sion amount on the slopes characteristics prior to the deepening of the drainage network; iii) the amount of erosion in the *calanchi* depends of the form of the initial slope.

On the other hand, the dimensional analysis has been successfully applied both in theoretical studies where a mathematical model of the problem is available (Barenblatt, 1993; Ferro and Pecoraro, 2000; Ferro, 2010) and in the processing of the experimental data (Ferro, 1997; D'Agostino and Ferro, 2004; Capra *et al*., 2009; Di Stefano and Ferro, 2011) as well as in the preliminary analysis of physical phenomena (Bagarello and Ferro, 1998; Di Stefano and Ferro, 1998; Bagarello *et al*., 2004). More in detail, according to the Π-Theorem of the dimensional analysis (Barenblatt, 1979, 1987), if a physical process can be mathematically represented by an equation relating n dimensional variables, which involve q fundamental physical quantities, the same process can be represented by a functional relationship in which n-q dimensionless groups Π_i ($i = 1, \ldots, n\text{-}q$) of variables appear. In order to determine the exact mathematical form of the functional relationship representing a physical process, the self-similarity theory can be applied (Barenblatt, 1979, 1987; Ferro, 2010).

A physical phenomenon is defined as self-similar in a given dimensionless group Π_n when the functional relationship $\Pi_1 = \varphi(\Pi_2, \Pi_3, \ldots, \Pi_n)$ representing the physical phenomenon is independent of Π_n. The self-similar solutions of a problem must be found in accordance to the surrounding conditions, that is, the behavior of the relationship φ must be solved for $\Pi_n \to 0$ and for $\Pi_n \to \infty$.

When the relationship φ tends to a finite limit and is different from zero, the phenomenon is not influenced by Π_n, and is expressed by the functional relationship:

$$\Pi_1 = \varphi_1(\Pi_2, \Pi_3, \ldots\ldots\ldots, \Pi_{n-1}) \tag{8}$$

in which φ_1 is a functional symbol, and the self-similarity is named complete in a given Π_n dimensionless group.

When the relationship φ has a limit equal to 0 or ∞, the physical phenomenon is expressed by the following functional relationship:

$$\Pi_1 = \Pi_n^{\varepsilon} \varphi_1(\Pi_2, \Pi_3, \ldots\ldots\ldots, \Pi_{n-1}) \tag{9}$$

in which ε represents a numerical constant. This instance is named incomplete self-similarity in the parameter Π_n (Barenblatt, 1979, 1987).

A *calanchi* area can be examined as a system where, excluding the anthropogenic influence, erosion processes consist of three components: i) rainfall; ii) soil characteristics; iii) eroded sediment distribution and surface runoff. Indeed, the characteristics of precipitation (*e.g*., amount, intensity, *etc*.) regulate their erosive power, which is the potential ability of the rainfall to cause soil loss (White, 2006). The mechanical and chemical properties of soil materials directly control their attitude to be eroded, which is also indirectly influenced by the presence of vegetation and plant roots (Charlton, 2008); the hydrological properties, such as soil permeability, control the occurrence of surface runoff. Finally, the third component influences the distribution of erosion/deposition processes within a *calanchi* catchment (Figure 6).

Caraballo-Arias *et al*. (2015) assumed that the erosion processes developing on *calanchi* landforms could be explained by the following functional relationship:

$$\varphi(V_c, A, L_{DN}, s, L_B, N, P, d, \gamma_s, i, K_s) = 0 \tag{10}$$

in which φ is a functional symbol, V_c (m^3) is the eroded volume of the *calanchi*, A (m^2) is the plane area of its drainage basin, L_{DN} (m) is the total drainage network length contained in the *calanchi*, s ($^{\mathrm{m}}/_{\mathrm{m}}$) is the mean slope of the *calanchi* basin, L_B (m) is the plane length of the drainage basin, N is the total number of streams in the *calanchi*, P (m) is the perimeter of the basin, d (m) is the mean diameter of the solid material contained in the basin area, γ_s (N/m^3) is the specific weight of the solid material, i (mm/h) is the mean rainfall intensity and K_s is the soil hydraulic conductivity (mm/h).

According to the Π-Theorem, since the functional relationship in Eq. (10) includes eleven dimensional physical variables and three fundamental physical units (length, time and force), the same relationship can be expressed by using eight dimensionless groups Π_i (i=1 to 8):

$$\varphi(V_c, A, L_{DN}, s, L_B, N, P, d, \gamma_s, i, K_s) = 0 \tag{11}$$

Choosing as *governing variables* having independent dimensions, A, γ_s and i, which are also representative of the basin morphology, soil characteristic and rainfall erosive power of the studied physical system, and applying the Π-Theorem, Caraballo-Arias *et al*. (2015) obtained the following functional relationship:

$$\frac{V}{A^{3/2}} = f\left(\frac{L_B}{L_{DN}}, s, N, \frac{P^2}{A}, \frac{d}{A^{1/2}}, \frac{K_s}{i}\right) \tag{12}$$

For a long-term erosive process, for which the relationship K_s/i can be ignored (a condition which is, instead, significant for single events) and for a soil with known textural characteristics, the relationship (12) becomes:

$$\frac{V}{A^{3/2}} = f\left(\frac{L_B}{L_{DN}}, s, N, \frac{P^2}{A}\right) \tag{13}$$

Assuming that the incomplete self-similarity hypothesis (Barenblatt, 1979, 1987; D'Agostino and Ferro, 2004; Ferro, 2010) the functional relationship (13) can be expressed by the following product of powers:

$$\frac{V}{A^{3/2}} = a_0 \left(\frac{L_B}{L_{DN}}\right)^{a1} s^{a2} N^{a3} \left(\frac{P^2}{A}\right)^{a4} \tag{14}$$

in which a_0, a_1, a_2, a_3 and a_4 are numerical constants to be determined experimentally.

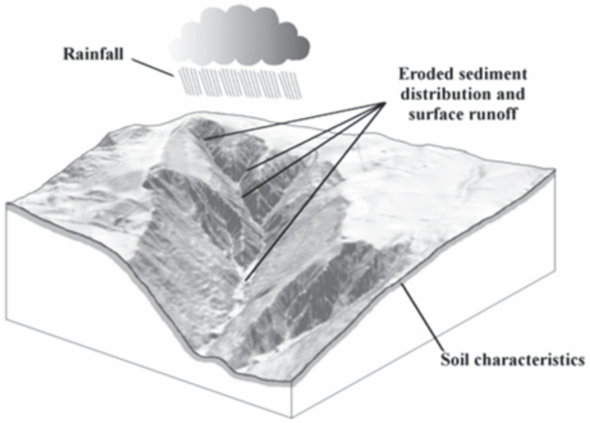

Figure 6. Components of a *calanchi* system.

Eq. (14) was calibrated and validated by Caraballo-Arias *et al*. (2015) using four different data sets, each including the morphometric characteristics of a group of small hydrographic units partially or completely covered by *calanchi* landforms. Two data sets correspond to the two-calanchi areas Anticaglia (18 basins) and Bicchinel (45 basins) and other two data sets were derived from Buccolini *et al*. (2012) (65 *calanchi* basins) and from Buccolini and Coco (2013) (81 *calanchi* basins).

Since the correlation analysis demonstrated that the parameter *s* in Eq. (14) could be neglected, the following relationship was obtained by Caraballo-Arias *et al*. (2015):

$$\frac{V}{A^{3/2}} = 0.1238\left(\frac{L_B}{L_{DN}}\right)^{-1.7861} N^{-0.7468}\left(\frac{P^2}{A}\right)^{-0.2563} \tag{15}$$

Since the predictive skill of Eq. (15) was found to be sensitive to the relative extent of *calanchi* landforms within their tributary areas, Caraballo-Arias *et al*. (2015) included the eroded area (A_E) in the following dimensionless group place to Π_9:

$$\Pi_9 = \frac{A_E}{A} \tag{16}$$

Introducing the Π_9 dimensionless group and neglecting the slope influence, Eq. (14) becomes:

$$\frac{V}{A^{3/2}} = a_0\left(\frac{L_B}{L_{DN}}\right)^{a1} N^{a3}\left(\frac{P^2}{A}\right)^{a4}\left(\frac{A_E}{A}\right)^{a5} \tag{17}$$

Since Eq. (17) should be able to predict the volume of sediments eroded from *calanchi* channels developing on drainage units entirely (or almost entirely) or only partially covered by badland, this equation was calibrated using both Anticaglia and Bicchinel data sets, obtaining a_0=0.1449, a_1=0.2077, a_3=0.3828, a_4= –0.6255 and a_5=1.6614. The measured $V/A^{3/2}$ ratios and those predicted by Eq. (17) are plotted in Figure 7.

Poor performance of the model are expected when the *calanchi* units have a size in the order of few hundreds of square meters and the resolution of the DEM and of the orthophotos that were employed to calculate the eroded volume of *calanchi* units and to map their drainage network, respectively, are not adequate for such small landforms.

Finally, the residuals *E* between the observed values of the ratio $V/A^{3/2}$ and those calculated by Eq. (17) were computed. The frequency distribution of *E* resulted normal (Figure 8) and the deterministic model can be considered complete, meaning that no additional variables are necessary in the model.

Research needs

Calanchi landforms constitute an important research environment for soil erosion investigations. Even though diverse morphometric relationships and models have been proposed, there is still the need of morphologically characterising these spectacular landforms, specially by creating inventories for the different areas in which these are present (not only in Italy, but also in the whole Mediterranean area). Such inventories might be helpful for comparing the morphometric features of *calanchi* landforms in areas where climatic conditions, geological settings and vegetation cover/land use are similar. New techniques, such as unmanned aerial vehicle for monitoring *calanchi* erosion need to be further exploited on this subject, especially since this type of badlands are not easily accessible.

Moreover, since *calanchi* exhibit, in small temporal and spatial scales, many of the geomorphic processes and landforms that may be observed in a fluvial landscape, this type of badland may be considered as micro-basins where geomorphic dynamics can be related to their geometric features. This idea leads to the quantitative analysis of *calanchi* morphometric properties in order to provide a multivariate characterisation of these landforms and to establish if *calanchi* have a behavior similar to fluvial systems. These analyses can be carried out by quantifying the attributes of the landforms, such as the size, surface, shape, relief and channel network incision properties. Size properties might derive from measurements of the basin outline as defined by the drainage divide, drainage network, basin length and perimeter, main channel length and stream order. Surface properties include the elevation surface, flow direction, terrain slope, contributing area and specific catchment area. Shape variables, such as the circularity ratio (Miller, 1953) and the elongation ratio (Schumm, 1956), are useful for characterising the shape properties of a basin. Relief properties bring the dimension of height into morphometric analysis, which might be used as indicators of potential erosion and denudation rate. Finally, the channel network properties indicate the landscape dissection quote by

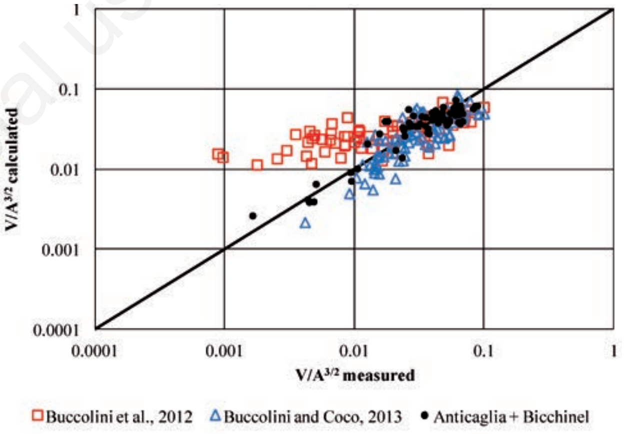

Figure 7. Comparison between the measured values of $V_c/A^{3/2}$ and those calculated with Eq. (16).

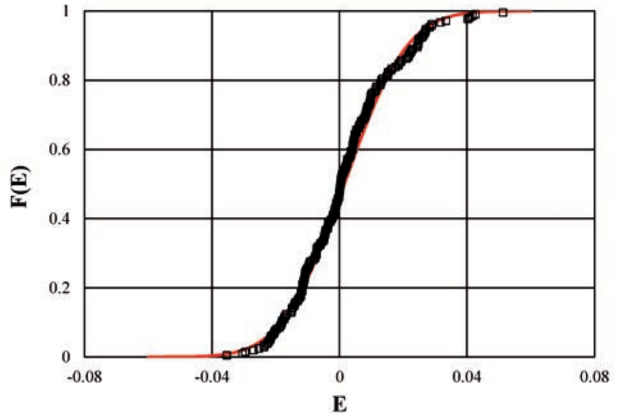

Figure 8. Frequency distribution of the residuals *E* between measured $V_c/A^{3/2}$ values and *those* calculated by Eq. (17).

the channel network. In this sense, drainage density (Horton, 1945) is the best-known indicator and high values of this pointer indicate highly dissected landscapes, short hillslopes and domination by overland flow runoff typical of badlands (Goodwin and Tarboton, 2004).

The similarity properties between *calanchi* systems and natural river basins might be also investigated from both a sediment transport point of view and by taking into account structural connectivity of these landforms. This approach might be explored by determining the travel time that soil particles require before arriving to an element of the channel network by using the slope length and steepness of the *calanchi* basins.

Finally, modelling of the erosion processes developing on *calanchi* landforms can be tested using *calanchi* with different characteristics [*e.g.*, type *B calanchi* sensu Moretti and Rodolfi (2000)].

Conclusions

Calanchi landforms are many times despised by farmers and public authorities, however they represent amazing landscapes where many types of landforms and geomorphic processes can be observed in smaller temporal and spatial scales. Their origin is an extremely complex phenomenon in which a combination of water erosion processes and environmental characteristics controls the development of this type of landforms. Researches focusing on calanchi landscapes have been increasingly carried out in the last years, but there are still many queries about this type of landforms.

Morphometric analysis of *calanchi* channels validates the idea that length of *calanchi* channels can be used as an optimal predictor for determining their eroded volume. Moreover, the achieved results pointed out that for a given length value its corresponding badland volume value is higher than the gully data from the literature. From a physical point of view, this result can be justified taking into account that the investigated *calanchi* are generally characterised by cross-sections which are deeper a wider than those of the gullies considered in the literature. Nevertheless, taking into account that the *calanchi* fall inside the same *L-V* range of gully measurements, it can be concluded that the *L-V* power relationship previously obtained for gullies can be also applied to the *calanchi* landforms. *Calanchi* channels showed a high degree of morphological similarity with the literature data from rills, ephemeral and permanent gullies. In other words, when grouping the morphological variables length, volume, width and depth of all types of studied landforms, a unique geometrical similarity condition between these four heterogeneous erosion landforms was found.

The Hack's law was also tested for the *calanchi* channels obtaining an exponent smaller than 0.5, which demonstrates that the shape of these landforms becomes wider with increasing their basin area.

Finally a theoretical derived model for estimating the eroded volume on *calanchi* landforms was presented. This model relates the eroded volume to a set of dimensionless groups of *calanchi* basin variables, which were selected assuming their controlling role on the physical process involved.

The model was calibrated and validated using four data sets including the morphometric characteristics of 209 *calanchi* drainage units. As the ratio of *calanchi* extent to the total drainage area was found to affect the predictive skill of the model, this ratio was included in a new version of the model, providing more reliable predictions of eroded volume on *calanchi* systems either entirely or partially covering their tributary area.

As the landforms employed to calibrate and validate the model present similar length characteristics (*i.e.*, high drainage density, V-shaped cross profiles, knife-edge ridges), further investigation could help determine whether a reliable estimate of eroded volume could be obtained on *calanchi* with different characteristics [*e.g.*, type *B calanchi* sensu Moretti and Rodolfi (2000)].

The presented methodologies for investigating *calanchi* areas used remotely sensed measurements, revealing that high-resolution DEMs can be considered a suitable source of data for morphometric analysis of *calanchi*. This encourages further investigations on badlands sites, where measurements on the field are time- and cost-consuming and, in some cases, very problematic.

In conclusion, the complexity of processes originating badland landscapes and their variability in space and time suggest that further studies are needed to establish new models able to explain the evolution of this very astonishing type of landform.

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