Determining future evolution of landslides from the past: the historical evolution of shallow landslides in the upper Cassarate catchment (Southern Swiss Alps)

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ABSTRACT
In mountain environments that were subject to intensive pastoralism, the abandonment of alpine pastures and the natural reforestation caused the main modifications in land use. These two factors may have had a significant effect on evolution of shallow landslides. In the upper Cassarate catchment, the evolution of the number and surface of shallow landslides between 1900 and 2014 was studied with diachronical mapping on historical analysis. Quantitative analysis of precipitation and antecedent standardized precipitation index (IPAS) allowed triggering thresholds of 55 shallow landslide events to be calculated. The good statistical fits between the difference of IPAS and, respectively, the minimal value of IPAS and the sum of precipitations, allows defining the shallow landslide triggering thresholds. Two scenarios of shallow landslide triggering were implemented thanks to numerical modeling with the TRIGRS program and allowed a validation of the triggering thresholds determined by the historical analysis. A forecasting of future shallow landslides evolution was possible by defining 1) potential aggravation zones of observed landslides; 2) potential triggering zones of new instabilities.

KEYWORDS
digital photogrammetry;historical analysis;numerical modeling;shallow landslide; Swiss Alps

INTRODUCTION
In mountain environments subject to intensive pastoralism since the second half of 20th century, modifications in land use derived usually from the abandonment of alpine pastures and the natural reforestation. These two factors may have had a significant effect on the number and surface of shallow landslides. A diachronic mapping was carried out in four study sites in order to quantify their evolution in the upper Cassarate catchment (Southern Swiss Alps) in the last century. This catchment is particularly affected by deep landslides, which cover 43% of its surface. The 160 deep rotational landslides inventoried by the photo-interpretative mapping carried out by Castelletti et al. (2014) cover 27% of the entire surface and characterize not only the loose materials but also the bedrock until 50–60 m depth. These landslides are generally comprised within the perimeter of 8 deep seated gravita-

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tional slope deformations (DSGSD, Figure 1), controlled by the geological and structural conditions of the valley, in particular by the dip slope conformation of the right side. These instabilities occupy the whole slope and often extend to the valley floor by mass transport phenomena (debris flows, earth flows, etc.) in ravines (Castelletti et al. 2014). In order to manage these effects, the upper part of the watershed was the target of major reforestation programs between 1880 and 2000 resulting in a reduction of the total areas affected by shallow landslides (Mariotta 2004). However, there are some areas where important slope erosion persists, even trends to increase.

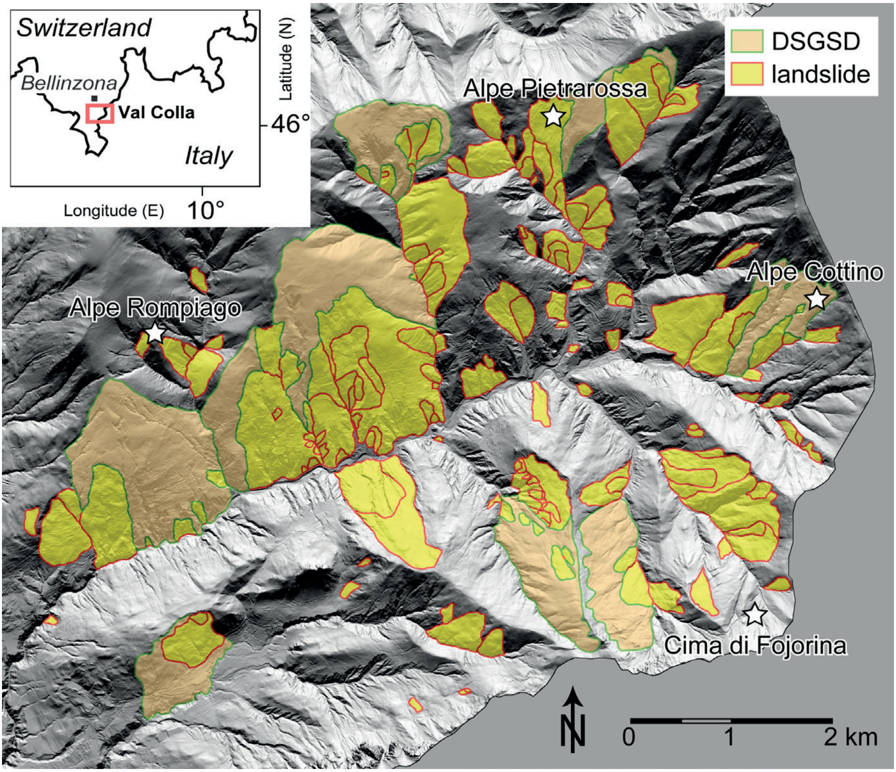

Figure 1: Geographical location and main slope instabilities in the upper Cassarate catchment (DSGSD: Deep Seated Gravitational Slope Deformation). Basemap: ©swisstopo.

Considering the framework described above, the Consortium "Valle del Cassarate e golfo di Lugano" (CVC) has mandated the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) to evaluate the evolution of shallow landslides and regressive erosion in the upper part of the watershed. The aim of this study is to provide essential basic data for an assessment of the present situation and an evaluation of the future evolution. The goal is the production of numerical scenarios for the evolution of shallow landslides. In this work, the identification and mapping of existent or potential slope instabilities (instability mapping; e.g. Guzzetti et al. 2012), the analysis of their evolution with time (diachronical mapping), the calculation of triggering thresholds based on historical events (e.g. Frattini et al. 2009), and the production of maps of potential landslide evolution (numerical modeling) are presented. The focus will be put on predicting future landslides by validation of triggering thresholds determined by correlation of shallow landslides with precipitation data, for better understand the relation between landslide occurrence and land use.

METHODS

Diachronical mapping

In order to map shallow and deep seated landslides, we applied 3D digital stereoscopic photogrammetry to analogical and numerical aerial photographs taken between 1950 and 2012 using the ArcGDS™ extension of the software ESRI® ArcGIS™ (Ambrosi and Scapozza 2015). The stereoscopic vision allows obtaining precise results and collects a large amount of data such as perimeters, surfaces and volumes of Quaternary formations and/or landforms. The ArcGDS™ tool make it possible the direct exploitation, visualization and digitization of stereoscopic digital linear scanned images (e.g. Digital Image Strips). Combined with high-resolution digital elevation models, ArcGDS™ is a powerful tool, particularly over large areas, as well as under forest cover and on very steep slopes (Ambrosi and Scapozza 2015).

Digital monophotogrammetry (or monoplotting) on ancient oblique non-metric photographs make it possible the shallow landslides identification for the period 1923–1950 (Figure 2A), moving back in time the 3D digital mapping of several decennia. Monoplotting allows the georeferentiation and orthorectification of single oblique unrectified photographs, which are related to a high-resolution digital elevation model (DEM; in this work the swissALTI3D, ©swisstopo). The monoplotting relates each pixel of the photograph to the corresponding real world pixel on the DEM (Bozzini et al. 2012; Conedera et al. 2013; Scapozza et al. 2014). By means of this technique, it was possible to recuperate spatial data obtained by the georeferentiation and orthorectification of photographs of the first half of the 20th century in a digital format and in a GIS environment (Figure 2B and C).

The diachronical mapping was based on the analysis and interpretation of terrestrial oblique photographs between 1923 and 1941, and of aerial photographs and orthophotos between 1950 and 2012. Because the lack of images, the period between 1942 and 1949 could not be analysed. This kind of mapping based on historical analysis allowed quantifying the evolution of the number and surface of shallow landslides. This approach based on the join analysis of both oblique terrestrial and vertical aerial photographs makes it possible in particular a differentiation between shallow landslides that: 1) have developed since the beginning of the 20th century; 2) remained stable across the decades; 3) have stabilized by means of reforestation programs.

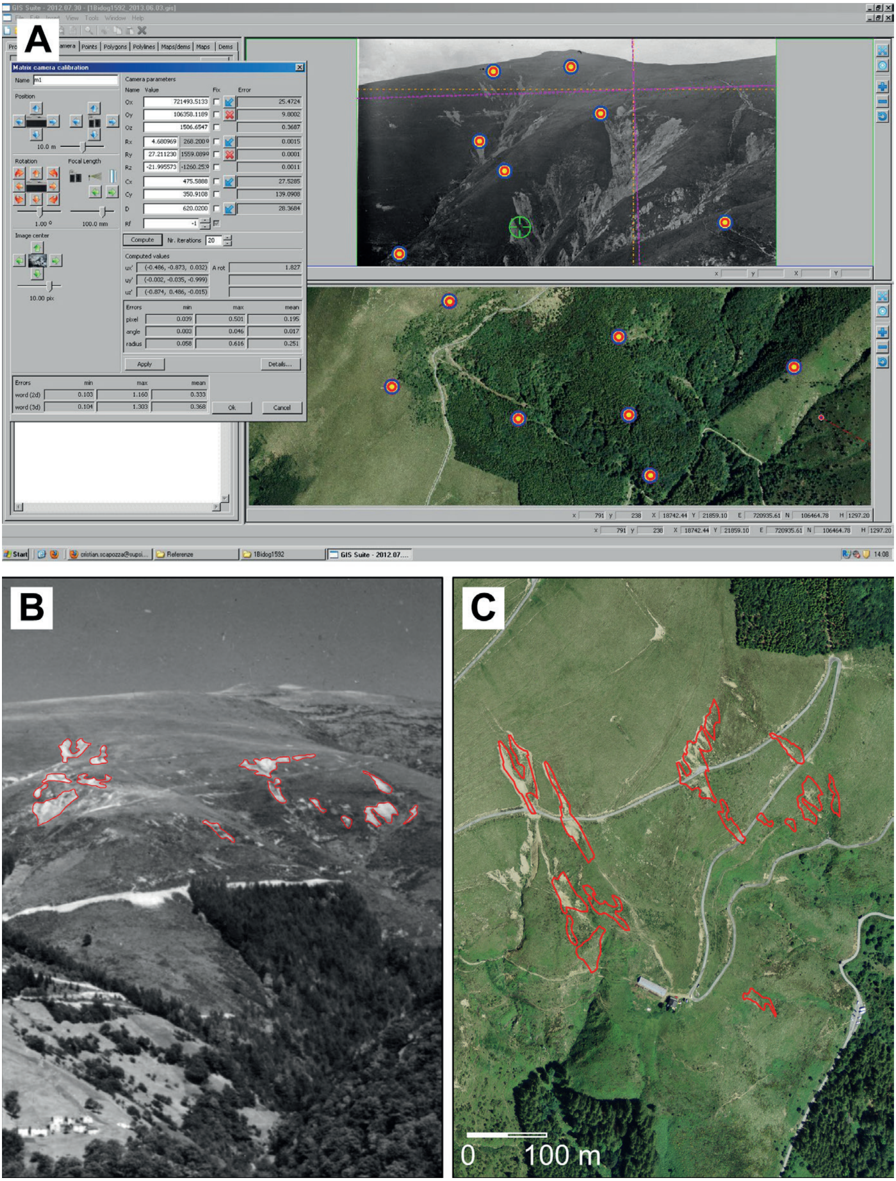

Figure 2: Example of mapping on an oblique terrestrial photograph. A) Georeferentiation and orthorectification of a terrestrial oblique photograph with the WSL-Monoplotting-tool: example of the Alpe Rompiago study area in 1923. B) Shallow landslides in the Alpe Rompiago study area in September 1941. C) The landslides shown in B) reported by the WSL-Monoplotting-tool on a 2012 orthophoto. Photographs ©CVC; orthophoto ©swisstopo.

Calculation of triggering thresholds

Evolution of shallow landslides was compared to a historical database of all mass movements occurred in the upper Cassarate catchment between 1900 and 2014. This database was compiled based on information on historical landslide events provided by S. Mariotta (unpublished data) and by our own work. This compilation was based on identification and verification of historical events reported in written press and in cantonal, municipal and consortium archives. The analysis of historical data revealed 62 events of which 58 were classified as shallow landslides and 4 as rockslides. Three events were excluded because their date and location were uncertain. Based on the statistical analysis of rainfall duration and intensity during the 55 shallow landslide events retained, triggering thresholds were calculated (e.g. Pedrozzi 2004).

For every event, a climatic quantitative analysis was performed considering the precipitation sum, the precipitation return times and an antecedent standardized precipitation index (IPAS), allowing the characterization of the state of moisture/drought of the near surface (Seiler et al. 2002). IPAS allows a classification of the ground moisture from extremely wet (IPAS ≥ 2.0) to extremely dry (IPAS ≤ -2.0). Normal values are comprised between 1 and -1. The regressions were computed considering 1$\boldsymbol{\sigma}$- and 2$\boldsymbol{\sigma}$-error (the probability coefficient of 0.68 and 0.95, respectively) and took into account: 1) the difference of IPAS before and after the three days prior to the event [ΔIPAS]; 2) the minimal value of IPAS [MIN-IPAS] during the three days preceding the event; 3) the sum of precipitations [$\boldsymbol{\Sigma P}$] of the 3 days prior to the analyzed shallow landslide event.

Numerical modeling

Numerical modeling of potential instability zones was performed using the TRIGRS program (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability; see Baum et al. 2008). This model is able to evaluate the effect of rainfall events on the temporal evolution of the slope stability considering local geotechnical characteristics and infiltration processes.

Input data of TRIGRS program concerns topography and hydrography, derived from a DEM (in this work the swissALTI3D, ©swisstopo), thickness of loose materials (derived from direct observation and geophysical prospecting), water table depth, pressure diffusion below the water table, cohesion and friction angle (determined from laboratory analysis).

This makes it possible to model the rainfall infiltration by the Richards equation as proposed by Iverson (2000), and the subsequent groundwater runoff in a spatial matrix defining the shallow subsurface. The slope stability is evaluated by the analysis of an undefined slope (Taylor 1948).

RESULTS

Quantification of variations in relative surface of shallow landslides was carried out based on the surface mapped for 1950 (Figure 3). For two study sites (Alpe Rompiago and Alpe Pietrarossa), surface variations derived from digital monophotogrammetry analysis show a slight increase in the area affected by shallow landslides in the decades before 1950. For the second half of 20th century, the data show a slow and gradual decrease in landslide area, which is in 2012 less than a half compared to 1950 (47% for Alpe Rompiago and 48% for Alpe Pietrarossa). In the two other study sites (Alpe Cottino and Cima di Fojorina) the increase in shallow landslides surface since 1923 is significant (+186% for Alpe Cottino and +389% for Cima di Fojorina with respect to 1950). And this despite an incomplete set of images (landslide surfaces from 1967 to 1977 are missing due to the poor coverage by aerial photographs for both sites). For Alpe Cottino, the main increase in landslide area was registered between 1983 and 1989 (+463% with respect to 1950), and a subsequent decrease until 2001. In the Cima di Fojorina, we registered a significant deterioration before 1983, where the total surface of instabilities was of +756% with respect to 1950.

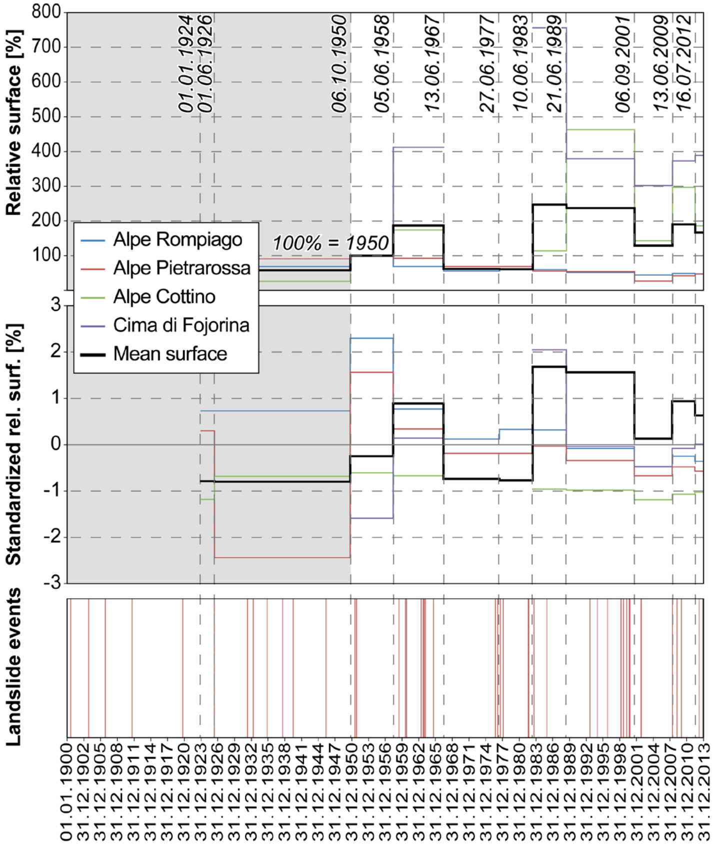

Figure 3: Evolution of absolute and standardized relative landslide surface and frequency diagram of the historical landslide events recorded in the upper Cassarate catchment. Standardisation was carried out by subtracting the mean and then dividing the standard deviation for obtaining dimensionless landslide surfaces and then compares the four study sites between them. In grey, data calculated by monophotogrammetry.

The increase observed between 1958 and 1983, particularly, was related to increasing erosion zones due to sheep herding.
Quantitative analysis of precipitation and IPAS allowed triggering thresholds of the 55 shallow landslide events occurred in the upper Cassarate catchment between 1900 and 2014 to be calculated (Figure 4). The statistical relationship between ΔIPAS and the shallow landslides historical dataset is very high, with 91.1% of the events that were predicted by this parameter.

Triggering thresholds based on an exponential relationship between the sum of precipitation and the IPAS minimal value provides the highest correlation coefficients. The difference of IPAS before and after the three days prior to the event [ΔIPAS3] and the minimal value of IPAS during the three days preceding the event [MIN-IPAS3] are correlated exponentially, with a good statistical fit (R = -0.79, R2 = 0.62, Figure 4A). This relation allows estimating the increase of IPAS with time and therefore quantifying the increase of moisture in the ground in the days before the landslide event. In addition, ΔIPAS has a good linear relationship with the sum of precipitations of the 3 days prior to the analyzed shallow landslide event [***ΣP3***] (R=0.74, R2 = 0.55, Figure 4B). By means of the two previous relationships, it was possible to calculate the final regression between ***ΣP3*** and MIN-IPAS3 and then define the shallow landslide triggering thresholds for the upper Cassarate catchment (Figure 4C). This last relationship was used for a classification of all the days between 01.01.1900 and 31.12.2014 (Figure 4D), in order to quantify positive and negative predictive values (PPV and NPV respectively). PPV of the triggering thresholds are lower than 5%, probably due to the very

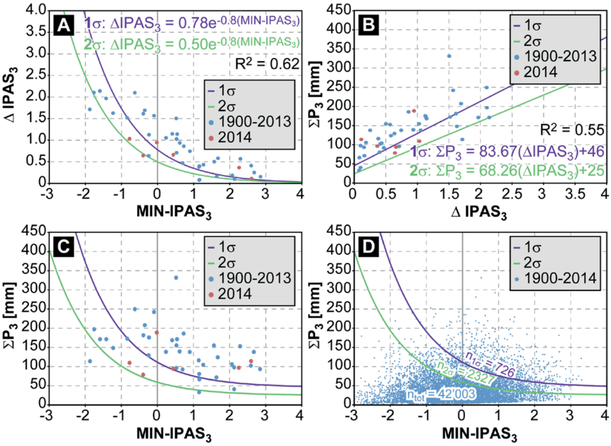

Figure 4: Statistical relationships between precipitations (data of the MeteoSwiss station of Bellinzona), IPAS and the occurrence of shallow landslides. A) Relationship between the difference of IPAS before and after the three days prior to the event [ΔIPAS3] and the minimal value of IPAS during the three days preceding the event [MIN-IPAS3]. B) Relationship between the sum of precipitations of the 3 days prior to the analyzed shallow landslide event [***ΣP3***] and ΔIPAS3. C) Relationship between ***ΣP3*** and MIN-IPAS3 based on regressions presented in A and B. D) Classification of all the days between 01.01.1900 and 31.12.2014 based on regressions presented in C.

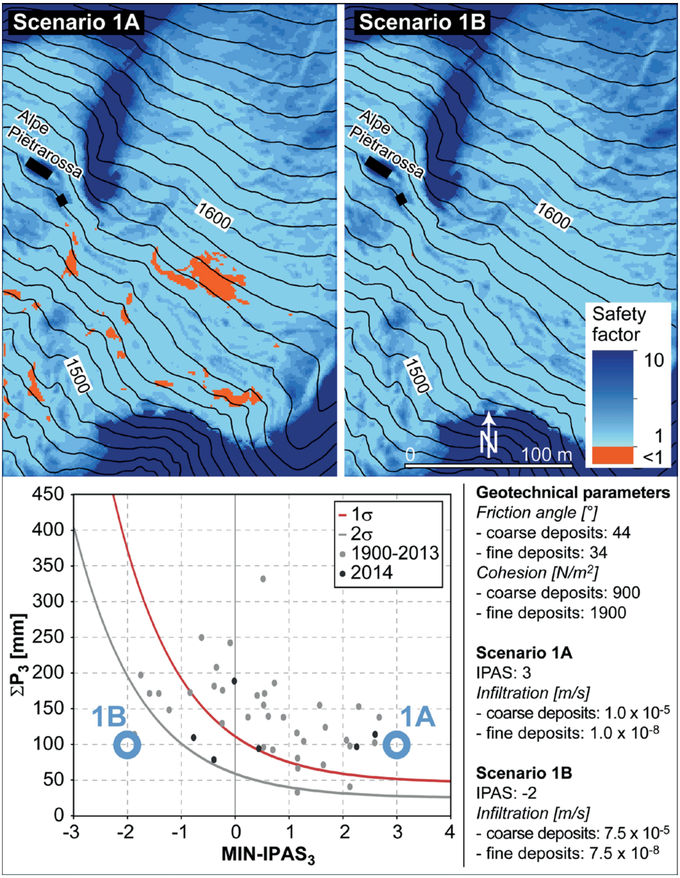

Figure 5: Safety factor maps obtained for Alpe Pietrarossa by numerical modeling with TRIGRS. Modeling was performed with a sum of precipitation of 100 mm in 3 days. According to calculated triggering thresholds, triggering probability is very high for Scenario 1 A and very low for Scenario 1B. Under Scenario 1A, we would simulate a situation of probable landslide triggering, whereas under Scenario 1B, triggering must to be very limited or even absent.

limited number of days with landslides (55) with respect to the total number of days analyzed (42'003 = 115 years). Despite this point, NPV are higher than 99.96%, indicating that it is very unlikely to have a landslide if this was not predicted.

Two scenarios of shallow landslide triggering were finally implemented in the TRIGRS program for numerical modeling of triggering thresholds calculated. Validation of the model was performed based on scenarios related to potential conditions of instability (safety factor lower than 1) under the same rainfall conditions but with different ground moisture (Figure 5). The adjustment of cohesion and friction angle parameters makes it possible the final calibration of the numerical model. By means of this calibration, it was possible to integrate the results of numerical modeling with those of diachronical shallow landslide mapping for producing maps of: 1) potential aggravation zones of observed landslides; 2) potential triggering zones of new instabilities. The surface of potential unstable zones with a MIN-IPAS value of -2 (extremely dry), respectively 3 (extremely wet) is completely different for the same rainfall intensity and duration. This result allows a validation of triggering thresholds and confirms by numerical modeling that the state of ground moisture before the rainfall event has more influence on the landslide triggering that the same duration of rainfall.

CONCLUSIONS

Four main conclusions can be drawn from the observations, measurements and numerical models carried out at the four study sites:

1. In the Alpe Rompiago and Alpe Pietrarossa study sites, the diachronical mapping illustrate a situation of relatively rapid closure of shallow landslide, produced by the significant decrease of intensive pastoralism and, as a consequence, the natural reforestation of these areas.
2. Increase in shallow landslide surface for Alpe Cottino and Cima di Fojorina, on the other hand, is related to the geotechnical conditions of the near surface, which favor the triggering of new surface instabilities in relation to intense rainfall episodes occurred since the 1980s.
3. Numerical modeling allowed the determination of areas with a potential safety factor below 1 to be determined on the basis of calculated triggering thresholds. This makes it possible to define two kinds of future instability zones: 1) potential zones that could present an increase of landslide area; 2) potential zones without an actual landslide that could generate a new instability.
4. From a methodological point of view, the diachronical mapping highlights the integration of several techniques of 2D and 3D digital stereo- and mono-photogrammetry, allowing the collection of a lot of information about natural phenomena and also the identification and mapping of shallow landslides evolution of during time. The monoplotting technique makes it possible, in particular, to going back in time in this kind of mapping of several decades with respect to the classical aerial photographs analysis.

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