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Interactive Comment

Interactive comment on "From slope- to regional-scale shallow landslides susceptibility assessment using TRIGRS" *by* M. Bordoni et al.

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The authors are grateful to the Anonymous Referee #2, whose comments and suggestions will contribute towards an improvement of the final paper. Point-by-point replies to the referee's comments follow.

In the "Introduction" section, we will follow the referee's suggestion, thus we will rearrange the redundant parts, adding also other more relevant references. The part from pg. 7411 line 25 to pg. 7412 line 4) will be corrected as followed: "Hydrological monitoring allows for identifying many shallow landslides predisposing and triggering mechanism. Matsushi et al. (2006) analyzed the rainwater infiltration and the groundwater fluxes towards underlying permeable bedrocks which lead to shallow landslides

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development. Some works identified the time changes in usually unsaturated soils hydrological features which then provoked the triggering of shallow landslides (Matsushi and Matsukura, 2007; Godt et al., 2009; Damiano et al., 2012; Springman et al., 2013). In particular, Godt et al. (2009) observed for the first time the development in natural setting of a shallow failure in unsaturated soil conditions linked to a rainfall event. Moreover, monitoring systems measured the increase in pore water pressure and the development of a perched water table in the covering soils that could promote shallow landslides (Lim et al., 1996; Godt et al., 2008a, b; Baum et al., 2010, 2011)". We will further correct the part from pg. 7412 line 13 to pg. 7412 line 20) justifying the choice of inserting the following references. The proposed corrected part is: "Recently, physically-based models proved rather promising in assessing the triggering zones of shallow landslides. Different type of models were developed for analyzing shallow landslides triggering time and location according to: the development of positive pore water pressures in saturated soils (Montgomery and Dietrich, 1994; Baum et al., 2002); the change in soil pore water pressure (Baum et al., 2008; Rossi et al., 2013) or soil saturation (Montrasio and Valentino, 2008) linked to rainfall intensity and duration; the possibility of modeling the size and the depth of shallow landslides at basin and regional scale (Alvioli et al., 2014); the connections between different points of a slope or a basin which influence the soil hydrological behavior and the development of unstable conditions (Lanni et al., 2012); the possibility of modelling the triggering conditions of shallow failures basing on the natural variability of geotechnical and hydrological soil features through a probabilistic approach (Grelle et al., 2014; Mergili et al., 2014; Raia et al., 2014). Furthermore, physically based models were used to determine rainfall thresholds for timing and localization of shallow landslides on a regional scale (Salciarini et al., 2006, 2008; Godt et al., 2008a, b; Papa et al., 2013)". We will improve the sentence from pg. 7412 line 21 to pg. 7412 line 26, considering the possibility of modeling spatial distribution of shallow landslides through a probabilistic analysis of the main soil hydrological and geotechnical features influencing slope stability. Thus, we will correct the sentence as followed: "At the moment, an important challenge is represented by the possibility of applying a slope stability model at different scales, providing of keeping the same level of reliability both on the single slope and on an area some square kilometers wide. The spatial distribution of both geotechnical and hydrological soil properties can be reasonably inferred only from a limited number of either field or laboratory tests, taking into account for the spatial variability of the parameters through a probabilistic approach (Simoni et al., 2008; Mergili et al., 2014; Raia et al., 2014)". According to this comment of the referee, we will perform a sensitivity analysis for all the soil hydrological and geotechnical input parameters of the model, whose results will be shown and explained in the following parts of our comment. As suggested by the referee, we will substitute the term "mapping units" at pg. 7412 line 29 with "unit mapping of the soil". In this way, we will better define the different zones of the studied area with homogeneous soil parameters. For avoiding misunderstanding, we will change "mapping units" with "unit mapping" also in the other parts of the paper. We will rearrange the part from pg. 7413 line 11 to pg. 7414 line 4 for improving the presentation of the main objectives of the paper. We will move the sentence "In this work, a methodology that links long-term field observations on a sample slope with the distributed slope stability analysis at local scale is presented." at pg. 7411 line 6. Moreover, we will correct the followed part in: "The TRIGRS-Unsaturated model (Baum et al., 2008) was applied to a study area in the Oltrepò Pavese (northern Italy; Fig. 1) to assess the triggering zones of shallow landslides referred to a well-documented case history occurred on 27–28 April 2009 (Zizioli et al., 2013). The main goals of the work were: (i) to identify the hydrological behaviour of the slope soils in the study area through a continuous field monitoring on a sample slope; (ii) using field data to calibrate the TRIGRS-Unsaturated model; (iii) to evaluate the efficiency of the TRIGRS-Unsaturated model on the estimation of the pore water pressure trend at slope scale; (iv) to compare results of the TRIGRS-Unsaturated distributed analyses at regional scale in the study area taking into account different unit mapping of the slope soils. In this way, a methodology linking long-term field observations at a site-specific scale with the distributed slope stability analysis at local scale has been developed. The study area is strongly characterized by a traditional viticulture which represents the most important branch of local economy, and most of shallow failures affected slopes cultivated with vineyards. For this reason, it is fundamental assessing the triggering zones of shallow landslides for a correct land use planning, to manage agricultural best practices and to reduce the economical effects of these landslides. The developed methodology may be then applied in other geological contexts where vineyards are located on slopes affected by shallow landslides (Tiranti and Rabuffetti, 2010; Galve et al., 2014)."

As suggested by the reviewer, we will correct the definition of the climate as temperate/mesothermal according to Koppen's classification of world climates. Furthermore, we will correct the definition of the water content values throughout the paper, passing form "m3 m-3" to "%".

We will better specify the meaning of the RMSE index in this paper. In Eq. 2, ψo is the observed pore water pressure in a particular hour i of the considered rainfall events of Tab. 7 and Tab. 8 of the paper, ψm is the pore water pressure estimated by the model in a particular hour i of the same event, n is the number of observations during a particular event, which corresponds to the duration of the rainfall. We considered only the comparison between measured and modeled pore water pressure trends at different depths in correspondence of the monitoring station in the sample slope.

We will correct the paper also according to the general comments of the reviewer to clarify many parts which have been, in the first manuscript draft, not completely clear. The authors' reply to reviewer's general comments follow.

We will correct, on the title and all along the paper, the term of "regional" in "local" to define the scale of the study area according with the classification proposed by Corominas et al. (2014).

We have made an analysis of the effect of the uncertainties of soil input parameters. We propose to add in Tab. 5 of the original paper the standard deviation of each parameter required by the model, also modifying the title of the table in "Table 5. Mean and standard deviation (sd) values of the soil parameters used as input data in TRIGRS-Unsaturated. The standard deviation values are in parentheses.". In this way, it will be possible to consider the potential variation of each soil parameter of a particular mapping unit. The modified table is on the supplement attached to this reply. Thus, we have performed a sensitivity analysis. The sensitivity analysis has been carried out by changing only one parameter in each simulation, keeping steady the other ones. We considered as variables the unit weight γ, the peak friction angle φ', the effective cohesion c' and the hydrological parameters (θs, θr, αG, Ks, D0). We made different simulations by considering for each parameter either the mean value or the value obtained by subtracting or adding its standard deviation. For c' parameter, we set its minimum value equal to 0 kPa. The results of the sensitivity analysis is shown in Fig. 1. As suggested by the Reviewer #1, the correct terminology of True Positive Rate (TP) in place of Success Index (SI) and False Positive Rate (FP) in place of Error Index (EI) has been used. We will correct the terminology in the text of the paper and in the figures of the paper where the terms are present. A negligible variation of both the True Positive Rate (TP) and the False Positive Rate (FP) are linked to the analysis of the influence played by γ parameter (Fig. 1a), with values changing in the order of 0.9 and 2.3% for geological and pedological unit mapping, respectively. As regards the hydrological parameters, the best results in terms of TP are obtained by considering the mean values, with an improvement in the order of 12.3-21.2% with respect to the values including the standard deviation. Instead, FP values keep substantially steady in all the simulations (Fig. 1d). Greater variations affect both TP and FP indexes by changing φ' and c' (Fig. 1b, c). The lowest values of these parameters determine an improvement on the correct identification of the real unstable areas, as indicated by the increase in TP up to 7.3%, but at the same time they lead to an increase of the areas wrongly mapped as unstable, as indicated by an increase in FP values up to 37.1%. In this case, a nil value of cohesion for both pedological mapping units (Fig. 1b, c) has been assumed. The highest values of φ' and c' cause a slight decrease in

FP, ranging between 0.2 and 5.7%, and a significant decrease in TP, ranging between 40.4 and 44.3% (Fig. 1b, c). A further index useful to evaluate the model performance is represented by the ratio between TP and FP. For each unit mapping, the highest ratio between TP and FP corresponds to the simulation obtained by considering the mean values of the soil input data for all the units. In particular, for the pedological unit mapping it is slightly higher than for the geological one. The mean values of the soil input data seem to be representative of the units that characterize the study area, and they seem to attain the best results in all the sensitivity analyses.

In correspondence of the monitored slope, we performed an analysis of the triggering zones locations referred to April 2009 event through TRIGRS-Unsaturated using also a DEM with the grid size of 2 m x 2 m. A comparison between the results of modeling with this DEM and with the DEM used for all the study area (10 m x 10 m) has been provided (Fig. 2). Mean values of the soil input parameters have been considered. The figure refers to the period when shallow landslides triggered (between 32 and 48 h since the beginning of the rainfall): after this time span, the scenarios keep steady, following the trend of modelled pore water pressure (Fig. 10 of the original paper). The results were the same considering as mapping either a geological or a pedological zoning. In both the reconstructions, shallow landslides scarps fell in areas modelled by TRIGRS-Unsaturated as unstable (Fig. 2). Instead, there is an overestimation of the unstable areas in both the reconstructions linked to the fact that the slope angle is quite steady along the hillslope (between 30 and 35°). It seems that an higher resolution of the DEM does not provide an improvement on the identification of stable and unstable areas in the sample slope.

According with the suggestion of the Reviewer, we will translate the paragraph 3.3 about the description of TRIGRS-Unsaturated model in an Appendix section to improve the readability of the paper.

We will add the following reference to the original paper:

Alvioli, M., Guzzetti, F., and Rossi, M.: Scaling properties of rainfall induced landslides predicted by a physically based model, Geomorphology, 213, 38–47, doi:10.1016/j.geomorph.2013.12.039, 2014. Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervas, J., and Smith, J. T.: Recommendations for the quantitative analysis of landslide risk, Bull. Eng. Geol. Environ., 73, 209-263, 2014. Godt, J.W., Baum, R.L., and Lu, N.: Landsliding in partially saturated materials, Geoph. Res. Let., 36, doi:10.1029/2008GL035996, 2009. Mergili, M., Marchesini, I., Alvioli, M., Metz M., Schneider-Muntau, B., Rossi, M., and Guzzetti, F.: A strategy for GIS-based 3-D slope stability modelling over large areas, Geosci. Model Dev., 7, 2969–2982, doi: 10.5194/gmd-7-2969-2014, 2014. Raia, S., Alvioli, M., Rossi, M., Baum, R.L, Godt, J.W., and Guzzetti, F.: Improving predictive power of physically based rainfall-induced shallow landslide models: a probabilistic approach, Geosci. Model Dev., 7, 495–514, doi: 10.5194/gmd-7-495-2014, 2014.

On the other hand, we will delete the following references:

Lu, N. and Godt, J. W.: Infinite-slope stability under steady unsaturated seepage conditions, Water Resour. Res., 44, W11404, doi:10.1029/2008WR006976, 2008. Simoni, A., Berti, M., Generali, M., Elmi, C., and Ghirotti, M.: Preliminary result from pore pres20 sure monitoring on an unstable clay slope, Eng. Geol., 73, 117–128, 2004. Smethurst, J. A., Clarke, D., and Powrie, D.: Factors controlling the seasonal variation in soil water content and pore water pressures within a lightly vegetated clay slope, Geotechnique, 62, 429–446, 2012. Qiu, C., Esaki, T., Xie, M., Mitani, Y., and Wang, C.: Spatiotemporal estimation of shallow landslide hazard triggered by rainfall using a three-dimensional model, Environ. Geol., 52, 1569–1579, 2007. Wu, W. and Sidle, R. C.: A distributed slope stability model for steep forested hillslopes, Water Resour. Res., 31, 2097–2110, 1995.

Please also note the supplement to this comment:

http://www.nat-hazards-earth-syst-sci-discuss.net/2/C3435/2015/nhessd-2-C3435-2015-supplement.pdf

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Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 7409, 2014.

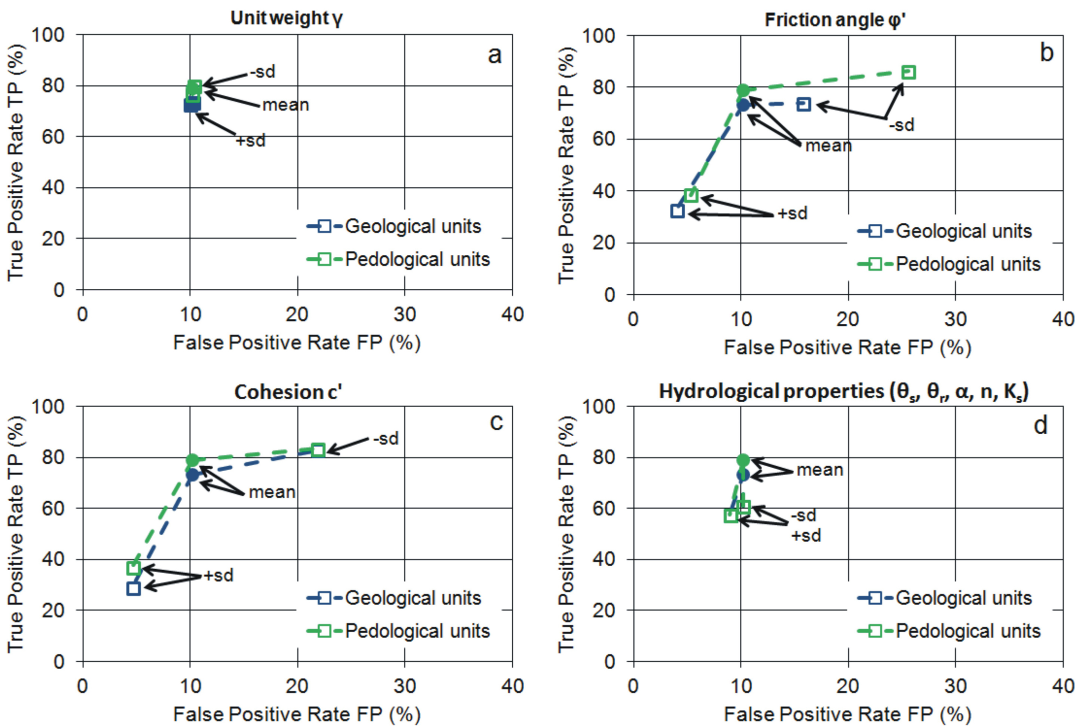

Fig. 1. Effects of different soil input data on FP and TP indexes obtained modeling with TRIGRS-Unsaturated considering the values in Table 5.

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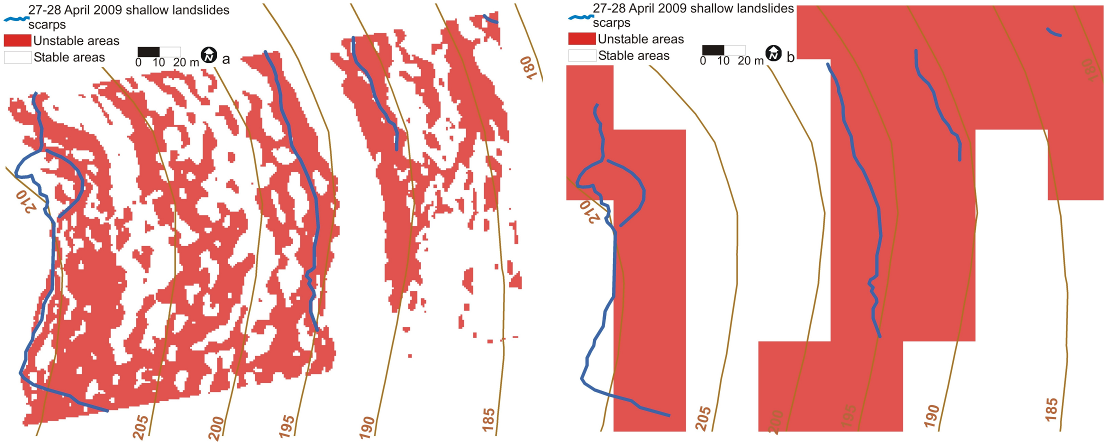

Fig. 2. Modeled scenarios for 27–28 April 2009 event for the monitored slope using different DEMs with grid size of 2 m x 2 m (a) and 10 m x 10 m (b).

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