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THE ROLE OF VOLCANIC AND ANTHROPOGENIC ACTIVITIES IN CONTROLLING THE EROSION PROCESSES AT VULCANO ISLAND (ITALY)

ABSTRACT: DI TRAPANI F.P., DI MAGGIO C. & MADONIA P., *The role of volcanic and anthropogenic activities in controlling the erosion processes at Vulcano Island (Italy)*. (IT ISSN 0391-9838, 2011).

The paper describes the erosion processes acting at La Fossa cone (Vulcano Island, Italy). La Fossa cone is a stratovolcano made up of pyroclastic deposits and lavas covered by tuffs from the last eruption, dated 1888-90. Its flanks are affected by intense water erosion phenomena leading to the formation of denudation surfaces due to sheet erosion, rills, gullies and small canyons. As a consequence of very intense rainfalls, episodic debris flows occur along main gullies and canyons. Fumarolic activity plays an important role in the control of erosion processes, being both an obstacle for the growth of vegetation and a weathering factor. The GIS analysis and comparison of geo-referenced maps and aerial photos highlighted the influence of man-made structures on erosion processes, with particular reference to deep modifications in the natural stream network induced by buildings and roads. The combined effects of volcanic and anthropogenic activities, together with the additional role played by the strong inter-annual variability of rainfall amounts and intensities, give rise to significant changes in water erosion rates. A total volume of 5,700 m^3 of volcanic products eroded between the years 1980 and 2008 from the upper portion of La Fossa cone has been estimated by GIS analysis.

KEY WORDS: Anthropogenic activity, Erosion processes, GIS, Volcanic activity, Vulcano Island.

INTRODUCTION

Volcanoes result from endogenous processes that directly create and destroy primary landforms (e.g. Thouret, 1999; Hampton & Cole, 2009). Unlike ordinary mountains, volcanoes are constructed rapidly and usually have a short-term existence; as a consequence of their rapid construction, many volcanoes are affected by intense erosion.

Water erosion is an important process in volcanic environments as it acts as a detaching and transporting agent. Detachment of soil is produced by raindrop impact and drag force of running water. Eroded particles are transported by overland (sheet or interrill erosion; sheet flood) and concentrated (rill erosion) flows (Lal, 2001); gullies can develop by sub-surface flows and sidewall processes (Bocco, 1991). Generally, water erosion is controlled by a number of factors such as weathering, climate, structure (tectonics and lithology), topography and anthropogenic activity. Particularly, human modification of the relief commonly produces accelerated erosion and concomitant environmental degradation.

The structural instability of the volcanic edifices also favours slope failures. These processes may produce collapses and landslides such as extremely mobile debris or mud flows that can travel at high velocities and for long distances beyond the flanks of volcanoes (Ferrucci & *alii*, 2005 and references therein). Debris flows are usually triggered by heavy and/or prolonged rainfalls and can start as landslides on hillslopes (e.g. Iverson & *alii*, 1997; Wieczorek & *alii*, 2000) or from bed erosion in steep channels (e.g. Tognacca & *alii*, 2000).

Tests and evaluation of erosion models are carried out through modern technology that provides efficient tools such as remote sensing and satellite imaging, GPS, GIS and expert systems (e.g. Ciccacci & *alii*, 1981; Sidorchuk & *alii*, 2003; Vrieling, 2006; Conoscenti & *alii*, 2008; Nigel & Rughooputh, 2010, and references therein).

The study presented herein constitutes an example where more tools, such as field survey, remote sensing and GIS, are integrated to determine the sensitivity of a volcanic area (La Fossa cone, Vulcano Island, Southern Italy) to denudation processes and its controlling factors, with particular reference to the relationships between volcanic and anthropogenic activities.

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STUDY AREA

Vulcano (fig. 1) is the southernmost island of the Aeolian Archipelago (South Tyrrhenian Sea, Italy), made up of 7 back-arc volcanic islands related to the subduction of the African under the European Plate (Barberi & *alii*, 1974). Its latitude and longitude are comprised between 38° 21' and 38° 25' N and 14° 56' and 15° 00' E respectively. It has a sub rectangular - sub elliptical shape with an 8 km NW-SE major axis and a 4 km NE-SW minor axis; its surface area is about 22 km^2.

The island is made up of three distinct topographic patterns built up by eruptions, tectonic movements, collapses and denudation processes:

1) Vulcanello, a volcanic edifice composed of three small pyroclastic cones (highest elevation 123 m a.s.l.) and a undulating lava surface characterised by gently dipping low relief.
2) La Fossa area, a caldera depression opened toward north and limited by semicircular-shaped rather steep slopes, inside which a broad cone with steep flanks and a funnel-shaped crater is located (maximum elevation in the eastern rim sector at 391 m a.s.l.). La Fossa area is connected northward to Vulcanello through a flat isthmus (tombolo).
3) Vulcano Piano, the relict of a caldera depression, made of a tabular relief bounded by steep slopes, that reaches a maximum height of about 500 m a.s.l.

The studied area is located in the northern sector of Vulcano Island, inside the topographic depression of La Fossa caldera, within which La Fossa cone, a small stratovolcano with an altitude of 391 m a.s.l. and about 1 km basal diameter (fig. 1), has grown over the past 6000 years (Ventura, 1994).

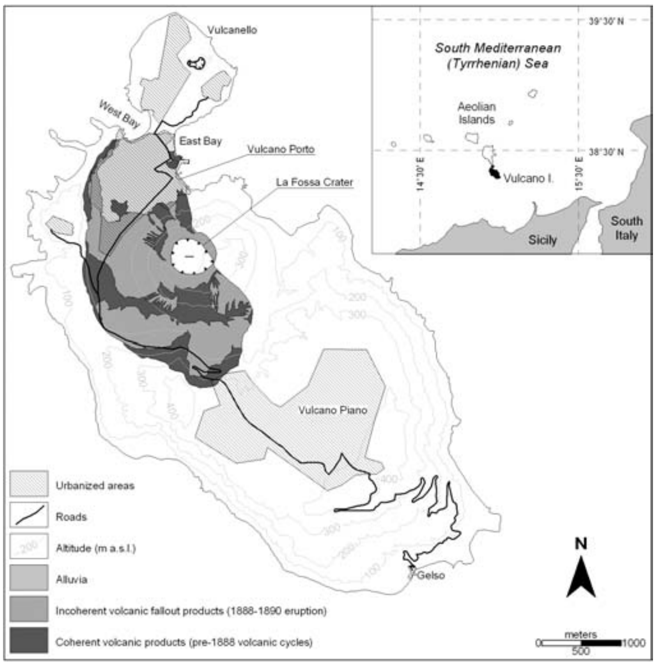

FIG. 1 - Map of Vulcano Island with the lithological classification of the studied area (simplified from De Astis & *alii*, 2006).

The last eruption occurred at La Fossa cone in 1888, lasted two years and was characterized by the deposition of fallout products of huge dimensions (bread crust bombs up to 2-3 m in diameter). Since the last eruption, Vulcano Island has been characterized by fumarolic activity, mainly concentrated in the inner northern flank of La Fossa cone (high temperature fumaroles up to 700 °C during periodic volcanic crises) and from two secondary peripheral fields located close to the sea in the northern (East Bay) and southern (Gelso) sectors of the island. According to Badalamenti & *alii* (1991), fumarolic (high temperature) fluids mainly consist of water vapor (80-96%$_{vol}$) and CO_2 (3-17%), with minor but significant amounts of acidic species (0.2-1.1% SO_2, 0.4-1.2% H_2S, 0.3-0.9% HCl and 0.03-0.24% HF). Percentages of acidic species are sensibly lower in the peripheral, low-temperature fumarolic emissions; due to their affinity for liquid state water, acidic gases concentrate in the vapor fraction condensed into the soil, whereas the residual fluids emitted in the peripheral fumaroles are mainly constituted of water vapor and CO_2. Diffuse CO_2 emissions from the soil have been also recorded all around La Fossa cone (Diliberto & *alii*, 2002).

Petro-stratigraphic features of La Fossa products have been widely described by several authors (De Astis & *alii*, 2006, and references therein). Taking into account their potential role in erosion processes, the volcanic products outcropping in the studied area may be grouped in three main classes (fig. 1):

a) Fluvial, slope and coastal deposits, derived by water erosion of the volcanic products and mass movements, and their accumulation in the coastal flat area.
b) The 1888-90 eruption incoherent products, consisting of an upper member, up to 2 m thick, mainly made of dense lapilli tuffs, with intercalated thinly bedded tuffs (fallout deposits). At its top are dense lapilli and blocks and scattered bread-crust bombs (up to 2 m). The lower member is a pyroclastic succession up to 4 m thick consisting of alternating tiny to medium bedded ash deposits, ranging from massive to asymmetrically laminated (dry surge deposits) and thin massive pumiceous lapilli beds, with isolated bombs (De Astis & *alii*, 2006).
c) The pre-1888 products, consisting of alternating successions of pyroclastic products and lavas, with very different thicknesses and petrographic characteristics.

The climate of Vulcano island is semi-arid Mediterranean; the data available for the period 1965-94 at the closest station of the regional agro-meteorological network (Salina Island, Aeolian Archipelago) report (all on yearly basis) a mean temperature of 18 °C, with the lowest temperature in January (11.8 °C)) and the highest temperature in August (25.9 °C); the mean annual precipitation is 615 mm, mostly concentrated between October and February.

Dry conditions prevail in late spring and summer, although short-lived thunderstorms can occur.

METHODS

To consider all the processes acting on a physiographic unit where anthropic and volcanic activities are both ongoing, the study has been focused on the coastal alluvial plain of Vulcano Porto and La Fossa cone, both comprised within the unique watershed represented in fig. 1. In order to define denudation processes and their controlling factors, and estimating the eroded rock volume, geomorphological studies have been performed on the selected area by means of field surveys and interpretation and comparison of topographic maps and aerial photos taken in different years.

Topographic material refers to the IGMI 1:25,000 map 244IIISE (last updated in the year 1958) and the 1:10,000 section 581160 of the Sicilian technical regional cartography (CTR in Italian), realized in 1990.

The maps have been compared with aerial ortho-photos (1:18,000 nominal scale) available on line via a web GIS server at the URL http://www.sitr.regione.sicilia.it/content/view/28/52/.

Geo-referenced maps and aerial photos have been analysed and compared using the ESRI ArcGis software (release 9.x).

DATA AND RESULTS

Geomorphological setting

The flanks of La Fossa cone are structural slopes originated by the emplacement of the volcanic products and characterised by moderate dip (30°-35°). A number of denudation surfaces, due to sheet erosion, rills and gullies affect the slopes (fig. 2). Generally, denudation surfaces, small rills and minor gullies are located in the upper portion of the flanks, where water erosion has wholly dismantled the most recent (1888-90) products and exhumed the underlying volcanic cycles; major gullies develop in the upper and middle portion of the slope, intersecting both the youngest and older volcanic deposits. Gullies show depths ranging from 0,5 to 3 m, maximum length of about 500 m and width between 0,2 and 1,5 m. Moving downslope, some gullies evolve into stream channels, sometimes creating canyon-like valleys of small-depth.

Rills, gullies and stream valleys are radially oriented from/to La Fossa eruptive vents, following their primitive slopes; consequently, narrow (at vent tops) or wider (at vent bottoms) ridges with triangular shape (planèzes), are interpreted as inverse forms originated by radial incisions, representing the least eroded surface of the primitive volcanic cone. At the crater base, run-off waters from all the incisions are received by temporary creeks with semicircular trends, which flow toward the NE coast.

During thunderstorms, episodic remobilization of pyroclastic material generates small volume debris flows, moving downslope water-saturated masses of volcanics along gullies and canyons and giving rise to small landslide cones at their ends. Debris flows are initially supplied by the 1888-90 incoherent products, resting on the less permeable substratum, whereas the channelled erosion of the underlying tuffs adds significant amounts of mud to the initial flows (Ferrucci & *alii*, 2005).

More deep-seated mass movements mainly affect the NE flank of La Fossa cone, where undercutting processes due to wave-cut erosion trigger rock falls and rock slides. These movements leave only scarps and bare rupture surfaces on the slope, because the landslide deposits are eaten away by marine erosion.

Relationships between volcanic activity and erosion processes

Since the last eruption ended in 1890, volcanic activity at Vulcano Island has mainly consisted of fumarolic emissions. The circulation of water vapour of volcanic origin, associated with variable amounts of acidic gases, exerts several direct and indirect influences on diffuse soil erosion.

As discussed by Madonia & Liotta (2010), the high chemical aggressivity of the fumarolic fluids emitted from La Fossa crater field represents a serious obstacle for the developing of vegetation. In particular, on the northern flank of the cone, soil is completely deprived of vegetation at altitudes higher than 150 m a.s.l. and the incoherent fallout products of the 1880-90 volcanic cycles are completely exposed to the direct action of rainfall.

The circulation of water due to the condensation of volcanic vapor plays opposite roles with respect to the erosion processes, according to the different chemical composition of volcanogenic fluids circulating at increasing distances from the main fumarolic field.

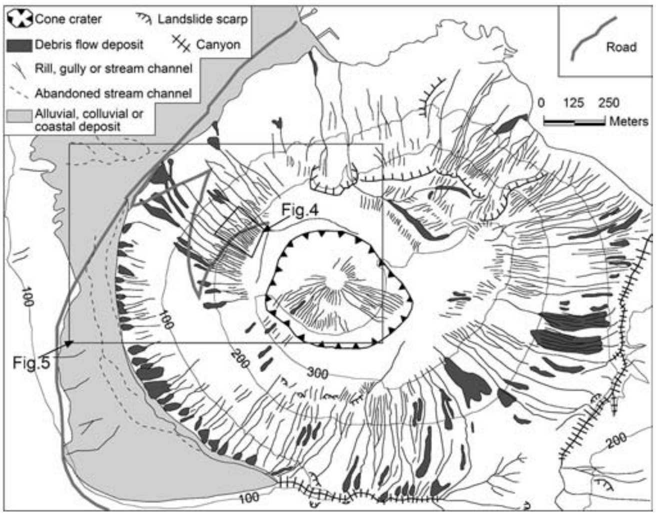

FIG. 2 - Geomorphological map of La Fossa cone.

Close to the high-temperature main fumarolic field, located in the northern sector of the 1888-90 eruptive vent, water vapor is associated to strong acidic species. Water-rock interactions give then place to the formation of a widely distributed coating (Fulignati & *alii*, 2002) that, covering the soft volcanic products, prevent them to be eroded. On the opposite, moving away from the main fumarolic vents, the residual volcanic vapor, strongly depleted in acidic species, condenses into liquid water at the cold rock-air interface without any significant chemical interactions with the volcanic products. The net effect is a constant high water content in the rock volumes around peripheral fumaroles, that favours the loose of coherence especially if the volcanic products are fine-sized incoherent tuffs deposited on steep slopes.

Relationship between anthropogenic structures and erosion processes

In the studied area at least two examples of mutual interactions between erosion and anthropogenic processes may be documented: (i) the superimposition of a heavy urbanized area on the pre-existing stream/gully network and (ii) the local accelerated erosion induced by the carving of an unpaved rock along the northern flank of La Fossa crater.

Figure 3 shows the stream/gully network as mapped in 1958 (IGM 1:25,000 map) with the superimposition of the urbanized area of Vulcano Porto (as reported in the 1990 CTR), built up since the 50's of the last century for the touristic development of the island. As clearly shown on the map, buildings and roads have created a barrage for the natural run-off collected by the streams; in particular, the paved road running along the NE La Fossa cone foothill and sloping down toward the sea, has become the only way for the drainage of the stream network descending from it. As a consequence, during heavy rains, especially in the early autumn, a mixed mud-debris flow is often channelled along the road and discharged into the sea inside the harbour, causing the flooding of all the ground-floors of the buildings facing the road.

A second example of an anthropic structure resulting from failure to take into account the natural high erosion sensitivity of La Fossa crater, is represented by the unpaved road carved along its northern flank after the 1988 volcanic unrest. Ever since it was constructed the road has acted as a channel collecting run-off waters and connecting, through elbows of capture due to up-slope migrating piracy in the stream/gully network upslope, several incisions which before that time flowed straight ahead along the maximum slope with a simple radial course. Figures 4a and 4b, based on a picture taken in winter 2004 and integrated with an in-situ survey, clearly show the described

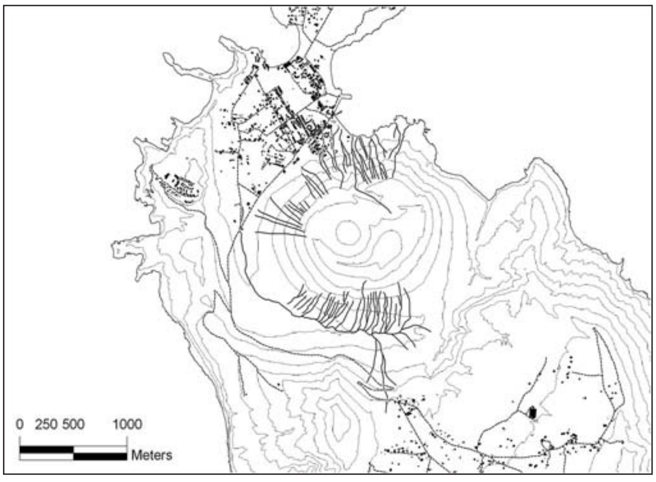

FIG. 3 - Stream/gully network (grey lines) as mapped in 1958 (IGM 1:25,000 map) with the superimposition of the urbanized area of Vulcano Porto as reported in the 1990 CTR (dashed dark grey lines are paved roads, black polygons are buildings); contour interval for elevation lines (pale grey) is 50 m.

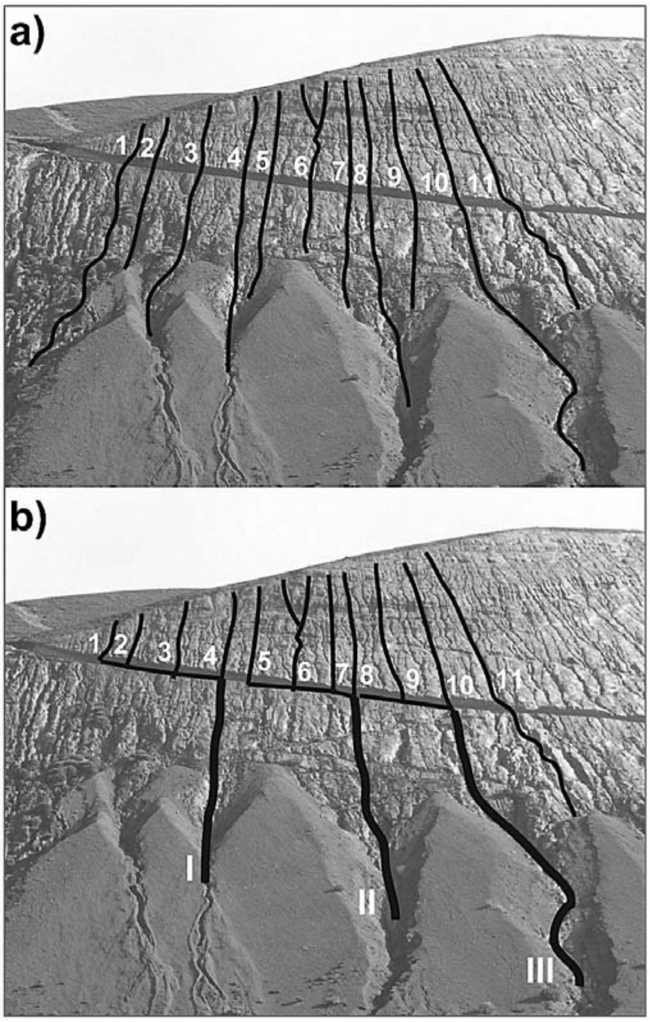

FIG. 4 - From the top to the bottom: a) Picture of the NE flank of La Fossa cone, taken in winter 2004, with the reconstruction of the main stream channel network (black lines, progressively numbered moving downslope) before the carving of the unpaved road and b) the same network in 2004 (the wide black lines with roman numeration are the main outflows downslope the road).

phenomenon. Based on the field survey, the original paths of 11 main channels, progressively numbered moving downslope, were reconstructed and reported on the picture (fig. 4a). After the road construction (fig. 4b), channels #1 to #3 were connected to channel #4, whose outflow downslope the road is reported in the figure as channel #I; channels #5 to #7 were connected to channel #8, whose outflow is channel #II. Finally, channel #9 was connected to #10 (outflow #III) and only channel #11 has remained undisturbed. The final effect on the erosion rate due to the channel network re-organization, consequent to the road construction, is difficult to be quantitatively estimated channel by channel because no data on channel depths are available before the year 2004 and both maps and ortho-photos are acquired at nominal scales not compatible with such a detailed analysis.

However, in the attempt of inferring a comprehensive evaluation of erosion rates changes, geo-referenced ortho-photos taken in the years 1980 (before road construction), 1999 and 2008 (after road construction), were compared. Erosion processes cause a downstream retreat of the contact between the 1880-90 and the older volcanic deposits; the most recent volcanic cycle appears as a grey layer covering the pale pink older cycles, thus their contact is clearly visible on ortho-photos. Areas and perimeters of erosion-exhumed, pre-1888 volcanic cycles outcropping around the channel network have been then measured using ARC/View GIS and the results are reported in tab. 1, whereas fig. 5 shows the comparison between the 1980 (grey) and the 2008 (dashed) limits of these outcroppings. As showed in the table, both area and perimeter yearly erosion rates have more than doubled in the second period (1999-2008, entirely after the road construction) with respect to the previous one (1980-99, roughly subdivided in two quite equal sub-periods before and after the road construction). This observation confirms a possible role for the road constructions in driving erosion, unless volcanic activity and/or rainfall rate variations could be also invoked in the explanation of the observed data. A possible role of volcanic activity in controlling erosion rates can be excluded, because this sector of La Fossa cone is not interested by fumarolic activity and, in any case, the two main volcanic unrests at Vulcano Island occurred in 1988 and 1996, thus both during the first period (1980-1999). Conversely, as highlighted in fig. 6 where hourly rainfall rates measured at Vulcano Island in the period 2006-2010 are reported, impressive year to year variations in rainfall rates normally occur. The comparison of rainfall dynamic between the two periods, i.e. 1980-1999 and 1999-2008, can not be done, because no reliable and continuous rainfall data are available prior to the year 2006 and no extrapolations can be obtained from surrounding stations, because rainfall amounts and intensities change dramatically from island to island and, very often, also within the same island (author direct observations carried out during the period 1995-2010). Thus, a possible effect of changes in rainfall

TABLE 1 - Variations in the period 1980-2008 of area and perimeter of the pre-1888 volcanic products outcropping in the NE upper sector of La Fossa cone

Year	Area (m^2)	Area erosion rate (m^2/y)	Perimeter (m)	Perimeter erosion rate (m/y)
1980	51374		2091	
1999	52330	101	2314	12
2008	54250	213	2551	26

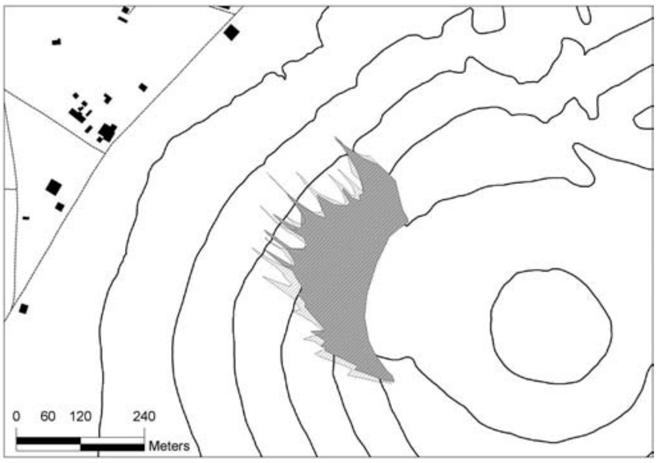

FIG. 5 - Comparison between the outcropping of pre-1888 volcanic products in the NE-upper portion of La Fossa cone as reported in the 1980 ortho-photos (grey polygon) with the same outcropping as in the 2008 ortho-photos (grey dashed polygon).

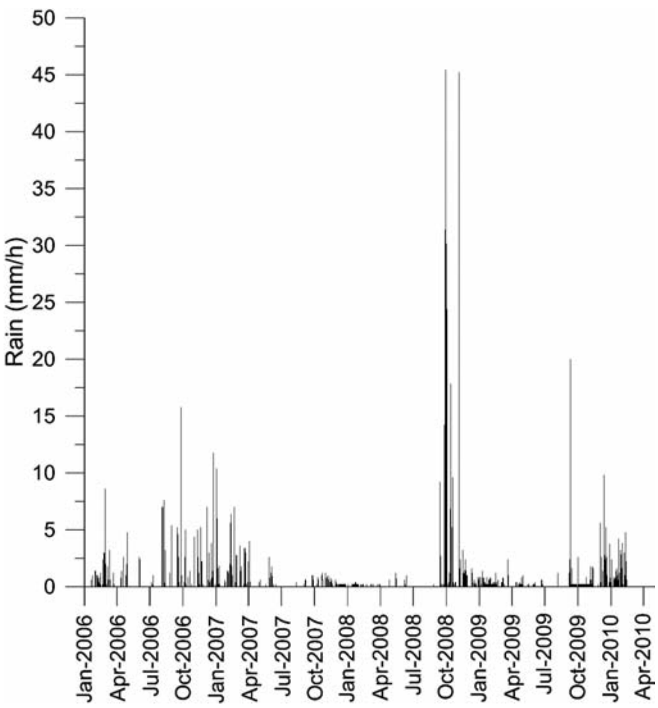

FIG. 6 - Hourly rainfall amounts measured at La Fossa cone (data from INGV, Sezione di Palermo database) from January 2006 to February 2010.

intensities in driving erosion rates can not be excluded and the observed changes could be the result of the combination of both climatic and anthropogenic causes.

Finally, taking into account that the average measured thickness of the 1888-90 products is about 2 m and using the area erosion data reported in tab. 1, the total volume of eroded material can be estimated at 5,700 m^3 in the period 1980-2008.

CONCLUSION

The present study confirms that volcanic reliefs at Vulcano Island are affected by geomorphic processes dominated by water erosion and landslides. Denudation is favoured by the presence of «soft» volcanic products (pyroclastic deposits), that are extremely vulnerable and may easily be picked up and transported by water flows and/or gravity. These processes are accelerated by fumarolic activity in two different ways. The condensation of volcanogenic vapour increases water saturation of pyroclastic products, diminishing their coherence. Moreover, in the neighbourhoods of the main fumarolic field, where high temperature volcanogenic vapour is enriched in acidic species, it prevents the growth of vegetation exposing the bedrock to the direct action of geomorphic agents.

In addition, human landscape modifications interact with volcanic activity in the control of erosion processes. In particular, this study highlighted two examples of geomorphological risk/hazard situations and accelerated erosion phenomena produced by anthropogenic activity.

The development of a heavy urbanized settlement along the foothill of La Fossa cone works as a barrage for the stream network, exposing to floodings the inhabited area during intense thunderstorms. Moreover, the unpaved road carved along the northern slope of La Fossa cone has modified the natural drainage network of its upper portion, causing deepening and transport of upstream eroded material along active channels which, capturing and beheading minor incisions, have widened their catchment areas. GIS analysis highlighted an overall increasing in soil erosion after the road construction, even if the concurrence of modification in rainfall rates could not be excluded.

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