SHALLOW LANDSLIDES SUSCEPTIBILITY MAPPING: COMPARISON OF DIFFERENT DETERMINISTIC METHODS

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1) INTRODUCTION

Shallow landslides are usually triggered by short-period but very intense rainfall events; they can cause widespread direct and indirect damage to the terrain, infrastructure, as well as urban and rural developments. Their high potential of causing damages and human losses make the assessment of the shallow landslides susceptibility an important issue for their forecasting.
An approach for the susceptibility assessment of the shallow landslide source areas consists on the physically based models. These models generally couple a hydrologic model, for the analysis of pore-water pressure regime, with an infinite slope stability model for the computation of the factor of safety (e.g. Montgomery and Dietrich, 1994; Pack et al., 1998; Baum et al., 2002). Oltrepo Pavese, which is located in the Northern Apennines of Italy, is characterized by high density of landslides and has historically suffered from widespread damage from landslides. The mass movements often developed in clayey-marly formations and are classified as complex movements. More recently extreme rainfall events have triggered shallow landslides in areas, which were not yet affected by these types of landslides. An important event happened subsequently to rapid snowmelt and intense rainfall in April 2009.
The main goal of this research is to evaluate the predictability of shallow landslide occurrence of April 2009 event using three physically based models: SHALSTAB (Montgomery and Dietrich, 1994), SINMAP (Pack et al., 1998) and TRIGRS (Baum et al., 2002) comparing them with the results obtained by a probabilistic way (Artificial Neural Networks). The results obtained from the three models are presented in order to highlight potential and limitation of these models for the forecasting of the potential source areas.

2) OLTREPO PAVESE TERRITORY

The Oltrepo Pavese, which is situated in Northern Italy, has an extension of about 1100 km². Its Southern part corresponds to the northwestern sector of the Apennines. The area is at heights of between 200 and 1,725 m a.s.l. and it is characterized by a complex geological and structural setting. The geology is dominated by sedimentary formations, with a dominant clay component. Clay shales (Varicoloured Clays, Chaotic Complex) outcrop throughout the Oltrepo Pavese area, while calcareous flysch, made up of alternating marls, calcareous marls, and scratched shales predominated in the eastern part. Silty and/or clayey deposits formed by weathering and down slope transportation cover the argillaceous bedrock units.
The pluviometric regime is substantially referable to the Apennine–Mediterranean type, characterized by dry summers and cold winters, with a primary peak of rainfall in autumn and a secondary maximum in spring. The mean annual temperature is 12°C. The average annual rainfall is around 700 mm in the plain and 998 mm in the hills with an increase of the rainfall amount from west towards east.

Fig.1 Location of the Oltrepo Pavese county and geological map of its eastern sector.

3) APRIL 2009 ESTREME RAINFALL EVENT IN OLTREPO PAVESE: EFFECTS ON THE LANDSCAPE

The 27th and 28th April 2009 the north-eastern sector of Oltrepo Pavese experienced extreme rainfall event. On April 28th a rain-gauge station (Cigognola) recorded 160 mm of rain in 62 h (20% of the annual average amount) with maximum 22 mm/h rainfall intensity. The April 2009 event occurred after a rather wet winter season with intense snowfall. The rainfall data show a distinct rainfall peak occurred at 9 p.m. (Fig.2); after this peak several shallow landslides were triggered which have caused fatal victim and damaged/blocked roads in several places.

Fig.2 Histogram of rainfall intensity during 2009 April 27th-28th heavy rainfall event.

Color aerial photographs taken immediately after the events in north-eastern part of Oltrepo Pavese with a spatial resolution of 15 cm were studied in order to map the existing landslides. Detailed field surveys have been carried out in order to detect:
- slope failures characteristics;
- site geomorphology;
- the thickness of failed soils;
- the presence of absence of groundwater seepage ;
- the location of landslides with respect to land use.
For some landslides a detailed stratigraphic profile was constructed and samples for laboratory investigations ((i) assessment of the physical parameters of materials (grain size distribution, bulk and dry densities and Atterberg Limits), (ii) standard geotechnical tests (direct shear tests)) were also collected.
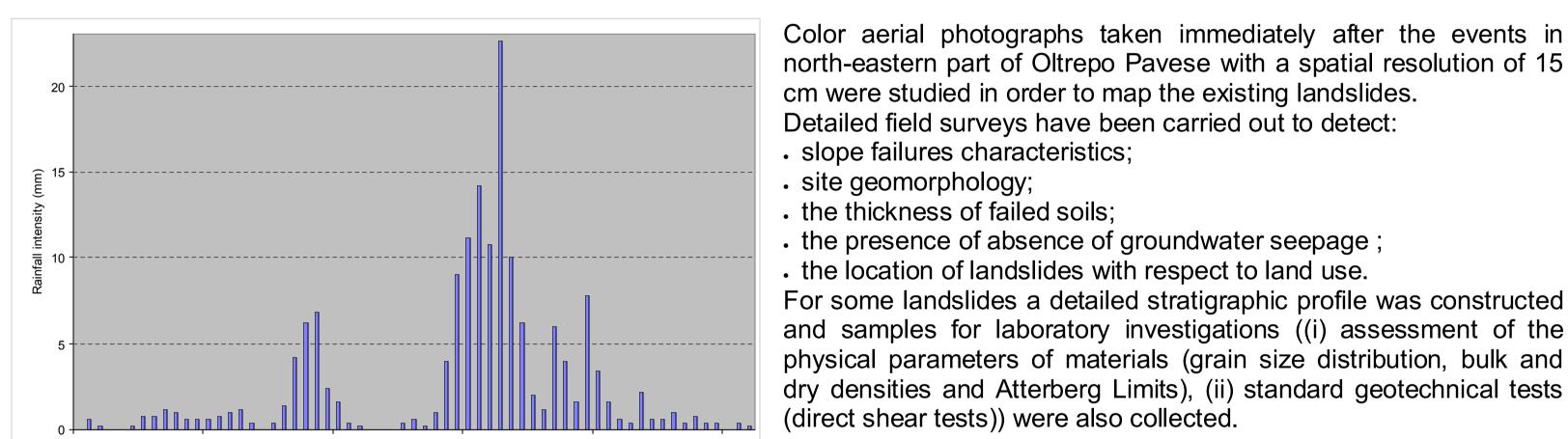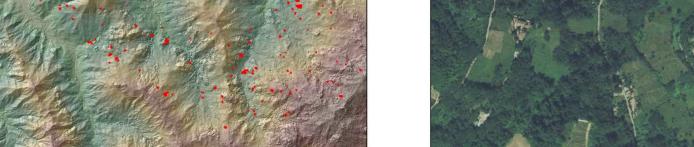

Fig.3 High resolution aerial image of the landslide in the Recoaro valley that completely destroyed a house causing one victim.

Aerial photo-interpretation coupled with field surveys revealed that the rainfall event of April 2009 triggered about 1,600 landslides in the north-eastern sector of Oltrepo Pavese (Fig.4). At least 492 landslides occurred in the Recoaro valley and adjacent areas (Fig.6).
Field observations indicated that the slides occurred mainly in colluvial soils. Most of the slides were shallow (thickness usually from 0.5 to 2 m) with the failure surface located along the contact between colluvial cover and the weathered bedrock; sometimes they reach completely the depth of bedrock.
Landslides appear on SW-NE oriented slopes and were observed in the slope range from 16° to 37°. The landslide frequency is higher for slope angles between 25°-30° and tends to decline with an increasing or decreasing slope angle. Most of the landslides tended to be concentrated in areas of slope angle change (e.g., from a gentle slope to a steep slope).
Generally landslides occurred in correspondence of slope angle changes which also correspond to changes in land use (from gentle slope with vineyards to steep slopes with wood-land).
Changes in land cover have played major role in landslide occurrence and distribution in the study area. From 1980 to 2009 woodland increased from 8% to 45% as a consequence of recolonisation of abandoned vineyards. "Woodlands" are then composed by trees and shrubs developed on abandoned vineyards and they are less than 20 years old. The roots extend generally in the first meters of the soil profile and are involved in the landslide. In the abandoned vineyards the old tillage pattern oriented across the maximum slope gradient allow also the concentration of water. This explains the occurrence of a great number of landslides in correspondence of the woodlands.

Fig.4 All the 1600 landslides occurred on April 2009.

Fig.5 The Recoaro valley in late spring 2008.

Fig.6 The Recoaro valley few days after the storm.

Fig.7-10 April 29th 2009 morning: the road at the bottom of the Recoaro valley was completely covered by mud. Several buildings were damaged and one person was found dead.

4) TEST AREA: THE RECOARO VALLEY

A test area, corresponding the surrounding of the Recoaro valley, with an extension of 17.5 km², was selected in the sector of Oltrepo Pavese with the highest density of the April 2009 landslides. The test site slopes are characterized by medium-high gradient (40% of the area have slope gradient higher than 15° - Fig.12) and are made up of marls (S. Agata Fossili Marls) and of gravel, sand and poorly cemented conglomerates (M. Arzolo Sandstones and Rocca Ticozzi Conglomerates - Fig.11).

A small portion of the area is characterized by the presence of Gessoso-Solfifera Formation (marls, sandy marls and vacuum limestones with lens of gypsum-rudites containing gypsum selenite). The strata dip towards the E-NE. Colluvial soils, derived by the weathering of the bedrock, have a thickness ranging from 0.5 to 2-3 m at the bottom of the valley.
The geotechnical characterization of colluvial deposits was based on standard soils analysis conducted according to the ASTM standard. The performed tests include (i) assessment of the physical parameters of materials (grain size distribution, bulk and dry densities and Atterberg limits), (ii) standard geotechnical tests (direct shear tests). On the basis of grain-size distribution (Fig.13), the colluvial soils derived by the weathering of the S.Agata Fossili Marls were classified as clayey silt; the colluvial soils derived by the weathering of M. Arzolo Sandstones and Rocca Ticozzi Conglomerates were classified as clayey sandy silt (the percentage of sand fraction is up to 13-17%). According to USCS classification the majority of the analyzed samples are non plastic or slightly plastic soils (CL). Coarse fragments consisting in marls or sandstone derived from the underlying bedrock are also present in the colluvial deposits.
In particular, dry density ranges between 15 kN/m³ and 16.3 kN/m³ and porosity ranges between 0.38 and 0.48. Shear strength parameters, which have been determined through direct shear tests on 15 samples, show a friction angle in the range of 23°÷32° (the highest values correspond to the colluvial soils of the Rocca Ticozzi Conglomerates and M.Arzolo Sandstones formations); the effective cohesion ranges between 0 kPa and 10 kPa (Fig.14).

Fig.11 Homogeneous region used for modeling.

Fig.12 Slope map derived from DEM.

Fig.13 Grain size distribution curves of soils.

Fig.14 Shear stress diagrams.

5) DESCRIPTION OF THE USED MODELS

SINMAP outputs the stability index value (SI). The stability index is defined as the probability that a location is stable assuming uniform distributions of the parameters over the uncertainty ranges. This value range between 0 (most unstable) and 1 (stable). Where the most conservative set of parameters (i.e. the set with the most unfavorable combination of parameters for stability) in the model results in stability, the stability index is defined as the factor of safety at this location.

SHALSTAB predicts the steady state rainfall necessary for slope failure throughout a study area. The output is represented by critical rainfall qcr: areas with lower qcr are interpreted as more susceptible to shallow landsliding, whereas areas with higher qcr are interpreted as more stable, as a less frequent rainfall event would be required to cause instability. Thus the spatial distribution of critical rainfall expresses the potential for shallow landslide initiation. If tanθ (θ=slope angle) equals or exceeds tanφ (φ=soil friction angle) slope instability will occur even under dry conditions according to the model. This category of instability is called "chronic". If tanθ<tanφ (1−pw/ps) (ps=wet soil density, pw=the density of water), then slope stability is unlikely as ground is not expected to fail even at saturation. Grid cells falling into this category are ranked as "stable".

TRIGRS (Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis) model is coded in Fortran and is designed for modeling the potential occurrences of shallow landslides by incorporating the transient pressure response to rainfall and downward infiltration processes (Baum et al., 2002; Baum et al., 2008). Under assumption of saturated or tension-saturated initial soil conditions, the TRIGRS program computes transient pore-pressure changes to find analytical solutions to partial differential equations, representing one-dimensional vertical flow in isotropic, homogeneous materials due to rainfall infiltration from storms with durations ranging from hours to a few days. The TRIGRS program uses an infinite-slope model to compute a factor of safety (FS) calculation for each grid cell.

ANNET landslide susceptibility model employed in this study is based on the general concept of slope stability considering multiple factors acting on slopes, some of which can cause weakness and produce failure, whereas other factors strengthen the slope and thereby protect against movement (Ermini et al., 2004; Gómez and Kavzoglu, 2005). A three-layer artificial neural network structure (Multilayer Perceptron, MLP), has been applied to the study area using Trajan 6.0 software and coupling as inputs terrain parameters derived from DEM (slope, ruggedness, slope position, landform classification, etc.) and geological-geotechnical characteristics. Many networks have been developed using back propagation algorithm for testing. The best one in term of accuracy was selected and the ROC curve (Beguería, 2006, Cervi et al., 2010) was used to compute the second derivative, in order to obtain appropriate susceptibility classes.
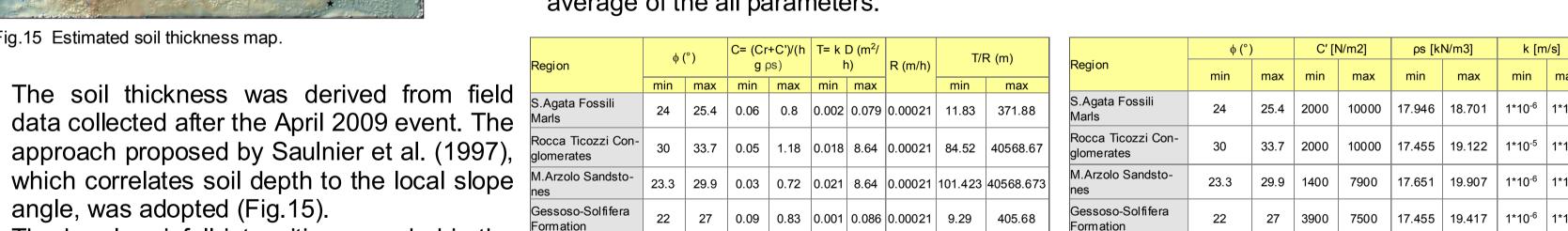
6) INPUT DATA

- A Digital Elevation Model (DEM) with grid size of 10×10 m provides the topographic basis.
- For the analysis with TRIGRS and SINMAP the study area was divided into 4 regions, characterized by quite homogeneous in situ conditions and soil properties (Fig.11, Tab.1, 2) and corresponding to the lithostratigraphic units.
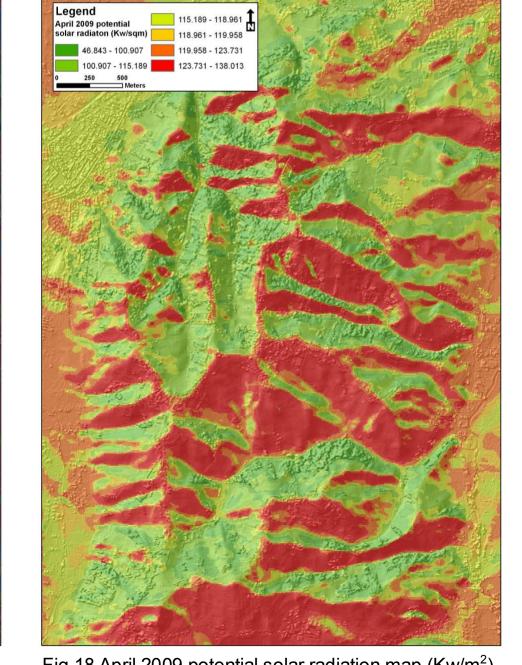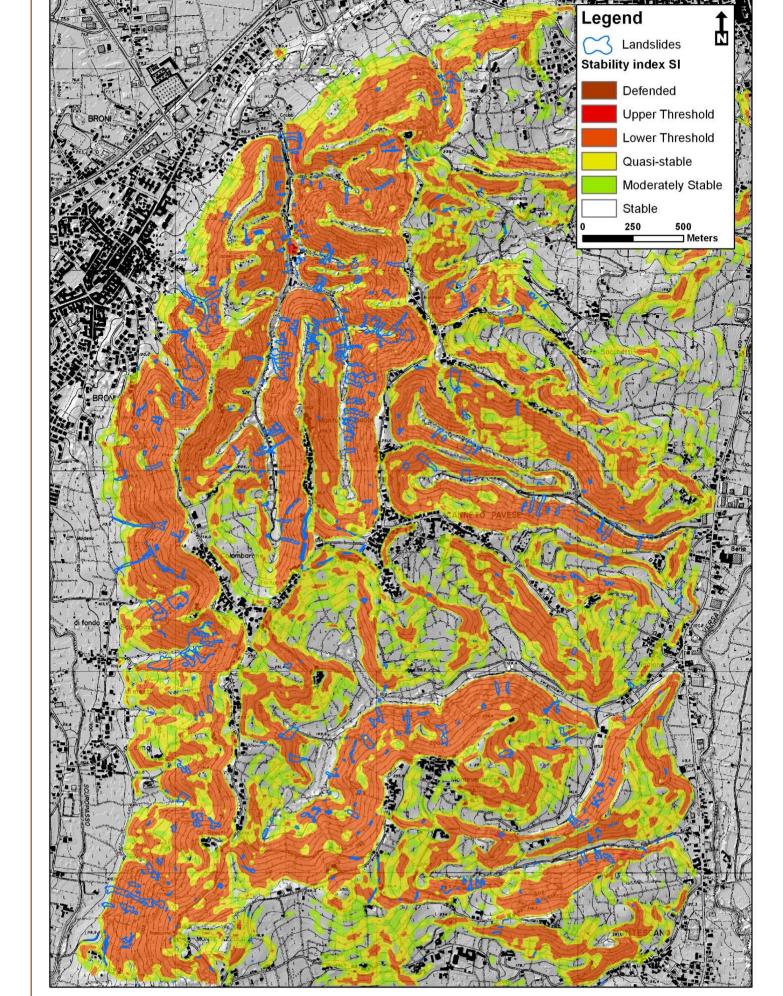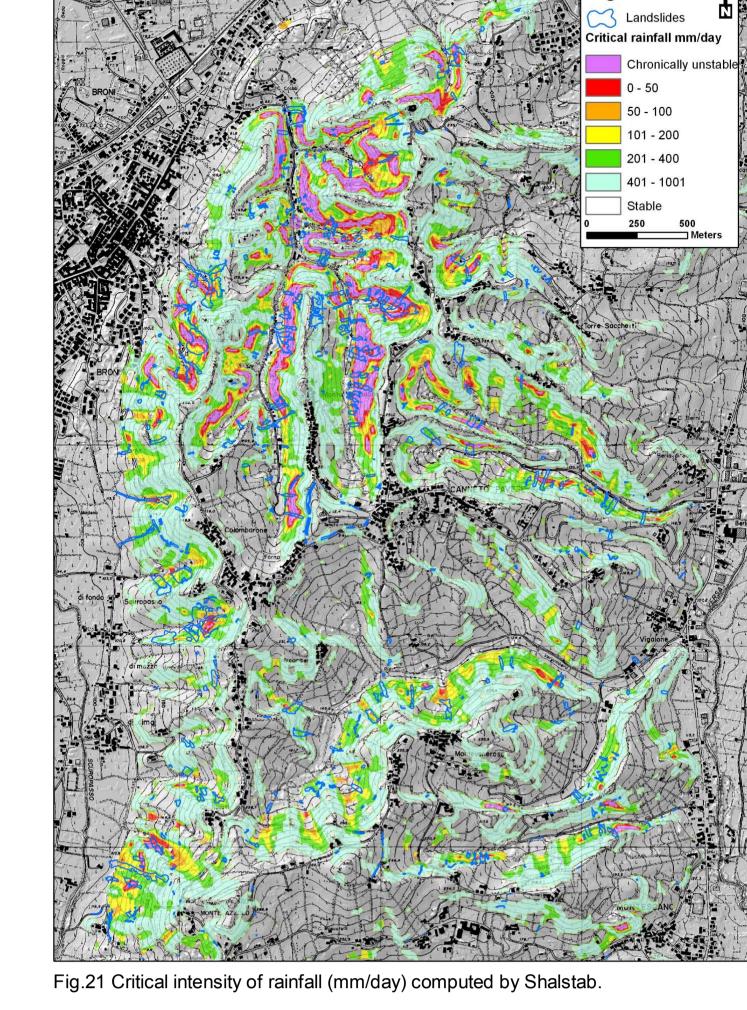- SINMAP allows uncertainty of the variables through the specification of lower and upper bounds. Formally these bounds define uniform probability distributions over which these quantities are assumed to vary at random (Tab.1).
- For SHALSTAB the parameters are considered constant and uniformly distributed all over the study domain, the model defines the topographic control on the location of shallow landslides. The geotechnical and hydrological parameters have been calculated as weighted average of the all parameters.

Fig.15 Estimated soil thickness map.

- The soil thickness was derived from field data collected after the April 2009 event. The approach proposed by Saulnier et al. (1997), which correlates soil depth to the local slope angle, was adopted (Fig.15).
- The hourly rainfall intensities recorded in the Cigognola rain gauge during the April 2009 event were assumed as boundary conditions at the slope surface (Fig.2).

- For SINMAP the ratio steady state recharge R/T soil transmissivity combines both climate and hydrogeological factors. The transmissivity T represents the water flow within the soil and was derived from the hydraulic conductivity (minimal and maximal). The parameter R (steady state recharge rate) is influenced by factors like rainfall intensity and duration. The recharge was assumed to be the effective precipitation. It means rainfall minus evapotranspiration and bedrock infiltration. For each region the potential evapotranspiration was calculated from the rainfall and temperature with the Thornthwaite and Mather method (1957). The soil land use map allows determining the water holding capacity necessary for the evapotranspiration calculation. The amount of infiltration depends on slope angle and we suppose that only ¼ of the water infiltrates in the substratum.
- As regards TRIGRS initial conditions a water table depth corresponding to the ground level was assumed.
- All the terrain parameters used in the neural network were derived from the original DEM (Figs.12, 15, 16, 17, 18, 19).

Tab.1 Initial setting for the input parameters for SINMAP. C=total cohesion [N/m²], C'=soil cohesion [N/m²], θ=slope angle, ps=wet soil density [kg/m³], pw=the density of water [kg/m³]; g=gravitational acceleration (9.81m/s²), D=the vertical soil depth [m], z the internal friction angle of the soil, h [m]=soil thickness; T is the soil transmissivity [m²/h]; R [m/h] steady state recharge.

Tab.2 Input parameters for TRIGRS.

Fig.16 Classified ruggedness index.

Fig.17 Landform classification derived from DEM.

Fig.18 April 2009 potential solar radiation map (Kw/m²).

Fig.19 Normalized slope position index.

7) MODELS OUTPUTS COMPARISON

Fig.20 Stability index map obtained by Sinmap.

Fig.21 Critical intensity of rainfall (mm/day) computed by Shalstab.

Fig.22 Safety factor map obtained by Trigrs.

Fig.23 Shallow landslides susceptibility map obtained using artificial neural networks.

Figures 20-22 show the results obtained with the three deterministic models; fig.24 is the output of the neural network. There is a general agreement between the source areas provided by the three models and the effective landslides source areas. The predictive capability of the three models was compared using the so-called receiver-operating characteristic (ROC) plot (Beguería, 2006) (Fig.24-28). In the ROC plot, the sensitivity of the model (the percentage of unstable cells correctly predicted by the model) is plotted against 1−specificity (the percentage of predicted unstable cells over the total). These values indicate the ability of the model to correctly discriminate between positive and negative observations in the validation sample. High sensitivity indicates a high number of correct predictions (true positives) whereas high specificity (low 1−specificity difference) indicates a low number of false positives. The area under the ROC curve (AUC), can serve as global accuracy statistic for the model and it is threshold-independent. This statistical ranges from 0.5 (random prediction, represented by the diagonal straight line) to 1 (perfect prediction) and can be used for models comparison.
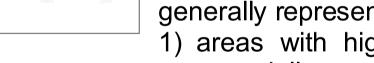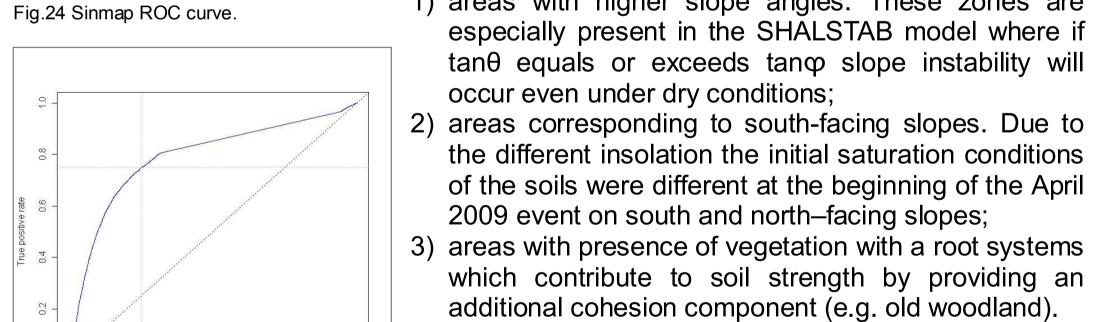
Global accuracy (AUC) is 0.787 for SHALSTAB (Tab.3). The incidence of shallow landsliding is high for areas mapped as "chronic" and for areas with critical rainfall lower than 200 mm/day (150 mm of rain in 48 h were recorded in the April 2009 event). This demonstrates that SHALSTAB is successful at identifying the most unstable areas of the landscape. The global accuracy of SINMAP is quite similar and it is equal to 0.773, although rather conservative. About the 32 % of the study area is classified with SI below one (upper threshold and lower threshold classes), which refer to conditions that are highly unstable and thus critical. A slightly better performance is measured for TRIGRS (0.807).

False positives (over prediction of landslide areas) are present both in SHALSTAB and TRIGRS; they are generally represented by:
1) areas with higher slope angles. These zones are especially present in the SHALSTAB model where if tanθ equals or exceeds tanφ slope instability will occur even under dry conditions;
2) areas corresponding to south-facing slopes. Due to the different insolation the initial saturation conditions of the soils were different at the beginning of the April 2009 event on south and north-facing slopes;
3) areas with presence of vegetation with a root systems which contribute to soil strength by providing an additional cohesion component (e.g. old woodland).
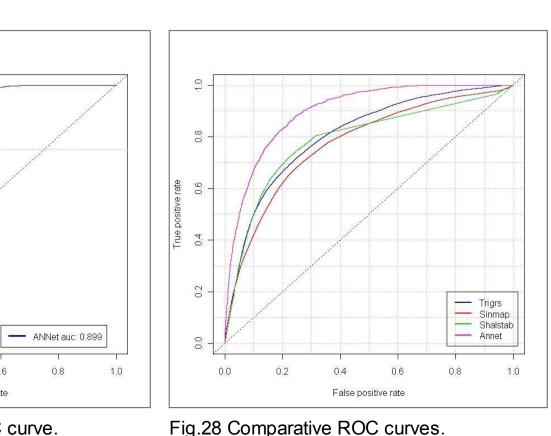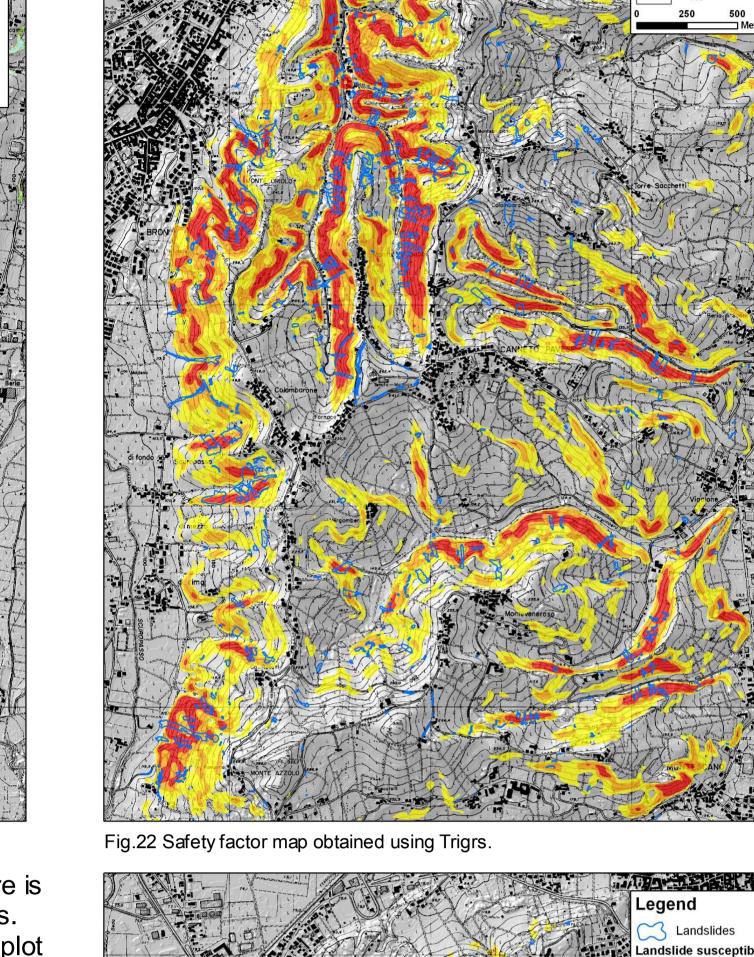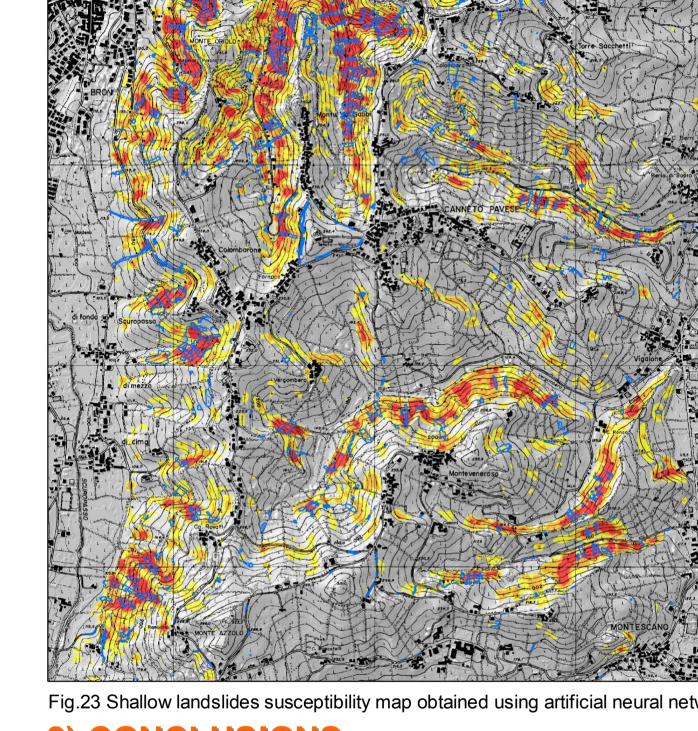The different conditions described in the points 2) and 3) were not taken into account in the used models.
A relative high number of false negatives are related to shallow landslides triggered by anthropogenic activity such roads, which have not been incorporated within the physically based model approaches (Fig.29). These areas concern rotational slides which developed in presence of road cut and which represent the 25% of the shallow landslides of the test site.

Fig.24 Sinmap ROC curve.

Fig.25 Shalstab ROC curve.

Fig.26 Trigrs ROC curve.

Fig.27 Neural network ROC curve.

Fig.28 Comparative ROC curves.

Fig.29 Road embankment landslide.

8) CONCLUSIONS

Three physically based models (SHALSTAB, SINMAP and TRIGRS) were used to evaluate the predictability of shallow landslide occurrence of April 2009 event in a test area of Oltrepo Pavese.
- TRIGRS and SINMAP model the source areas of shallow landslides for a specific event (the April 2009 event). Heterogeneity is accounted for by allowing material properties and other input values to vary from grid to grid.
- SHALSTAB provides the spatial distribution of critical rainfall which expresses the potential for shallow landslide initiation. SHALSTAB assumes constant properties in the whole area.
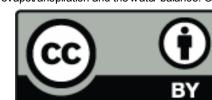- Even if the simplified assumptions about slope hydrology and kinematics (steady state slope parallel flow, translational slides) adopted by SHALSTAB and SINMAP are not very realistic in the test site, all the models forecast good agreement with the mapped inventory.
- SINMAP model furnishes more unrealistic scenarios than the others models.
- TRIGRS represents the most adequate physically based model for the analysis of shallow landslide source areas occurred within the study area.
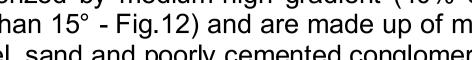- Around 90% overall accuracy (92% of true positive rate with 26% of false alarm) produced by the ANN technique were found promising for future studies in landslide susceptibility zonation.
- Physically based models are useful for the shallow landslides susceptibility assessment at regional scale, nevertheless they take not into account some important predisposing factors in the study area, namely the anthropogenic activity (roads cut and particularly those related to vineyards). Future researches are devoted to the identification of mapping units, which take into account the different land use of the territory and to the study of the role of the root systems of the different typology of vegetation (e.g. old woodland, abandoned vineyard).

	AUC	True positive	False alarm
Sinmap	0.773	75%	32%
Shalstab	0.787	75%	25%
Trigrs	0.807	75%	28%
Annet	0.899	75%	15%

Tab.3 Parameters derived from ROC curves.

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