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The 9 September 2010 torrential rain and flash flood in the Dragone catchment, Atrani, Amalfi Coast (Southern Italy)

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Abstract

In this paper we use a multi-hazard approach to analyse the 9 September 2010 flash-flood occurred in the Dragone basin, a 9 km² catchment located along the Amalfi rocky coastal range, Southern Italy. In this area, alluvial-fan-flooding is the most frequent and destructive geologic hazards since Roman time. Sudden torrent of waters (flash flood) are caused by high-intensity and very localized cloudbursts of short duration inducing slope erosion and sediment delivery from slope-to-stream. The elevated bed load transport produces fast-moving hyperconcentrated flows with significant catastrophic implications for communities living at stream mouth.

The 9 September 2010 rainstorm event lasted 1 h with an intensity rainfall peak nearly to 120 mm h⁻¹. High topographic relief of the Amalfi coastal range and positive anomalies of the coastal waters conditioned the character of the convective system. Based on geological data and post-event field evidence and surveys, as well as homemade-videos, and eyewitness accounts the consequent flash-flood mobilized some 25 000 m³ of materials with a total (water and sediment) peak flow of 80 m³ s⁻¹. The estimated peak discharge of only clear water was about 65 m³ s⁻¹. This leads to a sediment bulking factor of 1.2 that corresponds to a flow with velocities similar to those of water during a flood.

1 Introduction

The Amalfi Coast consists of a steep mountain front (up to 1444 m a.s.l.) that rises abruptly from the Tyrrhenian Sea (Fig. 1). It is a rocky coast mostly formed by a pile of Mesozoic carbonate rocks, covered by Tertiary to Quaternary siliciclastic and pyroclastic units tectonically uplifted since lower Pleistocene. Bedrock rivers and channels deeply dissect the carbonate bedrock forming a complex fluvial system characterized by small catchments that are very high relative to the base sea level. These rivers show a distinct seasonality and torrential behaviour, with main delivery areas into the adja-

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cent marine shelf (Fig. 2; Esposito et al., 2004b; Budillon et al., 2005; Violante, 2009; Violante et al., 2009).

During the last millennia this area has been repeatedly mantled by the pyroclastic products of the Somma–Vesuvius, that create favourable conditions for volcanoclastic debris to generate mass flows and flash floods in concomitance with rainy periods. The Plinian eruption that destroyed the Roman cities of Pompeii, Stabiae and Herculaneum in AD 79, deposited up to 2 m of erosion-prone volcanoclastic material (Sigurdsson et al., 1985) on the steep coastal slopes causing conditions of increased geomorphic instability.

Geologic evidences for rapid slope erosion following the Pompeii pyroclastic fall include alluvial reworked volcanoclastic sequences (locally called Durece) occurring as residual outcrops along narrow stream valleys (Cinque and Robustelli, 2009) and coastal fan-deltas fed by small alluvial fans at mouth of the main streams (Sacchi et al., 2009; Violante et al., 2009). These latter are composed of wedge-shaped coarse-grained alluvial deposits that thicken towards the sea and represent the subaqueous counterpart of small fans at river mouths (Fig. 2, inset).

Pyroclastic air-fall tephra derived from late Quaternary activity of the Somma–Vesuvius still occur as unstable sedimentary covers on top of the steep carbonate slopes of the Amalfi coast. These deposits creates conditions of elevated slope instability in conjunction with rainstorm events that frequently hit the Amalfi Coast through historical times. The slides are mostly shallow and very wide, extending all the way to the mountain ridge and crest, and largely ascribing to soil slip, debris/earth flow phenomena. Besides rapid sediment transport along valley flanks, landslide debris flowing from slope to streams produce fast-moving large debris torrents (flash flood) with significant catastrophic implications for local communities mostly living on alluvial deltas at stream mouths (Esposito et al., 2004a; Porfido et al., 2009). Here flood-prone streams have been artificially forced to flow underneath roads and squares to exploit the whole delta surfaces for urban development (Fig. 2).

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In this paper we analyse the 9 September 2010 rainfall event that hit the Costa d'Amalfi and its consequences in the Dragone catchment and Atrani village. Direct field observations that include geological investigations and damage to property and infrastructures have been combined with meteorological and hydraulic/hydrological analyses. Reconstruction and recurrence of past events based on different historical sources, and marine geophysical and geological data of the Dragone submerged delta have been also taken into account.

2 The Dragone catchment–fan–delta system

The Dragone catchment drains an area of 9.3 km^2 along the steep coastal slopes of the Amalfi Coast. The basin develops in a North–South direction and is strongly asymmetric, with the eastern flank composed of a short and abrupt slope corresponding to a fault scarp and the western flank formed by four main sub-basins: the Scalandrone, the Nocelle, the Senite, and the S. Caterina. A fifth sub-basin, the Frezzi, develops at the head of the Dragone stream (Fig. 3a). The drainage area rises up to 1267.5 m a.s.l. and cuts into Mesozoic limestone discontinuously mantled by Quaternary volcanoclastic and alluvial deposits. A low drainage frequency (5 km^{-2}) and a sub-dendritic pattern characterize the hydrographic network with the main stream, the Dragone, discharging directly into the Tyrrhenian Sea. Slope analysis based on a $5 \text{ m} \times 5 \text{ m}$ cell size DTM (Digital Elevation Model) indicates that topographic gradient of the catchment area is arranged into two main slope classes ranging from 15 to 35° and from 35 to 50° (golden/yellow and brown colours respectively in Fig. 3b). The mean slope is 30° .

The Dragone stream is 6.8 km in length with the terminal section covered by a roadway crossing the Atrani village. The entombment of the water course has an input section of $3 \text{ m} \times 9 \text{ m}$ ($h \times w$) that reduces to $1.80 \text{ m} \times 5.50 \text{ m}$ at closing section, and a total length of about 300 m. Runoff waters are regulated by concrete levees and bridles that extend over two third of the hydrographic network.

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At sea a submerged fan-delta occurs at closing section of the Dragone catchment (Sacchi et al., 2009; Violante, 2009). The delta body is 0.2 km² wide and reach a max thickness of 25 m. It displays a generally conical morphology with a delta front slope of 30° and foreset inclination ranging from 15 to 30°. This structure is composed of alluvial sequences that coincide with significant changes in river activity during streamflow phenomena. Increases in fluvial sedimentary discharge are recorded as successive phases of delta growths to which associate temporary shoreline progradations.

Detailed study of the internal stratigraphic architecture of the Dragone fan-delta indicates various depositional phases following the main AD 79 alluvial crisis, possibly modulated by the interplay between the availability of loose pyroclastic covers and the varying erosional rates due to the climatic oscillations occurring in the last millennia (Fig. 4; Sacchi et al., 2009; Violante et al., 2009). The major change detectable in the Amalfi fan deltas occurs in the Early Medieval Cool Period (c. AD 500–AD 800), that developed immediately after the Roman Warm Period. Further changes in the stratal patterns of the delta foresets indicative of high streamflow activity, may be correlated with the Medieval Warm Period (c. AD 900–AD 1100) and the Little Ice Age (c. AD 1400–AD 1850).

3 Rainstorm-induced geological effects

A field survey was undertaken soon after the 9 September 2010 rainstorm in the Dragone catchment and Atrani village. The observed rainstorm-induced geological effects include: surficial landslides and sediment removal along channels, a temporary dam in the mid-lower section of the Dragone stream, the partial outbreak of the main road crossing the Atrani village, and the deposition of a coarse terminal fan at mouth of the Dragone stream (Fig. 5).

The field data indicate that slope erosion triggered by the 9 September 2010 rainstorm was predominantly linear. Sediment removal by linear erosive processes significantly engraved tributaries and the main stream up to a depth of 2 m (Fig. 5a). The

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displaced materials were mostly composed of pyroclastic deposits and landfills occurring along channel beds often above hydraulic bridges. A large amount of tree trunks of different size mostly coming from rupture of artificial aisles built to cross ditches and tributaries was also included in the transported material.

Minor soil slips have been observed uphill on high slope declivity at Punta delle Castagne, a rock crest connecting the Senite, Nocelle, and Scalandrone watersheds (Fig. 5b) along the western flank of the Frezzi watershed. Here displacement of the channel sides occurred both at channel heads and, locally, in the mid-upper section of small tributaries.

Apart minor overspill deposits composed of white pumices observed at break-slopes just below the watershed areas and along the middle section of the Dragone stream, no significant aggradation has been observed in the catchment area. Removal of materials from stream bed was produced by a fast-moving debris torrent with high erosive capacity, transporting the mobilized materials all the way down to the coast. Here the Dragone stream is artificially forced to flow underneath the main road crossing the Atrani village resulting in siphoning and consequent outbreak of the above roadway (Fig. 5c). Once reached the coastline, the hyperconcentrated flow engraved the Atrani beach and dumped the transported materials at sea in the form of a coarse alluvial fan (Fig. 5e). This induced a shore progradation of about 30 m. The alluvial deposits entering into the sea were mostly composed of white-gray pumices including tree trunks, man-made materials, landfills, and rock boulders of different size. Some cars parked along the main road were transported up to the beach area and beyond (Fig. 5e).

Discharge and depth of flow downstream was probably increased by abrupt draining of a temporary dam reported by eyewitnesses in the lower section of the Dragone stream. Such damming was favoured by a narrow flow section and enhanced by a man-made structure built in the stream bed (Fig. 5d). Failure of temporary debris dams and draining of ephemeral lakes have been described for different flood events occurred in the study area (Passerini, 1924; Penta et al., 1954). This phenomena can produce exceptional temporary discharges and highly destructive peak flows reaching depths

infiltrates or is intercepted by vegetation, S is the potential maximum soil moisture retention during the runoff.

The value of S for a given soil is related to the curve number (CN) which is function of the hydrologic soil-cover complexes as (if S is expressed in mm):

$$5 \quad \text{CN} = \frac{25\,400}{S + 254}. \quad (2)$$

In the case of the Dragone basin the adopted CN value is 66 corresponding to forest-like cover (woods-grass combination), considering hydrological soil group B (moderate infiltration) with antecedent moisture condition II (average) and $I_a = 0.2S$.

10 The lag time t_{lag} has been estimated from concentration time t_c calculated by SCS formula (Chow et al., 1988):

$$10 \quad t_{\text{lag}} = 0.6 \times t_c = 0.6 \times 0.00227 \times L^{0.8} \left(\frac{1000}{\text{CN}} - 9 \right)^{0.7} i^{-0.5} \text{ [h]} \quad (3)$$

15 where L is the hydraulic watershed length expressed in meter (m) and i the mean basin slope as percentage (%). Figure 10 reports the results of the hydrological model where the estimated peak discharge of the clear water is about $65 \text{ m}^3 \text{ s}^{-1}$ occurring around 17:00.

6 Hydraulic model and sediment transfer

20 Due to the lack of streamgauge data, we analyzed the hydraulic response of Dragone catchment to the 9 September 2010 rainstorm event and the sediment transfer during flood on the base of (a) morphology of the Dragone basin, (b) pluviometric data, (c) field evidences, (d) homemade-videos and photos, (e) eyewitnesses accounts.

According to local eyewitness accounts, the peak flow of the Atrani flood event occurred between 16:50 and 17:10, that is about 40 min later of the hyetograph centroid,

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occurred at ca 16:25, while the flood duration was ranging from 40 to 60 min (Fig. 11). In the Atrani urban area the entombment of the Dragone stream splitted the flood wave in two different currents: a main flow within the entombment, below the road level (“via Dei Dogi”) along a closed section varying from 3 m (h) \times 9 m (w) at input section to 1.80 m (h) \times 5.50 m (w) at closing section; a second flow above the entombment, along the road, constrained by almost continuous man-made structures and buildings 5.5 m away from each others (see Fig. 5c). The maximum depth of the upper flow was about 1 m.

The highest flow velocity for both flows was estimated from amateur videos by tracking particles transported by the flood through the analysis of video frames with an approach similar to that used in PIV technique (Fig. 12; Raffel et al., 2007). Peak discharge is obtained by multiplying estimated flow velocity and the flow section.

The estimated flow velocity along via Dei Dogi street is about 3–4 ms^{-1} and, consequently, the peak discharge is approximately $20 \text{ m}^3 \text{ s}^{-1}$. For the entombed flow the estimated peak velocity is about 6–7 ms^{-1} while the peak discharge is in the order of $60 \text{ m}^3 \text{ s}^{-1}$, taking into account that the flow fills roughly the 80 % of the closed section. Then the total estimated peak discharge is $80 \text{ m}^3 \text{ s}^{-1}$ (water + sediment; see Fig. 11), which is $15 \text{ m}^3 \text{ s}^{-1}$ more than the estimated clear water peak discharge ($65 \text{ m}^3 \text{ s}^{-1}$) due to sediment load (Q_s). Similar values for total peak discharge ($98.4 \text{ m}^3 \text{ s}^{-1}$) has been reported by Ciervo et al. (2014) that used a dedicated numerical code for the hydraulic modelling of the 9 September 2010 Atrani flash flood.

Assuming that active sediment removal occurred in a time span of 40 \div 60 min, the calculated sediment volume mobilized during the event is:

$$V_s = Q_s \times t = 15 \times \frac{(40 \div 60)}{2} \times 60 = 18\,000 \div 27\,000 \text{ m}^3. \quad (4)$$

This value is in good agreement with volume estimation of the sediment deposited in the form of alluvial fan delta at the Dragone mouth and on the street and square that cover the the stream path (Fig. 13). To this aim, bathymetric data collected soon

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after the flood event were compared with an older dataset owned by IAMC_CNR enabling the measurement of sediment volume that flowed into the sea at ca. 14 000 m³ (Fig. 13). On land, sediment thickness along via Dei Dogi and Umberto I square reached depths averaging 0.5 m while beach aggradation was about 1 m, with a volume of sediment accumulation of ca. 7000 m³. Therefore, the estimated volume of the sediment transported to the terminal section of the Dragone stream is ca. 21 000 m³. Taking into account the additional volumes (estimated at about 20 % of the measured volume) removed by sea currents or related to dispersal of finer sediments at sea, a total volume of about 25 000 m³ can be obtained.

Sediment volume can be expressed as sediment bulking factor (BF; Gusman et al., 2009) that define the ratio between the peak flood discharge Q_B and clear water discharge (Q_w):

$$BF = \frac{Q_B}{Q_w} = \frac{Q_w + Q_s}{Q_w}. \quad (5)$$

In terms of sediment load, bulking factor can be also expressed as:

$$BF = \frac{1}{1 - \frac{C_v}{100}} \quad (6)$$

where C_v is the volume concentration of sediment.

In the case of the 9 September 2010 flood event the estimated BF to the flood peak is 1.2 (Eq. 5) that leads to a sediment concentration in the order of 20 % in volume (Eq. 6). This value is close to the lower limit of hyperconcentrated flow (Costa, 1988; Jakob and Hungr, 2005) and it corresponds to a flow in which peak discharge is comparable to that of a clear water flood and velocities are similar to those of water during a flood (Hungr et al., 2001; Pierson, 2005). This is also confirmed by amateur videos that show a very turbulent flow.

7 Historical documentation of past floods

A systematic analysis of documentary and bibliographic sources, as well as newspapers carried out at the State Archives in Naples and Salerno (Esposito et al., 2003, 2004; Porfido et al., 2009), complemented by data attained from scientific papers and national and international projects (Guzzetti et al., 1994; Guzzetti and Tonelli, 2004) allowed us to reconstruct the time-space distribution of flood events that have affected Atrani since 1540. The quality and completeness of the various sources were evaluated and carefully analyzed in their historical context, to obtain the best information rather than the best dataset quality (Barriendos et al., 2003). Nineteen events were identified and characterized on the basis of: (a) distribution of the flooded areas, (b) distribution of damaged localities, (c) duration and timing of the event and (d) number of casualties. The historical information show that most of the events (14 events) took place at season transition between summer and autumn, four events in winter and just one has been recorded into the spring season (Table 4).

The intensity and the duration of the rainfalls, the level and distribution of damage of man-made structures, the number of victims, and the induced geological effects have been considered to distinguish flash flood from minor flood types (Table 4; Casas Planes et al., 2003; Llasat et al., 2005; Barnolas and Llasat, 2007). In particular, shoreline progradation has been considered as a key element for flash-flood as it results from bed load transport and hyperconcentrated stream-flows. Based on this, 7 flood events out of 19 have been classified as flash flood:

- October 1540 – not much information are available for this event, but it is reported as “the great Atrani flood”. This indication along with the occurrence of severe damage and extensive landslides and inundation allow to classify it as a flash flood.
- August 1588 – a flood produced severe damage to properties, extensive inundation, landslides and shoreline progradation, as reported by the Cronaca Amalphitana, Ignoti auctoris 1588, cited by Camera (1881): “at the end of the past month

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of August 1588 much lava fell down... it destroyed the Seggio building... the force of the lava removed trees, wood, earth and rocks and... it filled the harbor and pushed the sea back seven roads (14 m) thereby enlarging the harbor”.

- 20 January 1764 – a flood caused much damage to the Santa Maria Acquabona Church and to many flour mills as well as to some bridges. Extensive landslide coming from Scala hit Atrani, causing two deaths. The sediment transfer from Scala to Atrani indicates a mass transport along the main stream likely produced by a flash flood.
- 17 January 1780 – heavy rain hit the Atrani village causing 26 casualties, a huge landslide and extensive damage (Greco, 1787). The elevated number of victims suggest a flash flood event.
- 18 August 1949 – on 18 August, water masses flooded along the Atrani main street and square, reaching the level of about three meters. A widespread pattern of destruction characterized this event: boats, nets, fishing gear were swept away or submerged by mud; damage to buildings, destruction of roads, aqueducts and sewer systems. Thousands of cubic meters of material and muddy debris were left in the Umberto I square as well as on the beach producing a shoreline progradation of about 20 m.
- 1 October 1949 – the effects of the past flood event were still evident when a second one occurred with a greater violence. Outbreak of the main street occurred in several places, and water supply pipelines, recently refitted, were destroyed again. Huge amounts of debris and mud were transported all the way down to the coast in addition to the material recently transported by the 18 August flood, so that a large beach developed at the foot of coastal cliffs in between the Atrani village and the nearby locality of Castiglione.

8 Conclusions

Detailed field surveys and measurements along with information from eyewitnesses and amateur videos proved to be critical for modelling and reconstruct the flash flood that affected the Atrani village on 9 September 2010. The collected data were combined with meteorological and historical analyses and marine geophysical surveys in order to reconstruct the physical features of the flood event and the recurrence of flash-flood in the study area. The main results can be summarized as follows:

- Overall the rainstorm that generated the 9 September 2010 flash flood in Atrani lasted 4 h and was strongly conditioned by the local orography and positive thermic anomalies of the coastal waters during the warm season.
- In Atrani the rainfall event lasted about 1 h with cumulative rainfall of 80.8 mm and maximum rainfall intensity nearly to 120 mm h^{-1} . It was produced by a single storm cell elongated in NE–SW direction with a very flat elliptical shape and of limited areal extent (from 50 to 70 km^2) that can be ascribed to a Mesoscale Convective System β type.
- The estimated peak discharge of the clear water produced in the Dragone stream is about $65 \text{ m}^3 \text{ s}^{-1}$ while the estimated total peak discharge (water + sediment) is $80 \text{ m}^3 \text{ s}^{-1}$ leading to a sediment concentration of about of 20 % in volume characteristic of a debris flood.
- Sediment removal mostly occurred through linear erosion that significantly engraved tributaries and the main stream. The displaced materials were mostly composed of pyroclastic deposits and landfills occurring at channel beds and behind hydraulic bridges. A reduced size of erodible sediment stored in channels may consequently reduce mud-flow hazard and provide protection for the residential area on the alluvial fan in Atrani.

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Table 1. Rainfall intensity (mm) registered at time intervals of 10 min and 1 h on 9 September 2010 by rain gauges in Salerno and Sorrento Peninsula. In bold are reported the maximum values. Data from Centre for weather forecast and monitoring of the Campania Region (Biafiore et al., 2010).

Rain gauge	Altitude (m)	Latitude N	Longitude E	Distance from Ravello (km)	Rainfall intensity (mm)	
					10'	1 h
Pontecagnano	36	40°38'36.9"	14°52'02.2"	21.8	15.0	53.6
Salerno Meteo	16	40°38'37.7"	14°50'11.5"	20.3	16.0	47.0
Ravello	390	40°39'24.3"	14°36'52.5"	0.0	19.4	80.8
Agerola Meteo	848	40°38'48.6"	14°32'26.2"	6.0	26.2	80.8
Agerola	623	40°38'21.3"	14°32'44.8"	5.7	21.6	66.8
Moiano	485	40°39'12.6"	14°27'50.0"	13.5	21.0	78.0
Pimonte	437	40°40'27.8"	14°30'17.4"	10.2	23.2	92.2
Maiori	10	40°39'05.7"	14°38'24.6"	3.0	12.0	43.0
Gragnano	195	40°41'15.1"	14°31'38.1"	8.6	14.8	70.0
Lettere	312	40°42'15.9"	14°31'58.3"	9.8	16.2	45.6
Corbara	424	40°43'32.8"	14°36'07.5"	9.1	18.4	45.0
Tramonti	422	40°42'13.9"	14°38'49.3"	6.9	12.4	42.6
Amalfi	114	40°37'23.7"	14°34'49.8"	1.4	11.0	28.6
Cetara	140	40°39'04.0"	14°42'12.5"	8.6	9.8	27.2

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Table 2. Main morphometric parameters used in the hydrologic model.

Sub-basin	Name	A (km ²)	L (m)	S (%)	H_{mean} (m a.s.l.)	H_{min} (m a.s.l.)
Basin_1	Scalandrone	1.39	3600	56.7	873	389
Basin_2	Nocelle	1.46	2450	60.5	922	479
Basin_3	Frezzi	2.66	2600	54.3	803	479
Basin_4	Senite	1.12	1000	46.7	570	389
Basin_5	S. Caterina	2.71	3200	60.3	411	0
Whole basin	Dragone	9.33	6800	56.5	692	0

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Table 3. Estimated lag-time values e CN parameter used in the hydrologic model.

Sub-basin	CN (–)	t_c (min)	t_{lag} (min)
Basin_1	66	44	26
Basin_2	66	32	19
Basin_3	66	34	20
Basin_4	66	17	10
Basin_5	66	38	23
Whole basin	66	72	43

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Table 4. Flood events occurred at Atrani from 1540 to 2010 with indication of the induced effects. FF: Flash-flood. MF: Minor flood.

Year	Month	Day	Damage	Victims	Geological Effect	Flood Type
1540	10	8	Severe	–	Slides	FF
1588	8	31	Major	Some	Shoreline progradation	FF
1764	1	20	Major	2		FF
1780	1	17	Severe	26		FF
1823	10	18	Minor			MF
1824	10	3	Minor			MF
1904	10	7	Minor			MF
1924	3	27	Minor		Slides	MF
1935	3	1	Minor			MF
1949	8	18	Major		Shoreline progradation	FF
1949	10	1	Major		Shoreline progradation	FF
1953	9	11	Minor			MF
1954	10	25	Minor			MF
1969	3	15	Minor			MF
1984	8	28	Minor	1		MF
1987	10	6	Minor			MF
1988	9	14	Minor			MF
2007	9	20	Minor			MF
2010	9	10	Severe	1	Shoreline progradation	FF

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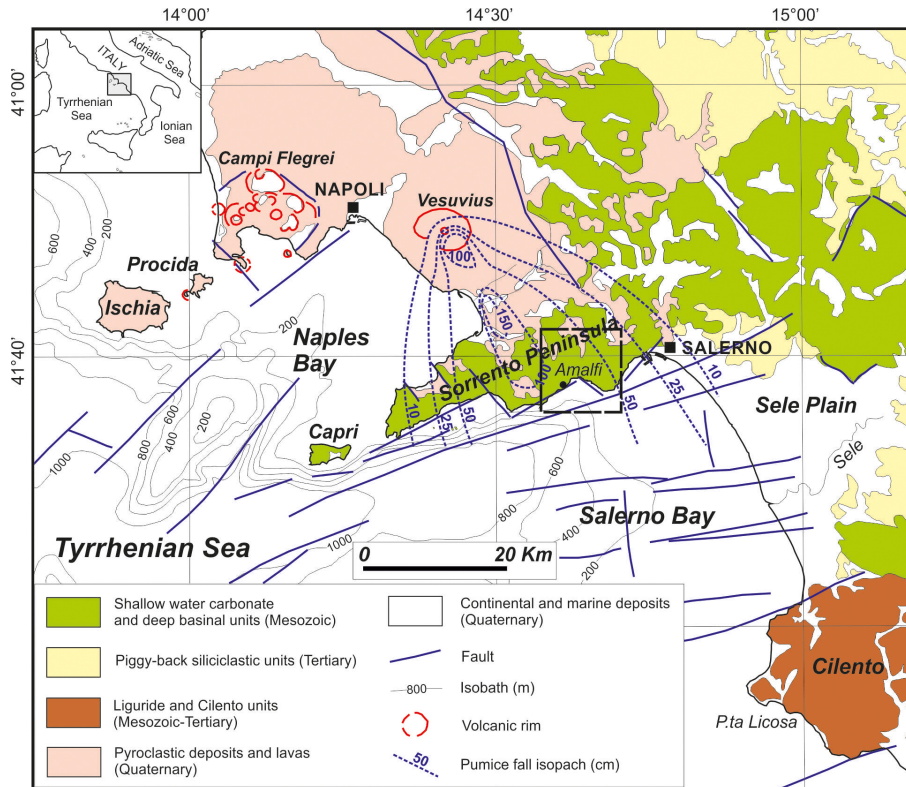


Figure 1. Geological sketch map and location of the study area (dashed box).

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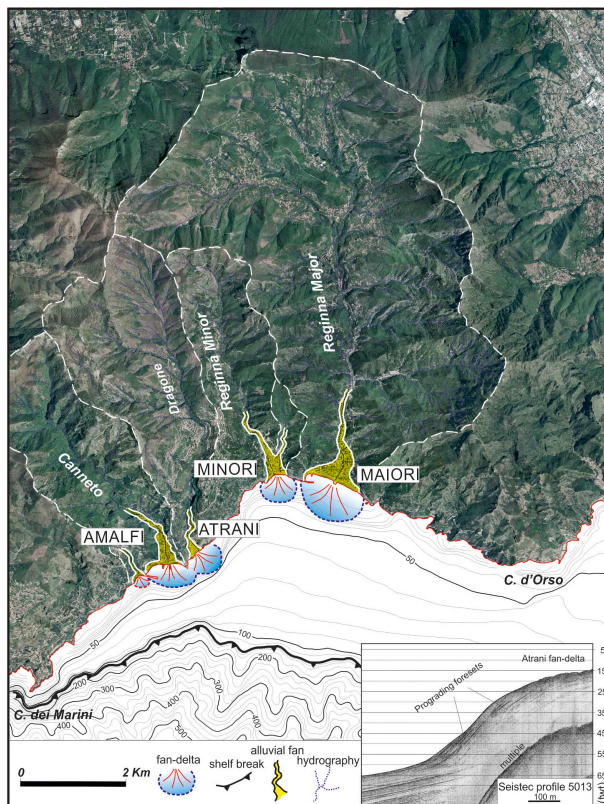


Figure 2. The Amalfi rocky coast system characterized by steep and high watersheds, urbanized alluvial-fan and fan-deltas at the mouth of main streams, reduced continental shelf engraved by canyons, and abrupt shelf break (fault-controlled). The fan-deltas are composed of prograding clinofolds resulting from flood activity as revealed by high-resolution seismic profiles (inset map in the lower right corner). Modified from Violante (2009) and Sacchi et al. (2009).

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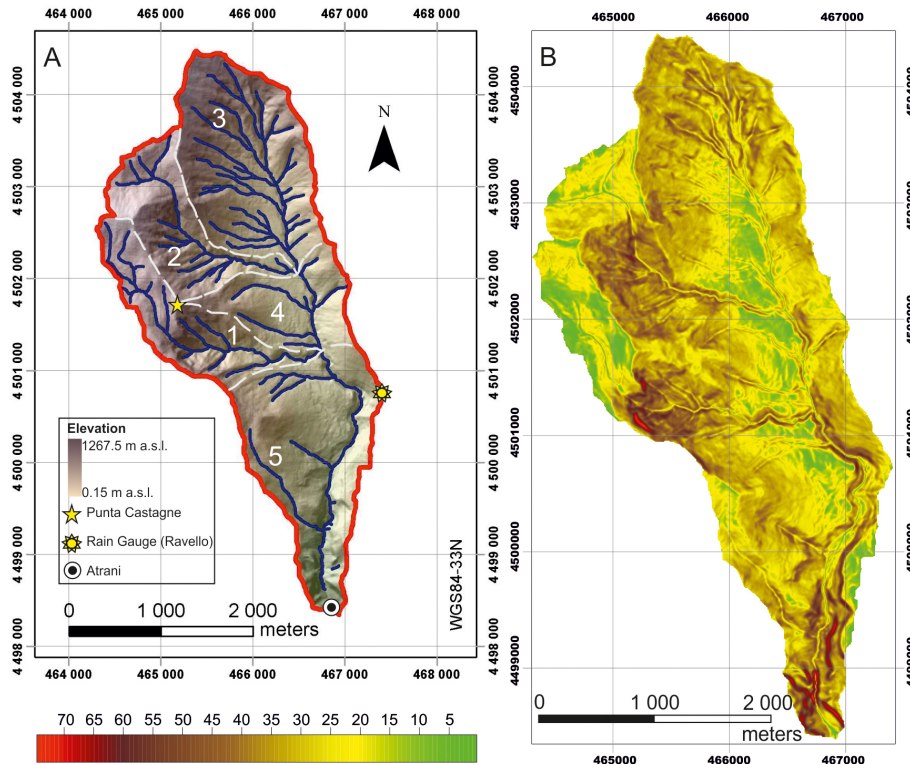


Figure 3. The Dragone catchment. **(a)** Basin elevation (DEM) and sub-basins of the Dragone stream. 1. Scalandrone, 2. Nocelle, 3. Frezzi, 4. Senite, 5. S. Caterina; **(b)** Slope map. Scale for slope map is in the left lower corner.

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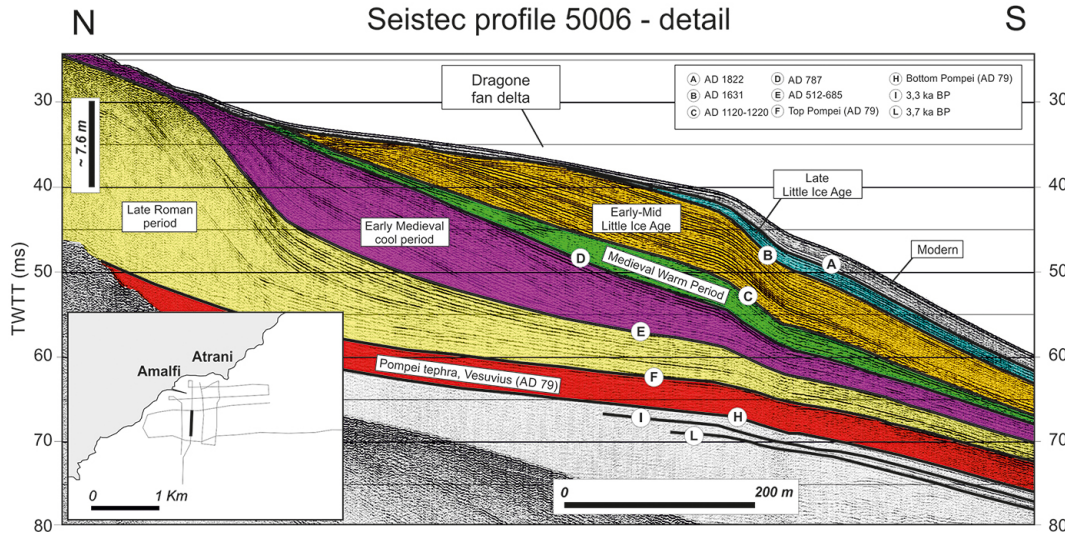


Figure 4. The Dragone–Canneto fan-delta body found off the Atrani village. Detail of a very high-resolution seismic profile showing flood-controlled seismic-stratigraphic units and their inferred association with major climatic changes of the last 2000 years. Letters A to L represent age-dated stratigraphic horizons. See inset map for location (modified from Sacchi et al., 2009).

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Figure 5. Geo-environmental effects induced by the 9 September 2010 rainstorm in the Dragone catchment. **(a)** Linear erosion engraving tributary channel. **(b)** Soil slip (arrows) at P. Castagne. Location in Fig. 3a. **(c)** Partial outbreak of the main road (Via dei Dogi) in the Atrani village. Red arrows indicate maximum height of the flow reaching ca 1 m above the street pavement. Location in Fig. 13. **(d)** Site of temporary damming in correspondence of a man-made structure built in the stream bed. **(e)** Terminal fan at mouth of the Dragone stream.

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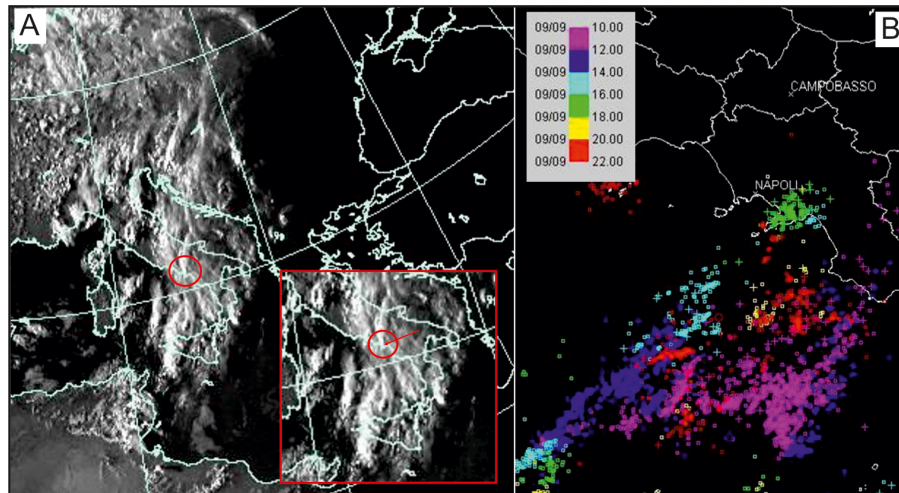


Figure 6. (a) Visible-captured Meteosat-image on 9 September 2010 at 17:00 UTC (modified) showing a mesoscale convective system (MCS) over the southern Tyrrhenian Sea and south Italy. Inset: detail showing the Atrani storm cell. (b) Thunderstorm activity on 9 September 2010. Intense electric activity is recorded between 14:00 and 16:00 (sky-blue) near the city of Salerno and between 16.00 and 18.00 (green) on the Amalfi Coast.

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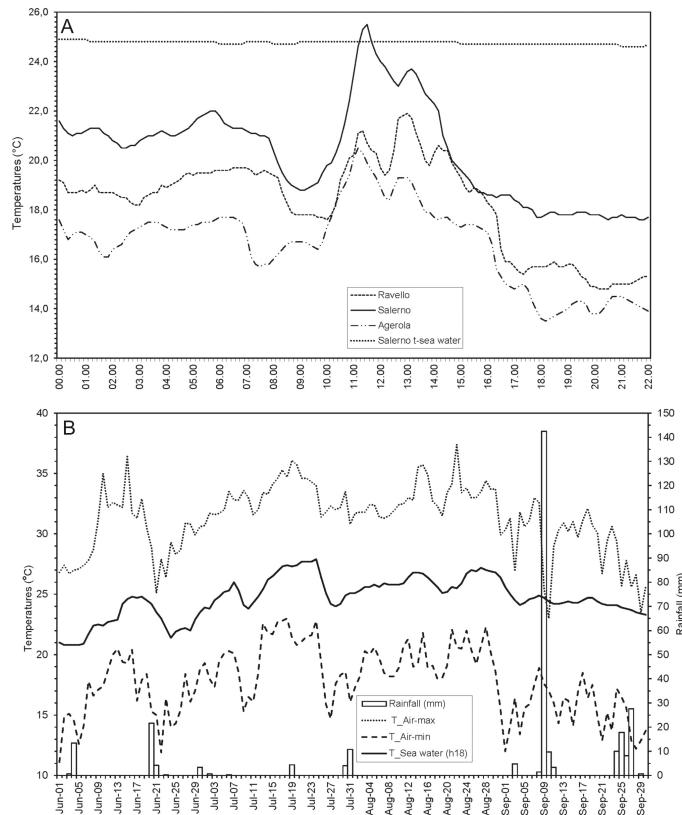


Figure 7. (a) Air and seawater temperatures at 10 min interval on 9 September 2010. (b) Rainfall intensity and air (min and max) and seawater temperatures measured at Salerno from 1 June to 30 September 2010. Data from Centre for weather forecast and monitoring of the Campania Region (Biafiore et al., 2010).

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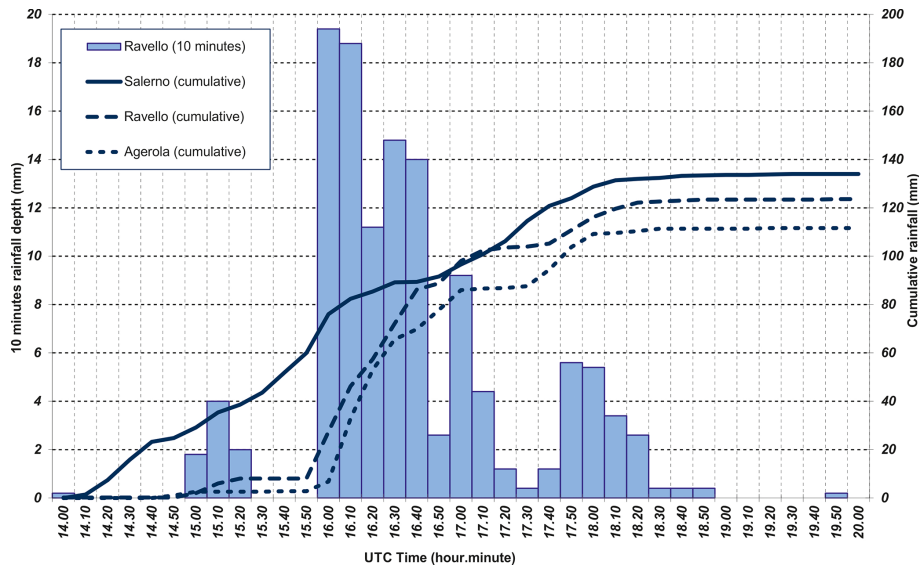


Figure 8. Cumulative rainfall at 10 min interval on 9 September 2010 from 14:00 to 20:00 UTC as recorded by the rain gauges of Salerno, Ravello and Agerola. Rainfall intensity at Ravello rain gauge is also reported. Data from Centre for weather forecast and monitoring of the Campania Region (Biafiore et al., 2010).

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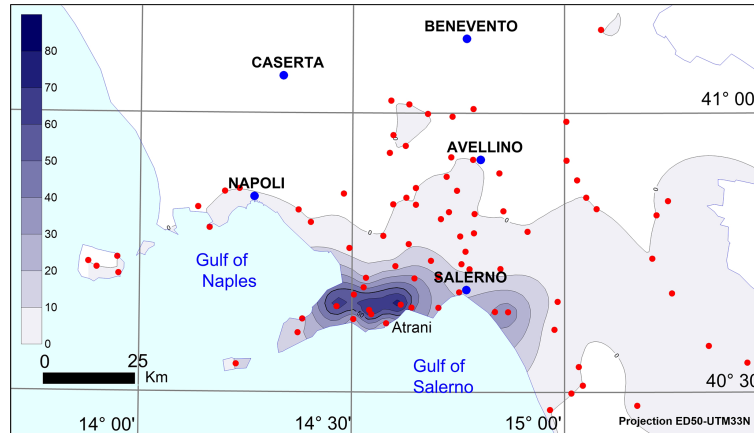


Figure 9. Isohyetal map of the cumulated rainfall from 16:00 to 16:50 UTC. Red dots are rain gauges.

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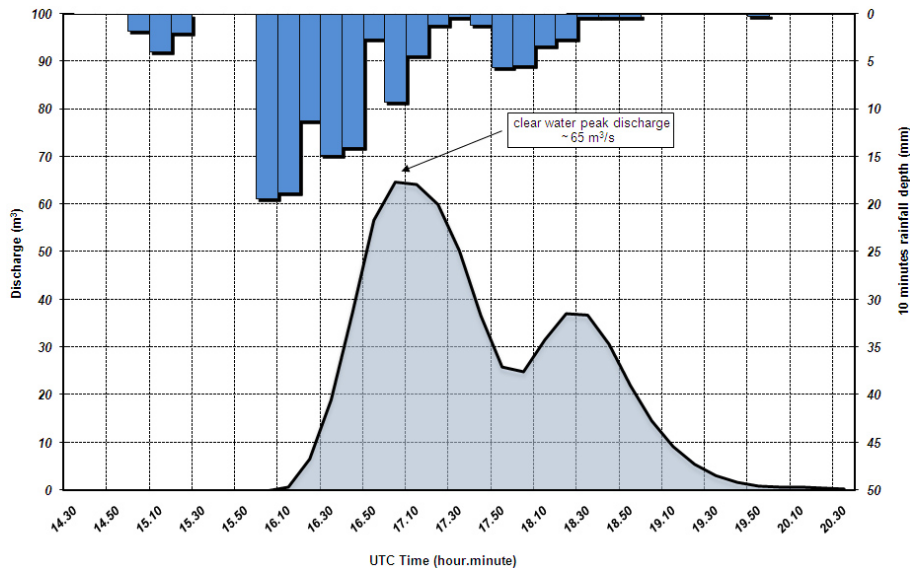


Figure 10. Clear water hydrograph resulting from the hydrological model.

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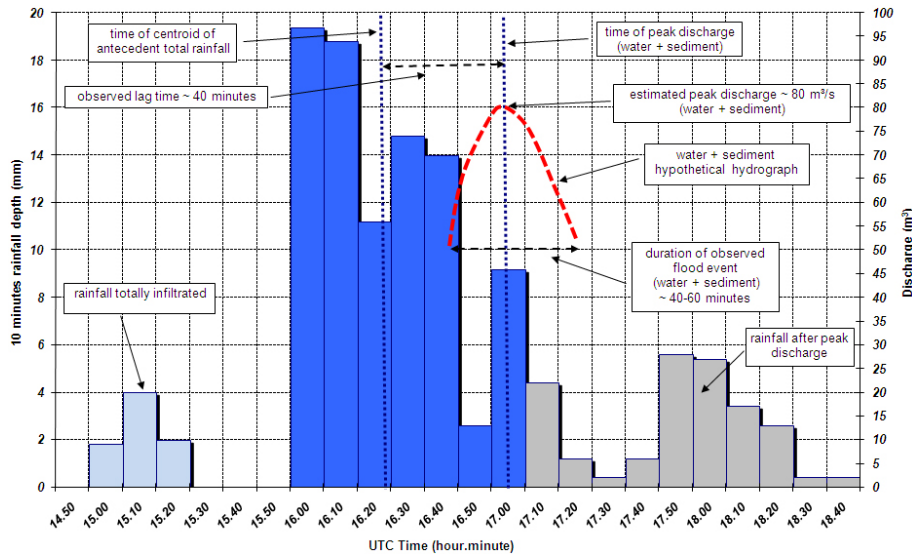


Figure 11. Hyetograph and estimated flood peak discharge.

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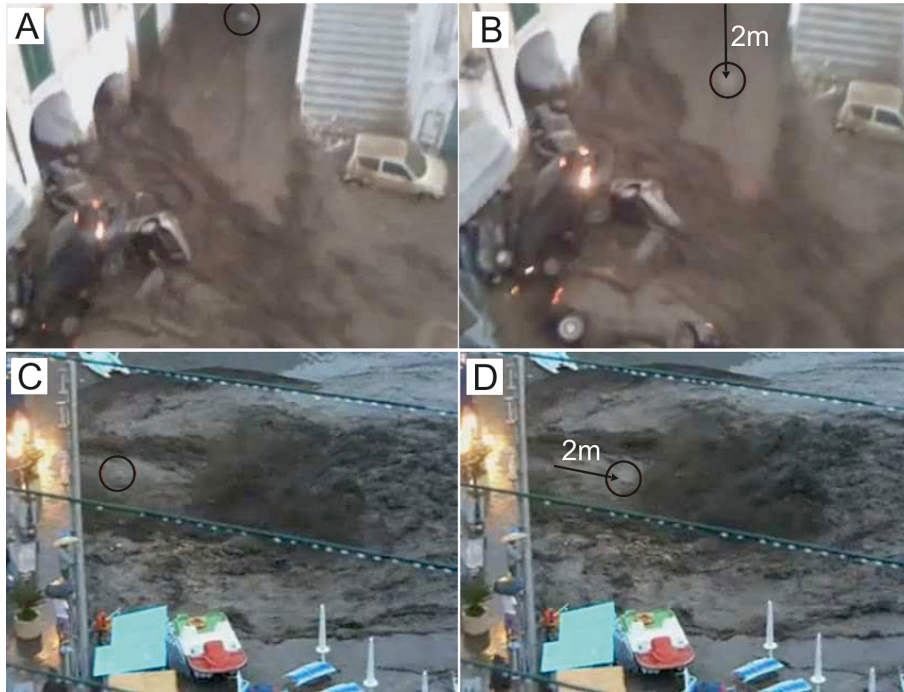


Figure 12. Estimation of flow velocity from amateur videos by tracking selected particles (black circle) transported by flood. **(a)** and **(b)** upper flow along via Dei Dogi. **(c)** and **(d)** entombed flow at the Dragone stream mouth. Location in Fig. 13. See text for discussion.

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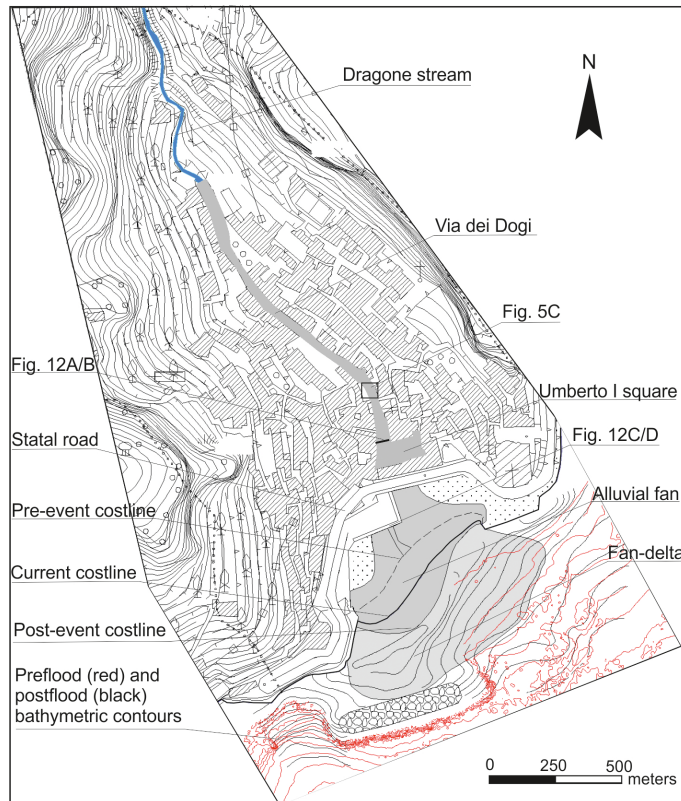


Figure 13. Map of the flooded area with indication of the alluvial-fan and the submerged fan-delta.