ABSTRACT
The surroundings of Corigliano and Rossano (NE Calabria) were damaged by a short-lasting and localized rainstorm on 12 August 2015, when more than 230 mm of rain in sixteen hours caused damage exceeding 100 million euros. In the Map, shallow landslides triggered by the event are shown at 1:50,000 scale, together with areas affected by soil erosion and flooding, and most damaged sites; historical landslides are also mapped. The main slope-stability controlling factors are mapped at 1:200,000 scale, and an event-based geomorphological landslide inventory of the most damaged sector (Citrea basin) is provided at 1:10,000 scale. Isohyets (cumulative over 16 h), as obtained by interpolating rain-gauge and weather-radar data by Kriging techniques, are shown together with the density of event landslides. Estimated rain maxima (ca. 506 mm in 16 h) by far overcome measured ones, and ground effects well fit the sectors heavily stricken by the storm.

1. Introduction

Heavy rains are known to trigger slope movements, soil erosion and flooding, commonly causing damage to urbanized areas and infrastructures, and sometimes fatalities (2006; Guzzetti et al., 2004). Inventory maps are a fundamental tool to investigate relationships among distribution, type, and magnitude of geomorphic effects – in particular, landslides – with climate and geomorphological characteristics (cf. e.g. Conforti et al., 2014; Lupiano et al., 2019; Malamud et al., 2004; Morgan et al., 1999; Parker et al., 2011), and allow to evaluate susceptibility, hazard, and risk (Brabb, 1991; 2008; van Westen et al., 2006). Specifically, event-based inventory maps show slope movements activated by a specific triggering event (e.g. by an earthquake or a rainstorm – cf. Guzzetti et al., 2004; Tanyag et al., 2017), and play a relevant role in landslide risk assessment.

Calabria (Southern Italy) is frequently affected by high-intensity rainfalls (Ferrari & Terranova, 2004; Terranova & Gariano, 2014), commonly characterized by short duration and small extent. Due to the peculiar orography, generally characterized by notable relief energy and small watersheds cut by high-gradient streams, such thunderstorms frequently cause flash floods and severe ground effects (e.g. Chiaravalloti & Gabriele, 2009; Iovine et al., 2009; Iovine & Merenda, 1996; Iovine & Petrucci, 1998; Rago et al., 2017; Terranova et al., 2016).

The study area (see location and Figure A on Main Map) is located in NE-Calabria. At the time of the rainstorm of 12 August 2015, the area included the territories of Corigliano and Rossano (with over 77,000 inhabitants). In 2018, the two villages joined in a single administrative municipality, giving rise to Corigliano-Rossano (the greatest Calabrian municipality). The area is crossed by the Ionian Railway “Taranto-Reggio Calabria” and the State Road E90 (SS106 and SS106bis) in the coastal sector, and by a number of Provincial Roads that connect to the main urbanized areas and the inner mountainous zone.

In this study, the ground effects caused by the 12 August 2015 rainfall event in the surroundings of Corigliano and Rossano are described. The area most severely affected by the storm extends ca. 100 km². No victims were reported, but more than 650 individuals, including inhabitants and tourists, had to be evacuated and housed in emergency facilities. According to municipalities’ reports, damage to urbanized areas and agriculture would exceed 100 million euros. The Main Map (at 1:50,000) highlights shallow landslides and soil erosion induced on slopes, flooding and overflow along the water network, and includes information on the most damaged sites. For the sector most heavily stricken by the storm, an event-based
geomorphological landslide inventory (cf. Landslide inventory map of the Citrea basin) at 1:10,000 is also provided. A set of smaller-scale thematic maps (Figure B–D, at 1:200,000) depict the main landslide controlling factors (lithotype and faults, slope, and soil types, resp.) of the entire study area. An estimate of cumulative rainfall (computed over 16 h), obtained by means of Kriging with External Drift (KED) interpolations by combining rain gauge and meteoro-radar data, is plotted in Figure E. Indices of ground effects of the 2015 storm and of pre-event instability processes are also included, for the entire study area and for the Citrea basin (Figure F–G). Finally, densities of shallow landslides triggered by the storm are shown in Figure H with isohyets of rain cumulative in 16 h. In the text, the distribution of the ground effects with respect to mentioned controlling factors and rainfall distribution is briefly discussed.

2. The study area

The study area (Figure A on Main Map), in the northeastern portion of the Calabrian Arc (Amodio-Morelli et al., 1976), extends ca. 454 km² along the Ionian coast between the mouths of the Crati River and of the Trionto River. The area (Figure 1(a)) includes some major watersheds (Malfrancato, Coriglianeto, Cino, and Colognati streams), and a number of smaller basins (Gennarito, Cino Piccolo, Pantano, Fico, Fellino, Citrea, Toscano, Nubrica and Frascone streams), whose extent ranges from a minimum of ca. 2.5 km² (Fellino) to a maximum of 66 km² (Colognati). The distal portions of the San Mauro and Coserie streams, and of the Crati and the Trionto rivers, are also to be found in addition to a few nameless inter-basin sectors.

From a geological point of view, the sector is characterized by a Hercynian crystalline basement (Silà Unit), covered by sedimentary rocks (Tortorici, 1982). The Silà Massif is the topmost nappe of the Arc, made of a metamorphic basement of Palaeozoic phyllite schist, intruded by granite and covered by Mesozoic carbonate and sin-orogenic terrigenous units. Late Miocene to Plio-Quaternary strike-slip and extensional tectonic phases (Tansi et al., 2007) originated sedimentary basins, later filled up by depositional sequences (upper Tortonian to Holocene) of poorly consolidated marine, deltaic, and fluvial clastic terrains (such as conglomerate, sand, and clay). Outcropping rocks are severely fractured and deeply weathered, due to the combined effect of tectonic activity and climatic conditions (Tortorici et al., 1995). As a consequence, they show low mechanical resistance and are highly susceptible to slope erosion and gravitational instability.

Elevations range from the Ionian coast to a maximum of 1475 m a.s.l. at Mt. Paleparto. A flat coastal portion extends up to 10 km inland from the coastline, and covers more than 55% of the considered territory. Conversely, its innermost portion is characterized by high slopes and notable gradients along the streams. Due to proximity of the mountain sector to the coast, streams are characterized by small concentration times and quite elongated shapes. Longitudinal profiles (Figure 1(b)) show steeper reaches in the inner sectors, cut into crystalline-metamorphic rocks, and gentler gradients in the distal alluvial sectors.

The Citrea basin (Figure 2) has an area of ca. 11 km², a length of ca. 9 km, and a mean slope of ca. 34%. In its inner sector, cut in the crystalline-metamorphic basement, the stream and two of its tributaries (Armena and Gatta) show a slope close to 100%. The stream is characterized by a torrential regime, generally dry for most of the year and subject to abrupt, high-discharge floods on occasion of severe rainstorms. Its hydrographic network shows a dendritic pattern in the mountainous sector; it is confined into artificial embankments downstream, and then assumes a rectilinear pattern by the coast. The stream reaches crossing the urbanized areas at Rossano-Stazione mainly flow artificially-buried, under squares, streets and houses.

The climate of the study area is of Mediterranean type, characterized by hot, dry summers and by cold, wet winters. At the closest rain gauge (Corigliano Calabro, Figure 3), the mean annual rainfall for the period 1921–1990 is ca. 800 mm (Caloiero et al., 1990).

In historic time, the area has been affected by several extreme rainfall events (Petrucci & Versace, 2005), with flooding along the drainage network and widespread triggering of landslides. On such occasions, loss of lives and severe damage to infrastructures and agriculture were reported. Among the most significant events, those occurred on 17–18 February and 8 November 1975 were particularly severe (in the second, the maximum precipitation in three hours for the period 1921–1980 was recorded). On 10 October 1980, a flood damaged houses and public places along the Citrea Stream, and several landslides affected the State Road n.177. More recently, exceptional rainfall hit the entire region on 9–11 September 2000, causing flooding and interruptions of roads in the study area.

3. Materials and methods

The ground effects induced by the storm of 12 August 2015 in the study area were mapped by means of field surveys (mainly carried out between August and September 2015), combined to geomorphological interpretation of available post-event images (oblique photos taken from surveyors; drone photographs of
the most affected sectors; multi-temporal images provided by Google Earth, dated April 2016 to July 2018). Ground effects were distinguished into: shallow landslides (soil slip, and complex soil slip-debris flow, sensu Campbell, 1975); soil erosion (including sheet, rill, and gully); stream erosion (vertical and lateral); flooding and overflows along the water network; mud/water puddling on flat areas (generally, at the base of the slopes). Main damaged elements (e.g. break of stream bank, road and railway interruption) and ‘sensitive’ sites (artificially buried watercourse, bridge, road along streambed, artificial channel, natural vs. artificial embankment, irrigation canal) were also mapped. In part, notices of ground effects and damaged sites were taken from reports of the Calabrian Basin Authority (ABR-Calabria, 2015; Arcuri et al., 2015).

Geomorphological features (e.g. mountain ridge, morphological scarp, edge of stream terrace, vegetated alluvium), fresh rock fall scarps along steep rocky ridges, and older slope movements were mapped also by interpretation of available pre-event flights (GAY, 1954/55, and IGM, 1990/91, aerial photos at 1:30,000 scale). Contrarily to shallow landslides triggered by the 2015 rainstorm (that mostly involved the regolith), pre-event slope movements are commonly deeper and mobilized the bedrock: based on type of movement, they were distinguished into rock slide and complex rock slide-earth flow. Due to scale problems and/or age of phenomena (that reflect into freshness of geomorphic evidence), single phenomena were not always easy to recognize and map: in such cases, unstable areas were classified as landslide area (LA), and distinguished into shallow (LA<sub>s</sub>) vs. deep (LA<sub>d</sub>) based on estimated depth of instability (LA<sub>s</sub> ≤ 2 m, LA<sub>d</sub> > 2 m).

As concerns the main predisposing factors with respect to slope stability:

- lithotypes and main faults were extracted from the Geological Map of Calabria at 1:25,000 (CASMEZ, 1969), and from the national catalogue of capable faults (ITHACA, 2019). In Figure B on Main Map, lithotypes are grouped into seven classes, based on litho-technical properties: sedimentary terrains predominate (ca. 53%, mostly alluvium, colluvium, and residual soils, followed by conglomerate and sandstone, and clay and clayey flysch), with igneous and medium–high-grade metamorphic rocks covering ca. 39% of the area, in the inner mountain sector.
- elevation and slopes were derived from the DTM (5 m cell-size) provided by Regione Calabria (CTR, 2008). In Figure C on Main Map, slopes are displayed in five classes: gentler slopes (<20°) account for about 63% of the area, and prevail in the coastal sector; steeper slopes (>30°) characterize more than 18% of the area, mainly in the innermost sector and along the stream flanks.
- thickness and texture of the regolith on slopes were obtained from the Soil map of Calabria at 1:250,000 scale by ARSSA (2003). Based on available information (at 1:25,000, in digital format), each item could be distinguished into 2 classes, and precisely: 0 ≤ thickness ≤ 50 cm; thickness > 50 cm; fine-grained; coarse-grained. Consequently, in Figure D, four types of soil classes are shown, as obtained by combining thickness and texture (note: in the coastal plain, all clastic outcrops were classified as alluvial deposits).

Regarding the triggering factor, rain data were derived from the regional rain-gauge network of the
 Functional Centre of the Regional Agency for the Protection of the Environment in Calabria (ARPACAL), and from the Italian Weather Radar Network, provided by the National Department of Civil Protection (NDCP). In particular, rain gauge data (available with a time resolution of one minute) refer to n.156 instruments over the 15,150 km² Calabrian territory. Radar data are collected in almost real-time, and processed by the NDCP: the output is mapped on a Cartesian grid, with a spatial resolution of 1 km and a time resolution of 10 min (2008).

In the present study, the rainfall field of the 2015 rainstorm was preliminarily estimated by applying two distinct geostatistical methods (Wackernagel, 2013): (i) by ‘Ordinary Kriging’ (OK) interpolation of rain-gauge data only and (ii) by ‘Kriging with

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**Figure 2.** (a) Longitudinal profiles (talweg) of the Citrea Stream and of its main tributaries. (b) Hydrographic network of the Citrea basin: (A) Armenia Stream; (B) Gatta Stream; (C) Citrea Stream; (D) San Paolo Stream.

**Figure 3.** The rain gauges closest to the study area: Corigliano Calabro (CO, 294 m a.s.l.), Sibari (SI, 3 m a.s.l.), Acri (AC, 790 m a.s.l.), and Cropalati (CR, 377 m a.s.l.). Land areas are in grey.
External Drift’ (KED) interpolation of combined rain-gauge and SRI radar data (‘Surface Rain Intensity’ – i.e. an estimate of the ground rain-rate, in mm/h). Interpolations were performed by means of the auto-Krige function (cf. Hiemstra, 2015). In KED, rain-gauge data were used as primary variable, and radar data (assumed to properly capture the spatial rain pattern) represented the auxiliary information.

Considering the usual dimensions of small rainstorm cells (cf. Harrold & Austin, 1974) – like the one that affected the study area on 12 August 2015 – a 1 km-size square mesh was adopted for estimating the spatial rainfall distribution (Gabriele et al., 2017). Accordingly, an interpolated precipitation field could be obtained with a spatial structure constrained to available rain ground measurements. Moreover, by taking into account the cumulative rainfall of the event between 00:00 and 24:00 (UT) of 12 August 2015, the maxima related to mobile windows of sizes Δt = 1, 3, 6, 12, 16 h (shifted every 10 min) were extracted for each cell of the computational domain.

4. Results

4.1. The rainfall event

According to both measurements at the closest rain gauges, and evidence obtained through Kriging analyses, the event of 12 August 2015 reached a climax in about 6 h, from 02:00 to 08:00 (UT), and then weakened over the next 10 h. The rain maxima, for durations of 1, 3, 6, 12, and 16 h, measured at the closest rain gauges, are listed in Table 1.

As concerns rain estimates based on statistical interpolations, OK and KED results are shown in Figure 4. Interpolated rain amounts confirm that the storm was strongly localized. The area mostly affected by the rainstorm would be located on the Corigliano-Rossano municipality, with maximum peaks in 16 h of 230.4 mm (OK, Figure 4(a)) and 506.3 mm (KED, Figure 4(b)) located in the middle sector of the Citrea basin. As concerns the cell-by-cell differences between KED and OK (Figure 4(c)), the greatest discrepancy (+345.5 mm) would be at Cozzo dell’Uovo, WNW of Rossano (OK: 160.8 mm, KED: 506.3 mm), with an average difference of +243.9 mm in the Citrea basin. For the area included in the dashed box in Figure 4(c), the statistical distribution of the differences for the cumulative rainfall is shown in Figure 4(d).

4.2. Induced ground effects

The ground effects caused by the rainstorm of 12 August 2015 in the study area are shown in the Main Map, where geomorphic evidence related to shallow landslides (soil slips and debris flows), run-off erosion on slopes, erosion and flooding along the streams, and overflows on flat areas are mapped at 1:50,000 scale. Shallow slope movements mostly involved the regolith in a strip between the Colognati and the Cino Piccolo streams (including the Citrea Stream). Run-off induced slope erosion (mainly sheet and rill), and puddling of mud and water on flat zones. The hydrographic network suffered from severe flooding and erosive effects (either vertical or lateral), and streams overflowed at places on lateral lands. By the coast, debris fans accumulated at the mouth of the streams (and were rapidly dismantled by sea currents in the following weeks).

In the Main Map, locations of the main damaged sites (e.g. along stream banks, roads, railways, and urbanized sectors) and of buried water courses are shown. Note that, due to scale limitations and extent of mapped phenomena, event landslides had to be symbolically shown by means of centroids. Older (pre-event) landslides are distinguished from event ones: they are, in general, inactive (dormant), of greater extent and deeper, and involve the bedrock. Where single slope movements could not be clearly distinguished, generic ‘landslide areas’ were mapped.

As concerns the effects of the 2015 rainstorm, a total number of 5301 shallow landslides were mapped for an area of 1.1 km² (average landslide area: 213 m²). Among them, soil slip-debris flows prevail on soil slips (3667 vs. 1634; total area: 0.9 vs. 0.2 km²; average area: 244 vs. 143 m²). In addition, LA † extended over 0.3 km² of the basin. The event also caused soil erosion on slopes for a total area of ca. 7.7 km², in addition to flooding, damage to embankments and overflows along the Citrea, Fellino, Fico, San Mauro, and Gennarito streams. As a consequence of heavy rains and stream overflows, plain areas were flooded by water or mud (tot. area: 0.7 km²), and numerous buildings suffered from serious damage (mostly, at Lido Sant’Angelo, at the mouth of the Citrea Stream). Furthermore, due to severe rainfall and related run-off, several interruptions were reported to roads and to the Ionian Railway, and flat sectors were flooded by mud or water.

### Table 1. Cumulative rainfall maxima (max_{max}, in mm) measured at the closest rain gauges on 12 August 2015, for durations (n) between 1 and 16 h.

| rain gauge | max_{1h} | max_{3h} | max_{6h} | max_{12h} | max_{16h} |
|------------|---------|---------|---------|---------|---------|
| Corigliano C. | 38.6    | 97.8    | 155.8   | 219.6   | 230.4   |
| Acri       | 5.4     | 10.6    | 11.6    | 18.2    | 23      |
| Croplati   | 32.2    | 33      | 41.4    | 45      | 48.4    |
| Silvoci    | 5.4     | 6.6     | 7.6     | 10      | 11.4    |

Notes: Maximum values are listed in bold per each duration; minimum values are in italics. The maximum amounts (recorded at Corigliano) refer to the following time intervals (UT): max_{1h} between 05:00 and 06:00; max_{3h} between 05:00 and 08:00; max_{6h} between 02:00 and 08:00; max_{12h} between 02:00 and 14:00; max_{16h} between 01:00 and 17:00.
In the same area, 7672 pre-event slope movements extend over a total area of ca. 25 km². Among such landslides, rock slides prevail on rock slide-earth flows (5570 vs. 2102 cases; total area: 19.2 vs. 5.7 km²; average area: 3444 vs. 2700 m²). In addition, LA effect 3.6 km².

Overall, the geomorphic effects caused on the slope by the 2015 storm affected ca. 0.3% of the study area, whereas pre-existing unstable sectors extend over 6.3%.

In Figure 5, the frequency distribution of the landslides triggered by the 2015 storm is shown: smallest sizes characterize most of the cases (about 57% are smaller than 100 m²).

As mentioned, the Citrea basin was greatly affected by the 2015 rainstorm and related ground effects. Shallow landslides mainly developed in a narrow strip south of Rossano Stazione, between the Cemetery and the historical centre of Rossano. A significant portion of damage to urbanized areas was recorded at Lido Sant’Angelo, next to the mouth of the Citrea Stream: here, buildings, roads, and accommodation facilities were flooded by mud and debris, causing the bankrupt of touristic and agricultural sectors. It is noteworthy that the distal reach of the San Paolo Stream (a tributary of the Citrea Stream, on hydrographic right) crosses the area of Rossano-Stazione.
as a buried channel. Along the courses of the Citrea and Fellino streams, break of streambanks and silting occurred at several locations, causing overflows on the alluvial plain (ABR-Calabria, 2015). At the mouth of the Citrea and Cino Piccolo streams, debris flow generated alluvial fans, with an advancement of the coastal line of 26 and 24 m, respectively.

In the Landslide inventory map of the Citrea basin (at 1:10,000 scale), the 1437 shallow landslides triggered by the 2015 storm, for a total area of 0.2 km² (at 1:10,000 scale), the 1437 shallow landslides triggered by the 12 August 2015 rainstorm in the study area and for the Citrea basin. In particular, for the whole study area, $L_i$ refer to shallow landslides (soil slip, soil slip-debris flow), shallow landslide areas, and slope erosion caused by the event (Figure F1-3); similar indices for the Citrea basin are shown in Figure G1-3. As concerns pre-event items, $L_i$ refer to slope movements (rock slide, rock slide-earth flow), and landslide areas for both the study area (Figure F4-5) and the Citrea basin (Figure G4-5 – note that landslide areas were distinguished into shallow and deep only in the Citrea basin, due to graphic constraints).

In the study area, the highest $L_i$ for the ground effects of the 2015 storm are related to run-off erosion and soil slip-debris flows, and developed on clastic terrains (conglomerate and sandstone, and subordinately clay and clayey flysch), on intermediate slopes (10–30°), and on deeper and finer classes of regolith cover. In the Citrea basin, a similar trend can be appreciated on clay and clayey flysch, whereas soil slip-debris flows and shallow landslide areas prevail on metamorphic and igneous derived soils, on steeper slopes (>30°), and on coarse-grained regolith.

As concerns pre-event slope instability, in the study area the highest indices are related to rock slide, and subordinately rock slide-earth flow, on metamorphic and igneous outcrops, mainly on moderate-steep slopes (>20°). In the Citrea basin, the highest values are related to landslide areas (subordinately, rock slide-earth flow) on metamorphic and igneous outcrops, and to steeper slopes (>30°). Among clastic terrains, notable indices are only to be found on conglomerate and sandstone.

5. Discussion

On 12 August 2015, a notable amount of precipitation in about 16 h (from 02:00 to 18:00 UT) hit an area of few square kilometres in NE Calabria, causing thousands of shallow landslides, severe erosion on slopes, and flooding along the hydrographic network. Great damage resulted in the middle-distal sector of the Citrea basin, with considerable flooding next to the mouth of the stream.

According to KED analyses (Figure 6), the sector mostly affected by the rainstorm of 12 August 2015, for durations 3–16 h, would be the middle sector of the Citrea basin. The upper sector of the same basin results to be the most affected only for 1 h duration.

When comparing the distribution of the shallow landslides triggered by the event to either OK or KED cumulative estimates of rain in 16 h (Figure 7),

![Figure 5. Cumulative frequency (%) of areas of shallow landslides triggered by the 12 August 2015 rainstorm in the study area.](image)
the greatest landslide indices do correspond to highest KED rainfall amounts, according to an exponential law. On the other hand, a clear relationship for OK values cannot be recognized.

In Figure E (on the Main Map), the cumulative rainfall in 16 h, as recorded between 2:00 and 18:00 (UT) of 12 August 2015 by the regional rain gauge network, is shown by blue dots, and related KED isohyets are mapped. In Figure H (on the Main Map), the density of the triggered landslides is shown together with KED isohyets of cumulative rains in 16 h. A strict relationship between heaviest rains and ground effects can be appreciated: the most affected area is included in the 200 mm isohyet, with greatest densities (10–19 sources per hectare) of shallow landslides nearby Rossano, in the middle sector of the Citrea basin. Notable landslide densities (up to 5 sources per hectare) are also to be found in the vicinity of Corigliano.

In agreement with Goudenhoofdt and Delobbe (2009), and Nanding et al. (2015), KED interpolations seem therefore to better capture the structure of the rainfall event, as recorded by the meteo-radar. KED results also better characterize the area most severely affected by ground effects caused by the rainfall. Undoubtedly, rain amounts measured at the rain gauge network are of paramount importance for data interpolation and model calibration purposes, but they usually fail to capture the essential characteristics of localized, short downpours — like the rainstorm that affected the Corigliano-Rossano area in the early hours of 12 August 2015.

6. Conclusion

Ground effects induced by a severe, short-lasting and localized rainstorm that affected the surroundings of Corigliano and Rossano (NE Calabria) on 12 August

![Figure 6. Maximum rainfall amounts (KED) for durations 1–16 h: (a) 1 h, (b) 3 h, (c) 6 h, (d) 12 h, (e) 16 h.](image)

![Figure 7. Shallow landslides triggered by the 2015 rainstorm. Landslide indices against cumulative rains in 16 h for OK and KED estimates (red and blue, resp.). The equation of the blue regression line (related to KED amounts) is also shown.](image)
2015 were mapped by means of field surveys and interpretation of available remote images. The Main Map (at 1:50,000) highlights shallow landslides and soil erosion induced on slopes, flooding and overflow along the water network, and includes information on the most damaged sites. For the sector most damaged by the event, an event-based geomorphological landslide inventory (at 1:10,000) is also provided. A set of smaller-scale thematic maps (at 1:200,000) depict the main landslide controlling factors of the entire study area.

Cumulative rainfall was obtained by means of Kriging interpolations by combining rain gauge and meteoradar data. Indices for ground effects of the storm and for pre-event instability processes are shown, and densities of shallow landslides triggered by the storm are plotted with isohyets of rain cumulative in 16 h.

Ground effects induced by the event fit well the sectors most heavily stricken by the storm. Overall, results are essential for successive elaborations, aimed at risk assessment and mitigation. Furthermore, rain maxima (ca. 506 mm in 16 h) – as estimated by Kriging with External Drift (KED) – by far overcome measured ones, thus remarking the paramount importance of a proper combination of direct (gauge) and remote (radar) techniques of rain assessment.

Software

Mapping was carried out by using the open sources software QGIS 3.14.

Geolocation information

Calabria, southern Italy.

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Disclosure statement

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References

ABR-Calabria. (2015). Rapporto di evento. Precipitazioni 11-12 Agosto 2015. [Event report. Rains of 11-12 August 2015]. Segreteria Tecnica, Autorità di Bacino, Regione Calabria, pp. 83.

Amadio-Morelli, L., Bonardi, G., Colonna, V., Dietrich, D., Giunta, G., Ippolito, F., Liguori, V., Lorenzoni, S., Paglionico, A., Perrone, V., Piccarreta, G., Russo, M., Scandone, P., Zanettin-Lorenzoni, E., & Zuppetta, A. (1976). L’arco Calabro-Peloritano nell’ortogene appenninico Maghrebide [The Calabrian-Peloritan Arc in the Apennine-Maghrebide orogen]. Memorie della Società Geologica Italiana, 17, 1–60.

Arcuri, S., Fusto, F., Marsico, L., & Rotundo, R. (2015). Evento meteopluviometrico del 12 agosto 2015. Rapporto speditivo di evento. [Meteo-pluvial event of 12 August 2015. Preliminary event report] ARPACAL, Centro Funzionale Multirischi della Calabria, Regione Calabria, pp. 17.

ARSSA. (2003). I suoli della Calabria. Carta dei suoli in scala 1:250.000 della Regione Calabria. Monografia Divulgativa 2003 [Soils of Calabria. Soil map of Calabria at 1:250,000 scale. Informative monograph 2003]. Rubbettino Industrie Grafiche ed Editoriali – Soveria Mannelli, 387 pp.

Brabb, E. E. (1991). The world landslide problem. Episodes, 14 (1), 52–61. https://doi.org/10.18814/epiugs/1991/v14i1/008

Caloiero, D., Mercuri, T., & Reali, C. (1990). Le precipitazioni in Calabria (1921–1980). CNR IRPI Geodata, 36.

Campbell, R. H. (1975). Soil slips, debris flows and rainstorm in the Santa Monica Mountains and vicinity, Southern California. U.S. Geol. Survey, Prof. Paper 851, 51.

CASMEZ. (1969). Carta Geologica della Calabria in scala 1:25,000 [Geological map of Calabria at 1:25,000 scale]. Poligrafica & Cartovalori.

Chiaravalloti, F., & Gabriele, S. (2009). Vibo Valentia–Pescara sections in Calabria (1921–1980). Roma: CNR.

Clarke, M. L., & Rendell, H. M. (2006). Hindcasting extreme events: The occurrence and expression of damaging floods and landslides in southern Italy. LDD, 17(4), 365–380. https://doi.org/10.1002/lrd.743

Conforti, M., Muto, F., Rago, V., & Critelli, S. (2014). Landslide inventory map for north-eastern Calabria (south Italy). Journal of Maps, 10(1), 90–102. https://doi.org/10.1080/17445647.2013.852142

CTR. (2008). Carta Tecnica Regionale in scala 1:5,000. Regione Calabria [Regional technical map at 1:5,000 scale. Calabria Region]. Files (vectorial, in DWG format). http://geoprotale.regione.calabria.it

Ferrari, E., & Terranova, O. (2004). Non-parametric detection of trends and change point years in monthly and annual rainfalls. Proceedings of 1st Italian-Russian Workshop New Trends in Hydrology (Publ. 2823, pp. 177–188). Roma: CNR.

Gabriele, S., Chiaravalloti, F., & Procopio, A. (2017). Radar–rain-gauge rainfall estimation for hydrological
applications in small catchments. *Advances in Geosciences*, 44, 61–66. https://doi.org/10.5194/adgeo-44-61-2017

Goudenhooft, E., & Delobbe, L. (2009). Evaluation of radar-gauge merging methods for quantitative precipitation estimates. *Hydrology and Earth System Sciences*, 13(2). https://doi.org/10.5194/hess-13-195-2009

Guzzetti, F., Ardivzone, F., Cardinali, M., Galli, M., & Reichenbach, P. (2008). Distribution of landslides in the upper Tiber River basin, central Italy. *Geomorphology*, 96, 105–122. https://doi.org/10.1016/j.geomorph.2007.07.015

Guzzetti, F., Cardinali, M., Reichenbach, P., Cipolla, F., Sebastiani, C., Galli, M., & Salvati, P. (2004). Landslides triggered by the 23 November 2000 rainfall event in the Imperia Province, Western Liguria, Italy. *Engineering Geology*, 73(2), 229–245. https://doi.org/10.1016/j.enggeo.2004.01.006

Harrold, T. W., & Austin, P. M. (1974). The structure of precipitation systems—a review. *Journal of Researches Atmospheriques*, 8(1–2), 41–57.

Hiemstra, P. H. (2015). CRAN – package automap. http://cran.r-project.org/web/packages/automap/automap.pdf

Iovine, G., Iaunlina, P., & Terranova, O. (2009). Emergency management of landslide risk during Autumn-Winter 2008/2009 in Calabria (Italy). The example of San Benedetto Ullano. In R. S. Anderssen, R. D. Braddock, & L. T. H. Newham (Eds.), *Proceedings of the 18th World IMACS congress and MOSIM09 international congress on modelling and simulation* (pp. 2686–2693). University of Western Australia. ISBN: 978-6-9738400-7-8.

Iovine, G., & Merenda, L. (1996). Alcune considerazioni sulla franosità nel bacino del torrente Straface (Alto Jonio, Calabria) [Some considerations on slope instability in the Straface stream basin (Alto Jonio, Calabria)]. *Geologia Applicata e Idrogeologia*, 28, 513–521.

Iovine, G., & Petrucci, O. (1998). Effetti sui versanti e nel fondaiole indotti da un evento pluviale eccezionale nel bacino di una fiumara calabra (T. Pagliara) [Ground effects along the slopes and the main stream caused by an exceptional meteoric event in the basin of a Calabrian fiumara (T. Pagliara)]. *Bollettino della Società Geologica Italiana (Italian Journal of Geosciences)*, 117, 821–840.

ITHACA Catalogue “Italy HAazard from CApable faults” – rel. (2019). https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/suolo-e-territorio-1/ithaca-catalogo-delle-faglie-capaci

Lupiano, V., Rago, V., Terranova, O. G., & Iovine, G. (2019). Landslide inventory and main geomorphological features affecting slope stability in the Picentino river basin (Campania, southern Italy). *Journal of Maps*, 15(2), 131–141. https://doi.org/10.1080/17445647.2018.1563836

Malamud, B. D., Turcotte, D. L., Guzzetti, F., & Reichenbach, P. (2004). Landslides, earthquakes and erosion. *Earth and Planetary Science Letters*, 229(1–2), 45–59. https://doi.org/10.1016/j.epsl.2004.10.018

Morgan, B. A., Iovine, G., Chirico, P., & Wieczorek, G. F. (1999). Inventory of debris flows and floods in the Lovingston and Horseshoe Mountain, VA, 7.5′ quadrangles, from the August 19/20, 1969, storm in Nelson County, Virginia (Open-file Report No. 99–518). Washington, DC: U.S. Geological Survey.

Nandling, N., Rico-Ramirez, M. A., & Han, D. (2015). Comparison of different radar-raingauge rainfall merging techniques. *Journal of Hydroinformatics*, 17(3), 422–445. https://doi.org/10.2166/hydro.2015.001

Parker, R. N., Densmore, A. L., Rosser, N. J., de Michele, M., Li, Y., Huang, R., Whadcoat, S., & Petley, D. N. (2011). Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth. *Nature Geoscience*, 4(7), 449–452. https://doi.org/10.1038/ngeo1154

Petrucci, O., & Versace, P. (2005). *Frame e alluvioni in provincia di Cosenza agli inizi del ’900*: ricerche storiche nella documentazione del Genio Civile [Landslide and flood at the beginning of ’900: Historical research in the documentaion of Civil Engineers]. In Università della Calabria Osservatorio di Documentazione Ambientale.

Rago, V., Chiaravalli, F., Chiodo, G., Gabriele, S., Lupiano, V., Nicastro, R., Pellegrino A. D., Procopio A., Siviglia S., Terranova O. G., & Iovine, G. R. (2017). Geomorphic effects caused by heavy rainfall in southern Calabria (Italy) on 30 October–1 November 2015. *Journal of Maps*, 13(2), 836–843. https://doi.org/10.1080/17445647.2017.1390499

Tansi, C., Muto, F., Critelli, S., & Iovine, G. (2007). Neogene-Quaternary strike-slip tectonics in the central Calabrian Arc (Southern Italy). *Journal of Geodynamics*, 43(2007), 393–414. https://doi.org/10.1016/j.jog.2006.10.006

Tanyas, H., van Westen, C. J., Allstadt, K. E., Anna Nowicki Jesse, M., Görütm, T., Jibson, R. W., Godt, J. W., Sato, H. P., Schmitt, R. G., Marc, O., & Hovius, N. (2017). Presentation and Analysis of a Worldwide Database of earthquake-induced landslide Inventories. *Journal of Geophysical Research: Earth Surface*, 122(10), 1991–2015. https://doi.org/10.1002/2017JF004236

Terranova, O. G., & Gariano, S. L. (2014). Rainstorms able to induce flash floods in a Mediterranean-climate region (Calabria, southern Italy). *Natural Hazards and Earth System Sciences*, 14(9), 2423–2434. https://doi.org/10.5194/nhess-14-2423-2014

Terranova, O. G., Gariano, S. L., Bruno, C., Greco, R., Pellegrino A. D., & Iovine, G. G. R. (2016). Landslide risk scenario of the Costa Viola mountain ridge (Calabria, Southern Italy). *Journal of Maps*, 12(1), 261–270. https://doi.org/10.1080/17445647.2016.1195300

Tortorici, L. (1982). Lineamenti geologico-strutturali dell’Arco Calabro-Peloritano [Geological-structural lineaments of the Calabrian-Peloritan Arc]. *Societa Italiana Mineralogia e Petrologia*, 38, 927–940.

Tortorici, L., Monaco, C., Tansi, C., & Cocina, O. (1995). Recent and active tectonics in the Calabrian arc (southern Italy). *Tectonophysics*, 243(1–2), 37–55. https://doi.org/10.1016/0040-1951(94)00190-K

van Westen, C. J., van Asch, T. W. J., & Soeters, R. (2006). Landslide hazard and risk zonation -why is it still so difficult? *Bulletin of Engineering Geology and the Environment*, 65(2), 167–184. https://doi.org/10.1007/s10040-005-0023-0

Vulpiani, G., Pagliara, P., Negri, M., Rossi, L., Gioia, A., Giordano, P., Alberoni, P. P., Cremonini, R., Ferraris, L., & Marzano, F. S. (2008, June 30 – July 4). *The Italian radar network within the national early-warning system for multi-risks management*. In Proc. of Fifth European Conference on Radar in Meteorology and Hydrology (ERAD 2008), Vol. 184, Helsinki, Finland.

Wackernagel, H. (2013). *Multivariate geostatistics: An introduction with applications*. Springer Science & Business Media.