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# Assessing, measuring and modelling erosion in *calanchi* areas: a review

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## Abstract

*Calanchi* are erosion landforms characterised by a heavily dissected terrain with steep, unvegetated slopes and channels with a dendritic pattern, which rapidly incise and extend headwards. Recent literature focusing on badland systems highlights their similarity with other larger fluvial landforms, stating that these behave as a full size laboratory, due to their rapid development in space and time and to the diversity of geomorphic processes involved.

In this paper, a brief review of the most important results on badland research is firstly presented. Then, the morphometric similarity between *calanchi* and other erosion landforms is discussed. Finally, models quantitatively relating the volume of sediments eroded from *calanchi* landforms and a set of geometric features of their tributary areas, by exploiting the dimensional analysis and the self-similarity theory, are presented.

## Introduction

The first Encyclopedia of Geomorphology (Fairbridge, 1968) defines *badlands* as a derivation from a term, employed by the U.S. western pioneers, meaning *extremely dissected landscapes, characterised by steep slopes, difficult to cross on horseback and agriculturally useless*.

Badlands are characterised by high drainage network densities, sparse or absent vegetation, shallow or absent regolith and rapid erosion rates (Alexander, 1980, 1982; Howard, 1994b; Charlton, 2008). Badlands are not continuous in space and generally intersect gentler landscapes with their steep slopes, they are usually erosion active and propagate towards their surrounding areas (Marinelli, 1915; Howard, 1997; Della Seta *et al*., 2009). Badlands are common in semi-arid regions with strongly marked seasonal contrast climates, while seem to be rare in regions with constant-uniform rainfall. Several geomorphic processes are involved in their origin, namely: weathering, rill and interrill erosion, gullying, piping, tunnel erosion and mass movements (Bazzoffi *et al*., 1997; Clarke and Rendell, 2006; Farifteh and Soeters, 2006; Della Seta *et al*., 2009; Faulkner, 2013; Nadal-Romero *et al*., 2013; Vergari *et al*., 2013). The primary factor influencing badland formation is the action of water: little miniature gullies form and enlarge as time passes, thereby causing destruction of the slope. Eventually, the miniature gullies with which the erosional and denudational processes begin, become deeper and broader. Soon they run into each other forming a drainage network.

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Authors studying these landforms established the following common characteristics of the areas where they take place: i) soft unconsolidated or poorly consolidated clay materials, giving place to landform asymmetry and rapid evolution of the processes; ii) arid or semi-arid climates with concentrated aggressive rainfall and a very marked seasonal contrast, triggering soil cracking; iii) they are mainly formed on south facing slopes where high solar radiation causes clay dehydration and desiccation, also preventing vegetation recovery and, therefore, maintaining badlands active (Alexander, 1982; Cerdà and García-Fayos, 1997; Torri *et al*., 2000; Picarreta *et al*., 2006; Capolongo *et al*., 2008; Alatorre and Beguería, 2009; Pulice *et al*., 2012).

In relation to climate, Gallart *et al*. (2002) proposed to classify badlands into three main groups: i) arid badlands; ii) semi-arid badlands; iii) humid badlands. Arid badlands form in areas where annual rainfall is less than 200 mm. Due to the dry conditions, vegetation is absent or very sparse and does not play a relevant control on erosion processes; however, as intense rainfall events are rare, erosion rate is usually quite low. Semi-arid badlands occur on areas where annual precipitation is between 200 and 700 mm. In these environments, erosion rate increases as rainfall amount grows, but it decreases as vegetation cover is developed enough to effectively control erosion processes. Humid badlands occur where annual rainfall exceeds 700 mm. The availability of water would allow a dense plant cover but the rapid erosion processes limit the growth of vegetation. Badland areas are often completely free of vegetation either because of strong seasonality, with an extended arid period, or as a consequence of land-use practices such as overgrazing (Bryan, 2000). The absence of vegetation not only allows erosion by rainwash and mass movements, but the effect of raindrop impact is also enhanced (Bryan and Yair, 1982; Howard, 1994b).

The origin of badlands is very complex to establish because of a high number of variables interacting together, from high clay content of the regolith to earthquakes producing landslides evolving into badland landforms, and from deforestation to redirecting natural channels and other inappropriate land use practices (Marinelli, 1915; Bryan and Yair, 1982; Torri *et al*., 2000; Romero Díaz *et al*., 2007; Vergari *et al*., 2013).

In Italy, numerous studies were carried out on badland environments due to their significant extension in the peninsula. Semi-arid climate with a marked seasonal contrast, clayey outcropping, the occurrence of mass movements (sometimes related to neo-tectonic activities), scarce or absent vegetation and a significant human impact are some of the main characteristics of the Mediterranean areas, which are also fundamental factors controlling badland formation (Della Seta *et al*., 2009; Battaglia *et al*., 2011; Pulice *et al*., 2012; Faulkner, 2013; Vergari *et al*., 2013).

In Italy, badlands are mainly distinguished in two types: *biancane* and *calanchi*. The former are mainly interpreted as residual hills of late stage *calanchi* evolution (*e.g*., Farifteh and Soeters, 2006), where slope retreat of *calanchi* fronts (Clarke and Rendell, 2006) or joint systems (Della Seta *et al*., 2009) may have played a prominent role; they are characterised by cones and hummocks separated by flatter surface wash deposits, and creep or similar processes (*e.g*., solifluction) may affect their upper crust (Pulice *et al*., 2012). The latter, on the other hand, are characterised by a heavily dissected terrain with steep, unvegetated slopes and channels with a dendritic pattern, which rapidly incise and extend headwards (Alexander, 1982; Moretti and Rodolfi, 2000; Farifteh and Soeters, 2006; Buccolini *et al*., 2012; Pulice *et al*., 2012). The *calanchi* landscapes occur more frequently along the Apennines, where they develop on Plio-Pleistocene deposits, which are highly susceptible to water erosion (Phillips, 1998; Farifteh and Soeters, 2006; Ciccacci *et al*., 2008; Castaldi and Chiocchini, 2012; Pulice *et al*., 2012; Vergari *et al*., 2013). In Sicily, the effects of intense water erosion phenomena are testified by the occurrence of badlands, constituting a common landscape in the central and southern areas of the Island, where slopes are frequently underlain by clay-rich deposits.

In the group of the *calanchi* landforms, Moretti and Rodolfi (2000) defined two types: type A *calanchi* which are mainly developed by concentrated water runoff on clayey substrates, but with high amounts of silt and sand content, giving place to *knife-edged* dissected landforms, with a high drainage density and *V-shaped* cross profiles (Figure 1); type B *calanchi* which are developed also by shallow slides usually on expendable clay substrates, characterised by gentler slopes and a drainage pattern less dense than type A *calanchi* landforms (Torri *et al*., 2000).

Recent literature focusing on badland systems highlights their similarity with other larger fluvial landforms, stating that these behave as a full size laboratory, due to their rapid development in space and time and to the diversity of geomorphic processes involved (Alexander, 1980; Bryan and Yair, 1982; Howard, 1994b; Bazzoffi *et al*., 1997; Buccolini *et al*., 2012; Torri *et al*., 2013). A previous study made by Schumm (1956), based on the measurements of the characteristics of the drainage system of the Perth Amboy badlands, revealed already that these miniature landforms are in agreement with the laws of drainage basin composition and that these intricate small-scale drainage systems develop in a manner similar to those of large systems.

In this sense, *calanchi* badlands exhibit, in smaller temporal and spatial scale, many of the geomorphic processes and landforms that may be observed in a fluvial landscape and, therefore, help to understand the more slowly developing portions of the landscape. Hence, *calanchi* hydrographic units may be considered as micro-watersheds where geomorphic dynamics can be related to their geometric features (Alexander, 1980; Bryan and Yair, 1982; Howard, 1994b; Ciccacci *et al*., 2008; Torri *et al*., 2013). Indeed, as for river basins, morphometric characteristics such as shape, area, length, slope steepness, drainage frequency or drainage density, significantly affect the distribution of erosion/deposition processes, as well as the sediment and water fluxes within the badland hydrographic units (Fryirs and Brierley, 2013). In light of the similarity between fluvial and *calanchi* landscapes, some recent studies have exploited morphometric attributes largely adopted to analyse river basins (*e.g*., basin length, basin area, circularity ratio, drainage density, drainage frequency) to model erosion processes on *calanchi* hydrographic units, identifying quantitative relationships between eroded volume and geometric features of their drainage basins (Buccolini and Coco, 2013; Buccolini *et al*., 2012).

In this paper, at first a brief review of the most important results on badland research is presented. Then, using the data obtained by a 2 m-mesh size of two Sicilian *calanchi* areas, the morphometric similarity between *calanchi* and other erosion landforms is discussed.

Finally, models quantitatively relating the volume of sediments eroded from *calanchi* landforms and a set of geometric features of their tributary areas, by exploiting the dimensional analysis and the self-similarity theory, are presented.

## Erosion assessment on badland areas

Some researches have tried to simulate the hydrological and erosive response of badland landscapes by assessing the runoff generation and runoff pathways. Solé-Benet *et al*. (1997) used rain simulations on the badland area located in Tabernas (Andalusia, Spain), in order to evaluate runoff, infiltration and sediment production by considering plant cover and type, length and width of cracks and stoniness. The results showed positive correlations between runoff and slope gradients, and negative correlations between the presence of plant cover and runoff and erosion rates, confirming that vegetation cover protects the soils from erosion processes.

Barthurst *et al*. (1998) tested in the Draix badlands (South Alps, France) the applicability of the physically-based distributed SHETRAN model. The results were encouraging for modelling the impact of land use change, but also indicated the need to reduce further uncertainty in the model parameter evaluation. In the same area Mathys *et al*. (2003) applied the spatialised ETC (*erosion des torrents en crue*) model, which works at event scale, for simulating runoff and sediment transport in the badland area. The model was capable of simulating bed load scouring, deposition and armoring, but the results also suggested a need to improve the representativeness of slope processes and channel sediment storage.

Researches focusing on the mapping, quantification of erosion rates and sediment yield from basins including badlands have been recently published. Clarke and Rendell (2006) used erosion pins in a badland site located in Basilicata, Italy, to determine the mean annual erosion rates. The rates of erosion obtained are smaller for *calanchi* than for *biancane* badlands and, even though the results did not show a linear relationship between the erosion pin data and the slope angle, the

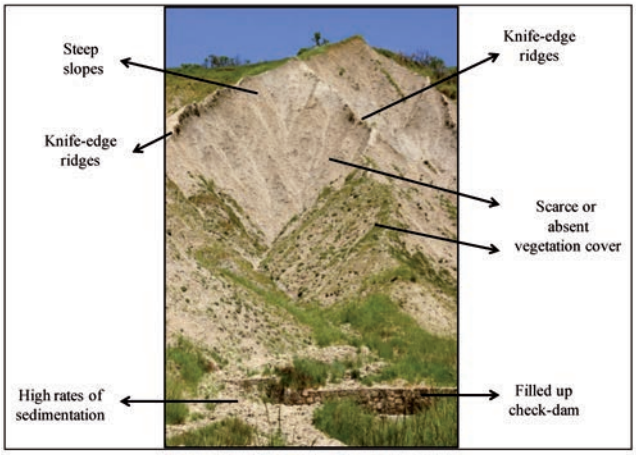

**Figure 1. An example of a type A *calanchi* badland. Anticaglia study area.**

maximum erosion rates coincided with high slopes (angle of 35°).

Della Seta *et al*. (2007) presented a quantitative direct and indirect evaluation of erosion processes in a badland area of Central Italy. The denudation rates obtained by indirect methods ranged from 200 to 10,000 t/km$^2$/year, while the direct evaluation, made with the installation of iron stakes and disks on the drainage basins affected by the most powerful denudation processes, showed erosion rates between 1 and 4 cm/year. The higher denudation rates were correlated with gravitational processes, which occurred after moderate rainfall events.

Ciccacci *et al*. (2008) made direct (field surveys, installation of stakes) and indirect measurements (interpretation of aerial photographs, analysis of DEM) in a sample area of Tuscany (Italy). Gravity was identified as the main morphogenetic process on landscape modelling and the erosion rates calculated ranged from 5 to 7.4 cm/y.

Later on, Gallart *et al*. (2013) studied a badland area in the Eastern Pyrenees, Catalonia, Spain, in which stream flow and suspended sediment loads were also monitored using three gauging stations. At the event scale, badland erosion was simulated with the KINEROS2 model allowing a long-term comparison between badland erosion and sediment yield at a small basin scale. Badlands are the main source of sediment in the basin for most of the events, but infrequent runoff events cause the removal of sediment stores and the activation of other sediment sources.

Regüés and Nadal-Romero (2013) evaluated the uncertainties on the estimation of suspended sediment yield in badland areas, showing important limitations in different methodologies, associated with the characteristics of the suspended sediment and its heterogeneous distribution in the flow during the events. Furthermore, outside of the Mediterranean region in a badland area located in Taiwan, erosion pins were also used to determine the erosion rates over a period of 4 years. The results showed an average erosion rate of 9 cm/y, which, according to the literature, can be considered very fast (Higuchi *et al*., 2013).

More recently, Vergari (2015) suggested a methodology for assessing soil erosion hazard in a badland area located in Italy by combining soil erosion susceptibility analysis with water erosion rate estimation. The model proposed a susceptibility assessment method based on conditional statistical analysis using different topographic, geological and morphometric parameters. It was concluded that the most influential causal factors in determining water erosion processes are altimetry, drainage density, amplitude of relief and slope and the results coincide with the decadal empirical investigations on denudation processes from other researchers (Della Seta *et al*., 2009; Vergari *et al*., 2013), emphasizing that this methodology could be useful even when direct erosion rate measurements are not available.

About vegetation cover and land-use, Lukey *et al*. (2000) used the SHETRAN technology for simulating changes in the natural and reforested vegetation cover at the Draix badlands in France. The results were encouraging for modelling the impact of land use change, but also indicated the need to reduce further uncertainty in model parameter evaluation. Clarke and Rendell (2000) studied the consequences of remodelling the badland morphology by using heavy earth-moving equipment. The results showed that remodelling the badland features creates longer slopes at lower angles, which can be cultivated using conventional farm machinery, but also results in an increase in the coupling of drainage networks and a net increase in soil erosion. Gallart *et al*. (2002) developed a model for analysing the competition between vegetation cover growth and erosion rates in arid, semi-arid and humid badlands. The results suggested that in arid badlands, when they are a pure physical phenomenon, there is no competition below a precipitation threshold. In semi-arid badlands, the results demonstrated that diverse cover densities may be stable for intermediate annual precipitation and finally, in humid badlands there was a clear distinction between fully covered and fully bare areas. Nadal-Romero *et al*. (2010) presented the hydrological response of two different environments: badland units and reforested slopes. The results confirmed the importance of vegetation on the reduction of flooding and erosion risks in the reforested area. Galiano and Ciccacci (2011) made a morphodynamic reconstruction of the Fabro badlands located in Umbria, Italy. The main results of this research were: i) a morphometric characterisation of the badlands with the use of photogeological analyses and field surveys (steep slopes, deep incisions, sharp knife-edge ridges); ii) an erosion rate estimation, ranging from 2 to 3 cm/y; iii) a major role of the clays dispersivity in *calanchi* badland development, when the analysis of the parental material were made.

Castaldi and Chiocchini (2012) studied the effects of land use change on badland erosion in Radicofani, Central Italy, concluding that land reclamation has played an important role in reducing erosion in the clayey substrate. Furthermore, vegetation has been also used as an indicator of erosion rates, as documented by Ballesteros-Cánovas *et al*. (2013), which used dendrogeomorphology to quantify the different geomorphic processes and erosion rates which have occurred on a badland landscape. They found that dendrogeomorphology has the advantage of providing information, not only about the average erosion rates, but also gives information about the dates and intensity on the events.

More recently, Bierbaß *et al*. (2014) studied the role of vegetation and soil properties on the erodibility and stability of badlands. The results indicated that the vegetated areas enhance the organic matter accumulation, water infiltration and sodium leaching, concluding that vegetation plays an important role on terrain stability.

Finally, other researchers focused on models concerning the long-term evolution of badlands as a particular example of the development of drainage networks. Howard (1994a, 1997) developed a drainage basin model for simulating long-term badland forms of development and evolution, successfully applied to the Mancos Shale Badlands (Utah, U.S.A.). This model is only adequate for arid badlands because it does not take into account the role of vegetation.

Faulkner (2008) developed a theoretical mesoscale closed-system model for the evolution of connected states in regionally isolated badlands. This model raises the hope of equifinality in the development of badlands systems and the possibility of system changes due to the evolution of drainage connectivity without invoking external forcing (climate) changes.

Buccolini and Coco (2013) studied three *calanchi* areas in Italy in order to relate the value of a morphometric slope index (MSI) with the activation and evolution of the landforms. They concluded that the development of erosion processes depends on the MSI and that areal processes induce a great amount of erosion. They finally deduced that *calanchi* initiation in that area was contemporaneously due to the common duration of the processes in all studied landforms.

The origin and evolution of a badland area, located in the north of India, was also assessed by Joshi and Nagare (2013). They calculated different geomorphic indices on the badland area in order to establish if tectonic stability could be the explanation for their origin. The results of this research suggested that those badlands could be initiated by neotectonic events.

## Badland morphology

### Length-volume functional relationship

High-resolution DEMs representing the topography of badland systems can be used to measure a set of morphometric attributes of the channels. Caraballo-Arias *et al*. (2014) investigated two *calanchi* areas (Anticaglia and Bicchinel), located into the Imera Meridionale and

Belice basins in Sicily. The vertical and horizontal resolutions of the used DEMs are 0.1-0.2 m and 2 m, respectively. The investigated erosion features were individuated and mapped using the software Google Earth$^{TM}$, by analysing the orthophotographs (pixel size 0.25 m) available for the investigated sites (http://www.sitr.regione.sicilia.it) and by means of a slope steepness map derived from the DEM; this approach allowed to recognise 14 representative *calanchi* channels in the area of the Bicchinel creek and 11 ones in the area of the Anticaglia creek.

To measure length $L$ and volume $V$ of each erosional channel, the latter were subdivided into segments by drawing transverse transects (Figure 2a) and these measurements were used to calculate the volume of each -$i$ segment of the *calanchi*, using the following equation:

$$V_i = 0.5\left(A_{iu} + A_{id}\right)L_i \quad (1)$$

where $V_i$ (m$^3$) and $L_i$ (m) are volume and length of the -$i$ channel segment, while $A_{iu}$ and $A_{id}$ (m$^2$) are the areas of the upslope and downslope cross sections, respectively. The total volume $V$ (m$^3$) of each *calanchi* was computed by adding the individual $V_i$ volume of all the -$n$ segments into which the channel was divided:

$$V = \sum_{i=1}^{n} V_i \quad (2)$$

The total length $L$ (m) of each channel was calculated by adding the partial length values $L_i$ of its -$n$ segments:

$$L = \sum_{i=1}^{n} L_i \quad (3)$$

Taking into account that Nachtergaele *et al*. (2001), Capra *et al*. (2009), Di Stefano and Ferro (2011) and Kompani-Zare *et al*. (2011), demonstrated that length of rills, ephemeral gullies (EGs) and permanent gullies (gullies) can be used to obtain a reliable prediction of eroded volumes by applying the following power relationship:

$$V = a\,L^{b} \quad (4)$$

where $a$ and $b$ are coefficients, $V$ (m$^3$) is the total eroded volume and $L$ (m) is the total channel length, the applicability of Eq. (4) was tested by Caraballo-Arias *et al*. (2014) for the 25 badland channels.

Figure 3 shows the relationship (4) calibrated by $L$-$V$ pairs observed on rills, EGs and gullies by Ichim *et al*. (1990), Daba *et al*. (2003), Bruno *et al*. (2008), Moges and Holden (2008) and Di Stefano and Ferro (2011). This figure demonstrates that the power equation (4) can be applied for rill, EG and gully data using the same exponent $b$, equal to 1.1, and a different scale factor ($a$ = 0.0036 for rills, $a$ = 0.0984 for EGs and $a$ = 35.8 for gullies). Therefore, the exponent of Eq. (4) can be assumed independent of the type of channelised erosion while a different scale factor holds for these three types of erosion.

The pairs $L$-$V$ related to Anticaglia and Bicchinel badlands, plotted in Figure 3, fall within the same range of gully measurements. However, as emphasised by Caraballo-Arias *et al*. (2014), for a given value of $L$, the corresponding value of $V$ for the *calanchi* is higher than those related to gully.

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 and wider than those of the gullies available in the literature. In other words, $L$-$V$ measurements on badlands can be also explained by the application of Eq. (4) with constants $a$ = 0.021 and $b$ = 2.85. Moreover, taking into account that badland data fall within the scattering of $L$-$V$ pairs employed for calibrating Eq. (4) for gullies, using $a$ = 35.8 and $b$ = 1.1, this equation can be used, also for badland channels, as an accurate predictor of sediment volume.

Moreover, in order to verify the morphometric similarity between rills, EGs, gullies and badland channels, Caraballo-Arias *et al*. (2014) applied the following power function between the two dimensionless groups proposed by Bruno *et al*. (2008):

$$\frac{V_i}{L_i^3} = m\left(\frac{w_i\,H_i}{L_i^2}\right)^{p} \quad (5)$$

where $V_i$ (m$^3$) is the eroded volume of the –$i$ channel segment, $L_i$ (m) is the channel length of the –$i$ channel segment, $w_i$ and $H_i$ are the mean width and depth of the cross sections delimiting the –$i$ channel segment and $m$ and $p$ are two numerical constants.

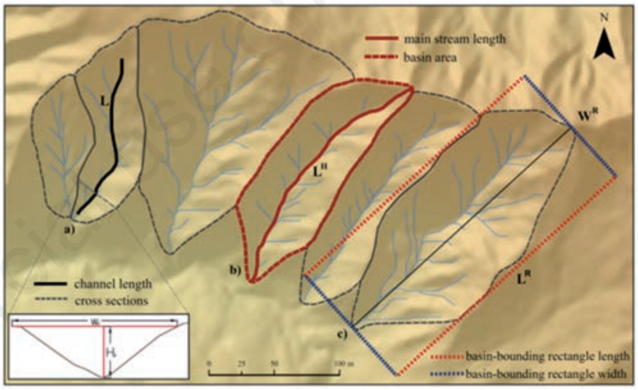

**Figure 2. Morphological characteristics of the studied *calanchi* basins: (a) example of cross-section, *L*=channel main length; (b) example of main stream and basin area for the Hack's law and, $L^H$=main stream length measured from the outlet to the basin divide; (c) example of length and width of a basin-bounding rectangle, $L^R$=maximum basin lenght, $W^R$=maximum basin width.**

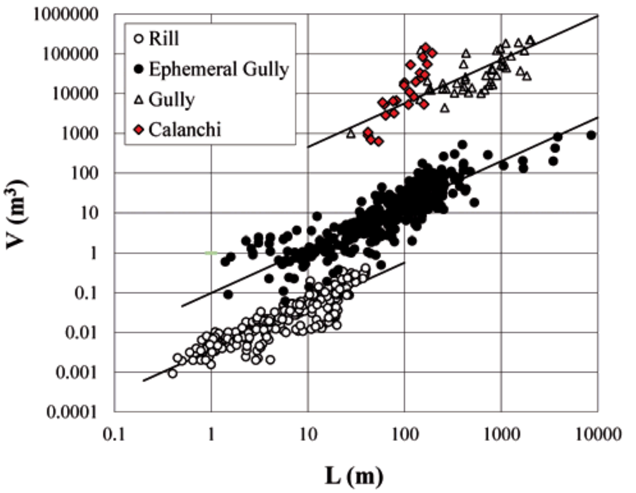

**Figure 3. *L*-*V* relationships between literature data researchers and the 25-badland morphometric measurements.**

Figure 4 shows the pairs of the dimensionless groups obtained from the literature data (Daba *et al*., 2003; Cheng *et al*., 2006; Zhang *et al*., 2007; Moges and Holden, 2008; Capra *et al*., 2009; Di Stefano and Ferro, 2011) and the ones corresponding to badlands. The diagram shows how badland points are well predicted by a power regression model (Eq. (5) with $m$=0.5341 and P=0.9379) calculated from smaller linear erosion landforms data (rills, EGs and gullies). The combination of morphometric parameters such as length, width, depth and volume of the channels, allows confirming a morphological similarity of rills, EGs, gullies and badland channels, even when they are controlled by different water erosion processes. In addition, the analysed landforms are cut into different soils and bedrock lithology suggesting that the morphology of linear erosion landforms is independent from their inherent characteristics, namely texture, organic content, structure, permeability, *etc*.

## Hack's law

Since badland are considered as drainage basin systems which develop in smaller scales an empirical power law relationship obtained by Hack (1957) can be applied to the badland landforms. The Hack s law has the following form:

$$L^H = c\,A^k \qquad (6)$$

where $L^H$ (m) represents the length of the main channel, measured from the basin outlet to the water divide along the main stream, $A$ (m$^2$) is the drainage basin area. For the fluvial case, Hack obtained coefficients $c$=1.4 and $k$=0.6 and affirmed that the value of the exponent in excess of 0.5 required that drainage basins became more elongate with increasing their size.

Figure 5 shows the pairs $L^H$ - $A$ of the *calanchi* measurements made in Anticaglia, Bicchinel area by Caraballo-Arias *et al*. (2014) and those obtained by Buccolini *et al*. (2012). This figure confirms the applicability of Hack's law for *calanchi* landforms with $c$=4.72 and $k$=0.39.

The exponent $k$ of Eq. (6) less than 0.5 demonstrates that the shape of *calanchi* landforms becomes wider with increasing the basin area. This last result is confirmed by the observation of the studied *calanchi* landforms, especially those from Bicchinel, which are limited by an upstream physical boundary which keeps the landforms from extending headwards, being only possible to extend sidewards.

When applying the approach proposed by Rigon *et al*. (1998), drawing a rectangle bounding each basin (Figure 2c), with one side parallel to the longest vector, traced from the basin outlet to the basin perimeter, a strong relationship between the length $L^R$ and width $W^R$ of a basin-bounding rectangle is confirmed (Caraballo-Arias *et al*., 2014).

## Modelling badland erosion volume

In recent years, Buccolini *et al*. (2012) and Buccolini and Coco (2013) proposed a methodology for analysing badland eroded. A morphometric index, called MSI was proposed for studying the slope geometry of *calanchi* landforms as a whole. The model analyses factors linked to the characteristics of the drainage network and the slope morphometry of the badlands. The investigations used the reconstruction of the initial geometry of the *calanchi* since slope processes and the development of the drainage network are markedly conditioned by the original topography of the supply hillside (Buccolini and Coco, 2010).

Buccolini *et al*. (2012) considered the following morphometric attributes: i) from the *calanchi* basins: inclination, plan length, plan surface area, circularity ratio, drainage density and frequency and the bifurcation ratio between the first and second orders; ii) from the assumed pre-*calanchi* slopes: the reconstructed surface area; and iii) the eroded volume obtained by comparing the 3-dimensional models of the current and reconstructed geometries. Buccolini *et al*. (2012) proposed to combine the main morphometric aspects of the slope in a single index called MSI, in order to analyse 65 *calanchi* basins in Sicily:

$$MSI = \frac{A_r}{A_{2D}} L_p\, R_c = 4\pi \frac{A_r}{P^2} L \qquad (7)$$

in which $A_r$ represents the reconstructed surface area, $A_{2D}$ the plan surface area, $L_p$ the plan length, $R_c$ the circularity ratio and $P$ the perimeter. The authors made statistical analysis correlating the drainage network organization on the initial topography, the relationships between slope parameters, the *calanchi* parameters and the eroded volumes. Buccolini *et al*. (2012) concluded that for the Sicilian *calanchi* study area, *MSI* is a good combined indicator of the morphometry of the slope prior to *calanchi* erosion, effectively summarising slope characteristics.

Later on, Buccolini and Coco (2013) further tested the *MSI* in 81 *calanchi* basins locates in Abruzzi, Marche and Tuscany regions. The *MSI* showed how the development of erosion processes depends on the proposed index, in particular: i) the dependence of the *calanchi* network on the tributary slope parameters; ii) the dependence on the ero-

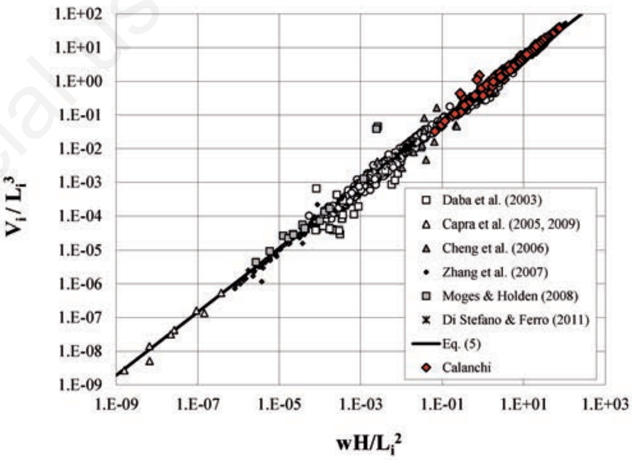

**Figure 4. Measured pairs of dimensionless groups from other authors and the ones obtained in the mentioned investigation.**

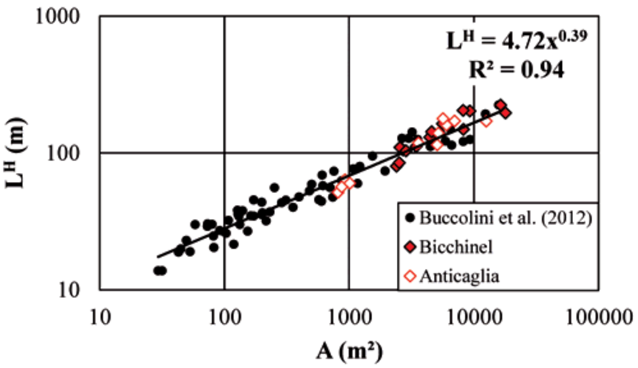

**Figure 5. Hack's law application for the 25-*calanchi* data and the data obtained by Buccolini *et al.* (2012).**

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 $\Pi_i$ ($i = 1, \ldots, n\text{-}q$) 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 $\Pi_n$ when the functional relationship $\Pi_1 = \varphi(\Pi_2, \Pi_3, \ldots, \Pi_n)$ representing the physical phenomenon is independent of $\Pi_n$. The self-similar solutions of a problem must be found in accordance to the surrounding conditions, that is, the behavior of the relationship $\varphi$ must be solved for $\Pi_n \to 0$ and for $\Pi_n \to \infty$.

When the relationship $\varphi$ tends to a finite limit and is different from zero, the phenomenon is not influenced by $\Pi_n$, and is expressed by the functional relationship:

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

in which $\varphi_1$ is a functional symbol, and the self-similarity is named complete in a given $\Pi_n$ dimensionless group.
When the relationship $\varphi$ has a limit equal to 0 or ∞, the physical phenomenon is expressed by the following functional relationship:

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

in which $\varepsilon$ represents a numerical constant. This instance is named incomplete self-similarity in the parameter $\Pi_n$ (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:

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

in which $\varphi$ 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*, $s$ ($^{m}/_{m}$) 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, $\gamma_s$ (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 $\Pi_i$ ($i$=1 to 8):

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

Choosing as *governing variables* having independent dimensions, $A$, $\gamma_s$ 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:

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

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:

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

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:

$$\frac{V}{A^{3/2}} = a_0\left(\frac{L_B}{L_{DN}}\right)^{a_1} s^{a_2} N^{a_3}\left(\frac{P^2}{A}\right)^{a_4} \quad (14)$$

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

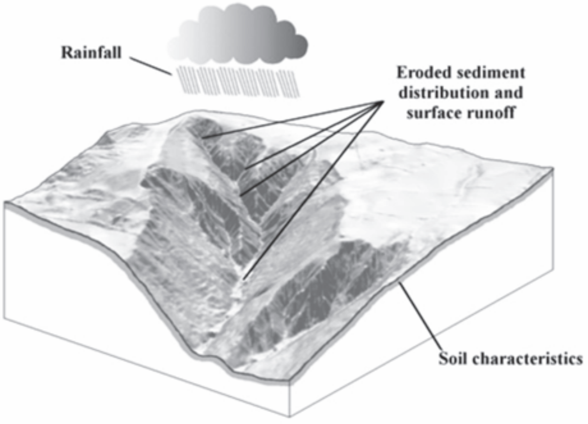

**Figure 6. Components of a *calanchi* system.**

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 $\Pi_9$:

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

Introducing the $\Pi_9$ 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

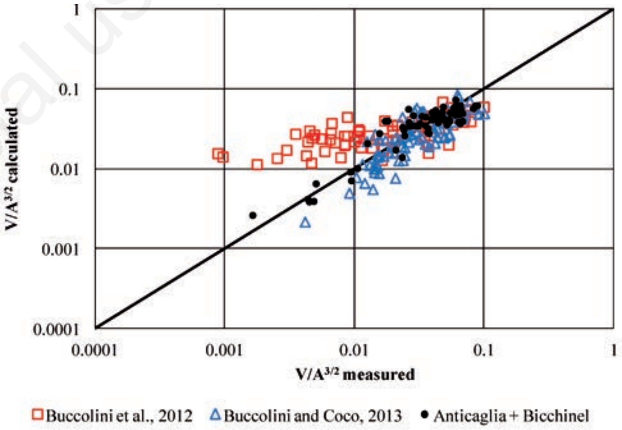

**Figure 7. Comparison between the measured values of $V_c/A^{3/2}$ and those calculated with Eq. (16).**

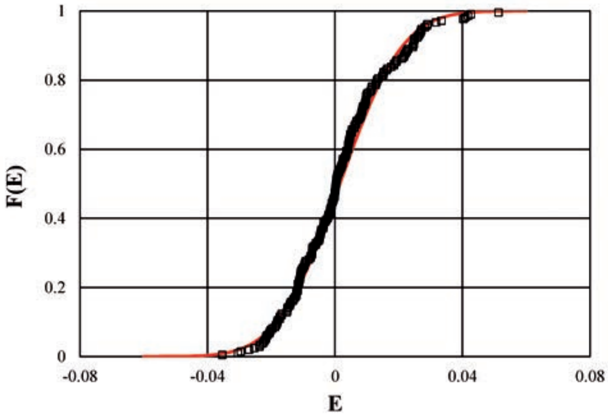

**Figure 8. Frequency distribution of the residuals *E* between measured $V_c/A^{3/2}$ values and *those* calculated by Eq. (17).**

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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