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The Effect of Morphometry, Land-Use and Lithology on Landslides Susceptibility: An Exploratory Analysis

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Abstract. GIS features provide simple and useful tools for landslides susceptibility and hazard studies, allowing the identification and the quantification of predisposing factors, and their relative importance. In lithologically homogeneous areas, the most influent factor of landslides is slope morphometry, in particular inclination, height and form. Moreover, within a hydrographic basin, landslides are coupled with drainage network. In fact landslides density and drainage density are positively correlated. Furthermore, human activity strongly influences the development of landslides. In our previous works, we introduced *MSI* (Morphometric Slope Index) as general index for slope morphometry, combining the main linear and areal morphometric features (area, form, length, inclination, width). Its formula is: $MSI = {A_{3D}}/{A_{2D} \cdot L \cdot R_c}$ (where A_{3D} is the three-dimensional area of the slope, A_{2D} is its plan area, L is the slope length and R_c is the circularity ratio). We tested *MSI* as driver of different erosion landforms, demonstrating its influence in determining, on the one hand, the development and the final arrangement of calanchi drainage network (the typical Italian badlands), and, on the other hand, the erosion processes within them, mainly gullies and landslides.

The present study is an exploratory application of this index to landslides susceptibility, aimed to analyze the combined effect of slope morphometry (summarized in *MSI*), lithology and land-use on the distribution of landslides in small catchments. The study is located in the Italian periadriatic foredeep, in the Abruzzo Region. This study has reinforced our perspective about the validity of the application of the techniques of geomorphometric analysis to the landslides susceptibility. Especially we consider this approach an efficient tool to summarize different controlling factors.

Keywords. Slope morphometry, land-use, lithology, landslides susceptibility.

1. Introduction

Advances in Geographical Information System (GIS) technology and the increasing availability of digital elevation models (DEMs) had been leading to the growth of quantitative analysis of earth surface for the last decades. These analyses are aimed in particular at landslides hazard and risk assessment (Korup, 2005; Carrara and Pike, 2006). Because the shape of the land surface plays a fundamental role in landslide processes, linking landslide inventories and GIS enables to model (1) the predisposing factors, (2) the triggering mechanisms, and (3) the interference with the drainage network. Mathematical/statistical tools allow to point out functional relations between landslide magnitude (such as affected area or volume, frequency or density) and topographical driver factors (Hovius et al., 1998; Dai and Lee, 2001; Guzzetti et al., 2005).

In lithologically and climatically homogeneous areas, one of the main driver factors of landslides is slope morphometry. The slope angle is considered the principal parameter, but also the elevation range where landslides occur, the slope aspect and shape are important factors (Guzzetti et al., 1999; Dai and Lee, 2002; Komac, 2006; Domínguez-Cuesta et al., 2007; Chen and Wang, 2007; Conforti et al., 2012; Rotigliano et al., 2012). However, some studies verified that the last two parameters are more sensitive to lithology and geological structure, and slope angle depends on its derivatives (irradiance, transverse and longitudinal curvature). Therefore it is sufficient to consider only one of the associated parameters (Regmi et al., 2010).

Moreover, within the hydrographic basin, slope and landslide processes quickly respond to the incision and development of the river drainage network. It exerts a direct control over the fluvial geomorphological processes (Korup et al., 2010). Drainage systems may adversely influence slope instability because surface water promotes landslides by undercutting and eroding slopes, and saturating their lower part (Dai et al., 2001; Yalcin et al., 2008; Regmi et al., 2010; Conforti et al., 2011).

At the same time, human activity influences slope stability through land use and land cover (LU/LC) changes. It is also one of the key factor responsible for landslides. Land cover acts as a shelter and reduces the susceptibility of soil erosion and landslides and reduces the effect of rainfall on the soils (Yalcin et al., 2008; Regmi et al, 2010). LU/LC is then often used as predisposing factor in landslide susceptibility assessment.

Some studies (Buccolini et al., 2012; Buccolini and Coco, 2013) introduced a unique reference index for basin morphometry, named *MSI* (Morphometric Slope Index). It includes both areal and linear features (such as size, shape, inclination, length and width) in the formula

$$MSI = {}^{A_{3D}}/_{A_{2D}} \cdot L \cdot R_c \tag{1}$$

where, A_{3D} and A_{2D} are surface and plane area, L is slope length, R_c is circularity ratio. The testes on *calanchi* (Italian badlands, considered as miniature catchments models, lithologically and climatically homogeneous) demonstrated its effectiveness in determining the arrangement of drainage network, the type of erosion processes (gullies and/or landslides) and the amount of erosion.

The present study is an exploratory application of *MSI* to landslides susceptibility in small drainage basins, aimed at analyzing the combined effect of the slope morphometry (summarized in *MSI*), the arrangement of drainage network, the lithology and the land-use on the distribution of landslides. Considering the current topography of some selected basins affected by superficial landslides, the influence of slope topography on the development of current landslides will be analyzed hereafter in combination with other predisposing factors (drainage network, land cover). The selected study areas are located in the Italian Periadriatic foredeep, in the Abruzzi Region.

2. Methodology

2.1. Study area

The Periadriatic belt of Abruzzi Region lies in the Pliocene and Pleistocene foredeep succession of the Apennine chain, and is composed of clays in which are interposed clastic deposits with lenticular geometry. A powerful deposit of sands, gravels and conglomerates of fluvial-deltaic or coastal environment closes the sedimentary cycle (Bigi et al., 1995). These deposits are arranged in a northeastern vergence monocline as consequence of the compressive phase and the subsequent uplift, started since the Pleistocene and still active (Cantalamessa et al., 2004; Crescenti et al., 2004). A significant synsedimentary tectonic activity displaced the basin in sectors at different tectonic-sedimentary evolution, some lowered (piggy-back basins), others elevated (Centamore and Nisio, 2003). The sedimentary sequence is cut from West to East by the main watercourses whose corresponding valley floors are often filled by fluvial deposits (Buccolini et al., 2007). The secondary valleys of the hilly sector are set in the erodible clay levels and are characterized by a marked asymmetry due to the substrate geological structure. The extensive coastal morphostructures are, on the other hand, cut by almost symmetrical low-order valleys directly flowing into the Adriatic Sea.

Climatically, this area belongs to temperate sub-littoral regime with scarce annual rainfall, mainly autumnal, and medium temperatures (Fazzini and Giuffrida, 2005). Summer is rather dry, especially near the coast and on the low-hills. These climatic conditions favor intense erosion processes.

2.2. Materials and methods

As sample basins, 17 small basins directly flowing in the Adriatic sea were selected in Abruzzi having quite homogeneous geological and climatic features: Giardino, Salinello, Borsacchio, Calvano, Cerrano, Piomba, Mazzocco, Vallelunga, Arielli, Riccio, Moro, Feltrino, Grande, Osento, Acquachiara, Lebba, Buonanotte (from N to S in Figure 1). They were handled within ArcGIS 9.3 using the regional

DEM with 10 m cell-size provided by the Cartographic Services Office of the Abruzzi Region.

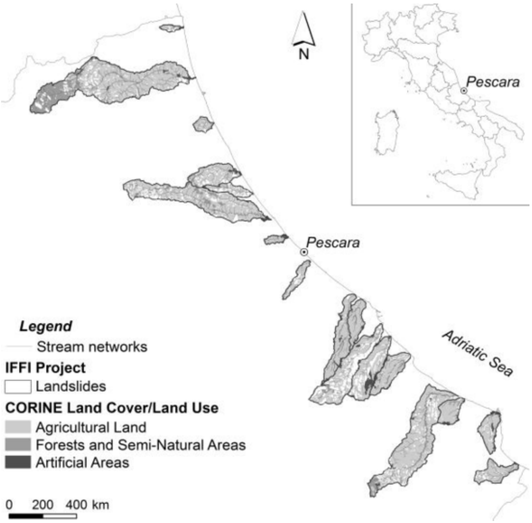

Figure 1. The analyzed basins (listed from N to S in the text).

The drainage features of each basin were extracted using *TauDEM* (Terrain Analysis Using Digital Elevation Models) toolbox developed by Prof. Tarboton and freely downloadable from his website (Tarboton, 1997). The *Single Watershed Model* tool was used, which automatically delineates stream networks and watersheds following a sequence of tools starting from the DEM and the outlet point shapefile, and producing the hydrological correct stream network and watershed shapefiles. They were subsequently compared by visual inspection to the Regional Topographic Maps (CTR) at scale 1:5000. After measuring the total stream length (l) and the plane area (A_{2D}) for each basin, the drainage density was computed by their ratio

$$D = \frac{l}{A_{2D}} \qquad (2).$$

Considering the actual surface on the DEM, the plan and tridimensional area (A_{2D} and A_{3D}, respectively), the basin length (L) and the circularity ratio (R_c) were measured to calculate *MSI* using Eq. (1).

As landslides inventory, the Inventory of Landslide Phenomena in Italy (IFFI Project 2003, *Inventario dei Fenomeni Franosi in Italia*) shapefiles were used. It was carried out by the Italian Institute for Environmental Protection and Research (ISPRA, *Istituto Superiore per la Protezione e la Ricerca Ambientale*) and supplies a detailed picture of the distribution of landslide phenomena within the Italian territory. In each selected basin, the total surface area occupied by landslides was estimated (A_L) and the areal Landslides Density (D_L) was calculated by

$$D_L = A_L / A_{2D} \qquad (3).$$

As land use inventory, the CORINE Land Cover 2006 (Co-ORdination of INformation on the Environment) database was used. It is a geographic LU/LC database encompassing most of the countries of the European Community, carried out by the European Environment Agency (EEA). The first level classification was considered which corresponds to the main categories of the LU/LC: Artificial Areas, Agricultural Land, Forests and Semi-Natural Areas. The areal surfaces covered by each category were measured in every basin and expressed in terms of basin area percentages, named respectively *%Art*, *%Agr*, *%Nat*.

Using statistics in Excel 2010 (*Data Analysis* tools), the relations among the areal frequency of landslides and the predisposing parameters were investigated, in order to define the functional relations between landslide magnitude and their main driver factors at basin scale.

2.3. Results

The complete database of the measured parameters is reported in Table 1.

The analysis of CORINE LU/LC at the basin scale showed an almost total homogeneity of the analyzed territory that fall almost entirely in the category ‘Agricultural Land’ except for small areas in ‘Artificial Areas’ and ‘Forests and Semi-Natural Areas’ (Tab. 1). Therefore, this parameter could not be considered in the statistics, because it was not possible to derive quantitative data in such uniform areas.

Table 1. Database of the measured parameters, sorted by increasing *MSI*.

Basins	*MSI* (m)	*D* (m^{-1})	D_L	*%Agr*	*%Nat*	*%Art*
Giardino	1845	0.0034	0.177	85.4	11.1	3.9
Mazzocco	1853	0.0043	0.015	79.4	0.6	20.5
Vallelunga	2493	0.0031	0.204	99.7	0	0.7
Borsacchio	2767	0.0043	0.087	99.8	0	0.6
Cerrano	3346	0.0034	0.284	91.7	4.6	4.0
Buonanotte	3385	0.0031	0.092	98.6	0.3	1.6
Riccio	3568	0.0020	0.015	90.0	7.3	3.1
Lebba	3752	0.0022	0.087	90.2	0	10.3
Arielli	3841	0.0016	0.033	84.8	9.9	5.8
Acquachiara	4006	0.0021	0.037	89.4	4.8	6.4
Grande	5037	0.0018	0.091	79.0	15.1	6.3
Calvano	5900	0.0025	0.150	91.5	5.0	3.8
Feltrino	6157	0.0022	0.254	84.6	3.0	12.9
Moro	6286	0.0025	0.380	89.7	7.7	3.1
Piomba	6681	0.0025	0.151	86.0	12.9	1.5
Osento	7015	0.0021	0.138	88.6	10.3	1.6
Salinello	8280	0.0027	0.115	71.0	27.6	1.7

The first step of the data analysis was the linear Bivariate Regression in which the distribution of D_L (dependent variable) with respect to *MSI* and *D* (independent variables) were separately examined for detecting their main trends. Both the bivariate distribution plot charts (Figures 2 and 3) showed the clustering of the data into three groups depending on the values of *MSI* and *D*:

- *Group 1* (grey dots in the figures) included the basins with *MSI* < 3350 m and $D \geq$ 0.0031 m^{-1} (Giardino, Mazzocco, Vallelunga, Borsacchio, Cerrano),
- *Group 2* (black dots in the figures) included the basins with 3350 m < *MSI* < 6300 m and $D \leq$ 0.0031 m^{-1} (Buonanotte, Riccio, Lebba, Arielli, Acquachiara, Grande, Calvano, Feltrino, Moro),
- *Group 3* (white dots in the figures) included the basins with *MSI* > 6300 m and *D* < 0.0031 m^{-1} (Piomba, Osento, Salinello).

The partial relations for the three groups showed different type of interpolations. Although just few regressions showed significant R^2 (> 0.6), all of them indicated the following specific trends:

- in the *Group 1* D_L increased with increasing *MSI* and decreasing *D*,
- in the *Group 2* D_L increased with increasing *MSI* and increasing *D*,
- in the *Group 3* D_L increased with decreasing *MSI* and decreasing *D*.

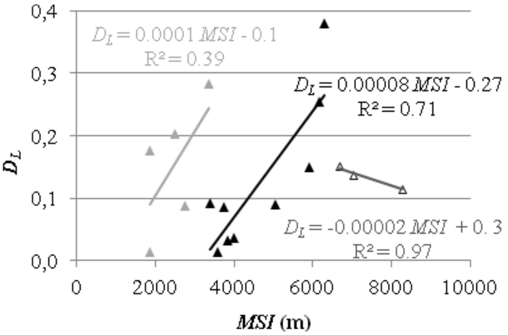

Figure 2. Regression between D_L and *MSI* with distinction of the three groups in different colors (grey for Group 1, black for Group 2, white for Group 3).

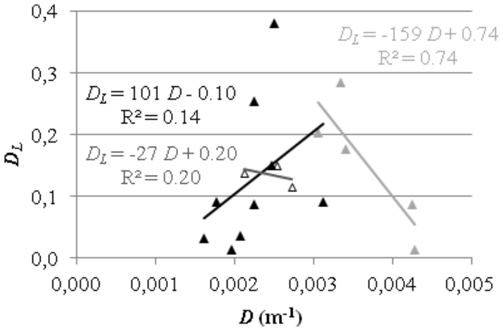

Figure 3. Regression between D_L and *D* with distinction of the three groups in different colors (grey for Group 1, black for Group 2, white for Group 3).

For detecting the combined effect of *MSI* and *D* on D_L a Multiple Regression analysis was conducted. *MSI* and *D* was considered as independent variables, D_L as dependent variable. This analysis was only conducted for the Group 1 and 2, because the 3rd was composed by 3 elements that are insufficient to enable significance results. The interpolation functions and relative statistical quality index (R^2, Fisher-F and its significance p) were reported in Tab. 2. They revealed that the two groups' data were interpolated by two different functions in which the partial relations are those previously described for the Bivariate Regression.

Table 2. Multiple Regression among D_L, *MSI* and *D* for the Groups 1 and 2.

	Multiple Regression Equations	R^2	*F*	*p*
1	$D_L = 0.49 + 0.00007\,MSI - 140.07\,D$	0.93	13.6	0.068
2	$D_L = -0.44 + 0.00008\,MSI + 84.22\,D$	0.81	12.5	0.007

The overall goodness-of-fit measures given by R^2 indicated that 93% of Group 1 and 81% of Group 2 followed the Regression functions. The Fisher-F is significant only for Group 2 ($F = 12.5$, $p < 0.05$) while for Group 1 it is slightly lower than the significance level ($F = 13.6$, $p = 0.068$) probably due to the poor dataset.

3. Discussion and Conclusion

The aim of the present study was to detect the influence of slope, drainage, lithology and land use features on the distribution of landslides in some small Italian catchments. From the land-use point of view, the analyzed basins are very homogenous, therefore it was not possible to consider this parameter in the statistics as quantitative data. From the lithological point of view, the selected basins lies on the same lithology, and the Geological Maps currently available (at a scale of 1:50000) did not enable to do a detailed parametrization. The statistics was carried out on the morphometric parameters regarding the slope, the drainage and the distribution of landslides. The outcomes highlighted the importance of the interplay of slope morphometry (through *MSI*) and drainage network (through *D*) on landslides distribution (D_L), allowing many considerations.

Firstly, the Bivariate Regression pointed out the individual role of each considered driver factors which is linked to the morphometric arrangement of the basin. In fact, *MSI* and *D* are linked each other and, depending on the combination of their values, the basin can be clustered in 3 groups with different behaviors: (1) within those having low *MSI* and high *D* ($MSI <$ 3350 m and $D \geq 0.0031\ \mathrm{m}^{-1}$) D_L increased with increasing *MSI* and decreasing *D*; (2) within those having high *MSI* and low *D* (3350 m $< MSI <$ 6300 m and $D \leq 0.0031\ \mathrm{m}^{-1}$) D_L increased with increasing *MSI* and increasing *D*; (3) within those having very high *MSI* and low *D* ($MSI >$ 6300 m and $D < 0.0031\ \mathrm{m}^{-1}$) D_L increased with decreasing *MSI* and decreasing *D*. Secondly, the Multiple Regression confirmed this the interplay between *D* and *MSI* in determining D_L, highlighting the different behaviors with different fitting equations for each group.

The link between *D* and *MSI* could be explained considering the local lithological features in the basins. Probably, in the basins with low *MSI* and high *D*, which had steep morphology (low *L* and high inclination), small surface (low *A* and R_c) and high drainage length, the outcropping lithology might be mainly conglomeratic and did not allow the enlargement of the catchment but allowed the incision of the streams; this could be the case of Group 1. In this case, the main geomorphological processes might be fluvial that tended to create well-defined drainage networks and stable interfluve slopes. Otherwise, in the basins with high *MSI* and low *D*, which had gentle morphology (high *L* and low inclination), wide surface (high *A* and R_c) and low drainage length, the outcropping lithology might be mainly clayey and allows the enlargement of the catchment in which the streams were ephemeral and little incised; this could be the case of Group 2. In this case, the main geomorphological processes might be the landslides that tended to occupy most of the basin area due to the lithology that tended to flow. The cases in which *MSI* was very high might correspond to wider basins that partially lied on marine substratum (mainly limestone or marl) in which generally *D* were lower, slopes were stable and less prone to landslides. This explanation was based on general consideration and on visual inspection of the Geological Maps at scale 1:50000, but needed further studies together with a detailed field survey.

The present study is exploratory and preliminary, but provides a good basis to work on for a complete characterization of the driver parameters of the landslides at catchment scale, aimed at assessing landslides hazard and risk. This study has reinforced our perspective about the validity of the application of the techniques of geomorphometric analysis to the landslides susceptibility, especially if we consider this approach as a means to summarize different controlling factors. Its strength lies in the fact that it is easy to model and simple to use by specialists and not and therefore could supply the institutions flexible logistic instruments for various terrain analyses and the prediction of natural disasters.

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