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Analysis and modeling of shallow landslides on the Lierza basin triggered by an extreme rainfall event on 2 August 2014: the impact of land use on shallow landsliding

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Analysis and modeling of shallow landslides on the Lierza basin triggered by an extreme rainfall event on 2 August 2014:

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by

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Abstract

The two primary aspects affecting the impact of shallow landslides, both in terms of downstream hazard and their geomorphic significance, are their location and size. Location affects travel distance and bulking-up potential, while size affects the amount of sediment discharged, as well as the scale of local morphological change. Moreover, the magnitude of shallow landslides (defined as the volume of material displaced) controls the extent of the hazard area, the intensity of impact within it and the vulnerability of elements at risk. This thesis aims to quantify the impact of land use (forest and vineyard land uses are considered) on the distribution and characteristics of shallow landslides. The landslide properties which are considered are spatial density and size. The analysis is carried out with reference to an extreme flash flood occurred in Veneto (Italy) on August 2, 2014, which impacted the small (7.5 km^2) upper Lierza basin triggering several (400) shallow landslides. Our results show that landslide density in vineyard (100 km^{-1}) is more than twice that in the wood area (43 km^{-1}). This result is important because it shows that that forested slopes are mostly more stable than significantly less steep slopes in open land. This happens even if rainfall was higher in forests than in vineyard. Landslides in forested areas are significantly larger than landslides in vineyard. It is speculated here that landslide size is determined by the balance of the benefits associated with larger size (increased driving forces relative to resistive forces) with the costs associated with a larger size (higher probability of including areas that contribute higher resistances). Our results show that land use characteristics impact significantly on this balance.

Key words: shallow landslide, land use, flood, topography, SHALSTAB model

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Chapter 1: Introduction

Landslides are a common, natural mass-wasting phenomenon in mountainous areas throughout the world. The term landslide in its strict sense is a relatively rapid mass wasting process that causes the downslope movement of a mass of rock, debris or earth triggered by a variety of external stimulus (Hutchinson, 1988).

Landslides in which the sliding surface is located within the soil mantle or weathered bedrock (typically to a depth from a few decimeters to several meters) are categorized as shallow landslides. This latter term is used to describe movements by which material is displaced over a discrete slip surface close to the land surface.

Some authors attribute the term ‘shallow’ to a function of the thickness of the unstable mass. Varnes (1984) uses the term ‘shallow’ for landslide than 2 m thick; those between 2 and 5 m are medium and those over 5 m are ‘deep-seated’; this thickness corresponds to the depth of the main rupture surface.

Shallow landslides are particular important in terms of natural hazard, as they often translate into rapidly moving debris flows (Iverson et al.,1997) that may affect human life, properties, constructed facilities, infrastructure and natural environment (Olshansky,1990; Schuster, 1996; Sidle and Ochiai, 2006; Keefer and Larsen, 2007).

In the last century, many researchers have documented severe landslide events that caused the loss of hundreds of lives and significant property damage.

Europe has experienced the second highest number of fatalities and the highest economic losses caused by landslides compared to other continents: **16,000 people have lost their lives** because of landslides and the material losses amounted to over $1700 million in Europe during the 20th century (source: EM-DAT- The OFDA/CRED International Disaster database)

In Europe, Italy is one of the most vulnerable countries in terms of exposure to natural hazards (Luino, 2005) and it has been the country that has suffered the greatest human and economic losses due to landslides. In Italy, an examination of a catalogue of landslides and debris flows compiled by Salvati et al. (2010) revealed that in the 59-year period 1950–2008 most of the 2204 landslides that have resulted in at least 4103 fatalities were rainfall induced shallow landslides or debris flows.

According to this, several studies had focused on evaluating the causes and mechanisms of inducing mass movements on the slopes.They found that shallow landslides may be triggered by different factors, either natural or related to human activities. Among natural factors, rainfall is certainly one of the most frequent causes of landslides occurrence. Intense storms with high intensity, long duration rainfall have great potential to trigger rapidly moving landslides and have been documented as one of the major cause for shallow landslide triggering (Anderson and Sitar 1995; Iverson et al. 1997; Montgomery and Dietrich, 1994; Van Asch et al., 1996; Terlien, 1998; Ng and Shi, 1998; Iverson, 2000; Sidle and Onda, 2004; Malet et al., 2005).

Moreover there are many others factors, such as slope morphology (Montgomery and Dietrich 1994 ; Di Crescenzo and Santo 2005; Guadagno et al.2005), the geological and structural setting (Coe et al.2004 ; D'Amato Avanzi et al. 2004 ; Revellino et al. 2010; Grelle et al. 2011), the mechanical properties of the soils (Moser and Hohensinn 1983; Moser 2002; De Vita et al. 2012),weathering (Calcaterra and Parise 2005; Meisina 2006; Calcaterra et al. 2007), hydrological and hydrogeological conditions (Iverson and Major 1986 ; Crosta et al. 2003;Casagli et al.2006), and changes in land use (Glade 2003 ; Guadagno et al. 2003 ; Beguerıa 2006) can also affect the origin and development of shallow landslides.

Additionally it will be important also to identify where and when the shallow landslide may occur, to enhance the prediction, and may reduce or even avoid damage caused by landslides. In order to attain a better understanding of the failure mechanisms of landslides they are mapped, assessed, monitored and modeled all over the world (Reichenbach et al., 2002; Reid et al., 2008; Shen & Fernandez-Steeger, 2011). Thus, to complete understanding the hazard potential of shallow landslide as well as all the factors that control them it is required to investigate the landslide susceptibility-hazards and risk.

In the literature, confusion exists between the terms landslide "susceptibility", landslide "hazard" and landslide "risk". Often, the terms are used as synonymous despite the three words expressing different concepts. Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of local terrain conditions (Brabb, 1984). In mathematical language, landslide susceptibility is the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions.

Landslide hazard was defined as "the probability of occurrence of a potentially damaging phenomenon (landslide) within a given area and in a given period of time" (Varnes et al. 1984) .As Guzzetti et al. (1999) and Aleotti and Choudhury (1999) pointed out, this definition incorporates the concepts of spatial location ("where"?), time recurrence ("when"?) and magnitude ("how powerful"?) as crucial elements in the prediction of future landslide behavior. Landslide risk defines the potential loss to the exposed subject or system, resulting from the convolution of hazard and susceptibility. In this sense, risk may be expressed in a mathematical form as the probability of surpassing a determined level of economic, social or environmental consequence at a certain site and during a certain period of time.

More generally, Landslide susceptibility assessment can be considered as the initial step towards a landslide hazard and risk assessment. The susceptibility maps can be converted into landslide hazard maps by including information of spatial, temporal and magnitude probabilities of landslides (Robin Fell, Jordi Corominas et al., 2008; Glade,Anderson et al., 2005; FaustoGuzzetti, Carrara, et al., 1999; Cees J. van Westen, CAstellanos, et al., 2008).

The assessment of the landslides susceptibility is made by different conceptual assumptions, operational tools and techniques can be used at different map scales, in relation to the available data set and the pursued aims (Fell et al. 2008).

A promising approach for the susceptibility analysis of the shallow landslides source areas relies on the use of the so called physically based models for their capability in reproducing the physical processes governing the landslides occurrence (Fell et al. 2008).

Modelling of landslide failures can be either qualitative or quantitative (Carraraet al.1999). Qualitative approaches integrate descriptive prediction, while quantitative applications are based on numerical simulations. Landslide modelling approaches can broadly be separated into models that are focusing on single landslide processes (i.e. local models), and models with greater spatial extent (i.e. regional models) (Crozier and Glade2005).

Different types of distributed models have been proposed in the scientific literature (e.g. Baum et al. 2002; Crosta and Frattini 2003; Montgomery and Dietrich 1994; Pack et al. 1998; Savage et al. 2004; Terlien et al. 1995; van Asch et al. 1999; Ward et al.1982; Wu and Sidle 1995) in order to predict zones which are susceptible to landslide activity in a certain area and give a better understanding of landslide triggering factors (D'Amato Avanzi et al. 2004; Gorsevski et al. 2006; von Ruette et al. 2011; Piacentini et al. 2012).

Topographic, geomorphological and hydrological features are seen as primary factors controlling landslide susceptibility (e.g. Atkinson and Massari 1998; D'Amato Avanzi et al. 2004; Fernandes et al. 2004; Sidle 2006; Miller and Burnett 2007; Goetz et al. 2011). However, it is still controversially discussed how important the effect of vegetation and land use is. (Rickli and Graf 2009).

According to Karsli et al. (2008), land use change has been recognized as the most important factor influencing the occurrence and reactivation of landslides triggered by rainfalls. In a heavily rainy environment, the relation between landslide and vegetation cover is extremely important and it should not be underestimated, since vegetation can influence the slope stability parameters, such as cohesion, internal friction angle, weight of the slope-forming material and pore-water pressure. Vegetation can both enhance effective soil cohesion due to root matrix reinforcement and soil suction or negative water pressure through evapotranspiration.

Further studies have evaluated in detail how the plants can modify the mechanical and hydrological properties of soil, saprolite, and bedrock and how the architecture and the distribution of the plant root system can strongly influence the stability (Stokes et al. 2008; Mao et al. 2014).

Changes in land use distribution and type can be natural or induced and controlled by human actions. Recent studies focusing on the effect of human-induced land use changes on slope stability have shown that in populated regions, human modification which include deforestation, unsuitable agricultural practices, forest fires, construction of artificial lakes and channels contributes significantly to the initiation of landslides (e.g., Vanacker et al. 2003; Meusburger and Alewell2008; Van Den Eeckhaut et al. 2009; Bruschi et al. 2013).

Sidle et al.,1985 revealed that other anthropogenic factors such as roads, farmland, terraced slope, native forest conversion to agriculture land are known to decrease slope stability

It well known also that Landslide frequency, size and position can be related to land use change in terms of its properties: soil property, root system, terraces, drainage, roads and forest conversion.

Landslide position–frequency-size curves are necessary for the correct understanding and characterization of regional landslide hazard. They allow one to resolve the probabilistic nature of landslide size, occurrence, and when calibrated against time, frequency (Guthrie and Evans 2005). This in turn leads to increased understanding of landslide hazard, impact, risk, as well as hillslope denudation and the role of landslides in shaping the landscape.

Unfortunately, there are few complete landslide inventories worldwide (Guzzettiet al.2005) and few researchers dedicated to the task.

Objectives and thesis outline

Given the above background, this work aims to quantify the impact of land use on the distribution and characteristics, such as spatial density and size, of shallow landslides. This analysis is carried out with reference to an extreme flash flood occurred in Veneto (Italy) on August 2, 2014, which impacted the small upper Lierza basin triggering several shallow landslides.

Following this introductory chapter, this thesis comprises of five chapters dealing with various aspects of the objectives mentioned in the previous section. In Chapter 2, a comprehensive literature review of shallow landslide processes and the effect of land use changes on shallow landslides are presented.

An introduction to the research area and presentation the data used for the study with detailed description to the methods applied are illustrated in the chapter 3.

Chapter 4 reports the most important results and the main outcomes from the application of the SHALSTAB model to the study basin.

The final chapter reports and discusses all the major findings from in this thesis. The methods developed throughout the thesis and results obtained from modeling are summarized, and evaluated. Limitations of the methods are presented, together with suggestions for future improvements and research needs.

Chapter 2: Literature Review

This Literature review gives a brief description of shallow landslide. Particular attention is paid to the effect of land use changes on shallow landsliding with mention for different aspects: change of root architectures, of soils and topography changes, like terraces and infrastructures. Then, effects of land use on shallow landslide shape are reviewed.

2.1 General landslide features

Landslide is a general term to describe down-slope movement of soil rock and organic matter under the influence of gravity (BC GEOLOGICAL SURVEY, 1993).

Satterlund and Adams (1992) describe it as a generic term that includes all types of mass wasting that exhibit perceptible motion. The most widely accepted landslide classification is by Varnes (Varnes, 1978). Any landslide is generally classified and described by two nouns: the first describes the materials (e.g. earth, debris or rock); and the second is the type of movement (e.g. falls, topples, slides, flows, spread etc.).

Glade&Dikau (2001) summarize the processes behind the mechanisms of gravitational mass movements and conclude that shallow, surface-parallel translational movements as well as rotational slope failures belong to this group. Landslides adversely affect a variety of resources, including the total or partial loss of the land.

Landslide in which the sliding surface is located within the soil mantle or weathered bedrock (typically to a depth from few decimetres to some metres) is called a shallow landslide. They usually include debris slides, debris flow, and failures of road cut-slopes.

Shallow landslides can often happen in areas that have slopes with high permeable soils on top of low permeable bottom soils. The low permeable, bottom soils trap the water in the shallower, high permeable soils creating high water pressure in the top soils. As the top soils are filled with water and become heavy, slopes can become very unstable and slide over the low permeable bottom soils. Say there is a slope with silt and sand as its top soil and bedrock as its bottom soil. During an intense rainstorm, the bedrock will keep the rain trapped in the top soils of silt and sand. As the topsoil becomes saturated and heavy, it can start to slide over the bedrock and become a shallow landslide.

The occurrence of shallow landslide is function of various parameters relating to bedrock geology, lithology, geotechnical properties, rainfall characteristics (intensity and duration), soil-moisture conditions, water table position, and land-use patterns. Additionally, in many cases human interferences are also responsible for triggering the landslides and create the same effects on a slope as a range of natural processes.

2.2 The effect of land use on shallow landslide

Land use is the interaction between many parts of humans and the biophysical environment. The interaction gives impacts on the structure, function, and dynamics of ecosystems at the various levels of ecological organizations, including local, regional, and global levels. Human activities on environment that produce changes in land cover such as agriculture, mining, and urban development influence the functioning of ecological systems. The influence has resulted in global climate change, soil, hydrological degradation, and increased biological extinctions (Aspinall et al., 2008).

In this review of the impact of land use and land cover change on shallow landslide, it is necessary to distinguish between land use and land cover concepts.

Meyer and Turner (1994) state that "By land cover is meant the physical, chemical, or biological categorization of the terrestrial surface, e.g. grassland, forest, or concrete, whereas land use refers to the human purposes that are associated with that cover, e.g. raising cattle, recreation, or urban living" (Meyer and Turner 1994,). Land use relates to land cover in various ways and affects it with various implications.

Land use/land cover is a dynamic variable that links different parameters which are responsible for triggering the landslides and create the same effects on a slope as a range of natural processes.

Some of the common examples of the parameters of land use leading to landslides are changes in land cover, type and distribution of vegetation, deforestation, changes in soil permeability and compaction, cutting of slopes, terraced slope, roads and forest conversion to agriculture ect...

According to Karsli et al. (2008) land use change have been recognized as the most important factor influencing the occurrence and reactivation of landslides triggered by rainfalls. In a heavily rainy environment, the relation between landslide and vegetation cover is extremely important. However little work has been done on this relation.

So it should not be underestimated, since vegetation can influence the slope stability parameters, such as cohesion, internal friction angle, weight of the slope-forming material and

pore-water pressure.
Consequently a thorough discussion of the framework for anticipating how landslides respond to land use changes is developed in the following section.

Meusberger and ALewell (2008) investigated the ways that landuse and climate changes are influencing the occurrence of landslides by investigating spatial landslide distributions in the Urseren Valley in Siwtzerland between 1959 and 2004. In this period, the area affected by landslides increased by 92 per cent. This can be explained by the increase in extreme rainfall events and by land use change. Specifically, goat pastures and spring pastures had disappeared and remote and less productive areas had been abandoned, being replaced by uncontrolled grazing within confined areas. Moreover, the abandonment of traditional farming practices, in combination with the mechanization of local agriculture, might have contributed to increased soil erosion and consequently to the occurrence of landslides. On the other hand, areas colonized by shrubs show low landslide density (Meusburger and ALewell, 2008).

Besides, Glade (2003) focus on geomorphic responses to anthropogenic land use and land cover changes in New Zealand. By analyzing sedimentation rates in swamp, lake, costal and marine environments, Glade (2003) concludes that the deforestation that took place after the arrival of the European settlers was connected with increased landslide activity, which was reflected in the sedimentation rates in these environments.

Deforestation is reported to have been followed by severe shallow landslidingbecause of changes in soil hydrology, and reduced soil strength arising from decreased root cohesion.

Furthermore one of the key ways of trees and other woody vegetation that contribute to slope stability and control a range of erosion processes is their development of root networks that enhance the mechanical reinforcement of soil (Phillips and Watson 1994; Genet et al., 2008; Stokes et al., 2009; Schwarz et al., 2010).
At the plant level, the interaction between mobilized root strength, root morphology and shear strength along the soil-root interface ensures the stability of the above ground biomass while, at the stand level, the reinforced soil may contribute positively to the overall stability of natural and manmade slopes. Root reinforcement is widely recognized as the most important beneficial effect of vegetation on slope stability. However, it is just one of the many ways by which vegetation influences slope stability, either directly by affecting the loads or resistance or indirectly through the hydrology. Root reinforcement requires that plant roots anchor the

soil mantle to bedrock or that roots act as fibrous binders of soil particles (Ziemer, 1981). The major biotic determinants of root induced cohesion (also called root reinforcement) are root strength and root architecture which are primarily dependent on plant species, while the major abiotic determinants are soil texture, depth, moisture content, the local slope angle and water table depth (Danjon et al., 2008; Genet et al., 2005).

In addition land-use conversion from trees to crops or grazing land significantly reduces rooting depth and strength, and also means that soils are dried to a lesser depth and degree due to shallower rooting patterns and lower levels of transpiration. Vanacker et al. (2003) clearly indicates that the conversion of secondary forest to grassland or crop land is likely to increase shallow landslide activity.

These alterations increase landslide risk and may be compounded by activities and factors associated with agriculture such as terracing, low soil cover and reduced root infiltration. (Sidle et al.2006).

Forest roads affect slope stability by: (1) altering natural hydrologic pathways and concentrating water onto unstable portions of the hillslope; (2) undercutting unstable hillslopes, thereby removing support; and (3) overloading and over steepening hillslopes (via fillslope material) (Sidle et al., 1985)

A comprehensive survey of road-related landslides in Puerto Rico found that landslide-affected areas around roads were five to eight times greater than areas outside of the road influence (Larsen and Parks, 1997). While roads are a necessary part of most forest land uses, the critical concerns related to slope stability are: the length of roads in steep terrain; cutting roads at mid-slope locations (including the width of the road); interception and removal of water along the road (including drainage design); recognition of highly unstable landscape features (e.g., geomorphic hollows, old slump blocks); overall road design, layout, and construction considerations; maintenance; and ultimate life and use of the road, including deactivation strategies

The terraced are must be considered. Landslide frequency was higher on concave hillslopes, particularly in the lowest parts thereof, where water tended to accumulate and the soil was saturated. García-Ruiz et al. (1988) showed that the density of landslides in terrace walls was positively correlated with hillslope gradient, and negatively associated with the density of plant cover. Lasanta et al. (2001) demonstrated that erosion was barely discernible on the flat portions of terraces, although intensive grazing trebled both the runoff coefficient and suspended sediment concentration, compared to data from non-grazed terraces. Lesschen et al. (2008) reported that all of potential drainage area, loamy texture, the presence of trees on terraces, and the growth of shrubs on terrace walls, were significantly correlated with terrace failure. Cammeraat et al. (2005) found that plant recolonization was very rapid following terrace abandonment in the Alcoy basin of southeast Spain, and was sufficient to reduce landsliding process. The main problem was that soil permeability decreased rapidly with depth, and potential failure planes were found 1–2 m down, at the level of contact between regolith and unweathered parent material. In such instances, anchoring by root systems failed to prevent mass movement. Llorens et al. (1997) noted that failures in terrace steps after land abandonment in the eastern Pyrenees were rare, and had little effect on erosion or landscape degradation because of dense plant cover of the topsoil at terrace edges.

In Mediterranean environments, olive groves experience moderate soil loss (Koulouri and Giourga, 2007; Pardini and Gispert, 2012), which increases if the terrace is planted with vines (Pardini and Gispert, 2012).

Common to all these studies is strong interlinkage between landslide occurrence and changes in vegetation cover. Numerous studies worldwide have shown that vegetation cover is believed to have a considerable effect on slope stability. Also road building, trail construction, terraces and forest conversion can have some effects.

Moreover several theoretical and observational researcheshave provided some insight on the effects of land use on shallow landslide size. Selby (1967) observed that landslide exhibit a smaller size in grasslands than in forested areas. Gabet and Dunne (2002) also observed that landslides were smaller in areas where root strength decreased as a result land use change. Reneau and Dietrich (1987) used a slope stability model that accounted for the effect of lateral root reinforcement and conducted a theoretical analysis illustrating how a decline in root strength results in failures having lower lengths and widths, while low gradients or high soil friction result in failures having higher lengths and widths. Casadei et al. (2003) used a similar model to perform a sensitivity analysis illustrating that minimum width for failure increases with root cohesion and friction angle, and decreases with increasing slope or increasing relative saturation.

2.3 Modeling the topographic control on shallow landslide

This part focuses on the structure of SHALSTAB for analyzing the topographic control of shallow landsliding. SHALSTAB quantifies terrain instability in terms of the critical effective rainfall required to trigger pore pressure induced instability. Therefore this model is useful to describe the influence of topographic variable on landsliding susceptibility and locate the unstable areas. A general description of this model is presented in the following section.

2.3.1 Description the model SHALSTAB

Rainfall-induced shallow landslides represent a major issue in the evaluation of landslide. Many authors demonstrate a clear relation between shallow landslide occurrence and the characteristics of rainfall events in terms of intensity, duration. (Baum, R.L *et al* 2010, Crosta ,G.B*et al*, 2007,)

That is why is essential to investigate an important aspect of the quantitative evaluation of the hazard according to shallow landslides which is the assessment of the critical rainfall defined as the minimum rainfall able to trigger the instability process. In fact physically based model for the definition of the critical rainfall for shallow landslide is presented. The deterministic model which has been chosen is SHALSTAB (Shallow Landsliding Stability Model) (Dietrich and Montgomery, 1998)

SHALSTAB is a coupled, steady-state hydrological model and infinite-slope stability model, proposed by Hammond et al. (1992), which can be used to map the relative potential for shallow landslide across a landscape.

The infinite-slope stability model provides a one-dimensional model for failure of shallow soils that neglects arching and lateral root reinforcement. Because of the geometry of an infinite slope, overall stability can be determined by analysing the stability of a single, vertical element in the slope. End effects in the sliding mass can be neglected, and so too can lateral forces on either side of the vertical element, which are assumed to be opposite and equal. Under these assumptions, the Factor of Safety (FS) of the infinite slope equation is:

$$FS = \frac{C_r + C_s + [\rho_s\, g\, (D - D_W) \cos^2\theta + (\rho_s g - \rho_W g) D_W \cos^2\theta + W \cos\theta] \tan\emptyset}{D \rho_s g \sin\theta \cos\theta + W \sin\theta} \quad (1)$$

where C_s and C_r are soil and root cohesion [KPa], respectively, ϕ is the internal friction angle of the soil [degrees], Ɵ [degrees] is slope angle, ρ_s is wet soil density [kg m^{-3}], ρ_w is the density of water [kg m^{-3})], g is gravitational acceleration[m s^{-2}] , D (m) the vertical soil depth, Dw (m) is the vertical height of the water table within the soil layer and W is vegetation surcharge [Pa].

The decrease of FS occurs with an increase of the water column due to the reduction of effective stress. Thus, during a rainfall event, the water table elevation reduces FS.

Different parameters are presented clearly in the figure below:

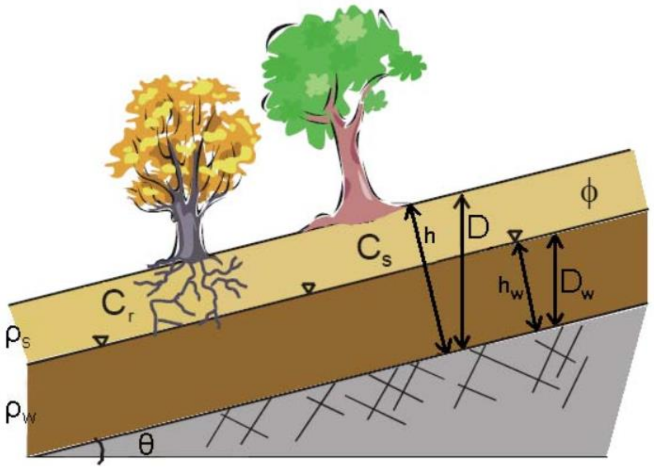

Figure1: The infinite slope equation as defined by Hammond et al., (1992) and Pack et al., (1998) where C r is root cohesion, CS is soil cohesion, θ is slope angle, ρs is soil density, ρw is the density of water, g is acceleration due to gravity, D is the vertical soil depth, Dw is the vertical height of the water table, and Φis the internal soil friction angle. H is depth is measured perpendicular to the slope.

Typically the factor of safety is interpreted using thresholds to categorize the hazard of landslide occurrence. In principle, $FS \geq 1$ indicates a slope in equilibrium or in limit equilibrium and $FS<1$ indicates an unstable slope. Because of its physical basis, the factor of safety equation may be considered more generally applicable, in terms of geographical location and for determining the impacts of land use and climate change, than are empirically derived threshold equations for landslide occurrence.

In several cases, only two factor of safety classes ($FS \geq 1$ and $FS<1$) are deemed enough to estimate the susceptibility of a landscape to shallow landsliding, and analysis of stability in relation to a range of precipitation values is required. In these situations, the concept of critical rainfall, introduced by Montgomery and Dietrich (1994), is worth using. The critical rainfall is the minimum steady state rainfall predicted to cause instability. Coupling between the slope stability model and a hydrologic model is required to allow the derivation of the critical rainfall (Montgomery and Dietrich, 1994).

The hydrologic model is based on the following assumptions:

1) Shallow lateral subsurface flow follows topographic gradient. This implies that the contributing area to flow at any point is given by the upslope area per unit contour width *a* [m].
2) The entire soil profile is initially wet to field capacity.
3) Lateral discharge at each point is in equilibrium with a steady state recharge *R* [mm day^{-1}], i.e. the infiltrating rainfall which passes through (or bypasses) the unsaturated zone to reach the saturated zone and eventually becomes subsurface runoff. The steady state assumption implies that the specific upslope area is a surrogate measure of the subsurface flow at any point in the landscape. However, this is only valid if recharge to a perched water table occurs for the length of time required for every point along the hillslope to reach subsurface drainage equilibrium and experience drainage from its entire upslope contributing area. Borga et al. (2001) proposed an alternative approach to relax this assumption.
4) The recharge rate equals the rainfall rate, thereby neglecting the vertical transport processes taking place between rainfall reaching the ground surface and recharge occurring at the soil base. Rainfall infiltrates quickly into the highly permeable soils dominated by subsurface runoff and this approximation should be adequate.
5) The capacity for lateral flux at each point is $T\,sin\theta$, where *T* is the soil transmissivity [m^2 day^{-1}].

Furthermore, the approach with the hydrologic model is to interpret the soil thickness as specified perpendicular to the slope (*h*), rather than soil measured vertically. The SHALSTAB model is based on the previous assumptions.

In SHALSTAB, the critical rainfall (Rc) is defined as

$$Rc = \frac{Tsin\theta}{a}\left[\frac{Cr+Cs}{\rho wghcos\theta tan\emptyset} + \left(\frac{\rho s}{\rho w} + \frac{W}{\rho wgh}\right)\left(1 - \frac{tan\theta}{tan\emptyset}\right)\right] \quad (2)$$

According to Montgomery and Dietrich [1994], four stability classes can be determined: unconditionally unstable, unstable, stable, unconditionally stable. The condition for unconditionally unstable slopes is expressed by:

$$tang\theta \geq tan\emptyset + \left[\frac{Cr+Cs}{[\rho sghcos\theta(1+W/(\rho sgh)]}\right] \quad (3)$$

The condition for unconditionally stable slopes is expressed by:

$$tang\theta < \left[1 - \left(\frac{1}{\frac{W}{\rho wgh} + \rho s/\rho w}\right)\right] tan\emptyset + \left[\frac{Cr+Cs}{\left[\rho sghcos\theta\left(1+\frac{W}{\rho sgh}\right)\right]}\right] \qquad (4)$$

In this work the simulation model SHALSTAB is implemented based on a special application, which returns a map in raster format "GRID" or "FLOAT" viewable through GIS program. The figure 2 presents the graphic application of this model. It is divided into three sections: section of input, output, and numerical parameters.
In the input section raster maps of DTM, upslope area, cohesion and soil depth are inserted. Obviously, all maps must have the same coordinate system and the same cell size. Cohesion and soil depth can be expressed as a constant value throughout the basin or with variable values. In the section of numerical parameters are defined values of the angle of internal friction, and the density of the soil saturated hydraulic conductivity. These can be expressed only as a constant value throughout the basin. Concerning the section of output there is a returned map raster of critical rainfall, with values expressed in mm / hr.

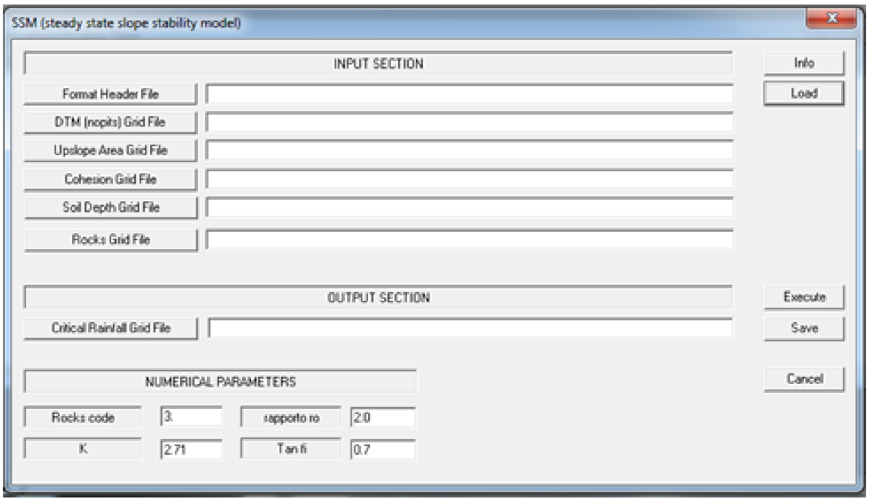

Fig 2: SHALSTAB graphical application

Table1 : Uniform values for soil parameters used in SHALSTAB modeling

Parameter	Value
Rocks code	3
$\rho w/\rho s$	1.8
K	1.66
Tang fi (45°)	0.84

Chapter 3: Material & Methods

3.1 Study area, land use and available data

The Rio Lierza basin is located in the northeastern Italian Prealps (Veneto region) and belongs to the Piave river system. The study area (Fig3), identified by the outlet at Molinetto dell Croda (45°56'16”, 12°11'29”), is part of the upper Lierza basin and covers about 7.5 km^2. The basin is characterized by hilly topography and elevations range from 180 to 474 m a.s.l (the mean elevation is 295 m a.s.l).The study area is located in the monoclinal relief of hogback type called VetteFeltrine, Southern Alps. The geology consists of Miocene conglomerates and mudstone affected by tectonic deformation. The soils are mostly silt loams. Slopes ranged from 25° to 35° are most common. The basin is ungauged: the closest raingauge station is located in Follina, where data are available since 1994. Examination of rainfall data from this rain gauge station show that average annual precipitation is 1630 mm, with the highest monthly average precipitation was in May and November. The climate pattern in the area has a typical transition profile between maritime and continental types, with mild winters and warm summers.

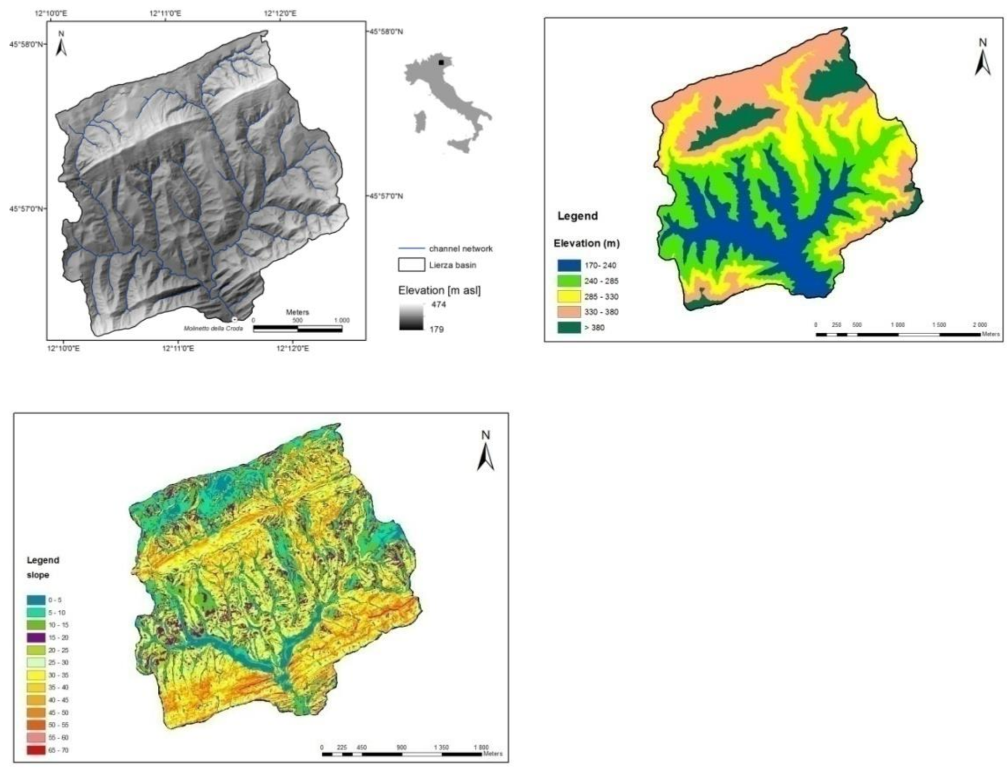

Fig. 3.The upper Lierza basin (a), with topography (b) and slope distribution in degrees (c).

Concerning land use data, they are documented through land use inventories available for 1890, 1960, 1989 and 2012 (Table 2) and illustrated for the year 2012 in Figure 4. The 2012 land use map is valid also for 2014, as assessed during the post event landsliding surveys.

Based on this map, in the basin the greater part of land cover is occupied bywood which represent 66.5% of the surfaceof the basin. Additionally this area is dominated by the vineyards which represent 31.8% of the surfaceof the basin and lower part is occupied by grass (8.8%).

The basin experienced significant land use changes since 1890, with a remarkable increase of wood areas and decrease of grasslands. An examination of the changes between 1989 and 2012 shows that the overall wood area remains almost constant in this period, with redistribution of vineyard and grass. However, these figures should be considered with respect to the land use conversions. Actually, during the period 1989-2012 29 ha (9 ha) of wood areas were converted to vineyard (grassland), whereas 39.2 ha of grassland and 7 ha of vineyard were converted to wood.

Table 2: Land use distribution

Land use	1890	1960	1989	2012
Wood	44.0	41.3	65.6	66.5
Vineyard	18.3	17.2	13.3	21.8
Grassland	34.3	37.7	18.5	8.8
Urban/bare soil	2.4	2.4	2.6	2.9

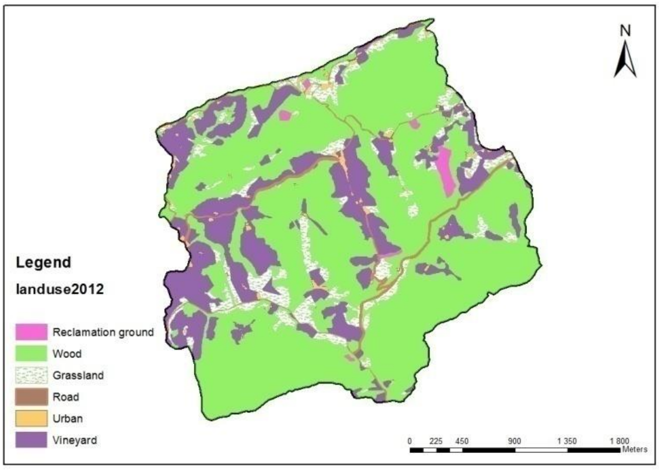

Fig4: Land use distribution for year 2012

Terracing is widespread in the basin to control water erosion and allow mechanized farming operation in vineyards.

3.2 The flood event

On August 2, 2015, an extreme rainstorm caused severe flash flooding and widespread shallow landsliding in the upper Lierza basin. Catastrophic precipitation started on August 2 at 18:10 and lasted for 1h and 40 minutes, ending at 19:50. The precipitation led to the formation of an extreme flash flood, with a peal of around 130 m^3 s^{-1} at the basin outlet. The flood caused the death of four people.

3.3 Rainfall estimation

Rainfall estimates were obtained by merging weather radar observations and raingauge data. Radar data were collected from the Concordia Sagittaria Doppler C-band antnna, which is located at about 50 km from the catchment. Radar reflectivity has been converted into rain rate using the relationship $Z = 300 \cdot R^{1.4}$, suitable for convective events over the region, providing rain rate with 500 m spatial and 10 min temporal resolution. Radar estimates have been adjusted removing the mean field bias with respect to rain gauge measurements in order to ensure quantitative accuracy. The standard error between radar and rain gauge event accumulations is 40% of the average rain gauge measurement and the correlation coefficient is 0.82.

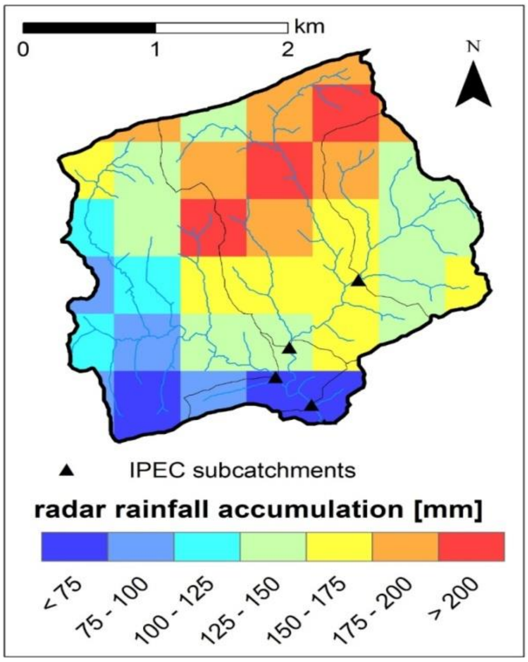

Fig5.: Radar rainfall accumulation of the August 02, 2014 rainstorm over the Lierza river basin

Fig.5 shows the radar rainfall accumulation in the upper Lierza river basin. The spatial distribution of the rainfall accumulation reflects the SW-NE trend of the August 02, 2014 rainstorm. The northeastern part of the study area received a local peak of 254 mm, with a maximum rainfall rate as high as 135 mm/10 min. In the southwestern part, at the outlet of MolinettodellaCroda, the lowest radar rainfall accumulation was observed. The storm hit the area at 18.10 (UTC), two peaks characterized it before finishing at 19.50. At 18.30 (UTC) the radar recorded the first peak rain in the southeast part of the basin, the maximum rainfall rate is 114 mm/10 minutes. At 19:20 (UTC) the basin received the highest peak rain (135/10 min).

3.4 Post-flood survey of rainfall and flood data

One week after the flash flood event, stream channel surveying began to provide post-flood indirect peak flow estimate. Five short reaches (40–100 m) were intensively surveyed with use of a total station for the purpose of indirect discharge calculations. A steep cascade, located at the MolinettodellaCroda (Fig. 3a,b), provided excellent opportunity for peak discharge estimation. High watermarks were flagged and surveyed. Other channel features such as thalweg, banks, slope breaks, and deposits of gravel and debris were also surveyed.

Two weeks after the flood a bucket survey of rain gauge was conducted in the study basin and nearby area. Nine rain gauges and other containers were recorded in the area and GPS waypoints were taken at each rain gauge location. Of the nine raingauge measurements collected, seven were deemed to be good quality measurements of rainfall, based on location, type of collector, and anecdotal information (e.g.,gauge/container likely not empty before storm, resident did not quite remember amount, gauge/container overflow).Local residents were interviewed about the severity of the storm and such factors as wind, hail, thunder and lightning, timing of rainfall and visible characteristics of runoff generation and propagation, such as rate of stream rise and timing of peak stage.

Fig.6: The cascade at the Molinetto della Croda (a);the outlet at Molinetto della Croda (b).

3.5 Shallow landslides: survey

During the winter 2014-15, a shallow landslides survey was carried out. Following a standardised protocol, a set of parameters was recorded for each landslide, including the dimensions of the slides, soil depth at the initiation point, and various site characteristics such as land use, geomorphology and interaction with river network and with infrastructures such as roads and terraces. The landslide dimensions and the slope inclination of the release zones were measured for each landslide. Given the irregular shape of most landslide scars, both maximum and min dimensions were recorded. In the study area some landslides were initiated by bank erosion along torrent channels. These landslides were not included in the present analysis because the study focuses on the effects of forest cover on rainfall-triggered slope processes. More than 500 shallow landslides were triggered by the high-intensity rainfall in the Lierza basin. A total of 406 landslides were mapped during the survey (Fig. 7)

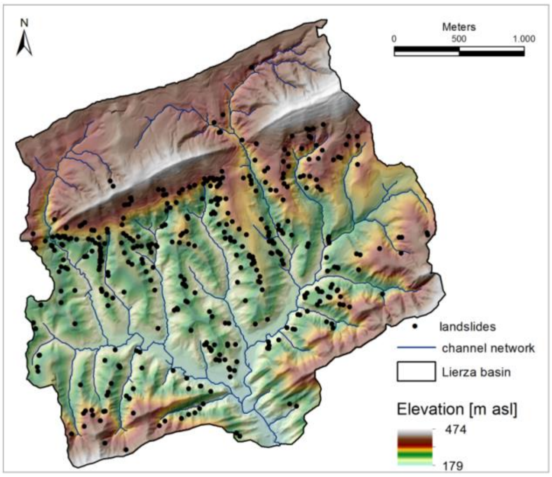

Fig. 7: Shallow landslide distribution in the Lierza basin.

3.6 Shallow landslide data: quality assessment

The occurrence of landslides is governed by complex interrelationships between factors, some of which cannot be determined in detail, and others only with a large degree of uncertainty. One of the cornerstones of scientific research is the quality of the data collected. Without an adequate understanding of the data quality, it is difficult to trust the derived results.

Some important aspects in this respect are the error, accuracy, uncertainty and precision of the input data, and the objectivity and reproducibility of the input maps. The accuracy of input data refers to the degree of closeness of the measured or mapped values or classes of a map to its actual (true) value or class in the field. An error is defined as the difference between the mapped value or class and the true one.

In this case the assessment of the data was done in order to enable a diagnosis of quality to remove data with errors. Most of the quality assessment was focused on land use mapping. As the remote sensing was used to map the land cover, so a variety of errors are encountered in an image classification. In fact careful examination was done manually. This was based on using land use data from land use maps and contrasting this with that observed during the survey.

Then we compare if the actual land use class of map refers to / is not the one reported in the field survey. It is essential to mention that we have 406 surveyed points. Each point belongs to a specific class of land use. In the excel file we organized a table which records land use in the map and land use in the survey with codes (table) in order to compute the different combinations and detect the errors.

3.7 The control factors

Different datasets were used to fulfill the intended purpose of the project. They are described and discussed below. The main software programs that were used to complete this project are ArcGIS Version 10 and Microsoft Excel. All the following datasets mentioned had been processed in ArcGIS, and then had further processed in Microsoft Excel.

3.7.1 Rainfall

The rain data in this area are obtained from radar and raingauges. We used this data to analyse the frequency distribution of rainfall and examine the effect of rainfall on occurrence to shallow landslide.

The steps in ArcGIS are described below.

Firstly the rainfall layer is converted from Float to Raster. Secondly, using the Spatial Analyst tools is aimed to extract values by points.

Finally, the raster values were exported into Microsoft Excel and interpolated for analyses and graphs were produced to show patterns of precipitation.

3.7.2 Slope

Slope angle is known to cause spatial variability in landsliding (De Rose, 1996; Dymond et al., 2006) and therefore a high resolution slope map of the study site was necessary for the purpose of analysing landslide slope distributions. Because of the known scale dependence of DEM-derived slope angles on cell resolution (Montgomery et al., 1998; Walker and Willgooge, 1999; Claessens et al., 2005) it was found necessary to build a DEM (fig) of the study site at a resolution suitable for representing the fine scale detail of landslide scars and which would provide adequate replication of field slopes.

Its value may be calculated from the DEM by the inclination computational method. As a result, the values of the slope angles are divided into classes in increments of 5° (i.e., 0°, 5°, 10°,15°…..55° 60°, and >65°) (Fig. 2)

3.7.3 Land Use

Many studies have revealed a clear relationship between land use and shallow landslide. There are different parameters that related to the land use and modified by the presence of vegetation as cohesion, internal friction angle, weight of the soil and pore-water pressure.

Vegetation can both enhance effective soil cohesion due to root matrix reinforcement and soil suction. According to Selby (1993), tree-coveredhillslopes are thought to increase soil shear strengthby about 60% depending on the tree type. Mehrotra et al. (1996) demonstrated that landslide activity increases by up to 15% in thoseplaces where the original vegetation cover has beenremoved or altered.

In order to correlate vegetation cover with landslide occurrence, a vegetation classification was carried out in this study. The intention was to discriminate between different vegetation cover types.

A land use map was also prepared. Aerial photograph taken in 2012 was also downloaded as a layer (shape) format for Lierza basin had 6 land cover classes. The image was converted into raster format and then reclassified into 6 main land cover classes.

The resulting image is presented in Fig.8 and used in further stages of this research.

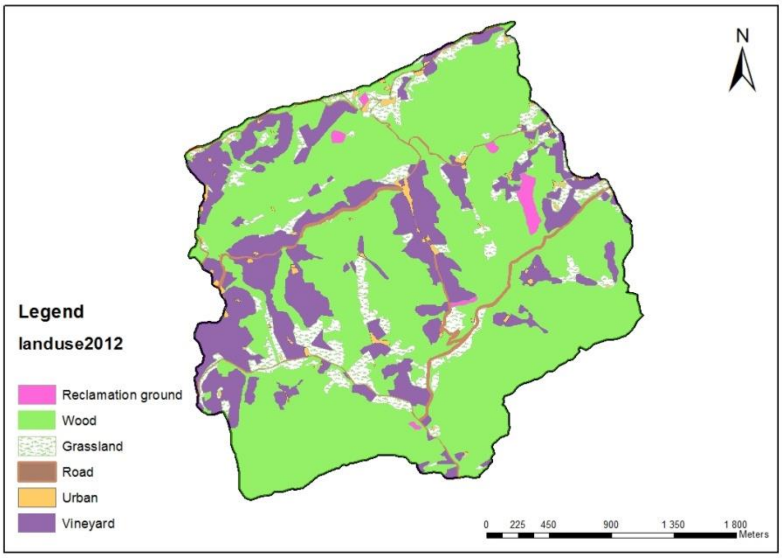

Fig .8The result of land covers classification for the Lierza basin

3.8 Statistical analysis

3.8.1 Wilcoxon rank-sum test

The Wilcoxon test, which refers to either the Rank Sum test or the Signed Rank test, is a nonparametric test that compares two paired groups.

It is based upon ranking the $n_X + n_Y$ observations of the combined sample. Each observation has a rank: the smallest has rank 1, the second smallest rank 2, and so on. The Wilcoxon rank-sum test statistic is the sum of the ranks $w_X$for observations from the samples X (the group having the smaller sample size).

The null hypothesis H_0 tests whether the two groups come from the same population, whether the alternative hypothesis is true, the two groups are different.

For large samples, the distribution of the test statistic w_X closely approximates a normal distribution and a z-statistic to compute the approximate p-value of the test was used. It is based on the near normality of the test statistic and has a mean (μ) and a standard deviation (σ) as in equation [1] and [2]:

$$\mu = n_X * (N+1)/2 \qquad [1]$$

$$\sigma = \sqrt{n_X * n_Y * (N+1)/12} \qquad [2]$$

Where $N=n_X+n_Y$.

In this study we use the Wilcoxon rank-sum test in order to determine whether slopes, landslides area, and cumulated rainfalls of the two land uses landslides groups come from the same population, or alternatively whether they differ only in location.

To conduct the analysis a MATLAB function was used. It tests the null hypothesis; data X and Y are samples from continuous distributions with equal medians, against the alternative that they are not. The test assumes that the two samples are independent, X and Y can have different lengths.

The Wilcoxon test detected also if the distribution of X is shifted to the right or left of distribution Y.

The P-value corresponding to the rank-sum test statistic at the 5% (α=0.05) significance level $w_X$and the value of the z-statistic was obtained.

The result h = 1 indicates a rejection of the null hypothesis, and h = 0 indicates a failure to reject the null hypothesis at the 5% significance level.

3.8.2 Application of Wilcoxon test on landslides parameters

In this statistics we considered mainly the two land use groups: woods and vineyard

Samples from two land uses were examined. The two groups,woods and vineyard, were compared with respect to the slope (landslide area, soil depth and critical rainfall) variable.

The data samples are:

- 214 slopes (soil depth and critical rainfall) in woods and 157 slopes, (soil depth and critical rainfall) in vineyard characterize three tests;
- 177 landslides area in woods and 117 landslides area in vineyard characterize the data.

The hypothesis that the data in woods (X) are the same as that in vineyard (Y) is the null hypothesis (2-sided test). The alternative hypothesis is that the data in wood is minor than data in vineyard, and the data in wood is greater than data in vineyard respectively.

H_0: X=Y

H_1=X<Y

H_2=X>Y

The test sorted the combined of two data set into ascending order and computed the sum of the ranks for observations from X.

We suppose that X<Y (1-sided test). In case of true hypothesis, the X sample is expected to be smaller than Y. Then we suppose X>Y (1-sided test), in case of true hypothesis the X sample is expected to be bigger than Y.

Chapter 4: Results and Discussions

4.0: Quality assessment of the data

The comparison between the land use in the map and those recorded in the surveyprovides the following results which are considered as errors:

- The land Use in the map records two areas as vineyards, whilst countryside survey records them as wood.
- The land Use in the map records 16 areas as wood , whilst countryside survey records them as vineyards

To make the understanding easier it is needed to highlight the reasons of the error.

At the beginning it is important to mention that there are diverse perspectives in the classification process, and the process itself tends to be subjective, even when an objective numerical approach is used. There is, in fact, no logical reason to expect that one detailed inventory should be adequate for more than a short time, since land use patterns change with demands for natural resources.

Furthermore this error may in part be due to the issues ranging from the properties of the sensor and ground to the methods used to preprocess the data can have a marked impact on the ability to accurately locate a pixel (Bastin, Edwards, & Fischer, 2000). This positional uncertainty can have a major detrimental effect on thematic mapping studies. Consequently significant misregistration problems have been observed.

Moreover the satellite Land use Map is based on the imposition of a grid on the land surface. Each grid cell is classified, on the basis of its dominant spectral signal, independently from those around it. The field survey differed in that boundaries between cover types were determined by the field surveyor, and once drawn; the areas within boundaries were assumed to have uniform land cover. In reality, woodland blocks are rarely (if ever) uniform in botanical structure. Such subtle variations may be overlooked or ignored by the field surveyor, but can result in a mosaic of cover types in the Land Cover Map. Thus, while the satellite map is based entirely on land cover, the field survey also uses elements of land use in recording blocks of homogeneous vegetation.

Also one of the basic reasons to find this combination that the vineyard is on the edge of a wood- land in this basin, where the wood are gradually being removed and replaced with grapevines.

A further reasons arises as a consequence of this error is the heterogeneity of landscape, this means the surveyed area is a mixed area with low productivity of wood. That is why for example the surveyor reports more vineyards in the field.

Other differences affected the quality of the input data is linked to many factors., such as the scale of the analysis, the time difference between the 2012 map and the 2015 field survey, money allocated for data collection, the size of the study area, the experience of the researchers, and the availability and reliability of existing maps.

4.1 Shallow landslide variability with land use

Vegetation influence on slope stability is an important factor through several propreties: root strength, evapotranspiartion, terraces, roads, drainage area. This section seeks to answer the question: How the different characteristics of shallow landslides (SL): frequency and size may be controlled by land use?

The influence of vegetation on the landslide distribution is, however, difficult to assess, at least in part, because geology, slope morphology and soil characteristics can influence vegetation, as well as the distribution of soil slips (Wieczorek et al., 1988)

Using the site survey and aerial photo interpretation, six main land use classes were identified: [1] road, [2] urban, [3] grassland, [4] vineyards, [5] reclamation ground and [6] wood. Computed percentages of landslides for land-use classes in the survey and in the basin show that the highest values are observed in the woodlands (66,55%) and in the vineyards (20,93%) in the basin (table 3) . Also an increase in landslide occurrence is observed in the same classes in the survey field.

Table 3: The percentage of landslides in the basin and in the survey linked to Land Use classes

Classes	% in the basin	% in the survey
1	1,45	2,5
2	1,35	0,5
3	8,79	3,75
4	20,93	37,75
5	0,93	0,25
6	66,55	55,25

So, comparing with the other classes of land Use, this study, clearly indicates that most landslides surveyed occurred in the woodlands and in the vineyards in the basin and the same for the survey. This difference between the land use classes in shallow may be due to differences in rainfall.

According to this, SIDLE *et al (*1985) and BEGUERIA (2006) confirm this obtained result since they found that vegetation and land use are widely recognized as important factors influencing the occurrence of rainfall-triggered landslides.

Tropeano (1983) pointed out that Vineyard cultivation is considered to be one of most erosive land uses in Mediterranean and humid environments.

The reasons for triggering landslide in vineyards are simple. Firstly, the cultivation of vines is relatively common on sloping land (sometimes approaching 10°) on the lower part of hill slopes, on old pediments, or between different levels of pediments and fluvial terraces.

Secondly, the soil is almost bare for a large part of the year. Between November and April the plants lack leaves, and in May the foliage is still moderate. Even in summer, when the plants have reached maximum development, part of the soil is unprotected. According to Lasanta and Sobrón (1988) , the ground cover is about 5% between November and March, 20% in April, 40% in May, 65% in June, 80% from July to September, and 70% in October. There is also a trend of decreasing percentage cover with the introduction of new plantation systems. If the vineyard is young, the density of cover can be very low, less than 10% even in summer. For this reason, vineyards provide little protection for the soil under the Mediterranean precipitation regime, since the autumn and spring rainfall occurs when the soil is almost bare.

Besides, there is different studies stress that the shallow landslide occurs in wood. This obtained result is explained by the dependence of shallow landslide occurrence on tree age and type of root. Thus the root of young tree and the root systems of juvenile trees extend generally in the first meters of the soil profile and are involved in the landslide. Also in the most regions forests are actually on steeper slopes than open land or cultivated land, and are more susceptible to landsliding. Therefore, this is true for Lierza basin.

The high percentage of shallow landslides in woodlands is probably attributable to their poor management. In addition the woodland soils have infiltration capacities that conduct rainfall to the subsurface rather than allowing overland flow. Moreover roads which are often built in conjunction with agriculture or forestry activities contribute the largest landside losses and affected the woodland areas.

4.2 Shallow landslide density

Landslide densities (number of slides per km^2) can help to evaluate the effects of specific site characteristics, such as vegetation cover, on slope stability. Here the landslide density is computed for the different land use classes and differences are reported.Results are reported in Table 4, where it is apparent that landslide density in vineyard (100 km^{-2}) is more than twice that in the wood area (43 km^{-2}). This supports results reported by Rickli and Graf (2009), who found that in five over six of the study areas the landslide density was greater in openland than in forested terrain, with the landslidedensity in forest areas amounting to about 50 to 80% of the density in open land.

This shows that forested slopes are mostly more stable than comparably steep slopes inopen land. The reason for this probably has to do with the reinforcing effect on slope stabilityof the diverse root systems of the trees and the associated forest vegetation, as many authorshave described. Several other landslide inventories have also found that shallow landslidesare less frequent in forests than in open land (Moser 1980; Moser and Schoger 1989;Fazarinc and Mikos 1992; Markart*et al.* 2007).

Table 4.Landslide density in the basin, vineyard and wood.

	area [km^2]	N°of landslide	N°of landslide/km^2
Basin	7.48	400	53
Vineyard	1.57	157	100
Wood	4.98	214	43
Others	0.93	29	7

4.3 Shallow landslide shape

The landslide area is computed for the different land use classes and differences are reported (figure9).

Significant differences (p-value < 0.05, Wilcoxon rank sum test) were discovered in landslide area of landslides in vineyard and in forest areas. P-value for the 2-sided test is smaller than α, we reject the null hypothesis, showing that landslides areas are different. For the 2-sided test, the left tail has a p-value greater than α, we accept the null hypothesis (table 5). In this study the areas of wood landslides exceeded those in vineyards (Fig.9).

Table 5: The results from the Wilcoxon test of landslide area.

tail	landslide area	
	p	h
both	6.24E-06	1
right	3.12E-06	1
left	0.999997	0

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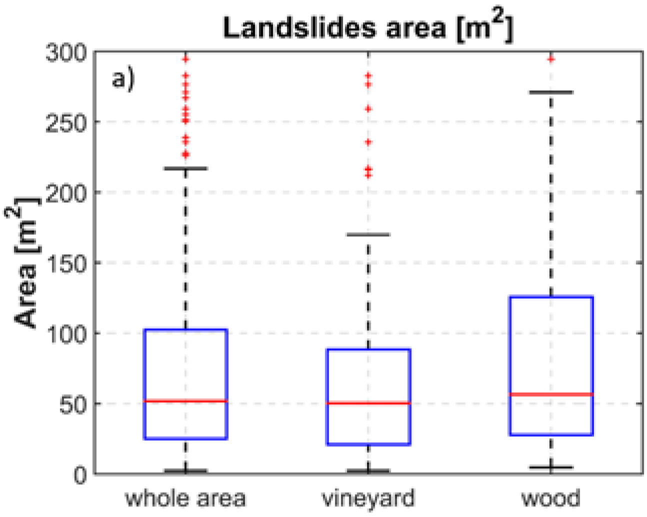


Fig.9: Boxplot of the landslide area as a function of land use in the Lierza.

This supports earlier results from Moser(1971), who showed that the largest slides occurred within forested areas, and Moser and Schoger (1989), who found that the surface areas of forest slides were larger than those in open land.

4.4Rainfall

In this section we want to evaluate the role of cumulated rainfall as a factor on shallow landslide occurrence through investigating the frequency distribution of landslides in different classes of Rainfall in the basin and in the survey, and as a function of land use.

Table 6: Frequency Distribution of Rainfall

Classes (mm)	% in the basin	% in the survey	cumulative frequency in the basin	Cumulative frequency in the survey
44	0,00	0,25	0,00	0,25
80	8,32	6,16	8,32	6,41
116	13,65	14,29	21,97	20,70
152	30,28	28,57	52,25	49,27
188	25,24	28,08	77,49	77,35
224	19,17	15,76	96,66	93,11
260	3,34	6,9	100,00	100,00

The computed the percentage of landslide within the rainfall classes in the basin can be compared with those observed in the survey to evaluate the impact of rainfall on occurrence of shallow landslide. This comparison indicates that there is no significance difference between the percentages of landslide in the basin and in the survey. In fact we found no clear correlation between landslide incidence and cumulated rainfall distribution.

This interpretation is confirmed in figure which reports the cumulative frequency distribution of rainfall in the basin and in the survey.

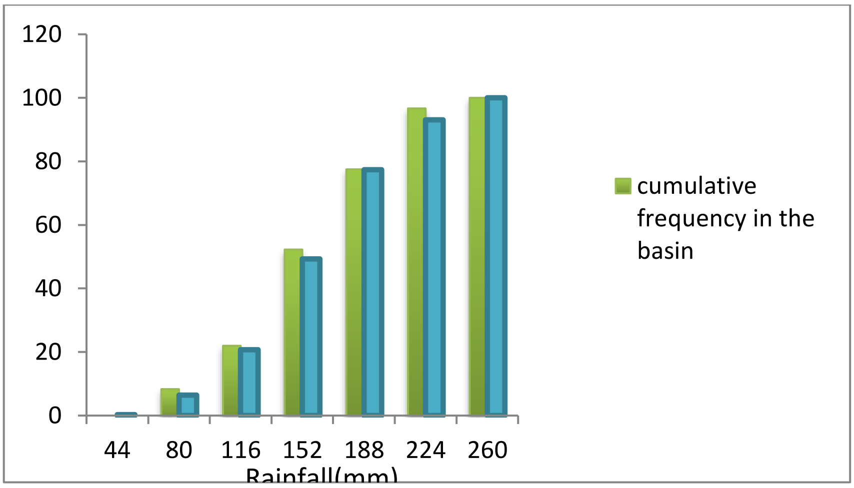


Fig10: Frequency distribution of landslides in different classes of rainfall in Basin Lierza

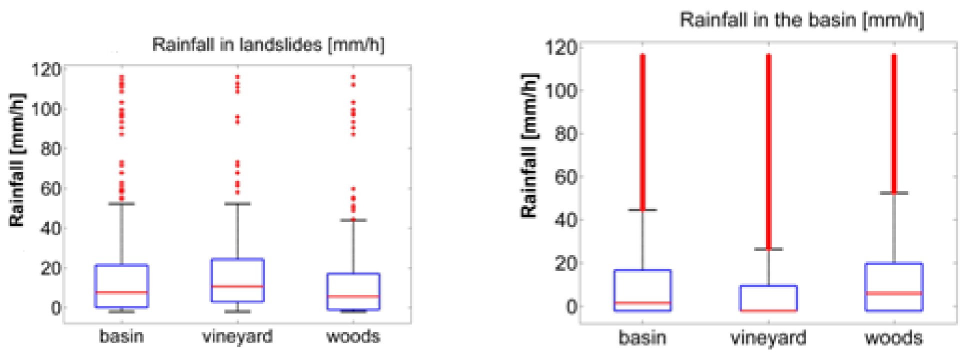
A possible explanation of this result is that the slopes react rapidly to the rainfall events. Also even the lowest recorded amount of precipitation for landslide occurrence was exceeding that required for landsliding triggering.

Rainfall data were tested for significat diffrences usingWilcoxon Rank Sum test. Some major findings can be concluded from the table and figure:

- The Wilcoxon test for rainfall in wood and in vineyard shows that P-value for the 2-sided test is smaller than α, we reject the null hypothesis, rainfall come from different population. For the 2-sided test the right tail has a p-value greater than α, we accept the null hypothesis, the rainfall in vineyard is greater than in woods.(table7)
- The rainfall exerts a great influence on shallow landslide within the land use classes. Based on the figure 11, we found that the mean rainfall is different between the vineyards and forests in the landslide and in the basin. It is less higher in the latter one.

Table.7The results from the Wilcoxon test of rainfall

tail	Rainfall	
	p	h
both	0.00534	1
right	0.997338	0
left	0.00267	1



(a) (b)

Fig 11. Boxplot of the rainfall distribution in landslide (a) and in the basin as a function of land use

4.5 Slope

Topograhic slope is one of the most important topographical factors influencing landslide occurrences by computing the frequency distribution of landslide within different classes of slope in the basin and in the survey. This section aims to better assess the role of slope to rain-caused landslides for the different land uses.

Table 8: Frequency Distribution of slope

Classes (degrees)	% in the basin	% in the survey	Cumulative frequency in the basin	Cumulative frequency in the survey
0-5	4,65	2,22	4,65	2,22
5-10	8,79	1,48	13,44	3,69
10-15	12,35	4,43	25,78	8,13
15-20	15,15	8,13	40,93	16,26
20-25	17,44	13,30	58,37	29,56
25-30	17,75	24,63	76,12	54,19
30-35	12,83	21,92	88,95	76,11
35-40	6,89	16,75	95,84	92,86
40-45	2,66	5,67	98,50	98,52
45-50	0,82	0,99	99,32	99,51
50-55	0,37	0,25	99,68	99,75
55-60	0,22	0,25	99,90	100,00
> 60	0,10	0,00	100,00	100,00

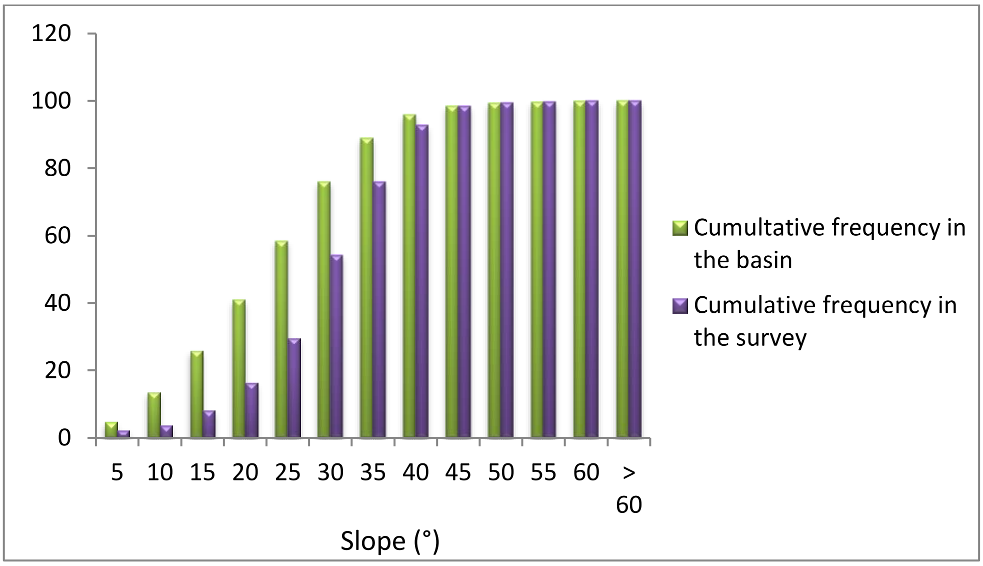


Fig12: Frequency distribution of landslides in different classes of slope gradients in Basin Lierza

As shown in the table, the highest frequency of landslides (24.63%) in the survey and (17.75%) in the basin was in the slope range of 30°.

At lower slope gradients, the frequency of landslides is low because the terrain is gentle and covered with thick colluvium and/or residual soils which require higher water levels to initiate slope failures. Meanwhile, at very high slope gradients, the frequency of landslides is also low because the terrain is very steep with a small amount of colluvium. The most common slope range varies from 20° to 35° in the field survey and in the basin.
Besides, the cumulative frequency distributions of slope emphasize some important characteristics. (fig12). In fact there is a clear difference between the cumulative frequency of landslide in the basin and in the survey. For instance the cumulative frequencies of landslide on the slope range of 20° varies from 16,26 % in the survey to 40,93 % in the basin. Based on the obtained result it was possible to say that the slope gradient is one of the most important topographical factors influencing landslide occurrences.

The statistics analysis above indicates:

- That P-value for the 2-sided test is smaller than α, we reject the null hypothesis. Slopes from woods and vineyard come from different population, slope in woods are greater than slopes in vineyard.(Table9)
- The variability between the wood and vineyards associated landslide for slope gradient is shown in the boxplots (fig13) . Concerning the slope: inspection of the box plots

reveals that the mean slope of landslides in woods was larger than the mean slope in the vineyards.

Table 9: The results from the Wilcoxon test of slope

tail	Slope	
	P	h
both	9.27E-11	1
right	4.64E-11	1
left	1	0

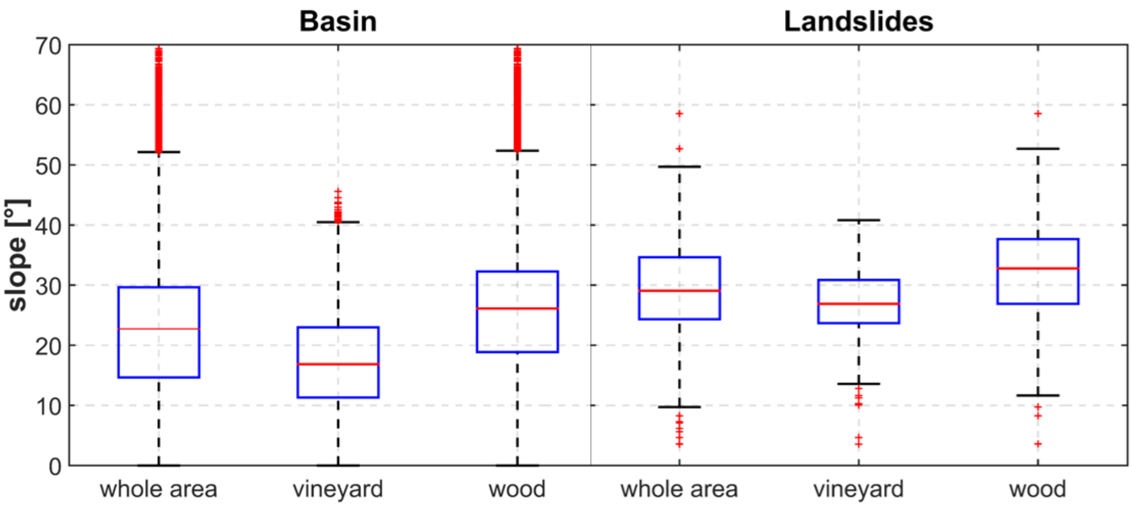


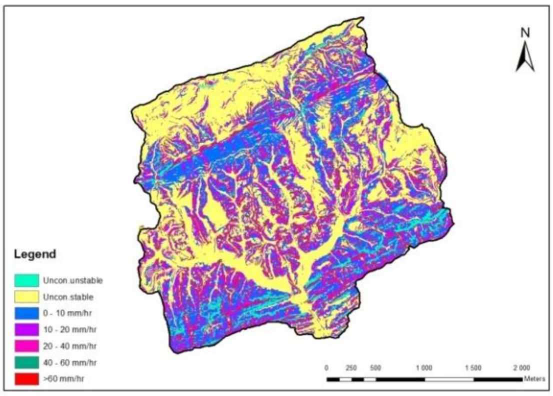
Fig 13. Boxplot of the slope values as a function of land use in the Lierza basin and in the landslides.

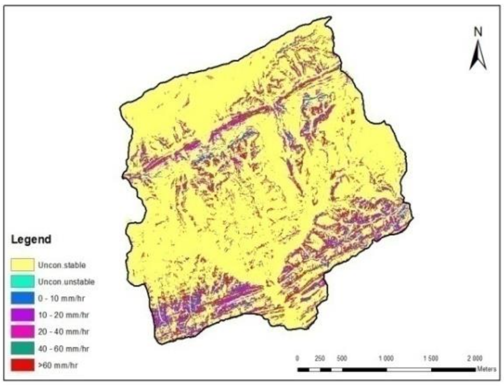
4.6. Topographic analyses via SHALSTAB

The output of SHALSTAB is the critical rainfall.

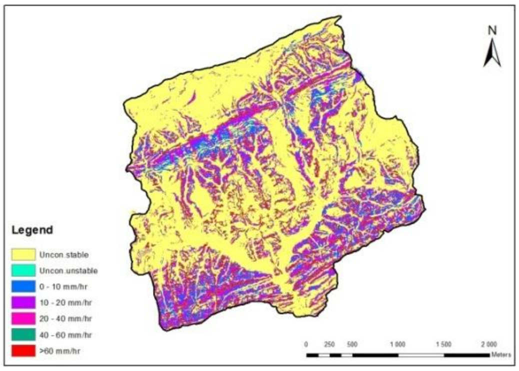
The results of SHALSTAB simulation, using the parameters of table, are shown in fig where the classification is based on seven stability classes established originally by Dietrich and Montgomery (1998). The model considered most of the flat areas as unconditionally stable, and they are not susceptible to shallow landslides even with strong rainfall. In contrast, steeper areas were classified and they are susceptible to landslides even without rainfall as unstable areas. The five intermediate classes show degrees of instability.

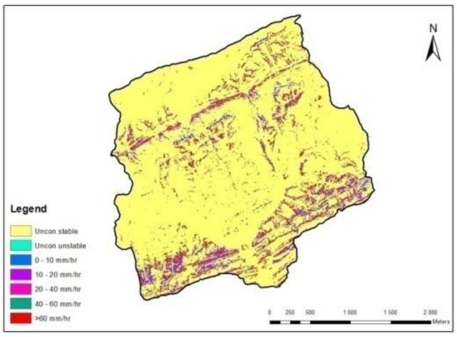
The five graphs (Fig14. a–e) show a comparison between the simulated and the measured data for the five experimental cohesions (0, 2, 4, 5 and 7 KPa).



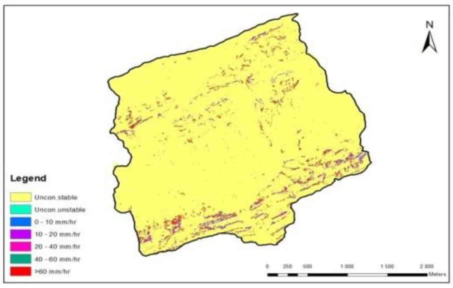


(a) (c)





(b) (d)



(e)

Fig14: Map of critical rainfall for the Lierza basin tested with different cohesion (a= 0, b= 2, c= 4, d= 5 and e= 7 KPa)

Good model performances are expected when a large percentage of landslides and a small percentage of catchment areas occur for low values of critical rainfall. For example, this is the case when the cohesion equal to zero and the soil depth equal to 1 m, the percentage of catchment area with critical rainfall varied from 0 to 10 mm/hr is equal to 17.51%, while the corresponding fraction of observed landslide area is equal to 32.25% (table10)

Table10 .Percentage of catchment and landslide area in each critical rainfall range for the Lierza basin.

a.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	4.89	11.75	31.75
0 - 10 mm/hr	17.51	32.25	39.25
10 - 20 mm/hr	13.73	16.75	16.75
20 - 40 mm/hr	12.50	15.25	8.25
40 - 60 mm/hr	4.51	5.75	1.00
> 60 mm/hr	4.11	5.50	3.00
Stable	42.76	12.75	0.00

b.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	1.93	3.25	12.00
0 - 10 mm/hr	7.02	13.75	34.00
10 - 20 mm/hr	7.78	12.50	19.75
20 - 40 mm/hr	10.55	20.75	20.50
40 - 60 mm/hr	5.30	9.25	5.75
> 60 mm/hr	5.76	9.75	8.00
Stable	61.66	30.75	0.00

C.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	0.88	1.00	3.75
0 - 10 mm/hr	2.05	4.75	19.75
10 - 20 mm/hr	2.73	6.75	12.50
20 - 40 mm/hr	5.25	13.50	23.00
40 - 60 mm/hr	3.73	7.25	9.25
> 60 mm/hr	5.62	13.00	31.75
Stable	79.74	53.75	0.00

D.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	0.61	0.75	2.50
0 - 10 mm/hr	1.05	1.50	13.00
10 - 20 mm/hr	1.40	3.75	10.00
20 - 40 mm/hr	3.10	9.75	17.25
40 - 60 mm/hr	2.54	5.50	10.25
> 60 mm/hr	4.80	12.25	47.00
Stable	86.50	66.50	0.00

E.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	0.28	0.00	0.75
0 - 10 mm/hr	0.30	0.50	2.50
10 - 20 mm/hr	0.38	0.25	4.25
20 - 40 mm/hr	0.83	2.25	6.75
40 - 60 mm/hr	0.81	2.50	4.00
> 60 mm/hr	2.32	6.25	81.75
Stable	95.09	88.25	0.00

The graphs give an indication that SHALSTAB is more sensitive to changes to some parameters than others. A significant increase in cohesion causes more of the study area to be designated as unconditionally stable.

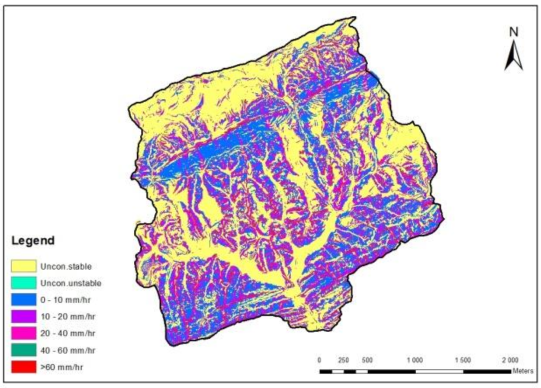
As the value of cohesion increases, the spatial extent of erosion retreats. In the lowest case of cohesion (C= 0 kPa in Figure 14), shallow landslide spread up in some divergent hillslope positions. The simulation example driven by C= 7 kPa show that erosion is confined to the valley bottoms and shows discontinuities. This is due to the increase root strength since there is direct evidence that root reinforced soil is stronger than the same soil without roots (Ziemer, 1981).

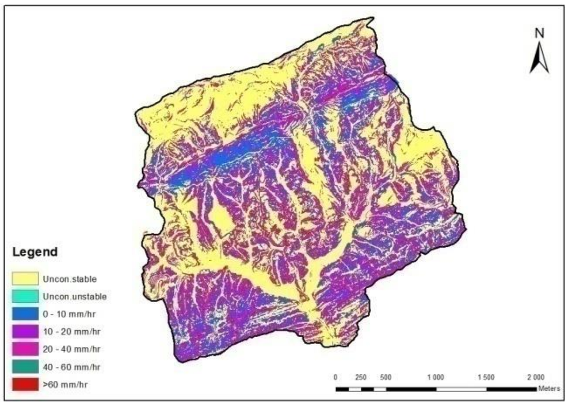
The importance of cohesion is not a new finding, but these maps appear to be a good portrayal of how realistic changes in cohesion alter the location and relative instability of the basin.

Criticalelementswithrainless than10mm/hrare interpreted aspotentially unstableandthereforesusceptibletolandslides. The instabilitydecreases as thecriticalrain, until you get toelementswithvalues greater than60 mm/hrconsidered potentiallystable.

Concerning the results derived from 3*3 grid cell, it is clear that the percentage of landslide area of potentially unstable to unconditionally decreased dramatically as cohesion increased from 31.75% to 0.75%.

SHALSTAB seems to be not sensitive to changes in soil depth because the percentages of catchment, landslide area and even 3*3 grid cell reported in table for the soil depth equal to 0.8 m are quite equal to those reported for the soil depth equal to 1.2 m. There is no significant influence that soil thickness exerts on slope stability. This is because of the low permeability of these soils.





(a) (b)

Fig15: Map of critical rainfall for the Lierza basin tested 2 values of soil depth (a= 0.8 m ; b= 1.2m)

Table 11.Percentage of catchment and landslide area in each critical rainfall range for the Lierza basin. (a=0.8m and b=1.2 m)

a.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	4.89	11.75	31.75
0 - 10 mm/hr	21.61	37.25	43.25
10 - 20 mm/hr	14.16	17.50	17.25
20 - 40 mm/hr	10.73	12.75	4.75
40 - 60 mm/hr	3.13	3.75	0.25
> 60 mm/hr	2.72	4.25	2.75
Stable	42.75	12.75	0.00

b.

Critical rainfall Mm/hr	Catchment area (%)	Landslide area (%)	Kernel3x3
Unstable	4.89	11.78	31.75
0 - 10 mm/hr	14.64	28.57	34.75
10 - 20 mm/hr	12.79	16.04	17.50
20 - 40 mm/hr	13.57	17.29	10.75
40 - 60 mm/hr	5.51	5.76	2.25
> 60 mm/hr	5.84	7.77	3.00
Stable	42.76	12.78	0.00

As a final remark, our results suggest that implementing different values of cohesion into the model (SHALSTAB) lead to improvement the potential stability. Contrarily soil depth doesn’t generate a significant effect on slope stability.

Chapter 5: Conclusions and Perspectives on Future Research

Understanding hazards posed by rainfall-triggered shallow landslides requires predicting*where* landslides will occur, *when* they will occur, *how big* will they be, *how fast* they willmobilize, and *how far* will they go. The two primary aspects affecting the impact of shallow landslides, both in terms of downstream hazard and their geomorphicsignificance, are their location and size. Location affects travel distance and bulking-up potential,while size affects the amount of sediment discharged, as well as the scale of local morphologicalchange. Moreover, the magnitude of shallowlandslides (defined as the volume of material displaced) controls the extent of the hazard area,the intensity of impact within it and the vulnerability of elements at risk.

This thesis reports a body of research that aims to quantify the impact of land use (forest and vineyard land uses are considered) on the distribution and characteristicsof shallow landslides. The landslide properties which are considered are spatial density and size. The analysis is carried out with reference to an extreme flash flood occurred in Veneto (Italy) on August 2, 2014, which impacted the small (7.5 km^2) upper Lierza basin triggering several (400) shallow landslides.

When comparing shallow landslides forest and in vineyard areas, we takeinto account the differencesarising in topography and rainfall between the two land uses. Indeed, it is important to take into account that human settlement and land use over centuries have affected the allocation of forests and open land. As a result, in the study area forests are actually on steeper slopes than open land or cultivated land, and as such are more susceptible to landsliding. Moreover, differences in shallow landslides between land uses may be due to differences in rainfall. We havetherefore analysedhow rainfall, slope and SHALSTAB topographic factor will vary with land uses, and if these variations may explain variations in shallow landslides properties.

We identified statistical significant differences in the general distribution of rainfall and topography on the areas characterized by vineyard and wood:

- slope is significantly higher in the forested area;
- cumulated rainfall is slightly (but still significantly) higher in the forested area than in vineyard.

We also identified statistical significant differences in the general distribution of landslide properties on the areas characterized by vineyard and wood:

- landslide density in vineyard (100 km^{-2}) is more than twice that in the wood area (43 km^{-2}) . This supports results reported by Rickli and Graf (2009), who found that in five over six of their study areas the landslide density was greater in open land than in forested terrain, with the landslide density in forest areas amounting to about 50 to 80% of the density in open land.This result is important because it shows that that forested slopes are mostly more stable than significantly less steep slopes in open land. This happens even if rainfall was higher in forests than in vineyard. The reason for this probably has to do with the reinforcing effect on slope stability of the diverse root systems of the trees and the associated forest vegetation, as many authors have described. Several other landslide inventories have also found that shallow landslidesare less frequent in forests than in open land (Moser 1980; Moser and Schoger 1989; Fazarinc and Mikos 1992; Markart*et al.* 2007).

- Landslides in forested areas are significantly larger than landslides in vineyard. This supports earlier results from Moser (1971, who showed that the largest slides occurred within forested areas, and Moser and Schoger (1989), who found that the surface areas of forest slides were larger than those in open land. It is speculated here that landslide size is determined by the balance of the benefits associated with larger size (increased driving forces relative to resistive forces) with the costs associated with a larger size (higher probability of including areas that contribute higher resistances). Our results show that land use characteristics impact significantly on this balance.

The SHALSTAB model provides the spatial distribution of critical rainfall, which determines the potential for shallow landslide initiation. This model is useful for shallow landslide susceptibility assessment at the regional scale, and itcan be used as “background knowledge’’ which provides information regarding the areas where landslides are likely to be initiated and will be useful in planning long-term risk reduction strategies. We have presented a generalized analytical framework for assessing the stability of infinite slopes under different degrees of cohesion(C= 0, 2, 4, 5 and 7 KPa) and soil depth (Sd= 0.8 and 1.2 m). This framework relies on the existing an improvement of potential stability with increasing cohesion. Contrarily soil depth doesn’t generate a significant effect on slope stability. This demonstrates that SHALSTAB is successful in identifying the most unstable areas of the landscape and also allows spatially distributed rainfall thresholds to be derived. However it was unable to identify differences among the two land uses.

Perspectives on Future Research

This study has offered a local scale analysis of the impact of land use on shallow landslide density and shape (magnitude). The most logical perspective of future research concern the feasibility of accounting for shape (magnitude) in landslide modeling. Mapping areas susceptible to landslides is essential for risk management and is becoming a standard tool to support land management decision-making. Therefore, a next idea following this line of research could be moving to a susceptibility mapping that account for landslide magnitude.This may add significantly to risk management becausethe magnitude of shallowlandslides (defined as the volume of material displaced) controls the extent of the hazard area,the intensity of impact within it and the vulnerability of elements at risk.

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