Application of a physically-based model to forecast shallow landslides at regional scale

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Abstract.

In this work, we apply a physically-based model, namely the HIRESSS (High REsolution Stability Simulator) model, to forecast the occurrence of shallow landslides at regional scale. HIRESSS is a physically based distributed slope stability simulator for analysing shallow landslide triggering conditions during a rainfall event. The software is made of two parts: hydrological and geotechnical. The hydrological model is based on an analytical solution of an approximated form of the Richards equation while the geotechnical stability model is based on an infinite slope model that takes into account the unsaturated soil condition. The test area is a portion of the Valle d'Aosta region, located in North-West Alpine mountain chain. The geomorphology of the region is characterized by steep slopes with elevations ranging from 400 m a.s.l of Dora Baltea's river floodplain to 4810 m a.s.l. of Mont Blanc. In the study area, the mean annual precipitation is about 800-900 mm. These features lead to the territory to be very prone to landslides, mainly shallow rapid landslides and rock falls. In order to apply the model and to increase its reliability, an in-depth study of the geotechnical and hydrological properties of hillslopes controlling shallow landslides formation was conducted. In particular, two campaigns of on site measurements and laboratory experiments were performed with 12 survey points. The data collected contributes to generate input map of parameters for HIRESSS model. In order to consider the effect of vegetation on slope stability, the soil reinforcement due to the presence of roots has been also taken into account based on vegetation maps and literature values of root cohesion. The model was applied in back analysis on two past events that have affected Valle d'Aosta region between 2008 and 2009, triggering several fast shallow landslides. The validation of the results, carried out using a database of past landslides, has provided good results and a good prediction accuracy of the HIRESSS model both from temporal and spatial point of view.

1 Introduction

Landslide prediction at regional scale can be performed following two approaches: a) rainfall thresholds based on statistical analysis of rainfall and landslides and b) physically-based deterministic models. While the first approach is currently extensively used at regional scale (Aleotti, 2004; Cannon et al., 2011; Martelloni et al., 2012; Rosi et al., 2012; Lagomarsino et al., 2013), the latter is more frequently applied at slope or catchment scale (Dietrich and Montgomery, 1998; Pack et al., 2001; Baum et al., 2002, 2010; Lu and Godt, 2008; Simoni et al., 2008; Ren et al., 2010; Arnone et al., 2011; Salciarini et al., 2012, 2017; Park et al., 2013; Rossi et al., 2013). The poor knowledge of hydrological and geotechnical parameters spatial distribution, caused by the extreme heterogeneity and inherent variability of soil at large scale (Mercogliano et al., 2013; Tofani et al., 2017), mainly avoid the physically-based model application at regional scale. On the other hand, physically-based models allow to predict spatially and temporally the occurrence of landslides with high accuracy producing accurate hazard maps that can be of help for landslide risk assessment and management.

In this work, we apply the physically based model, named HIRESSS (Rossi et al., 2013) in Eastern part of Valle d'Aosta region (Italy), in North-West Alpine mountain chain in order to test the capacity of the model to forecast the occurrence of shallow landslides at regional scale. In particular, the objectives of the work are: i) to properly characterise the geotechnical and hydrological parameters of the soil to feed the HIRESSS model and to spatialize this punctual information in order to have spatially-continuous maps of the model input data ii) to test the HIRESSS code for two selected rainfall events that have triggered several shallow landslides and to validate the model results. HIRESSS is a physically based distributed slope stability simulator for analysing shallow landslide triggering conditions in real time and in large areas using parallel computational techniques. In the area selected, an in-depth study of the geotechnical and hydrological properties of hillslopes controlling shallow landslides formation was conducted, performing two campaigns (12 survey points) of in-situ measurements and laboratory tests. Furthermore, the HIRESSS model has been modified to take into account the effect of the root reinforcement to the stability of slopes based on plant species distribution and literature values of root cohesion.

2 Study area and rainfall events

The study area, called alert Zone B by the regional civil protection authorities, is located in eastern part of Valle d'Aosta region, in North-West Alpine mountain chain (Fig. 1). The area is characterized by three main valleys: Champorcher valley, Gressoney or Lys valley, and Ayas valley. The first is located on the right side of Dora Baltea water catchment, and represents the southern part of the study area. The second and third valleys show N-S orientation, and they are delimited to north by Monte Rosa massif (4527 m a.s.l) and to south by Dora Baltea river.

From a geological point of view, the Valle d'Aosta is located NW with respect to the Insubrica Line, in particular, there are three systems of Europa chain: the Austroalpino, the Pennidiche and the Elvetico-Ultraelevato systems (De Giusti, 2004). Fig. 2 shows the lithological map of the study area obtained by reclassifying the geological units according to 11 lithological groups: landslides, calcareous schist, alluvial deposits, glacial deposits, colluvial deposits, glacier, granites, mica schists, green stone, black schists and serpentinites. In detail in the study area the main lithologies outcropping are metamorphic and intrusive rocks, in particular granites, metagranites, schists and serpentinite.

The geomorphology of the region is characterized by steep slopes and valleys shaped by glaciers. The glacial modelling is shown in the U-shaped of Lys and Ayas valleys, and the erosive depositional forms found in the Ayas valley. The three valleys' watercourses, the Lys creek, the Evançon creek, and the Dora Baltea river, contributed to the glacial deposits modelling with the formation of alluvial fans. The climate of the region is characterized by high variability strongly influenced by altitude (ranging from 400 m a.s.l of Dora Baltea's river floodplain to 4810 m a.s.l. of Mont Blanc), with a continental climate in the valleys floor and an Alpin climate at high altitudes.

The slope steepness, together with mean annual precipitation of 800-900 mm are the main landslide triggering factors. These features lead the study area to be prone to landsliding, in particular rock falls, deep seated gravitational slope deformations (DSGSD), rocks avalanches, debris avalanches, debris flows, and debris slides (Catasto dei Dissesti Regionale – form Val d'Aosta Regional Authorities). In this work we model the triggering conditions of shallow landslides, i.e. soil slips and translational slides and we do not take into account the other types of movement.

The HIRESSS model simulated two past events, one in 2008 and one in 2009, and the validation of the model performance was carried out comparing the results with the landslide regional database.

In particular:

- 24 - 31 May 2008: on 28 and 29 May 2008 intense and persistent rainfall was recorded across the Valle d'Aosta region with a total precipitation in the study area of about 250 mm causing flooding, debris flows and rockfalls.
- 25 - 28 April 2009: from 26 April to 28 April 2009 heavy rainfall affected the south-eastern part of the Valle d'Aosta region, with the highest precipitation recorded at the Lillianes Granges station of about 268 mm. This precipitation triggered several landslides.

3 Methodology

3.1 HIRESSS description

The physically-based distributed slope stability simulator HIRESSS (Rossi et al., 2013) is a model developed to analyse shallow landslide triggering conditions on large scale at high spatial and temporal resolution using parallel calculation method. Two parts compose the model: hydrological and geotechnical (Rossi et al., 2013). The hydrological part is based on a dynamical input of the rainfall data which are used to calculate the pressure head and provide it to the geotechnical stability model. The hydrological model is initiated as a modelled form of hydraulic diffusivity, using an analytical solution of an approximated form of the Richards equation under the wet condition (Richards, 1931). The equation solution allows us to calculate the pressure head variation (h), depending on time (t) and depth of the soil (Z). The solutions are obtained by imposing some boundary conditions as described by Rossi et al. (2013).

The geotechnical stability model is based on an infinite slope stability model. The model considers the effect of matric suction in unsaturated soils, taking into account the increase in strength and cohesion. The stability of slope at different depths (Z values) is computed since the hydrological model calculates the pressure head at different depths. The variation of soil mass caused by water infiltration on partially saturated soil is also modelled. The original FS equations (Rossi et al., 2013) were modified taking into account the effect of root reinforcement (c_r) as an increase of soil cohesion (c') according to the Eq. 1:

$$c_{tot} = c' + c_r$$

(1)

Regarding the geotechnical influence of roots on the soil strength, roots seem to affect the cohesion parameter only, while the friction angle would be poorly or not at all interested by reinforcement (Waldron and Dakessian, 1981; Gray and Ohashi, 1983; Operstein and Frydaman, 2000; Giadrossich et al., 2010). Therefore, is necessary to consider the root cohesion in calculating FS and consequently in applying HIRESSS model.

The root reinforcement (or root cohesion) can be considered equal to (Eq. 2):

$$c_r = kT_r(A_r/A)$$

(2)

where T_r is the root failure strength (tensile, frictional, or compressive) of roots per unit area of soil, A_r/A the root area ratio (proportion of area occupied by roots per unit area of soil), k a coefficient dependent on the effective soil friction angle and the orientation of roots. The measure of c_r varies with vegetal species, within a single species depends on how plants respond to environmental characteristics and fluctuations.

The new equation of FS at unsaturated conditions is therefore (Eq. 3):

$$FS = \frac{\tan\varphi}{\tan\alpha} + \frac{c_{tot}}{\gamma_d y \sin\alpha} + \frac{\gamma_w h \tan\varphi\{\left[1+\left(h_b^{-1}|h|\right)^{\lambda+1}\right]^{\frac{\lambda}{\lambda+1}}\}^{-1}}{\gamma_d y \sin\alpha} \tag{3}$$

where φ is the friction angle, α is the slope angle, γ_d is the dry soil unit weight, y is the depth, γ_w is the water unit weight, h is the pressure head, h_b is the bubbling pressure, and λ is the pore size index distribution. In saturated condition the equation of FS (Rossi et al., 2013) becomes (Eq. 4):

$$FS = \frac{\tan\varphi}{\tan\alpha} + \frac{c_{tot}}{(\gamma_d(y-h)+\gamma_{sat}h)\sin\alpha} - \frac{\gamma_w h \tan\varphi}{(\gamma_d(y-h)+\gamma_{sat}h)\tan\alpha} \tag{4}$$

where γ_{sat} is the saturated soil unit weight.

One of the major problems, associated with the deterministic approach employed on a large scale, is the uncertainty of the static input parameters or geotechnical parameters of the soil. The method used for the estimation of parameters spatial variability is the Monte Carlo Simulation. The Monte Carlo simulation achieves a probability distribution of input parameters providing results in terms of slope failure probability (Rossi et al., 2013). The developed software uses the computational power offered by multicore and multiprocessor hardware, from modern workstations to supercomputing facilities (HPC), to achieve the simulation in reasonable runtimes, compatible with civil protection real time monitoring (Rossi et al., 2013). The HIRESSS model loads spatially distributed data arranged as 12 input raster maps and the maps of rainfall intensity. These input raster maps are: slope gradient; effective cohesion (c'); root cohesion (c_r); friction angle (φ'); dry unit weight (γ_d); soil thickness; hydraulic conductivity (k_s); initial soil saturation (S); pore size index (λ); bubbling pressure (h_b); effective porosity (n); and residual water content (q_r). and rainfall intensity.

3.2 HIRESSS input data preparation

The input parameters can be divided in two classes: the static data and the dynamical data. Static data are geotechnical and morphological parameters while the dynamical data is represented by the hourly rainfall intensity. Static data are read only once at the beginning of the simulation while dynamical inputs are continuously updated.

The HIRESSS input are in raster, therefore point data and parameters have to be adequately spatially distributed. In this application the spatial resolution was 10 m.

Static data

The slope gradient was calculated from the DEM (Digital Elevation Model). The DEM has a resolution of 10 m and is dated 2006. Effective cohesion, friction angle, hydraulic conductivity, effective porosity and dry unit weight, were obtained, spatializing according to lithology, the soil punctual parameters derived from the in situ and laboratory geotechnical tests and analysis.

In particular, the properties of slope deposits were determined by in situ and laboratory measurements (Bicocchi et al., 2016; Tofani et al., 2017) at 12 survey points. To carry out the in situ tests the survey points were selected following these characteristics: i) physiography, ii) landslides occurrence, and iii) geo-lithology (Fig. 2). Regarding the first point, a high-resolution DEM (from Val d'Aosta Regional Authorities) together with a careful first surveys were used to identify the most suitable slopes. The surveys took place in two sessions, the first one in August 2016, and the second one in September 2016. The following analyses were conducted:

- registration of geographical position using a GPS and photographic documentation of the site characteristics (morphology and vegetation);
- in situ measurement of saturated hydraulic conductivity (k_s) by means of the constant-head well permeameter Amoozemeter;
- sampling of an aliquot (~2 kg each) of the material for laboratory tests, including grain size distributions, index properties, Atterberg limits and direct shear tests.

The permeability in-situ measurements and the soil samplings were made at depth ranging from 0.4 to 0.6 m below the ground level. The evaluation of the k_s (saturated hydraulic conductivity or permeability) was made with the *Amoozemeter* permeameter (Amoozegar, 1989). The measurement was obtained by observing the amount of water required to maintain a constant volume of water into the hole. In situ measurements are then applied into the Glover solution (Amoozegar, 1989), which calculates the saturated permeability of the soils. The k_s is a very useful parameter not only for slope stability modelling but also for many other hydrological problems (groundwater, surface water runoff and sub-surface, flow calculation of water courses).

In addition, the *in situ* collected samples were examined in the laboratory to define a wide range of parameters to characterize more extensively the deposits. In particular, the following tests were performed in order to classify the analysed soils:

- grain size distribution (determination of granulometric curve for sieving and settling following ASTM recommendations), and classification of soils (according to AGI and USCS classification, Wagner, 1957);
- determination of the main index properties (porosity, relationships of phases, natural water content w_n, natural and dry unit weight γ and γ_d) following the ASTM recommendations;
- determination of Atterberg limits (liquid limit LL, plastic limit PL, and plasticity index PI);
- direct shear test on selected samples.

Soil thickness was calculated by the GIST model (Catani et al., 2010; Del Soldato et al, 2016). Soil characteristic curves parameters (pore size index, bubbling pressure, and residual water content) were derived from literature values (Rawls et al., 1982).

Root cohesion variations in the area (at the soil depth chosen for the physical modelling with HIRESSS) were obtained firstly, identifying the plant species and determining their distribution from *in situ* observations and vegetational maps (Carta delle serie di vegetazione d'Italia, Italian Ministry of the Environment and Protection of Land and Sea). Then, the measure of cohesion due to the presence of roots was assigned to each subarea according to the dominant plant species and literature root cohesion for that species (Bischetti, 2009; Burylo et al., 2010; Vergani et el., 2013, 2017) that were calculated considering the Fiber Bundle Model (Pollen et al., 2004). The measure of c_r varies with vegetal species, within a single species depends on how plants respond to environmental characteristics and fluctuations, so map of root cohesion variations obtained as mentioned is a simplification of reality. This is a necessary simplification as the known methods to evaluate root cohesion variations are not suitable for wide areas and acceptable measurement times.

The last static input data, in this case of study, is the exposure rock mask. This was defined considering the lithological and land use maps, so that HIRESSS model avoided the simulation on steep slopes made of bare rocks.

The geotechnical properties and root cohesion of the soils have been spatialized with respect to a lithological classification.

For each lithological class and plant species the mean value has been selected in order to obtain the HIRESSS input raster parameters.

Dynamic data

In the study area, the rainfall hourly data from 27 pluviometers were available, therefore it was necessary to spatially distribute them to generate 10x10 m cell size input raster to ensure the correct program operation. The rainfall data were elaborated applying the Thiessen's polygon methodology (Rhynsburger, 1973) modified to take into account the elevation. Thiessen's polygon methodology, in fact, allows us to divide a planar space in some regions, and to assign the regions to the nearest point feature. This approach defines an area around a point, where every location is nearer to this point than to all the others. Thiessen's polygon methodology do not consider the morphology of the area, so the alert Zone B was divided in three catchment areas and the polygons were calculated for each rain gauges considering the reference catchment basin (Fig. 3).

4 Results

4.1 HIRESSS input data

The results of the geotechnical and hydrological characterization of the soils of the 12 survey points are shown in Table 1 for all survey sites.

The results of granulometric tests show that the analysed soils are predominantly sands with silty gravel (Fig. 4 and Table 1). Regarding the index properties, the natural soil water content values were predominantly about 20% by weight, with a maximum and minimum values of 5.1% and 26.2%, respectively. These values reflect their different ability to hold water in their voids. The measured natural unit weight (γ) was variable between 15.3 kN/m^3 and 21.7 kN/m^3, depending not only on the different grain size distribution but also by different thickening and consolidation states. Regarding saturated unit weight (γ_{sat}) the measured values range between 18.2 kN/m^3 and 21.5 kN/m^3 (Table 1).

The Atterberg limits (LL and PL) were measured on samples with a sufficient passing fraction (> 30% by weight) through 40 ASTM (0.425 mm) sieve. For sandy prevalent samples, LL values are predominantly around 40% of water content (% by weight), while the PL is around 30% (Table 1).

The effective friction angle varies between a minimum of 25.6° and a maximum of 34.3°, while the effective cohesion ranges from a minimum of 0.0 kPa to a maximum of 9.3 kPa. Consistent with the presence of sandy soils, the saturated permeability values were around a medium-high value of 10^{-6} m/s. The minimum and maximum values were found between $1.36 \cdot 10^{-7}$ m/s and $1.54 \cdot 10^{-5}$ m/s. Considering the poor variability of samples, the permeability values were relatively homogeneous and in accordance with the values reported in the literature (Table 1).

The additional cohesion induced by roots assumes different values not only depending on plant species and environmental characteristics, but also on depth of soil, as roots diameter and density vary with latter. Because of such evidence, studies on roots cohesion of different species report values as function of depth of soil. In the area of the case study, soils have thinner thickness than those ones in which these studies are carried out. In such thin soils, root systems organize their growth depending on available space not reaching the same depth of roots of thick soils. Consequently, in this context root cohesion of species at the different depth is dissimilar related to literature values. Considering this, map for variation of root cohesion is processed taking for each species the minimum cohesion (among those specified for each species at the different depth) reported in literature. By doing this, contribution of vegetation to stability of slopes is considered in FS calculate and at the same time, it is avoided an overestimate of root cohesion.

In the area, root cohesion defined as mentioned above ranges from a minimum of 0.0 kPa (mainly in the outcrop area) to maximum of 8.9 kPa (area occupied by mountain maple on the left bank of river Dora Baltea).

In Table 2, the mean values of each input parameters respect to lithological class were reported.

The pore size index, bubbling pressure and residual water content are constant in whole area of: 0,322 (-); 0,1466 m and 0,041 (-), respectively.

The distributed soil parameters maps are shown in Fig. 5. The results of rainfall data elaborated using Thiessen's polygon methodology are 192 and 96 rainfall hourly maps for the 2008 and 2009 event, respectively. In Fig. 6 are reported the cumulative maps of each event.

4.2 HIRESSS simulation

The HIRESSS model has simulated two past events; one in 2008 (24 - 31 May) and the other in 2009 (25 - 28 April) which have triggered several landslides in the study area.

The HIRESSS input data have been inserted in the HIRESSS model to obtain day-by-day maps of landslide occurrence probability. The main characteristics of simulation are shown in Table 3.

The results of the simulations for both events have shown that the first day of simulation pixels with high probability of occurrence in absence of rainfall. These pixels are false positive, (i.e. pixels identified unstable by the model but not real unstable) because of morphometric reasons, predominantly high slope angles. To remove these false positive, a numeric mask was applied. Using the GIS software commands, it was possible to calculate the number of pixels of the first simulation day with a trigger probability value greater than 80% and delete them (Fig. 7). The mask was then applied to the rest of landslide occurrence probability maps. The resulting maps for each days of the simulated events are shown in the Fig. 8 and Fig. 9.

The results of the first simulated event (24 - 31 May 2008) are shown in Fig. 8. The failure probability in the whole area is negligible for the first four days (from 24 to 27 May 2008) (Fig. 8a). The rainfall intensity increased since 27 May, reaching the highest value on 29 May, when the precipitation value was around 100 mm in the eastern sector of study area. The HIRESSS model well simulate this passage: the 28 May and 29 May 2008 landslide occurrence probability maps show a considerable increase of the probability of failure with maximum values around 90% at the East of alert Zone B (Fig. 8b, c). In the following days rainfall intensity decreases, and also the probability slowly decreases, being anyway still high on 30 May 2008.

Concerning the second event (25 - 28 April 2009) landslide occurrence probability is negligible for the first two days (25 and 26 April 2009) in the whole area (Fig. 9a, b), because of the low rainfall intensity. From 27 April 2009 rainfalls become more intense, especially in the southeast sector of the region, where the cumulated rainfall average was about 151 mm. The probability maps show high values during these days (Fig. 9c, d). This event led to many landslides triggered during these days (as reported in the database).

In order to validate the HIRESSS simulations the database of landslides triggered during the two events have been compared with the models results.

In general, for both events temporal validation shows that the daily highest probability of occurrence, computed by HIRESSS, correspond with the days with landslide occurrence and with the most intense precipitation.

For the first simulated event landslides reported in the database are dated 30 May and 31 May 2008 (Fig. 8d) which correspond to the days with highest probability of occurrence. The same is for the second event; many landslides have triggered during 27 and 28 April 2009 (as reported in the database).

In Table 4 the results over 75% of slope failure probability for both events are highlighted and confirm the correct temporal occurrence of landslides. In particular we can notice that for the first event (2008) the number of unstable pixel (failure probability > 75%) increases the 29th of May with a total extension of the unstable area of about 24 km^2, while for the event of 2009, the number of unstable pixel increases the 27th of April with an extension of 33 km^2.

The temporal validation was also carried out considering daily cumulative rainfall compared to the landslide failure probability. In particular, a median of landslide occurrence probability was calculated for four pluviometric areas identified by Thiessen's polygons methodology, modified according to limits of river basins, both for the event of May 2008 and for the April 2009 event (Fig. 10a, b). As it could be expected, the results show that when the highest rainfall intensity is measured, the highest probability of occurrence is computed for the all areas and for both events.

Spatial validation was performed following a pixel by pixel method: this method is the most complex since it consists in comparing the probability of instability of each pixel with the pixels involved in the actual event that occurred. This validation implies a great deal of uncertainty in the results since the reports of landslide events may have errors on the precise spatial location and on the size of the phenomenon. To overcome this problem and taking into account probable errors caused by the actual spatial location in the database, an area of 1 km^2 (called influence area) around the point of the landslide were considered in the validation analysis. Inside the influence area, pixels that have the 75% of probability of failure were considered instable.

Figure 11 shows an example of landslide event occurred in the Arnad municipality on 30 May 2008. The model computes a low failure probability on 24 May 2008 and an increase of probability on 30 May 2008. In Fig. 11a and b it is possible to note that inside the red circle the red and yellow area increase on 30 May with respect to 24 May. In this case, the model is able to identify correctly such movement. To better highlight this validation, Figure 11c shows the number of pixels above 75% of probability calculated by the model, within the circular area of about 1 km^2 around the all landslides occurred during the event of 2008. For some of the reported landslide events, the number of pixels above 75% increases on 30 May 2008, only in case of the Champdepraz and Montjovet 2 events the probability does not increase. This may be caused by the low precision of location of the reported landslide, and maybe because some of the real landslides reported are other types of movements (rockfalls, rotational slides) that cannot simulated by the HIRESSS model.

5 Discussion

The application of the HIRESS model to a portion of the Valle D'Aosta region has provided good results in term of spatial and temporal accuracy of the model as highlighted in section 4.2. The advantage of the regional physically-based model, with respect to rainfall-thresholds one, is that is possible to predict with metric spatial resolution and hourly temporal resolution the occurrence of shallow landslides.

On the other hand, the application of the HIRESSS model has highlighted some important drawbacks, mainly related to the i) validation of the models results, ii) uncertainty of the input parameters.

Validation of the model results

To perform a solid validation is necessary to have information on spatial location and temporal occurrence of landslides. In particular, the time of occurrence is very rarely known with hourly precision, and usually landslides are related to a rainstorm, without any more precise information on time of occurrence (Rossi et al., 2013). Concerning the spatial landslides locations, in many cases they are included in the database only as points without any information on the area involved. In our database, provided by the local authorities, landslides are points with information on the day of occurrence.

In synthesis the main problems encountered during the model validation are:

- Incompleteness of landslide dataset: in general event-based database are incomplete due to a lack of reporting in mountainous areas scarcely populated while most of reported landslides involve infrastructure or water streams (Mercogliano et al., 2013, Tofani et al., 2017). In our case we have two datasets for the two events simulated (2008 and 2009) with 9 and 11 landslides respectively. The number of reported landslides is very low and not suitable to perform a correct validation for the whole area. Infact in both events there are some areas that show an high failure probability even though there are no landslides reported. For example for the 2008 event (Fig. 8), the municipalities of Gressoney Saint Jean and Gaby in the NE portion of the study area and the municipalities of Pontboset and Issogne in south part of the study area show high failure probabilities (> 75%) but no landslides reported. The same happens for the event of 2009 (Fig. 9) when again Gressoney Saint Jean and Pontboset as well as Lillianes and Fontainemore in the SE portion of the study area show high failure probabilities but no recorded landslides. In these cases, we are not able to discriminate if the model has overestimated the landslide occurrence or it has correctly predicted landslide occurrence since we are not sure about the completeness of the database.
- Correct spatial location: In our validation landslide dataset the accuracy of the spatial location is very low and the landslides are reported as points (yellow dots in Fig. 8 and Fig. 9). Anyway we don't know exactly if these points correspond to the triggering area, that would constitute the desirable situation, or the deposition one or, even worst, to the position of the elements at risk (house, road, river) interested by the landslides. For this reason, we have performed the spatial validation considering an area of 1km^2 around the point in order to take into account the error in the spatial location of the landslides (Fig. 11). In these cases of uncertain position of the landslides, an alternative solution could be to perform a validation aggregating the results using different spatial units, for example first or second order basins as proposed in Rossi et al., (2013). If the spatial aggregation overcome the problem of the correct location of the landslides for the validation, on the other hand it allows to loss the high spatial resolution of the HIRESSS model that is on the major benefit of the analysis. The ideal situation would be to have a landslide database realized with the same resolution of the HIRESSS model.
- Temporal occurrence: The event landslide database has the information concerning the day of the occurrence of the landslides. The HIRESSS has a higher temporal resolution since it is able to provide hourly failure probability maps (Table 3). In order to make a temporal validation, model outcomes have been temporally aggregated in daily maps (Fig. 8 and Fig. 9).The results of the temporal validation are quite satisfactory, anyway due the insufficient information of the landslide database, we are not able to make a real validation of the model performance on hourly basis. Also in this case a satisfactory analysis of the model performance could have been carried out only if available information on the exact time of failure.

Uncertainty of the input parameters

Another important limitation related to the application and the accuracy of the physically-based model is the availability of detailed databases of physical and mechanical properties of soils in the study areas. The performance of a model can be strongly influenced by the errors or uncertainties in such input data (Segoni et al., 2009; Jiang et al., 2013). Furthermore, the punctual information of soil properties have to be spatialized and in general they are characterized by high spatial variability and their measurement is difficult, time-consuming and expensive, especially when working on large, geologically complex areas (Carrara et al., 2008; Baroni et al., 2010; Park et al., 2013; Bicocchi et al., 2016; Tofani et al., 2017).

In order to prepare the raster maps of the input data and to feed the physically based models, we have adopted a set of constant values of the parameter for distinct lithological units, as derived from direct measurements. In particular we have measured soils parameters in twelve survey points (Table 1, Fig. 2) and then we have spatialized the punctual data according to different lithologies (Table 2). Then, within the HIRESSS model the soil parameters are treated with the Monte Carlo simulation, using a equiprobable distribution for each of them.

The HIRESSS model, fed with these parameters has provided good results (section 4.2), although all the limitations of the validations process described above.

Anyway further analysis has to be carried out in the study area in order to define the impact of the uncertainties of the input parameters on model results and to set-up the correct approach to increase the efficiency of the model. In particular:

- Increase the number o survey points in order a sufficient number of points for each lithology;
- Use inside the Monte Carlo simulation of the normal Gaussian frequency model instead of equiprobable one for some soil parameters. The normal distribution model, when applicable, allow to obtain more accurate results than using an equiprobable one: given a mean value and a standard deviation obtained from the normally distributed samples analysed, extremely low or high values are associated to low probability of occurrence, moreover dramatically reducing the simulation time. (Bicocchi et al., 2016, Tofani et al., 2017);
- To test another approach to spatialize the soil parameters based for example on the soil parameters values as random variables using a probabilistic or stochastic approach as proposed by Fanelli et al., (2016) and Salciarini et al. (2017).

6 Conclusion

The HIRESSS code (a physically-based distributed slope stability simulator for analysing shallow landslide triggering conditions in real time and in large areas) was applied to the eastern sector of Valle d'Aosta region in order to test its capability to forecast shallow landslides at regional scale. The model was applied in back analysis to two past rainfall events that have triggered in the study areas several shallow landslides between 2008 and 2009. In order to run the model and to increase its reliability, an in-depth study of the geotechnical and hydrological properties of hillslopes controlling shallow landslides formation was conducted. In particular, two campaigns of on site measurements and laboratory experiments were performed with 12 survey points. The data collected contributes to generate input map of parameters for HIRESSS model according to lithological classes. The effect of vegetation on slope stability in terms of root reinforcement has been also taken into account based on the plant species distribution and literature values of root cohesion to product a map of root reinforcement of the study area. The outcomes of the model are daily failure probability maps with a spatial resolution of 10 m. To evaluate the model performance both temporal and spatial validation were carried out, and in general for both the simulated events the computed highest daily probability of occurrence corresponds to the days and the areas of real landslides.

The application has highlighted also some drawbacks that are mainly related to the validation of the model performance and to the uncertainty of the model input parameters. In particular, a satisfactory validation of the model is possible only if available a complete event database of landslides with spatial and temporal resolution equal to the HIRESSS model ones. On the other hand a correct geotechnical and hydrological characterization of the soil parameters as input data of the model, as well as a correct approach to spatialize the data are both fundamental to apply the model and to have sound result at regional scale.

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