Use of airborne laser scanning to characterise land degradation processes – the Dead Sea as a case study

S. Filin*[1], A. Baruch[1], S. Morik[1], Y. Avni[2] and S. Marco[3]

Evaluation of surface processes requires efficient means to quantify their effect. Despite the span and three-dimensionality of these processes, they are usually monitored using land surveying or naive 2D image interpretation. Therefore, the results are partial in terms of coverage and detail, and are mostly qualitative. We study in this paper the application of high resolution airborne laser scanning data for detection and characterisation of geomorphic processes. The Dead Sea region, where lake level drop of >1 m/year has led to dramatic change in the surrounding geomorphic system, and is endangering the natural environment and infrastructure, is used here as our case study. We propose a feature extraction methodology which responds to the measurement noise and surface texture and show how laser data are optimal for detecting such phenomena, accurately characterising them and providing quantitative data, which are all necessary to understand their development.

Keywords: Airborne laser scanning, Geomorphology, Dead Sea, Land degradation, Channel incision, Sinkholes

Introduction

One main effect of environmental deterioration in the semi-arid regions is the shrinkage of water bodies (e.g. Lake Chad, the Aral Sea and the Dead Sea) as a result of the climatic transition from glacial to post-glacial and amplification by human use of fresh water for domestic needs. The exposure of new coasts, due to the drop in water level, is leading to enhanced landscape reshaping processes reflected in erosion processes, fresh water channelling that destructs wetland ecosystems and head-cut migration that endangers the natural environment, infrastructures and ultimately population [**11**], [**6**], [**3**]. The effect of such processes requires efficient monitoring means which enable coverage of wide regions and provide detailed information for quantifying the undergoing changes. Even though such surface processes are three-dimensional in nature, they are usually monitored in two-dimensions using either classical geodetic techniques or naive interpretation of aerial images [**15**], [**20**], [**16**]. Consequently, they are incapable of properly characterising and quantifying the impact of such processes on the land, where detailed typological characterisation and quantitative erosional data are needed [**14**]. In this regard, airborne laser scanning technology, which enables broad 3D data coverage in high level of accuracy [**8**], may be considered optimal for this task. Use of airborne laser scanning for geomorphic related tasks has been receiving growing attention in recent years, applied for, e.g. landslide detection [**10**], [**18**], coastal dunes analysis [**19**] or studies of alluvial fan morphology [**17**], all indicating the attractiveness of this technology for geomorphic related studies. These properties enable detailed analysis of wide regions, evolution of existing features and detection of new features that may be size-wise small but significant in their lateral effect.

In order to benefit from the advantages that this technology offers, this paper studies utilisation of airborne laser data to quantify the evolution of geomorphic systems in areas which are undergoing active processes of land deterioration. As a study case, it focuses on the Dead Sea region, where lake level drop has led to a dramatic change in the surrounding geomorphic system and triggered a series of complex surface reshaping processes. These processes are endangering the natural environment and infrastructure, and in some parts have brought regional development to a halt. In addition to assessing the applicability of laser scanning data to characterise these phenomena, the paper presents a computational methodology for detection of related features and extraction of detailed geometric information about them in terms of shape and volume. Contrasting common image based, or even laser scanning based, analyses, which focus on qualitative interpretation, we show that largely autonomous models can both extract and quantify these diverse set of phenomena. Detailed high resolution quantification of such phenomena offers valuable data for appropriate strategy development for future regional planning, aiming to combat land degradation processes.

[1]Mapping and Geo-Information Engineering Technion, Israel Institute of Technology, Haifa 32000, Israel
[2]Geological Survey of Israel, Jerusalem 95501, Israel
[3]Geophysics and Planetary Science, Tel-Aviv University, Tel Aviv, 69978, Israel

*Corresponding author, email filin@technion.ac.uk

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a collapse sinkhole field near a beach resort; *b* collapse of a bridge following a flood as a result of a headcut backward migration along the stream channel, demonstrating the effect of a powerful flood that was caused by the widening of the stream channel
1 Environmental deterioration along the Dead Sea coast

Study site

The Dead Sea is a terminal lake that drains extensive regions in the surrounding countries. During the middle of the twentieth century, the lake was at a level of 392 m below the mean sea level (m.b.m.s.l.) and the southern shallow basin was flooded. Increased diversion of water from its northern drainage basin since the mid-1960s initiated a continuous process of artificial drop in the lake level that accelerated since the 1970s and reached an average rate of >1 m/year in the last 10 years. The present lake level is 422 m.b.m.s.l., 30 m lower than the twentieth century high stand. The rapid, level drop is causing dramatic widening of the coastal plain, reaching 200–2500 m of a newly exposed strip since 1945. This newly exposed area began developing complicated erosional patterns immediately after and since the lake retreat. Over time, channelling, gulling and headcut migration occurred in the coastal plains, migrating upstream towards the basin boundaries [**3**], [**7**]. The rapid artificial drop in the lake level has undermined the stability of the geomorphic systems around the Dead Sea and triggered a chain of reactions, impacting the coastal area of the lake in the form of:

- (i) extensive (up to 2·5 km) exposure of mudflats around the lake
- (ii) exposure of steep slopes along the lake coasts
- (iii) rapid increase in areas affected by collapse of sinkholes (Fig. 1*a*)
- (iv) intensive incision of streams and gullies in the newly exposed mudflats and within the alluvial fans.

The incision is propagating upstream towards the infrastructures along the coast, causing heavy damage to the road pavement and bridges (Fig. 1*b*), and preventing further development of the area. Such damages are only supposed to increase in coming years.

Geomorphic feature

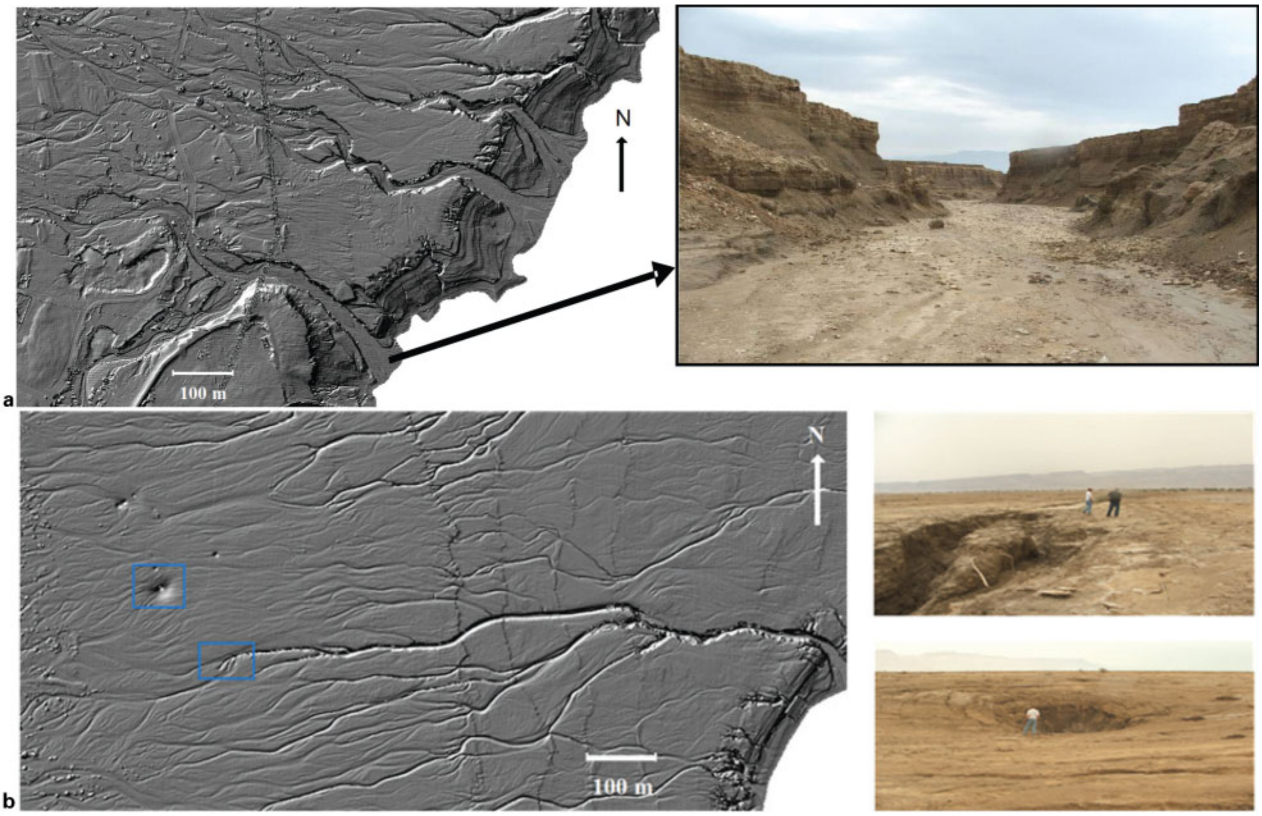
Among the different changes along the Dead Sea coastal plain, two conspicuous features are of great concern: collapse sinkholes and incision of gullies. Sinkholes have been developing as a result of a subsurface dissolution of a thick salt layer deposited by the former lakes predating the present Dead Sea. This layer, located at 20–50 m below surface, is dissolving by fresh water running in the subsurface towards the receding lake [**1**], [**9**]. As the subsurface caverns expand through time, they lead to the collapse of the surface above it, thereby forming embryonic sinkholes that evolve over time into larger form, sometimes into a sinkhole field (Fig. 1*a*). Sinkholes are characterised by an oval shape, ranging from 1 m size to several tens of metres as they develop through time [**1**], [**9**]. Because of their sudden appearance and their hazardous nature, it is important to distinguish their embryonic structure and localise their position. Their increasing number makes them difficult to monitor using terrestrial methods, and as they develop from embryonic, metre size form, it is difficult to track them using aerial photography, particularly when their size is small.

Gullies have been forming along the coastal plain of the Dead Sea as a result of the drop in the lake level and the exposure of steep slopes at the outlet of the fluvial channels. The steep slope exposure has triggered rapid incision of the streams that in most cases maintain the level of the dropping lake by forming deep gullies in the fans. These gullies are dynamic features, which are under a continuing evolution. Their depth, width and longitude profiles are changing rapidly in a direct relation to the flood regime and the resistance of the alluvial material (fine or coarse) to erosion. During floods, gully headcuts migrate upstream in a rate ranging between several metres to several hundred metres. This instability makes their monitoring an important task for better planning of this region.

In the following, the focus is turned mainly to gully characterisation, as an illustration to the level of detail that can be extracted from the laser scanning point cloud in an unbiased manner. Morphometric analysis of sinkholes along the coast can be found in Ref. [**9**].

Data processing and detection

Use of laser scanning data as a means to characterise these features requires methods that can handle the point cloud. The dense point cloud incurs a huge volume of data, which are hardly manageable and do not easily land themselves to manual processing. As a result, designated algorithms for handling and extracting information from the data have been developed, with the two key processes being: the extraction of terrain related returns from the point cloud, and extraction of the geomorphic features and their quantification.



a channels formed in the last decades in the Ze'elim alluvial fan: left, a shaded relief map derived from laser scanning data; right, an image taken in this channel, showing its dimensions; *b* derived shaded relief in the Ze'elim alluvial fan, features as gullies, knickpoints, sinkholes and the developing channels are clearly seen; right, an image showing the actual knickpoint and the developing channel emerging from it and sinkhole with tension rings surrounding it (people as scale)

2 Reflection of the geomorphic features in the laser scanning data

Extraction of the terrain returns from the data follows the methodology proposed in [**2**], a combined global and local terrain representation strategy. The global representation aims at providing a general terrain description at some level of resolution as well as resolving uncertain occurrences in the terrain such as disconnected terrain patches, discontinuities, gaps and others. The local representation supports the inclusion of fine, local, terrain features, e.g. ridges or seam lines that the global representation cannot capture via surface curvature based analysis [**2**].

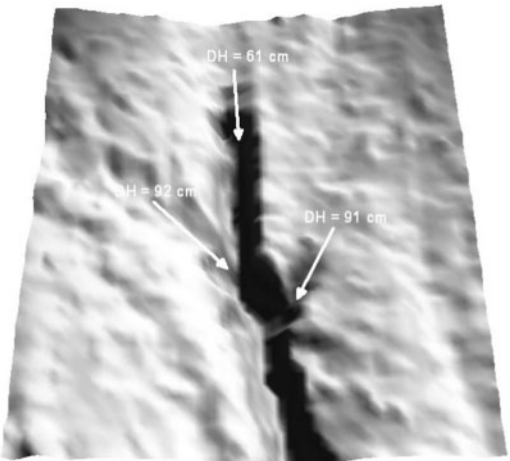
Detection

Key geomorphic features are characterised by drop in the topography. Sinkholes for example have a closed circular depression form and gullies are characterised by their elongated linear shape. The edges between the fan and the geomorphic features may be considered optimal for detection because of the sharp transition between the ground and features. Even though a functional description, which is driven by seeking strong first derivatives ($\|\nabla\|$), seems appropriate (e.g. [**12**]), the rough surface texture that characterises alluvial fans generates noisy responses which are hard to discriminate, makes edge driven analysis hard to apply. Instead, we seek the actual features, e.g. sinkhole bottoms or gully thalweg related points. These points can be described as local extrema in the surface curvature. Thus, the characterisation of terrain objects is implemented by principal curvature analysis via the eigenvalues $\lambda_{\min}$ and $\lambda_{\max}$ of the Hessian form. The Hessian is computed numerically via

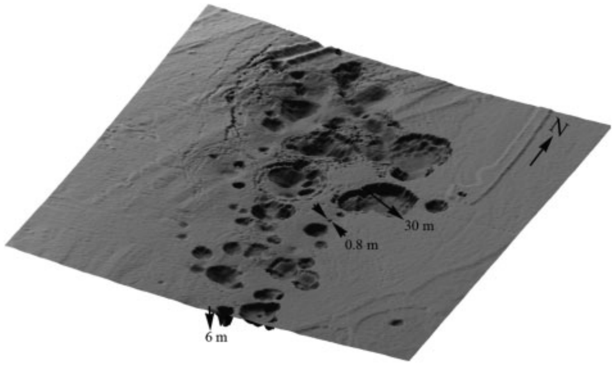
$$
\begin{aligned}
&\partial^2 Z/\partial x^2 = \left(Z_{y_0,x_0+d} - 2Z_{y_0,x_0} + Z_{y_0,x_0-d}\right)/d^2 \\
&\partial^2 Z/\partial y^2 = \left(Z_{y_0+d,x_0} - 2Z_{y_0,x_0} + Z_{y_0-d,x_0}\right)/d^2 \\
&\partial^2 Z/\partial xy = \\
&\left(-Z_{y_0-d,x_0-d} + Z_{y_0-d,x_0+d} + Z_{y_0+d,x_0-d} - Z_{y_0+d,x_0+d}\right)/(2d)^2
\end{aligned}
\tag{1}
$$

where $Z_{x,y}$ is the surface elevation at points x and y, and d is half the window size. While polynomial derived estimations (e.g. [**5**], [**13**]) can be considered an option, the numerical estimation is both computationally efficient and enables characterising the variety of size, shape, form and direction that these features wear.

Contrasting the common fixed-kernel fixed-threshold detection practices that cannot handle the variety of feature forms and surface texture, we detect features in multiscale manner, searching for a 'significant' response in different scale levels. In principle, the eigenvalues sign characterises the type of entity to which the point is related, where surface depressions dictate positive maximal curvature. The minimal curvature defines the nature of the given point: where sinkholes, should have positive minimal value, and gully thalweg points should have a nearly zero curvature value (the flow direction). Deriving upper and lower bound response levels for the eigenvalues is estimated theoretically by deriving accuracy estimates for eigenvalues as a function of the elevation accuracy as propagated into equation (1). Following the propagation of the elevation accuracy



3 Knickpoint expression in the laser scanning data, illustrating the level of detail that can be observed



4 Collapse sinkhole field in the laser scanning data showing sinkholes in different dimensions and levels of development

onto these parameters and onto the eigenvalues, we obtain

$$m_{\lambda_{\max,\min}} = \pm \frac{6^{1/2}}{d^2} m_Z \quad (2)$$

where m_λ is the accuracy estimate of the eigenvalue, and m_Z is the laser elevation accuracy.

For gully detection, one eigenvalue should be positive while the other should theoretically equal to zero. Setting response level bounds ε_1 and ε_2 for the minimal detection level, we define a gully such that $\lambda_1 > \varepsilon_1$ and $|\lambda_2| \leqslant \varepsilon_2$. In setting the response level, we consider ranging noise and the minimal detection level, ΔZ (minimal object response or detectable gully depth) which we define by the terrain's surface roughness. The minimal object response is defined as

$$\lambda_1 \approx \frac{2\Delta Z}{d^2} \quad (3)$$

Using equation (3), a hypothesis test for λ_1 can be established with: H_0: $\lambda_1 \leqslant 2\Delta Z/d^2$ (indicating that there is no channel there) versus H_1: $\lambda_1 > 2\Delta Z/d^2$ as the null and alternative hypotheses (indicating that there is a gully). The test for λ_2 has the form: H_0: $\lambda_2 = 0$ versus H_1: $\lambda_2 \neq 0$. For a given confidence level α, the two hypotheses define the detection bounds for shallow gullies

$$\lambda_1 > z_{1-\alpha} m_\lambda + \frac{2\Delta Z}{d^2} \quad \text{and} \quad |\lambda_2| \leq z_{1-\alpha/2} m_\lambda \quad (4)$$

where z is the normalised Gaussian distribution. Therefore, instead of setting a unique threshold for the entire scene, each point is examined via its own z-test, for a scale which can accommodate the first significant response.

For a complete gully characterisation, banks are extracted using steep ascent along the profile crossing the channels up to the fan surface level. The process is performed using computation of directional derivatives along the profile direction and terminates when the derivatives indicate a flat surface.

Results and discussion

Evaluation of the laser scanning data suitability to characterise the geomorphic features, as well as evaluation of the detection model is carried out based on a high resolution laser survey along the Dead Sea coastal plains using the Optech 2050 scanner, operating at 50 kHz. Flying altitude was ~500 m above ground level (m.a.g.l), leading to a ~4 parts m^{-2} sampling density. Validation of the laser survey had both quantitative and qualitative parts. Quantitative evaluation consisted of GPS field survey using the new Israeli GPS virtual real-time network that can reach horizontal accuracy of about 2–3 cm and vertical one of about 5–6 cm. Comparison of the GPS survey (consisting of 200 measurements) with the laser scanning data shows a standard deviation of ± 10 cm with only 4% of the points (eight points) having offset >25 cm. Qualitative analysis was carried via field work that was aimed at evaluating the features in the laser scanning data against their actual form.

Geomorphic features expression in the data

Figure 2 shows extracts from the laser scanning data in a form of a shaded-relief derived map of one of the main fans in the Dead Sea region. In Fig. 2*a*, a 9 m deep gully that has been developing in the past 20 years is shown. The steep banks are clearly seen there. Close to the shore, along the steep slopes, a set of terrace like features can be noticed. These are markers of the annual lake retreat, which are formed by wave impact over winter (the rainy season) during episodic lake level rise (along the general retreat trend).

In the upstream segment, gullies end with an almost vertical headcut which serves as a topographic knickpoint between the bottom of the gully and the almost flat coastal plain or alluvial fan surface (Figs. 2*b* and 3). The expression of the different gully forms in the laser data is clearly evident. Furthermore, knickpoints, which are markers for the current state of the developed channels, are clearly seen and are easily measurable (Fig. 3). Emerging from them, the course of the developing channels is well seen. These 20–30 cm deep entities feature the level of detail which is noticeable in the laser scanning data. Figure 2*b* and particularly Fig. 4 show expression of collapse sinkholes. Among the sinkholes, some are of ~1 m diameter. Notice also sub-metre cracks around the sinkholes, indicative of the future evolution of this field. This level of detail means that sinkholes, in their embryonic stage of formation, can be traced.

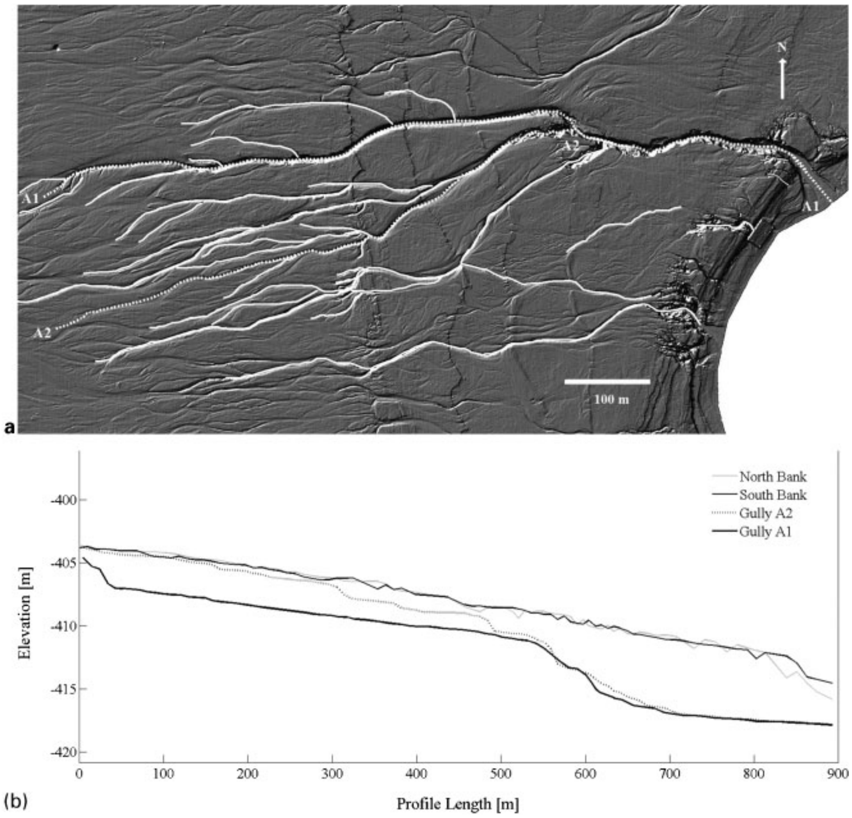
Comparing the laser scanning related level of detail with the one obtained by aerial images is demonstrated in Fig. 5. Notice that the radiometric texture makes it difficult to distinguish the sinkholes in the data from

5 Comparison of image and laser data: notice the clear expression of the sinkholes in the laser data contrasting the difficulty in distinguishing them in the aerial image as well as separating them from shrubs and rocks

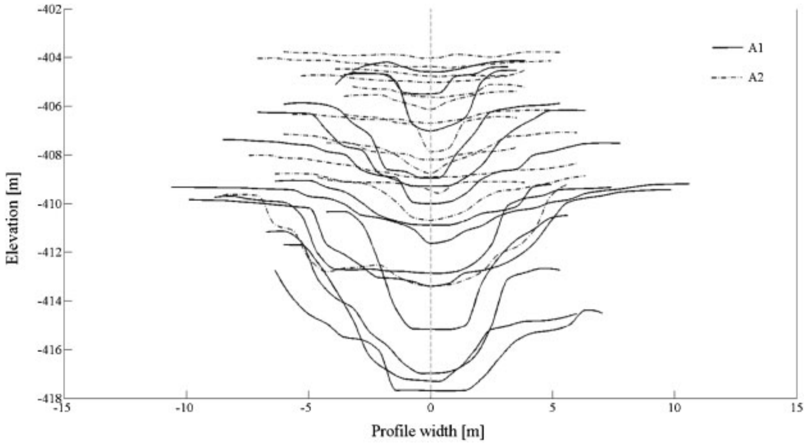
shrubs. Evaluation of full photogrammetric based extraction of data compared with the information obtained by the laser data is given in Ref. [9] showing partial extraction as well as missed and false detections.

Extraction of quantitative data

Results of gully network detection are presented in Fig. 6. Evaluation of the detection performance against manual interpretation has shown that the proposed method is both accurate and provides a more complete characterisation [4]. Having identified thalweg and banks, three-dimensional characterisation of the channel can take effect. Figure 6*b* demonstrates the analysis, focusing on the main channel path and one of its tributary branches. Using the extracted data, both thalweg profile and a dense set of cross-section along both main channel and braches can be extracted, evaluated and assessed comparatively (Fig. 6*b*). Figure 6*b* reveals the incision process that this channel has been undergoing. Several observations can be drawn from the graph, where the first is that the profile has several 'steps' along its path, with the rightmost features the channel headcut. The step, 300 m from its outlet, reflects the more substantial incision of the channel as it adapted to the receding lake level. This incision echoes the process that began as the receding lake reached the distal part of the fan (reflected



6 Extracted gully thalweg profiles from airborne laser scanning data and channel banks reflecting the fan surface



7 Cross-sections along the channel and one of its branches

in the steep slopes, e.g. Fig. 2*a*), where the elevation drop became more dramatic. However, the channel development after its first initiation is influenced both by the receding lake, causing the elongation of the channel towards it, and acting simultaneously with the backward incision of the headcuts upstream. This parallel incision is shaping an almost linear dynamic feature with a dendritic pattern, connecting the distal part of the active fan with the receding lake. The concave profile of the channel in its lower part is a result of ground water seepage flowing in the channel and causing large slumps.

Figure 7 shows stacking of cross-sections of both the main channel and branch. The profile shows that as the channels develop, they both widen and deepen, most likely simultaneously. One can also notice that the channels and branches develop at the same pace and almost have same shape when matched by their height. This stacking, which facilitated the correlation could not have been made using any other data acquisition source.

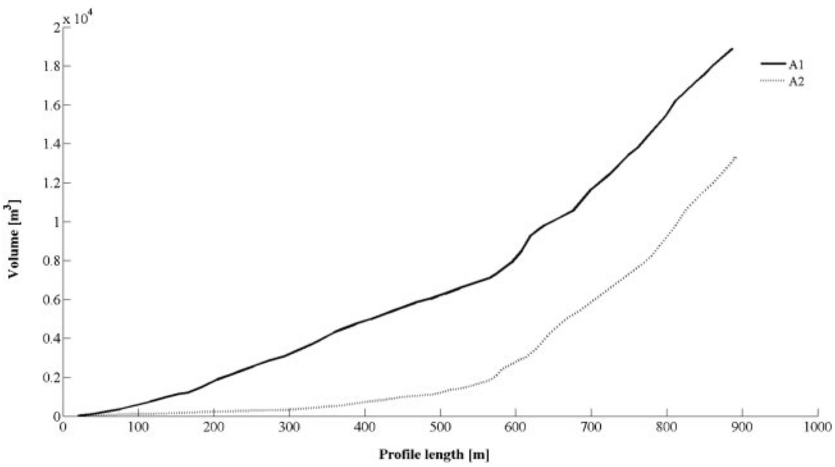
Of particular importance in analysing the geomorphic system is the extraction of volumetric information that provides us with direct knowledge of soil loss due to erosion. For gullies, volume measures, which account for soil loss, are computed as a summation of a sequence of prismoid volumes

$$V = \sum_{\mathrm{i}=1,3,5}^{n-2} 2h \frac{S_{\mathrm{i}} + 4S_{\mathrm{i}+1} + S_{\mathrm{i}+2}}{6} \tag{5}$$

where V is the volume, S_{i} is the area of the prismoid bases (bottom, intermediate and top) and h is the prismoid length. The prismoid bases are profiles extracted across channel path, where the interval between them (the height) dictates the resolution of the computation. For the extracted channel (Fig. 7), a volume of ~20 000 m^3 was computed. Figure 8 shows the volume accumulation as a function of the gullies' length, showing a nearly exponential trend. Volume measure provides a direct figure of soil loss due to channel incision since the initiation of the gully in the last decades. Integration of the data from the rest of the gullies dissecting the fan enables calculation of the total annual rate of the soil loss from this terrain. This procedure enables prediction of the land degradation processes in the region and future planning.

Conclusions

This paper demonstrated the ability of airborne laser scanning data to detect sub-metric geomorphic features, such as thin and small gullies, small headcuts and embryonic sinkholes in sub-metre scale. This ability, combined with the accurate location of these features given by the airborne laser scanning is of prime importance in describing the environmental hazards in this active region. Furthermore, the ability to calculate the 3D dimensions of geomorphic features such as gullies and sinkholes is a powerful tool for estimating



8 Volume accumulation of eroded material along the studied channels

the total volume of soil losses, soil erosion and growth rates of features such as gullies, headcuts and sinkholes fields endangering the natural environment and infrastructures in any given terrain.

The present paper focused on the Dead Sea region, which served as a field laboratory presenting active and rapid geomorphic and environmental changes. However, most of these active features described from the Dead Sea coast are known from other active regions on earth. As demonstrated here, the ability to detect these features made this methodology applicable for other regions around the globe facing geomorphic changes such as land degradation, soil erosion, gully formation and headcuts migration.

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