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ORIGINAL ARTICLE

An analysis of debris-flow events in the Sardinia Island (Thyrrenian Sea, Italy)

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Abstract On 6 December 2004, the Villagrande Strisaili area (middle-east Sardinia), was struck by debris flows; 330 mm of rainfall took place within 3 h with an hourly intensity of 120 mm, which is far more above than normal for the study area. In the urban center stony and driftwood deposits accounted for a total volume estimated as 10,000 m^3. The event claimed huge amount of infrastructural loss and two human lives. According to the chronicle reports, the area experienced two debris-flow events in the last century. The present paper is the outcome of an intensive study of such debris-flow events including their physical processes and geomorphological effects through both field survey and laboratory analysis.

Keywords Storm rainfall · Debris flow · Sardinia Island

Introduction

Flash flood and debris-flow processes are common natural hazards in Italy not only in the Alpine region but also along the Thyrrenian coast and in the islands (e.g. Iotti and Simoni 1997). Vulnerable geological structure, unscientific and unplanned usage of land along with heavy and concentrated rainfall have led to the occurrence of such vicious hazards which claims huge amount of human life and resource loss, as recently occurred in Southern Italy, Sicily (Bisson et al. 2005) and Sardinia (Canu and Lorenzini 2006).

On 6–7 December 2004, a heavy cloudburst (up to 580 mm of rain in 24 h) struck the middle-eastern part of the Sardinia Island (Mediterranean Sea). The event originated due to the obstruction of a SE–NW flowing cloud by Gennargentu Mountains (1,600–1,800 m a.s.l.). Heavy and concentrated rainfall since 1.00 p.m. on 6 December severely damaged few localities in proximity of the eastern coast of the island and particularly the Villagrande Strisaili area. The rainfall depths recorded at the *Bau Mandara* station (6 km northeast to the settled area of Villagrande Strisaili) attained an hourly intensity of 120 mm and a cumulative value of 330 mm in 3 h. The mountain slope above the inhabited area of Villagrande was affected by severe gullying, soil slips, stream-bank erosion, channel deepening and massive bedload transport along with stream incisions. Alluvial fan sectors were partially re-activated and secondary stream channels were newly originated or rejuvenated (Fig. 1). The incoming fury of water brought down cars, debris, trees and materials of broken houses and two persons died.

Almost all built-up structures of Villagrande were rapidly flooded and invaded by debris mass of all sizes accounting for about 10,000 m^3 as a whole (Tropeano et al. 2005). Anthropogenic intervention has enhanced the consequences of per se critical hydrologic conditions of the stream channels (partly artificially reshaped), like artificial filling of earth material (generated from the cutting of

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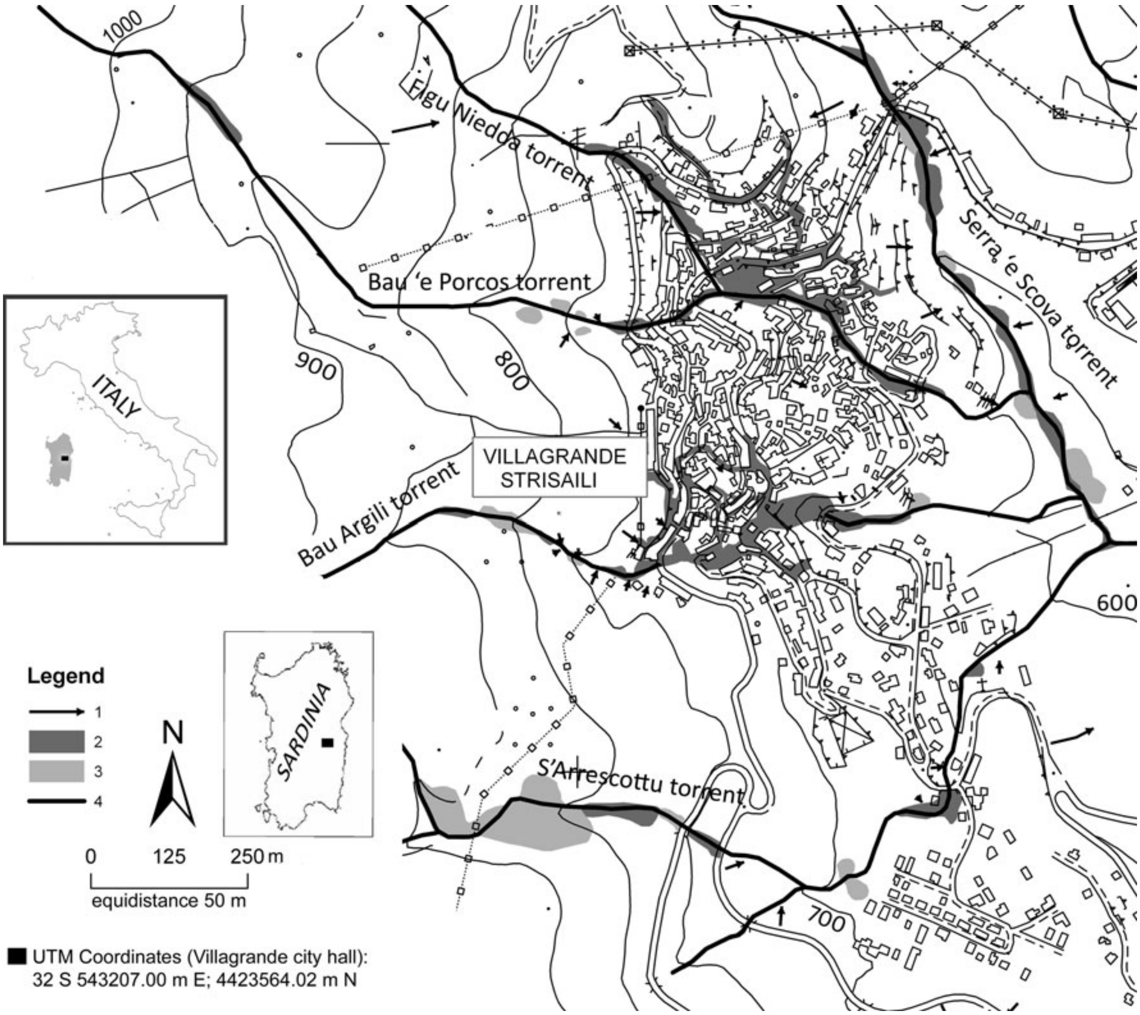

Fig. 1 Effects of the 6 December 2004 event in Villagrande Strisaili area (Ogliastra Province, middle-east Sardinia): *1* soil slip, *2* area characterized by debris torrent and/or bedload processes, *3* area with prevailing bouldery deposits, *4* main drainage network

terraces for cultivation) along the river bank has restrained the stream flow in the mountain reaches. Such conditions favored the genesis and flow of coarse-sediment rich floodwaters down the main urban road network. Road network in the surrounding area was diffusely interrupted due to bridge collapse in three localities.

Regional setting and flood events in the Villagrande area

The "Villagrande" settlement is located along the Eastern slopes of a mountain complex that attains a altitude of 1,360 m a.s.l. Five torrential catchments originated from such slopes, namely *Serra 'e Scova* (2.18 km^2), *Figu Niedda* (0.35 km^2), *Bau 'e Porcos* (0.79 km^2), *Bau Argili* (0.44 km^2) and *S'Arrescottu* (1.25 km^2). After flowing in a South–North direction across the houses (Table 1), the torrents meet with a major stream (*Riu Sa Teula*). The average slope of such channels above the village of Villagrande is about 17 % and average relative relief between the spring zones (1,229 m a.s.l.) and settled area (700 m a.s.l.) is about 530 m. The channel slope of *Figu Niedda, Bau e' Porcos* and *Bau Argili* torrents increases just above the housing sectors, i.e. within a stretch of 540 m channel length the slope varies between 26 and 32 %.

Geologically, the site under study is characterized by Paleozoic formations, composed mainly of shallow-metamorphic schist (arenite, quartzite and phyllar), bearing intrusions of acidic igneous rocks (granodiorite, microgranite, porphyric granite) (Carmignani et al. 1992). They are widely covered with alluvial and colluvial debris of Quaternary origin.

The schist outcrop in N–NE of the Villagrande housing lies in the intrusive granitic belt. Such intrusive body is widely spread in the region and its establishment is to be ascribed to several phases of the Hercynian orogenesis. Other minor units are associated with the facies of "compound layers and basic inclusions", i.e. fine-grained

Table 1 Daily rainfall data of different gauging stations of the hydrographic sector of *Regione Autonoma della Sardegna* (recorded between 9:00 GMT of 6 December 2004 and 9:00 GMT of 7 December)

Rain-gauge station	Elevation (m. a.s.l.)	Daily rainfall (mm)
Bau Mandara	812	590
Bau Mela	812	299
Bau Muggeris	820	548
Sa Teula	251	287
Sicca d'Erba	825	336
Talana	682	500.6
Villagrande	679	428.2
Arzana	674	134.8
Gairo Taquisara	784	206.8
Genna Silana	1,010	283.6
Giustizieri	700	194
Jerzu	550	137.4
Montes	1,060	214.2

granodiorite of shallow depth and microgranular inclusions of dark color. The composition of such facies varies from diorite to tonalite, spheroidal or ellipsoidal in shape and dimensions range from 10 to 30 cm. The post-Hercynian layers include both acidic and basic intrusions and are connected to the late-Hercynian or more recent basement fracture tending in N–S and NW–SE directions.

Tectonic and metamorphic evolution of the basement is rather complex. Several superposed deformation phases have been discerned that can be related to the origin of the intrusive bodies. The setup of the brittle structure of the Hercynian basement began with the post-collision gravitational collapse of the same Hercynian chain that continued throughout the Permo-Carboniferous and Permo-Triassic periods. The structure so originated, after a relatively calm orogenetic period has been affected very marginally by Alpine orogenesis. It has occurred due to the development of a tectonic "spread" as a response to the re-activation of already existing tectonic structures. During middle-upper Pliocene, such structures have almost been stabilized and the landscape modeling processes took place depending on the existing weather conditions.

Morphological and tectonic evolution of the area is primarily conditioned by N–S oriented fracturing systems, further interrupted by cross-directed lineaments of Hercynian origin (Carmignani et al. 1992). The main watercourses along with the minor stream incisions in the middle-east Sardinia have originated from those lineaments, the same has happened to the torrents flowing across the Villagrande built-up area.

Lowering of the Eastern plate has induced rejuvenation in the innermost zones. Increased heavy and concentrated rainfall during the interglacial periods in those areas has resulted in the massive reshaping of reliefs. The slopes in granite are prominent, displaying high relief energy and steep slopes due to erosion. Water divides often correspond to porphyry layers rising above the masses of granite and schist, while the slopes are often steep and composed of bare rocks. The slopes of Paleozoic metamorphic units are round-shaped, incised by ravines and covered with thick alluvium deposits.

Numerous NS, NW–SE and NE–SW oriented open-angled fault and fracture systems are connected with the post-orogenic relaxing forces, favoring bedrock to break down into small fragments and produce detrital cover due to deep chemical weathering. Debris product plays significant role both as filling material into large open superficial cracks (even up to 1 m) and also undergo erosion along slopes. Deep cracks are generally filled with comparatively finer materials (than debris) produced by rock weathering, i.e. coarse sand with low percentage of clay. The prevailing lithology of the area (granite) is accompanied by deep fissures containing water, as evidenced from the existence of frequent springs. Cracks and fissures are mostly responsible for the occurrence of rockfall that constitute big boulders of tetrahedral and prismatic shape. Weathering processes are active since Permian that has diffusely affected the granitic formation thereby producing coarse and fine arkosic sand in situ. Post-orogenic rifting appears as a primary cause influencing the channel deepening processes and by consequence the erosion processes at the foot of slopes; they play an important role in promoting landslide events inside the detrital cover and the weathered layer mentioned above.

The upper part of the five catchments, between 1,000 and 850 m a.s.l., shows sub-rounded, eastward-elongated forms, with exception of the watershed ridges, often bearing outcropping porphyry veins protruding upright from the granitic mass. The granitic slopes of the catchments, since 850 m down to 600 m (above and downslope the settled area of Villagrande) can be recognized by a sharper relief energy; the stream incisions are reflecting the hercynian minor lineaments mentioned above, thus being encased with a symmetrical profile. Throughout the stream network slope erosion processes are well-evidenced in the detrital cover and in the arkosic layer above the bedrock.

The slopes are densely covered with ilex grove (*Quercus Ilex*), an indigenous vegetation type in Sardinia that usually thrives in dry weather conditions. The root apparatus is able to wedge itself inside the cracks of the rock substratum even several meters deep in search of moisture. This leads to a twin effect: firstly, these deeply penetrating roots tend to lose cohesion "embarrassing", displacing the rock elements and favoring weathering. Secondly, the root elements hold the materials so tightly that it (even boulders as large as one cubic meter) often hinders the movement or fall of rock fragments for a long time. It is found that along some of incised stream stretches, weathered rock outcrops/blocks are lobbed around mature tree roots and crop out for several meters above the channel (Fig. 2). Dismantling processes of the basement has generated a detrital cover over the slopes with increasing thickness downslope; the deposits have been modified by man over centuries for agriculture. Pasture (swine- and sheep farm breeding) and cultivation (kitchen gardens) is restrained to few land stripes today. Most of the slopes also bear man-made terraces bounded downslope by stony walls but their regular maintenance is mostly neglected. Their extension is a function of soil depth slope inclination.

Analysis of historical reports through the main regional newspapers reveals that flash floods and paroxysmal sediment transport are rather frequent in the Sardinia Island, especially in late autumn and springtime. The highest rainfall values are typical of the East Sardinia. During the 1960s and 1970s rainfall depths recorded at the station of *Arzana*, 15 km away from Villagrande, are the highest ever recorded in Sardinia.

Fig. 2 On the right bank in the catchment head of the *Bau Argili* torrent, the 2004 flood has generated bank erosion and barking on trees. The plant roots, well developed deep down the granitic bedrock failures, are exerting a "sling" effect on even huge boulders, as is the case here depicted. *Arrow* marks the flow line

Data published on *Annali Idrologici* (Ministero dei Lavori Pubblici 1921–2004), show that the area under study is strongly affected by intense rainfall of short duration and as a consequence is prone to torrential floods. This phenomenon is mainly attributed to the regional orography (a mountain chain oriented N–S, attaining 1,000 m a.s.l., adjacent to the Mediterranean acts as a sudden barrier to the warm and moist air currents coming from the SE) that results in cloudburst, sometime with disastrous effects.

Historical records in different regional newspapers cited above were collected from the University Library of Cagliari since 1895 till date excepting the first half of the twentieth century (those were not found). Since 1940, ten flood events were reported for East Sardinia with an average recurrence interval of 7 years. From the historical records it is found that the area was affected by flood in mid-October 1940 and mid-October 1951. During the later period, almost one-third of the whole Sardinia was hit by intense rainfall of about 400–500 mm in a day. At Villagrande, some houses were destroyed, five people died and the whole area was affected by sudden cloudburst.

Other major flood events were reported during early November 1964 (two victims in East Sardinia), 10–11 March 1965 and 25 October 1965 along with a flash flood on 7 November 1983. In response to such occasions construction of protecting ditches above the mountainous settlements was suggested. At a glance, from past records it appears that the event for the present study is the most severe one till date in the Villagrande area before 2004. Apart from the aforesaid general flood reports, a municipal resolution of 1899 of the Villagrande Municipality (collected from the Municipal archives of Villagrande) depicts that damages through cloudbursts were a cyclic calamity in the Ogliastra Province. It had described the effects of a storm that occurred during that time, which sounds as a true prophecy of the present event and casualty, written one century before—"heavy rainfall bursts in the night of 20–21 October 1899 onto the Villagrande area…torrent floods and overflow all swept away. At the dawn of 21 October the damage was apparent…houses destroyed, gardens disappeared, carts and rural tools carried away together with century old plants, all urban roads were dispossessed of cobbled paving, damaged by gullies of about 2 m deep and infilled with granite cobbles and boulders…It was luck or grace of God that no death was lamented" (translated from the manuscript).

On 6 December 2004, heavy rainfall affected the whole territory of Villagrande Strisaili. It was generated as a consequence of incoming strong warm and moist air masses from the SE, obstructed by the Gennargentu mountain chain and thereby creating a deep convective system. A narrow strip of land was severely affected by such event.

Some inhabitants, yet troubled by strong uninterrupted rainfall, around 16:00 GMT received the sound of "deafening rumbling water never heard before" flowing into the concrete culverts through which the torrents were canalized several years before to cross the settled area. Around 16:30 GMT water started to spring up to the grids attaining 2 m depth from the uppermost bridge on the artificial channel *Rio Bau Argili*. The highest hourly rainfall was recorded between 18:00 and 19:00 GMT (112 mm) accompanied by conspicuous hail-storm; when the first flood pulse took place. As a response to the sudden influx of discharge into the streams, huge amount of detrital and fluidal mixtures including rock fragments, coarse sediments, mud and woody debris were carried down the torrents that spread over the adjoining roads and houses in the village. Soil slips, huge mass transport as well as torrential flood processes with massive debris transport (according to eye witnesses) resulted in the sudden movement of saturated regolith and soil over slopes. Man-made reworked deposits have collapsed and flowed downslope into the stream incisions.

After a short break, stormy rainfall started again around 00:00 GMT and muddy debris flows once more invaded the housings. Such phenomena, according to the eye witnesses, ended in the next early morning.

The flood passage has removed plagues of loose debris from the catchment head of the *Bau Argili* torrent and has exposed its bedrock while the woody and stony deposits were left in situ in an unstable condition. Dense vegetation along valley side slopes and carelessness in the stream flow maintenance have played a vital role in the occurrence of such floods by choking cross-sectional flow and increasing temporary dam effects. It was apparent that the same effects had occurred in several channel stretches containing large boulders (even larger than 2 m of diameter) and other detritus. Failures in such obstructions have suddenly led to the release of conspicuous liquid and solid masses, with a stop-and-go mechanism, progressively increasing downslope (Fig. 3). Debris materials were deposited due to the reduction of slopes resulting in the origin of a number of ephemeral pools that are bordered downstream by major blocks and the channel has been transformed into a "flight of steps" shape. In proximity to the settled areas, uprooted trees were borne and settled down by the floodwaters. Choking of channels due to huge amount of hail has resulted in the collapse of several structures. A first bridge in the locality was destroyed that has hindered rescue operations after the flood. Correspondingly, another bridge downslope has collapsed due to high hydraulic pressure combined with huge amount of detritus. Flow obstructions along the channel artifacts have pushed water and debris mixtures along the adjoining areas causing huge damage to houses, roads, vehicles and other objects.

Along the *Bau 'e Porcos* stream and its adjoining upper catchment area the flood has left clear traces of passage. Numerous erosional phenomena have been encountered that have close association with massive sediment transport

Fig. 3 At the catchment head of the *Bau Argili* torrent, the dimension of the blocks set in motion by the 2004 flood also exceeded 2 m. Stream-bank erosion (*left* on the picture) has removed the uncohesive sediment infilling the bedrock fractures, weakening the stability conditions of the blocks. Flow line (*arrow*) and maximum flow depth (*dashed line*) are indicated

Fig. 4 In the lower catchment sectors in vicinity of the housings, widely diffused, privately owned kitchen gardens, sustained by typical man-made stony walls, were partly invading the flood cross-section of the torrent. Several shallow slides just originated in such terraces, giving an important supply of materials in channel sediments during the 6 December 2004 event. As shown in the picture, such process occurred on the right slope in the upper stretch of the *Figu Niedda* torrent

leaving huge coarse debris in very unstable equilibrium. Forest tracks along the slopes have acted as preferential flow paths intercepting running water on the loose embankment materials resulting in deep gullies. In this case, the intensely fractured and weathered granitic bedrock have appeared to play a key role along the whole channel in the provision of materials. Processes that occurred along the *Figu Niedda* torrent are also similar with the previous one, but it differs from other watercourses due to greater steepness in channel profile and erosional processes operating in the channel bottom. In the catchment head, man-made terraces along the banks were partly removed and reworked and that has increased the sediment load in the downstream section (Fig. 4).

Upper part of the *S'Arrescottu* catchment also exhibits similar characteristics. In the *Bau Argili* and *Bau 'e Porcos* streams there exists several terraces which indicates that the stream became unstable during the flood event and collapsed. The torrent, very much incised in deeply weathered granite has intensely eroded the channel bottom. Its intense erosional capability is also partly attributed to the increasing steepness of the slope. The moving materials left residual of two tier levees on the banks those were gradually taking the shape of debris-flow deposits. Above the "*S'Arrescottu*" bridge, along the periphery of the lower part of the Villagrande village, the cross-section at the mouth of the canalized channel was choked by debris mass and most of the neighboring houses were widely flooded. Running water overflew the bridge, partly destroying the channel downstream, raising up and overturning the structure.

The *Serra 'e Scova* torrent touches the Villagrande village only at its margins. In the catchment head, running water eroded the slope and forestry track embankments were deeply under-excavated that exposed the fractured and weathered granite bedrock (Fig. 5). The torrent caused death of two persons; their bodies were recovered several hundred meters downstream from their house.

Further downstream, the *Serra 'e Scova* enters into the inflowing torrents *Figu Niedda*, *Bau 'e Porcos*, *Bau Argili* and *S'Arrescottu*. Flowing one km downstream through the *Sa Teula* stream it entered the *II° Salto Flumendosa* reservoir which is well known for electric power generation. It continuously supplied huge amount of sediments to the reservoir through the flood event.

Methodology

Immediately after the occurrence of the event, special attention was given to collect both hydrological and geomorphological data, in order to analyze the causes and

Fig. 5 Gully erosion in a forestry track above the Villagrande village (*Serra e' Scova* catchment), produced by intense runoff. In the uppermost part of the village, erosion phenomena are particularly apparent along streams and forestry tracks. As a matter of fact, most of the area undergone to the cloudburst on 6 December 2004 is densely covered by well-managed oak wood, which had exerted a shading effect on the heavy rainfall

consequences of such devastating phenomena. Field survey was carried out, together with photo-interpretation on oblique imagery taken by the Fire Brigade helicopter; onsite photographs were also taken to identify the processes involved during the flood event and post-event effects. Structural and geomorphological measurements, collection of samples from deposited materials and marking the signatures of process dynamics (e.g. to detect flow marks through barked trees, trapped floating twigs, suspended pockets of deposits) have been made in the catchments in order to find out the evidences of pre- and post-geomorphological status of the study area.

Historical documents have been collected from the State Archive at Cagliari and the Municipal Archive of Villagrande to search the records of past events in the locality and surrounding areas.

Maximum rainfall intensity and their corresponding recurrence intervals have been estimated on the basis of TCEV method (Cunnane 1988; Francés 1998). The two-component extreme value (TCEV) distribution is a statistical model widely applied in several Italian regions valuable both at ungauged sites and at short-record gauged sites (e.g. Cannarozzo et al. 1995). The rainfall intensity, which determines the maximum flood discharge (critical rainfall) is drawn by the rainfall possibility curve which expresses the law of variation of annual rainfall maxima as a function of the rainfall duration, by a given event frequency or return period. It has been demonstrated that TCEV model also apply to Sardinia (Deidda et al. 1997) well interpreting the characteristics of frequency of the historical series there recorded; in fact the empirical observation of samples of annual maxima of short-lasting rainfall has lead to recognize the existence of some exceptional values extremely higher than others. The correct statistic interpretation of such extreme values is that to consider them as belonging to a different population, connected to a different meteorological phenomenology, which must be reproduced by the probability distribution law. The peculiarity of TCEV model is just its ability to translate in statistical terms the different provenance of hydrological extremes, formally being expressed as the product of two possibility functions of Gumbel type: the first, called basic component, assumes values as not highest but frequent, while the second, extraordinary component, generates more rare, but in average higher-value events. To reduce in any case the incertitude of estimates, a regionalization procedure is necessary being convinced that the regional estimates of parameters are more reliable than those obtained from local series alone.

Torrential peak discharge of the liquid/solid mixture was drawn by analytical computations, supported by experimental data and analyses. Samples of debris deposits, collected from the affected sites after the event, have been analyzed in determining grain size and rheological properties. The model proposed by Herschel and Bulkley (1926) was applied for rheometric analysis of the samples.

In the laboratories of the of University for Natural Resources and Applied Life Sciences (Bodenkultur University) of Wien a vertically rotating flume (VRF) has been set up in order to test the properties of non-newtonian flowing mixtures under different grain size, water content and viscosity conditions. The main advantage when using VRF is the possibility to establish a motion in stationary conditions over a long time period. When compared to the belt conveyor flume, VRF may more easily be equipped with measuring sensors of given parameters as the axial wringing momentum, normal- and tangential stresses. On other hand, the flow behavior is more complex due to the bending of channel bed and friction effects of the walls which may exceed the effects induced by conveyor belt apparatus.

The instrumentation has been calibrated at first by using on-market available homogeneous visco-plastic materials, then making use of several debris-flow samples (Kaitna and Rickenmann 2007; Kaitna et al. 2007), obtaining flow parameters of the Bingham model, then compared with results gained independently for the same samples through a conventional rheometer with coaxial cylinders (Bohlin Visco 88BV), a Conveyor Belt Flume and a Ball Measuring System developed and implemented in the Paar Physica MCR 300 Rheometer (Muller et al. 1999).

For the present research we have choose to deeply investigate the rheologic properties of the materials involved in the event here in study, in order to acquire a better knowledge of the phenomenon and to properly define it in order to make comparisons with other debris-flow processes of different type. Aiming to make experiments on samples bearing grain size in adequate scale to represent the materials involved in the 6 December 2004 event in the S'Arrescottu catchment (the largest one out of the five catchments here in study), natural samples have been collected from the flow matrix (in which floated even coarse clasts) from flow lobes recognized in the immediate post-event. A suitable amount of materials, ca. 1 m^3, was sent to the above mentioned laboratories in Wien, where tests have been made on parts of the sample materials with different grain size and water content (Demurtas 2011). The results have been analyzed aiming to try to extrapolate the tendency which allows evaluating the rheologic behavior of the whole sample under different solid concentration values per volume unit (ranging volume between 50 and 70 l per sample; concentration varying between 0.32 and 0.70). Grain-size analysis allowed at first to detect some differences between the pure sandy matrix which characterizes the debris flow here in study and the composition of classic mud suspensions, so defined for a composition made by particles lower than 0.04 mm in diameter in a percent less than 10 (Coussot 1994). As clearly appears from the results, the whole sample shows, beyond a sharp majority of purely sandy passing, a maximum boundary of 8 mm. Remembering that matrix-supported coarser clasts have been excluded in the analysis, one may immediately notice that the per cent weight of the grains accounting for few cm size is slightly above 1 %. Thus the assumption of the 8 mm as boundary value for test purpose may be deemed correct.

Another test has been made on a sample fraction with maximum diameter equal to 1 mm which represents both an intermediate value between the samples considered and in the complexity of materials took into account the fraction with the largest retained value. The tests on materials of $d_{\max}$ 0.125 mm have been made through a conventional rheometer, the Bohlin Visco 88 Viscometer of Bohlin Instruments®, provided with two coaxial cylinders into which mixtures have been placed with different water content: while a cylinder sets materials in motion the other measures the shear strength according to deformation rates imposed by a specific software.

The other tests have been developed through VRF, purposely calibrated to carry out for the first time experiments on samples arising from Sardinia. Such instrument, in form of a flattened drum, accounts for 2.46 m diameter. The inner side of such circular channel is made fluent to avoid possible flow turbulence due to curvature unevenness of the channel bed. The channel section is rectangular, 0.45 m wide and confined from one side by inoxid steel and from the other by a acrylic glass to allow lateral watching of the flow. To avoid sliding of materials toward the channel bottom, the inner circumference has been made wrinkled through a synthetic net 1-mm-thick and 5 × 5-mm mesh. The vertical flume is fixed at one side. The maximum speed rotation supplied though a transmission engine is 32 r.p.m. equaling ca. 4.2 m/s at the circumference. Between the transmitting unit and the drum axis a flange and a friction intake are inserted. The first one records the wringing momentum developed by the motor to set at constant speed the flow of materials, the second is amorcing the fluctuations induced by the transmitting unit. Along the circumference of the drum nine sensors are placed in order to record shear stress, normal stress, neutral pressure, flow wave geometry and surface velocity of the flow inside the channel. All data are amplified and transferred on pc, in order to be treated through the Catman® Professional software and cleaned from noise effects through computational script developed in Mat-Lab environment.

An important aspect of debris-flow analysis is the determination of the solid content during peak flow period. This in general depends on the nature and amount of liquid flow during such period. Starting from the hypothesis of an unlimited sediment source, we must calibrate the result in terms of the actual erosive power of the torrent and the availability of erodible material. With the value of peak liquid flow Q_{lmax} corresponding to a recurrence interval of 200 years, the volumes of solids and water in debris flows Q_{dmax} have been estimated on the basis of following method (Eqs. 1 and 2) (Takahashi 1978, 1981):

$$Q_{\mathrm{dmax}} = Q_{\mathrm{lmax}}(C^*/C^* - C) \tag{1}$$

The formula can also be expressed as:

$$Q_{\mathrm{dmax}} = Q_{\mathrm{lmax}}k \tag{2}$$

where, $k = (C^*/C^* - C)$; C^* is the concentration of maximum "packing" or the static concentration of sediments, that is, the concentration before the material becomes mobilized (C^* values can be 0.65–0.7); C is the balanced volumetric concentration of the stationary front of the moving flow.For determining the balanced concentration the following three formulae (Eqs. 3, 4 and 5) have been used:

$$C = [\rho \tan\beta/(\rho_s - \rho)(\tan\varphi - \tan\beta)] \quad \text{(Takahashi 1991)} \tag{3}$$

$$C = [4.3C^*(\tan\beta)^{1.5}]/[1 + 4.3C^*(\tan\beta)^{1.5}] \quad \text{(Ou and Mizuyama 1994)} \tag{4}$$

$$C = [2.9(\tan\beta)^2]/[1 + 2.9(\tan\beta)^2] \quad \text{(D'Agostino 2006)} \tag{5}$$

where ρ = water density (kg m^{-3}); ρ_s = solid density (kg m^{-3}); φ = internal friction angle (°); β = channel slope (°).

Equation 3 has been considered for analyzing the flow conditions of debris flow main wave front, whereas whole debris-flow conditions (including both wavefront and tail) has been analyzed on the basis of Eqs. 4 and 5. It is because Eq. 3 (Takahashi 1991) generally gives higher values of the constant k, by which the peak value of the flood hydrograph can be multiplied, giving a more prudential estimate of the debris flow. In some cases concentration can be obtained from experimental data, as considered in the present study. In any case, the aforesaid three methods are suitable for the determination of debris-flow discharge following paroxysmal and heavy rainfall events of producing water inputs for mass transport of materials.

Equation 5 (D'Agostino 2006) is empirical and leads to understand the behavior of debris-flow graph from that of flow hydrograph

Mobilization depends on the critical flow discharge Q_{cr}, that is, the discharge by which the solids begin to flow, under the influence of the liquid flow. The minimal value for the liquid flow, above which movement of solid is activated, has been estimated on the basis of Eq. 6 (Schoklitsch 1957)

$$Q_{\mathrm{cr}} = 0.26\,[(\rho_s - \rho)/\rho]^{5/3}(d^{3/2}S^{7/6})\,B = 0.6\,B(d^{3/2}S^{7/6}) \tag{6}$$

where B = flow channel width (m); d = diameter of the solid elements (m); S = slope steepness feeding the motion (°).

The condition that can be assumed for the starting and cessation of the debris flow corresponds to a flow equal to 2–3 Q_{cr}. The peak debris-flow discharge, however, was determined by calculating the maximum flow condition corresponding to the maximum water flow discharge value.

Results and discussion

Rainfall data pertaining to *Servizio Idrografico* of the *Regione Autonoma della Sardegna* (Table 1) show that the highest rainfall occurred at the stations of *Bau Mandara* (590 mm), *Bau Muggeris* (548 mm), *Talana* (500.6 mm), *Villagrande Strisaili* (428.2 mm) and *Sicca d'Erba* (336 mm). Such rainfall amounts are almost similar with the maxima recorded in Sardinia. More specifically, data collected from *Bau Mandara* (having a rainfall intensity of 553.6 mm in 12 h) is higher than historical values found at the *Sicca d'Erba* locality in the *Ogliastra* Province (close to the site considered here), accounting for 585 and 535 mm in 24 h on 16 October 1951 and 18 October 1940, respectively (Ministero dei Lavori Pubblici 1955) (Fig. 6). The analysis

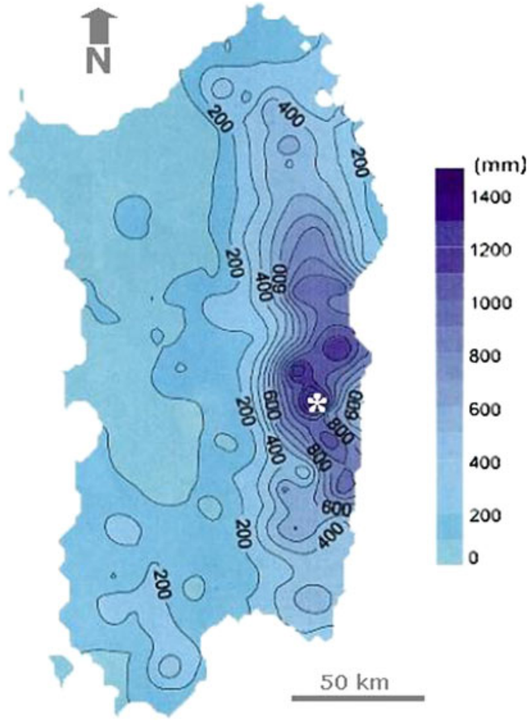

Fig. 6 Isohyets (equidistance: 200 mm) concerning rainfall depth of 15, 16, 17, 18 October 1951 (Image adaptation from *Servizio Agrometeorologico Regionale*-http://www.sar.sardegna.it). *Asterisk* marks location of the Villagrande village (geographical coordinates: see Fig. 1)

of maximum rainfall intensity for 1, 2, 3, 6, 12 h duration applied to Sardinia (Fig. 7) and the corresponding recurrence interval values computed with the TCEV method indicates that the high-intensity rainfall continued for a few hours. In the rain-gauge station of *Bau Mandara* about 77 % of the daily rainfall occurred in the lapse of 6 h. Recurrence intervals of the maximum intensity of rainfall recorded in the region for thousands and ten thousands years, based on which the hydrological models have been prepared, do not match with the short-duration analysis and needs to be changed (Puligheddu 2005).

Rainfall recorded at Villanova Strisaili, only 4 km away from the Villagrande rain-gauge station (belonging to the *Servizio Agrometeorologico della Sardegna*) on 6 December 2004 show the amount of 552 mm in 24 h. The 10 min rainfall graph (Fig. 8) indicates 2 peaks of rainfall at 16:00–16:10 GMT (21 mm) and 22:30–22:40 GMT (21.2 mm).

Grain-size analysis of the sample matrix shows that the proportion of sand was much higher than that of silt and clay. Two other samples of channel sediments were collected from two different streams *Bau Argili* and *Bau'e Porcos*. The first sample was collected from the catchment head zone (left alluvial bank, a matrix of an old deposit) and the second one from a stretch of upstream to the village (left bank, a fresh deposit). The resulting mean diameters of particles (D50) are 1 mm and 0.5 mm for *Bau Argili and Bau 'e Porcos*, respectively. In both samples coarse sand and gravel prevail (48 and 30 % respectively) and the finer fractions are the same (medium-to-fine sand 18 %, silt 4 %). The result confirms the fact that the debris-flow matrix was mostly composed of arkosic sand produced by the degradation of granite and was present in the stream channels.

From the said analyses the rheology of the samples belonging to pseudo-plastic fluids has been classified. In particular, the samples analyzed for shallow deformation rate revealed a parabolic, pseudoplastic behavior that followed the Herschel and Bulkley (1926) model. For high deformation values, the material tends to assume Bingham behavior; the rheological properties vary exponentially with the concentration of the solid fraction.

The value of the coefficient (*C*) has been obtained to estimate balanced solid concentration, a parameter which

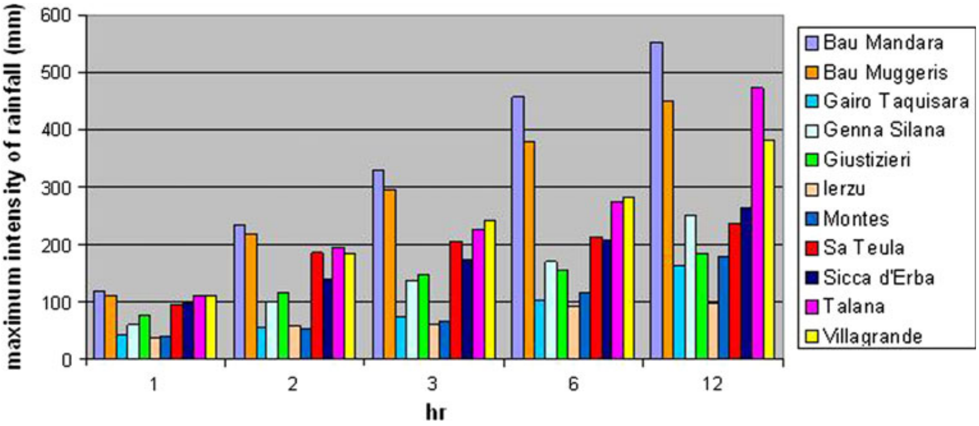

Fig. 7 Maximum intensity of rainfalls (mm) during the event of 6 December 2004

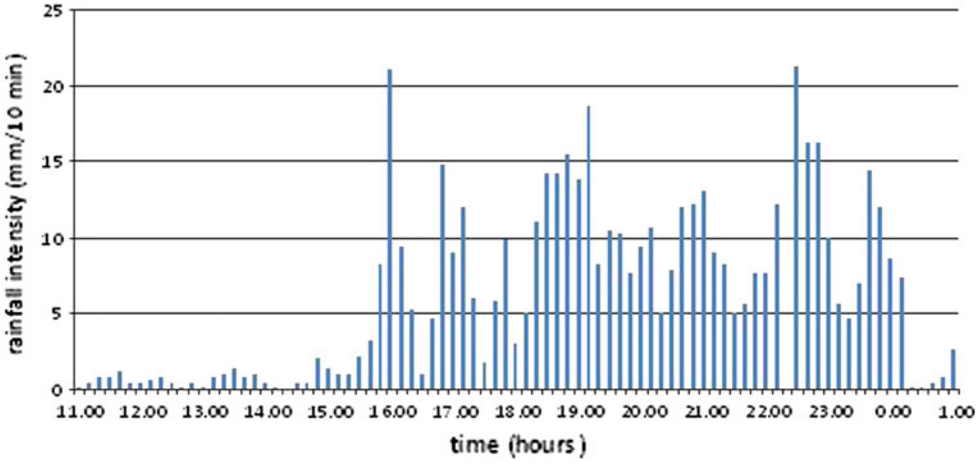

Fig. 8 Rainfall intensity (mm/10 min) data at the Villanova Strisaili rain gauge (*Servizio Agrometeorologico Regionale*), ca. 4 km west-northward from Villagrande, recorded from 11:00 GMT of 6 December 2004 to 01:00 GMT of the following day

Table 2 Maximum solid discharge of four stream catchments above the urban centre with a return period interval of 200 years

Catchment (flow section above the urban center area)	Area considered (km^2)	Main channel length considered (km)	Slope (%)	Concentration time (h)	Maximum solid discharge (m^3 s^{-1}); return interval 200 years
Figu Niedda	0.13	0.37	25.08	0.17	23
Bau ‘e Porcos	0.33	1.12	17.67	0.29	60
Bau Argili	0.31	1.32	16.97	0.23	48
S’Arrescottu	0.34	0.74	13.98	0.21	36

has a major influence on the peak solid discharge. It was observed that the solid concentration for velocities above 6 m s^{-1} has naturally developed in front of the flow direction. Considering the largest particles for the present experiment the value of C was found to be 0.42 which indicates that movement of solid particles depends on the discharge and velocity of the flow.

From the functional behavior of the water discharge hydrograph with a recurrence interval equal to 200 years as well as from the concentration time, we have received moderate to high amounts of debris-flow discharge (23, 60, 48 and 36 m^3 s^{-1} for the river catchments of the *Figu Niedda*, *Bau ‘e Porcos*, *Bau Argili* and *S’Arrescottu*, respectively) at peak flow corresponding to the return time Tr$_{200}$ (Table 2).

Analysis of the results above illustrated allow a better understanding of both causes and development of the event in study. Persistent and intense rainfall acted on the pore pressure of the loose materials covering the slopes and just above the stream channels inducing evenly distributed saturation and fluidization processes. By consequence, this allowed discrete portions of soil including rock fragments and boulders to be detached by weathering process and all other stony and vegetal detritus in the topsoil to collapse by rotational or translational sliding. Along the stream incisions, the materials were set in motion owing to the sudden increase in discharge, temporarily clogging of the flow section rushing downstream by dam-break effects.

Man-made terraces for kitchen gardening along the channel banks or even intruding into the channel flow section have been involved in the failure process giving rise to shallow slides (mostly soil slips). Besides a lot of materials are also supplied by gully erosion on the slopes and discharged directly in the channels or along flow directions. This has led to an increase in the bedload. Paroxysmal bottom erosion has produced channel undercutting, locally up to 1–2 m deep in the arenitic granite (*Rio S’Arrescottu*) sometimes re-exhumating the bedrock.

Onsite survey in the middle-upper reach of the channels has put in evidence old detrital deposits along the streams, primarily supplied by past floods or rockfalls from the rocky walls bordering the incisions. Such deposits look as reworked in most cases by massive transport, connected to pulsatory flood sequences, bearing unstratified clasts of all sizes, structurally chaotic in texture, with sand matrix prevailing. Such morphology and mode of deposition is likely inherited from past debris-flow events. We also noticed that the banks were void of slurry traces of the flood peak passage; instead, bark pieces scraped off and shock signs on the tail of trees were frequently observed that as marked the maximum flow depth attained. It was also witnessed that boulders and coarse sand prevailed among solid mixture components in a relatively “clear” floodwater. On the contrary, the finer deposits left in the houses and along the lower road trunks are a proof of low-energy, sediment-laden flood waters.

Table 3 Morphologic and hydrometric parameters of the Villagrande Strisaili catchments

Catchment name	Total catchment area (km^2)	Total main channel length (km)	Catchment slope (%)	Concentration time (min)	Maximum peak discharge (m^3 s^{-1}); return interval 50 years
Serra‘e Scova	2.18	3.28	14.96	29	65.8
Figu Niedda	0.35	0.703	25.14	9	18
Bau‘e Porcos	0.79	1.19	18.13	16	31.3
Bau Argili	0.44	1.35	11.91	14	18.1
S’Arrescottu	1.25	1.24	13.98	23	42
Total	5.01				175.2

Concerning the flood in the housing of Villagrande, it strikingly appears that the response of the five torrents to the extraordinary rainfall was almost instantaneous due to their extremely short concentration times, ranging from 9 to 29 min (Table 3).

Final comments

The flood passage into the stream network inside the village of Villagrande has been conditioned significantly by several factors such as: strong hourly intensity of rainfall, small dimension of the catchments, steepness of slope and marked average inclination of the channels. In addition, the structural conditions of the bedrock, controlled by three main fault and fracture families, is the primary factor in mechanical dismantling of the substratum and penetration of water leading to weathering effects. This has resulted in more or less diffused detrital cover in which large blocks or boulders were emerging disarticulated that rolled down from the slopes into stream incisions and were further carried downstream during flood. Under such conditions of short-duration, intense and localized rainfall in the evening of 6 December 2004, the transport of conspicuous volume of solid materials concentrated with water was triggered.

From the historical records of rainfall at the Villagrande station since the nineteenth century it is clear that the area experiences a rather high frequency of intense rainfall events. But it was only in the following 2 years 1940 and 1951 that such events of torrential sediment transport was reported.

The event of December 2004 occurred suddenly, affecting the inhabitants by quickly invading the roads and swept away all things along its ravaging floats. Subsequent to such casualty, the nature of change in the dimensions of channel artifacts, like the reduction of a sharp cross-section in the settled area, has been noticed with the support of solid and liquid masses, displaying high-intensity characteristics both in terms of magnitude and amplitude of the phenomena. The road crossings in the settled area and along the provincial roads showed failures in the planning stage, conditioned in shape and functions due to high volumes of water discharge. In the stream reaches above the settlement, runoff was mainly concentrated along the stream incisions and forestry tracks. A good optimization of the regime can be visualized around the vegetation covered areas. As a matter of fact, the vegetation-void areas have undergone soil erosion. The improper maintenance of the man-made terraces employed for agriculture partly contributed to bank failure along the torrents due to insufficiency of the reinforcement structures.

Another key factor in the debris delivery is the condition of the bedrock masses in which the torrents are incised. Continuous disruption and weathering effects lead to the disarticulation of blocks and thereby a progressive increase in the material load liable to be set in motion. Lesson must be taken from such events towards the formulation of firm resolutions in land interventions, both in terms of restoring protective works and in terms of urban planning. In the context of coping with the hazard and reducing future risk situations connected to paroxysmal events, the past chronicles proved to be cyclic. In other words, both recent and old collective historical records must be considered by the community for future planning.

Analysis of past events (which forms part of the method applied in the present study) could be deemed as a first step toward an urgent research project. The various historical archives of Sardinia may prove helpful pertaining to data towards the prevention of further consequences of streamfloods in the recently developed urban sites. Combining historical reports with rainfall series and applying geomorphological research methods for obtaining effective semi-quantitative hazard maps may prove effective.

The facts here exposed once again demonstrate the glaring necessity towards effective town planning schemes; especially in the light of past flood risks prevalent prior to two or three generations.

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