strength angle for effective stress,  $\delta$  is slope gradient,  $\Psi(Z, t)$  is the ground water pressure head ( $\Psi = u/\gamma_w$ ), depending on  $Z$  (vertical coordinate direction) and  $t$  (time),  $\gamma_w$  is unit weight of ground water,  $\gamma_s$  is soil unit weight.

To compute the factor of safety above the water table, the matric suction,  $\Psi(Z, t)\gamma_w$ , is multiplied by  $\chi$ , Bishop's (1959) effective stress parameter.

Therefore, the equation to evaluate the  $F_s$  becomes:

$$F_s(Z, t) = \frac{\tan\phi'}{\tan\delta} + \frac{c' - \chi\Psi(Z, t)\gamma_w \tan\phi'}{\gamma_s Z \sin\delta \cos\delta} \quad (2)$$

According to Vanapalli and Fredlund (2000),  $\chi$  can be approximated as:

$$\chi = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad (3)$$

where:

$\theta$  is the volumetric water content,  $\theta_r$  is the residual water content, and  $\theta_s$  is the water content at saturation.

This analysis allows the factor of safety in each cell of the domain in which the study area is discretized to be calculated. Moreover, the analysis is sensitive to some of the required input data such as hydraulic properties of soils, initial steady-state groundwater conditions and soil depths (Godt et al. 2008; Salciarini et al. 2006; Sorbino et al. 2007, 2010).

TRIGRS and TRIGRS unsaturated, combined with a geographic information system (GIS), allow us to distinguish unstable cells ( $FS \leq 1$ ) from those stable ( $FS > 1$ ).

In order to quantify TRIGRS and TRIGRS unsaturated results and evaluate their performance in the back-analysis and forecasting of shallow landslide source areas, the error index (EI) has been used combined with the forecasting index (FI) (Fig. 5). The error index is defined, as follows:

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why only this soil horizon?

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Because, in the study area, shallow landslides triggering sources affected only class VI. So we considered only this weathering class.

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It is not clear.

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now the paper reads better.

$$EI = \frac{A_{TL} - A_{UTL}}{A_{TL}} = \frac{\sum Cells_{TL} - (\sum Cells_{TL} \cap \sum Cells_{FS \leq 1})}{\sum Cells_{TL}} \quad (4)$$

Where  $A_{TL}$  are the landslide source areas according to the landslide inventory (observed source areas),  $A_{UTL}$  areas computed as unstable located within the  $A_{TL}$  (observed source areas),  $\sum Cells_{TL}$  summation of cells really affected by landslide source areas according to the landslide inventory,  $\sum Cells_{FS \leq 1}$  summation of cells computed as unstable by model. EI is the complementary of the true positive fraction of the model (TPF), also called *sensitivity*.

The forecasting index, FI, is defined as follows:

$$FI = \frac{A_{UN} - A_{UTL}}{A_{ST}} = \frac{\sum Cells_{FS \leq 1} - (\sum Cells_{TL} \cap \sum Cells_{FS \leq 1})}{\sum Cells_{ST}} \quad (5)$$

where:  $A_{UN}$  areas computed as unstable,  $A_{ST}$  the area of the basin not affected by triggering phenomena,  $\sum Cells_{ST}$  summation of cells not affected by landslides according to the landslide inventory.

Herein FI is considered as a forecasting index in order to define the areas potentially affected by landsliding but uninvolved by shallow landslide source areas until now. The equation 5 was originally defined “*false positive proportion/fraction (FPF or 1-Specificity)*” by Metz (1978) and Swets (1988), and actually used in statistical studies by several authors (e.g., Calvello et al., 2013; Fressard et al., 2014; Calvello and Ciarleo 2016; Ciarleo et al. 2016).

#### 4. ANALYSES AND RESULTS

Tables 1 and 2 report the geotechnical and hydraulic properties of class VI gneiss available for different contexts. Particularly, the saturated unit weight values ( $\gamma_s$ ) range from 19.22 kN/m<sup>3</sup> to 21.98 kN/m<sup>3</sup>; the cohesion value ranges from 0 kPa to 5 kPa and the shear strength angle from 30° to 44°, Table 1.

Regarding to hydraulic properties specific data for the study area were not available from scientific literature. To this purpose, the values proposed by Gullà and Sorbino (1994); Cascini et al. (2006); Calvello et al. (2008) and Schilirò et al. (2015), coming from laboratory tests (Richards pressure plate) and in situ tests (permeability tests) performed on gneiss similar for genesis and weathering grade (Class VI), were used in this study (Tab. 2). In particular, Gullà and Sorbino (1994), Calvello et al. (2008) and Cascini et al. (2006) identified for gneiss of class VI of the Unit of Sila (Calabria) saturated permeability values ( $K_s$ ) ranging from 1.27E-06 m/s to 3.50E-05 m/s; and Schilirò et al. (2015) identified, for gneiss of class VI of the Unity of Aspromonte (Sicily), saturated permeability values varying from 7.91E-06 m/s to 6.60E-05 m/s, the same authors provided indication also on the values of saturated volumetric water content  $\theta_s$ , ranging from 0.38 to 0.39, and of saturated hydraulic diffusivity coefficient  $D_0 = 1.55E-04 \text{ m}^2/\text{s} - 3.84E-04 \text{ m}^2/\text{s}$ .

Regarding the initial pore water pressure condition, general information has been provided by investigations and studies developed in weathered gneiss by Gullà and Sorbino (1996). The authors showed that at a depth of 1.45 m, the tensiometer measurements show values close to 0 in the months between February and May 1994 where shallow landslides of flow type occurred.

Referring to rainfall data, it has been decided to consider the most intensive rainfall event (10 days before the 2001 landslide triggering data as reported in Figure 4) in order to simulate the most critical condition.

The overall data collected in stage I were used as input parameters of TRIGRS in stage II.

The other input data employed within TRIGRS are the following: digital elevation model (DEM), flow direction, cover depth, initial water table location. The spatial data are expressed in raster format using 5×5 m<sup>2</sup> square grid cells, and flow direction has been directly derived by DEM.

Considering the presence of a thin layer of class VI over the parent material, it has been assumed a finite depth for the impermeable basal boundary. To this regard, we consider a constant soil thickness equal to 1.5 m. This assumption is on the safe side and it is coherent with borehole logs S1 and S2 (Fig. 3) that underline a thickness of class VI ranging from 1.5 m (S2) to 2.0 m (S1) in the upper part of the slope where shallow landslides dated 2001 triggered. Furthermore, within the source areas of the shallow landslides triggered on 12 May 2001 and 31 March 2005, the geomorphological evidence shows 1.5 m slip surfaces located at the contact between class VI and the underlying bedrock.

Referring to the initial water table, we consider different locations depending on the different cases of analysis. The first one has been implemented by considering the water table located at the contact between class VI and the parent rock in the whole study area that is coherent with the data provided by Gullà and Sorbino (1996) and summarized above; the second one has been implemented considering the influence of the secondary road in the upper part of the basin where shallow landslides dated 2001 triggered. To do this, we considered a buffer zone constituted by three contour lines, each one equal to 5 m, below the secondary road and two different locations of the water table respectively at 0 m and 0.5 m from the ground surface (Fig. 6).

The study area has been analyzed by TRIGRS and TRIGRS unsaturated and parametric analyses have been performed (Table 3) following 36 different cases in saturated and unsaturated conditions. Table 3 summarizes the parameters used for the modelling, the first column reports a progressive identification number followed by the letter S, indicative of total saturation condition (TRIGRS), or U for unsaturated conditions (TRIGRS unsaturated).

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Numero: 1 Autore: Oggetto: Sticky Note Data: 8/20/2018 4:04:54 PM  
Why do you change the previous name?

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because the term "false positive" could be associated to an error. On the contrary, for us it is an index used to forecast landslide occurrence.

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Numero: 2 Autore: Oggetto: Sticky Note Data: 8/21/2018 11:17:36 AM  
what do you mean by different contexts?

Autore: ciurl Oggetto: Nota Data: 8/6/2018 4:56:19 PM  
thanks, now the text reads "geographycal contexts"

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Numero: 3 Autore: Oggetto: Sticky Note Data: 8/6/2018 4:58:24 PM  
rephrase this sentence.

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Done.

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Numero: 4 Autore: Oggetto: Sticky Note Data: 8/20/2018 4:04:41 PM  
what do you mean by rainfall event? the 10 day accumulated rainfall?

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thanks for your suggestion. this part has been changed.

In all cases, we have assumed: i) a constant value of soil thickness equal to 1.5 m of depth from the ground surface; ii) the average value of hydraulic data ( $\theta_s$ ,  $\theta_r$ ,  $k_{sat}$ ); iii) an initial steady state water table located at the bedrock–soil interface, in the whole study area, except in the road buffer zone (zone “A” in Fig. 6). In the zone “A”, parametric analyses that consider a depth of water table located at 1.5 m, 0.5 m and 0 m from the ground surface have been carried out in order to simulate the influence of the road on shallow landslides triggering. It is worth highlighting that in the cases where the water table in the “zone A” is assumed equal to 0 m, TRIGRS unsaturated works equal to TRIGRS (i.e. the factor of safety was evaluated considering  $\Psi = 0$  at the ground surface and  $\chi$  Bishop’s (1959) = 1). On the contrary, in the remaining study area (zone B, Figure 6) TRIGRS unsaturated considers different values of  $\Psi$  and  $\chi$  depending on the soil water content curves.

Finally, the saturated hydraulic diffusivity ( $D_0$ ) has been calculated according to Grelle et al. (2014) and Schilirò et al. (2015) using the formula, as follows:

$$D_0 = \frac{K_s H}{S_y} \quad (6)$$

where  $K_s$  is the saturated hydraulic conductivity,  $H$  the average soil thickness (1.5 m) and  $S_y$  the specific yield that can be assumed equal to 0.34 for the analyzed soils according to Johnson (1967), Loheide II et al. (2005) and Schilirò et al. (2015).

Particularly, several parametric analyses in saturated and unsaturated conditions have been performed using different combination of shear strength data and location of water table in the buffer zone, cases S and U in table 3.

For both saturated and unsaturated conditions, all cases have been implemented considering the average values of hydraulic parameters. Particularly, in saturated condition, we assumed  $K_s=1.79E-05$  m/s,  $D_0=7.92E-05$  m<sup>2</sup>/s and  $\theta_s=0.39$ ; in unsaturated condition, we considered the same hydraulic parameters as saturated condition plus residual volumetric water content  $\theta_r=0.042$  and the parameter  $\alpha=11.7$  in order to approximate the soil-water characteristic curve for wetting of the unsaturated soil (Gardner, 1958).

With reference to shallow landslide inventory, it is worth highlighting that the multi-temporal shallow landslide map used for the evaluation of the performance of TRIGRS analyses, has been obtained by combining the information provided by Giofrè et al. 2016 (dated 2001 and 2005) with official landslide inventories of the Calabria region (dated 2001 and 2016) and the sliding scarps identified by Bonavina et al. (2005) and Moraci et al. (2017).

Referring to the official landslide inventories of the Calabria region, we considered in the inventory only phenomena classified as debris flows or complex shallow phenomena, and the sliding scarps were transformed in circles starting from crowns, in GIS environment.

The results obtained by TRIGRS (Figs. 7, 8) show values of Error Index (EI) ranging from 5.9% to 47.1%. The smallest value of EI equal to 5.9%, obtained for cases 15S and 17S, means that the associated susceptibility map is able of predicting more than 90% of the inventoried landslides. The highest computed value of EI=47.1%, obtained for case 1S, indicates that more than half of the observed landslides (52.9%) falls within cells computed by the model as susceptible. In both cases, these values are often greater than the threshold identified by Fressard et al. (2014) equal to 50%.

The maps obtained by TRIGRS unsaturated (Figs. 9, 10) show values of EI range from a 10.2% (for case 17U) to 73.9% (for case 1U). This latter value underlines the scarce ability of the map computed for the case 1U to back-analyze the landslide source areas observed in the study area.

Tables 4 and 5 report a summary of obtained results, organized in a crescent order of EI, and the values assumed by two statistics true positive fraction (TPF) and forecasting index (FI).

Table 4 shows TPF values ranging from 94.1% (Cases 17S and 15S) to 52.9% (case 1S) and a FI ranging from 31.4% (Cases 17S and 15S) to 13% (case 1S). The values assumed by TPF are complementary of EI, while the values assumed by FI indicate that an area going from 31.4% to 13% (depending on cases of analysis), at the present not affected by shallow landslides (following the available landslide inventory), could be susceptible to shallow landslides triggering in the future. The values of FI in table 5 range from 26.5% (Case 17U) to 6.2% (Case 1U) showing the model capability (TRIGRS unsaturated) to take into account the effect of suction on slope stability (reducing the areas to be considered susceptible to shallow landslides).

## 5. DISCUSSION AND CONCLUDING REMARKS


Tables 4 and 5 show parametric analysis results listed in a crescent order of EI. The overall parametric analyses have been implemented considering: i) a constant value of soil thickness, equal to 1.5 m of depth from the ground surface; ii) the average value of hydraulic data ( $\theta_s$ ,  $\theta_r$ ,  $k_{sat}$ ); and iii) an initial steady state water table located at the bedrock–soil interface, in the whole study area, except in the road buffer zone (Zone A in figure 6). The best results, in terms of the smallest value of EI and so the highest value of TPF, have been obtained by the first group of analyses (cases 17, 15 and 13) in saturated as well as in unsaturated conditions. This group has been carried out considering the average value of cohesion ( $c'=2.5$  kPa) and the minimum value of shear strength angle ( $\phi'=30^\circ$ ). The difference between the cases has to be ascribed to the location of the initial water table in the road buffer zone (constituted by three contour lines, each one

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this is the average?


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Thanks, 1,5 m is the constant value of thickness considered. This part now reads better.


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why?


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The use of the indexes FI and EI are based on a ratio between areas so we decided to transform the crown in the most similar geometric shape that is a circle.


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This analysis was carried out using the pixels or by landslide units?


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Using the area of pixels.

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 Numero: 4      Autore:      Oggetto: Sticky Note      Data: 8/20/2018 4:25:08 PM  
It is a little bit difficult to follow the discussion. The English technical redaction should be improved. And according to the content, there is not a discussion, it is more like the results description.

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done.

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equal to 5 m, from the secondary road) imposed at a depth of 0 m for case 17, 0.5 m for case 15 and 1.5 m for case 13. So doing, the first group of analyses shows values of  $EI < 8\%$  in saturated conditions and  $EI < 13\%$  in those unsaturated.

Particularly, cases 17S and 15S show  $EI = 5.9\%$  and TPF values equal to 94.1%, so testifying the ability of the model to back-analyze the phenomena occurred from 2001 to 2016. FI values are, in both cases, equal to 31.4% so asserting that 31.4 % of the study area, not affected by landslides until now, could be susceptible to landslides in the future.

In unsaturated conditions, cases 17U and 15U, EI increases reaching the value of 10.2% (case 17U) and 10.4% (case 15U), the TPF values are equal to 89.8% (case 17U) and 89.6% (case 15U). FI values pass from 31.4% (in saturated condition) to 26.5% (in partially saturated condition), so asserting that 26.5 % of the study area could be susceptible to landslides in the future.

Case 13, located at the third place in tables 4, 5, shows values of EI ranging from 7.6% (in saturated condition) to 12.4 (unsaturated), TPF values are 92.4% (saturated) and 87.6% (unsaturated) and FI changes from 31.2% (saturated) to 26.3% (unsaturated).

The second group of analyses (cases 12S, 8S and 4S) (Tab. 4) has been carried out considering totally saturated conditions, the minimum value of cohesion ( $c' = 0$  kPa) and the average value of shear strength angle ( $\phi' = 38^\circ$ ). The obtained results show value of EI ranging from 11.5% to 13.8%. These values are higher than those obtained by the previous described cases (17S, 15S and 13S) but are less than 15% so testifying the ability of the analyses to predict more than 85% of instable areas, as reported by TPF results equal to 88.5% (case 12S), 88.3% (case 8S) and 86.2% (case 4S). In unsaturated conditions, cases 12U, 8U and 4U (Tab. 5) show value of EI ranging from 20.0% to 22.6%, sensibly higher than those obtained by cases 17U and 15U.

Moreover, it is worth highlighting that cases 13 ( $c' = 2.5$  kPa and  $\phi' = 30^\circ$ ) and 4 ( $c' = 0$  kPa and  $\phi' = 38^\circ$ ), implemented considering a water table located at 1.5 m of depth from the ground surface, only partially back-analyze the landslides occurred on 12<sup>th</sup> of May 2001 (Fig. 11a). On the contrary, cases 17 and 12 implemented considering the same geotechnical properties but a water table located at 0 m from the ground surface, are able to back-analyze the two landslide triggering occurred on 2001 (Fig. 11b).

Therefore, Fig. 11 clearly underlines that if we do not consider the water table located near the ground surface in the secondary road buffer zone (e.g., 0 m from the ground surface – case 17S and 12S, Fig. 11b), one of the phenomena occurred in 2001 cannot be back analyzed by the model (Fig. 11a) also considering the smallest value of shear strength angle and the average value of cohesion (case 13S) or the smallest value of soil cohesion and an average value of shear strength angle (case 4S). This is due to the important influence played by the secondary road which, during the landslide event, channeled a greater quantity of water to the buffer zone. This aspect, quantified in the present paper, has been already discussed by Antronico et al. (2006), Bonavina et al. (2005). The authors asserted that a decisive role in the evolution of the debris flows, occurred in Favazzina slope, can be ascribed to the action of the water channeled along the road, located in the upper part of the basin where the phenomena occurred, that in 2001 did not have an adequate system of runoff regimentation. The just discussed results can testify the great influence of the road on the triggering phase of phenomena.

On the contrary, independently on the location of the water table in the road buffer zone, Cases 9S, 5S and 1S, performed considering the average value of cohesion and shear strength angle ( $c' = 2.5$  kPa,  $\phi' = 38^\circ$ ), show values of EI equal to 43.6% (case 9S), 44.7% (case 5S) and 47.1% (case 1S). In unsaturated conditions, EI values become 68.6% (case 9U), 70.1% (case 5U) and 73.9% (case 1U) sensibly higher than those obtained for cases 17, 15 and 13 (both in saturated and unsaturated conditions).

To sum up, the comparison of TRIGRS and TRIGRS-unsaturated results shows that  $A_{UTL}$  areas computed as unstable located within the  $A_{TL}$  (observed source areas) assume values greater than those obtained in TRIGRS-unsaturated. Thus, EI (equation 4) decreases and TPF, that is the complementary of EI, increases. Particularly, in saturated condition (TRIGRS), in all cases, the model is capable of predicting more than half of the landslides occurred from 2001 to 2016 (Fig. 12). This ratio becomes less than 40% in unsaturated conditions (TRIGRS unsaturated), particularly for cohesion value equal to 2 kPa and 2.5 kPa and shear strength angle equal to  $38^\circ$  (cases 10U, 6U, 2U, 9U, 5U, 1U). However, for this study, we state that error index values above 20% cannot be accepted because of a well-defined susceptibility map should at least be capable of predicting the 80% of the observed landslides, contrary to the threshold stated by Fressard et al. (2014) equal to 50%.

The overall accuracy of the best tests carried out in the study area, 17S and 15S, is evaluated by the ROC curves and the area under the ROC curves (AUC). ROC curves plot “sensitivity” on the Y axis versus “1-specificity” on the X axis (Metz 1978; Swets 1988). An AUC of 1 represents a perfect test; an area of 0.5 represents a model not better than random. According to Fressard et al. (2014), AUC values less than 0.7 are indicative of a poor performance, values ranging from 0.7 to 0.8 represent a fair performance of the model, values between 0.8 and 0.9 reflect a good performance and only overcoming the threshold of 0.9, the predictive ability of the model can be considered excellent. The obtained AUC values are 86.32% (case 17S) and 86.16% (case 15S) so testifying a good performance of the model. Case 17S has been considered the best map because of it shows the lowest value of  $EI = 5.9\%$  and the highest value of  $AUC = 86.32\%$  (Fig. 13). It has been implemented using: i) the average value of cohesion and the minimum value of shear strength angle, ii) the average value of hydraulic parameters and iii) a water table located at 0 m from the ground surface in the secondary road buffer zone - in order to consider the role played by the road in the canalization of rainfall water - and 1.5 m from the ground surface in the remaining study area.

1 It is worth highlighting that the obtained results show the ability of the methodology to predict shallow landslide source  
2 areas especially when few geotechnical input data are available. Indeed, the obtained best map, when compared with the  
3 landslide events that affected the study area from 2001 to 2016, shows an AUC of 0.86 that testifies a good level of  
4 forecasting ability. Furthermore, within the literature dealing with landslide susceptibility and hazard assessment by  
5 physically based models, only few papers report AUC values higher than 0.80 (e.g., Schilirò et al. 2016; Ciurleo et al.  
6 2017). Referring to the obtained FI value (31.4%) for case 17S, it is highlighted that the 31.4% of the study area is  
7 susceptible to shallow landslide triggering events in the future.

8 The obtained landslide susceptibility map can be considered a preliminary quantitative map able to select more limited  
9 zones where detailed in situ investigation and laboratory tests should be carried out. These analyses, to be performed  
10 only in the areas identified as susceptible to shallow landslides, are aimed at better characterize the mechanical and  
11 hydraulic properties of weathered gneiss especially in unsaturated conditions and reconstruct the thickness of class VI  
12 for the whole study area, so defining a detailed geotechnical model of slope. This will allow us a rigorous  
13 characterization of shallow landslide source areas (especially in terms of volume) and the best obtained susceptibility  
14 map represents a starting point for a proper use of physically based models in the analysis of propagation phase. This  
15 should provide a quantitative assessment of debris flow susceptibility and hazard to design the most appropriate  
16 countermeasures.

## 17 **Acknowledgment**

18 All authors have contributed in equal manner to the development of research and to the extension of memory.

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Sorry, but it is not clear for me the ability of the methodology to forecast landslide occurrence. In this case was a back analysis, and it is not possible to say that the best scenario for this study applied for a different area. So the methodology is useful to know the possible scenario which triggered previous landslide, but not for predicting new ones.

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Thanks for your comment, now the text reads better.

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This conclusion are not directly related to the main aim of the study, according to the introduccion. It could be a conclusion; however it is necessary to provide a conclusion related to the aim of the study, or change the scope of the study..

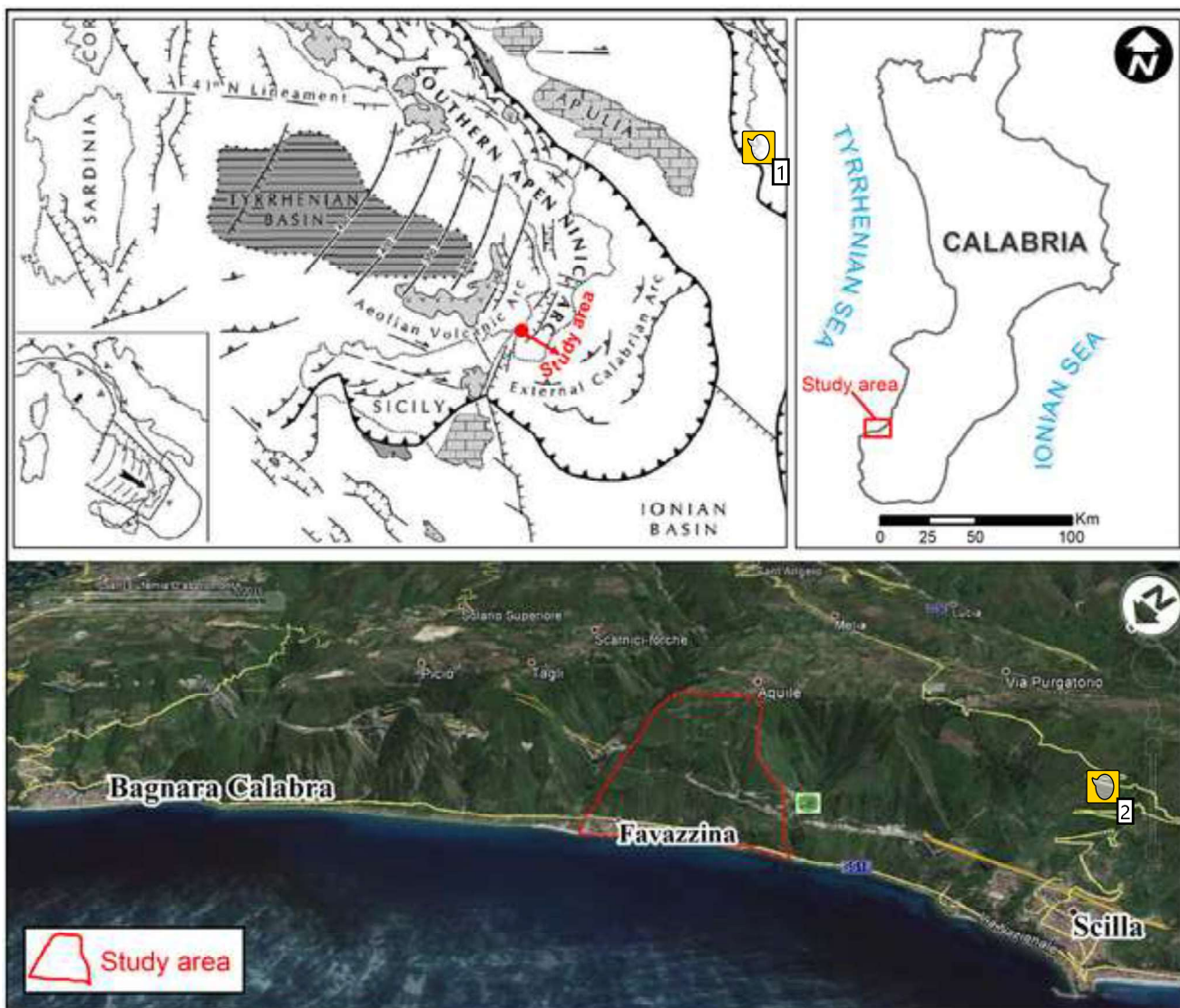
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The text has been significantly changed. Now this conclusion appears more coherent with the aim of the paper.

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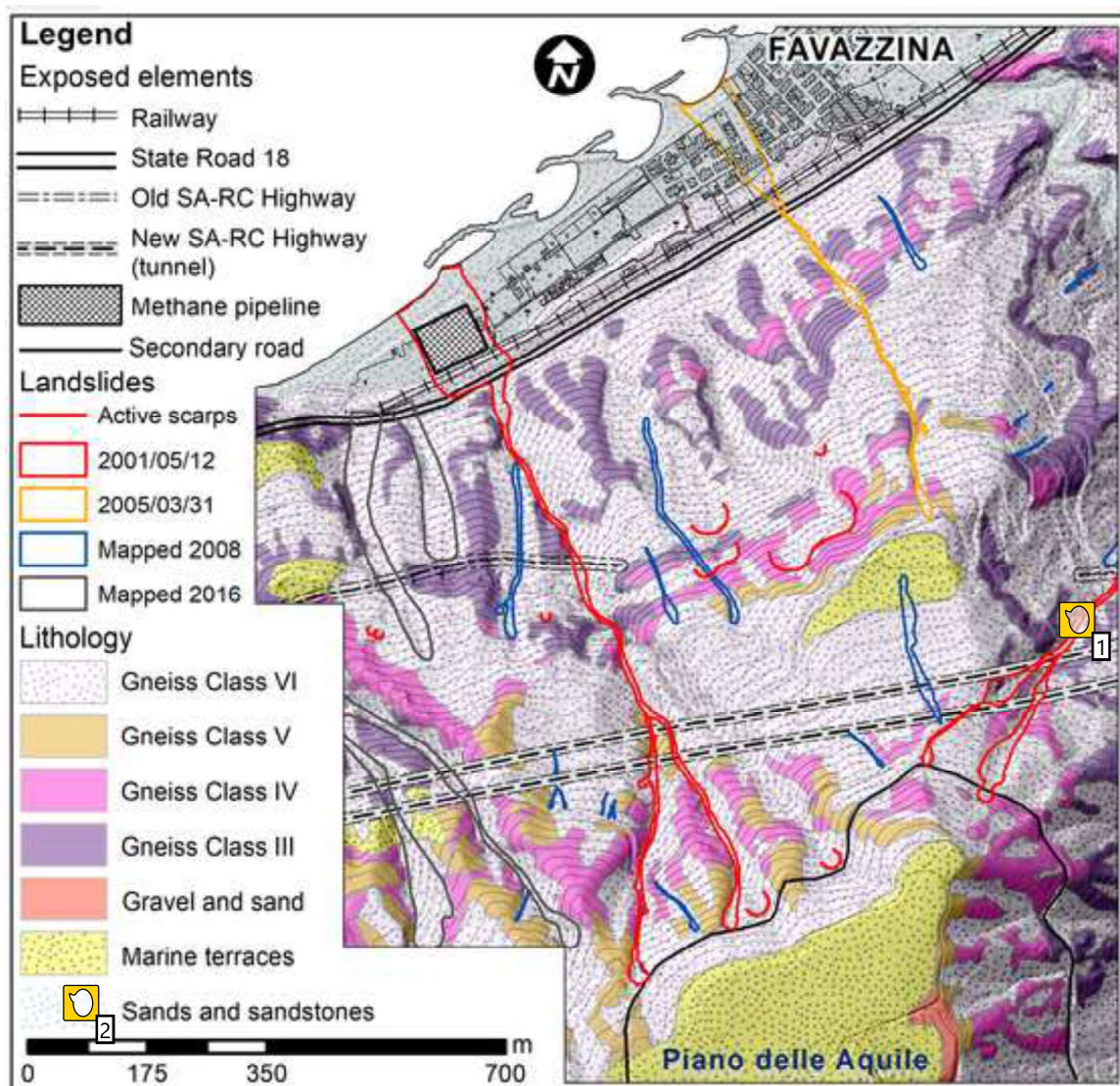
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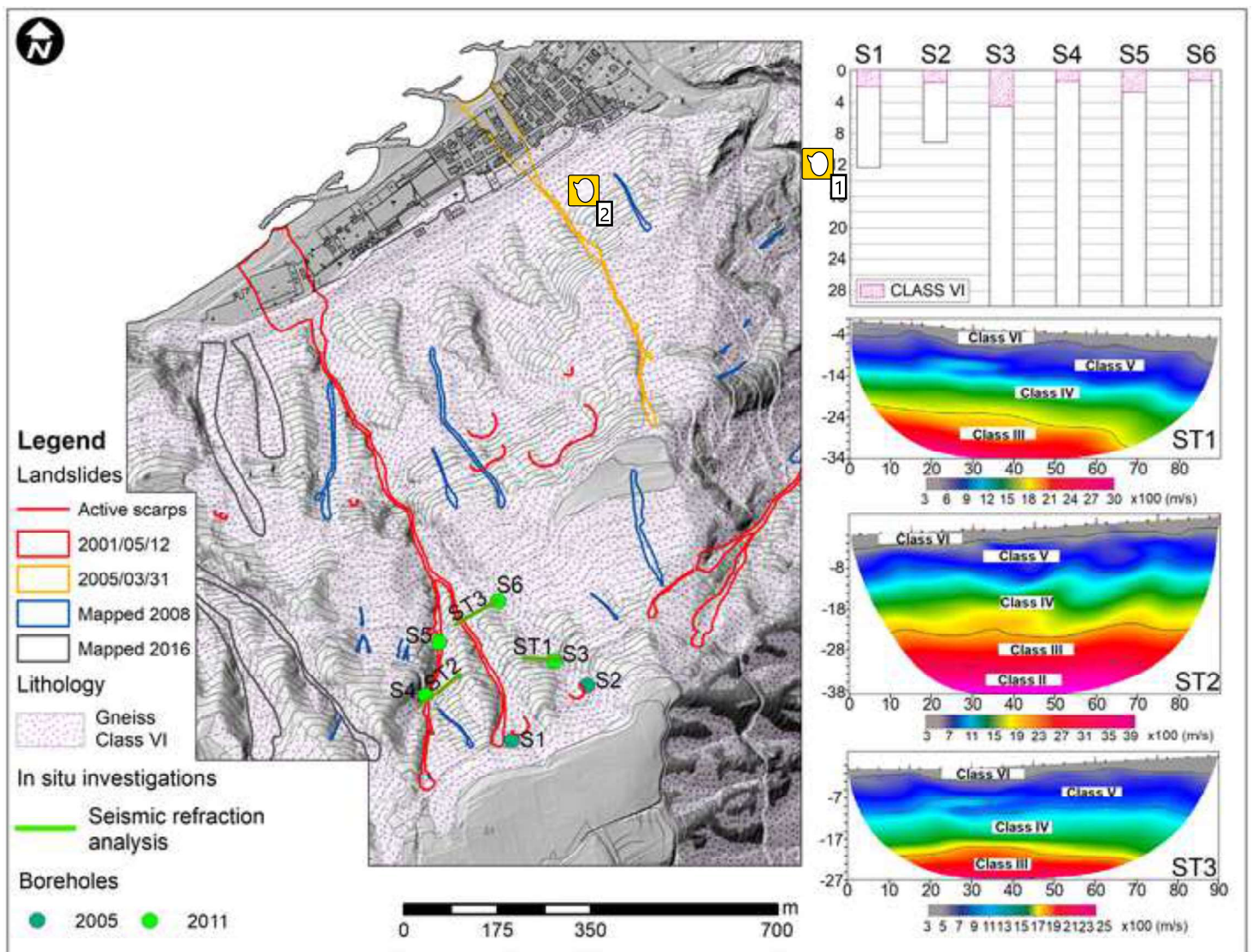
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it is not clear.


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changed




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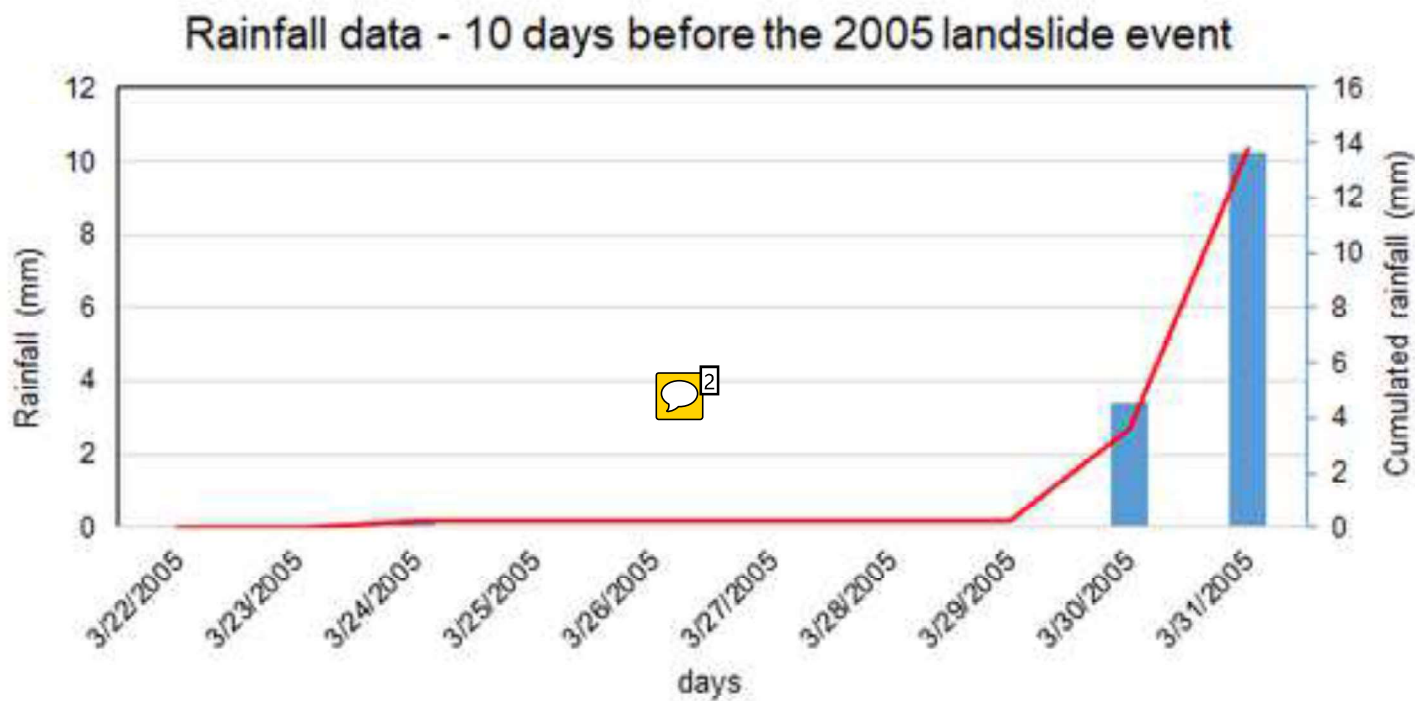
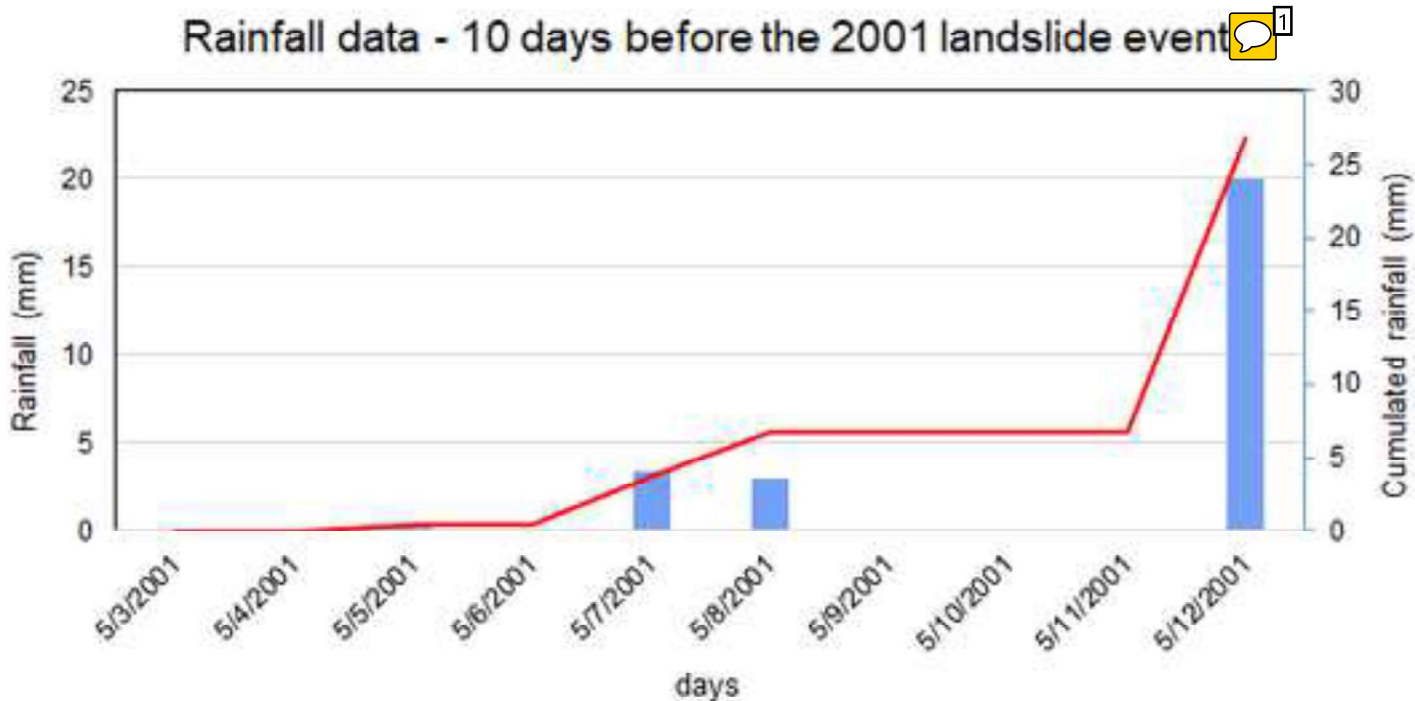
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units?

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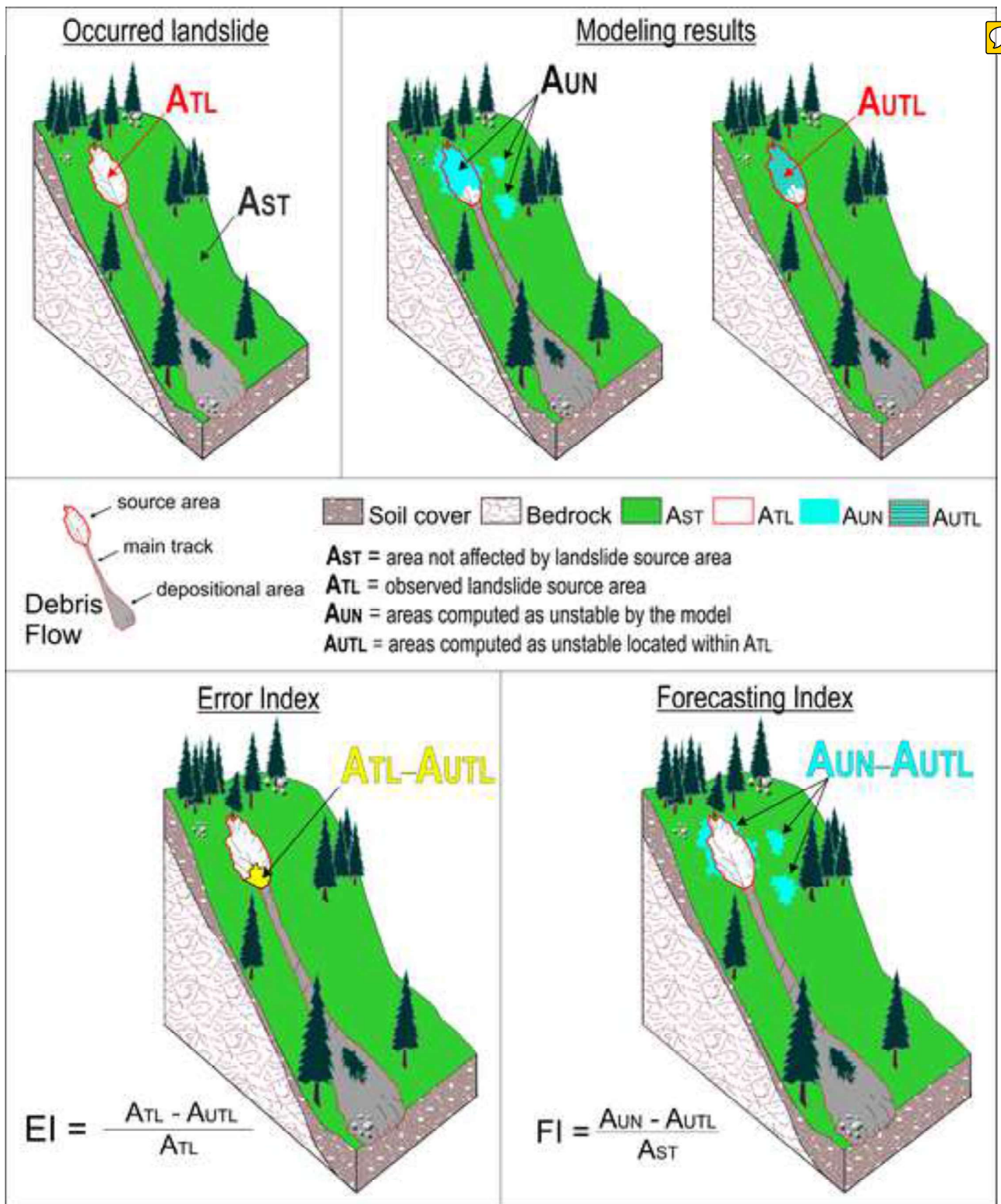
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Why to go 10 days before, if there is not significant rainfall there?

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thanks for your suggestion, this figure has been deleted and only two days before the rainfall event have been considered.


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no rain...

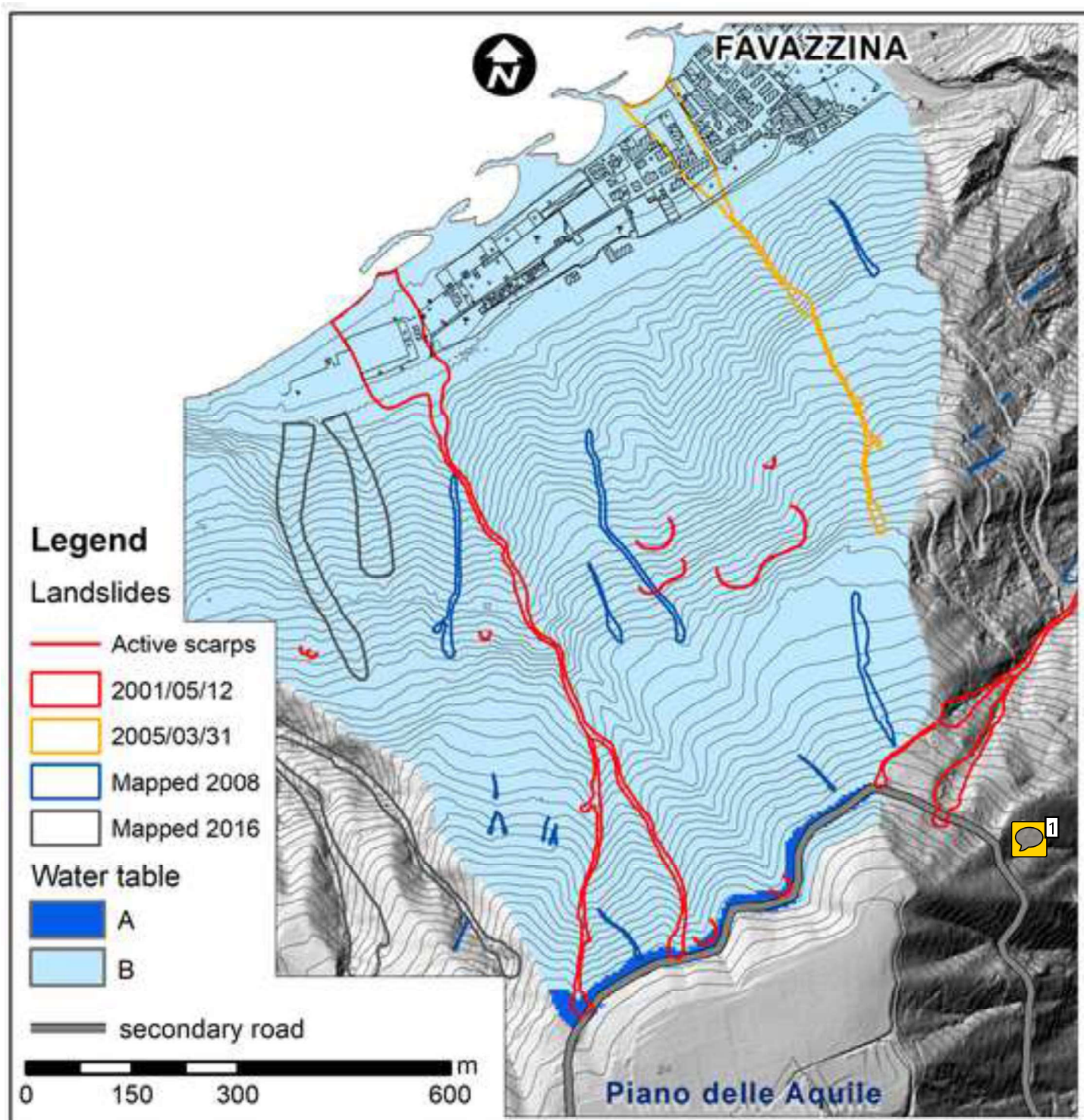
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deleted.




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 Numero: 1      Autore:      Oggetto: Sticky Note      Data: 8/10/2018 9:14:00 AM  
this is a very well known concept. I think this figures are not needed.

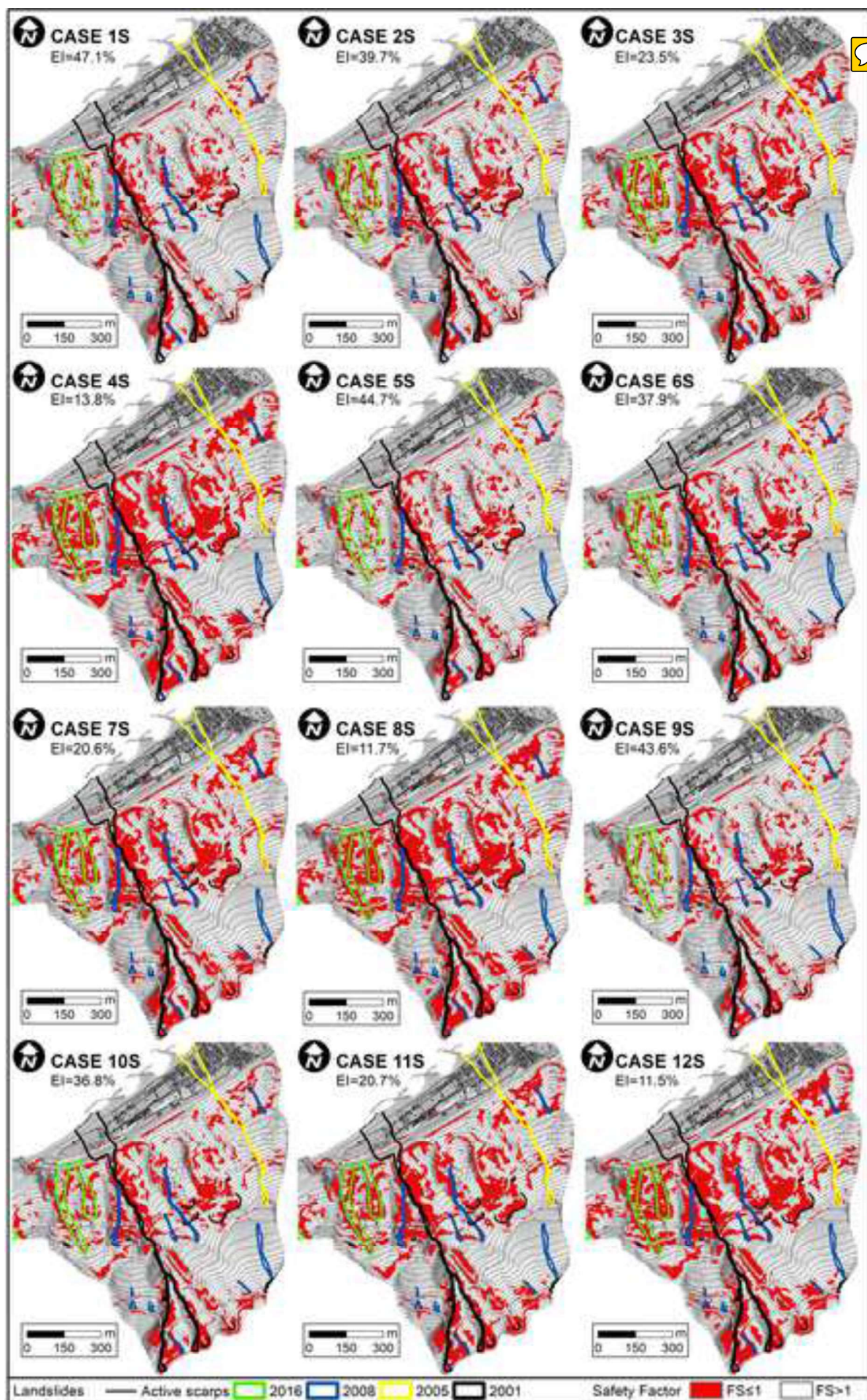
 Autore: ciurl      Oggetto: Nota      Data: 8/20/2018 4:14:41 PM  
Referring figure 5, the authors think that this figure could be used for a further clarification of Error and forecasting indexes for readers not properly expert in this field. We prefer to keep this figure.



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 Numero: 1      Autore:      Oggetto: Sticky Note      Data: 7/30/2018 10:57:25 PM  
this figure is not clear? what is the purpose of?

 Autore: ciurl      Oggetto: Nota      Data: 8/20/2018 4:15:05 PM  
Figure 6 has been used to show two different zones: zone A and zone B where different initial water tables have been assigned according to the data provided in table 3.




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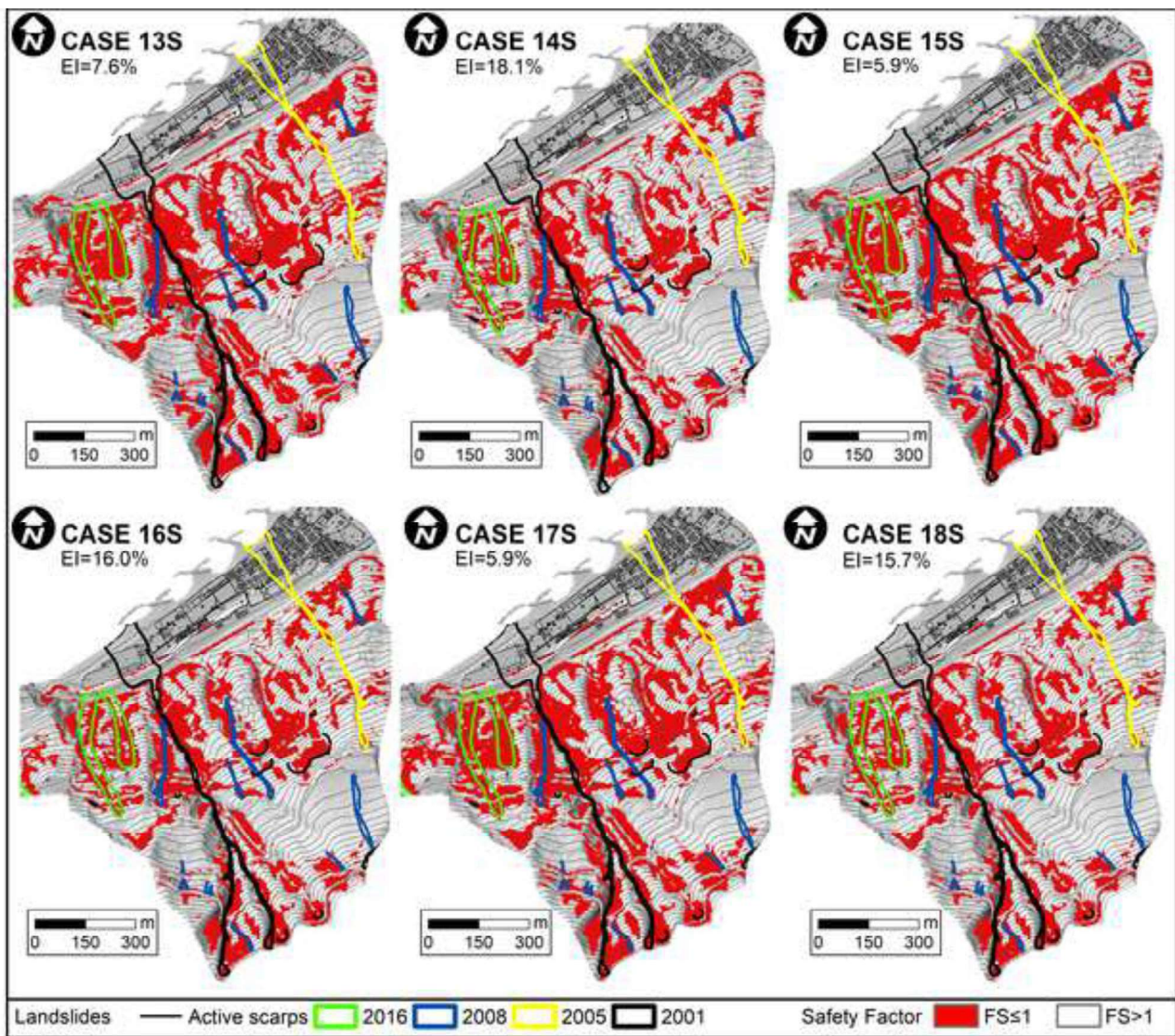
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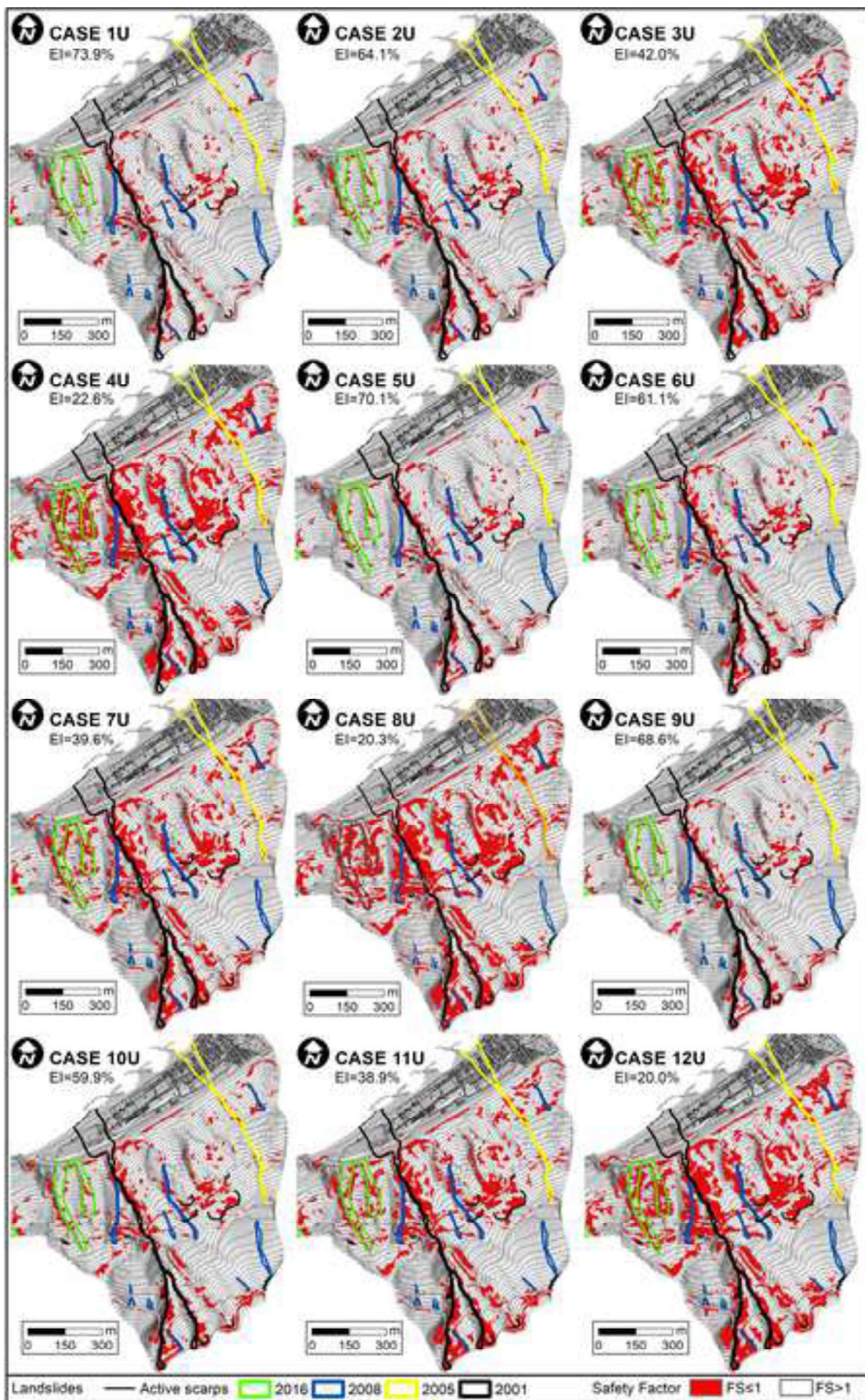
too much maps. I think using tables is better for showing the results and the differences.

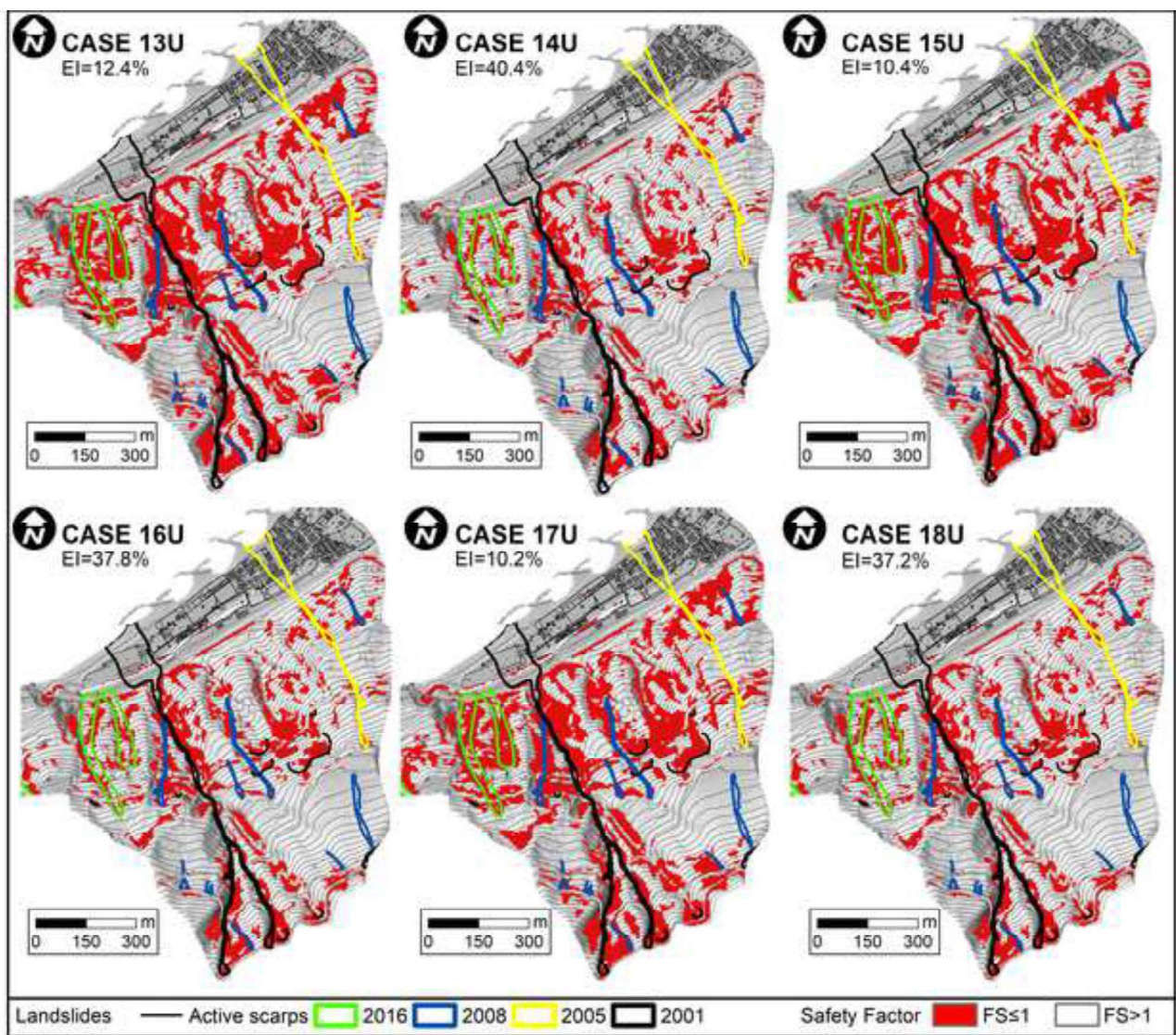
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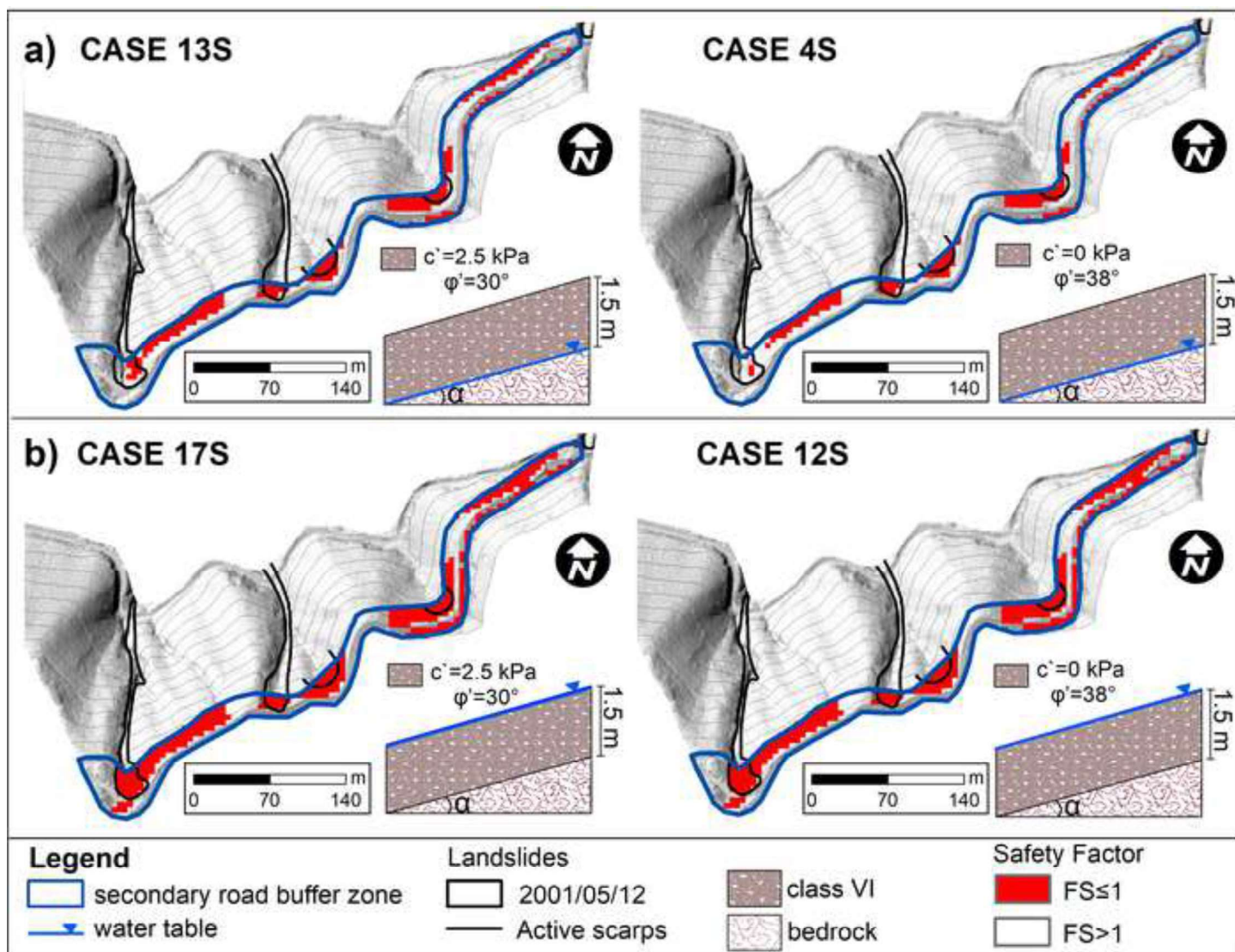
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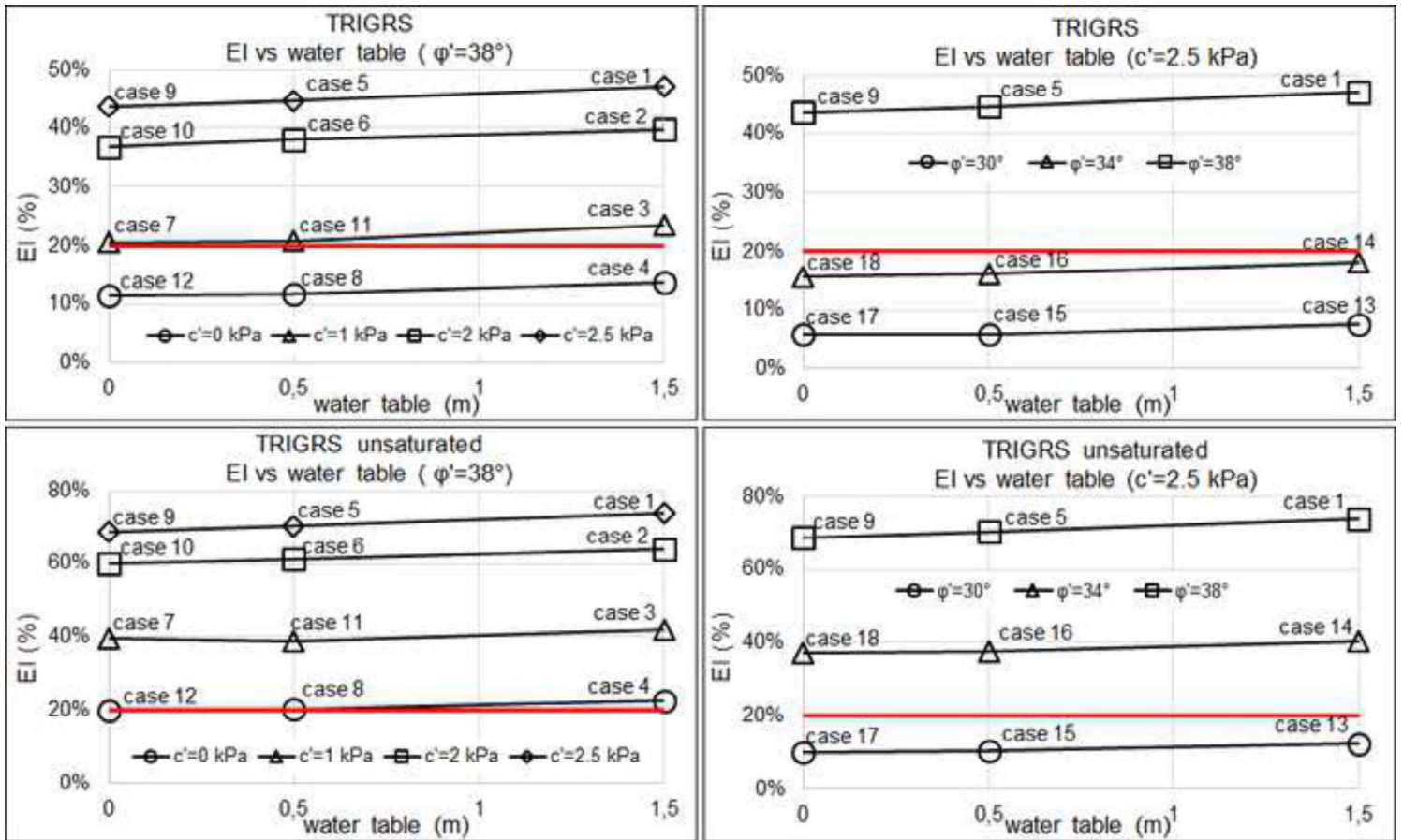
Figures from 7 to 10 have been deleted.

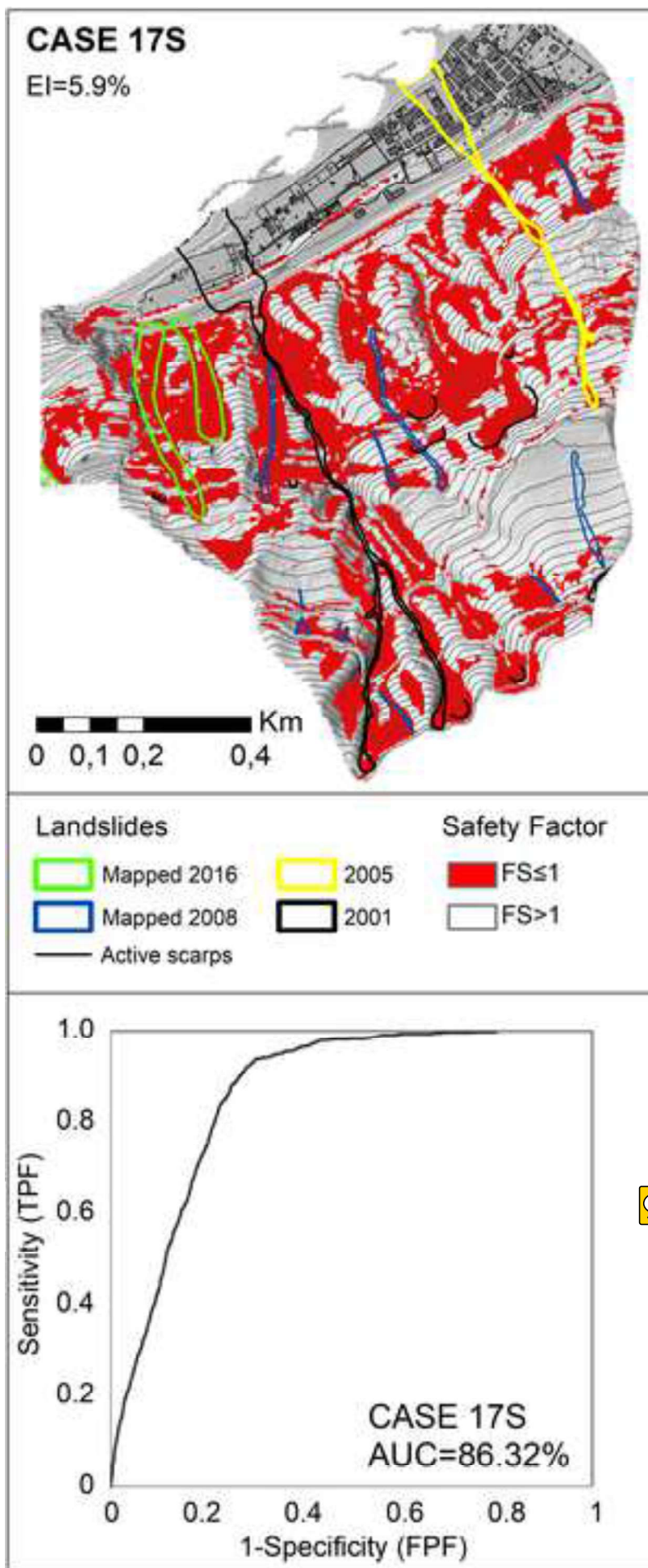














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 Numero: 1      Autore:      Oggetto: Sticky Note      Data: 8/20/2018 4:27:17 PM  
what about the other AUC?

 Autore: ciurl      Oggetto: Nota      Data: 8/20/2018 4:16:18 PM  
the AUC has been evaluated only for the best obtained calibrated map.

**LANDSLIDE SUSCEPTIBILITY ASSESSMENT BY TRIGRS IN A FREQUENTLY  
AFFECTED SHALLOW INSTABILITY AREA**

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University of Reggio Calabria, Reggio Calabria, Italy

**Cover Letter**

Dear Editor,

the authors greatly appreciated the Editor and Reviewers' work and would like to thank you for the time you have devoted to reading and evaluating the manuscript.

We are pleased to submit the improved version of the manuscript (LASL-D-18-00281\_R1), according to your suggestions.

Kind regards

Nicola Moraci

**Fig. 1** – Geostructural and geographical localization of the study area.

**Fig. 2** – Lithological and weathering grade map of the Favazzina slopes.

**Fig. 3** – Landslide inventory and in situ investigations.

**Fig. 4** – Indexes used to quantify the obtained results.

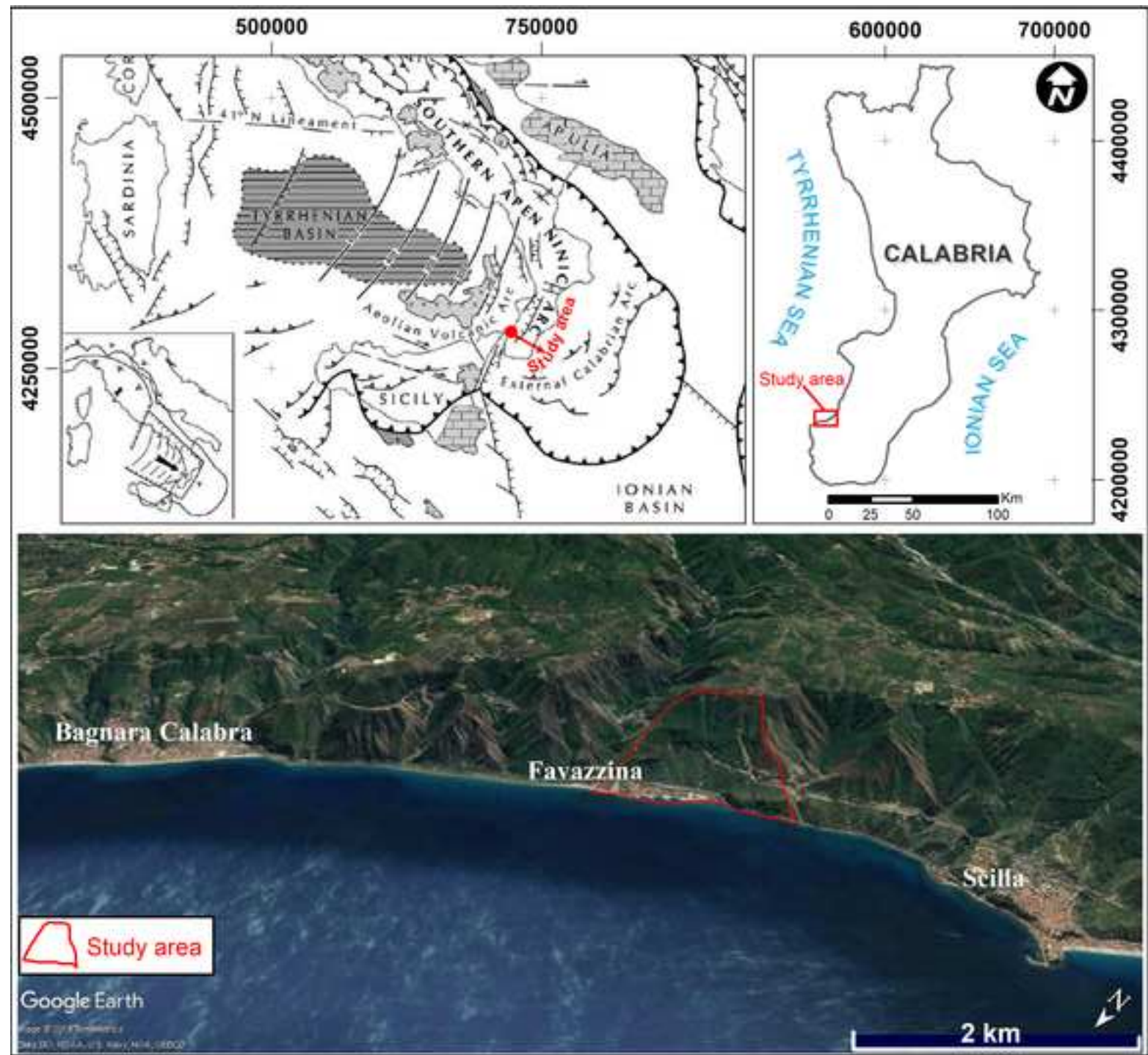
**Fig. 5** – Initial water table locations. Legend: A=0 m, 0.5 m or 1.5 m from the ground surface; B= 1.5 m from the ground surface.

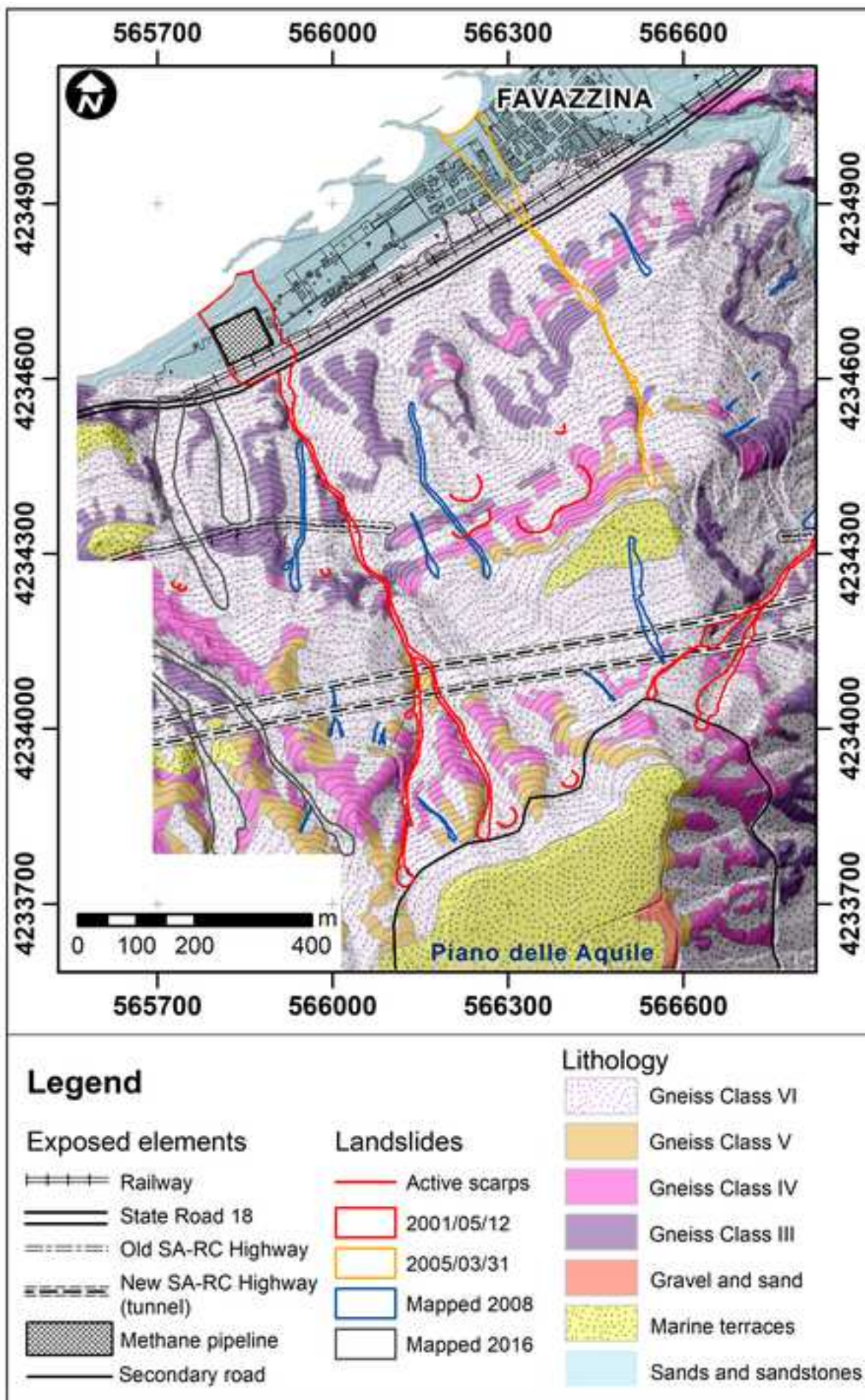
**Fig. 6** – EI versus water table. a) results obtained considering saturated condition for  $\phi'=38^\circ$  and  $c'$  varying from 0 kPa to 2.5 kPa; b) results obtained considering saturated condition for  $c'=2.5$  kPa and  $\phi'$  varying from  $30^\circ$  to  $38^\circ$ ; c) results obtained considering unsaturated condition for  $\phi'=38^\circ$  and  $c'$  varying from 0 kPa to 2.5 kPa; d) results obtained considering unsaturated condition for  $c'=2.5$  kPa and  $\phi'$  varying from  $30^\circ$  to  $38^\circ$ . Each symbol/point in the graph represents a different implemented case.

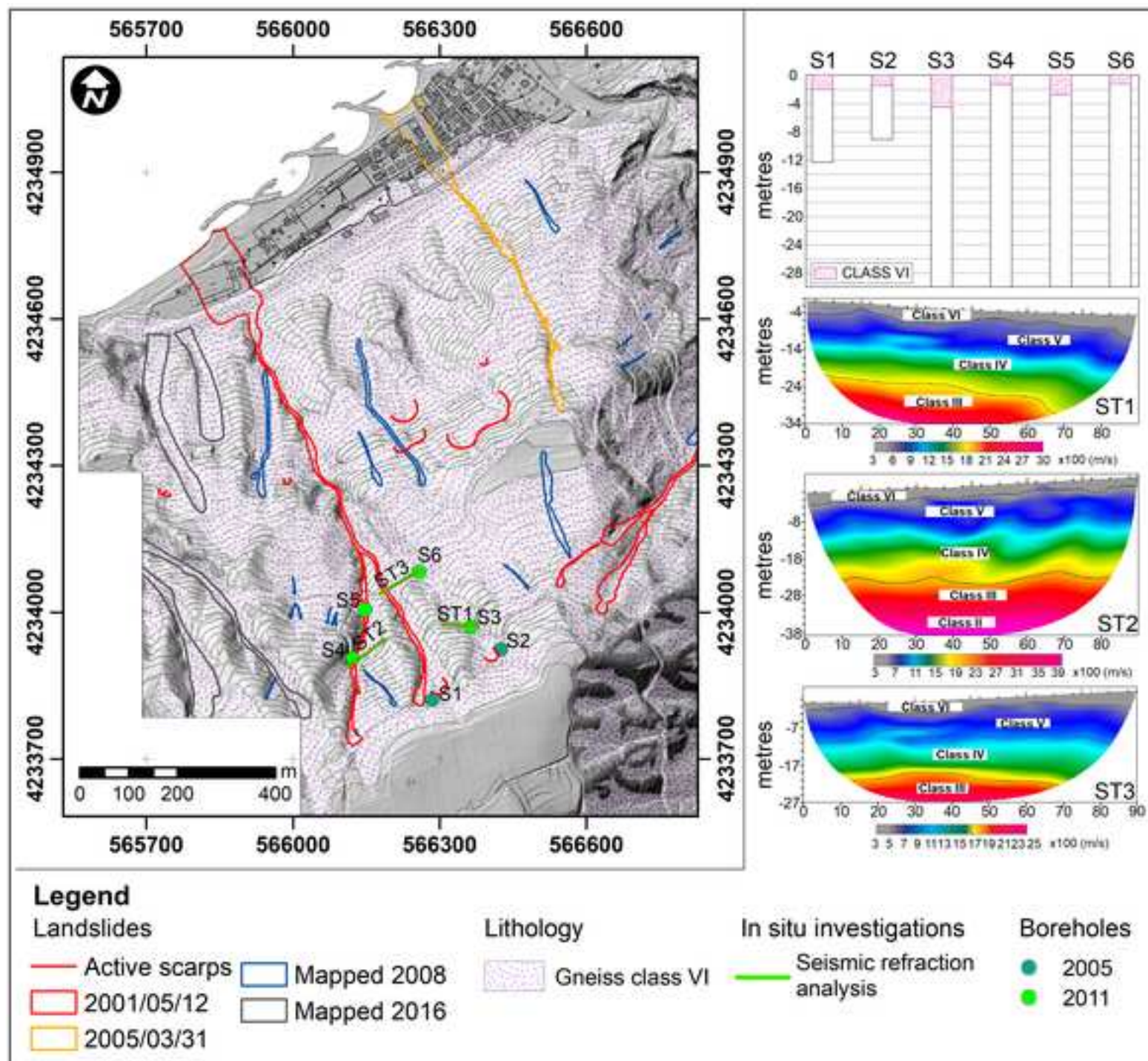
**Fig. 7** – Comparison between the results obtained by TRIGRS for cases 13S, 4S and 17S, 12S in the upper part of the Favazzina slope. a) water table located at 1.5 m from the ground surface in the whole study area; b) water table located at 0 m from the ground surface in the secondary road buffer zone. Legend:  $\alpha$  is the slope angle and it changes cell by cell.

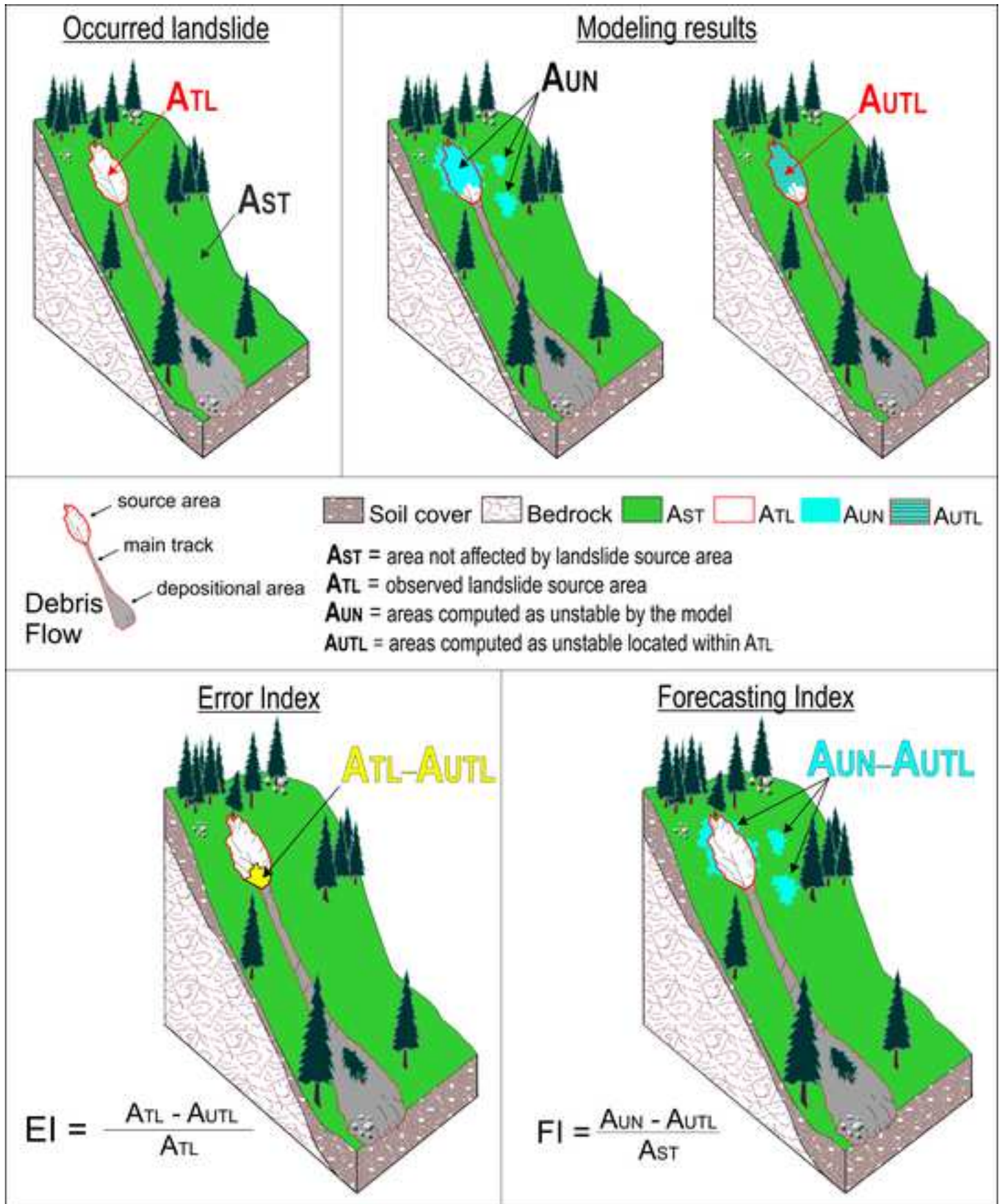
**Fig. 8** – Landslide susceptibility computational map; receiver operating characteristic curve and AUC value.

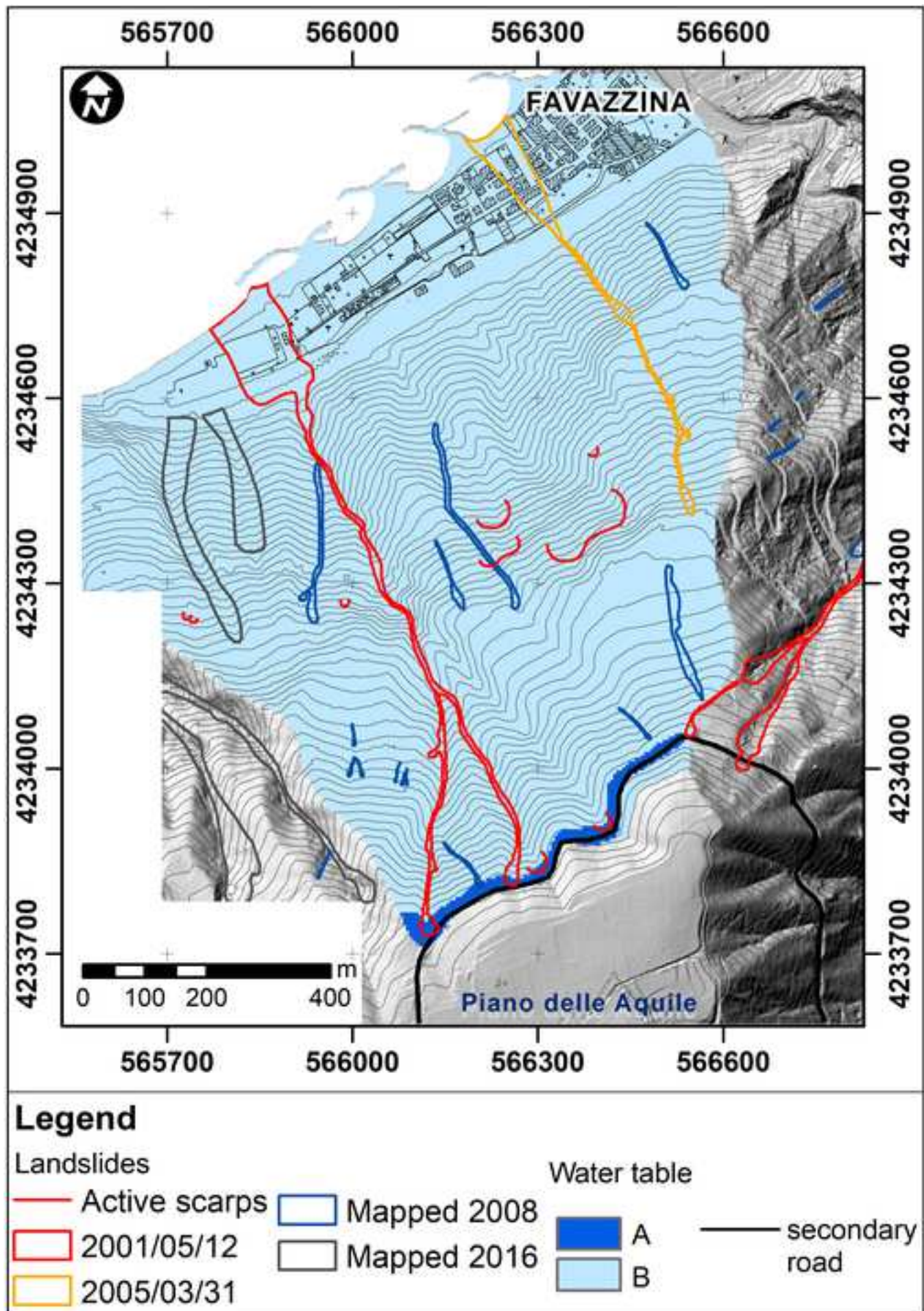
Figure 1

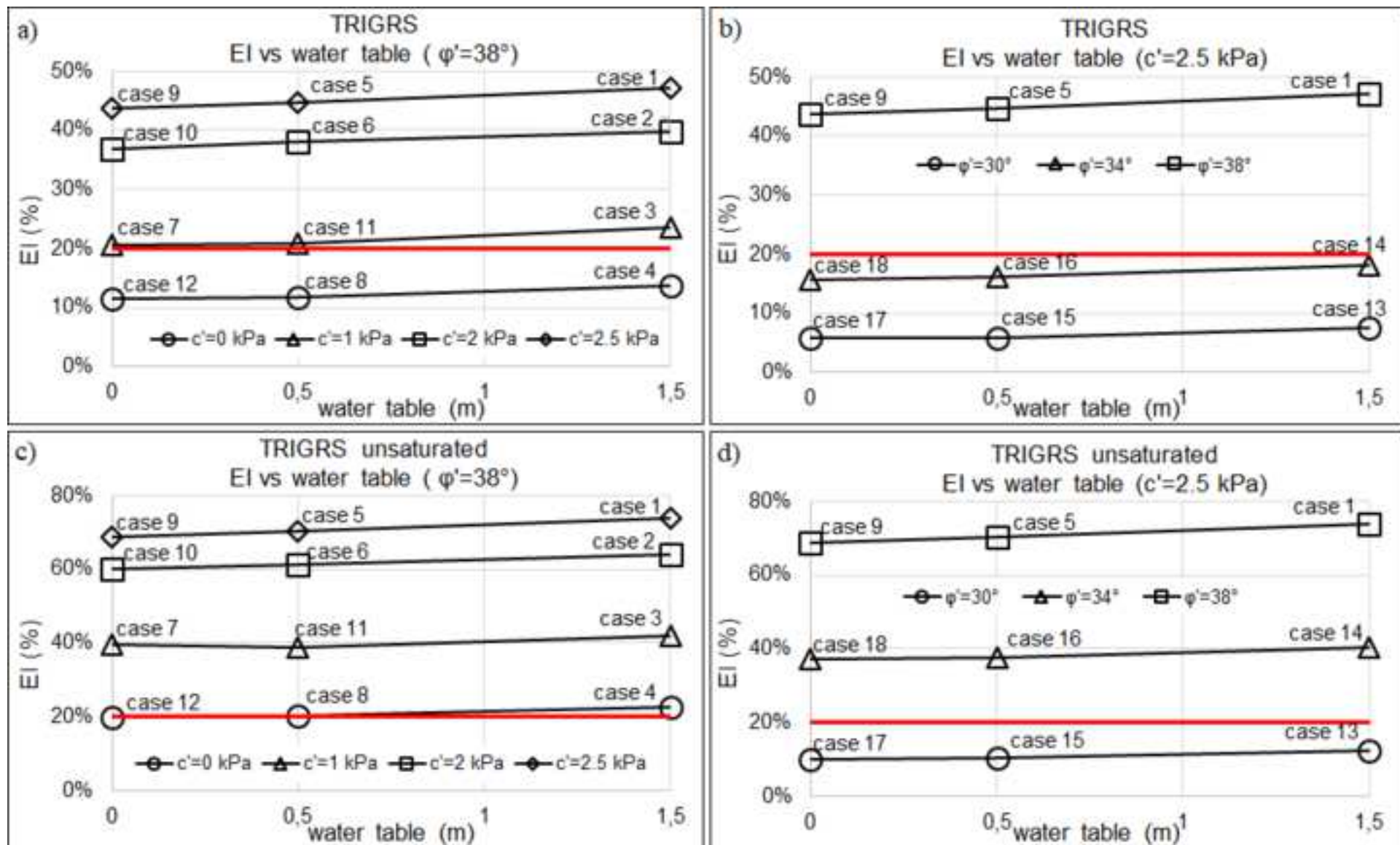


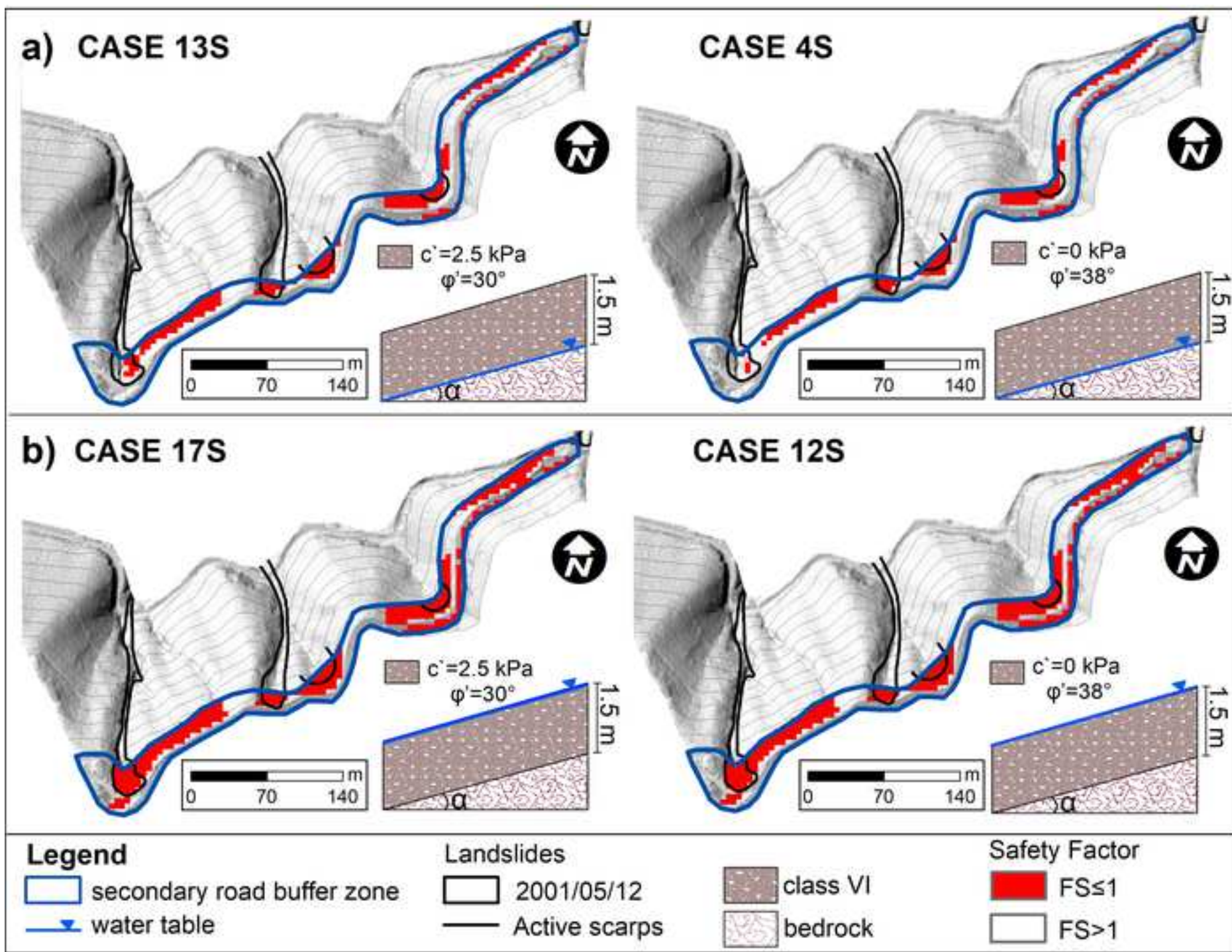


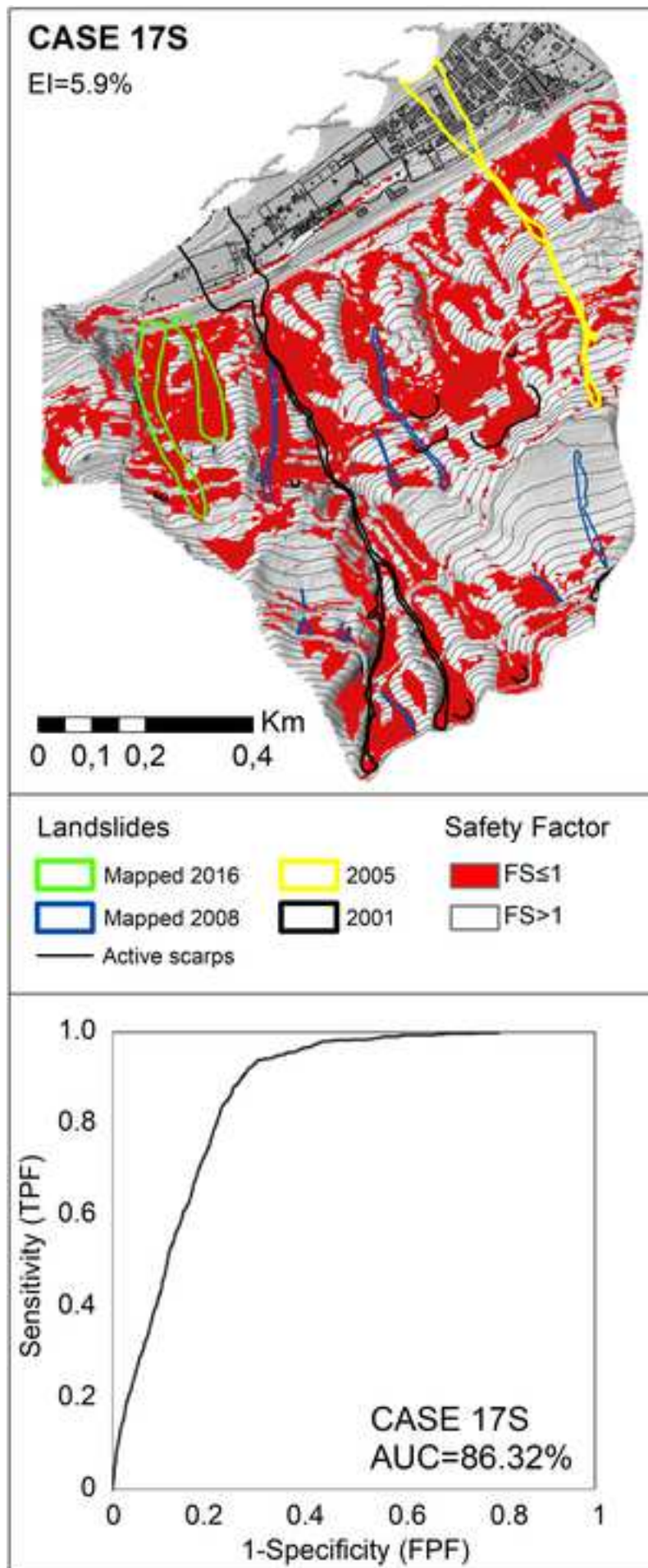












**Tab. 1** – Geotechnical properties of weathered gneiss of class VI

REFERENCES	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	$\gamma_{sat}$ (kN/m <sup>3</sup> )	$c'$ (kPa)	$\varphi'$ (°)
Antronico et al. 2006	50.58	27.26	19.05	3.11	19.46– 21.98	0	38
						0	44
						0	38
Schilirò et al. (2015)	24.2-58.1	27-52.5	5.9-15.3	1.1-8	19.22	0	30
						5	40

**Tab. 2** – Hydraulic properties of weathered gneiss of class VI

REFERENCES	$K_s$ (m/s)	$\theta_s$ (-)	$\theta_r$ (-)	$D_0$ (m <sup>2</sup> /s)	$\alpha$ (m <sup>-1</sup> )
Antronico et al. (2006)	0.40				
	0.54				
Schilirò et al. (2015)	6.60E-05	0.38	0.05	1.55E-04	11.8
	1.25E-05	0.39	0.04	3.84E-04	11.1
	7.91E-06	0.38	0.04	2.43E-05	12.2
Calvello et al. (2008)	1.27E-06	0.32			
	8.10E-06	0.32			
	2.78E-06	0.35			
Cascini et al. (2006)	3.50E-05				
Gullà and Sorbino (1994)	1.00E-05				

**Tab. 3** – Input data used in TRIGRS in saturated and unsaturated conditions.

TRIGRS					TRIGRS unsaturated				
<b>CASE*</b>	WATER TABLE IN THE ZONE "A" (m)	WATER TABLE IN THE ZONE "B" (m)	c' (kPa)	$\phi'$ (°)	<b>CASE*</b>	WATER TABLE IN THE ZONE "A" (m)	WATER TABLE IN THE ZONE "B" (m)	c' (kPa)	$\phi'$ (°)
<b>1S</b>	1.5	1.5	2.5	38	<b>1U</b>	1.5	1.5	2.5	38
<b>2S</b>	1.5	1.5	2	38	<b>2U</b>	1.5	1.5	2	38
<b>3S</b>	1.5	1.5	1	38	<b>3U</b>	1.5	1.5	1	38
<b>4S</b>	1.5	1.5	0	38	<b>4U</b>	1.5	1.5	0	38
<b>5S</b>	0.5	1.5	2.5	38	<b>5U</b>	0.5	1.5	2.5	38
<b>6S</b>	0.5	1.5	2	38	<b>6U</b>	0.5	1.5	2	38
<b>7S</b>	0.5	1.5	1	38	<b>7U</b>	0.5	1.5	1	38
<b>8S</b>	0.5	1.5	0	38	<b>8U</b>	0.5	1.5	0	38
<b>9S</b>	0.0	1.5	2.5	38	<b>9U</b>	0.0	1.5	2.5	38
<b>10S</b>	0.0	1.5	2	38	<b>10U</b>	0.0	1.5	2	38
<b>11S</b>	0.0	1.5	1	38	<b>11U</b>	0.0	1.5	1	38
<b>12S</b>	0.0	1.5	0	38	<b>12U</b>	0.0	1.5	0	38
<b>13S</b>	1.5	1.5	2.5	30	<b>13U</b>	1.5	1.5	2.5	30
<b>14S</b>	1.5	1.5	2.5	34	<b>14U</b>	1.5	1.5	2.5	34
<b>15S</b>	0.5	1.5	2.5	30	<b>15U</b>	0.5	1.5	2.5	30
<b>16S</b>	0.5	1.5	2.5	34	<b>16U</b>	0.5	1.5	2.5	34
<b>17S</b>	0.0	1.5	2.5	30	<b>17U</b>	0.0	1.5	2.5	30
<b>18S</b>	0.0	1.5	2.5	34	<b>18U</b>	0.0	1.5	2.5	34

\* S = saturated, U = unsaturated

**Tab. 4** – Input data and values of indexes used in saturated conditions to evaluate the reliability of TRIGRS for susceptibility analyses.

<b>CASE</b>	WATER TABLE IN THE ZONE "A" (m)	WATER TABLE IN THE ZONE "B" (m)	c' (kPa)	$\phi'$ (°)	TPF (%)	FI (%)	EI (%)
<b>17S</b>	0.0	1.5	2.5	30	94.1	31.4	5.9
<b>15S</b>	0.5	1.5	2.5	30	94.1	31.4	5.9
<b>13S</b>	1.5	1.5	2.5	30	92.4	31.2	7.6
<b>12S</b>	0.0	1.5	0	38	88.5	25.7	11.5
<b>8S</b>	0.5	1.5	0	38	88.3	25.6	11.7
<b>4S</b>	1.5	1.5	0	38	86.2	25.5	13.8
<b>18S</b>	0.0	1.5	2.5	34	84.3	23.1	15.7
<b>16S</b>	0.5	1.5	2.5	34	84.0	23.0	16.0
<b>14S</b>	1.5	1.5	2.5	34	81.9	22.8	18.1
<b>7S</b>	0.5	1.5	1	38	79.4	21.3	20.6
<b>11S</b>	0.0	1.5	1	38	79.3	22.8	20.7
<b>3S</b>	1.5	1.5	1	38	76.5	21.0	23.5
<b>10S</b>	0	1.5	2	38	63.2	16.0	36.8
<b>6S</b>	0.5	1.5	2	38	62.1	15.9	37.9
<b>2S</b>	1.5	1.5	2	38	60.3	15.7	39.7
<b>9S</b>	0.0	1.5	2.5	38	56.4	13.3	43.6
<b>5S</b>	0.5	1.5	2.5	38	55.3	13.2	44.7
<b>1S</b>	1.5	1.5	2.5	38	52.9	13.0	47.1

**Tab. 5** – Input data and values of indexes used in unsaturated conditions to evaluate the reliability of TRIGRS for susceptibility analyses.

CASE	WATER TABLE IN THE ZONE "A" (m)	WATER TABLE IN THE ZONE "B" (m)	c' (kPa)	$\phi'$ (°)	TPF (%)	FI (%)	EI (%)
17U	0.0	1.5	2.5	30	89.8	26.5	10.2
15U	0.5	1.5	2.5	30	89.6	26.5	10.4
13U	1.5	1.5	2.5	30	87.6	26.3	12.4
12U	0.0	1.5	0	38	80.0	21.6	20.0
8U	0.5	1.5	0	38	79.7	21.5	20.3
4U	1.5	1.5	0	38	77.4	21.3	22.6
18U	0.0	1.5	2.5	34	62.8	15.9	37.2
16U	0.5	1.5	2.5	34	62.2	15.8	37.8
11U	0.0	1.5	1	38	61.1	15.0	38.9
7U	0.5	1.5	1	38	60.4	14.9	39.6
14U	1.5	1.5	2.5	34	59.6	15.6	40.4
3U	1.5	1.5	1	38	58.0	14.7	42.0
10U	0.0	1.5	2	38	40.1	9.0	59.9
6U	0.5	1.5	2	38	38.9	8.9	61.1
2U	1.5	1.5	2	38	35.9	8.6	64.1
9U	0.0	1.5	2.5	38	31.4	6.6	68.6
5U	0.5	1.5	2.5	38	29.9	6.5	70.1
1U	1.5	1.5	2.5	38	26.1	6.2	73.9