CHARACTERIZATION OF LAND DEGRADATION PROCESSES USING AIRBORNE LASER SCANNING

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ABSTRACT:

Land degradation is a cause for increased concern in many regions around the world, requiring to quantify the geomorphic processes that such regions are undergoing. Even though the processes that influence the surface topography are three dimensional in nature, they are usually monitored in two dimensions using surveying techniques or naive image interpretation. We present in this paper a methodology for quantifying geomorphic processes in the form of soil erosion, channel incision, and the development of collapse sinkholes in high resolution using airborne laser scanning technology. As a study case, we use the Dead Sea region, where lake level drop of more than one meter per year has led to dramatic changes in the surrounding geomorphic system, leading to the destruction of wetland environments, rapid headcuts migration that endanger the natural environment and infrastructure, and development of sinkhole fields, which in some parts halted regional development. We show how laser data is optimal for detecting such phenomena, accurately characterizing them, and determining volume and evolutionary rates all are necessary to understanding their development.

1. INTRODUCTION

Environmental deterioration such as soil erosion and land degradation are a cause for increased concern in many regions around the world. In this regards, understanding the geomorphic processes that these regions are undergoing is the most fundamental step towards quantification of such phenomena and thereby promotion of suitable solutions. One pronounced 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. Due to the drop in water level, the newly exposed coasts are subjected to enhanced erosion processes, fresh-water channeling that cause destruction of wetland environments, salination, and headcut migration that endanger the natural environment, human population and infrastructures (Mainguet and Le'tolle, 1998; Bowman et al., 2004; Avni et al., 2005).

The effect of landscape reshaping processes on the environment, infrastructure, and ultimately population, requires efficient means to monitor their evolution. These means should enable coverage of wide regions and provide detailed information for quantifying the undergoing changes. Although processes that influence surface topography are three dimensional, they are usually monitored in 2D using either classical geodetic techniques or naive interpretation of aerial images (Marzolf et al., 2002; Ries and Marzolf, 2003; Wu and Cheng, 2005; and Avni, 2005). Therefore, they are incapable of properly characterizing and quantifying the actual impact of such processes on the land. In this regards, airborne laser scanning technology, which enables broad 3D data coverage in high level of accuracy may be regarded optimal for this task. Airborne laser scanning has been receiving growing attention in recent years, applied for, e.g., landslide detection, (Glenn et al., 2006), coastal dunes analysis (Woolard and Colby, 2004), or studied of alluvial fans morphology (Staley et al., 2006); all indicating the attractiveness of this technology for geomorphic related studies. The level of detail that can be noticed in the data facilitates high level of automation in the detection of geomorphic phenomena. 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. Comparative quality assessments of digital elevation models accuracy (e.g., Chang et al., 2004) also show laser scanning derived elevation models reaching levels of 0.1-0.3 m, which are higher, compared to other techniques, e.g., photogrammetry and Radar.

This paper proposes utilization of airborne laser technology for monitoring the evolution of the geomorphic system in areas undergoing active processes of land deterioration. As a study case, the paper focuses on the Dead Sea region where lake level drop has led to a dramatic change of the surrounding geomorphic system. Level drop in a rate >1 my^{-1} (as a combined human- and climate-induced effect on the water balance in the lake) in the last decades has widened of the coastal plain and triggered a series of complex surface reshaping processes. The newly exposed coasts are subjected to erosion processes, such as gully incision and headcut migration that endanger the natural environment and infrastructure, to destruction of wetland environments due to channeling of fresh-water springs, and development of large sinkhole fields that in some parts halted regional development. Laser-scanning data offer unprecedented level of detail for detecting and accurately characterizing such phenomena, as well as determining their evolutionary rates. In this regards, the paper focuses on computational methodologies for detection of related features, and extraction of information about them. Contrasting common image driven or even laser scanning related techniques, which focus on qualitative interpretation, we show that largely autonomous models can both extract and quantify these diverse set of phenomena. By integrating wide scale analysis and quantitative data, parameters and rates that could not be extracted otherwise can be derived. Detailed high-resolution quantification of such phenomena offers valuable data for appropriate strategies development for future regional planning, aiming to combat land degradation processes.

2. BACKGROUND

The Dead Sea region is a deep basin surrounded by active fault-controlled steep shoulders of mostly sandstone, limestone and dolomite along its margin (Garfunkel, 1981). The Dead Sea itself is a terminal lake that drains extensive regions in the surrounding countries. During the middle 20th century, the lake was at a level of 392 m below mean sea level (m.b.m.s.l.) and the southern shallow basin was flooded. Increasing diversion of water from its northern drainage basin since the mid-1960s initiated a continuous process of artificial drop in the lake level that was accelerated since the 1970s and reached an average rate >1 my^{-1} in the last 10 years. The present level of the lake is 422 m.b.m.s.l., 30 m lower than the early 20th century high stand. The rapid, continuous 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 a complicated erosional pattern immediately after and since the lake retreat. Over time, channeling, gulling, and headcut migration occurred in the coastal plain, migrating upstream toward the basin boundaries (Bowman et al., 2004; Abelson et al., 2006). The rapid artificial drop in the lake level undermined the stability of the geomorphic systems around the Dead Sea and triggered a chain of reactions with a disastrous impact on the coastal area of the lake. Impact of the lake retreat appear in the form of: i) exposure of extensive (up to 2.5 km) of mudflats around the lake, ii) exposure of steep slopes along the lake coasts, iii) rapid increase of areas affected by collapse of sinkholes (Figure 1a), iv) intensive incision of streams and gullies in the newly exposed mudflats and within the alluvial fans, and v) channeling of freshwater springs, causing the destruction of the wetland environment previously existed along the lake. The concentration of fresh water springs, seeping along the former coastline into well-defined channels and gullies is leading to drying-up of most of the wetlands that existed along the Dead Sea coastal plain prior to the lake level drop. This process is followed by rapid soil erosion and banks collapse, destruction of vegetation and biomass, thus leading towards increasing land degradation in the region (Bowman et al., 2004; Avni et al., 2005). The incision is propagating upstream towards the infrastructures along the coast causing heavy damage to the road pavement, bridges and accompanying infrastructure lines. Figure 1b demonstrates the effect of a powerful flood that was caused by the widening of the stream channel and resulting in the collapse of a major bridge in that region. The changes along the coastline endanger existing infrastructures and prevent further development of the area; they are only supposed to increase in coming years.

3. GEOMORPHIC FEATURES ANALYSIS USING LASER SCANNING

Among the different changes along the Dead Sea coastal plain two conspicuous features are of great concern – the first is the development of collapse sinkholes, and the second is incision of gullies that have been developing along the newly exposed shore and the alluvial fans.

Figure 1. 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.

Sinkholes along the coast 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 toward the receding lake (Abelson et al., 2006). As the subsurface caverns expand through time, they cause the collapse of the surface above it, thereby forming embryonic sinkholes that evolve over time into larger form, and sometimes into a sinkhole field (Figure 1a). Sinkholes are characterized by an oval shape, ranging from one meter size to several tens of meters as they develop through time (Abelson et al., 2006). Sinkholes may be accompanied by a conical collapse structure, followed by concentric tensional rings reaching dimensions of up to 100 m. Because of their sudden appearance and their hazardous nature, it is important to distinguish their embryonic structure and localize their position. Their increasing number makes them difficult to monitor using terrestrial methods, and as they develop from embryonic, meter size, form, it is difficult to track them using aerial photography, particularly when their size is small.

Gullies are formed 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 exposed steep slopes trigger rapid incision of the streams that in most cases maintain the level the dropping lake by forming deep gullies in the fans. These gullies are dynamic features, which are under

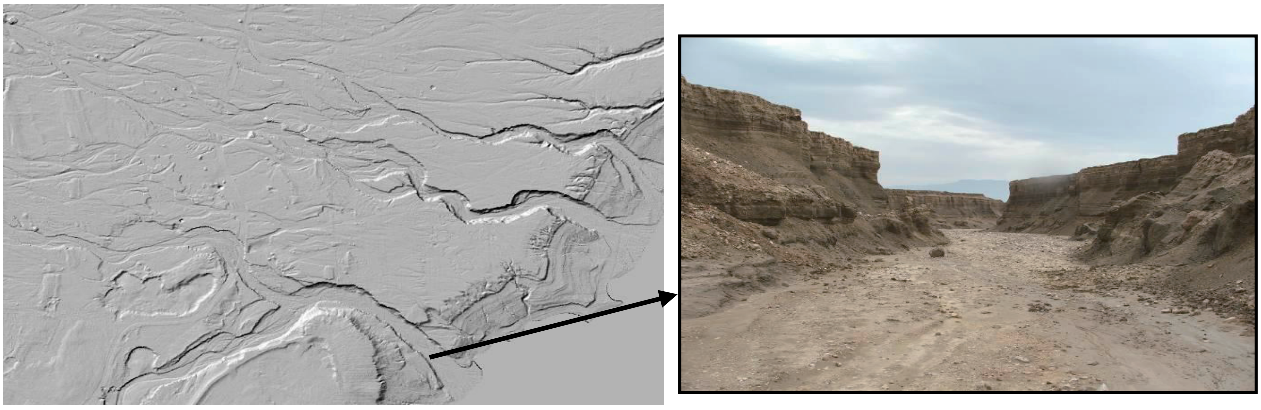

Figure 2. Channels formed in the last decades in the Ze'elim alluvial fan, left) a shaded relief map derived from laser scanning data, right) an image taken in this channel, showing its dimensions.

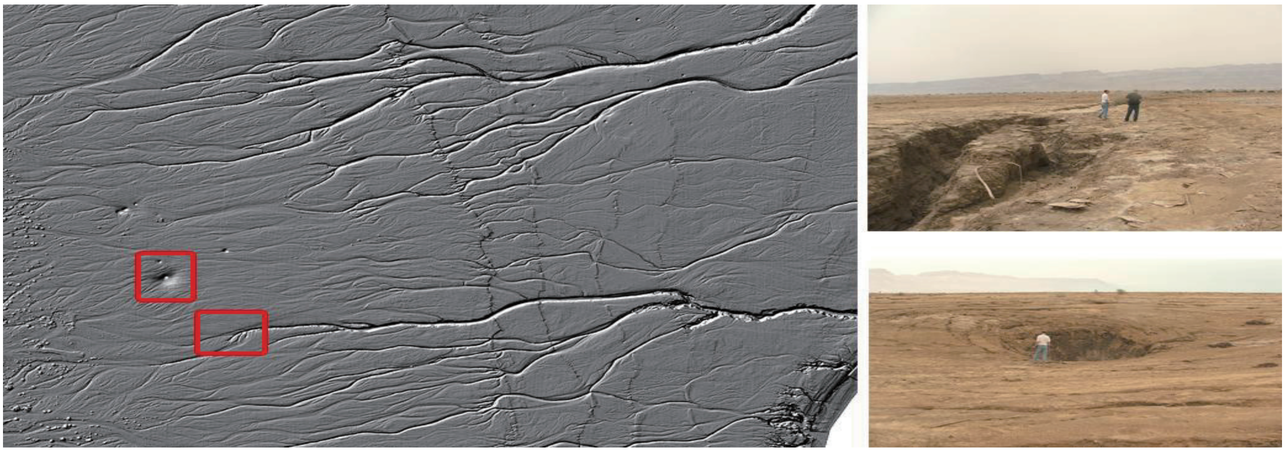

Figure 3. derived shaded relief in the Ze'elim alluvial fan, noticeable features as the gullies, the well defined nickpoints, sinkholes, and the emerging, developing channels; right) an image showing the actual nickpoint and the developing channel emerging from it and sinkhole with tension rings surrounding it (people as scale).

an ongoing evolution. Their depth, width and longitude profile are changed rapidly in direct relations 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 meters to several hundred meters. This instability endangers infrastructures built along the Dead Sea coastal plain and makes their monitoring an important task for better planning of this region.

3.1 Realization in laser data

Figures 2 and 3 show an airborne laser scanning derived shaded relief map of one of the main fans in the Dead Sea region. Sampling density is ~4 pts/m^2. Figure 2 shows a 10 m deep, well developed gully that has been developing in the past 20 yrs. In their upstream segments gullies end with an almost vertical headcut which serves as a topographic nickpoint between the bottom of the gully and the almost flat coastal plain or alluvial fan surface (Figure 3). Both Figures show the clear reflection of the different of gully forms in the data. Furthermore, nickpoints, which are markers for the current state of the developed channels, are clearly seen in the data and are easily measurable. Emerging from them, the course of the developing channels is well seen. These developing channels are 20-30 cm deep illustrating the minute details that are noticeable in laser scanning data.

Figure 3 also shows realization of collapse sinkholes in the data. One can notice a cluster of sinkholes in the lower left part and several small and solitary sinkholes in the middle right part of the Figure. Among the sinkholes in the upper part, some are of ~1.4 m diameter. This level of detail means that sinkholes, in their embryonic stage of formation, can be traced.

3.2 Data processing and detection

The dense point cloud resulting from airborne laser scanning survey incurs a huge volume of data to process. Such datasets 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. Two key processes are in need, the first is detection of terrain-related reflections within the point-cloud, the second concerns extraction of the geomorphic features and their quantification.

3.2.1 Filtering

Extraction of the terrain from laser data concerns their classification into two groups: terrain and non-terrain, and in essence modeling how the terrain is featured in airborne laser scanning data and what distinguishes it from off-terrain objects. The applied model is based on combining global and local representations of the terrain. The global representation aims at providing a general terrain description at some level of resolution. As such, it facilitates a separation of terrain points 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 seamlines that the global representation cannot capture. For the global model, a set of two-dimensional orthogonal polynomials is applied. The polynomials coefficients are estimated robustly with a guiding assumption that when a function is fitted to a mixture of terrain and off-terrain points, off-terrain points will have positive residuals while terrain points will have negative ones. To reduce off-terrain points effect on the function, the weight of positive-residual points is reduced between iterations, thereby limiting their influence. The local model that follows is based on the realization that global models can follow the terrain up to a given level of resolution. Therefore, a local analysis of points that neighbor terrain points is carried out. Based on curvature analysis, points that form a smooth addition to the already extracted surface are added in. The process ends when no further points are added (Akel et al., 2007).

3.2.2 Detection

Key geomorphic features are characterized by drop in the topography. Sinkholes for example have a closed circular depression form, and gullies are characterized by their elongated linear shape. The edges between the fan and the incised gullies may be considered optimal for detection because of the sharp transition between the ground and features. Whereas a functional description which is driven by seeking strong first derivatives ($\|\nabla\|$) seems appropriate, the rough surface texture that characterizes alluvial fans generates rather noisy responses which are hard to discriminate, making an edge driven analysis hard to apply. Instead of searching for terrain-to-feature transitions, we seek the actual features, e.g., sinkholes bottom or gully thalweg points. Points relating to gullies or sinkholes can be described as entities forming a local extrema in the surface curvature. Thus, the characterization of terrain objects can be implemented by principal curvature values. The two principal curvatures of a given point can be estimated by the eigenvalues, $\lambda_{\min}$ and $\lambda_{\max}$ of the Hessian form, **H**

$$\mathbf{H} = \begin{pmatrix} \dfrac{\partial^2 Z}{\partial x^2} & \dfrac{\partial^2 Z}{\partial x \partial y} \\ \dfrac{\partial^2 Z}{\partial x \partial y} & \dfrac{\partial^2 Z}{\partial y^2} \end{pmatrix} \quad (1)$$

with Z the heights as derived from the airborne laser scanning data. **H** is computed numerically via:

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

with d the window size. While polynomial derived estimations (e.g., Besl, 1988; Mitášová and Hofierka, 1993) can also be considered an option, the numerical estimation we apply is both computationally efficient and enables characterizing the variety of size, shape, form, and directions that these features wear. The eigenvalues are therefore given by:

$$\lambda_{\max,\min} = \frac{\left(\partial^2 Z/\partial x^2 + \partial^2 Z/\partial y^2\right) \pm \sqrt{\left(\partial^2 Z/\partial x^2 - \partial^2 Z/\partial y^2\right)^2 + 4 \cdot \left(\partial^2 Z/\partial xy\right)^2}}{2} \quad (3)$$

The common detection practice is based on applying a fixed kernel size and searching for sufficiently strong responses. However, it is almost impossible in the present case to set a predefined threshold value that can manage capturing “strong” responses relating to the locally maximal curvature. Additionally, smoothing the data to attenuate noise effect might blur the fine features and eliminate them. Because of the variety of forms and surface texture characteristics, responses may have different magnitudes. Therefore, the eigenvalue computation is performed in a multi-scale, in different levels from fine to coarse, searching for a "significant" response.

To assess the responses, the retrieved parameters are studied in terms of the limit of detection. In principle, the eigenvalues sign characterizes the type of entity to which the point is related, where in the present case, surface depressions dictate positive maximal curvature. The minimal curvature defines the nature of the given point: where sinkholes, having positive minimal value, while gully thalweg points should have a nearly zero minimal curvature (the flow direction). Deriving an upper and lower bound response levels, ε_1 and ε_2, for the eigenvalues can either be approached by learning from examples, or be estimated theoretically by deriving accuracy estimates for $\lambda_{\max}$ and $\lambda_{\min}$ as a function of the elevation accuracy. The accuracy of $\lambda_{\max}$ and $\lambda_{\min}$ is controlled by the second-order partial derivatives (assuming that second-order mixed derivatives equals to zero in ridge and valley points) accuracy as derived from Eq. (2). Following the propagation of the elevation accuracy onto these parameters and onto the eigenvalues we obtain

$$m_{\lambda_{\max,\min}} = \pm \frac{\sqrt{6}}{d^2} m_Z \quad (4)$$

with m_λ the accuracy estimate of the eigenvalue, and m_Z the laser elevation accuracy. This enables to establish hypothesis test derived measures for the eigenvalue via a confidence level, α, e.g.,

$$\lambda_{\max} > z_{1-\alpha} \cdot m_\lambda + \frac{2\Delta Z}{d^2} \quad \text{and} \quad |\lambda_2| \le z_{1-\frac{\alpha}{2}} \cdot m_\lambda \quad (5)$$

for gullies, with z the normalized Gaussian distribution. Eqs. (4), and (5) show that m_λ is scale dependent and with the increase of d (scale decrease), λ is estimated more accurately. 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.

4. RESULTS AND DISCUSSION

The laser scanning survey along the Dead Sea coastal plains was aimed at testing the ability to detect and quantify the existing geomorphic features. A 4 pts/m^2 was defined as the sampling density for the survey. Because of the fine shape of some of the gullies and the evolving nature of sinkholes (beginning from a small size and then expanding) coupled with their spread along large parts of the Dead Sea coast, the key objective was to establish means to detect them as a first step in monitoring their evolution.

Validation of the laser survey had both qualitative and quantitative parts. Qualitative analysis was carried via field work that was aimed at evaluating the features in the laser scanning data with their actual form. Further to the fact that the features in the laser data correspond indeed to the actual entities shapes (as Figures 2 and 3 show), one clear observation that resulted from the study was their ability to reveal patterns that were difficult to detect from close range. Quantitative evaluation consisted of GPS field survey using the new Israeli GPS virtual real-time network that can reach horizontal accuracy of ~2-3 cm and vertical one of ~5-6 cm. Comparison of the GPS survey (consisting of 200 measurements) to the laser scanning data show a *std.* of ±10 cm with only 4% of the points (8 points) having offset bigger than 25cm. The positional accuracy was of high order as well.

4.1 Extraction of quantitative data

Results of the gully thalweg detection for a given network are presented in Figure 4. For a complete analysis, the channel banks were then extracted using steep ascent along the profile crossing the channels up to the fan surface level. The process was performed using computation of directional derivatives along the profile direction and termination when the derivatives indicate a flat surface. Having identified both thalweg and banks, three-dimensional characterization of the channel took effect. Figure 4b demonstrates the analysis, focusing on the main channel path and two 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 (Figure 4b). Figure 4b 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. Step 'S4' 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, where 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 toward 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 detection and quantification of sinkholes is demonstrated on the example in Figure 5. Here sinkholes were formed inside a palm-tree orchard. One can notice two sinkholes in front of the orchard and some small pits resulting from the extraction of date trees following the formation of sinkholes that brought to an end the agricultural activity in this area. Following the filtering of the data (Figure 5b) one can notice that some additional sinkholes are inside the orchard. Following their detection, their delineated a boundary is shown in Figure 5b. Metric measures that include location, diameter, perimeter and volume can then be extracted. In the current site sinkholes radii vary between 1.3–5.6 m, their perimeter from 7.7-100 m^2 and their measured depth reaches up to 6 m deep. Application of our model on larger areas (data not shown here) enabled generating a geo-hazard map of this region and providing means to detect and analyze newly formed fields.

Other than the ability to detect geomorphic features and to characterize them properly in the laser scanning data, the geo-referenced 3D information allows also to extract quantitative information. Of particular importance 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

$$V = \sum_{i=1,3,5}^{n-2} 2h \frac{S_i + 4S_{i+1} + S_{i+2}}{6} \qquad (6)$$

with V the volume, S_i the area of the prismoid bases (bottom, intermediate, and top), and h the prismoid length. The prismoid bases are profiles extracted across channel path, where the interval between them (dictating the height) dictates the resolution of the computation. For the extracted channel (see Figure 5), a volume of ~20,100 m^3 was computed. This 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.

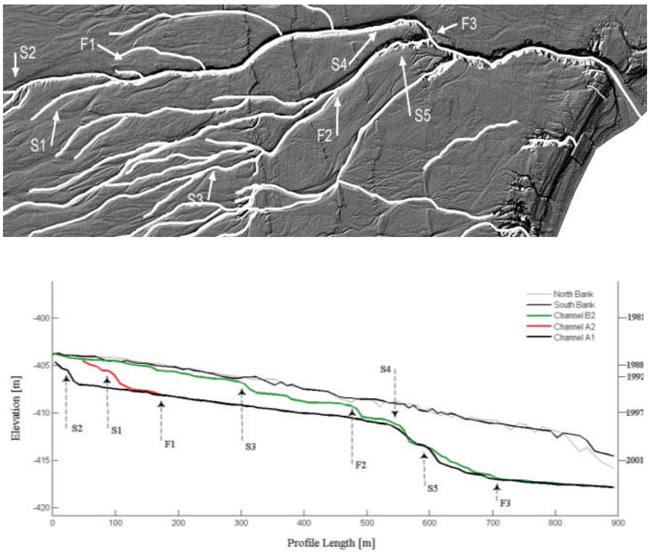

Figure 4. Extracted gully thalweg profiles from airborne laser scanning data and channel banks reflecting the fan surface.

5. 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-meter 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 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.

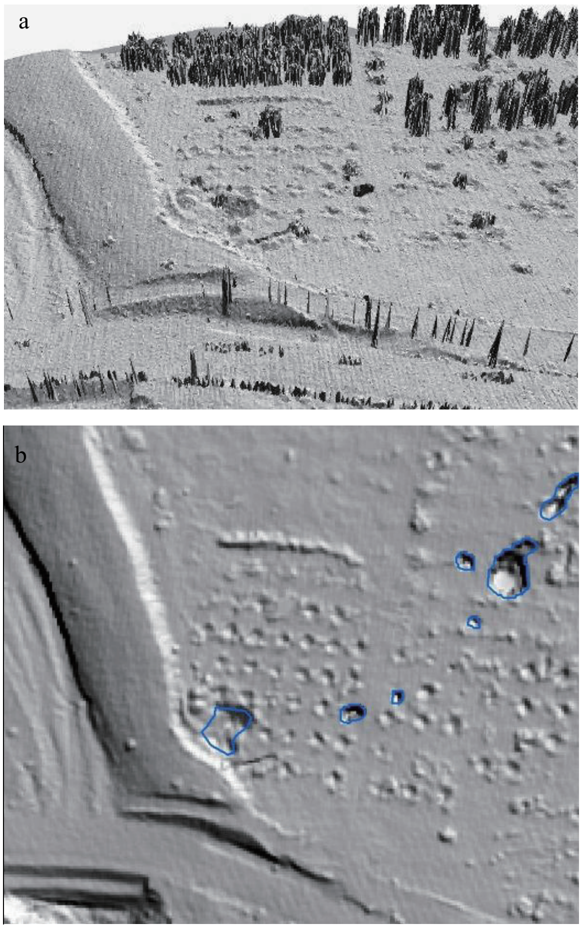

Figure 5. Sinkholes detection, a) a shaded relief of a palm-tree orchard, b) data after filtering, with the sinkholes detection results (delineated).

6. ACKNOWLEDGEMENTS

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