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Discussions

A coupled empirical approach for rainfall and land use correlation to landslide occurrence in the Esino river basin, central Italy

E. Gioia, T. Carone, and F. Marincioni

Department of Life and Environmental Sciences, Università Politecnica delle Marche, Ancona, Italy

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Correspondence to: F. Marincioni (f.marincioni@univpm.it)

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A coupled empirical approach for rainfall and land use correlation to landslide occurrence

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Abstract

A coupled empirical approach for studying possible correlations among rainfall, vegetation segmentation and landslide occurrence is discussed. To reveal such links two important rainfall events, occurred over the Esino river basin in central Italy, in November 2013 and May 2014, were analysed. The correlation between rainfall and landslides was carried out applying an intensity–duration (ID) threshold method, whereas the correlation between vegetation segmentation and landslides was investigated using the Morphological Spatial Pattern Analysis (MSPA). This coupled approach represents an attempt to find both timing and location of landslide occurrence through an empirical (black box) analysis. Results showed that: (i) the ID minimum threshold proposed in a previous study (Gioia et al., 2015) was verified as an effective equation to assess the rainfall conditions likely to trigger landslides in the study area (“when”), and (ii) the Core areas and the fragmented vegetation structures defined by the MSPA were the most affected by slope failures (“where”). These encouraging findings prompt for additional testing and application of such coupled empirical approach to possibly achieve an integrated basis for landslide forecasting.

1 Introduction

Landslides are common phenomena in Italy and in the Marche Region. According to the 2008 report of the Italian Ministry of Environment on hydrogeological hazard, about 99 % of the municipalities in this Region are prone to mass movements, and indeed 91 % of these towns had been affected by landslides (Ministry of Environment Territory and Sea, 2008).

Undeniably, each landslide occurrence responds to specific local conditions and generally known triggering conditions. Among the most studied triggers are rainfall (e.g. Caine, 1980; De Vita and Reichenbach, 1998; Giannecchini, 2006; Guidicini and Iwasa, 1977; Guzzetti et al., 2007; Wilson and Wieczorek, 1995) and vegetation presence or

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absence (e.g. Istanbulluoglu and Bras, 2005; Marston, 2010; Kai et al., 2014). Land use change is also recognized as an important factor influencing mass movements (e.g. Cruden and Varnes, 1996; Strudley et al., 2008; Fell et al., 2008; Wasowski et al., 2010). To this extent, an interesting aspect, though little explored, is the contribution of vegetation segmentation to rainfall-triggered landslides.

This paper proposes an empirical (black box) approach to identify the influence of both rainfall and vegetation segmentation to landslide occurrence. Two recent rainfall events that triggered widespread landslides over the Esino river watershed, central Italy, were studied applying the intensity–duration rainfall statistical model (Caine, 1980) and a Morphological Spatial Pattern Analysis (MSPA) integrated with GIS (Soille and Vogt, 2009; Vogt, 2014); the former method was used to define a rainfall threshold, the latter to detect the vegetation segmentation patterns more subjected to slope failures. The analyses were carried out in the mountains and valleys-low hills areas of the basin.

Authors are aware that landslide initiation is the result of numerous factors dynamically interacting over broad spatial and temporal scales, and the mere exploration of a few predisposing factors, such as rainfall intensity–duration or vegetation segmentation, cannot provide an overall landslide-triggering model. However, the promising correlations between rainfall, land use and landslide occurrence found in this study, prompt for further investigations of the proposed coupled empirical approach, which could certainly contribute to a better understanding of slope dynamics and possibly advance landslide hazard mapping within the study area.

2 The area and rainfall events studied

The Esino river basin was selected because it is one of the largest and most inhabited watershed of the Marche Region (National Institute of Statistics – ISTAT, 2014), and as such it is continuously monitored and suitable databases on past rainfall events and landslide occurrences exist. The Marche Region is located around latitude 43° N

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and longitude 14° E, with a total surface area of 9385 km^2 and 1 565 000 residents. The regional climate is affected by the presence of the Adriatic Sea to the East and of the Apennines mountains chain to the West. From East to West, the region can be subdivided in three different climatic and geomorphological bands: coastal, valleys-low hills, and mountains. Valleys and low hills, prevalently composed of clayed sandstone sediments, represent the 69 % of the territory; the 31 % are mountains with a large part composed of massive limestone. Only a small portion presents coastal morphology along the Adriatic seaboard. Finally, about 30 % of the territory is covered by forests.

The Esino watershed extends for approximately 1223 km^2 and is inhabited by about 440 000 people. Its lithology is characterized by almost exclusively sedimentary rocks roughly divided into (i) carbonate, (ii) terrigenous, and (iii) post-orogenic sediments (Coltorti and Nanni, 1987; Gentili and Dramis, 1997). The carbonate rocks prevail in the basin's westward section of the mountainous Umbro-Marchean ridge. The terrigenous sediments dominate in the hilly central Marchean ridge area, and a post-orogenic complex of clays, silts, sands and conglomerates, covers the valleys and low hill eastward section of the basin, from the sub-Apennine hills to the Adriatic coast (Gentili and Dramis, 1997). For this study, the Esino river basin was divided in 2 sections of approximately the same size: (i) mountains – western part, mainly composed of carbonate sediments, and (ii) valleys and low hills – eastern part, mostly characterized by post-orogenic sediments (Fig. 1).

Two rainfall events that affected the entire Marche Region have been selected for this study: (a) 10–13 November 2013 and (b) 2–4 May 2014. The first rainfall event (10–13 November 2013) brought widespread and persistent precipitations, with a maximum of 499 mm of rain over the Sibillini Mountains (CFRM, 2013), which caused several but contained floods and extensive slope failure phenomena throughout the Region, producing sizeable damages to the road network. Within the Esino river basin numerous landslide reports were collected by the local civil protection monitoring and forecasting service (Centro Funzionale Multirischi della Regione Marche – CFRM), especially in the mountains where the highest cumulative rainfalls were registered. The second rainfall event (2–4 May 2014) was characterized by particularly intense rainfall that insisted on the valleys and low hills over the eastern portion of the Region. The most intense rainfalls have occurred in the first 6 h of 3 May, with a maximum of 161 mm of rain over the lows hills area of Pesaro. The main damages were caused by the flooding of the Misa river in Senigallia (located North of the Esino), and because of the overflowing of the Triponzio channel, a tributary of the Esino river. Also with this rainfall event, numerous landslides were recorded across the Marche Region. Within the Esino river basin landslides occurred mainly in the valleys and low hills, rather than the mountains (CFRM, 2014).

3 Methods

3.1 The intensity–duration (ID) analysis

The rainfall data were downloaded from an online database made available by the CFRM, which manage a network of rain gauges distributed fairly homogeneously over the study area. Landslide data and information were gathered from reports also made available by the CFRM. Collected data were georeferenced in the Gauss–Boaga coordinate system and digitalized into a GIS environment. Each landslide was then paired to a rain gauge station using a criterion of proximity.

The correlation between rainfall and landslides was studied applying the intensity–duration (ID) threshold methodology developed by Caine (1980). The ID threshold assumes the general form of the following equation:

$$I = c + \alpha \times D^{-\beta} \quad (1)$$

where I is the rainfall intensity, D is the rainfall duration, and c, α and β are empirical parameters of the specific site conditions.

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In particular, in this study it was tested the performance of the ID threshold modelled by Gioia et al. (2015) through statistical analysis of mostly shallow landslides activated in the valleys and low hills section of the Esino river basin over the period 1953–2011:

$$I = 1.61 \times D^{-0.21} \; (4 < D < 167) \tag{2}$$

where I is the mean rainfall intensity in $\mathrm{mm\,h^{-1}}$ and D is the rainfall duration in hours.

The data collected during the 2013 and 2014 events, once plotted into the Gioia et al. (2015) intensity–duration logarithmic graph, could further validate Eq. (2) as an effective ID threshold over the entire river basin.

3.2 The Morphological Spatial Pattern Analysis (MSPA)

The Morphological Spatial Pattern Analysis (MSPA) was performed over the study area's anthropogenic agricultural land cover categories (e.g. Mixed cultivations, Crops, Shrubs, Mixed forests or Grasslands) by using the open source software GUIDOS 2.0. (Vogt, 2014). Applying Soille and Vogt's (2009) binary calculations, the following vegetation segmentation patterns (MSPA classes) were mapped:

- Core – interior foreground area excluding foreground perimeter of a vegetation patch;
- Islet – disjoint foreground object and too small to contain Core;
- Edge – external foreground, object perimeter;
- Perforation – internal foreground, object perimeter;
- Bridge – connected at more than one end to different Core areas;
- Loop – connected at more than one end to the same Core area;
- Branch – connected at one end to Edge, Perforation, Bridge or Loop.

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Overlapping such a MSPA map to the landslide distribution map of the November 2013 and May 2014 events, the vegetation segmentation patterns more subjected to slope failures were highlighted.

Results were then compared with Carone et al. (2015) which already performed a multitemporal MSPA over the Marche region, including the Esino river basin, to assess land cover changes from 2000 to 2006. Such study pointed out a higher number of landslides in the Edge, Branch and Bridge classes, which represent transition patterns between different land covers. Core areas showed a great influence in Crops land covers.

4 Results and discussion

The rainfall event of November 2013 triggered 35 landslides, 3 in the valleys and low hills, and 32 in the mountains, whereas the event of May 2014 triggered 20 landslides, of which 19 in the valleys and low hills and 1 in the mountains (Fig. 1). Table 1 lists the average rainfall intensities and durations logged by the rain gauge stations, while Fig. 2 plot new and old data (Gioia et al., 2015) in relation to Eq. (2).

In the event of November 2013 (Table 1), the maximum range (2.41–4.60 $\mathrm{mm\,h^{-1}}$) of mean rainfall intensity was registered within the mountains. The rain gauges recording the minimum (Fabriano 2) and maximum (Sassoferrato) intensity values, also accounted for the lowest (1) and the highest (14) number of landslides. The duration (rainy hours) of the rainfall event was relatively uniform over the entire watershed (60–69 h). The plot of the ID data, shown in Fig. 2, highlights that all the values are located well above the Gioia et al. (2015) threshold. This confirms the feasibility of Eq. (2) as minimum threshold for both the mountains and valleys-low hills areas. Moreover, the particular rainfall variability of the mountains data along the *y* axis (mean intensity), underlines how a single rainfall event can change its intensity within a relatively small area, and can cause very different landslide triggering effects, such as for example, for Fabriano 2 and Sassoferrato gauging stations (Table 1).

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In the event of May 2014 (Table 1), the values of mean rainfall intensity are relatively uniform over the entire watershed, showing a minimum in the rain gauge of Genga (1.53 mm h^{-1}), mountains, and a maximum in Jesi (2.06 mm h^{-1}), valleys and low hills. On the other hand, a higher variability is observable in terms of durations (rainy hours). The rainfall events in the eastern part of the watershed lasted between 35 and 43 h, while in the western part lasted 78 h. Figure 2 displays this variability on the *x* axis (duration). Also, for this event the plot of the ID data are located above the threshold, thus validating Eq. (2) in both the mountains and valleys-low hills areas of the Esino river basin. In addition, the ID data of the May 2014 event fall within the cloud of ID values that triggered landslides in the past. Thus, it is possible to compare the effects of the historical rainfalls with the studied ones. Indeed, the ID values registered in Agugliano and Cupramontana (i.e. the lowest pink dashes in Fig. 2), to each of which were paired 2 landslides (Table 1), are similar to those of the past minor rainfall events (those triggering two landslides). Furthermore, the ID values of the Jesi gauging station (i.e. the upper pink dash in Fig. 2), to which were paired 15 landslides (Table 1), are similar to those of the past main rainfall events (those triggering more than 10 landslides). These results suggest that in the valleys and low hills areas the number of landslides triggered by a rainfall event is linked to a specific range of ID values. This is not true in the mountains area. As a matter fact, the ID values logged in the mountainous Genga gauging station (Table 1) would foretell, according to Fig. 2, a high probability of 10 landslides or more, yet only one mass movement was recorded. Therefore, the considerations made about the number of rainfall-triggered landslides in the valleys and low hills section of the Esino river basin, cannot be exported to its mountains section.

From the perspective of land use influence on landsliding, the MSPA performed for this study revealed that the typologies of agricultural covers most susceptible to mass movements are Crops and Mixed cultivations (Table 2). In November 2013 numerous landslides were recorded in the mountains (13 in Crops and 10 in Mixed cultivations), while in May 2014 the valleys and low hills were the most affected (9 in Crops and 10 in Mixed cultivation). In terms of vegetation segmentation patterns, the Core class registered the highest occurrence of landslides, with noticeable differences between the two typologies of agricultural covers. Core patterns in Crops covers tallied 61.5 % of occurrences in 2013 and 55.6 % in 2014, while in Mixed cultivations covers tallied 40 % in 2013 and 50 % in 2014 (Table 2).

The other MSPA classes showing high incidence of landslides were those with higher fragmented vegetation structures. In 2013, mass movements occurred in Branch (7.7 % in Crops – 20 % in Mixed cultivations), Edge (23.1 % in Crops – 20 % in Mixed cultivations) and Bridge (7.7 % in Crops – 20 % in Mixed cultivations). Very similar values were recorded in 2014 (Table 2). Such results are coherent with the previous multi-temporal MSPA performed over the period 1990–2006 and listed in Table 2 (Carone et al., 2015). Consequently, the areas more prone to landsliding are those showing both a higher degree of vegetation fragmentation and an intensive presence of anthropogenic low-structured vegetation covers, such as Crops and Mixed cultivations.

5 Conclusions

The purpose of this study was to compare two empirical (black box) methods to predict possible landslide triggering conditions: (1) rainfall intensity–duration threshold and (2) Morphological Spatial Pattern Analysis (MSPA) to detect the vegetation segmentation patterns more subjected to slope failures. The first posit when a landslide can initiate (meteoclimatic conditions), the second delimits where (land cover setting). Both methods had been applied in a novel fashion to test the applicability of the coupled empirical approach. For example, the rainfall intensity–duration thresholds are usually modelled on areas from regional to global level scales, rarely at the river basin scale. At smaller scales, the process-based approaches are usually applied. Thus, employing an empirical approach to a small or medium size river basin was uncertain. Notwithstanding, the ID data collected during the November 2013 and May 2014 rainfall events validated the previously modelled threshold for the Esino river basin (Gioia et al., 2015).

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These additional testing made evident that a further refinement of the ID threshold could be done separating the mountains from the valleys and low hills. The rainfall values recorded during the November 2013 landslide occurrences, which mainly affected the mountainous area, plotted well above the cloud of ID data of the historical landslides in the valleys and low hills area studied by Gioia et al. (2015). Considering that the rainfall values logged during the May 2014 landslide occurrences, which mainly affected the valleys and low hills area, fall within the cloud of the historical ID data, we could develop an additional threshold curve for the mountain area, maintaining Eq. (2) as a general minimum threshold curve for the Esino river basin. This choice is also supported by the different lithologies of the two areas, mainly carbonate in the mountains and post-orogenic outcrops in the valleys and low hills. Certainly, more research effort should be directed to adjust the scale of the empirical model to fit the hydrogeological setting of the study area. As a matter of fact, the significant difference between the ID values recorded in the two studied rainfall events, November 2013 and May 2014, may be also attributable to the natural variability of atmospheric seasonality.

Coupling the intensity–duration method with the spatial analysis perspective of MSPA, individuating the vegetation structures more inclined to landsliding, could enable reasoning about landslide mitigation, early warning mechanisms, or land use management. For example, an effective integration of the two approaches will facilitate the development of landslide susceptibility maps, crucial to any disaster risk reduction strategy (from urban to emergency planning). Indeed, the use of vegetation in mitigating landslides is emphasised by many policies. Yet, beyond the fact that vegetation is a viable measure that could be applied to help stabilise slopes, not much has been discussed or done toward the establishment of sizeable evidence base on how vegetation structures and patterns may control landsliding processes; knowledge base necessary for example to justify the spending of public money on the selection or development of different approaches to manage landslide risk.

All this said, while keeping the feet on the ground, authors acknowledge that the triggering conditions highlighted in this study at the moment are limited evidences, though encouraging, that an empirical correlation between landslides, rainfall and land use can be obtained expeditiously over a small – medium size river basin. Of course, these methods should be tested in other geographical setting with similar as well as different characteristics, both in terms of hydrogeology and land covers.

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Table 1. Values of rainfall mean intensity and duration registered in each rain gauge and number of paired landslides during the events of November 2013 and May 2014.

Nov 2013	Rain gauge	Mean intensity (mm h^{-1})	Duration (h)	Landslides
Valleys and low hills areas	Jesi	4.29	61	2
	Fabriano 1	3.52	69	1
Mountains	Fabriano 1	3.52	69	4
	Fabriano 2	2.41	63	1
	Fabriano 3	3.01	60	10
	Genga	3.56	66	3
	Sassoferrato	4.60	68	14
May 2014	**Rain gauge**	**Mean intensity (mm h^{-1})**	**Duration (h)**	**Landslides**
Valleys and low hills areas	Agugliano	1.57	38	2
	Cupramontana	1.72	35	2
	Jesi	2.06	43	15
Mountains	Genga	1.53	78	1

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Table 2. Multitemporal Morphological Spatial Pattern Analysis (MSPA) analysis in the Esino watershed. Values represent the percentage of landslides occurrence over the different vegetation segmentations in the two most affected land cover categories: Crops (Cr) and Mixed cultivations (Mix).

	Land cover categories									
	1990 Whole basin		1990–2000 Whole basin		2000–2006 Whole basin		2013 Mountains		2014 Valleys and low hills	
Segmentation classes	Cr	Mix	Cr	Mix	Cr	Mix	Cr	Mix	Cr	Mix
Branch	10	10	22.22	8.16	5.56	7.7	7.7	20	11.2	10
Edge	20	15	25	28.57	16.67	26.92	23.1	20	22.3	30
Islet	0	0	0	2.04	0	0	0	0	0	0
Core	70	60	44.45	59.18	61.12	65.38	61.5	40	55.6	50
Bridge	0	15	8.34	2.04	11.12	0	7.7	20	0	10
Loop	0	0	0	0	5.56	0	0	0	11.2	0

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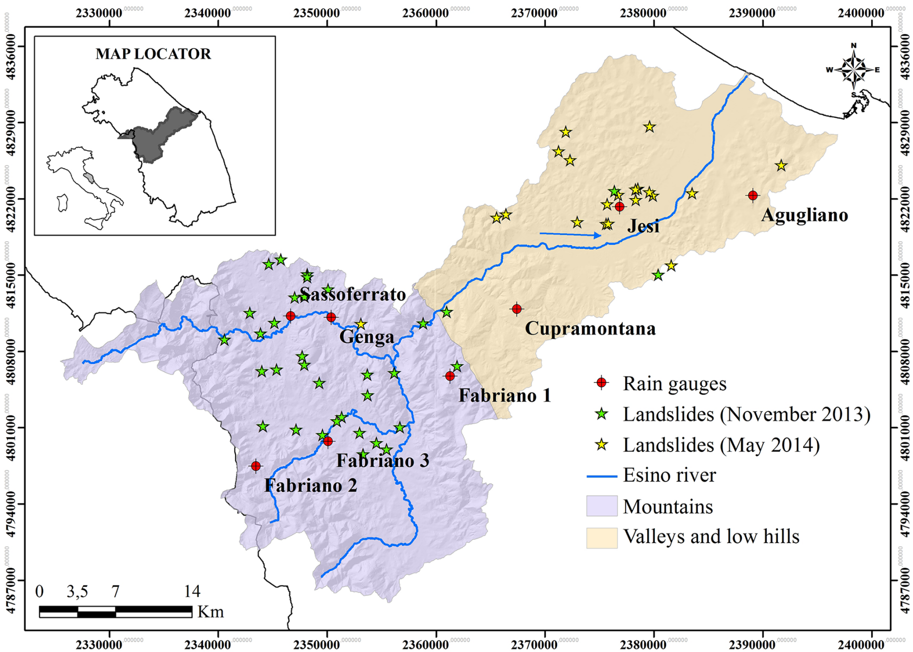

Figure 1. Study area. The Esino river basin divided in mountains (purple) and valleys-low hills (light brown) areas. Map shows also the selected rain gauge stations and the landslides triggered during the events of November 2013 and May 2014.

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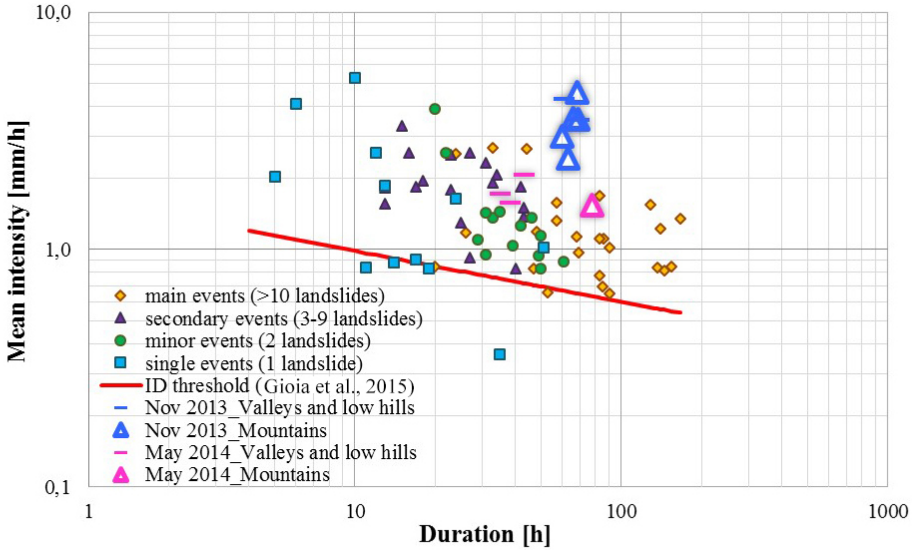

Figure 2. Intensity–duration logarithmic graph modified after Gioia et al. (2015). Figure shows the comparison between the ID values of historical rainfall events (1953–2011), the ID threshold and the ID data of the November 2013 (blue) and May 2014 (pink) rainfalls. The gauging stations are differentiated according to their location: mountains or valleys-low hills. Symbols differentiate also the historical rainfall events that triggered only 1 landslide (square), 2 (circle), 3–9 (triangle) or more than 10 (diamond).

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