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ORIGINAL ARTICLE

Landslides and flash floods induced by the storm of 22nd November 2011 in northeastern Sicily

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Abstract
On 22nd November 2011, after extreme rainfall (more than 350 mm fell in 10 h), thousands of shallow landslides evolving into debris flows occurred in several torrent catchments of Peloritani ridge, northeastern Sicily, carrying a large amount of wood. A rapid increase in torrent discharge occurred during the storm, inducing floods of the Longano and Mela torrents, also amplified by wood obstructions of bridges. A detailed reconstruction of the main geo-hydrological events has been done. Landslides have been mapped by satellite photos and checked by field surveys, and were found to be particularly concentrated in the Longano, Mela and Saponara catchments. The timing of landslide initiation has been estimated by technical report data, eyewitnesses, and by calibration of the Leaky Barrel Model [Wilson, Wiezoreck, Environ Eng Geosci 1(1):11–27, 1995]. The recorded amount of rainfall has been transformed into the torrent discharge by the HEC-HMS model, using a detailed digital elevation model (DEM) with resolution of 2 × 2 m, and the torrent hydrograph has been obtained corresponding to several river sections. In the urban area of Barcellona Pozzo di Gotto, the torrent discharge reached its peak before the arrival of the large trunks, indicating that the main cause of the inundation in the urban area was the bridge obstruction. The aim of this study is to provide a detailed case history of landslides inducing floods, and their relationship with the use of simple hydrological models, which could help in estimating the risk of inundation caused by a large amount of wood in unmonitored catchments.

Keywords Debris flow · Flood · Rainfall · Hydrological model · Sicily

Introduction

Intense storms can induce landslides in mountain areas and floods in the depressed zones of catchments. In many cases, these processes are strictly connected, and man-made modifications of natural environments can amplify their effects (Guzzetti et al. 2005; Cheng et al. 2005; Llasat et al. 2010; Calcaterra and Guadagno 2013; Cevasco et al. 2015; Bathrellos et al. 2016, 2017).

In many wooded mountain areas, landslides and debris flows are the main processes transporting a large amount of wood along the slopes up to torrent. These phenomena usually occur after intense rainfall in small catchments of mountain areas, which are able to increase rapidly the torrent discharge, causing flash floods (Marchi et al. 2009; Wohl 2011).

In the northeastern area of Sicily, these phenomena occur frequently due to favorable morphological and climatic conditions (Ciampalini et al. 2015); locally, the high and narrow ridge of the Peloritani Mountains is characterized by steep

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slopes and small torrent catchments which extend between the Ionian and Tyrrhenian seas.

On 22nd November 2011, an intense storm hit a wide area of the Tyrrhenian sector of the Peloritani mountains (Fig. 1), which induced thousands of shallow landslides, and caused alluvial phenomena in many urban areas (Barcellona Pozzo di Gotto, Milazzo, Saponara, Torregrotta, Villafranca). Hydrological features of the 22nd November 2011 storm has been described by Fiorillo et al. (2016), who reconstructed the spatial distribution of rainfall integrating rain gauge data into satellite data, and analyzed the historical series of hourly maxima rainfall of period 1930–2011. Other flood events had previously hit the same area (11th December, 2008 and 2nd November, 2010) as well as recently (10th October, 2015).

On the other side of the Peloritani ridge, along the Ionian coast, many other landslide events occurred recently; a catastrophic event hit the village of Giampilieri on 1st October 2009, causing 36 deaths (Aronica et al. 2012; Schilirò et al. 2015), and on 25th October 2007, an intense rainstorm induced many landslides and floods (Aronica et al. 2008).

For its morphological conditions, the Peloritani ridge constitutes one of the most landslide-prone areas of Italy and, due to urban spread that occurred during recent decades, the landslide risk has rapidly increased. Locally, the interaction between landslides along the slopes and flood phenomena almost always occurs.

In this study, we reconstructed the landslides that occurred on 22nd November 2011, describing the typology and time of activation, and their relationship with the flood events that affected the urban area of Barcellona Pozzo di Gotto, Milazzo and Saponara. The aim of this study is to provide a detailed case history on the landslides inducing floods, using specific surveys, chronological reconstruction of the events, and hydrological models.

This case history can be assumed as a typical representative of Peloritani area, as both the role of urban areas and landslide materials can amplify the effect of floods on areas located downstream of narrow valleys.

Materials and methods

Due to a lack of aerial photos after the event of 22nd November 2011, landslides have been mapped from the panchromatic type of satellite images (EROS satellite) taken on June

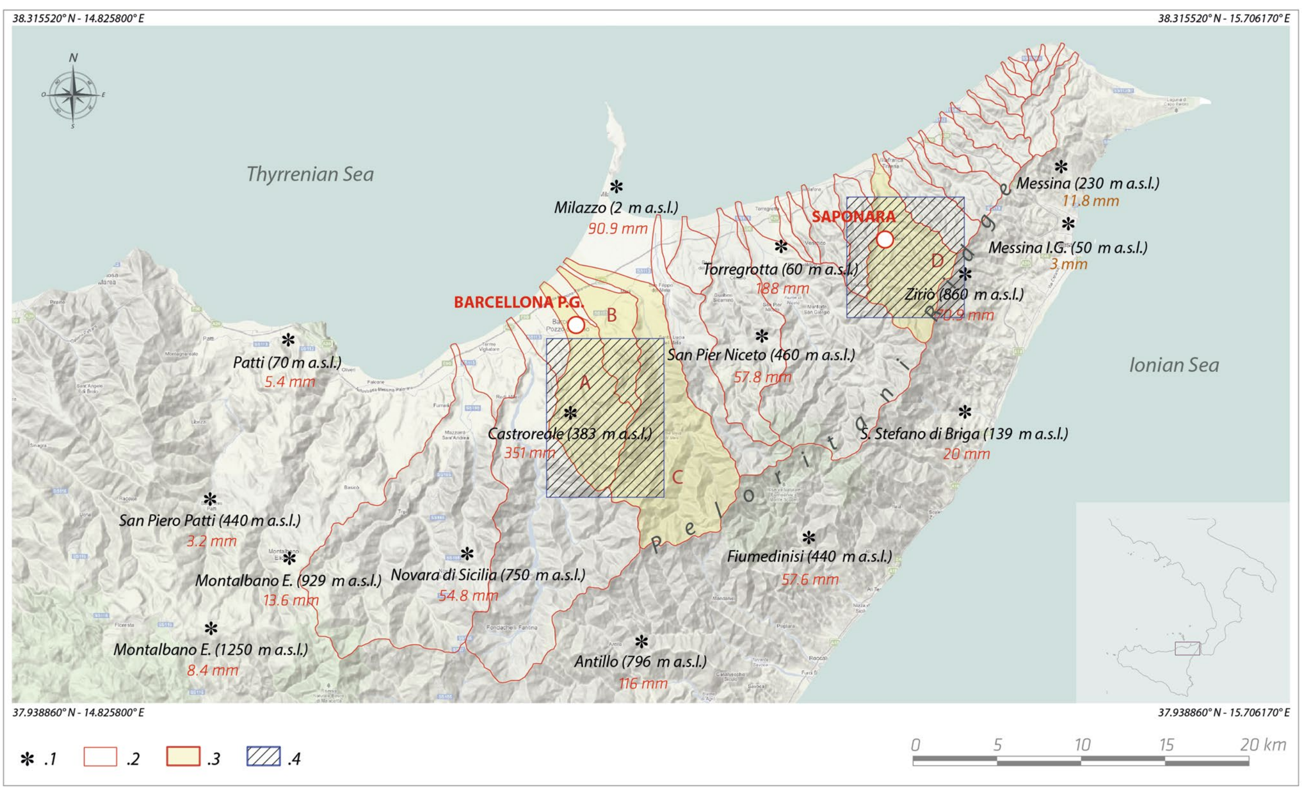

Fig. 1 Northeastern sector of Sicily, characterized by the Peloritani ridge, extended between the Tyrrhenian and Ionian sea; (1) rain gauge network working and rainfall recorded on 22 November 2011; (2) catchment boundary of the Peloritani ridge, Tyrrhenian side; (3) catchment of Longano (A), Idria (B), Mela (C) and Saponara (D) torrent interested by floods on 22 November 2011. (4) Mapped landslide area

2012, with a ground resolution of 0.70 × 0.70 m (Fig. 2). These geo-referenced images have enabled the mapping of thousands of landslides induced by the 22nd November 2011 storm, that otherwise would have been almost prohibitive to detect. The characteristics of these landslides are described in the next section, after the description of the physical features of the study area, the main hydrological features of the 22nd November 2011 storm, and the methods used in the hydrological analysis.

Physical features of the area

The Peloritani ridge is oriented approximately 45°N, with elevation around 1100 m a.s.l., and exceeding 1200 m a.s.l. corresponding to several peaks. The Thyrrenian coastal sector is characterized by a wide flat area, constituted by recent (Quaternary) alluvial and marine deposits, with ground elevation being up to few tens of meters a.s.l., which includes the Milazzo plain. In the terrains of the substratum outcrop inland, the ground elevation increases rapidly and slope angle can be higher than 45°.

Following the recent geological map of Italy (ISPRA 2009), scale 1:50,000 (Foglio n. 600 "Barcellona Pozzo di Gotto" and Foglio n.601 "Messina and Reggio Calabria"), the substratum belongs to a metamorphic complex of Paleozoic and to marine sedimentary complexes of Tertiary age (Flysch di Capo d'Orlando and Argille scagliose), both involved in Tertiary tectonic activity of the Apennine chain. Marine synorogenetic deposits of Miocene (Formazione di San Pier Niceto) and Pliocene–Pleistocene (Formazione di Rometta) lie on the older terrains, and they outcrop between the coastal and inland sectors.

A complex of normal faults have caused the general uplift of the area during the Pliocene and Pleistocene; marine deposits of lower Pleistocene actually lie at 560 m a.l.s. (Rometta village), testifying of the high uplift rate during the Quaternary. As a consequence, the hydrographic network is cashed in the substratum, and determines steep and unstable slopes.

A diffuse soil mantle covers the slopes, constituted by colluvial and eluvial deposits which originated from the weathering and erosion of the substratum; this soil mantle constitutes the main material involved in the landslide processes, and generally, the thickness does not exceed ½ m along the slopes.

Along these slopes and after numerous fires that have occurred, the arboreal vegetation was destroyed; however,

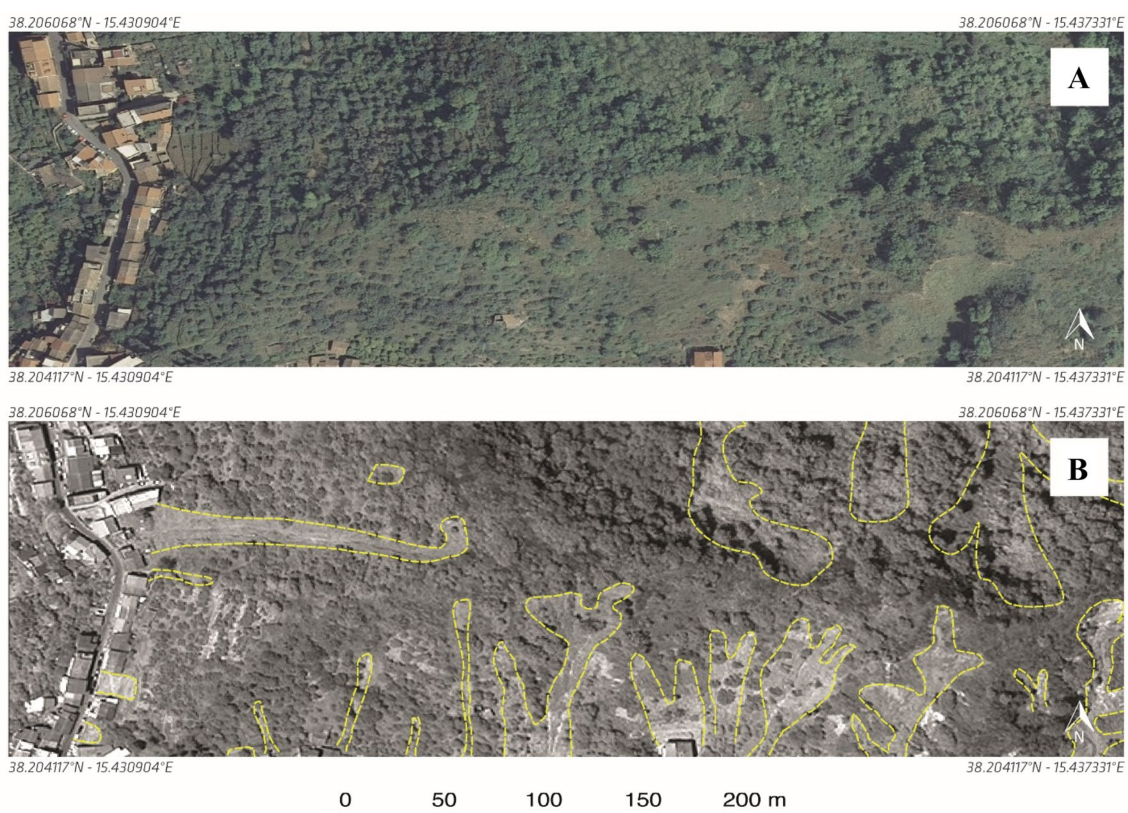

Fig. 2 Saponara village (Scarcelli district): orthophotos (**a**) and landslide mapping from satellite photos (**b**) and field checking

mixed forests of conifers and chestnuts are present in the higher zones but with discontinuity.

Numerous catchments characterize the Peloritani ridge, generally elongated in the NW–SE direction, with a much greater length than the width, high slopes, and area extensions up to tens of km^2. Due to the presence of low permeability rocks in the basins, the torrent flow rates increase as a result of intense rainfall events in autumn and winter, and then vanish in summer due to Mediterranean climate and the absence of large perennial springs. In general, rapid and strong variation of the discharge can be observed in the torrents; due to morphological and geometrical characteristics of catchments, intense rainfall distributed in a few hours is able to increase considerably the torrent discharge, especially if they occur after a wet period.

The entire area has witnessed several modifications during the long historical time, which has caused the spread of urban areas, the building of bridges, concreting of river channels, and the diversion of the river Mela during the Spanish period (sixteenth century). Also, fire destroyed the rich tree vegetation along the slopes many times and in the different zones, making it prone to erosion and landslides, as well as the progressive abandonment of agricultural practices in mountain areas occurred during the last decades.

Figure 3 shows the urban expansion of the Barcellona Pozzo di Gotto, and the progressive construction of bridges along the Longano torrent. After 1942, the Longano creek has been progressively covered by a road area in the urban tract. The bridges and their pylons have reduced the torrent sections, hindering the outflow during floods (Fig. 4).

In other catchments, as in the Mela basin, the torrent bed has been filled by waste materials, and some sections of embankments damaged during floods have never been repaired.

The 22 November 2011 storm

The meteorological conditions leading to 22nd November 2011 storm were connected to anomalous barometric gradient that occurred between the northern side (Tyrrenian basin) and south-eastern side (Ionian sea) of the Peloritani Mountains, inducing high-speed sirocco winds. These winds generally cause intense rainfall on the Ionian side of the Peloritani mountains due to barrier effect of this ridge, and the highest accumulated rainfall was locally expected. But due to the very high intensity of winds on 22nd November 2011 towards the North, the rainfall accumulated mainly on the other side of the Peloritani water divide, causing unexpected landslides and flash floods along the Tyrrhenian side of the Peloritani ridge (Fiorillo et al. 2016). This storm behavior is known locally as "Alcantara effect", because the wind from south rises along the valleys between Etna volcano and Peloritani mountains and crosses the watershed of Peloritani (Ingemi 2011). The storm has a typical Enhanced-V shape from satellite images, and it reached the southern Calabria few hours later, inducing further landslides and flash floods. Fortunately, no further deaths were caused by a derailed train near Lamezia Terme.

Figure 5 shows the accumulated hourly rainfall recorded by rain gauges during the 22nd November, 2011 storm. Castroreale rain gauge recorded the most intense rainfall, and between 6:00 and 15:00 a major part of the precipitation was caused by the storm. Towards the North–East, (Torregrotta, San Pier Niceto and Ziriò) the most intense rainfall occurred up to 10 h later. Many eyewitnesses described that in the area of Saponara, the major precipitations occurred in the afternoon of 22nd November 2011, highlighting that the rain gauge network was insufficient to catch the spatial–temporal distribution of the rainfall. In general, storms migrated from West to East, according to satellite images (Fiorillo et al. 2016). In Messina town, only few millimeters of rainfall were recorded.

To improve the rainfall spatial distribution on 22nd November 2011, rain gauge data have been integrated with data from the TRMM satellite platform (Tropical Rainfall Measuring Mission-NASA). Figure 6 shows that the storm event of 22nd November 2011 is characterized by two rainy centers, elongated in the direction of South–West and North–East, one located transversely to Longano, Idria and Mela catchments and the other is in the area of Saponara catchment.

Fiorillo et al. (2016) carried out statistical analyses on the available historical data of Castroreale rain gauge; in particular, the annual maxima of hourly rainfall were transformed in the standardized values, enabling definitions of several categories of the intensity of storms, similar to Standard Precipitation Index of McKee et al. (1993). After this transformation, the storm of 22nd November 2011 was classified as "extreme" and was the most intense in the historical series for all rainfall durations (1, 3, 6, 12 and 24 h), period 1930–2011.

Methods used

The Leaky Barrel Model (Wilson and Wiezoreck 1995) has been used to investigate the role of rainfall on slope stability in the absence of any field measurements of the pore pressure in the colluvial mantle. This is a mono-dimensional model which allows to fix a threshold for landslide initiation, on the basis of rainfall records. Because of its simplicity, this model cannot describe the complexity of slope hydrology during a storm, but it allows to overcome the difficulties connected with the absence of hydrological monitoring data.

In this model, the rainfall intensity is transformed in the pore-water pressures, which can trigger slope failures in shallow colluvium; the simulation is carried out by the

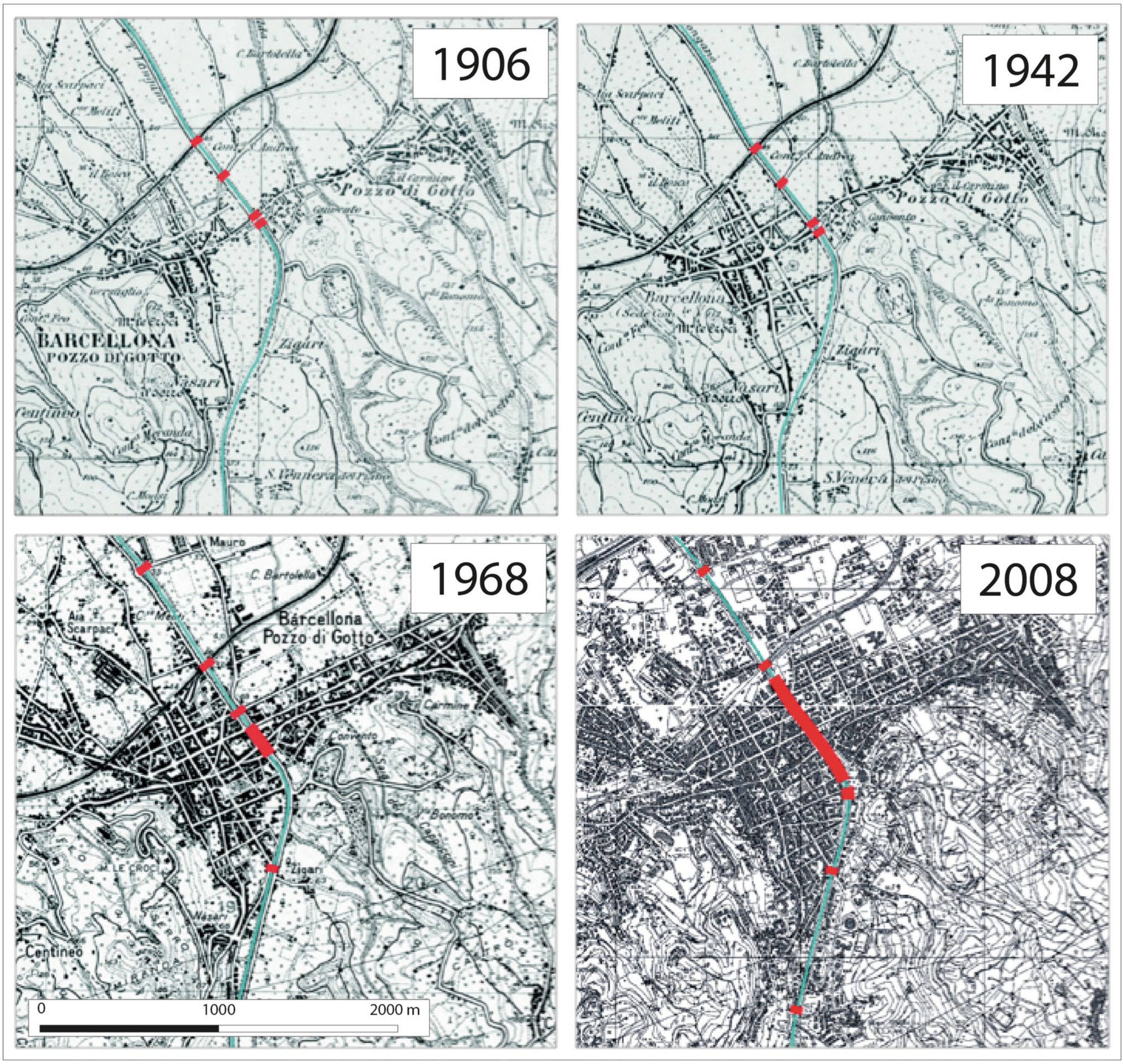

Fig. 3 Urban expansion of Barcellona Pozzo di Gotto as reported by Istituto Geografico Militare Italiano (IGMI), topographic map, scale 1:25:000; the added red lines indicate the bridges (and the covered sections) of Longano creek

hourly rainfall distribution. In particular, an amount of rain water, Z (mm), is assumed to be temporarily retained within a hillslope during periods of heavy rainfall. During each increment (for example, 1 h), the incoming rainfall, I (mm/h), is added to the amount retained, Z, but an amount is also subtracted for "drainage". The net rate of change of retained water may be expressed as a linear first-order differential equation (Wilson and Wiezoreck 1995):

$$\frac{Z}{\mathrm{d}t} = I(t) - K_{\mathrm{d}} \cdot Z \tag{1}$$

where K_{d} is the drainage coefficient, assumed to be a constant value for a given location, and has a dimension $[\mathrm{T}^{-1}]$. Under a constant rainfall intensity, I_{o}, the retained rain water level will approach a steady-state equilibrium with a value, $Z_{\mathrm{o}} = I_{\mathrm{o}}/K_{\mathrm{d}}$. Storms with the same total amount of rainfall may have different maximum values of Z, ($Z_{\max}$), which is a function of rainfall distribution over time and the K_{d} value. For storms that occur after the field capacity of the soil has been reached, the model may be applied directly.

To evaluate K_{d}, the model may be calibrated by comparing Z response to observations of the timing of debris-flow

Fig. 4 **a** Longano torrent in urban area of Barcellona Pozzo di Gotto and **b** during the flood of 2011. **c, d** Landslides and wood mobilization in the Longano catchment

activity from eyewitness accounts (Fiorillo and Wilson 2004). During this period, the water retained, Z, has to be higher with respect to a value Z_t, which is the minimum amount of retained water used to trigger the landslides. During the period of landslide initiation, the value Z has to be $Z > Z_t$. Whereas, outside this time interval (before and after landslide initiation) Z has to be $Z < Z_t$. The model can be calibrated based on this by finding the value of Z_t and fixing K_d.

To estimate the river discharge for the main floods that occurred during the main storms, the recorded rainfall has

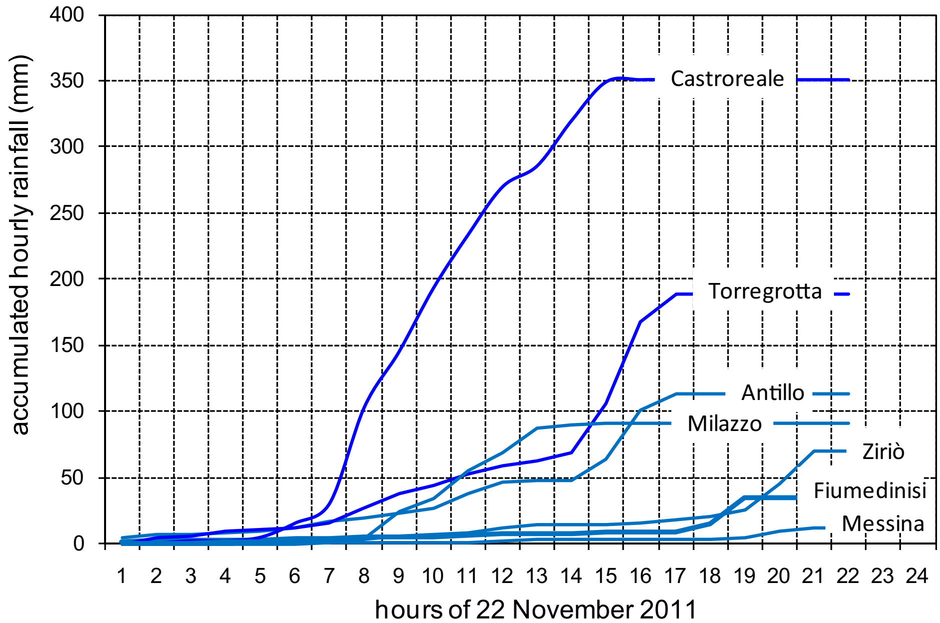

Fig. 5 Hourly rainfall of 22 November 2011 for several rain gauges

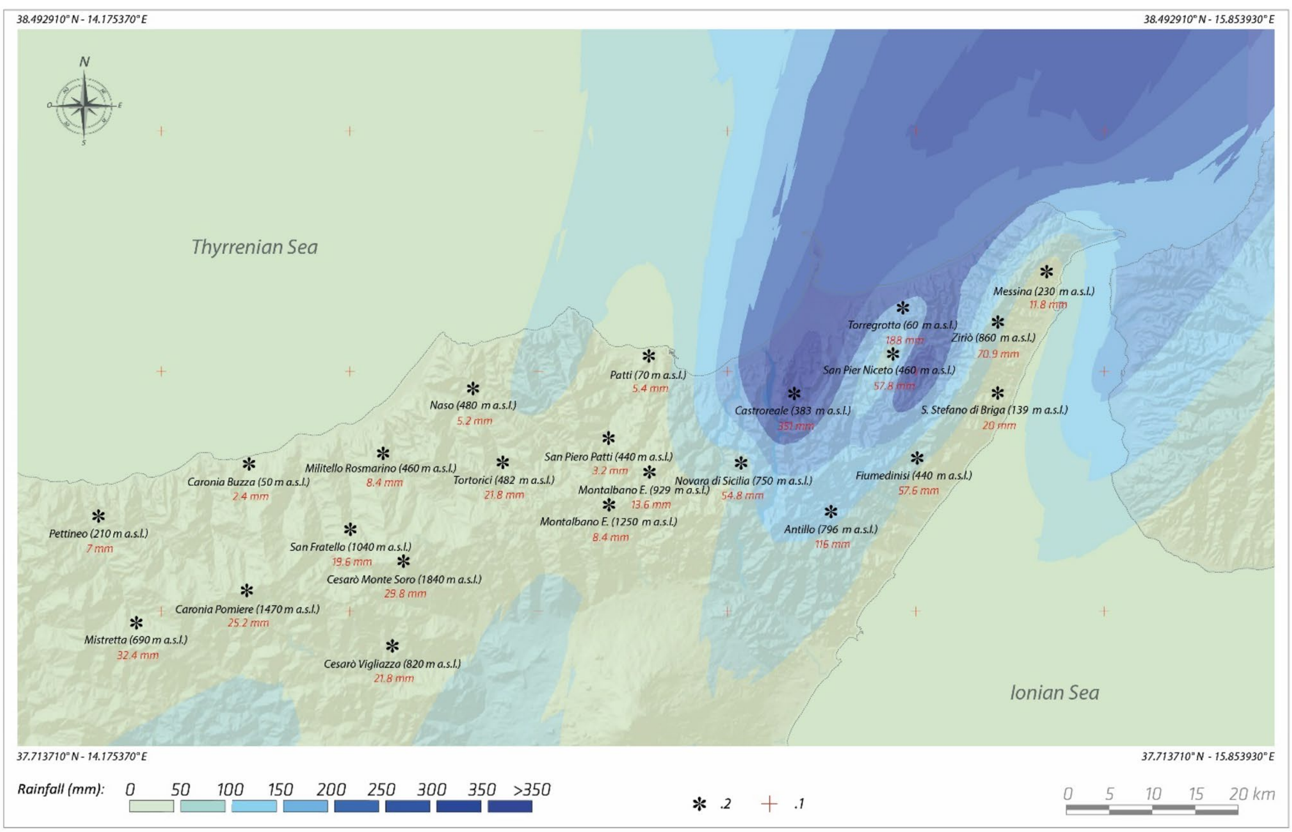

Fig. 6 Rainfall of 22 November 2011 reconstructed by kriging interpolation on available rain gauges (2) and TRMM satellite data (1) (Fiorillo et al. 2016)

been transformed in the discharge using the HEC-HMS model (HEC-HMS 2000). This is a free software, working in a GIS environment, which allows to simulate the river discharge, on the basis of some geometric and hydraulic features of its catchment. Analysis has been focused on the Longano torrent, which led to the main flood phenomena in the Barcellona Pozzo di Gotto urban area. As the discharge measurements in the torrent are missing, the use of the HEC-HMS model helps to understand the development of flood during a storm, rather than the exact estimation of the discharge, which depend on many unknown parameters. However, this model allows to compare floods induced by several storms that occurred during the recent years.

The HEC-HMS model is based on two main components: (1) the Basin model and the (2) Meteorological model. The first component defines the main geometrical features of the catchment, as the sub-basins and the junction points. The second component estimates the rainfall distribution on the catchment; considering the limited extension of the catchment (about 30 km^2), the same rainfall distribution has been used for all sub-basins.

The loss of the basin has been estimated by the SCS Curve Number module and the transformation of the rainfall in the discharge has been carried out by the SCS Unit Hydrograph module.

Using a detailed Digital Elevation Model (DEM) with resolution of 2×2 m, the preferential paths of runoff have been defined; the flood wave at the end of the catchment has been estimated by the Routing Method Lag module.

The landslides of 22nd November, 2011

The storm of 22nd November, 2011 induced thousands of landslides along the steep slopes of the Peloritani mountains. Two main sectors were particularly affected by the high density of landslides, and are located both in the middle catchment of the Saponara torrent and in the catchment of Mela and Longano torrents.

A detailed survey of landslides was conducted in the field, and by satellite photos.

The landslides resulted from mobilization of the soil cover on steep slopes, and evolved into debris flows. In particular, many of them originated from translational slides, thereafter evolving as complex landslides (Cruden and Varnes 1996). Scars left in the source area of debris flows were characterized by a spoon shape; however, in some cases, the initial slide occurred as tabular masses, due to the presence of net discontinuity between soil cover and substratum. The thickness of the summital slide was around 1–2 m, and after the initial detachment, the moving landslide material has eroded the soil cover down to the bedrock, greatly increasing its volume; as observed during the surveys and from eyewitnesses, the landslide transforms into a debris avalanche, with increasing velocity and volume up to the base of the slope. Similar to the occurrence in many zones of the Longano catchment, the tree trunks uprooted along the slopes (Fig. 4b, c) were carried by the debris flows up to the torrent; mud and debris were transported by water together with a large amount of wood, which caused the blockage of the torrent flow in correspondence to bridges of Barcellona Pozzo di Gotto.

On the basis of field observations, most landslides of 22nd November, 2011 occurred as debris slides, thereafter, evolving into debris avalanche and to debris flow, similar to that described by Fiorillo et al. (2001) for Campanian debris flows.

The landslide of Saponara catchment

Over 1800 landslide initiation zones were mapped in the Saponara catchment, of which some of them directly hit the urban area of Saponara and several villages (Figs. 7, 8).

The distribution of the landslides highlights how their development is concentrated along the slope of Saponara torrent up to a ground elevation of 400 m a.s.l., above which only few landslides were observed. These characteristics of the landslide distribution, supported by the rainfall data of high-elevated rain gauges, suggests that the 22nd November, 2011 storm had its maximum rainfall height along the foothill sector of the Saponara catchment, and that it rapidly diminished in intensity uphill. The rain gauge of San Pier Niceto, located between Castroreale and Saponara at 460 m a.s.l. recorded only 57.8 mm on 22nd November 2011; the rain gauge of Zirió, located at 860 m a.s.l. and 2.5 km far from the landslide area of Saponara, recorded 76.8 mm .

Considering the rainfall data recorded at different rain gauges (Figs. 5, 6), the storm of 22nd November 2011 moved towards the northeast; in Barcellona Pozzo di Gotto, the torrent flood ends at 14:30. In Torregrotta, the rainfall peak is observed between 15:00 and 17:00. In Saponara village, it is possible to hypothesize high hourly peak rainfall (above 40 mm/h) between 16:00 and 19:00; toward Sud, the maximum rainfall occurred 1 h later (between 17.00 and 20.00), according to landslides that occurred in the S. Pietro fraction and to rainfall recorded in Zirió rain gauge.

Considering the rainfall data recorded, and reports from eyewitnesses, rainfall that occurred in Saponara could be compared with that of Torregrotta rain gauge, but increases with final hourly peaks.

The urban area of Saponara was also hit by similar landslides during the storm on 2nd November 2010, and technical documents indicate that debris flows occurred also on 1972, 1973, 1978 and 1996.

Fig. 7 Landslides occurred in the Saponara catchment, S.Pietro locality

The landslides of Longano catchment

Landslides developed diffusely along the steep slopes of Longano catchment; many landslides also occurred in the nearby catchments of Idria and Mela torrent (Figs. 9, 10).

In this large area, more than 1200 landslide initiations were mapped, and some of them hit directly villages of the municipal area of Barcellona Pozzo di Gotto. Many debris avalanches and debris flows reached Case Migliardo, Femmina Morta and Varela villages, causing the destruction of numerous houses. However, most of the landslides occurred in forested areas, causing damage to local road network. These landslides caused the uprooting of trees and the arrival of thousands of tree trunks in Longano torrent, which obstructed the flow of river in correspondence to the first bridges in the urban area of Barcellona; the inundation of the city center was induced by this obstruction of the torrent.

Based on news obtained from several witness, landslides occurred during the entire duration of the storm, starting from the morning 09:20 (Pio La Torre Street, Castroreale), and up to 16:00 (S. Venera Bosco locality) at the end of storm. Most of the landslides occurred in the upper part of the Longano catchment (Fig. 9); their activation caused the arrival of thousands of tree trunks in the Barcellona village (Fig. 10).

Hydrological analyses and discussion

Figure 11 shows the hyetograms of the 22nd November 2011 storm, and the retained water variable, Z, of the Leaky Barrel Model deduced for different drainage discharge coefficients, K_d. Based on knowledge of the time of failure, a value of $K_d = 0.4\ h^{-1}$ and $Z_t = 73$ mm was fixed. As shown in Table 1, the 22nd November 2011 storm caused conditions for $Z > Z_t$ (landslide occurrences) between 09 and 16 h (7 h).

After calibration of the model, it can be assumed that the number of landslides induced is connected to the difference $Z - Z_t$, as it provides a severity of the hydrological conditions for shallow landslides during the storm (Fiorillo and Wilson 2004). Following this assumption, the number of induced landslides for each hour, N_i, has been expressed in terms of fraction of the total amount,

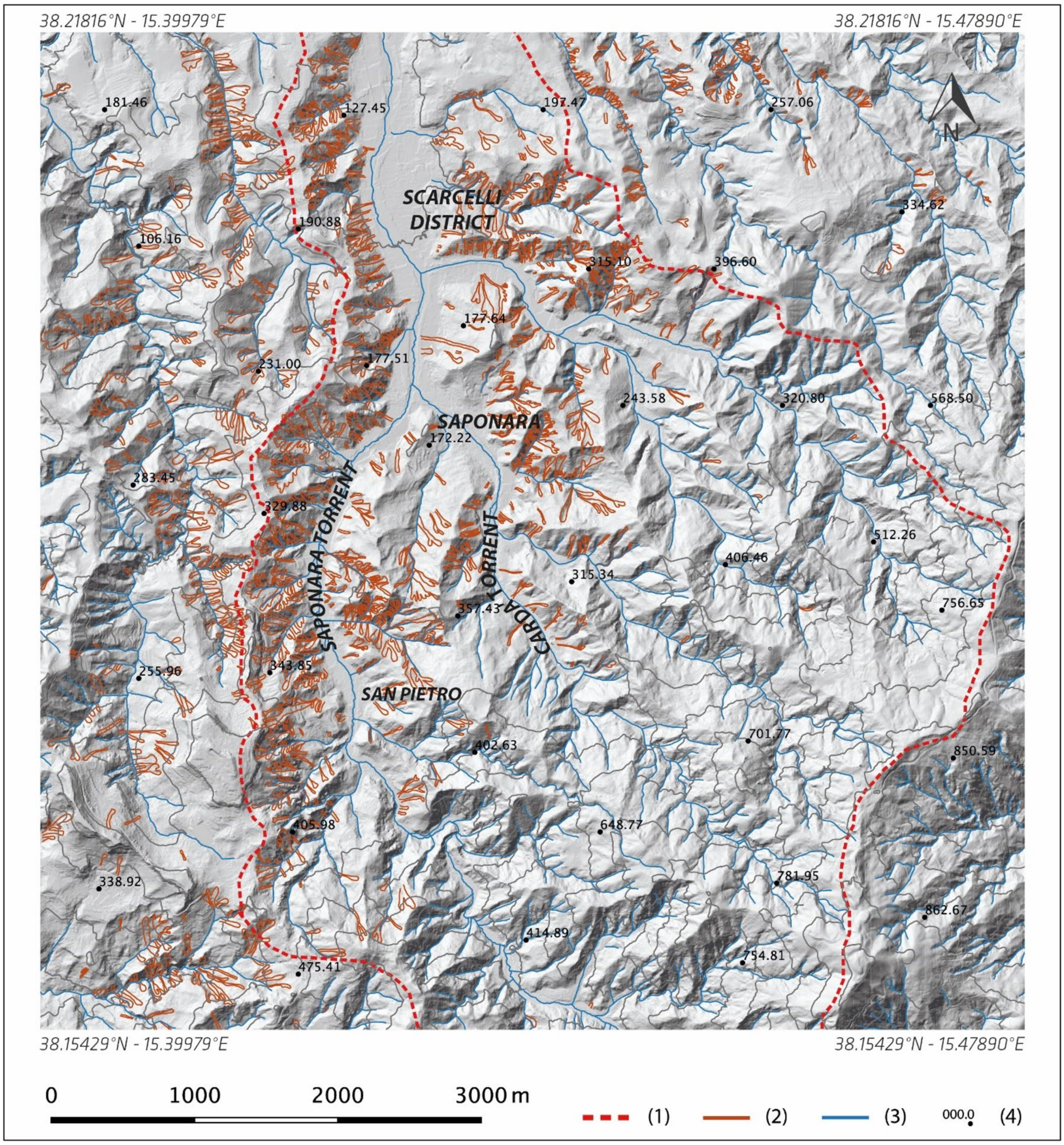

Fig. 8 Landslides occurred on 22 November 2011 in the Saponara catchment, mapped by field surveys and satellite imagine. (1) Saponara torrent basin limit; (2) landslide boundary; (3) drainage line; (4) ground elevation m a.s.l.

proportional to the difference $(Z - Z_t)_i$ of each hour, i, of the time interval during which occurs $Z > Z_t$, by the following relation:

$$N_i = \frac{(Z - Z_t)_i}{\sum_{i=1}^{i=n} (Z - Z_t)_i} \tag{2}$$

with n number of hours during which $Z > Z_t$ ($n = 7$). In Fig. 11b the number of induced landslide, N_i, is expressed in percentage; most of the landslides, about 73%, occurred between 10:00 and 12:00. This result is in line with reports from several eye witnesses which states that most of the landslides in the Mela and Longano catchments are activated at the end of this time interval.

Rain gauges are missing in the Saponara catchment. Using the hourly rainfall of Torregrotta rain gauge and the values of Z_t and K_d found for the Castroreale rain gauge, the values of Z would reach the maximum value Z_{max} = 78 mm on 16:30, and conditions for $Z > Z_t$ (landslide occurrences) only last for 1 h (between 16:00 and 17:00). This suggests that the rainfall in the Saponara landslide area was higher than that recorded at Torregrotta rain gauge, as described by Fiorillo et al. (2016).

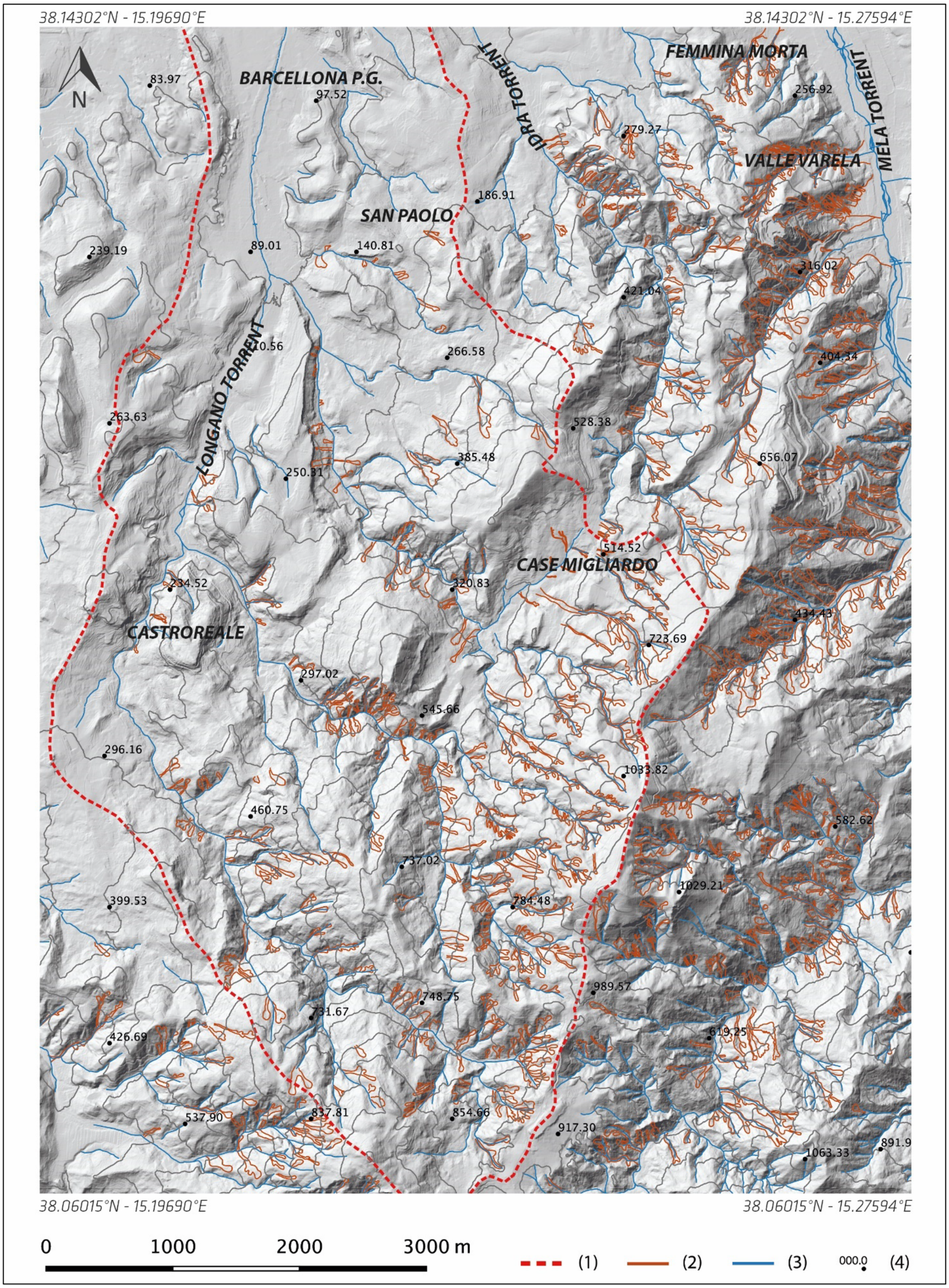

Fig. 9 Landslides occurred on 22 November 2011 in the Longano catchment (and part of Idria and Mela catchments), mapped by field surveys and satellite images. (1) Longano torrent basin limit; (2) landslide boundary; (3) drainage line; (4) ground elevation, m a.s.l

Fig. 10 Barcellona Pozzo di Gotto. **a** Debris flow hit the Varela locality. **b, c** Wood deposited in the urban area

Considering rainfall which fell since the beginning of the hydrological year (1st September 2010; Fig. 12), there is need to outline that an intense storm on the Peloritani ridge occurred on 9th November, 2011 (13 days before the storm of 22nd November, 2011) as recorded at Antillo rain gauge (300 mm; 796 m a.s.l.) and Ziriò rain gauge (171 mm; 860 m a.s.l.). This storm which occurred on the 9th of November 2011 did not induce landslides, but caused floods of several torrents, and the Saponara torrent overflows at different points. Differently, the storm of 22nd November 2011 was not intense at high-elevated ground surface of the Saponara catchment (Ziriò rain

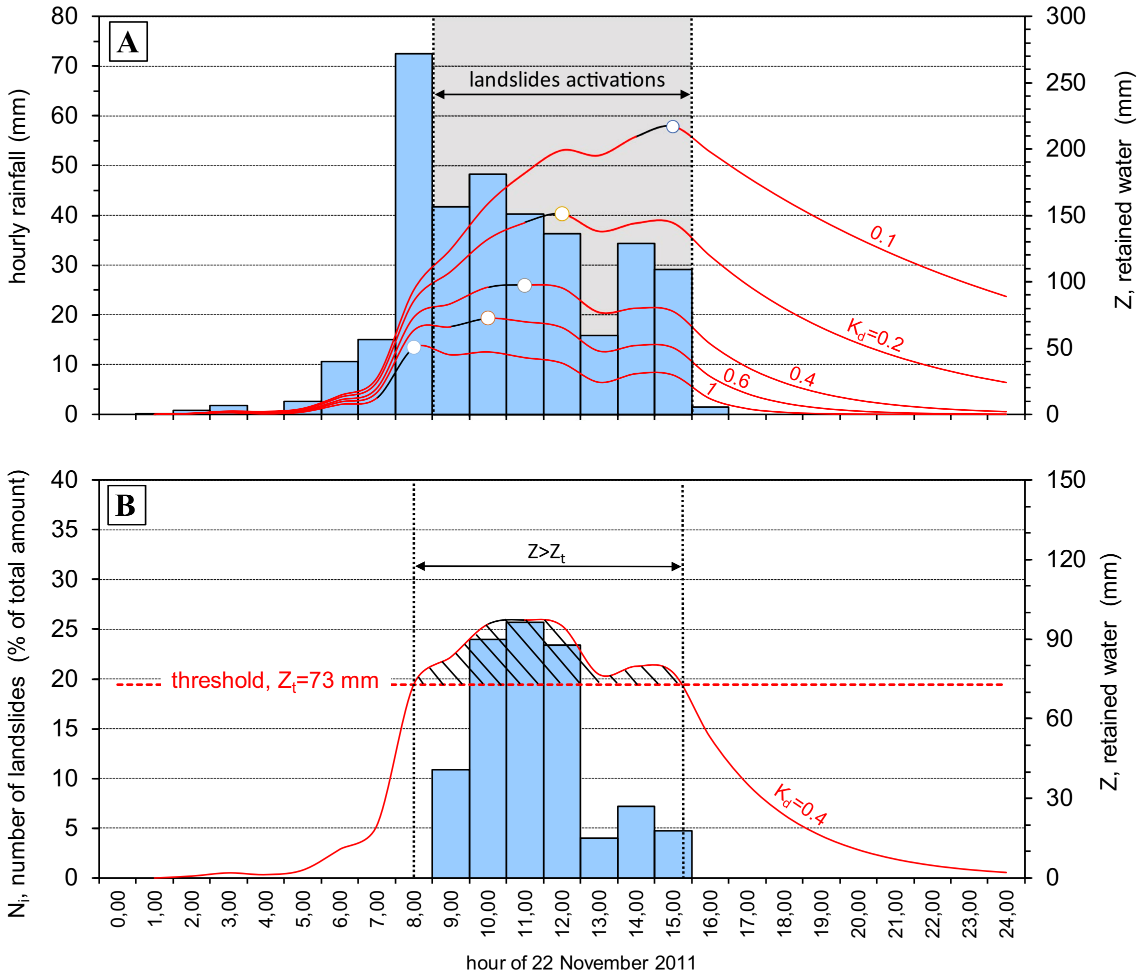

Fig. 11 **a** Hourly rainfall of the 22 November 2011 storm (Castroreale rain gauge) and retained rainfall, Z, as a function of the drainage coefficient, K_d, computed by Leaky Barrel Model (Eq. 1). The white circle is the maximum value reached, Z_{max}, for each K_d value. The time interval of shallow landslide activation has been used to fix K_d and the threshold for landslide initiation, Z_t. **b** Number of induced landslides, N_i, computed as function of the $Z_{max} - Z_t$ (Eq. 2); the time interval during which $Z > Z_t$ (dashed area), corresponds approximately to landslides activations time

Table 1 Results from Leaky Barrel Model application (Castroreale rain gauge): K_d, discharge coefficient; Z_t, minimum retained rainfall needed for debris-slide initiation; Z_{max}, maximum value of retained water; T, period of time for $Z > Z_t$

Storm	k_d (h^{-1})	Z_t (mm)	Z_{max} (mm)	$Z_{max} - Z_t$ (mm)	T (h)
22 Nov 2011	1	50.3	50.3	0.0	0
	0.6	63.6	72.7	9.1	4
	0.4	**73.0**	**97.2**	**24.3**	**7**
	0.2	85.6	151.3	65.7	9
	0.1	93.7	217.1	123.3	15
2 Nov 2010	0.4	–	68.7	–	–
12 Dec 2008	0.4	73.0	85.4	12.4	2

Bold numbers mean the selected values by the calibrated model

gauge recorded 71 mm) and, in fact, the landslides were induced mainly below 400 m a.s.l. (Fig. 8). Thus, in the Saponara catchment, the flood of 10 November 2011 may have been more intense than 22 November 2011.

A detailed analysis of discharge has been carried out for the Longano torrent, where the rainfall of recent storms (including that of 22nd November, 2011) has been recorded at Castroreale rain gauge (383 m a.s.l), located in the upper-median zone of the Longano catchment (ground elevation mean is 423 m a.s.l.). Landslides occurred up to watershed of this catchment, which reaches 900 m a.s.l., indicating that intense rainfall fell on the entire catchment, differently as occurred in the Saponara catchment. The rainfall recorded at Castroreale rain gauge can be assumed over the entire Longano catchment, and appears useful to model the torrent discharge by hydrological model simulation.

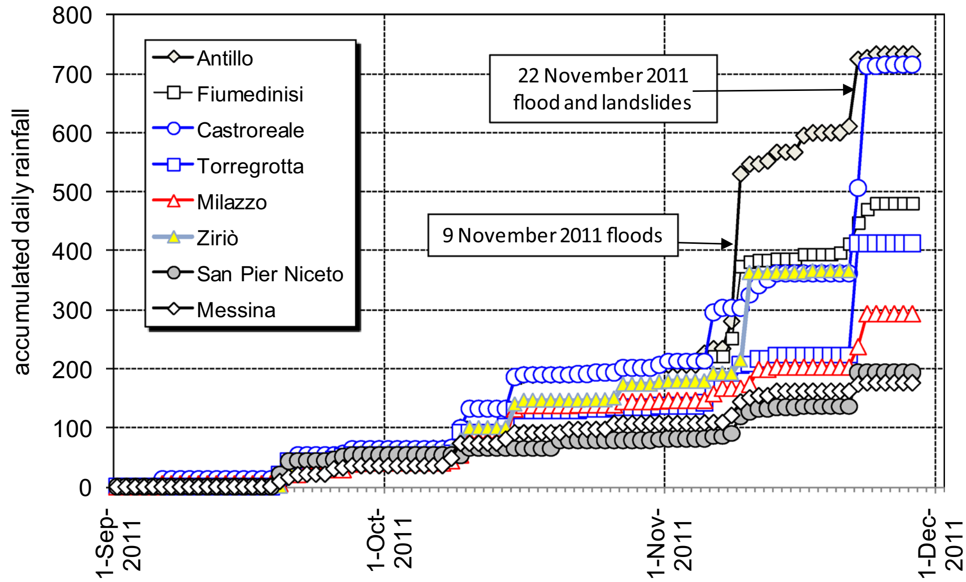

Fig. 12 Daily rainfall (accumulated) recorded at several rain gauges since 1st September 2011

Table 2 Main geometrical and hydrological features of the sub-basin of Longano catchment

Sub-basin	Mean of ground elevation (m a.s.l.)	Area (km^2)	Curve number (–)	Time of concentration (min)
1	573	7.67	69.4	98.2
2	604	5.99	68.1	72.0
3	479	7.49	66.2	76.4
4	214	2.85	80.9	39.4
5	99	6.43	81.6	113.9
Total	423	30.44		210.2

Table 2 shows the main geometrical and hydrological features of the sub-basins of Longano catchment, used by local Basin Authority (PAI 2003). Figure 13 shows the hydrological scheme of Longano torrent used by HEC-HMS model, and time of concentration of the catchment at the mouth.

Table 3 shows the discharge estimated for the events of 22nd November 2011; 11th December, 2008; and 2nd November; 2010.

The event of 22nd November, 2011 caused the maximum discharge; at Regina Margherita bridge (urban area of Barcellona Pozzo di Gotto) the events on December 2008 and November 2010 caused a lower discharge, about 86% and 76% of that of November 2011, respectively.

Figure 14 shows the discharge simulated for the Longano torrent at Regina Margherita bridge during the 22nd November 2011 storm, and the main news items reconstructed according to newspaper and eyewitnesses. It should be noted that simulated discharge of the Longano torrent has been carried out without considering the inundation phenomena; thus, downstream the Regina Margherita bridge, the discharge simulated overestimates the actual discharge on 22nd November, 2011.

The maximum discharge on 22nd November 2011 is estimated at 11:20 in the urban area of Barcellona Pozzo di Gotto; this is in agreement with observations made by eyewitnesses in regards to the Regina Margherita bridge. The entire flow of the river could go through the section of the bridge, and only a small amount leaked because of the flow turbulence. About 2 h later (on 13:30), when torrent discharge decreased to 270 m^3/s (about 76% of the peak discharge), thousands of tree trunks carried by the water flow reached the urban stretch of the river and blocked the section of the Regina Margherita bridge. This caused the inundation of the urban area of Barcellona Pozzo di Gotto as testified by numerous videos and eyewitnesses.

In smaller catchments, characterized by lower concentration time (less than 1 h), floods have occurred earlier, between 08:00 and 09:00, as a gully of the Idria catchment (Saia Bizzarro), which led to the inundation of a large area of Pozzo Perla locality.

As previously described, the landslide activity can be restricted to a time interval, 09.00–16.00, but the most critical conditions occurred between 10:00 and 12.00 when 73% of the landslides became activated; probably most of the landslides were activated at the end of this time interval, because of the shift between the most severe hydrological conditions and the initiation of the shallow landslides; this circumstance occurs as a result of the not so perfect relationship existing between cause and effect in the landslide phenomena (Doglioni et al. 2012).

The concentration of the landslide initiations at the end of the time interval 10:00–12:00 explains the thousands of tree trunks that arrived at 13:30 in correspondence to the first bridge of urban area of the Barcellona Pozzo di Gotto.

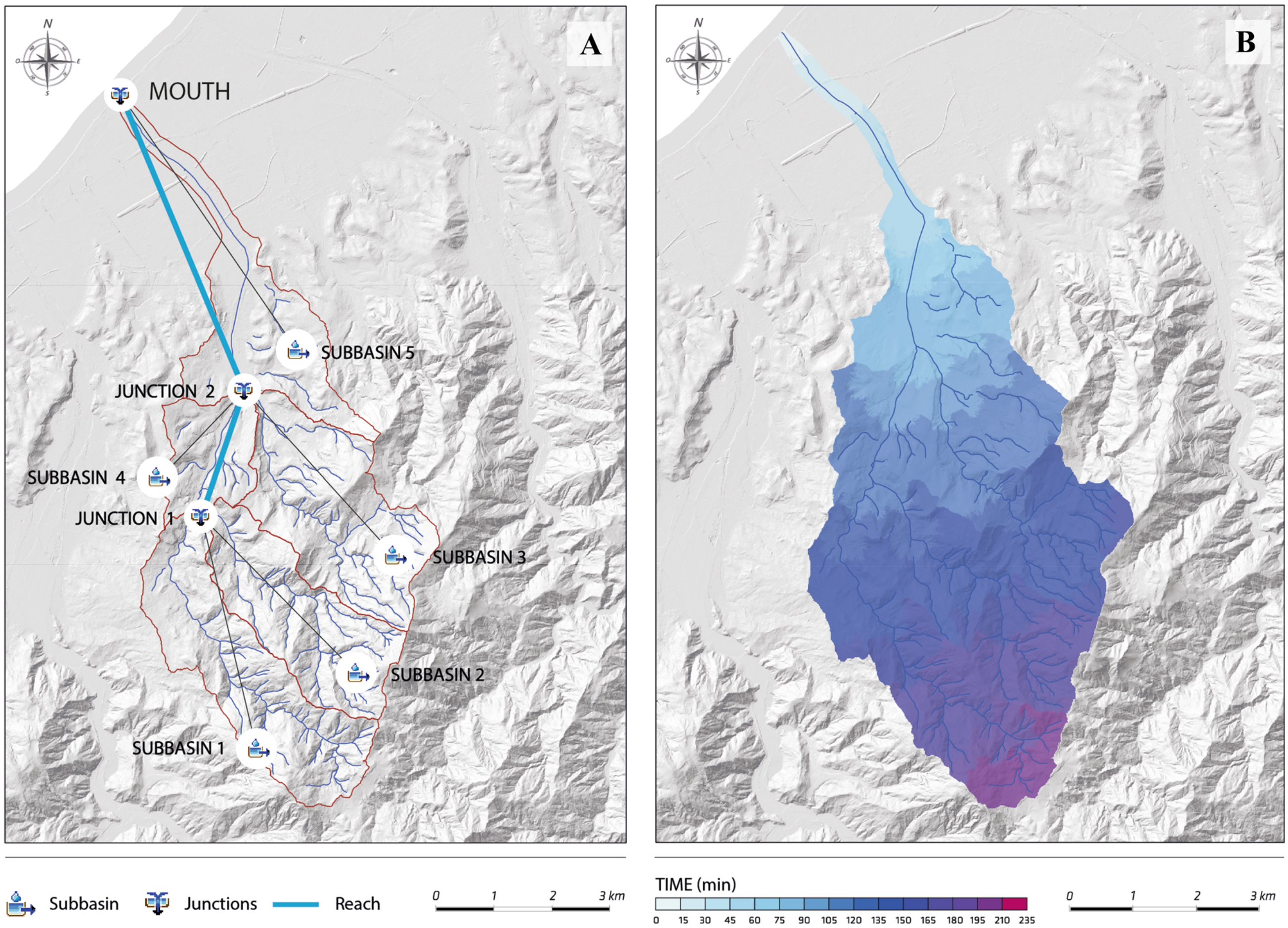

Fig. 13 **a** Hydrological scheme of Longano torrent used by HEC-HMS model; **b** time of concentration of Longano catchment at the mouth

Table 3 Longano torrent discharge computed by HEC-HMS model, in correspondence of specific sections, and for events of 22 November 2011, 2 November 2010 and 11 December 2008

Section	22 Nov 2011		2 Nov 2010		11 Dec 2008	
	Max (m^3/s)	Time	Max (m^3/s)	Time	Max (m^3/s)	Time
Sub-basin 1	92.4	10:40	67.4	08:30	81.8	07:10
Sub-basin 2	76.6	10:20	58.9	07:45	69	06:40
Junction 1	168.4	10:30	125.4	08:16	150.3	07:00
Sub-basin 3	95.0	10:20	72.2	07:50	85.3	06:45
Sub-basin 4	45.1	08:20	35.5	07:15	37.6	06:15
Junction 2	295.8	10:40	224.2	08:15	266	07:05
Sub-basin 5	74.5	11:00	53.4	08:55	65.3	07:15
Regina Margherita bridge	350.6	11:20	265.9	09:10	300.6	07:50
Mouth	368.7	12:00	276.1	09:30	316.6	08:20

The time difference between the peak discharge and the landslide timing shown in Fig. 14, about 2 h, is compatible with the travel time between the main landslide zone of the Longano catchment and the urban area. Thus, most of the landslides occurred almost at the end of the storm, after more than 75% of the total accumulated rainfall, which caused the observed shift between peak discharge of the torrent and the arrival of woods. In other geomorphologic context, Tatra mountains (southern Poland), Ruiz-Villanueva et al. (2016) found a contrary behavior, of which the peak of wood transport is generally reached before the flood peak.

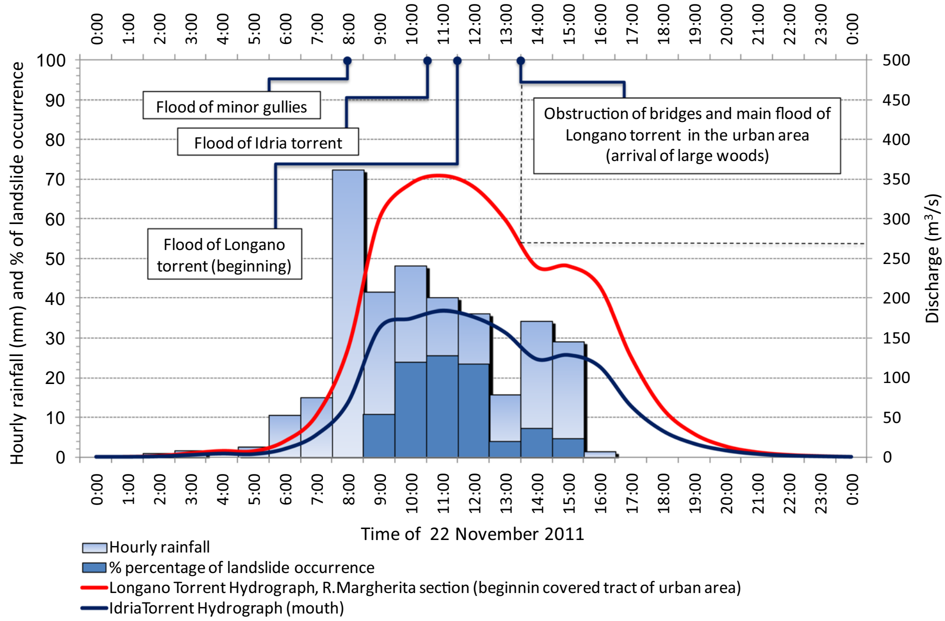

Fig. 14 Results of torrent discharge simulations using hourly rainfall recorded at Castroreale rain gauge, and highlights of 22 November 2011 flood in Barcellona P.G. urban area

Conclusion

The Peloritani ridge is characterized by small catchments, where the local geometrical and morphological conditions cause a rapid increase in the river discharge, with concentration times of few hours. In these geomorphologic environments, intense storms can cause disastrous flash floods and landslides; the initial torrent discharge of few liters/sec can reach in 1–2 h hundreds or thousands of m^3/s. In most minor gullies, the concentration time can be lower than 1 h, and flash floods can develop rapidly.

Many torrents cross urban areas, where several bridges were built in the previous decades. The main inundation risk of these areas is connected to the development of landslides which can produce large woods, and the consequent obstruction of the torrent flow in correspondence to bridges.

This condition occurred in Barcellona Pozzo di Gotto urban area on 22nd November 2011, after the activation of numerous debris flows in the mountain area of the Longano catchment. Locally a continuous removal of the materials deposited in the riverbeds is necessary to limit obstacles to the water flow during floods. However, for some sectors, the widening of the hydraulic section of the stream should be carefully considered.

It has been outlined how the peak discharge of the Longano torrent in the urban area occurred 2 h before the arrival of the large amount of wood, and locally this circumstance reduced the damages induced by the flash flood of 22nd November, 2011. Thus, the time of landslide activation play an important role on the risk of inundation of downstream areas; its estimation can be useful in evaluating the river obstruction, and it has been the main objective of this study. The worst condition is when the river obstruction occurs before the peak discharge of the torrent. However, even if the peak discharge is connected to the time of concentration of basins, it depends on rainfall distribution within the period, which controls also the time of landslide activations. The distance between landslides zone and obstruction point of rivers appears to be another factor controlling the possible synchronism between discharge peak of torrents and arrival of large woods.

The use of hydrological models, as the Leaky Barrel and HEC-HMS models could be used to understand the relationship between flash floods and landslides activation, and could help one estimate the risk of inundation caused by a large amount of wood in ungauged catchments.

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