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Detection of gullies in roughly textured terrain using airborne laser scanning data

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ABSTRACT

Airborne laser scanning data contain information about surface features, some of which are of subtle form. These features are usually embedded within the terrain, and rarely form distinct shape-transition to their surroundings. While some efforts have been made in extracting linear elements from laser scanning data, attention was mostly turned to dominant elements that are very clear and distinct. We present in this paper a detection model for gullies of various dimensions using airborne laser scanning data. Gullies are regarded as one of the main landform-reshaping agents, having a pejorative effect on the environment and on regional development. They are commonly observed along receding lakes as a common response to water-level drop. The paper demonstrates how a multi-scale approach enables the extraction of various gully forms, from well developed to subtle. It then proposes an optimization driven model for handling fragmentation in the detection. Results show that using the proposed model, gully networks can be reconstructed and ~30 cm deep features can be identified and separated from their surroundings using moderate point density data.

1. Introduction

Owing to its accurate and detailed surface characterization, airborne laser scanning offers an excellent means for landform documentation. However, the attractiveness of this technology is encumbered by the volume of data, feature span, and their complex nature; rendering manual quantification difficult. In contrast with objects like buildings and trees, which form a distinct topographic signature in the landscape, land features such as gullies are usually embedded within the terrain, hardly forming distinct surface signatures. Their varying size, form, and appearance add further challenges to their detection. This paper presents a new method for the detection of gullies from airborne laser scanning data, focusing on those of modest size that are embedded within roughly textured terrain.

Gullies are regarded as one of the main landform-reshaping agents contributing to land degradation (Poesen et al., 2003; Wu and Cheng, 2005; Valentin et al., 2005). They develop through surface-runoff concentration at the gully head (termed nickpoint) and evolve via three main processes – headcutting, which refers to the upslope migration of the nickpoint (lengthening the gully); downcutting, which refers to deepening and widening of the gully bottom; and sidewall collapse which contributes to their broadening. Their evolution is often rapid during the initiation period when morphological characteristics have not yet reached a stable state (Brooks et al., 2003; Valentin et al., 2005). Even though gully dimensions can be relatively modest, they concentrate runoff and prevent floodwater irrigation. They thereby disallow for normal land use, and are often considered responsible for enhanced drainage, accelerated land degradation, and consequent aridification (Ries and Marzolff, 2003; Poesen et al., 2003; Avni, 2005; Valentin et al., 2005). Gullies may also have severe impact on existing infrastructure. Such examples can be observed along receding lakes (e.g., Lake Chad, the Aral Sea, and the Dead Sea – Glazovsky, 1995; Mainguet and Le'tolle, 1998; Avni et al., 2005; see Fig. 1a), where newly exposed soil (composed mostly of unconsolidated costal material) is subjected to rapid gully development, which can reach orders of 100 my^{-1} (Avni et al., 2005). Their development along the coastal plains causes heavy damages to infrastructure (Fig. 1b), and generates a severe threat to the future of the regions in which they occur (Mainguet and Le'tolle, 1998; Valentin et al., 2005; Avni et al., 2005; Ben Moshe et al., 2008).

Presently, erosion and active-morphology studies make use of traditional land-surveying techniques (Wu and Cheng, 2005; Avni, 2005; Ben Moshe et al., 2008), spaceborne images (Giordano and Marchisio, 1991; Martínez-Casasnovas and Stuiver, 1998; Torrion, 2001; Liberti et al., 2009), or photogrammetrically derived digital elevation models in low (Ries and Marzolff, 2003; Martínez-Casasnovas et al., 2003), and higher resolution (Betts and DeRose, 1999; Martínez-Casasnovas et al., 2004). Despite the technological advances that allow gully erosion to be measured, these techniques require an intensive acquisition phase, are limited in scope, and are usually insufficient to describe small- to medium-scale systems

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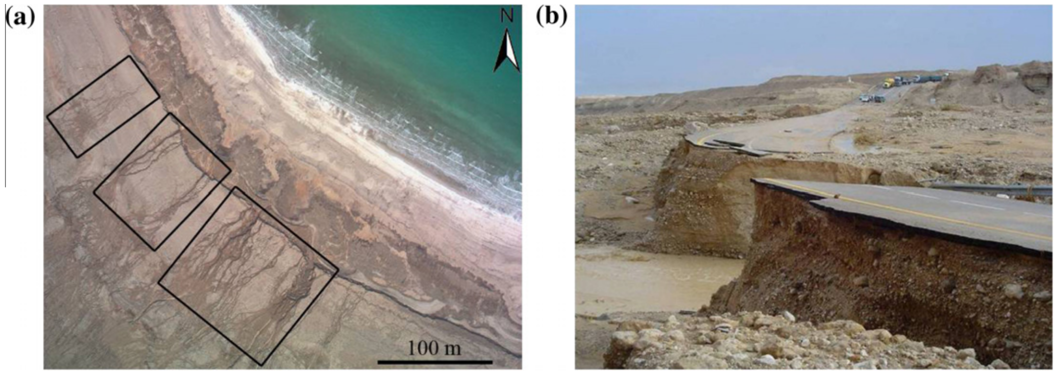

Fig. 1. Gully incision along the Dead Sea coastal plains and their environmental impact, (a) an aerial photograph showing a network of gullies in different development stages (marked), all have been developing in the past 10–20 years and (b) impact of gully incision on infrastructure.

($\sim$10–20 km^2) where detailed typological characterization and quantitative erosional data are needed (Peroy et al., 2010).

In this regard, studying related features via airborne laser data hold great promise due to its dense and accurate 3D surface description as well as its growing availability. Reviewing previous studies utilizing airborne laser scanning data, Ritchie (1996) used airborne laser altimetry data for quantifying landscape features, among them gully and stream cross-sections. Lohani and Mason (2001) and Mason et al. (2006) extract tidal channels from airborne laser scanning data-derived DEMs. James et al. (2007) characterize extent and density of channels and headwater streams under forest canopy. Eustace et al. (2007) model gullies impact on stream water quality by determining their extent via laser scanning data. Cho and Slatton (2007) detect channel streams under forest canopy. Notebaert et al. (2009) evaluate the feasibility of airborne laser scanning data to identify geomorphic phenomena within fluvial systems, and Eustace et al. (2009) compare gully volume estimates produced by ground and airborne laser scanning systems (detection and mapping is carried out by using a semi-automated object classification).

Extraction of channel-like features from elevation models has drawn attention over the years, and methods including the steepest gradient approach (Jenson and Dominque, 1988), profile-scan (Chorowicz et al., 1992), multiple-direction flow (Costa-Cabral and Bruges, 1994) or multi-level skeletonization (Meisels et al., 1995) have been proposed. These techniques tend to limit water-flow into one of eight fixed directions, assume that slopes along the channel path remain positive, and consider flow-path as beginning near ridges and in relatively high curvature values. Such assumptions may not apply for developing gullies embedded in gentle slopes, such as those located within alluvial fans.

For laser scanning-driven channel extraction, Lohani and Mason (2001) propose emulating manual interpretation strategies for autonomous extraction. Channel fragments are first identified using edge detection and are then joined via topological-related cues (e.g., continuity). This method is limited to low-resolution data where channel width is on the single-pixel level. Mason et al. (2006) extend this method to handle high-resolution data by first detecting high gradient values using an edge-detector (assumed to be channel banks), followed by a fragment-connecting procedure that is based on proximity criterion. The approach is applied to tidal channels – relatively smooth features surrounded by smooth topography. Its application to an alluvial environment (characterized by rough terrain) generates a large amount of fragments causing model failure (Fig. 2). In reference to ravine-like features (though opposite in shape), Rutzinger et al. (2006) present an object-driven analysis for moraine extraction which is based on maximum curvature segmentation. The authors use predefined window and thresholds to limit the detection to objects of interest. Cho and Slatton (2007) use a predefined window size for binary operations attempting to extract stream channels under forest canopy.

Approaches such as these may apply for deep and wide profile features, but not for channels embedded within a strongly textured terrain. Consequently, their application is likely to generate a large amount of false detections, or alternatively ignore channels when stronger thresholds are set (Fig. 2). The objective of the proposed model is to reconstruct gully networks forming within alluvial environments. These networks can be sparse or dense and span over large regions. For detailed characterization of these evolving features, the model aims also at detecting their modest and shallow (30–40 cm) segments. As the paper shows, preferential erosion, surface texture, sediment deposition along the gully bottom, and sidewall collapse (see Fig. 3c), may lead to a partial detection of the channel-path. Therefore, not only the detection, but also linkage of detected fragments into a consistent network poses challenges. The existence of fragments and the braided

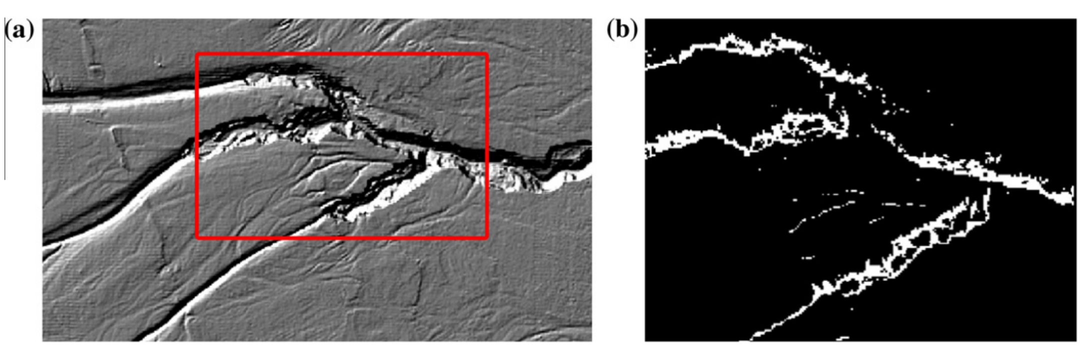

Fig. 2. Application of common extraction methodologies on the studied gullies, (a) a shaded relief map of a gully segment and (b) detection results: relatively shallow gullies are ignored while noisy responses are observed near deeper segments. Tested extraction methodology here is based on Mason et al. (2006), thresholds were set to capture a 30 cm channel depth.