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Geomorphological Instability Triggered by Heavy Rainfall: Examples in the Abruzzi Region (Central Italy)

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1. Introduction

Heavy rainfall is one of the most important triggering causes of landslides - particularly in Mediterranean areas, that are characterised by moderate to low annual precipitation and, occasionally, by high precipitation intensity (up to >200mm/day)-. In agricultural or poorly vegetated hilly landscapes - particularly when characterised by clayey lithologies - heavy rainfall triggers very rapid geomorphological processes, such as floods, soil erosion (rill, gullies) and landslides (rapid earthflows) inducing strong erosion rates on the hilly landscape, sediment transport and sedimentation along the alluvial plains and at the mouths of rivers.

The distribution of geomorphological processes and landforms triggered by these events is variable and controlled by several geological, geomorphological, meteorological and land-use factors. In this work, we analyse the landforms triggered by heavy rainfall in three case studies from the Abruzzi region in Central Italy.

Over the last ten years, the Abruzzi region was affected by several heavy rainfall events. Three of them have had daily rainfall > 100 mm and >200 mm over few days: 1) on 23-25 January 2003 (in the whole region), 2) on 6-7 October 2007 (in a small part of the hilly and coastal Teramo area), and 3) on 1-2 March 2011 (in the hilly and coastal Teramo and Pescara area). These events have triggered different types of geomorphological instability: landslides, soil erosion and flooding. The distribution and types of instabilities and landforms is different in the three cases.

The 2003, 2007 and 2011, heavy rainfall events were analysed with regard to their meteorological aspects, and geological and geomorphological features, highlighting both common and distinct geomorphological effects on the landscape.

The meteorological aspects were studied by processing a >40 pluviometric station database. The data processing enabled the analysis and comparison of hourly rainfall intensity, cumulative rainfall, daily rainfall, monthly rainfall and previous monthly rainfall.

Geomorphological effects of heavy rainfall were analysed through a field surveys, aerial photo analysis and inventories and technical reports, mapping the distribution of the landslides, soil erosion and flooding.

This work allowed us to highlight that these types of methods, investigations and data are basic in applied studies for the stabilisation and management of slopes and minor or major drainage basins, and for general land management. Only a high level of knowledge of geomorphological instability, connected to drainage, geological-geomorphological and morphostructural features and to meteorological events - particularly when joined to geotechnical data - allows effective stabilisation and management plans.

Finally, these types of studies are basic and complementary to recent methods of the investigation and mapping of land sensitivity to such geomorphological processes as landslides, soil erosion and desertification, etc. They allow us to define the future scenarios - which sustainable land planning and management should be based on - by taking into account the specific destination of different areas and contributing to the identification of proper sites for quarries, dumps and purification plants, or else proper areas for industry, urban expansion, thereby generally supporting the process of creating an urban plan.

2. Study area

The Abruzzi region is located in the central eastern part of the Italian peninsula along the Central Apennines (Fig. 1). The regional physiographic and morphostructural setting of Abruzzo is defined by three main orographic and morphostructural domains: the Apennine Chain, Piedmont area and the Coastal Plain (D'Alessandro et al. 2003b).

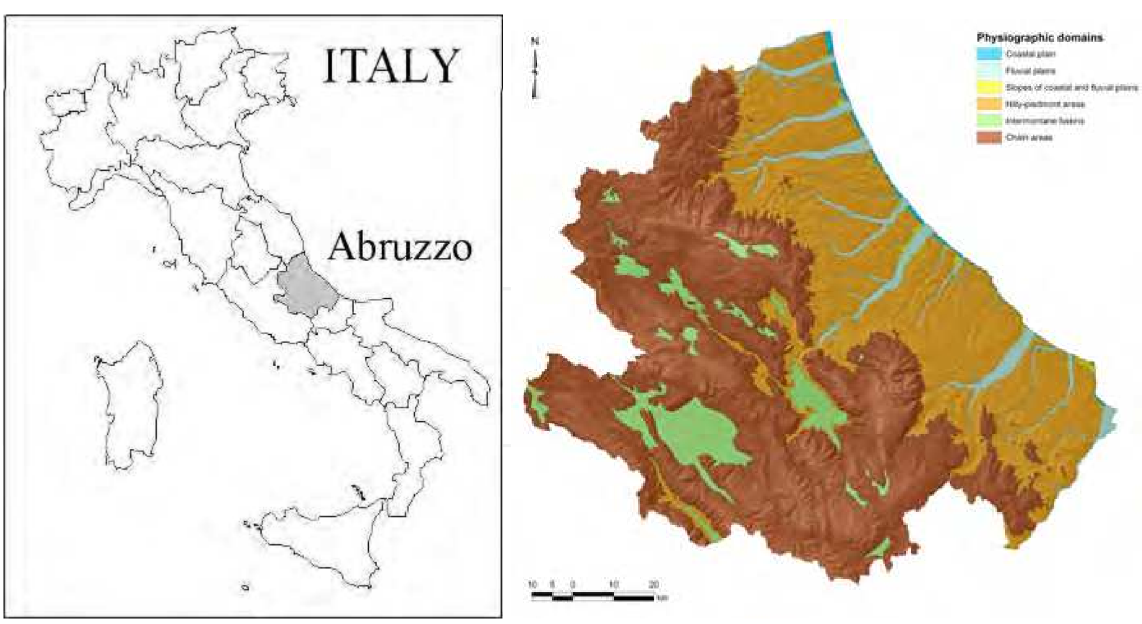

Fig. 1. Location map (a) and main physiographic domains of the Abruzzo region (b).

The hydrography of the region is characterised by three main types of rivers and hydrographic basins, mostly perpendicular to the coast: 1) rivers rising from the inner part of the chain and cutting it transversally, flowing through the piedmont area to the coast; 2) rivers rising from the front of the chain, incising the piedmont down to the coast; 3) rivers rising within the piedmont area and rapidly reaching the coast. A fourth, secondary type - but very important in heavy rainfall events - is given by small catchments flowing on the coastal slopes directly to the coastal plain.

The relief of the Apennine Chain is made up of carbonate ridges (NW-SE, NNW-SSE, N-S) separated by parallel valleys carved in terrigenous foredeep deposits or filled up with continental ones and by wide intermontane basins partially filled with Quaternary continental deposits. To the east, the relief abruptly slopes down into the piedmont area, where a hilly landscape is carved by cataclinal valleys (SW-NE) on arenaceous-pelitic thrusted and faulted successions and on a gently NE-dipping homocline of clay, sand and conglomerate deposits. Along the valleys and close to the coast, alluvial plains with fluvial and alluvial fan deposits join a narrow coastal plain.

The lithologies of the Abruzzo area are made up of different units, mostly of sedimentary origin. In the recent official Geological map of Italy (CARG Project, Geological Survey of Italy, ISPRA, 2011) the lithological units are referable to pre-orogenic units (mostly marine Meso-Cenozoic carbonate rocks), syn-orogenic units (mostly Neogene arenaceous and pelitic rocks), and post-orogenic units (marine Plio-Pleistocene clay-sand-conglomerate rocks and Quaternary clastic continental deposits). These can be grouped in a limited number of units (Fig. 2). These units are mantled, particularly in piedmont slopes and valleys, by eluvial and colluvial, cover up to several meters thick.

The structural setting of the chain area is defined by thrust ridges and faulted homocline ridges separated by tectonic valleys and basins. Main regional fault systems affect the chain area: Mio-Pliocene NW-SE to N-S low angle thrust faults, Pliocene NW-SE to NNW-SSE high angle normal faults, Quaternary (in some cases still active) NW-SE and SW-NE high angle normal faults. The piedmont area is defined in the inner part by thrust reliefs which are affected by regional NNW-SSE Pliocene thrusts and by minor high angle normal faults and, in the outer part, by a wide homocline slightly NE-dipping which is affected by minor high angle normal faults.

The geomorphological processes affecting the whole Abruzzo region are mainly fluvial slope processes and mass wasting. In the coastal areas, marine and aeolian processes are also very important, while in mountain areas karst landforms are present and the landform remnants of ancient Pleistocene glacial processes are preserved. These processes are frequently activated by the heavy rainfall events that affect the region. Fluvial processes affect the main rivers, alternating between channel incisions and flooding. The slope processes that are due to running water mostly affect the clayey and arenaceous-pelitic hills of piedmont and the coastal areas, generating outstanding landforms such as badlands (or "calanchi") and minor landforms, such as rills, gullies and mudflows (which are very common all over the hill slopes).

Mass wasting processes have induced the formation of a huge number of landslides and mass movement in the Abruzzi region, mostly affecting the hilly piedmont area as well as the chain area and - locally - the coastal one (Fig. 2; D'Alessandro et al., 2003a, 2007).

This geological and geomorphological setting is the result of a complex geological and morphostructural evolution due to the Neogene compressional deformation of different Meso-Cenozoic paleogeographic domains and Neogene foredeep domains (that formed a NE-verging thrust belt) and to Quaternary extensional tectonics and uplift (that formed

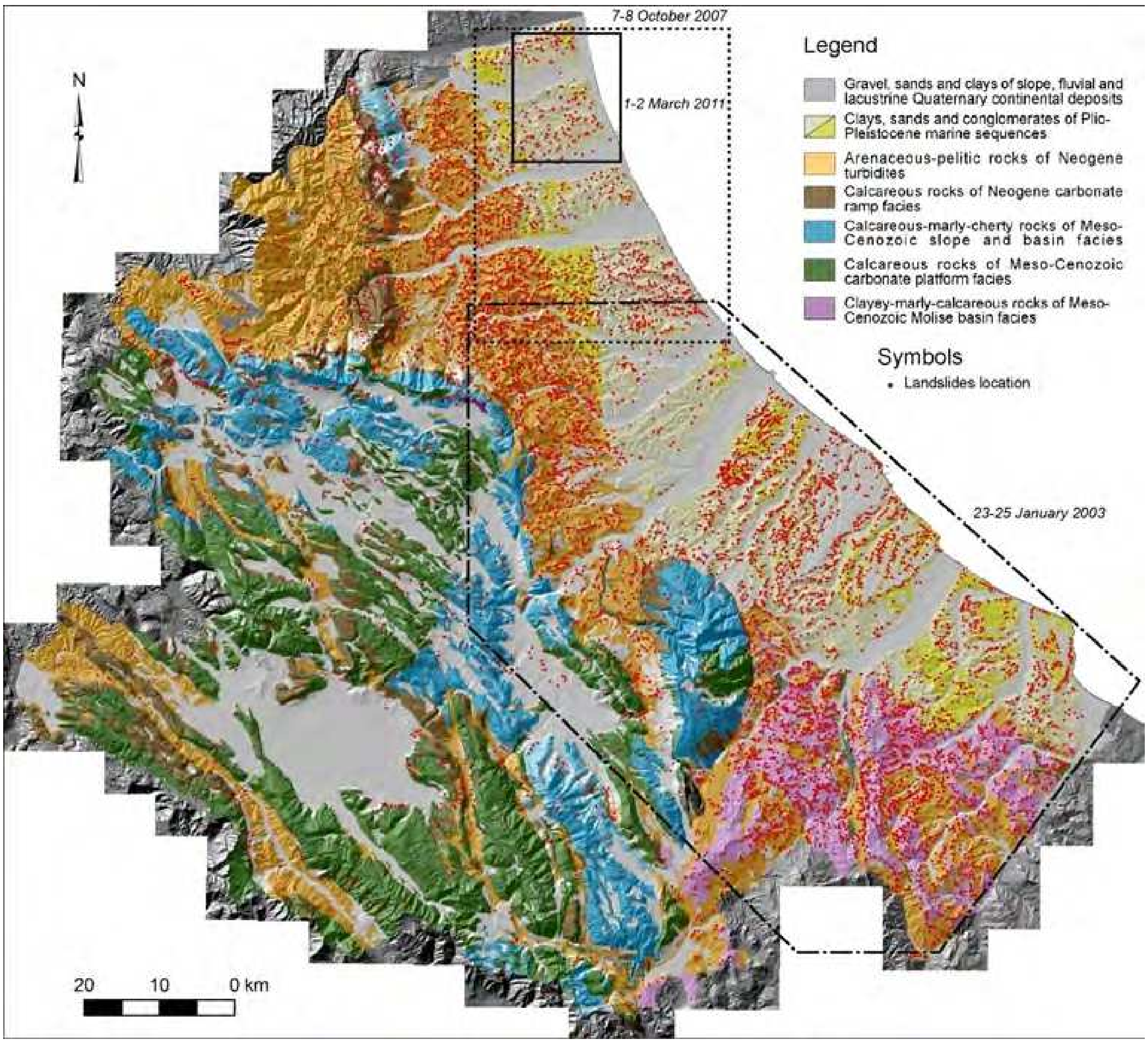

Fig. 2. Geological scheme of the Abruzzo Region (modified from Vezzani and Ghisetti, 1998; ISPRA, 2011); the red dots indicate the location of landslides (modified from Progetto IFFI, D'Alessandro et al., 2007). The black boxes indicate the approximate distribution of heavy rainfall events and related geomorphological effects: a dash-dot line for the 2003 event; a continuous line for the 2007 event; a dashed line for the 2011 event.

faulted homocline ridges, tectonic basins and homocline reliefs) (Cipollari et al., 1997; Lavecchia et al., 2004; Parotto and Praturlon., 2004; Patacca and Scandone, 2007; Cosentino et al., 2010). In the chain as a whole, the morphogenetic processes began during the last phases of thrust belt emplacement in the Early Pliocene. However, the most important morphogenetic impulses are due to the regional uplift processes and the development of extensional tectonics. After the Apennine area emerged, the activity of morphosculptural processes in the continental environment began in a variable relationship with morphostructural processes. This process, together with the morphostructural action of the extensional tectonics, has controlled the geomorphological evolution of the ridge, basin and valley of the chain and in the piedmont relief of the major fluvial valleys systems and the coastal plain. These processes also induced the mantling of slopes and valleys with a cover of Quaternary continental deposits (slope, fluvial, lacustrine and coastal deposits) (Demangeot, 1965; Bigi et al., 1996; Miccadei et al., 1999; D'Agostino et al., 2001; D'Alessandro et al., 2003b; Pizzi, 2003; Farabollini et al., 2004; Miccadei et al., 2004; Ascione et al., 2008; D'Alessandro et al., 2008).

3. Methods

This work is based on the analysis of the meteorological aspects and geomorphological effects of heavy rainfall occurring during the three events affecting the piedmont and coastal area of the Abruzzi region: 1) on 23-25 January 2003 (in the whole region), 2) on 6-7 October 2007 (in a small part of the hilly and coastal Teramo area), and 3) on 1-2 March 2011 (in the hilly and coastal Teramo and Pescara area). The analysis was performed by means of the statistical processing of precipitation data and by means of field surveys, aerial photo analysis and inventories and technical reports.

The meteorological aspects were studied processing a >40 pluviometric station database provided by Servizio Idrografico e Mareografico (Direzione Protezione Civile e Ambiente, Regione Abruzzo), including daily and monthly historical data (30-70 years) and 5-15 min pluviometric registrations for at least six days around the main events. The data processing enabled the analysis and comparison of hourly rainfall intensity, event cumulative rainfall, daily rainfall, monthly rainfall and previous monthly rainfall.

The geomorphological effects of these heavy rainfall events were analysed through field surveys, aerial photo analysis, and inventories and technical reports, and they enabled the mapping of landslides, soil erosion and flooding. The percentage and areal distribution of these effects was also analysed for the different events and so also concerned the affected lithologies, providing a contribution for the definition of the controlling factors' role.

4. Heavy rainfall events

4.1 2003 event (23-25 January)

The 2003 heavy rainfall event affected almost the entire region - but mostly the central and south-eastern part (Chieti and Pescara province and part of L'Aquila and Teramo) - for almost 72 h.

The monthly rainfall analysis shows January 2003 values very much higher than the average historical values, ranging from 50 mm to 150 mm (Fig. 3a), which in some cases is up to 3 times. Several values are >250 mm and some are > 300 mm, up to a maximum recorded value of 388 mm (Salle station; Fig. 3a). These values are close or in some cases higher than the previous historical January maximum values (Fig. 3a). Moreover, the rainfall occurred after a December which had already been very rainy, with a two month precipitation value up to 60% or even 80% of the average annual precipitation (D'ALESSANDRO et al., 2004).

The daily rainfall is high but less than it was for the 2007 and 2011 events. The higher values - up to > 120 mm - are recorded along the front of the chain, in the Maiella area (Salle, Popoli; Fig. 4a).

Hourly rainfall is not as critical as the daily, monthly and event rainfall are. The values do not exceed 9-10 mm/h (Fig. 5a). With regard to the event rainfall, the values are critical, reaching - and in some cases exceeding - 200 mm in three days (Fig. 5a).

In summary, the 2003 event can be considered to be of moderate to high intensity (~10-15 mm/hr, 80-120 mm/day) but very long (72 h), with a high cumulative rainfall (up to >200 mm) which occurred after two months of high rainfall (up to 80% of the average annual rainfall).

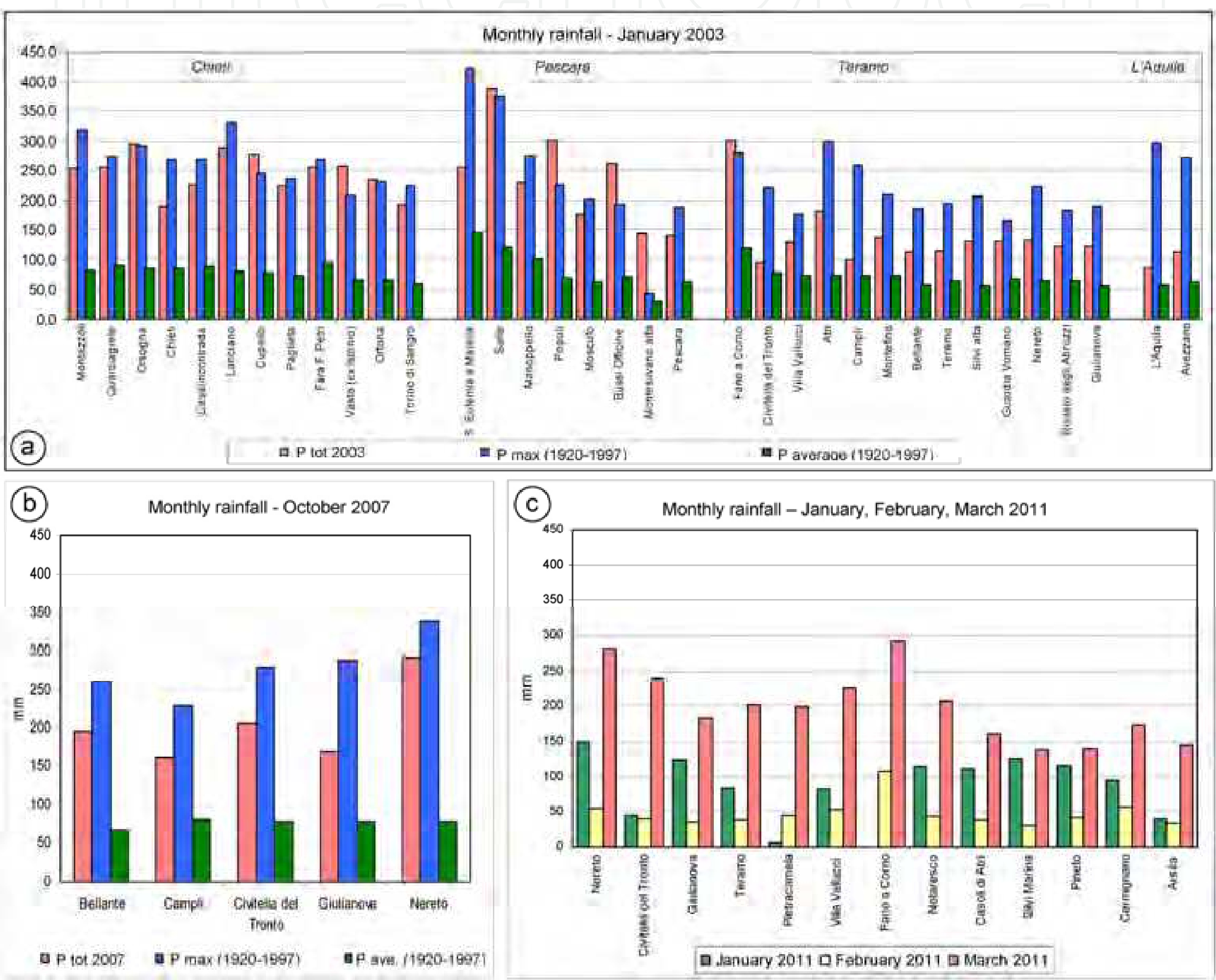

Fig. 3. Monthly rainfall: a) January rainfall histogram for the Abruzzi area; from left to right, data from the pluviometric stations of the Chieti, Pescara, Teramo and L'Aquila provinces. For each station, the total January 2003 rainfall, previous historical maximum January rainfall (1920-1997) and previous average January rainfall (1920-1997) are compared (modified form D'Alessandro et al., 2004); b) October monthly rainfall in the Teramo province's hilly and coastal areas. Comparison of the total October 2007 rainfall, the previous historical maximum October rainfall (1920-2006) and the previous average January rainfall (1920-2006); c) Monthly and daily rainfall; d) 2011 January, February and March rainfall.

4.2 2007 event (6-7 October)

The 2007 heavy rainfall event affected a local area in the northern Abruzzo (hilly and coastal Tortoreto area within the Teramo province, between the Salinello and Vibrata rivers; Fig. 2) for a short time (14-16 h).

The monthly rainfall was higher than the average historical values, ranging from 60 mm to 80 mm (Fig. 3b). The values are >150 mm and some are > 200 mm, up to the maximum recorded value of 291 mm (Nereto station; Fig. 3b). These values are close to the previous historical October maximum values (Fig. 3b). This event occurred after a relatively dry summer period.

The daily rainfall in this case was very intense, with values ~100 mm in the hilly area close to the coast, up to a maximum of 205 mm (Nereto station; Fig. 4b), even when of a short event duration. Along the coast, the recorded daily precipitation is around 60-80 mm (Fig. 4b).

The hourly rainfall was very high, with values from 10 mm/h in the coastal area to 40 mm/h in the hilly area (Nereto station; Fig. 5b).

Taking into account the short duration of the event (14-16 h), the cumulative rainfall during this time interval was also very high, with values from 60-80 mm in the coastal area to 220 mm in the hilly area (Nereto station; Fig. 5b). At the Nereto station, the 24h precipitation recurrence interval is estimated to be between 1000 to 5000 years.

In summary, the 2007 event is an extreme event (for the Mediterranean environment), with a high intensity (10-40 mm/hr, up to >200 mm/day), a high cumulative rainfall (up to 220 mm) and occurring after two months of low rainfall.

4.3 2011 event (1-2 March)

The 2011 heavy rainfall event affected a provincial area (hilly and coastal Teramo area between Vomano, Tordino, Salinello and Vibrata rivers; Fig. 2) for a moderately short time (22-26 h).

The monthly rainfall was very high compared to the average March values. The values are between 150 mm and 250 mm, up to the maximum recorded values of 282 mm (Nereto station; Fig. 3c) and 291 mm (Fano a Corno station; Fig. 3c). This event occurred after a moderately humid winter period comparable with the historical average values.

The daily rainfall was very intense - as in the 2007 event - with values of ~100-120 mm/d in the hilly area close to the coast, up to a maximum of 180 mm (Nereto station; Fig. 4c).

The hourly rainfall was again very high, with values around 15-20 mm/h in the coastal area, and up to 35 mm/h in the hilly area (Pineto and Nereto stations; Fig. 5c).

Taking into account the duration of the event (22-26 h), the cumulative rainfall during this time was again very high, with values from 100-130 mm at most of the stations up to a maximum of 211 mm in the hilly area (Nereto station; Fig. 5c). Also, in this case, at the Nereto station the 24h precipitation recurrence interval is estimated to be between 1000 to 5000 years.

In summary, the 2011 event is an extreme one (for the Mediterranean environment), although intermediate in respect of the previous ones: it affected a provincial area for a moderately short duration (22-26 h) with a high intensity (15-35 mm/h, up to >180 mm/d), high cumulative rainfall (up to 211 mm) and occurring after two months of moderate rainfall.

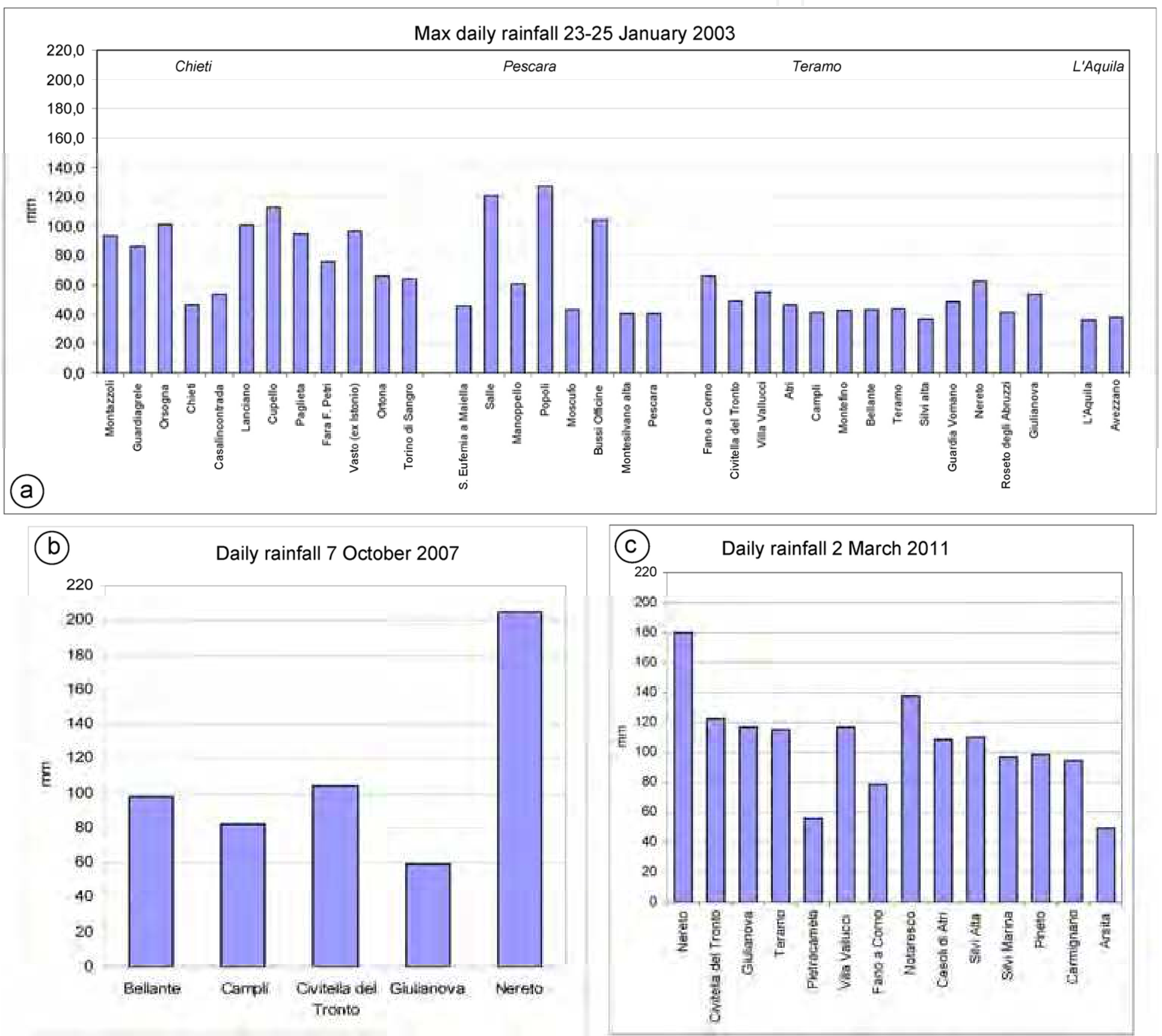

Fig. 4. Maximum daily rainfall occurred: a) on 23-25 January 2003; b) on 7 October 2007; c) on 2 March 2011.

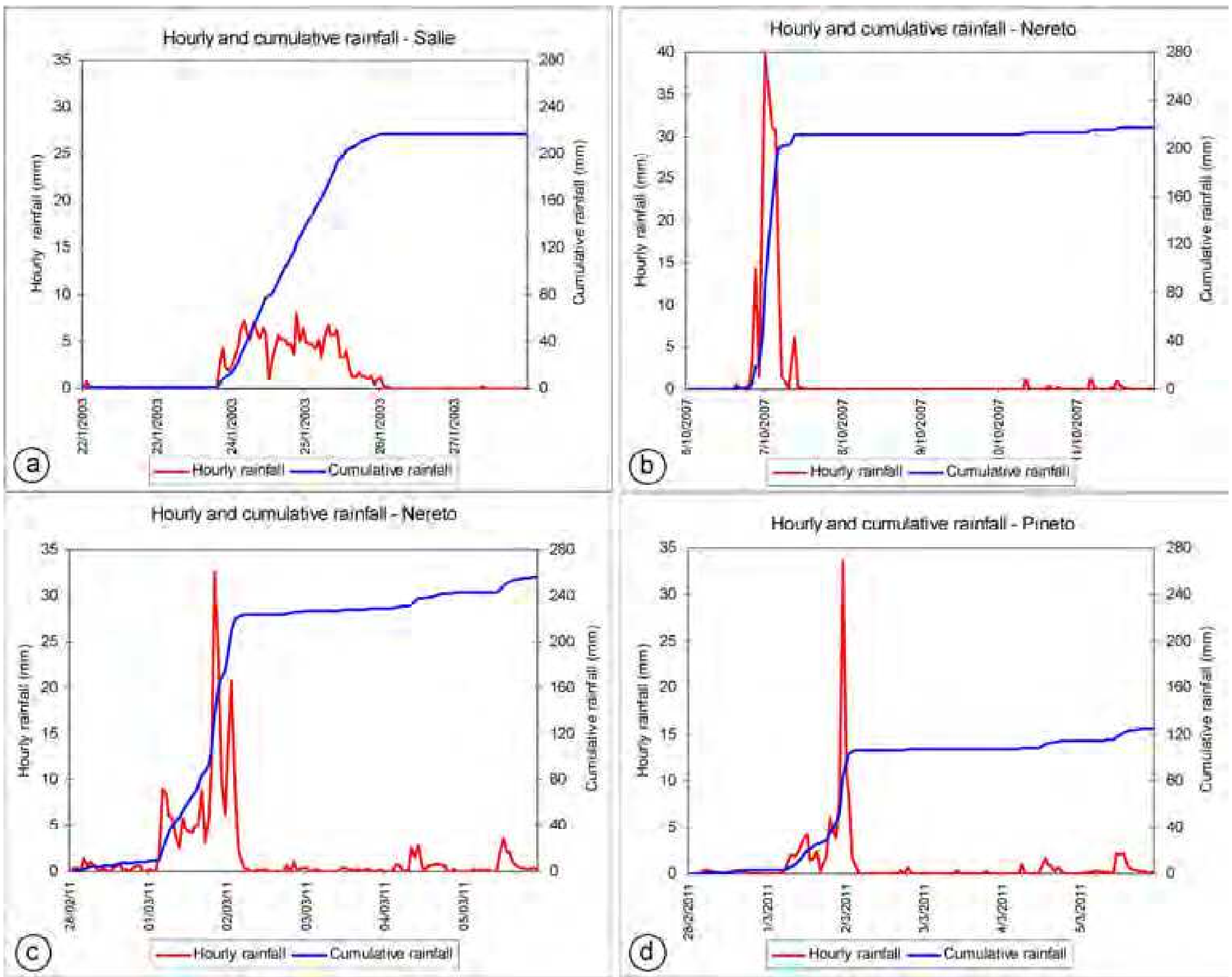

Fig. 5. The hourly and cumulative rainfall occurring during the heavy rainfall events: a) on 23-25 January 2003 at the Salle (PE) station; b) on 7 October 2007 at the Nereto (TE) station; c) on 2 March 2011 at the Nereto (TE) station; d) on 2 March 2011 at the Pineto (TE) station.

5. Geomorphological effects and landforms triggered by heavy rainfall events

5.1 2003 event (23-25 January)

At the end of January, according to the meteorological aspects of the event, outcropping lithologies and surface eluvial and colluvial covers were already very humid and - in almost water saturation conditions - had a strong susceptibility to slope instability. In these conditions, the occurrence of prolonged and intense precipitation on 23-25 January 2003 induced heavy flooding within the main alluvial plains (the rivers Sinello, Sangro, Trigno, Foro and Alento) and triggered ~1300 landslides ranging from the small to the very wide (mostly rapid earth flows and debris flows, secondary rock falls and rotational/translational sliding). The type and distribution of landslides were strictly controlled by the lithology and morphostructural setting and by the poorly vegetated landscape due to the winter season (Fig. 6; D'Alessandro et al., 2004).

The landslides on Quaternary continental deposits (7%) were mostly small flows and slides, located along the scarp edge of fluvial terraces or affecting the talus slopes in the mountain area. The landslides affecting the cuesta and mesa reliefs on the sands and conglomerates of Plio-Pleistocene marine succession of the Abruzzi piedmont area (17%) were distinct type of landslides, on high gradient slopes or else along structural scarps: rapid earth flows affecting surface colluvial cover triggered by heavy surface runoff; falls and topples affecting the edge of structural scarps on sandstones and conglomerates; rotational and translational sliding, which was less frequent but developed for a long time after the event due to deep water infiltration in the permeable conglomerates and sandstones laying on impermeable clays. The landslides on the hilly slopes and cuesta and mesa slopes affecting clays of Plio-Pleistocene marine succession of the piedmont area (32%) were mostly earth flows, from the small to the very wide (Fig. 7a). The landslides on the arenaceous-pelitic and marly rocks of the Neogene syn-orogenic foredeep succession of the piedmont area (15%) consisted of mostly rapid surface flows and sliding (Fig. 7b), affecting the eluvial and colluvial cover, particularly where it is more clay-rich. The landslides on the structural or fault slopes on the marine Meso-Cenozoic carbonate rocks of the chain area ridges (2%) were mainly rockfalls of single blocks or else volumes of fractured rock, which affected several mountain roads (Fig. 7c). The landslides on the slopes and isolated reliefs on the clays and fractured shales (“Argille varicolori” Auctt.) of the Meso-Cenozoic Molise basin succession outcropping in the SE Abruzzo area (27%) were mostly flows and complex landslides occurring on all the slopes with a low gradient, due to the bad geotechnical properties of these rocks.

Finally, floods occurred along the fluvial plain of most of the main rivers (Trigno, Sinello, Sangro, Foro, Alento; Fig. 7d).

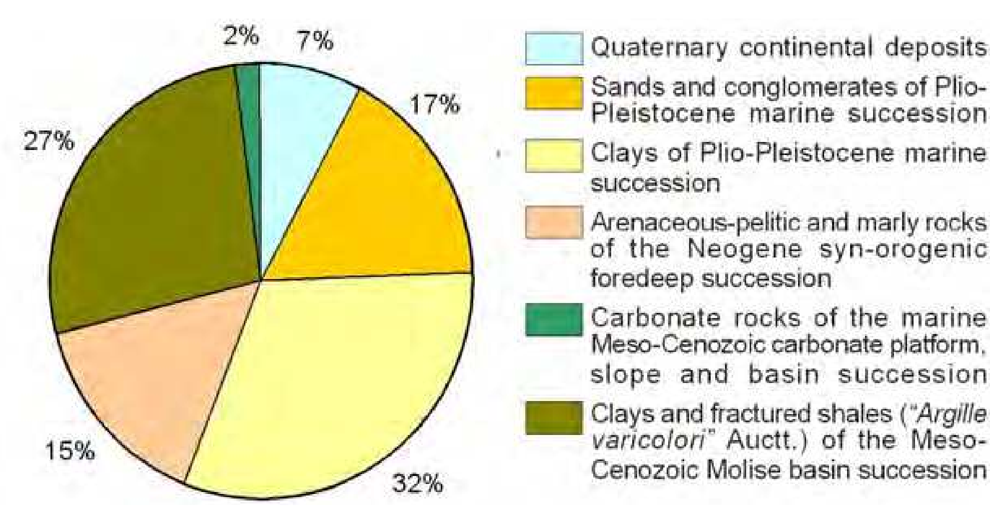

Fig. 6. Percentage distribution (by lithology) of landslides triggered by the 2003 heavy rainfall event (modified from D’Alessandro et al., 2004).

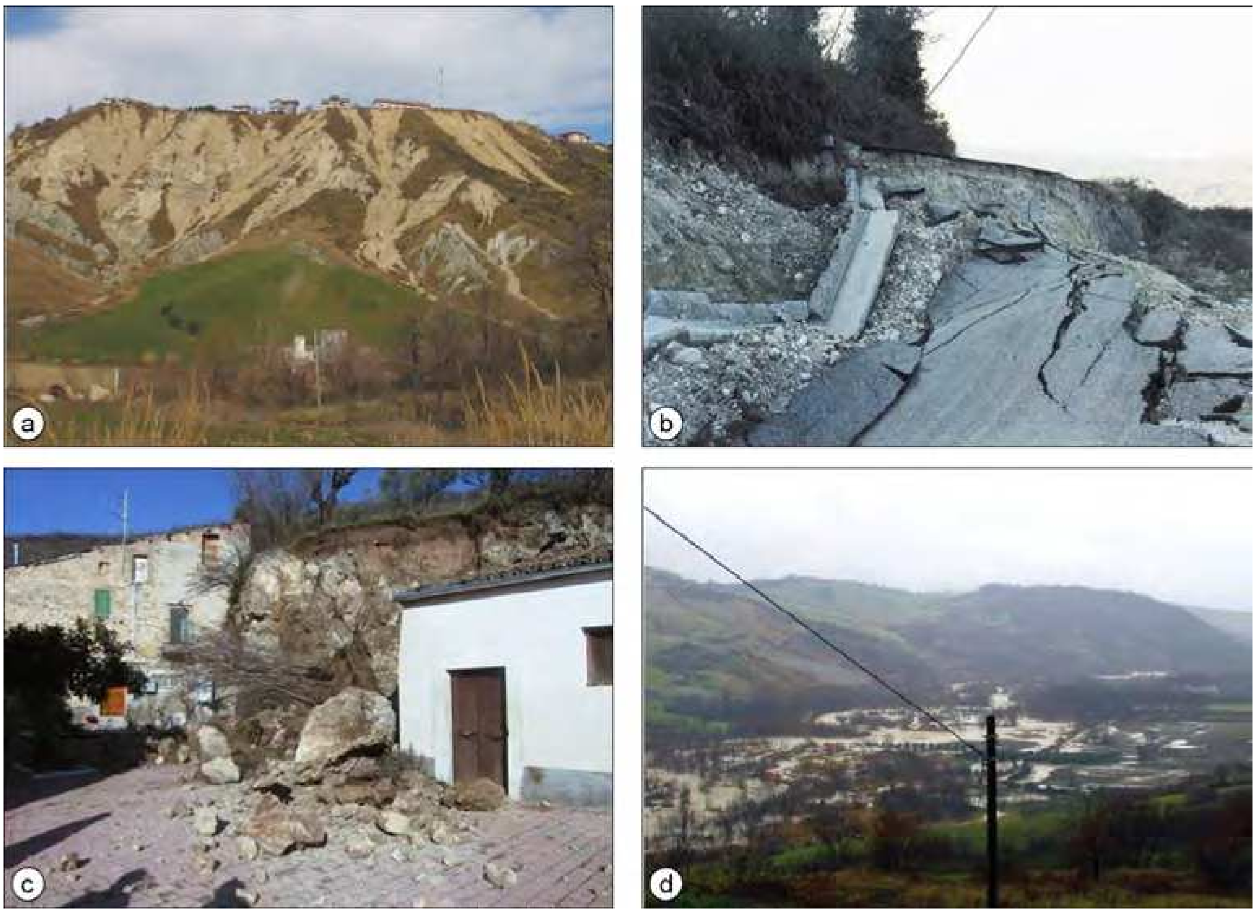

Fig. 7. Examples of landslides and flooding triggered by the 2003 heavy rainfall event (modified from D'Alessandro et al., 2004): a) Atessa, rapid earth flow on clayey and sandy deposits; b) Fresagrandinaria; slides on pelitic-arenaceous deposits; c) Popoli, rockfall on carbonate rocks; d) F. Salinello, flooding.

5.2 2007 event (6-7 October)

The event affected a very poorly vegetated landscape of the hilly coastal area, particularly the agricultural areas (arable land, vineyards and olive groves) due to ploughing on erodible rocks (marine Plio-Pleistocene clays, sands and conglomerates) and clayey eluvial and colluvial cover. This provided a strong propensity towards soil erosion.

These features induced heavy soil erosion processes on slopes (sheet, rill, and gully erosion), rapid mud flows at the base of slopes or minor drainage basins, and flooding within the main river and coastal plains, mostly at the outlet of minor tributary catchments. The distribution of landforms is controlled by the orography of the basins (slope and aspect) and by land use, particularly with regard to vegetation cover.

The landform analysis shows that hilly catchments and slopes, during this event, were affected by gully erosion (31% of the affected area, Fig. 8) and sheet and rill erosion (35% of the affected area, Fig. 8) for an extent up to >50% of the total area. The low gradient slopes and ridges with the vineyards and olive groves - or in general those not ploughed - were mostly affected by low sheet-rill erosion. The high gradient slopes - particularly where ploughed in down slope direction - are incised by gullies up to ~1m deep and 3-4 m spaced.

Along the channel of the main catchments, channel incision occurred. Also very common were mud flows (6% of the affected area, Fig. 8) and flooding (29%, Fig. 8) at the bases of the slopes, along the channel of small catchments or at the junction between small catchments and the flood plain or coastal plain. Mud flows are the result of heavy soil erosion on the slopes, inducing the mobilisation of huge sediment volumes of silts and clays from the eluvial and colluvial cover. Extensive mud and water flooding affected both coastal plains, coming more from the small catchments of the coastal slopes and river plain slopes, more than from the main rivers.

As such, the landform distribution seems to be controlled by the structural geomorphological features of the radial drainage pattern, incorporating the coastal streams and tributary streams of the main valleys of F. Salinello and T. Vibrata.

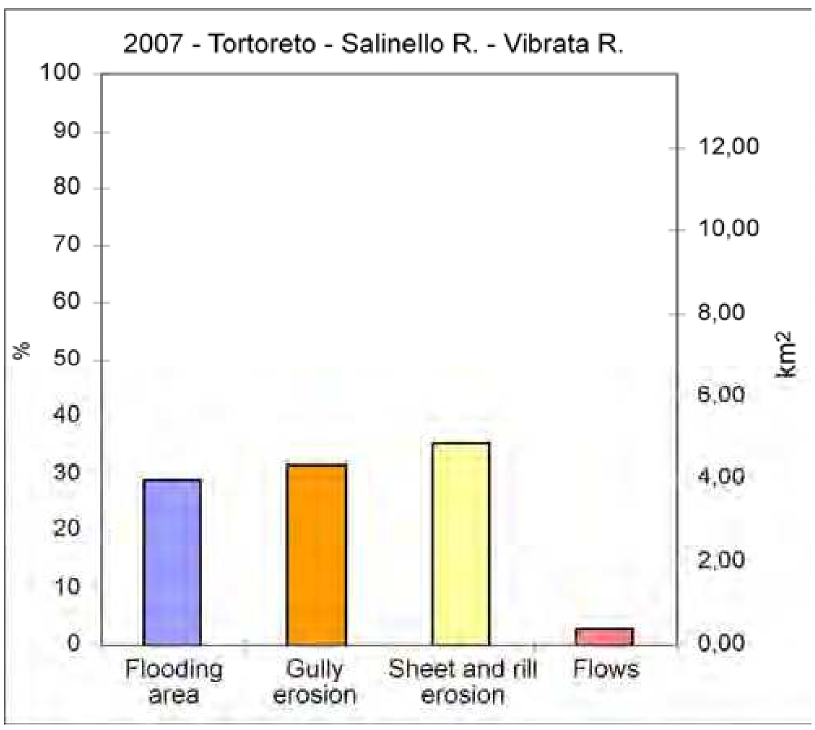

Fig. 8. Percentage and surface distribution of the geomorphological instabilities triggered by the 2007 heavy rainfall event in the Tortoreto hilly and coastal area between the lower T. Vibrata valley and lower F. Salinello valley.

5.3 2011 event (1-2 March)

This event occurred after two months of moderate rainfall on moderately humid clay-sands-conglomerate rocks and clayey eluvial and colluvial cover. In respect of the 2007 event - which partially affected the same area - the 2011 one occurred on a moderately vegetated landscape with agricultural areas (arable land, vineyard and olive groves) in an initial crop growth stage and grass development, less susceptible to soil erosion. Crop and grass cover promoted surface runoff directly into the main rivers, protecting the slopes from soil erosion.

The geomorphological analysis performed after the event outlined the landforms due to sheet and rill erosion, gully erosion, mud flows and flooding, as with the 2007 event but with a different proportion and a minor total extent. Also, in this case, the distribution is controlled by the catchments' orography and land use, with especial reference to crop and grass cover.

Soil erosion occurred on a small extent (9-17% of the area affected by instabilities; Fig. 9) as well as rapid mud flows (4-7%, Fig. 9) due to the vegetation cover. Low gradient slopes were affected by sheet and rill erosion. High gradient slopes were affected by mud flows, at the base of the slopes (Fig. 10a), and by gullies up to 0.6 m deep and sparse in respect of the 2007 event. Gullies occurred on the channels of tributary catchments or on slope undulations, in some cases enlarging natural or man-made notches or else simply notches due to agricultural work (Fig. 10b). Along the main rivers, channel incision or lateral erosion occurred (Fig. 10c,d), inducing severe damage to valley roads and bridges (Fig. 10e,f).

Heavy mud and water flooding is the prevailing effect of this event (75% of the area affected by instabilities; Fig. 9) and it affected almost seamlessly the coastal plains between the Tronto river and the Piomba river as well as the river plains of the Salinello, Tordino, Vomano, and Calvano rivers. Coastal plains flooding came from the small coastal slope catchments and partly from the main rivers, while river plains flooding mostly came from the main rivers' overbank flow and - secondarily - from the tributary catchments' flow. Extensive overbank flooding along main the rivers induced the formation of wide and long crevasse splays on the floodplain (Fig. 10c,g). As with the 2007 event, but to a lesser degree, the junction between slopes, small catchments and plains was affected by rapid mud flows.

Also, in this case, and finally, runoff and flooding were controlled by the structural geomorphological features of the radial and trellis drainage pattern of the Teramo hilly area.

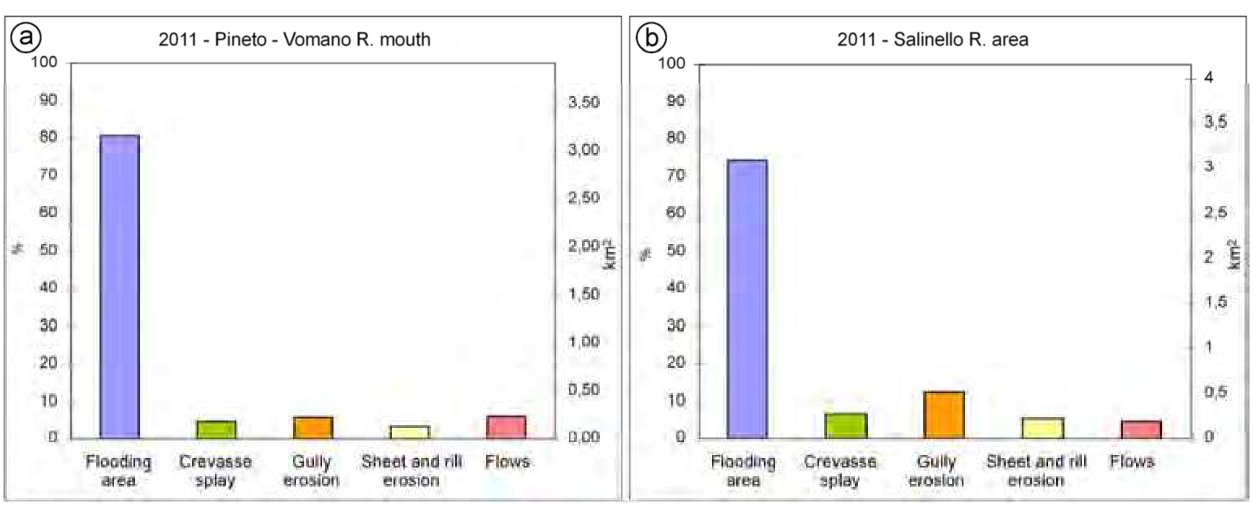

Fig. 9. Percentage and surface distribution of landforms triggered by the 2011 heavy rainfall event: a) The Pineto coastal and hilly area between F. so Foggetta and F. Vomano; b) The Lower F. Salinello valley and the hilly and coastal slopes of the Tortoreto area.

Fig. 10. Landform triggered by the 2011 heavy rainfall event: a) Mosciano S. Angelo, rapid earthflows; b) Pineto, gullies on the coastal slope; c) F. Salinello, crevasse splay and fluvial erosion scarps; d) F. Salinello, fluvial erosion scarp affecting the valley road; e) F. Vomano, main river flooding affecting main roads; f) F. Salinello, damage to a bridge; g) F. Salinello, flooding and crevasse splays along the main alluvial plain.

6. Conclusion

This work deals with the distribution of flooding and mass movements triggered by heavy rainfall events, analysing the effects of three events which occurred over the last ten years in the Abruzzo region (Central Italy). The analysis is carried out with regard to the geographical extent of the events (regional-local), its meteorological and pluviometric features (monthly, daily, hourly and cumulative rainfalls), the lithological and morphostructural setting, land use (also concerning the vegetation state and agricultural maintenance of cropland, olives and vineyards). The three events that are analysed all had different features (Tab. 1), concerning:

- geographical extent (2003 regional; 2007 local; 2011 intermediate);
- lithological setting;
- duration (2003 ~3 days; 2007 <1 day; 2011 ~1 day);
- season of occurrence (2003 winter; 2007 autumn; 2011 winter end);
- previous humidity conditions (2003 very humid; 2007 very dry; 2011 moderately humid).

This variable conditions, taking into account also the general geomorphological setting and landslide distribution of the Abruzzo region, induced the trigger of different geomorphological instabilities (landslides, mass movements), concerning type and areal distribution, as summarised by Table 2.

Event	Date	Extent	Season	Durat. (hours)	Ih_{max} (mm/h)	Pd_{max} (mm)	Pc_{tot} (mm)	Pm_{tot} (mm)	$P^{previous}$
2003	23-25 gen	regional	winter	~72	10-17	40-130	80-230	120-380	elevate
2007	6-7 ott	local	autumn	14-16	10-40	60-205	60-220	200-300	scarce
2011	1-2 mar	intermediate	winter end	22-26	15-35	60-180	120-211	150-300	moderate

Table 1. Main meteorological characteristics of the three heavy rainfall events studied in this work. Legend: Ih_{max} - maximum hourly rainfall intensity during the event; Pd_{max}- maximum daily rainfall during the event; Pc_{tot} - cumulative rainfall during the event; Pm_{tot} - total rainfall during the event's month; P previous - rainfall in the month before the event.

Event	Landslides	Flooding	Gullies	Rills and sheet erosions	Crevasse splays
2003*	>1300 landslides	Alento, Foro, Sangro, Sinello, Trigno	n.d.	n.d.	n.d.
2007	~ 0,6 km^2(6%) flows	~ 3,8 km^2 (29%)	~ 4,0 km^2 (31%)	~ 4,5 km^2 (35%)	-
2011	~ 0,5 km^2 (6%) flows	~ 6,5 km^2 (75%)	~ 0,8 km^2 (9%)	~ 0,4 km^2 (5%)	~ 0,5 km^2 (6%)

Table 2. Geomorphological instability and landforms triggered by the three heavy rainfall events studied in this work. *Data for the 2003 event are from D'Alessandro et al., 2004.

This work allowed us to highlight that these types of methods, investigations and data are basic to applied geomorphological studies for the stabilisation and management of slopes and minor or major drainage basins as well as for general land management. Only a high level of knowledge of geomorphological instability - connected to drainage - geological-geomorphological and morphostructural features and meteorological events - particularly when joined to geotechnical data - allows for effective stabilisation and management plans.

Finally, these types of studies are basic and complementary to recent methods for the investigation and mapping of land sensitivity to geomorphological processes, such as landslides, soil erosion and desertification, etc. (Mitasova *et al*., 1996; Fluegel *et al*., 2003; Grimm *et al*., 2003; Agnesi *et al*., 2006; Ciccacci *et al*., 2006; ISPRA, 2006; Marker *et al*., 2008; and references therein), and they allow us to define future scenarios - which sustainable land planning and management should be based on - taking into account the specific destination of different areas and contributing to the identification of proper sites for quarrying, dumping and purification plant, etc., or else the proper areas for industries, urban expansion or supporting in general the process of creating an urban plan.

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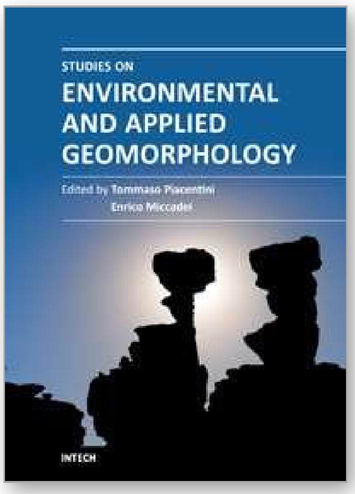

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