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Measuring rill erosion by laser scanning

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ABSTRACT

This paper reports the results of a field investigation on the rill morphology and the corresponding soil loss, using a Terrestrial Laser Scanner (TLS), at the Masse experimental station (Umbria, Central Italy). Laser scanning is a survey method that allows determining the three-dimensional position of a large number of points (point cloud) through the measurement of angles (azimuth and zenith) and distances. For this paper five scans were made of some rills, which formed during particularly erosive rain in the plots of the Masse station. The point cloud was first interpolated by the natural neighbor method to create a discrete 0.02 m × 0.02 m square cell grid Digital Elevation Model (DEM) used for mapping the flow network. The same cloud was also used to generate a continuous modeling of the surface (by the Triangulated Irregular Network model, TIN) to quantify the total eroded volume and the morphological characteristics of the rill formations. Three methods were applied to the DEM for detecting the channel network: the slope method (Horn, 1981; Wood, 1996), the constant drop method, described by Broscoe (1959) and the method of landform curvature (Tarolli et al., 2012). The comparison has shown a good agreement between the three methods, but Broscoe's method seems to be more accurate for rill recognition. The morphological characteristics of the rill formations derived by the TIN model (i.e. length, width, depth and volume) were compared with the corresponding characteristics obtained manually using a profilometer. The analysis showed a good agreement between the width at the top measured by the two methods, a general overestimation of the maximum depth and of the cross section areas and an underestimation of the rill length when the manual method is used. Lastly, the comparison between the volumes obtained by the TLS survey and by the manual method showed that the total volume calculated by the manual measurements overestimates that evaluated by the TLS, with a good agreement between these variables.

1. Introduction

The following sections summarize the most recent advances in the soil erosion and in the applications of high-resolution topography. The goal is to present the state of the art, providing useful information to better understand the purposes of the paper.

1.1. Soil erosion

Soil erosion and runoff are the result of a complex interaction between soil and rainfall. These two processes are characterized by a considerable spatial–temporal variability (Nachtergaele et al., 2001, 2002). It was also clearly stressed recently by González-Hidalgo et al. (2007) that the most intense erosive events play a very important role in the annual soil loss. These are typically characterized by the presence of both interrill and rill erosion. Rill erosion is caused by the concentrated flow of water (Bryan, 2000; Govers et al., 2007; Knapen et al., 2007) and is considered to be the most important process of sediment production (and thus, soil loss) (Cerdan et al., 2002; Di Stefano et al., 2013; Poesen, 1987). Generally, rill erosion is understood as the effect of flowing water exceeding a certain threshold of soil resistance (Knapen et al., 2007). During the last decades, several approaches have been developed to describe and predict soil detachment and sediment transport in rills, and great efforts have been made to evaluate their suitability for that purpose (Giménez and Govers, 2002; Govers et al., 2007; Hessel and Jetten, 2007). Unfortunately, the different approaches to describe this phenomenon have turned out to be weak, if not contradictory (Giménez and Govers, 2002; Govers et al., 2007; Merz and Bryan, 1993). This is attributed mainly to methodological differences in all the monitoring and experimental setups to achieve the rills (Knapen et al., 2007; Merz and Bryan, 1993). It also appears that particle detachment and sediment transport may be controlled by different characteristics of the flowing water and, therefore, a comprehensive description may not be possible (Govers et al., 2007). However, soil erosion measurements are still lacking (Stroosnijder, 2005) and there is a recognized need to perform field experiments to ascertain the role of rills in soil erosion (Govers et al., 2007). As the observation of erosion in the field is subordinated to the stochastic character of the erosion events (Auerswald et al., 2009) and to a high dependency of the measurement

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technique (Casali et al., 2006), standardized and reproducible field experiments are needed, in which it is possible to produce data to characterize the behavior of rills in their environment (Wirtz et al., 2012, 2013). However, there are few field studies for the quantification of the associated soil loss (Di Stefano et al., 2012; Vinci et al., 2014) and for the direct observation of the rill formations (Bruno et al., 2008; Di Stefano and Ferro, 2011; Di Stefano et al., 2013; Mancilla et al., 2005).

1.2. High resolution topography and Terrestrial Laser Scanning

In the last decade, new remote-sensing techniques have led to an important increase in terrain information, providing a basis for developing new methods for analyzing Earth surfaces (Tarolli et al., 2009). Among the available remote-sensing technologies there are the Unmanned Aerial Vehicle (UAV), the Time-of-Flight (ToF) cameras (or range cameras) and airborne and terrestrial Light Detection and Ranging (LiDAR). The UAV, commonly known as a drone, is an aircraft without a human pilot on board. It has integrated autopilot technology, which gives it semi- or fully-autonomous navigation, flight control and image acquisition capabilities (Hugenholtz et al., 2013). This recent remote sensing technology is growing fast and the scientific community is witnessing a significantly increasing use of UAVs for Earth surface analysis (e.g. Jaakkola et al., 2010). Hugenholtz et al. (2013) used a small unmanned aircraft system for the feature detection and accuracy assessment of a photogrammetrically-derived Digital Terrain Model (DTM) and the results gave evidence of the effectiveness of this technology in Earth surface analysis (Tarolli, 2014). The Time-of-Flight cameras are a new generation of active sensors, which allows the acquisition of 3D point clouds without any scanning mechanism and from just one point of view at video frame rates. The working principle is the measurement of the Time-of-Flight of a signal emitted by the device towards the object to be observed, with the advantage of simultaneously measuring the distance for each pixel of the camera sensor (Piatti and Rinaudo, 2012).

LiDAR is a technology for measuring positions of physical objects, rapidly. Furthermore it is useful because it can collect tens of thousands to over a million positions per second. LiDAR data can be collected from airborne or terrestrial vehicles, from fixed positions, usually on a tripod, and offshore platforms. In recent years the use of LiDAR has grown rapidly, both in terms of the number of application domains and in the prevalence of the method in real-world practice (Fekete et al., 2010; Lato et al., 2009; Mason et al., 2007; Zhou et al., 2004). In the case of airborne acquisition, the LiDAR is placed in an unobstructed location in a fixed wing aircraft or helicopter. The density of the measurements is determined by the LiDAR data collection rate, the elevation and ground speed of the aircraft. Data from airborne scans is corrected for position and then processed for various output products. One typical product is the generation of a bare-Earth elevation model. In terrestrial acquisition, the LiDAR unit is mounted either on a tripod or on a vehicle. The point density will be much higher than the airborne LiDAR, as great as a few points per square cm.

LiDAR (aerial and terrestrial) provides high resolution topographic data with notable advantages over traditional surveying techniques (Slatton et al., 2007); in particular, the capability to produce sub-meter resolution Digital Terrain Models (DTMs), Digital Surface Model (DSM) and to better characterize and differentiate landslide morphology (Cavalli et al., 2008). LiDAR relies on two sets of measurements to generate a cloud of point locations for features around the known location of the scanner. First, the position and pointing direction of the laser must be known for each measurement. Depending on the physical mechanism of the scanner the points may be evenly or unevenly distributed on the target, and because systems normally operate on an angular offset between successive measurements, targets closer to the device will have a higher point density than those farther away. The second piece of information needed is the distance. The distance of each scanned point could be measured by different approaches: Time-of-Flight and phase-based. Time-of-Flight LiDAR sends a laser pulse, waits, and measures the time of arrival of the return pulse (s). Given the travel time (the speed of light) and very precise time measurement, a distance can be derived. Phase-based LiDAR employs an amplitude modulated continuous waveform (AMCW) laser. When the beam interacts with a target, the phase is reset, and the returned shifted signal is processed to derive distance in combination with the duration of the flight.

Valuable characteristics of the TLS, compared to more traditional photogrammetric techniques, are: 1) the capability to derive topographic data related to the bare ground surface by automatically filtering vegetation or other objects on the surface; and 2) the capability to produce sub-meter resolution Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) over large areas.

Furthermore, thanks to the availability of high-resolution topography, the procedures for channel network extraction (Passalacqua et al., 2010; Pirotti and Tarolli, 2010; Pirotti et al., 2012; Sofia et al., 2011) have been reconsidered, introducing new methods and achieving more detailed results than those obtained in the past (Tarolli, 2014).

The identification of a channel network is of fundamental importance in landscape-scale geomorphic and hydrologic analyses (Montgomery and Foufoula-Georgiou, 1993), and it is a key step when studying catchment hydrological responses to rainfall events (Tucker et al., 2001).

The new approaches for channel network extraction (e.g. Lashermes et al., 2007; Pirotti and Tarolli, 2010; Tarolli and Dalla Fontana, 2009)

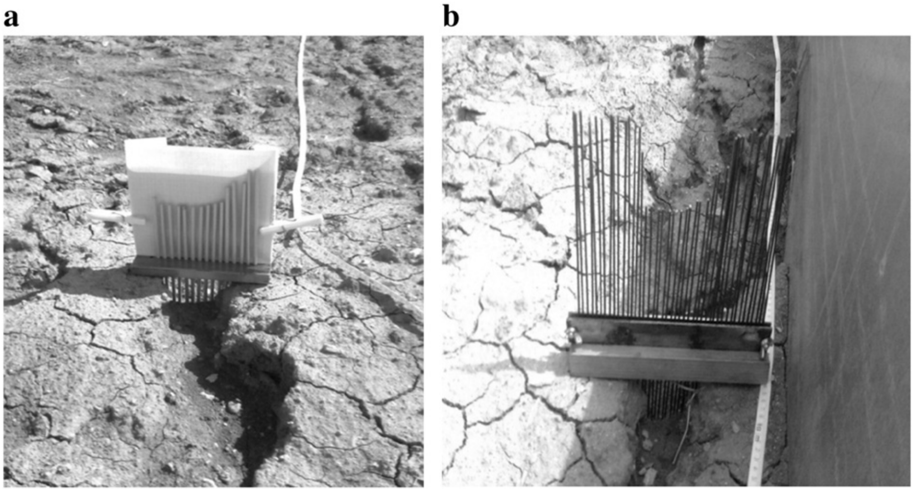

Fig. 1. Profilometers used for the manual survey of the rills (a), (b).