Geomorphic effects caused by heavy rainfall in southern Calabria (Italy) on 30 October–1 November 2015

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ABSTRACT
A severe rainfall event occurred in southern Calabria between 29 October and 2 November 2015, causing two deaths and serious damage to transport infrastructure. Widespread slope erosion and thousands of shallow landslides were triggered on the slopes, combined with flooding and transport of debris along the streams. Rains recorded by the regional gauge network and the national radar monitoring system were analysed by means of Kriging techniques. Ground effects were surveyed in the field, and mapped using post-event air photos taken along the coastal sector. Shallow landslides, soil erosion (including sheet, rill, and gully erosion), flooding, lateral erosion, and debris deposition along streambeds, overflow on lateral slopes, and fan deposition at the mouths of the streams were mapped at 1:60,000 scale. Isohyets of the rainfall event – in terms of cumulative maxima over 24 h – are also shown on the Main Map. In Annex A, a list of notices of processes and/or damage, arranged by municipalities, with coordinates, types of ground effect, and synthetic descriptions, is also provided.

1. Introduction
High-intensity rainfall is frequent in Calabria, with some days receiving amounts usually recorded in some months (Ferrari & Terranova, 2004; Terranova & Gariano, 2014). Such rainfall events commonly induce significant geomorphic effects on slopes and along streams, and can cause deaths and severe damage to anthropic areas (Capparelli, Iaquinta, Iovine, Terranova, & Versace, 2012; Conforti, Muto, Rago, & Critelli, 2014; Gullà, Antronico, Iaquinta, & Terranova, 2008; Iovine & Merenda, 1996; Iovine & Petrucci, 1998; Iovine, Iaquinta, & Terranova, 2009; Sorriso-Valvo et al., 2004; Terranova et al., 2016; Vennari et al., 2014). There is thus an urgent need for detailed studies aimed at ‘geo-hydrological’ hazard mapping (i.e. ground effects caused by meteorological phenomena, distinguished into hydraulic, landslide, and groundwater categories – sensu Canuti, Casagli, Pellegrini, & Tosatti, 2001) and risk management.

Among the major historic events occurred in Calabria, those of 12–18 October 1951 and 21 October 1953 caused widespread damage, deaths, and injuries in the southern part of the region (Antronico, Coscarelli, & Terranova, 2005; Botta, 1977; Caloiero & Mercuri, 1980; Catenacci, 1992). During the 1951 event, 1770 mm fell in 6 days on the Aspromonte massif, and 535 mm in 24 h at Santa Cristina d’Aspromonte (for the location of places mentioned in the text, see Figure 1 and Main Map). Seventy-seven municipalities were affected, mainly along the southern Ionian sector, causing 70 deaths and leaving 4500 homeless. About 1700 dwellings and 26 bridges were destroyed, aqueducts suffered damage in several locations, and some urban centres had to be abandoned (new settlements had to be built on safer places). Reggio di Calabria (the most affected province) suffered over 15.5 M€ damage. During the 1953 event, 362 mm of rain were recorded at Badolato, and 315 mm at Stilo in just few hours. The event caused 200 deaths, many injured, and thousands of homeless (4000 of them in Reggio di Calabria).

Further heavy events struck southern Calabria, causing deaths and damage on several occasions (Gullà et al., 2009; Terranova et al., 2013; Terranova & Gariano, 2014). Among the most severe, maximum daily rainfall up to 306.6 mm was recorded at Palmeriti between 9 September and early October 2000. During the same period, rainfall in 3 days exceeded 630 mm at Ferdinandea, and 560 mm at Caulonia and Chiaravalle Centrale. The event triggered
widespread shallow landslides and flooding, with damage recorded mainly along the Ionian coast where 13 people were killed by a flood along the Soverato stream (Antronico, Gullà, & Terranova, 2002; Sorriso-Valvo et al., 2004). More recently, another event hit southern Calabria between 29 October and 2 November 2015, causing two deaths and serious damage to infrastructure. The affected area is crossed by regional transport lines and hosts numerous villages, in addition to the town of Reggio di Calabria facing the Messina Strait. Widespread geomorphic effects were caused by the heavy rains: slope erosion and shallow landslides were triggered on the slopes; streams flooded and caused breaking of banks and bridges due to debris transport; the state road (SS.106) and the railroad remained closed for days; electricity, telecommunications, water and sewage networks were also damaged at several locations. A couple of days after the event, a ‘state of emergency’ was requested from the National Government, based on an overall estimate for remedial works and mitigation actions exceeding 322 M€ (Regione Calabria, 2015), including over 58 M€ for immediate rescue, mitigation actions, and assistance to population. On 3 March 2016, the Italian Government declared a state of calamity, allocating 11.8 M€ for immediate rescue actions. A few days later, an order concerning damage to farms was signed by the Minister of Agriculture and Forestry.

In this study, this latter rainfall event and its geomorphic effects in southern Calabria are briefly described. Induced erosive and gravitational processes are synthesized in an inventory map, including notices from field inspections and isohyets derived from combined rain gauge and radar data.

2. Study area

The Calabrian Arc, in southern Italy, is an accretionary wedge caused by the Africa–Europe collision (Amodio-Morelli et al., 1976; Tortorici, 1982). It is a series of ophiolite-bearing tectonic units and overlying basement nappes, piled up by prolonged orogenic phases started between the Cretaceous and the Late Eocene. Since the Miocene, overthrusting has been associated with a regional strike-slip tectonic regime, whilst in the Late Pliocene-Early Quaternary an extensional phase caused fragmentation of the Arc. In the Middle Pleistocene, a regional strike-slip phase started, originating the ‘Calabrian-Sicilian rift-zone’ along the western side of the Arc, coupled with strong regional uplifting (Monaco, Tapponnier, Tortorici, & Gillot, 1997; Tansi, Muto, Critelli, & Iovine, 2007).

The study area is in the coastal sector of the southern portion of the Arc. It is characterized by a pile of crystalline nappes, including metamorphic and plutonic rocks, and related Meso-Cenozoic sedimentary sequences (Tortorici, 1982). Due to the complex tectonic history of the Arc, the rocks of the basement are diffusely fractured and weathered, with regolith depths up to 10s or even 100s of metres (Guzzetta, 1974; Le Pera & Sorriso-Valvo, 2000). These low-resistance materials are combined with high relief, produced by recent and active tectonics, and by slope erosion.

On Fig. A (on Main Map), lithological outcrops of southern Calabria are combined in nine classes, based

Figure 1. Location of southern Calabria (grey rectangle) and Sicily. The red square marks the limits of the study area. The main stream network (cf. blue lines) and toponyms mentioned in the text are also shown. Black triangles mark radar locations at Mt. Pettinascra and Mt. Lauro. Black squares show locations of Aspromonte massif and Serre mountain chain.
on litho-technical properties (CASMEZ, 1969). In the study area (i.e. in the coastal sector), outcrops of clastic materials (mainly alluvium, colluvium, and residual soils, followed by clay and clayey flysch, conglomerate and sandstone, and sand and silt) dominate (> 90%), igneous and medium–high-grade metamorphic rocks follow (~7.4%), with minor extents of the remaining lithotypes. Rock classes are not uniformly distributed. Igneous and medium–high-grade metamorphic rocks, and conglomerate and sandstone, crop out mainly along the western coast, clay and clayey flysch is mainly found along the southern and eastern coast, and alluvial deposits are common, except for the Costa Viola sector in the NW.

On Fig. B (on Main Map), slope values are displayed in five classes, based on Jenks natural breaks method. In the study area, ‘very low’ to ‘low’ slope values account for about 66%; less than 18% of the area shows ‘high’ to ‘very high’ slope values. As with lithology, slope classes are not uniformly distributed. Gentler slopes occur mainly in the Ionian coastal sector, whereas steeper slopes are found on the Costa Viola.

3. Methods

Rain data were derived from the regional gauge network and from the national radar monitoring system. In particular, rainfall recorded by the Regione Calabria-ARPACAL (Regional Agency for the Protection of the Environment in Calabria) – Functional Centre, with time step of 1 min, provided a total of 156 observations points over the entire Calabrian territory (~15,150 km²). Meteorological radar data (in C band, ~5 GHz) provided by the National Civil Protection was also used. Suitable instruments are at Mt. Pettinascnura (1725 m a.s.l., long. 16.618 E, lat. 39.370 N), and in Sicily, at Monte Lauro (980 m a.s.l., long. 14.836 E, lat. 37.116 N) – for radar locations, see Figure 1. With a time step of 10 min, radar measurements of the Italian network are processed on a 1 km² grid to obtain Surface Rainfall Intensity values (SRI, [mm h⁻¹]), by means of a standard Marshall and Palmer Z–R relation (Vulpiani et al., 2008; 2012).

By considering the usual dimensions of smaller rainstorm cells (cf. Harrold & Austin, 1974), a 1 km-size square mesh was adopted for an estimation of the rainfall distribution. Cumulative rainfall, measured by the gauge network between 00:00 on 29 October ($t_1$) and 09:00 on 2 November ($t_2$), was then calculated by Ordinary Kriging (OK estimates, $R_{OK}^{tot}$). Radar and rain gauge information were then merged in $R$ (a free software environment for statistical computing and graphics, cf. https://www.r-project.org/) to obtain cumulative rainfall by means of a Universal Kriging regression technique with an external-drift algorithm (UK estimates, $R_{UK}^{tot}$). For both OK and UK estimates, the interpolation processes were performed by the ‘autoKrig’ functions implemented in the Automap and Gstat libraries of R (Hiemstra, 2015; Hiemstra, Pebesma, Twenhöfel, & Heuvelink, 2009). As a way of investigating the amounts of rain deemed responsible for the observed types of ground effects, and considering the extent of the affected basins, the maximum amounts of UK cumulative rainfall in 24 h between $t_1$ and $t_2$, $R_{max}(24)$, were also extracted for each cell of the domain. In fact, shallow landslides, flash floods and slope erosion commonly result strongly related to high intensity, short duration rainfall events (Cascini & Versace, 1986, 1988; Terranova & Gariano, 2014; Terranova, Gariano, Iaquinta, & Iovine, 2015).

Ground effects caused by the Autumn 2015 rainfall event in the study area were surveyed by combined aerial photo interpretation and site investigations. Immediately after the storm, colour air-photographs (scale 1:22,000) were taken along the coastal sector of southern Calabria, between Roccella Jonica and Seminara, covering a strip 4–6 km wide. Surveyed ground effects were obtained from notices of site investigations carried out by a team coordinated by the regional Civil Protection (Regione Calabria, 2015). Air-photo interpretation was used to map processes induced by the rainfall event – i.e. soil erosion, slope movements, and hydraulic phenomena along the streambeds down to the coast. In more detail, the following processes were taken into account: (i) shallow landslides (including sources areas, transport, and deposition zones); (ii) soil erosion on slopes (including sheet, rill, and gully erosion); (iii) flooding, lateral erosion, and debris deposition along the streambeds, overflow on lateral slopes, and fan deposition by the coast.

4. Results

4.1. The rainfall event

The severe rainfall event that struck southern Calabria between 29 October and 2 November 2015 was concentrated on the Aspromonte massif and the eastern slopes of the Serre mountain chain. Based on gauge data, more than 746 mm of rain were recorded at Chiaravalle Centrale, and 605 mm at S. Agata del Bianco (at the same sites, annual average rainfalls are 1446.6 mm and 1065 mm, respectively). Between 31 October and 1 November, the study area received more than half of the annual average rainfall. On 1 November, 370.4 mm were recorded at S. Agata del Bianco, and 364.4 mm at Chiaravalle Centrale. The coastal sector was also affected, although with lower intensities.

UK and OK estimates of the total amount of rain between $t_1$ and $t_2$, as obtained by Kriging interpolations, are shown in Figs. C(a) and C(b) (on Main Map); a cell-by-cell comparison of the above estimates is also provided in Fig. C(c). Two zones appear to be most affected by rainfall. The first is along the Serre
mountain chain, between Chiaravalle Centrale, Serra San Bruno, Fabrizia, and Badolato (i.e. just north of the area here described), and the second is on the Aspromonte massif, between Gambarie, Roccaforte del Greco, Bruzzano, and San Luca. The difference map between UK and OK estimates \( R^\text{UK} - R^\text{OK} \) shows that the greatest values (\( > 250 \) mm) are on the Serre mountain chain, between Chiaravalle Centrale, Serra San Bruno, Fabrizia, and Badolato. UK estimates indicate higher rainfall maxima with respect to OK, with a maximum of 818 mm about 14 km south of Chiaravalle Centrale (at the same site, OK values are \( \sim 70\% \) of UK). Other notable discrepancies (up to 73 mm) can be recognized in the Aspromonte massif (between Gambarie, Roccaforte del Greco, Bruzzano, and San Luca), where OK values are \( \sim 86\% \) of UK. Here, according to UK estimates, the area most severely hit by rainfall is larger and more continuous with respect to OK estimates. In Fig. C(d), the distribution of the above differences in terms of elementary and cumulative frequencies shows that:

- only 10\% of the cells are characterized by similar rainfall amounts;
- in about 25\% of the cells, differences are smaller than 10 mm;
- in 10\% of the cells, rain amounts were overestimated by OK (from 10 to 70 mm);
- in 67\% of the cells, rain amounts were underestimated by OK (from 10 to 250 mm).

The UK map of the \( h_{\text{max}}(24) \) is shown in Fig. D (cf. Main Map). The highest values roughly correspond to maxima of \( R^\text{UK} \) shown in Fig. D(a), and are located some distance from the available rain gauges of the regional network.

### 4.2. Induced ground effects

Widespread shallow slope movements, soil erosion on the slopes, and flooding triggered by the Autumn 2015 rains were recognized along the coastal sector of southern Calabria, between Roccella Jonica (on the Ionian side), and Seminara (on the Tyrrhenian side). As a whole, about 8100 shallow landslides were mapped, affecting a total area of about \( 1.3 \times 10^6 \) m\(^2\), and resulting in an average extent of \( \sim 163 \) m\(^2\). About 67\% of slope movements activated along the Ionian sector of the study area, between Roccella Ionica and Brancalone; only 8\% were triggered along the southernmost portion of Calabria, between Brancalone and Motta S. Giovanni; the remaining 25\% of cases affected the Tyrrhenian coast, between Motta S. Giovanni and Seminara. The density of triggered landslides is shown in Fig. E (on Main Map), together with isolyets of \( h_{\text{max}}(24) \). Greatest landslide densities are found along the eastern coast between Bianco and Africo (22–47 sources per hectare), with notable amounts between Benestare and Ardore (10–21 sources per hectare), roughly corresponding to \( h_{\text{max}}(24) \) of 400–450 mm. Remarkable landslide densities (10–21 sources per hectare) are also found in the vicinity of Reggio di Calabria, despite being characterized by lower rainfall amounts (\( h_{\text{max}}(24) = 150 \) mm).

Triggered slope movements are mostly soil slips (\( \text{sensu Campbell, 1975} \)), mainly of translational type, that mobilized coarse soils from the regolith cover. Debris slides frequently fluidized into flows during propagation along slopes and channels. Accordingly, they could either be ascribed to debris flows or debris avalanches (cf. channelled vs. open-slope cases – Cruden & Varnes, 1996; Hungr, Leroueil, & Picarelli, 2014; Sharpe, 1938).

The frequency distribution of landslide extent is shown in Figure 2. Most of the triggered slope movements are of small size. More than 55\% of the cases are smaller than 100 m\(^2\), and only 1.5\% exceeds 1000 m\(^2\). Furthermore, \textit{clay and clayey flysch} crop out in more than half of the area affected by shallow landslides, followed by sand and silt, conglomerate and sandstone, and igneous and medium-high grade metamorphic rock (Figure 3). Nevertheless, if the relative extent of the different lithological classes is also taken into account, greater ‘landslide indices’ characterize flysch outcrops, followed by clay and clayey flysch and igneous and medium-high grade metamorphic rock. Most of the landslides developed in the high slope class, followed by the very high and medium classes. On the other hand, the landslide index shows an increasing trend from very low to very high slope values (Figure 4).

In addition to gravitational processes, about 1.2 \( \times \) \( 10^6 \) m\(^2\) suffered from sheet erosion, including 0.3 \( \times \) \( 10^6 \) m\(^2\) also affected by rill development. Gullies were activated for a total length of about 83 km (min: 2.6 m; max: 501 m; average: 73 m; standard deviation: 69.3). Areas affected by either sheet or rill erosion (in places, combined with gullies) were mostly located in the Ionian sector (66\%), and smaller areas in the Tyrrhenian (19\%) and in the southernmost (15\%) portions of the study area. Widespread effects were observed along the streambeds, with flow diversions, flooding, and/or sedimentation that also caused appreciable morphological changes along the coastline, where alluvial fans developed at the mouths of the streams.

Ground effects caused widespread damage on slopes and along streambeds, down to the coastline. Common types of damage range from soil disruption (due to either shallow landslides or erosion), to embankment piping or breaks, flooding and debris deposition along the streams, in some locations causing blockage of bridges and destruction of roads or railway lines. If comparing the distribution of landslide sources with \( h_{\text{max}}(24) \) isolyets (Figure 5), greater landslide indices – and related damage – roughly correspond with
higher rainfall amounts. A summary of surveyed types of damage notices/ground effects surveyed by Regione Calabria (2015) is listed in Table 1.

On the Main Map at 1:60,000 scale, the surveyed ground effects induced in the study area by the...
Autumn 2015 rainfall event are shown, together with the isohyets of $h_{\text{max}(24)}$. The boundaries of the surveyed area are limited by the extent of post-event air-photo coverage. Note that, due to scale limitations (cf. extent of the study area and of average mapped phenomena), landslides are only symbolically shown. Furthermore, notices of processes and/or damage – as reported by Regione Calabria (2015) – are mapped by a series of suitable pink symbols to exemplify all possible combinations of hydraulic processes (A), slope movements (B), and damage/remedial works (C). Occurrences of the same notices are summarized in Table 2: the complete list, arranged by municipalities, is reported as supplementary material (Annex A) with coordinates of the sites of investigation, types of observed ground effect/damage, and descriptions. Finally, some photographic examples of surveyed ground effects are shown on the Main Map (locations of the sites are shown by means of brown circles linked to the photos).

5. Discussion and conclusion

The ground effects induced by the Autumn 2015 rainfall event in southern Calabria were surveyed and mapped, together with the isohyets obtained by analysing gauge and radar data. According to UK estimates, two zones were most affected by the rainfall along the Ionian side of southern Calabria from 29 October to 2 November. The first, along the Serre mountain chain, and the second on the Aspromonte massif. UK-estimated results were appreciably higher than those obtained via OK. These discrepancies confirmed that gauge networks could be unsuitable for capturing rainfall distribution in convective storms. If maxima in 24 h, instead of total amounts, are taken into account, the sectors mainly affected by the rainfall do not significantly change; a similar result is obtained by considering maxima aggregated at 3, 6, 12, and 48 h. In this case, the aggregation period has therefore only a small influence on the rainfall pattern.

Ground effects totalled an area of 2.5 km²: they consist of thousands of shallow landslides (debris slides of small size, fluidized in 2/3 of the cases into debris flows or avalanches), mainly triggered on higher-slope classes and sedimentary outcrops, and of soil erosion processes. In addition, flooding occurred along the main streams, with debris deposition along the channels and by the coast. About 2/3 of the soil slips originated in the Ionian coastal sector, followed by the Tyrrenian (1/4), with only minor occurrences along the southernmost portion.
of the study area. A similar spatial pattern characterized areas affected by soil erosion.

When comparing the density of triggered landslides to the isohyets of $h_{\text{max}}(24)$, greatest landslide densities are found along the eastern coast (between Bianco and Africo, and between Benestare and Ardore), roughly corresponding to 400–450 mm of rainfall. Remarkable landslide densities are also found in the vicinity of Reggio di Calabria, despite characterized by lower rainfall amounts (150 mm). The above discrepancy seems to point out quite heterogeneous susceptibility conditions to initiation of shallow landslides in the study area. In other words, similar rainfall amounts may or may not trigger shallow landslides in different sectors of southern Calabria, depending on their interplay with the predisposing factors (e.g., lithotype, steepness, soil type, land use). For instance, despite receiving higher rainfall amounts, only minor ground effects were recorded in the Serre mountain chain compared to the Aspromonte massif. This difference could be explained by taking into account the gentler morphological setting that characterizes most of the Serre area struck by the storm. Consequently, hydrological studies aimed at estimating shallow-landslide area. In other words, similar rainfall amounts may or may not trigger shallow landslides in different sectors of southern Calabria, depending on their interplay with the predisposing factors (e.g., lithotype, steepness, soil type, land use). For instance, despite receiving higher rainfall amounts, only minor ground effects were recorded in the Serre mountain chain compared to the Aspromonte massif. This difference could be explained by taking into account the gentler morphological setting that characterizes most of the Serre area struck by the storm. Consequently, hydrological studies aimed at estimating shallow-landslide thresholds should be focused mainly on homogeneous environmental sectors rather than at regional scale (e.g., [Vennari et al., 2014]). Further analyses are presently being performed to refine rainfall thresholds in the study area, based on mapped phenomena and by considering different aggregation periods.

**Software**

Mapping was carried out using Esri ArcMap 10.1; minor editing was performed by using Adobe Photoshop CS5.

**Geolocation information**

Calabria, southern Italy.

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No potential conflict of interest was reported by the authors.

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