Geomorphology 231 (2015) 292–300

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A new empirical model for estimating *calanchi* Erosion in Sicily, Italy

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ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form 6 December 2014
Accepted 10 December 2014
Available online 20 December 2014

Keywords:
Soil erosion
Badlands
Calanchi
Dimensional analysis
Self-similarity theory
Sicily

ABSTRACT

Calanchi (plural of *calanco*) are typical badland landforms of the Italian landscape. They consist of dense networks of V-shaped valleys, with a sparse or absent vegetation cover, which frequently develop on unconsolidated or poorly consolidated clayey deposits. In this paper, the dimensional analysis and the incomplete self-similarity theory were used to deduce a model relating the volume of sediments eroded from the *calanchi* area to a set of geometric attributes of their tributary areas. The morphometric characteristics of 209 *calanchi* basins were used to calibrate and validate the model. The predictive skill of the model was assessed by calculating the mean square error and the Nash–Sutcliffe model efficiency coefficient. The model was found to provide a reliable prediction of eroded volume from basins entirely covered by *calanchi* landforms as well as from basins only partially affected by badland erosion processes. Furthermore, as the residuals between the calculated and the measured volume of the eroded material are normally distributed, the deterministic model may be considered complete, meaning that no other variables are necessary to explain the studied physical process. In other words, the model is able to predict erosion volume in *calanchi* landforms from a deterministic point of view.

1. Introduction

The term badlands refers to intensely dissected areas which are difficult to cross and are useless for agriculture (Fairbridge, 1968). Badland landscapes are characterized by sparse or no vegetation cover, steep slopes, shallow to no-existent regolith and rapid erosion rates (Bryan and Yair, 1982; Howard, 1994a). Several geomorphic processes are involved in badland development, namely: weathering, splash, rill and interrill erosion, gullying, piping and mass movements. Lithology is the main factor controlling badland formation, being of greater importance than tectonics, climate, topography or land use (Campbell, 1989; Gallart et al., 2002, 2013 and references therein). Indeed, occurrence of badlands requires soft, unconsolidated or poorly consolidated geological materials, whereas other environmental conditions could be quite variable.

In relation to climate, Gallart et al. (2002) proposed the classification of badlands into three main groups: i) arid badlands, ii) semi-arid badlands, and 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 scarcely affects 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 the 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.

In the Mediterranean areas, where climate is characterized by a marked seasonal contrast between the dry and the humid seasons, the occurrence of intense human activities and the presence of not consolidated or poorly cemented clayey materials, are key conditions for the development of badland landscapes (Alexander, 1982; Bryan and Yair, 1982; Moretti and Rodolfi, 2000; Torri et al., 2002; Picarreta et al., 2006; Romero Díaz et al., 2007; Capolongo et al., 2008; Pulice et al., 2012; García-Ruiz et al., 2013; Martínez-Murillo et al., 2013; Vergari et al., 2013).

The typical badland landforms developing in Italy are known as *calanchi* (plural of *calanco*). This term is commonly used in the literature to indicate a dense network of V-shaped valleys, in which each channel is delimited by steep slopes and knife-edge ridges (Alexander, 1980; Moretti and Rodolfi, 2000; Buccolini et al., 2012; Pulice et al., 2012; Nadal-Romero et al., 2013; Summa and Giannossi, 2013). 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; Cicacci et al., 2008; Castaldi and Chiocchini, 2012; Pulice et al., 2012; Vergari et al., 2013).

This type of badlands exhibits, in smaller temporal and spatial scales, many of the geomorphic processes and landforms that may be observed in a fluvial 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,

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http://dx.doi.org/10.1016/j.geomorph.2014.12.017
0169-555X/

1982; Howard, 1994a; 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 analyze river basins (e.g. basin length, basin area, circularity ratio, drainage density, and drainage frequency) to model erosion processes on *calanchi* hydrographic units, identifying quantitative relationships between the eroded volume and geometric features of their drainage basins (Buccolini and Coco, 2010, 2013; Buccolini et al., 2012).

Similar relationships among morphometric attributes of erosion landforms have been recently identified also by applying the dimensional analysis and the self-similarity theory (Barenblatt, 1979, 1987). For example, Bruno et al. (2008) exploited the dimensional analysis and the self-similarity theory to model rill erosion processes, identifying a unique relationship among a set of morphological variables (length, width, depth and volume) measured on a sample of rills. Afterwards, the equation proposed by Bruno et al. (2008) was demonstrated to fit very well also with the morphometric data measured on gullies (Capra et al., 2009; Di Stefano and Ferro, 2011) and on the *calanchi* landforms (Caraballo-Arias et al., 2014).

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) as well as in the preliminary analysis of physical phenomena (Bagarello and Ferro, 1998; Di Stefano and Ferro, 1998; Bagarello et al., 2004).

The Π theorem or Riabucinski–Buckigham theorem of the dimensional analysis states that the functional relationship representing a physical phenomenon, which does not depend on the choice of the measurement units of the involved variables, can be expressed in a dimensionless form (Barenblatt, 1987). Using dimensionless groups permits the reduction of the number of experimental runs and the testing of global effects of the variables that occur in each group rather than the effect of each singular variable.

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 k fundamental physical quantities, the same process can be represented by a functional relationship in which $n - k$ dimensionless groups of variables appear Π_i ($i = 1, \ldots, n - k$). 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 $\Pi_1 = \varphi_1(\Pi_2, \Pi_3, \ldots, \Pi_{n-1})$ 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:

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

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

The main objective of this research is to exploit the dimensional analysis and the self-similarity theory to deduce a new model quantitatively relating the volume of sediments eroded from the *calanchi* landforms and a set of geometric features of their tributary areas. To this aim, we carried out a morphometric analysis of 63 *calanchi* basins, which were identified in two badland sites of Sicily (Italy). The geometric characteristics of these watersheds, in addition to those of other 146 Italian *calanchi* basins derived from the literature, are used to calibrate and validate the model.

2. The proposed model

In the literature, many functional relationships have been studied for erosional processes, by utilizing dimensional analysis and other methods. For example, Howard and Kerby (1983) studied channel changes in two different types of badlands: those formed on bedrock materials and those formed on alluvial beds. They proposed a model in which the erosion rate is related to the slope and drainage area of the channels. Seidl and Dietrich (1992) quantified the erosion by using the same law, relating drainage areas and slopes on principal channels and tributaries. Howard (1994b) suggested that drainage basins are the result of a linear combination of diffusional and concentrative processes, where the drainage density and basin scales are determined by the processes occurring at that contributing area where they have equal required gradients. Tucker and Singerland (1997) proposed a model which analyzes the response of an idealized, steady-state drainage basin, to perturbations in one or more climatically sensitive parameters. They showed that higher runoff intensity gives place to a higher drainage density and therefore higher denudation rates. Perron et al. (2009) exploited dimensional analysis to investigate how erosion and transport processes control the spacing between uniformly spaced valleys and ridges in landscapes where bedrock is mechanically homogeneous. They developed a numerical model that simulates the evolution of a landscape shaped by a combination of soil creep processes and stream channel incision.

For our research we examined the *calanchi* areas as a system where, excluding the anthropogenic influence, the erosion processes consist of three components: i) rainfall; ii) soil characteristics; and iii) eroded sediment distribution and surface runoff. Indeed, the characteristics of precipitation (e.g. amount and intensity) 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 the surface runoff. Finally, the third component influences the distribution of erosion/deposition processes within a *calanchi* catchment (Fig. 1).

Given the complexity of the *calanchi* systems, a very large amount of information and variables might be requested to describe each component. For this reason, we decided to intuitively select and test a group of main variables representative of each component of the badland erosion process. In other words, each component was described using the most important characteristics to predict the erosion volume in *calanchi* basins.

Consequently, we started from the assumption that the erosion processes developing on *calanchi* landforms could be explained by the following functional relationship:

$$\phi(V, \; A, \; L_{DN}, \; s, \; L_B, \; N, \; P, \; d, \; \gamma_s, \; i, \; K_s) = 0 \tag{2}$$

in which φ is a functional symbol, V (m^3) is the eroded volume of the *calanchi*, A (m^2) is the plane area of a its drainage basin, L_{DN} (m) is the total drainage network length contained in the *calanchi*, s (m m^{-1}) 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*,