Miccoli, M.N., Capolongo, D., Piccarreta, M. and Caldara, M. 2014. Geomorphic analyses using NEXTMap topographic data: application for the badlands of the Basilicata region (Southern Italy). *Boletín Geológico y Minero,* 125 (3): 315-328
ISSN: 0366-0176

Geomorphic analyses using NEXTMap topographic data: application for the badlands of the Basilicata region (Southern Italy)

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ABSTRACT

Technological innovations for topographic surveying such as airborne Interferometric Synthetic Aperture Radar (IFSAR) allow increasing availability and accuracy of high-resolution digital elevation models (DTMs). The DTM-based extraction of geomorphic parameters such as drainage areas, slopes, curvatures, etc. is very useful for detailed morphological analyses. Bilogarithmic plots of slope and drainage areas could be used to characterize regions with different dominated erosional processes on the basis of Flint's law. This study uses IFSAR-derived NEXTMap® Europe DTM with a spatial resolution of 5 m, for distinguishing geomorphological signatures of surface processes occurring in two river basins in the Basilicata region, in southern Italy (i.e. the Basento and Cavone Rivers). The analysis of 81 longitudinal gully-channel profiles shows that the uppermost slopes, which are dominated by debris flows and small shallow landslides, are straight or slightly convex with slope values greater than 0.1-0.4 m/m. Below this slope range, fluvial dynamics predominate compared to the debris-flow erosion processes. Downstream, fluvial erosion conditions change from detachment-limited erosion, with highly concave and relatively steep channels, to transport-limited erosion, with lower concavity and slope. Although the lithology, in particular, intact caprock on the top of the hillslopes, influence the gradient of the relief, it does not affect the acting morphological processes; in fact, topographic parameters and erosional processes on the slopes do not change in the different regions, whether caprock is present or not, in addition landscape morphology does not seem to be affected by north or south exposure.

Key words: badland gullies, channel concavity, high-resolution DTM, slope- area relationship, surface process transitions.

Análisis geomorfológico utilizando datos topográficos NEXTMap: aplicación a la region de Cárcavas de Basilacata (sur de Italia)

RESUMEN

Las innovaciones tecnológicas para la investigación topográfica, tales como la interferometría radar de apertura sintética (IFSAR), permiten una disponibilidad creciente de modelos digitales de elevaciones (MDEs) precisos y de alta resolución. La extracción de parámetros geomorfológicos basados en MDEs, tales como áreas de drenaje, pendientes, curvaturas, etc., resulta de gran utilidad para los análisis morfológicos de detalle. Los gráficos bilogarítmicos de pendiente y áreas de drenaje se podrían utilizar para caracterizar regiones con diferentes dominios de procesos erosivos, atendiendo a la ley de Flint. Este estudio utiliza el MDE NEXTMap® Europe obtenido por IFSAR con una resolución espacial de 5 m para distinguir firmas geomorfológicas de procesos superficiales que tienen lugar en dos cuencas fluviales (los ríos Basanto y Cavone) en la región Basilicata en el sur de Italia. El análisis de 81 perfiles longitudinales de canales de cárcavas muestra que las pendientes más altas, que están dominadas por flujos de detritos y pequeños deslizamientos someros, son rectas o ligeramente convexas con valores de pendiente mayores que 0.1-0.4 m/m. Por debajo de este rango de pendientes, predomina la dinámica fluvial con respecto a los procesos erosivos de flujos de detritos. Corriente abajo, las condiciones de erosión fluvial cambian de erosión limitada por la disgregación, con canales relativamente pendientes y *altamente cóncavos, a erosión limitada por la capacidad de transporte, con menor concavidad y menor pendiente. Aunque la litología, en particular el recubrimiento intacto en la parte superior de las laderas, influencia el gradiente del relieve, no afecta los procesos morfológicos actuantes; de hecho, los parámetros topográficos y los procesos erosivos sobre las pendientes no cambian en las diferentes regiones, ya esté el recubrimiento presente o no. Además la morfología del paisaje no parece estar afectada por la exposición norte o sur.*

Palabras clave: cárcavas, concavidad del canal, MDE de alta resolución, relación pendiente-área, transición de procesos en superficie.

VERSION ABREVIADA EN CASTELLANO

Introducción

Muchos estudios recientes han discutido la relación entre los valores de pendiente y el área de drenaje en un perfil ladera-canal que puede mostrar cambios en los procesos de erosión (por ejemplo, Flint, 1974; Tarboton et al., 1991; Sklar and Dietrich, 1998; Snyder et al., 2000; Whipple, 2001; Wobus et al., 2006). La interpolación de modelos digitales del terreno y sus técnicas de procesado permiten extraer información de geoformas directamente de los perfiles de los cauces sin requerir intensivas campañas de campo. Asimismo, la dinámica del paisaje se podría reconstruir de las leyes de los procesos geomorfológicos sobre datos topográficos digitales.

Con la intención de avanzar en esta dirección, se han extraído y analizado datos de las incisiones de las cárcavas en la región Basilicata (Sur de Italia) a partir de un modelo digital de elevaciones (MDE) de 5 m de resolución IFSAR NEXTMap® Europe (producido por Intermap Technologies, https://www.intermap.com/en-us/databases/nextmap.aspx). El MDE facilita el análisis de grandes áreas del territorio y proporciona alta resolución espacial (precisión horizontal de 5 m y resolución vertical de 1 m).

En este trabajo se han identificado las firmas de los procesos erosivos y los puntos de transición a lo largo de los perfiles de los casos de estudio seleccionados, utilizando la relación entre pendiente y área de alimentación en relación a la litología, clima y vegetación.

Área de estudio

El área de estudio está localizada en la región Basilicata al sur de Italia, en particular en el territorio de Pisticci, entre dos grandes ríos, el Basento y el Cavone (Figura 1). La litología en el área de estudio es uniforme, lutitas de plataforma abierta del Plio-Pleistoceno (Argillesubapppennine) que afloran ampliamente y sobre ellas están superpuestas de modo disconforme depósitos regresivos de arena con grava organizados en terrazas marinas de diferentes órdenes (Boenziet al., 1971; Brückner, 1980) y un recubrimiento definido. Sedimentos aluviales están en la parte inferior de los relieves.

La situación morfológica está caracterizada por una parte alta del relieve con ángulos de pendiente de hasta ~30°, y una parte más suave, con gradientes de ~15°. La parte más alta corresponde a débiles e inestables lutitas y está dominada por flujos de detritos, deslizamientos superficiales (Figura 2a) y cárcavas encajadas en la roca infrayacente (Figura 2b) en los cuales el sedimento no se acumula (Figura 2c); mientras que la parte más baja es una superficie aluvial que se une con las pendientes más pronunciadas en una discordancia angular marcada (Figura 2d) y que está caracterizada por cárcavas en el relleno del valle con sección en forma de U con paredes y cabeceras verticales (Figura 3).

El área tiene un clima mesomediterráneo típico, caracterizado por veranos secos y calurosos e inviernos suaves y húmedos. La influencia del clima semiárido, es visible en lados opuestos de los valles en cuanto a la disparidad en la cohesión del suelo, contenido en humedad y vegetación, que vienen determinados por las condiciones más húmedas de las laderas orientadas al norte. En consecuencia, las pendientes norte tienen arbustos y hierba más densos, mientras que las pendientes orientadas al sur tienen menos vegetación o no tienen vegetación. La distribución de la vegetación influencia la morfología de la ladera: las pendientes orientadas al norte con una gruesa cobertera de hierba son largas y más suaves mientras que las desnudas pendientes orientadas al sur son más cortas, más abruptas y con muchas formas del paisaje típicas de zonas acarcavadas (Figura 4).

Datos de entrada y métodos

Se examinaron 81 canales sobre las cuencas fluviales de los ríos Basento y Cavone (Figura 1) utilizando el MDE IFSAR NEXTMap con una resolución de 5 m para distinguir firmas geomorfológicas de procesos superficiales actuantes. El conjunto de datos ha sido producido Intermap Technologies con una técnica de interferometría radar de apertura sintética (Interferometric Synthetic Aperture Radar, IFSAR) aerotransportada. Los detalles de precisión del MDE se muestran en la Tabla 1.

Después del procesado del MDE utilizando SpatialAnalysis Tool in ArcMap® 9.2., se extrajeron datos geomorfológicos (por ejemplo, área de drenaje aguas arriba, distancia a la divisoria, distancia desde el punto vertiente, elevación y pendiente) para cada canal y se representaron con la herramienta Profiler (http://www.geomorphtools.org/) desarrollada por Snyder et al. (2000), Kirby et al.(2003) and Wobus et al. (2006). En particular, los perfiles longitudinales resultantes de los 81 canales se han analizado para identificar las transiciones de los procesos superficiales actuantes. Diferentes tendencias en las representaciones pendiente-área (S-A) representan diferentes procesos y el cambio en la pendiente de regresión con disminución del área de drenaje es la transición entre los procesos difusivos sobre las laderas y los procesos advectivos sobre la parte canalizada del relieve. Los puntos de transición de las regiones generan gran interés en la relación entre las condicionantes topográficas sobre la morfología del paisaje y los procesos erosivos.

Resultados y discusión

Los datos experimentales muestran cuatro regiones diferentes en la relación pendiente-área: Región 0, Región 1, Región 2 y Región 3.

La Región 0 tiene una aparición esporádica en las representaciones pendiente-área y se pueden reconocer solamente en la parte más alta de los perfiles. Está caracterizada por valores del índice de concavidad negativos y menores a -0.30 indicando la existencia de perfiles de laderas cóncavas sin canalizar. La Región 1 corresponde al lado superior de los diagramas donde los valores de pendiente permanecen generalmente constantes o aumentan o disminuyen ligeramente con el incremento del área de drenaje y con índices de concavidad, θ*, en el rango de -0.2 y 0.2. La Región 2 corresponde a la parte media del dibujo donde la pendiente es pronunciada y disminuye conforme el área de alimentación aumenta con índices de concavidad,* θ*, en el rango de 0.50 y 2.71. Esta variación corresponde al cambio del perfil, de plano a convexo, y marca los procesos de transición de flujos de detritos a incisión fluvial. Finalmente, la Región 3 se ha eliminado del análisis porque está caracterizada por muy pocos datos pendiente-área para poder aplicar el análisis de regresión. Los canales de las cárcavas se caracterizan por pendientes con gradientes muy suaves en esta parte del paisaje por lo que no es posible realizar el análisis geomorfológico. Las Regiones 2 y 3 están dominadas por los procesos fluviales.*

En la figura 5 se ha dibujado un subconjunto de los 81 perfiles de los canales de las cárcavas y en la figura 6 se han representado los gráficos pendiente-área para 4 cárcavas representativas: (a) el canal número 3 corresponde a una cárcava del norte de Basento, (b) el canal número 32 a uno del sur de Basento, (c) el canal número 43 a uno del norte de Cavone y (d) el número 68 y (e) 71, cárcavas del sur de Cavone.

Los valores de pendiente en la transición de la Región 1 a la Región 2 están entre 0.1 y 0.7 m/m (Figura 7a) y en la transición de la Región 2 a la Región 3 están entre 0.001 y 0.257 m/m (Figura 7b). No hay una relación entre pendiente y el área de alimentación para los umbrales inferior y superior como se evidencia por el grupo de datos en las figuras 7a y 7b.

Si se fusionan las Regiones 1 y 2 se obtienen las formas típicas curvadas en los datos pendiente-área que corresponden a la firma característica de flujos de detritos en otros paisajes, pero en el área de estudio la transición a incisión fluvial del recubrimiento tiene lugar frecuentemente en el cambio de tendencia de los datos pendiente-área. Se ha reconocido una falta de concavidad positiva en el manto de sedimentos desde la deposición de flujos de detritos, y en el campo se han apreciado marcas de erosión de una corriente (fluting and scouring) sobre las rocas del lecho fluvial, confirmando la existencia de procesos fluviales.

La transición entra la Región 2 y la Región 3 se podría atribuir a cambios en los procesos erosivos o a variación en la litológica. Se piensa que la litología produce la transición inferior ya que los sedimentos aluviales toman el lugar de las lutitas.

Conclusión

Se ha presentado un análisis geomorfológico con la relación pendiente-área de un MDE NEXTMap Europe obtenido por IFSAR con una escala espacial de 5 m. En el área de estudio entre las cuencas fluviales de los ríos Cavone y Basento en la región de Basilicata (sur de Italia) el análisis muestra tres, raramente cuaro, regiones. Las firmas morfométricas corresponden a diferentes procesos erosivos que dominan esas cuatro regiones. Es más, se ha mostrado como el análisis empírico de los perfiles de los cauces a partir de MDEs de buena resolución permite la evaluación directa de la morfodinámica bajo diferentes condiciones climáticas y geológicas.

El análisis de umbrales ha permitido establecer que la relación de escala entre la pendiente y el área de alimentación fluvial no tiene límites matemáticos para su aplicación, sino que sus límites están controlados por limitaciones en los procesos. La posición para el límite superior de los canales en roca está afectada por el área de alimentación crítica para la canalización, y por las pendientes, donde hay interacción entre los flujos de detritos y procesos difusivos. Es más, la orientación de la ladera no parece influenciar los procesos dominantes sobre los relieves y la litología no tiene un papel muy acusado.

Introduction

Erosional processes determine river-basin landforms. The use of morphometric quantitative analysis of river-basin landscape features to recognize the dominant process has been extensively investigated in the literature (e.g., Flint, 1974; Tarboton *et al.*, 1991; Sklar and Dietrich, 1998; Snyder *et al.*, 2000; Whipple, 2001; Wobus *et al.,* 2006). In particular, the relationship between local channel slope (S) and drainage area (A) is used to identify the erosional processes along a length profile of a relief as either advection or diffusion. Flint (1974) was one of the first to document the existence of the S-A relation*:* $S=k_sA^\theta$ with S as the local gradient (m/m), A the drainage area (m^2), k_s and θ as the channel steepness index and the intrinsic channel concavity, respectively.

Linear regression on log(S)-log(A) data evaluates the values of k_s and θ. The steepness index (k_s) depends on bedrock incision rates, which are controlled by uplift rates and change with the geological and climatic conditions. The concavity index (θ) describes the shape of a portion of landscape*.* Values smaller than 0.4 correspond to short and steep drainages affected by debris flows or to downstream drainage increased by either incision rate or rock strength (Kirby and Whipple, 2001; Kirby *et al.*, 2003). A range of 0.4 to 0.7 is associated with lithological homogeneous bedrock channels or incisions in uniform uplift rock areas. Values higher than 0.7 may indicate downstream decreases in rock uplift rate or rock strength (Kirby and Whipple, 2001, Kirby *et al.,* 2003; Gasparini and Brandon, 2011) or downstream transitions to fully alluvial conditions. Extreme concavities (negative or >1) are related to knickpoints produced by changes in substrate properties along the channel or to spatial or temporal variation in bedrock incision rates and/or tectonic uplift rates (Whipple, 2004)*.*

Several studies have demonstrated that the change in erosion processes is readily visible from plotting the values of slope and drainage areas along a hillslope-channel profile (e.g., Whipple and Tucker, 2002; Gasparini *et al.*, 2007). Using topographic analysis, Montgomery and Foufoula-Georgiou (1993) identify different regions of landscapes based on variations of the S-A trend. The change in the log(S)-log(A) regression represents a change in the dominant geomorphic process and break points between the trends correspond to the transition between two processes. They recognize two thresholds: the first is identified at a slope value of ~ 0.2 m/m and between 10^4 and 10^6 m^2 of drainage area separating diffusion-dominated and fluvial-dominated regions, whereas the second at a drainage area greater than 10^6 m^2 and a slope value of ~ 0.7 m/m marks the transition between debris-flow channels and alluvial channels. Stock and Dietrich (2003) and Stock *et al.,* (2005) suggest that longitudinal profiles show a clear deviation from the power-law prediction at slopes of 0.03-0.12. On these steeper slopes, scour by episodic debris flows predominates, leading to a nonlinear plot of log(S) against log(A).

The morphometric investigations using automated terrain analysis are strongly affected by the DTM accuracy (Montgomery and Foufoula-Georgiou, 1993; Zhang and Montgomery, 1994; Tarolli and Tarboton, 2006; Tarolli and Dalla Fontana, 2009) as well as by the DTM interpolation and processing techniques (Grimaldi *et al.*, 2007; Nardi *et al.*, 2008; Santini *et al.*, 2009). Grimaldi *et al.,* (2004, 2005, 2007) and Nardi *et al.*, (2006, 2008) show that a correct digital elevation map is useful for hydrologic-hydraulic and hydrogeomorphic applications to define drainage directions, to reproduce natural terrain features and to processes and evaluate distribution of elevations, slopes and curvatures (Vivoni *et al.*, 2008). In particular, Tarolli and Dalla Fontana (2009) compare different resolution DTMs (1 m to 30 m) derived from LiDAR and determined that DTMs with cells of 20-30 m hide the real topographic signature of a landscape, whereas DTMs finer than 10 m identify the region dominated by debris flows and landslides and channel incisions.

NEXTMap® Europe digital terrain model dataset (produced by *Intermap Technologies,* https://www.intermap.com/en-us/databases/nextmap.aspx) is based on the airborne Interferometric Synthetic Aperture Radar (IFSAR) technique (hereafter named as IFSAR NEXTMap). It enables analysis of large areas of the country and provides high spatial resolution (horizontal accuracy of 5 m and vertical resolution of 1 m). The high precision of the DTM makes it suitable for application in many fields, such as geomorphology, hydrology, environmental planning, etc.

In this paper, we extract and analyse topographic data of gully incisions in the Basilicata region from the 5 m IFSAR NEXTMap DTM. The analysis shows performances in the identification of the signature of erosional processes and transition points along the profiles of selected case studies, using the relationship between the slopes and contributing area. With this contribution we attempt to discuss the ability to extract geomorphic information directly from stream profiles without demanding intensive field surveys. We show how geomorphic process laws could be investigated with digital topographic data to gain insight into landscape dynamics.

Geology and Geomorphology of the study area

The Basento and Cavone are two large rivers located in the Basilicata region in southern Italy. The study area pertains to the territory of Pisticci, in a part of the Bradanic trough, which is an uplifted sedimentary basin with a NW-SE trend limited by the southern Apennines and Apulian foreland (Figure 1). Open-shelf mudstones refer to Plio-Pleistocene and with a thickness of more than 1000 m crop out extensively, the *Argille subappennine* Formation (Ricchetti, 1981). They consist of silty clays with middle-high plasticity and include illite, kaolinite and montmorillonite. The strong tendency to disperse rapidly when wetted depends on the high Na^+ (Piccarreta *et al.*, 2006) and makes them particularly prone to erosion and to extensive badland formation.. The mudstones are unconformably overlaid by sandy-gravelly regressive deposits, organized in multi-order marine terraces (Boenzi *et al.*, 1971; Brückner, 1980). In the Middle Pleistocene, the Bradanic trough experienced a regional uplift and the rivers incised deep valleys perpendicularly to the coast. The fluvial and marine terraces and the generalized homocline setting of the *Argille subappennine*, gently dipping north-eastwards (Amato, 2000), are the evidence of this uplift (Boenzi *et al.,* 2004).

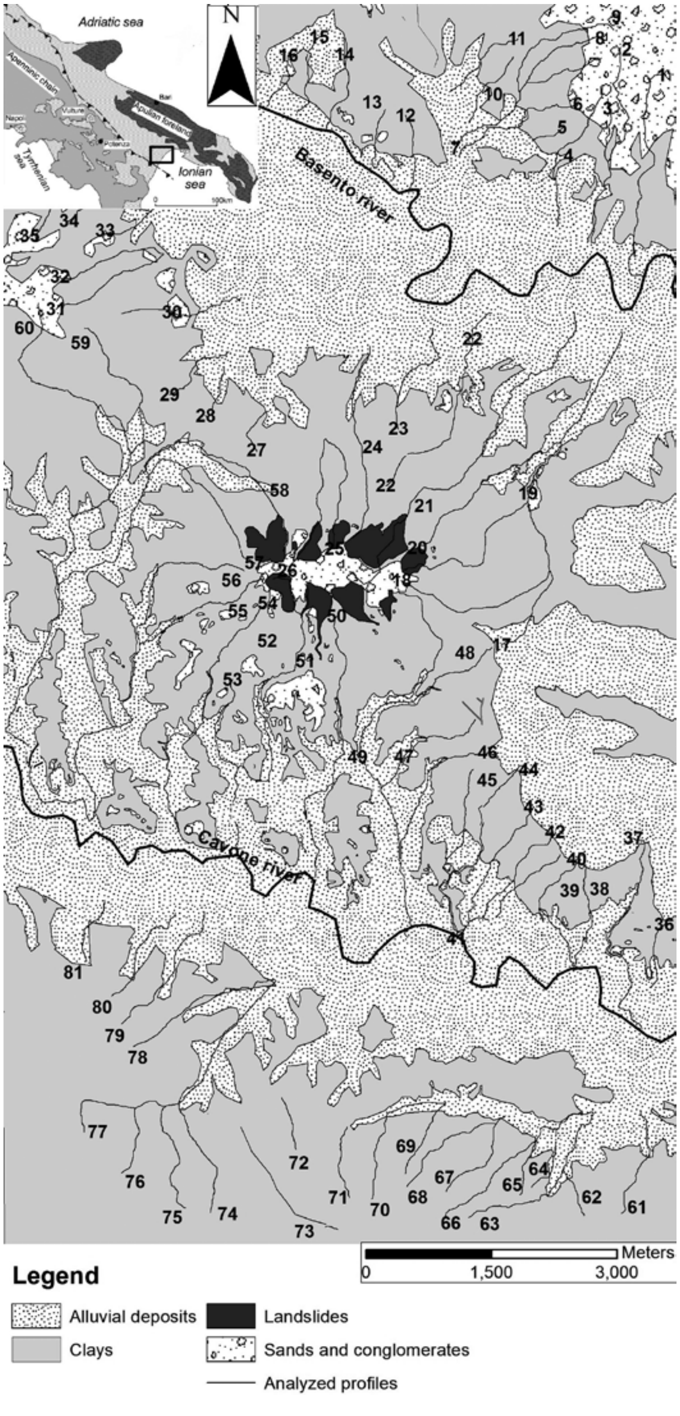

Figure 1. Lithological map of the study area with channel profiles. The inset shows the location within the bradanic trough.

Figura 1. *Mapa litológico del área de estudio con los perfiles de los canales. El detalle muestra la localización dentro de la Bradanic Trough (Sur de Italia).*

The relicts of the marine terraces are located at an elevation range from 350 to 200 m a.s.l. and are characterized by a 40 m thick caprock made up of sands and conglomerates*.* They correspond to the higher part of the relief where the slope angles are up to ~30°. Underlying the caprock, the weaker mudstones are highly unstable at steep slopes and, as a result, this part of the landscape is dominated by debris flows and shallow landslides that often initiate in low order streams (Figure 2a). These processes are commonly connected to extreme events (Piccarreta *et al.,* 2005, Piccarreta *et al.*, 2012) that rapidly saturate the soil, increase pore pressure and trigger landslides. Moreover, gullies incise mudstone bedrock with very steep slopes and they often seem to originate from this slope instability (Figure 2b). Due to the steep slope and the high sediment transport capacities, the main channel does not accumulate sediment (Montgomery *et al.*, 1996), as shown in Figure 2c. In some areas the low order channels show a clear structural control due to inherited tectonic structures (Capolongo *et al.*, 2005).

An alluvial surface with gentler gradients (~15°) meets the steep slopes at a sharp angular discordance. The alluvial surfaces often receive their drainage from the upper part, the steeper bedrock gullies (Figure 2d), but in other cases new channels occur. These channels have the typical morphology of gullies in valley fill, U-shaped in cross-section with vertical sidewalls and heads (Figure 3). Their valleys are wider near the mouth and slightly narrowed headward.

The Cavone and Basento rivers deposited up to 15 m of silty-sandy alluvial sediment due to climatic shifts during the Holocene that controlled cycles of erosion and deposition (e.g. Boenzi *et al.,* 2008; Piccarreta et al., 2011). These deposits form a series of fluvial terraces in the respective valleys of the two systems. The main channels and the lower parts of the gullies are now incising into these deposits.

The area has a typical meso-mediterranean climate, characterized by hot, dry summers and mild, wet winters. Average annual precipitation is 600 mm, concentrated from November to January and the yearly average temperature ranges from 16° to 17.5°C, with an average maximum between 24° and 25.5°C during the summer and an average minimum of between 8° to 9.5°C during the winter (Piccarreta *et al*., 2004). Grasses, such as *Lygeum spartum*, and shrubs (e.g. *Rosmarinus officinalis* and *Pistacia lentiscus*) are typical, spontaneous vegetation. Very scarce thickness or absence of soil, and the poor nature and salinity of the clayed substrates characterizes the steep slopes of the study area. These conditions are worsened by heavy, brief rains that influence the vegetation enormously: only the *Lygeum spartum* is able to spontaneously grow because of its thick roots (García-Fuentes *et al*., 2001).

Similar lithology, spatial uniform tectonic conditions and semi-arid climate strongly influence the establishment of vegetation. Opposite valleys sides are affected by disparities in soil cohesion, moisture content and, consequently, vegetation establishment. North-facing slopes are denser and richer in shrubs and grasses due to the wetter conditions, whereas south-facing slopes are often less vegetated or just bare soil. Vegetation distribution influences hillslope morphology: the north facing slopes with thick grass cover are longer and gentler, whilst the bare south-facing slopes are shorter, steeper and with widespread badland landforms (Figure 4).

The geo-lithological characteristics linked to climate and vegetation conditions strongly influence the morphological landscape. In the upper part, the caprock controls the gradient inducing landslides in the high relieves. In fact, profile morphology reports old, rotational slides that occur along the slopes where hard, competent rocks of Quaternary age overlie soft, incompetent sediments of the Pliocene. It determines that the topography is steep in the upper part, along the geological contact, and becomes gentler in the weak material below the caprock. Moreover, just under the caprock, in underlying mudstones, the slope

Figure 2. In high gradient relief, debris flow in low order channels could be associated to gully development (a); Bedrock gully development in high slope relief (b); Section of a fluvial valley in bedrock (c); Middle Basento river basin aerial image with pediments in the upper part of the relief and the bedrock gullies in the high gradient relief connected to gullies in valley fills in the floodplain with very low slopes (d).

Figura 2. *(a) En el relieve con gradiente alto, el flujo de detritos en canales de orden bajo se podría asociar al desarrollo de cárcavas; (b) Desarrollo de cárcavas en roca, en relieve de pendiente alta; (c) Sección de un valle fluvial en la roca; (d) Imagen aérea de la cuenca fluvial media del río Basento con pedimento en la parte superior del relieve y las cárcavas en la roca infrayacente en el relieve de gradiente alto conectado con cárcavas en rellenos de valle en la llanura de inundación con pendientes muy bajas.*

Figure 3. An example of a Basento tributary gully in valley fills: evidence of runoff, a rill in the upper part of the head (a); the initial part of the gully (b); the gully head with a narrow plunge pool (c); the widest valley near to the mouth and the vertical sidewalls (d).

Figure 3*. An example of a Basento tributary gully in valley fills: evidence of runoff, a rill in the upper part of the head (a); the initial part of the gully (b); the gully head with a narrow plunge pool (c); the widest valley near to the mouth and the vertical sidewalls (d).*

gradient is still high (>25°). Here, small landslides and debris flows dominate the landscape, often connected to the channel in the lower part of the slope. These channels have a V-shaped cross-section and correspond to particular fluvial channels, identified as hillslope gullies.

Moving to the valley bottom, the slope is gentler, and the most frequent forms are gullies in valley fills, incised in alluvial sediments (Boenzi *et al.*, 2008).

Intermap's NEXTmap ® database

The IFSAR NEXTMap DTMs are produced by Intermap Technologies with the airborne Interferometric Synthetic Aperture Radar (IFSAR) technique. They are bare-earth models that contain elevations of natural surfaces. Elevation due to vegetation, buildings and roads are digitally removed from the original digital surface model (DSM) obtained as a first-reflective-surface model.

These datasets are void-filled via interpolation or with ancillary data to create a fully populated elevation data, and hydro-enforced by removing bridges or other anthropic structures, flattening water surfaces and verifying the downstream direction of the water flow.

For the dataset of western Europe, the ground sampling distance is 5 m and the vertical accuracy is 1 m LE90% in open land of slopes of less than 10 ° (Table1).

Methods

Geomorphic analysis was conducted in the study area using the 5 m resolution NEXTMap DTM. We examined 81 channels in the Basento and Cavone river basins and the locations are shown in Figure 1 and are numbered progressively. For each channel, geomorphic data (e.g. upstream drainage area, distance from divide, distance from outlet, elevation, and slope) were extracted and plots of longitudinal profiles and log(S) against log(A) were generated using the Profiler tool (http://www.geomorphtools.org/) developed by Snyder *et al.*, (2000), Kirby *et al.*, (2003) and Wobus *et al.*, (2006). The tool simplifies the surface analysis of raw topographic data by applying a group of built-in functions in ESRI ArcGis to create flow accumulation arrays and to delineate drainage basins and then MATLAB® scripts to analyse the stream profile data.

Data type	WESTERN EUROPE		
	Resolution	Accuracy	Coverage area of the dataset estimated to meet the listed accuracy specification
DSM, DTM	5 m	<1 m LE90% (vertical)	40%
		1-3 m LE90% (vertical)	40%
		>3 m LE90% (vertical)	20%

Table 1. *Details about Intermap's NEXTmap ® database.*
Tabla 1. *Detalles de la base de datos Intermap's NEXTmap ®.*

Figure 4. Badland landforms where south facing slopes are bare and north-facing slopes are vegetated. Vegetation variation affects morphology of slopes: the north facing slopes with a thick grass are longer and gentler and the bare south-facing slopes are shorter, steeper and with badland forms.
Figura 4*. Formas acarcavadas donde las pendientes orientadas al sur están desnudas mientras las pendientes orientadas al norte están con vegetación. La variación de vegetación afecta a la morfología de las pendientes: las pendientes orientadas al norte con una cubierta de hierba espesa son más largas y suaves mientras las pendientes desnudas, orientadas al sur, son más cortas y pronunciadas y con formas acarcavadas.*

The pre-processing of the DTM consisted of the filling of the pits and holes, before generating the flow accumulation and the flow direction of the study area, using the *Spatial Analysis Tool* in ArcMap® 9.2. For accurate analysis with the Profiler tool, elevation data is not smoothed because the raw data is very precise and not markedly scattered, so that obscure natural breaks in scaling along the profiles are not obscured and the surface data are collected along each channel over a 2 m vertical interval. Moreover, steepness indices (k_{sn}) normalized to a reference concavity of 0.45 are calculated along the length of each channel profile, performing regression on the slope-area data. The normalized steepness index is useful for comparing a number of different channels, as discussed by Wobus *et al.,* (2006).

The resulting longitudinal profiles and, in particular, slope-area plots of the 81 gully channels, were analyzed to identify the surface processes transitions. Different trends in the S-A plots represent different processes and the change in regression slope with decreasing drainage area is the transition between the diffusive processes on the hillslopes and the advective processes on the channelized part of the relief.

Particular attention was paid to transitional points of the regions to better understand the relation between topographic constraints for the landscape morphology and erosional processes and finally our S-A data was compared with previous works.

The aim of this analysis was also to assess if different signatures on S-A plots might correspond to a lithological change.

Data and results

Figure 5 shows a subset of the 81 gully channel profiles and in Figure 6 the corresponding slope-area plots for 4 representative gullies is inserted: channel number 3 (a) corresponds to a northern Basento gully, channel number 32 (b) to a southern Basento gully, channel number 43 (c) to a northern Cavone gully and channel number 68 (d) and 71 (e) to a southern Cavone gully.

Data plots reveal four different slope-area regions that we indicate as *Region 0, Region 1*, *Region 2* and *Region 3*. *Region 0* has a sporadic appearance in S-A plots, which can be identified only in the uppermost part of 12 stream profiles. Negative and smaller than -0.30 concavity index (Figures 5e and 6e) values characterized the *Region 0* showing the existence of hillslope concave unchanneled profiles.

Region 1 is located on the upper side of the diagrams where slope values generally remain constant or slightly increase or decrease with increasing drainage area. Generally, its concavity index, θ, ranges between -0.2 and 0.2, indicating that the upstream valleys are basically straight in platform and normalized steepness index, k_{sn}, ranges from 45.59 to 49.45 $m^{0.9}$ for a reference concavity of 0.45. At these steep slopes and small contributing areas, only debris flows and small shallow landslides may scour valleys. The high frequency of inflection points between *Region 1* and *Region 2* occur at a slope of 0.1-0.7 m/m (~94%) and a contributing area of 1.16×10^4 m^2 and 9.58×10^5 m^2 (78%), as shown in Figure 7a. They correspond to the change in landform from planar to convex profiles and mark the transition in erosion processes from debris flows to fluvial incision.

Region 2 corresponds to the middle part of the plot where the slope is steep and decreases as the contributing area increases. Normalized steepness indices, k_{sn}, range from 4.12 to 49.66 $m^{0.9}$ for a reference concavity of 0.45, whereas concavity indexes, θ, are between 0.50 and 2.71. About 62% of the channels in *Region 2* show extreme values, which are greater than 1. Conversely, *Region 3* goes to a smaller regression gradient and has concavity indexes, θ, between 0.16 and 2.57 and normalized steepness indices, k_{sn}, range from 5.57 to 148.52 $m^{0.9}$ for a reference concavity of 0.45. We have excluded *Region 3* from our analysis because it is characterized by insufficient slope-area data for the regression to be applied. Gully channels in this portion of the landscape have extremely gentle slope gradients that do not allow a

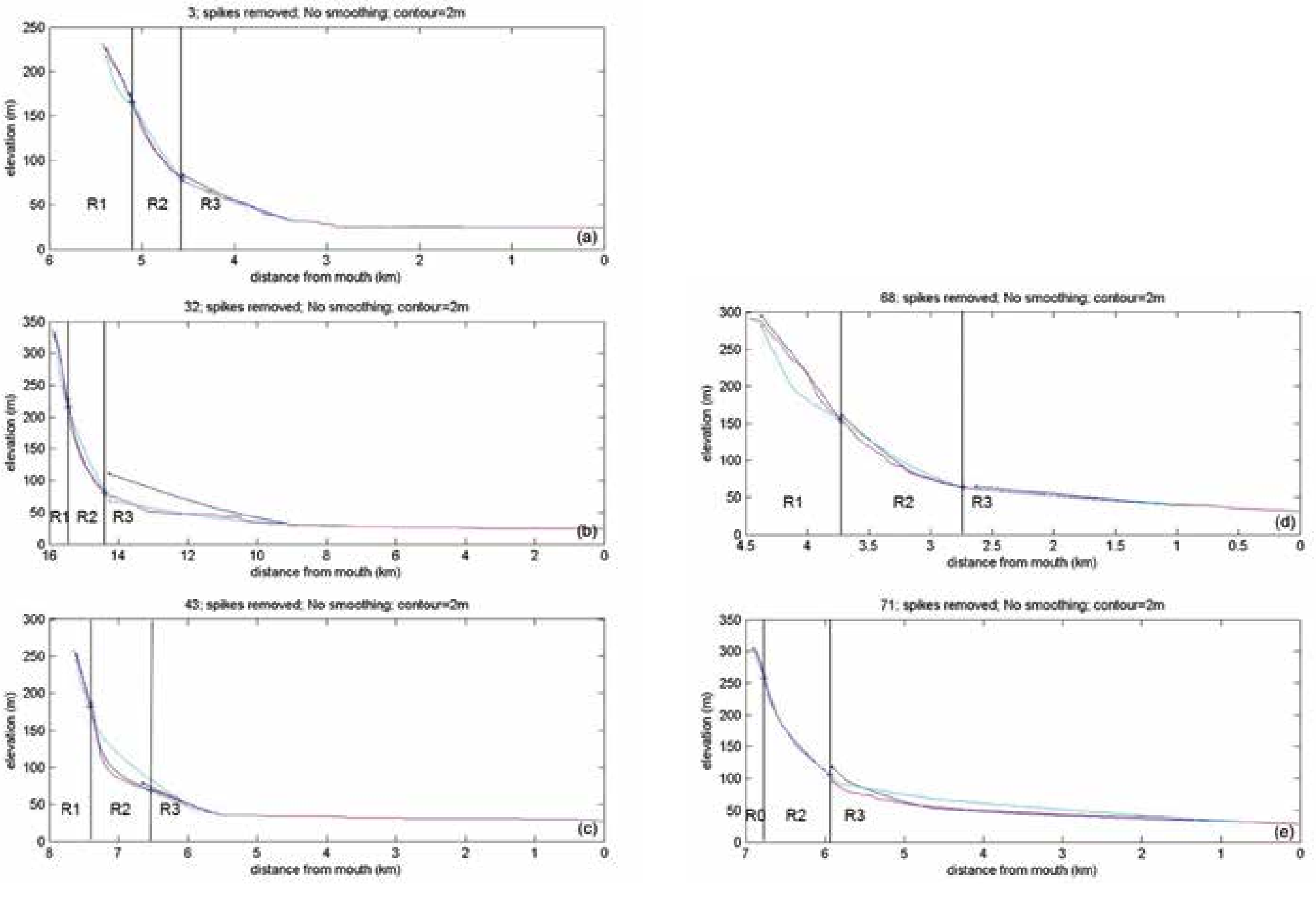

Figure 5. Profiles plotted with the Profiler tool (Wobus et al 2006). The profiles analyzed are (see Figure 1 for location): the northern Basento gully, number 3 (a), the southern Basento gully, number 32 (b), the northern Cavone gully, number 43 (c) the southern Cavone gully, number 68 (d) and number 71 (e). The four different regions are shown: Region 0 (only in Figure 5 e), Region 1, Region 2 and Region 3. In the plots, raw elevations are in green and smoothed in pink, whereas the profiles predicted by the regressed channel concavity, θ are shown as dark blue lines and by specified reference concavity, θ_{ref} are cyan lines. Marks indicate the locations of transition positions.

Figura 5. *Perfiles representados con la herramienta Profile (Wobus et al 2006). Los perfiles analizados son (ver Figura 1 para la localización): (a) la cárcava Basento norte, número 3: (b) la cárcava Basento sur, número 32, (c) la cárcava Canove norte, número 43; (d) las cárcavas Cavone sur número 68 y (e) número 71. Se muestran las cuatro regiones diferentes Región 0 (sólo en la Figure 5 e), Región 1, Región 2 y Región 3. En las representaciones, las elevaciones originales están en verde y los valores suavizados en rosa, mientras en los perfiles predichos por regresión de la concavidad del canal θ se muestran como líneas azul oscuro y la concavidad especificada como referencia θ_{ref} son las líneas añiles. Las marcan indicas las localizaciones de las posiciones de transición.*

correct slope – drainage area analysis in *Region 3*. Both different scaling regimes are fluvial dominated portions.

The lower transition points occur in the slope range between 0.001 and 0.257 and in the contributing area range from 2.15 × 10^4 m^2 and 4.46 × 10^6 m^2. No relationship between slope and contributing area characterizes the lower threshold as evidenced by the data cluster in Figure 7b. In theory, a change in trend in the S-A plots might be ascribed to a variation in erosional processes but could also be ascribed to a variation in the lithology. We imagine that the lithology could affect the lower transition because alluvial sediments take the place of mudstones. At the lower transition, a concavity change is shown, although it is not clearly defined because the transition occurs at a very low gradient. For this reason, we limit the lower threshold analysis on S-A relation and not on S-A regression of the channel points.

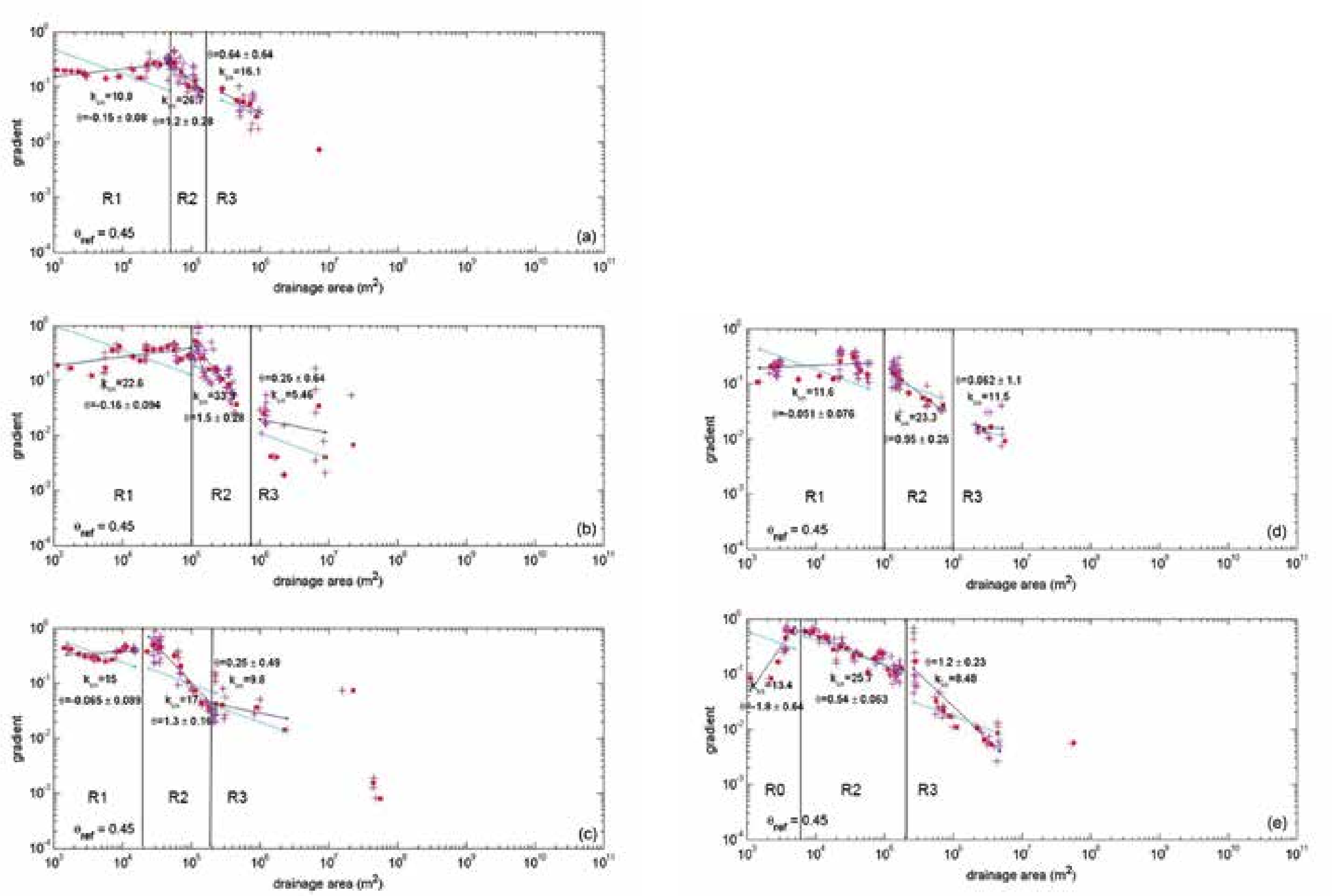

Figure 6. Slope-drainage area data plotted Profiler tool corresponding to the profiles in Figure 5: the northern Basento gully, number 3 (a), the southern Basento gully, number 32 (b), the northern Cavone gully, number 43 (c), the southern Cavone gully, number 68 (d) and number 71 (e). Region 0 (only in Figure 6 e), Region 1, Region 2 and Region 3 indicate four different slope-area regimes identifiable in the S-A plot for trend changes and for the first two regimes the evaluated values of the channel concavity, θ, and of the normalized steepness index, k_{sn}, are shown. In the S-A plot the same blue and cyan colors show the regressed and reference concavities, respectively. Red squares are log- bin averages of the S-A data and open circles show the thresholds locations.

***Figura 6**. Datos pendiente-área de drenaje dibujados con la herramienta Profiler correspondiente a los perfiles en la Figura 5: (a) la cárcava Basento norte, número 3: (b) la cárcava Basento sur, número 32, (c) la cárcava Canove norte, número 43; (d) las cárcavas Cavone sur número 68 y (e) número 71. Región 0 (sólo en la Figure 5 e), Región 1, Región 2 y Región 3 indican cuatro regímenes pendiente-área (S-A) diferentes en el dibujo S-A para cambios de tendencia y para los dos primeros regímenes se muestran los valores evaluados de la concavidad del canal, θ, y el índice normalizado de inclinación k_{sn}. En el gráfico pendiente-área los colores azul y añil muestran las concavidades de regresión y de referencia respectivamente. Los cuadrados rojos son promedios en clases logarítmicas de los datos S-A y los círculos abiertos muestran las localizaciones umbrales.*

Discussion

S-A plot analysis suggests that the morphological signature may correspond to different erosional processes. We identify four distinct regions similar to those of Ijjasz-Vasquez and Bras (1995) and Tarolli and Dalla Fontana (2009): *Region 0* at a smaller contributing area and a positive relationship between slope and area is not recognizable in every channel plot; *Region 1* with a small drainage area and a high slope corresponds to higher part of the reliefs characterized by roughly planar slopes; *Region 2* with positive and often very high values of concavity; *Region 3* with reduced gradient slopes.

The regression parameters allow to us to identify the erosional processes connected to the different regions. In the hillslope, we distinguish two different trends: *Region 0* is the hillslope dominated by diffusion as described by the positive regression corresponding to concave profiles, whereas *Region 1* is either planar or slightly curved with relatively low concavity values, which range between -0.2 and 0.2 defining straight upstream valleys, and slope values above 0.1-0.4. This signature is similar to that found by Tucker and Bras (1998) that individuate processes such as debris flows and shallow landslides. Field surveys support that fast hillslope transport processes dominate this region.

The S-A scaling changes from a positive relationship to a negative trend, signing the transition between *Region 1* to *Region 2*. It represents the transition from hillslope to fluvial processes, which occurs at drainage-area values of between 10^4 and 10^5 m^2. This range is within the critical drainage area (10^4-10^6 m^2) necessary for channel initiation suggested by Montgomery and Dietrich (1992). Finally, both *Region 3* and *4* have negative trends demonstrating the presence of channel processes, but different values characterize the regression. Lower values of concavity index describe *Region 3* and, if compared to *Region 2*, demonstrate a difference in dominated fluvial processes. Notwithstanding the high resolution of the DTM, the very gentle gradients on the lower part of the reliefs make S-A analysis difficult. Consequently, we could only transfer the field observations for erosion interpretation: the lithological change from mudstone to alluvial sediments is due to the gradient change from *Region 2* and *Region 3,* corresponding to a likely lower transition between fluvial erosion processes that is from a detachment limited to transport limited erosion. Alluvial sediments that filled the lower parts of gullies were deposited by base level variations in the Cavone and Basento Rivers during the Holocene climatic shifts.

Slope values at the transition from *Region 1* to *Region 2* are between 0.1 and 0.7 m/m (Figure 7a). The

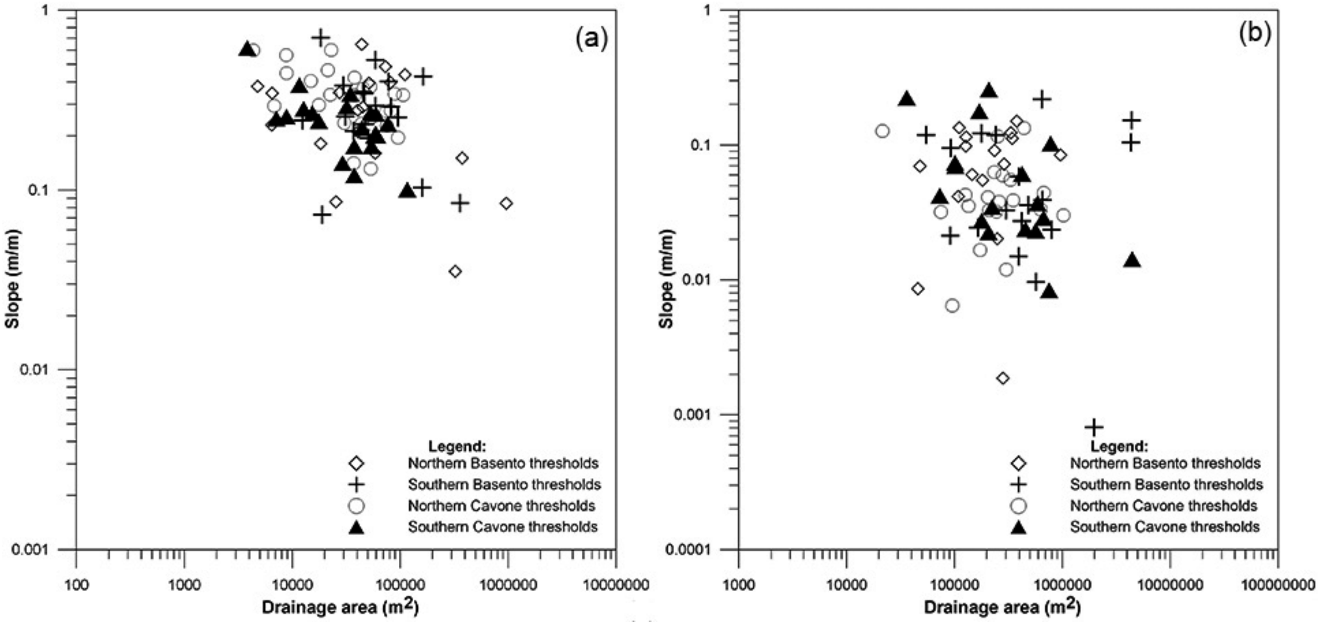

Figure 7. Slope versus drainage area plot for upper threshold between Region 1 and Region 2 (a) and lower threshold between Region 2 and Region 3 (b).

Figura 7. *(a) Pendiente frente área de drenaje para el umbral superior entre la Región 1 y la Región 2 y (b) umbral inferior entre la Región 2 y la Región 3.*

upper reaches of *Region 2* are often non-linear in S-A space, even though this region is dominated by bedrock fluvial incision, and in some areas the slopes are very steep. In steep unglaciated valley networks, Stock and Dietrich (2003) observed that debris flows dominate at slope values of between 0.03-0.10 m/m and that the transported sediment hinders fluvial incision. Montgomery and Buffington (1997) also suggest that debris flows rarely affect slopes below 0.05-0.10 m/m. In our study area, although debris flows may dominate a greater portion of reliefs, we recognized a lack of positive concavity in the sediment mantle from debris flow deposition. In the field, we have also individuated fluting and scouring marks on the fluvial bed rocks, confirming the existence of fluvial processes. Thus, *Region 1* and *2*, if linked, seem to have the typical curved form in the S-A data that correspond to the signature of debris flows in other landscapes, but we demonstrate that in our area transition to fluvial bedrock incision often occurs at the trend change in S-A data.

Extremely high concavity indexes (>1) characterize the ~62% of *Region 2* in the analyzed channels, contrasting with many authors who have indicated a range from 0.3 to 0.7 (e.g. Tarboton *et al.,* 1991; Seidl and Dietrich, 1992; Sklar and Dietrich, 1998; Snyder *et al.*, 2000; Tucker and Whipple, 2002). The location of the transition from hillslope to bedrock channels is fixed by the critical drainage area (10^4-10^5 m^2) necessary for channel initiation, whereas the lower transitions are set in a range of 10^4-10^6 m^2, probably influenced by the local lithology, a change from mudstone to alluvial deposits. We suggest that it is possible that both the upper and lower transition points are pinned, and that the bedrock channels must conform to both boundary conditions. One way that bedrock channels could adapt to these limitations is by varying their concavity values and by imposing high concavity index values to *Region 2*.

The lithology in the study area is uniform; in fact, mudstone crops out widely and only in the higher parts of the north and south Basento and the north Cavone conglomerate caprock lays on mudstone, whereas alluvial sediments lay on the lower part of the reliefs. The lithology contribution does not produce a variation in local settings, so that we were able to observe the direct correlation between the steepness index and tectonic activity. Although it is not completely possible to compare k_{sn} values in different areas because of the variable climatic and lithological settings, we note how the values in our study region are lower than the literature data (e.g. Wobus *et al.*, 2006; DiBiase *et al.,* 2010). Moreover, the absence of knickpoints indicates an actual limited tectonic activity, which related with k_{sn} values, determine low erosion rates. This could be confirmed by the general regional uplift rates of ~ 0.5 mm/y estimated from marine and fluvial terraces for the Late Pleistocene – Holocene time period (Boenzi *et al.,* 2008 and reference therein).

Conclusion

Geomorphic analyses using the slope-area relationships are presented using IFSAR-derived *NEXTMap Europe DTM* with a spatial scale of 5 m. The analyses show how it is possible to identify different processes by the produced morphometric signatures representative of local conditions, using DTM data at high resolution coupled with field observations. Moreover, we demonstrate how empirical analysis of stream profiles on accurate DTMs allows direct evaluation of morphodynamics under different climate and geological conditions.

Three regions, rarely four, are recognized on the S-A plots of 81 longitudinal profiles of the tributaries of the selected study domain, corresponding to the Cavone and Basento river basins in the Basilicata Region in southern Italy.

The transition between *Region 0* to *Region 1* corresponds to the variation between positive to negative relation gradient. Here, fluvial processes (erosion) replace diffusion. Data points in *Region 1* show planar surfaces or surfaces with relatively low concavity or convexity and slope values above 0.1-0.4 m/m and they are associated with debris flows and small shallow landslides. *Region 2* and *Region 3* have smaller gradients and, in particular, *Region 2* has the highest gradient and the lowest concavity index values. The transition between *Region 1* to *Region 2* identifies the portion of the landscape where the slopes becomes upward-concave and the fluvial processes begin to dominate to the detriment of debris flows and small shallow landslides that characterized *Region 1*. On the other hand, the differences in two fluvial reaches (*Region 2* and *3*) are probably due to a lithological variation from marine mudstone to alluvial sediments. Therefore, we can affirm that the upper limit of this scaling law determines where channelization begins and changes in the concavity of fluvial channels may signal the lower threshold from bedrock to alluvial channel.

The threshold analysis allows us to state that the slope-contributing area fluvial scaling relationship has no mathematical limits for its application, but its bounds are controlled by process limitations. The position of the upper limit for bedrock channels is affected by the critical contributing area for channelization, and by the slopes, where there is interaction between debris flow and diffusive processes.

High resolution DTM data analyses (S-A relation of the profiles and threshold-point relationship) and field observations, allow us to argue that there is no strong role for the lithology on the geomorphic signatures of the examined hillslope channels. The caprock presence in the upper part of the relief of northern and southern Basento, and in the northern Cavone area, does not determine a change in topographic characteristics in the southern Cavone area, where caprock does not occur. However, the lithology affects the local badland morphology, influencing debris flows and shallow landslide formation.

Moreover, different exposure does not seem to influence the dominating processes on the reliefs. We might expect different hydrological settings (infiltration alteration, runoff generation, evaporation losses and subsurface flow formation) to determine a change in vegetation on north and south facing slopes that govern the type of erosion, and thus the signature along the profiles. Contrary to this, the topographic data does not change with exposure and vegetation. The studied area is characterized by unfavourable conditions for vegetation (steep slopes, high salinity, soil absence and flash flood occurrence) where only *Lygeum spartum* can grow. Its roots are too thin and weak to increase sediment cohesion, consequently diffusion is inhibited and linear erosion is promoted.

Acknowledgments

We thank Fernando Nardi, an anonymous referee and the editor for their constructive criticisms and insightful suggestions.

This study has been financially supported as part of Research Project COFIN MIUR 2010 2011 "Response of morphoclimatic systemdynamics to global changes and related geomorphological hazard" (National Coordinator: Prof. Carlo Baroni, Università degli Studi di Pisa).

The authors wish to thank Dr Ralph Feldman for his help in correcting the manuscript and his advice on the English language in the text.

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Recibido: agosto 2013
Revisado: febrero 2014
Aceptado: marzo 2014
Publicado: septiembre 2014