

## LAND DEGRADATION MONITORING USING AIRBORNE LASER SCANNING

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### ABSTRACT:

Environmental deterioration such as soil erosion and land degradation are a cause for increased concern in many regions around the world. In this regard, understanding and quantifying the geomorphic processes that such regions are undergoing is a fundamental step that can promote efficient solutions. Even though the processes that influence the surface topography are three dimensional in nature, they are usually monitored in 2D using either classical geodetic techniques or naive interpretation of aerial images. We present in this paper a methodology for quantifying geomorphic processes in the form of soil erosion, channel incision, land degradation, and the development of sinkholes, in high resolution using airborne laser scanning technology. As a test case, we choose the Dead Sea region, where lake level drop of almost one meter per year has resulted in dramatic changes to the geomorphic system leading to the destruction of wetland environments, rapid headcuts migration that endanger the natural environment and infrastructure, and development of sinkhole fields that in some parts halted regional development. We show how laser data is optimal for detecting such phenomena, accurately characterizing them, and determine their evolutionary rates as well as predicting their future development.

### 1. INTRODUCTION

Environmental deterioration such as soil erosion and land degradation in the arid and semi-arid regions of the world is a cause for increased concern among scientists and global organizations (see e.g., Mainguet, 1991; Bruins and Lithwick, 1998; UNCCD, 1995). Among the different manifestations of soil erosion in those regions (e.g., rill, sheet and gully), it is gully erosion was found to be the primary agent for the majority of soil loss and land degradation within the drainage basins (Bull, 1979; Poesen et al., 2002; 2003), consequently leading to a decrease in agricultural and range potential (Avni, 2005). Environmental deterioration in the semi-arid regions can also be noticed in the shrinkage of water bodies (e.g., Lake Chad, the Aral Sea, and the Dead Sea) as a result of the increasing usage of fresh water for irrigation and domestic needs. Due to the drop in water level, the newly exposed coasts are subjected to erosion processes, channeling of fresh-water springs that cause the 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 on the environment, population, and infrastructure requires efficient means to monitor its evolution. Such means should support the coverage of wide regions and provide detailed information for monitoring and quantifying the undergoing changes. This paper presents the utilization of airborne laser technology for monitoring the evolution of the geomorphic system in areas undergoing active processes of land deterioration. Key features that make LiDAR technology optimal for this task are the dense three-dimensional description that laser systems provide, their high level of

accuracy, and the level of detail that can be noticed in range data. Compared to alternative techniques airborne laser scanning provides a wider coverage than classical geodetic methods (as e.g., in Wu and Cheng, 2005, and Avni, 2005), has better resolution than spaceborne Radar, and automatically provides dense surface information in contrast to image based mensuration techniques (see e.g., Marzolf et al., 2002, Ries and Marzolf, 2003). Additionally, the direct acquisition of 3D information paves the way to high level of automation in the detection of geomorphic phenomena. These properties are of great value for detailed analysis of wide regions, for monitoring the evolution of existing phenomena, and for detecting the occurrence of new features that may be small in size but significant in their lateral effect. 3D quantification of soil erosion over wide areas also provides a broader picture of these processes and in turn enables developing models for active deterioration processes in marginal lands in semi-arid and arid zones sharing similar geomorphic conditions, (e.g., Bull, 1997; Fanning, 1999; Billi and Dramis, 2003; Poesen et al., 2002; 2003; Wu and Cheng, 2005).

Recent applications of LiDAR to geomorphologic features such as tidal channels (Lohani and Mason, 2001), landslide detection, (Makean and Roering, 2004), or changes to coastal dunes (Woolard and Colby, 2004) are indication to the growing attractiveness of LiDAR technology. Furthermore, comparative studies (see e.g., Chang et al., 2004) about the accuracy of Digital Elevation Models (DEM) from LiDAR, Radar, and photogrammetry show LiDAR elevation models to be of high level of accuracy (in fact the authors conclude they are the most), with height differences between 0.09-0.3 m.

The application of LiDAR based 3D monitoring of geomorphic processes is applied in the Dead Sea basin, a region where processes associated with land degradation are clearly manifested. Dropping lake level in the last decades in a rate of almost  $1 \text{ my}^{-1}$  (as a combined human- and climate-induced effect on the water balance in the lake) has led to the formation of sinkholes and the incision of new channels. Both have halted development along parts of the Dead Sea lakeshores and endanger existing infrastructure (Avni et al., 2005). The rest of the presentation is organized as follows, we begin with a short overview of the geomorphic system in the Dead Sea region; we then focus on the detection and quantification of geomorphic features – sinkholes and gullies – which are of prime interest in this area. Analyzing the level of detection of such features and the type of information that can be extracted from the data is then studied in detail. We conclude the presentation with a demonstration of the level of automation that can be reached and with an outlook for the next stage in the study.

## 2. LAND DEGRADATION IN THE DEAD SEA

The Dead Sea area is a deep basin surrounded by active fault-controlled steep shoulders of mostly limestone and dolomite strata along its western margin and a combination of sandstone, limestone and dolomite along its eastern margin. 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.b.s.l. and the southern shallow basin was flooded. Increasing diversion of water from its northern drainage basin since the mid-1960s started a continuous process of artificial drop in the lake level that was accelerated since the 1970s and reached an average rate of  $1 \text{ my}^{-1}$  in the last 10 years. The present level of the lake is 418 m.b.s.l., 26 m lower than the early 20th century high stand. The rapid, continuous drop in the lake level is causing the dramatic widening of the coastal plain, reaching 200-2500 m of a newly exposed belt since 1945. This newly exposed area started developing a complicated erosional pattern immediately after and since the lake retreat. During time, channeling, gulling, and headcut migration occurred in the coastal plain, migrating upstream toward the basin boundaries (Bowman et al., 2004; Avni et al., 2005). 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. These appear in the form of: i) exposure of extensive (up to 2.5 km) of mud flats around the lake, ii) exposure of steep slopes along the lake coasts, iii) rapid increase of areas affected by collapsed of sinkholes, iv) intensive incision of streams and gullies in the newly exposed mud flats and within the alluvial fans, and v) channeling of freshwater springs, causing the destruction of the wetland environment previously existed along the lake.

The steep slopes, which are currently exposed along the coast, trigger rapid incision of the streams that in most cases are keeping in place with the dropping lake level, by forming deep gullies in the mud flats and the alluvial fans. The concentration of the fresh water springs, seeping along the former coastline into well-defined channels and gullies is causing the 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 toward increasing land degradation in the region (Bowman et al., 2004; Avni et al., 2005). The incision is retreating upstream toward the infrastructures running along the western coast causing heavy damage to the

road pavement, bridges and accompanying infrastructure lines. Figure 1 demonstrated the effect of a powerful flood in May 2001 caused by the widening of the stream channel and resulting in the collapse of the Arugot Bridge. The changes along the coastline endanger existing infrastructures and prevent further development of the area; they are only supposed to increase in coming years (Avni et al., 2005).



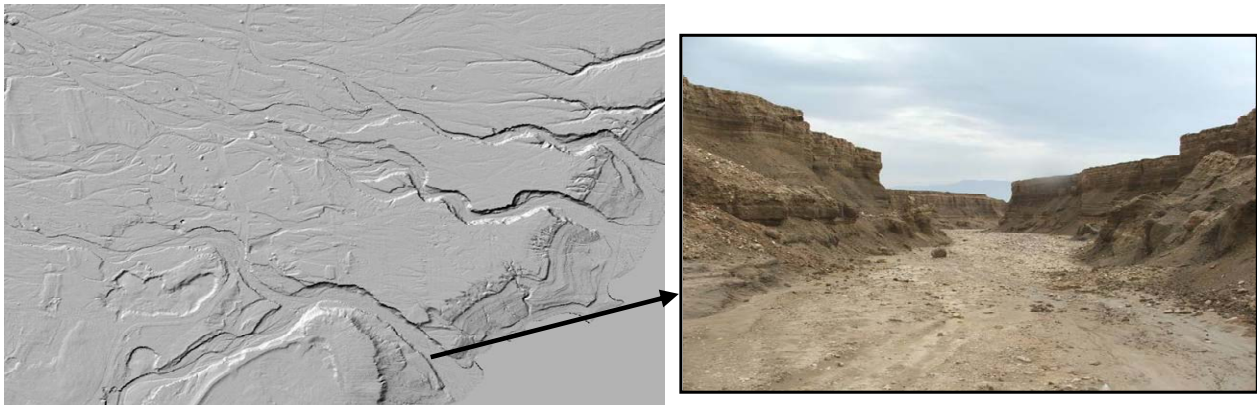
**Figure 1.** The Arugot Bridge during the May 2001 flood; the bridge collapsed as a result of a headcut backward migration along the stream channel.

## 3. GEOMORPHOLOGIC FEATURES IN LIDAR DATA

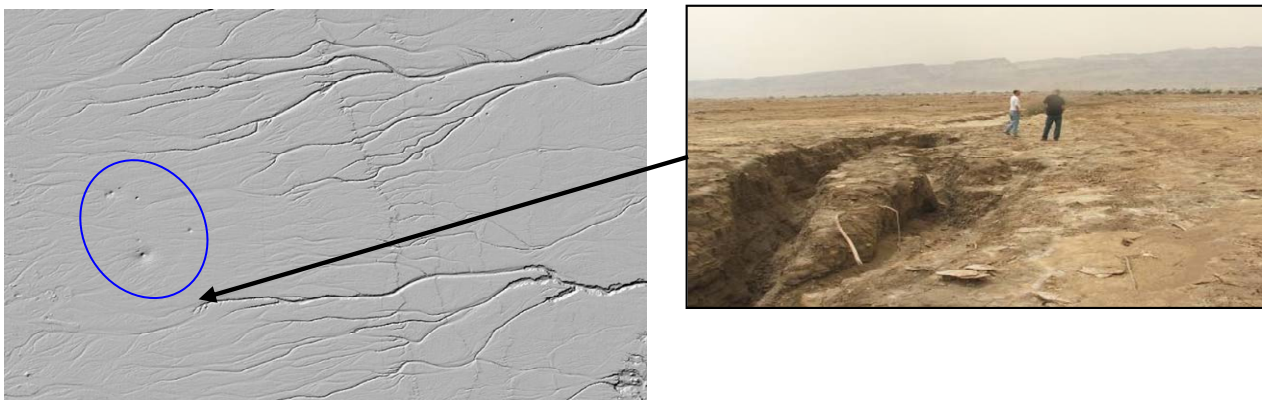
Among the different changes along the Dead Sea coastal plain two types of features are of the greatest concern in our analysis – the first are sinkholes that are formed along the coastal plains, and the second are the new channels and gullies that were developed along the newly exposed shore and the alluvial fans.

**Sinkholes** along the Dead Sea were developed as a result of a subsurface process of dissolving a thick layer of salt deposited by the former lakes predating the present Dead Sea. This layer, located at present in a depth of 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 an embryonic sinkhole that has the potential to grow up. Sinkholes along the Dead Sea coast are usually organized in clusters that were developed through time forming sinkholes fields (Abelson et al., 2006). They are characterized by an oval shape, ranging in size from sub-metric dimensions to several tens of meters as they develop through time. Occasionally they are accompanied by a conical collapse structure, followed by concentric tensional rings reaching dimensions of up to 100 m. Because of the sudden appearance of the sinkholes and their hazardous nature, it is important to distinguish their embryonic structure and localize their position. The increasing number of sinkholes makes them difficult to be monitored using terrestrial methods and the fact that new sinkholes fields initiate as embryonic features of meter size makes it difficult to be tracked and monitored using aerial photography particularly when their size is small.

**Gullies** are formed in the coastal plain of the Dead Sea as a result of the drop in the lake level and the exposure of steep bathimetric slopes at the outlet of the fluvial channels. The gully is a dynamic feature, which is under an ongoing evolution. Its 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, the gully



**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 size and magnitude.



**Figure 3.** LiDAR derived shaded relief in the Ze'elim alluvial fan, noticeable features as the gullies, the well defined knick points, sinkholes, and the emerging, developing channels; right) an image showing the actual knick point and the developing channel emerging from it (people as scale).

headcut 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 unique region.

### 3.1 Realization in laser data

A laser scanning survey we have conducted along the Dead Sea coastal plains was aimed at testing the ability to detect and quantify those features. A point density of  $\sim 3$  point/m<sup>2</sup> 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 in time.

Figures 2 and 3 show a LiDAR based shaded relief map Ze'elim stream fan where both gullies and sinkholes are clearly manifested. Figure 2 shows a typical gully that is relatively narrow and its two banks are almost vertical. Upstream the gully ends with an almost vertical headcut, which serve as a topographic knick point between the bottom of the gully and the almost flat surface of the coastal plain or the alluvial fan (Figure 3). Both Figures show how the different forms of the gullies are clearly reflected in the LiDAR data. The underlying 3D information also offers the ability to extract volumetric information on the soil loss. Furthermore, the knick points,

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 a designated sinkhole field. One can easily notice a cluster of sinkholes in the lower left side (encircled in the Figure) and several small and a solitary sinkhole in the middle right side of the Figure. Among the sinkholes in the upper part of the cluster, some are of  $\sim 1.4$  m diameter. The fact that such small sinkholes are noticeable in LiDAR data illustrates on one hand the fine level of detection that can be reached with this technology, but also means that sinkholes, in their embryonic stage of formation, can be traced by LiDAR data. Analysis of the point cloud shows that in all sinkholes more than five returns from inside the hole were found. Having a cluster of returns from "underneath" the terrain is an indication to the fact that an actual physical phenomenon has been detected by the scanning system.

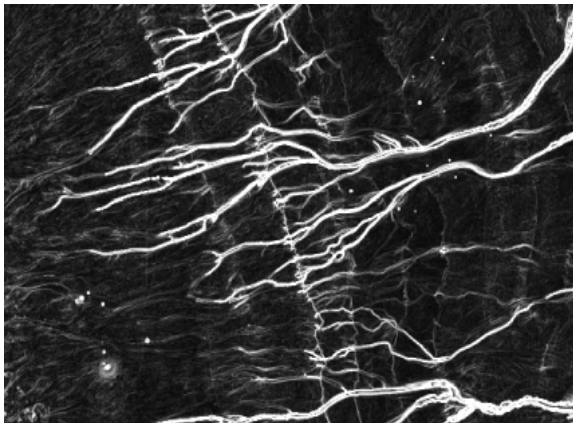
### 3.2 Data processing and detection

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 lend themselves to manual processing. As a result designated algorithms for handling and extracting information from the data must be

developed. Two key processes are in need, the first concerns the separation of terrain and off-terrain points to facilitate the analysis of geomorphic features that are terrain related phenomena, the second concerns the extraction of the geomorphic features and their quantification.

### 3.2.1 Filtering

Extraction of the terrain from laser data can be viewed as a classification into two classes, terrain and non-terrain. This classification (termed also filtering) concerns modeling how the terrain is featured in airborne laser scanning data and what distinguishes it from off-terrain objects. Our model is based on combining a global and a local representation of the terrain. The global representation aims providing a global description of the terrain at some level of resolution. As such, it facilitates the separation between terrain and off-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 did not 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 the effect of off-terrain points on the fitted function, the weight of points with a positive residual is reduced between iterations, thereby reducing 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 can be added. For greater detail see Abo-Akel et al., 2006.



**Figure 4.** A LiDAR derived gradient strength map of the Ze'elim alluvial fan showing the clear realization of the gullies and sinkholes in the data.

### 3.2.2 Detection

Both gullies and sinkholes are characterized by the depression in the land they create – closed circular one for the sinkholes and an elongated linear one for the gullies. Their functional description is therefore best featured by discontinuity in the first derivative of the surface that follows the application of the filtering model. Figure 4 shows a gradient strength map

( $\left\| \nabla_x^2 + \nabla_y^2 \right\|$ ) of the wadi Ze'elim alluvial fan where gullies

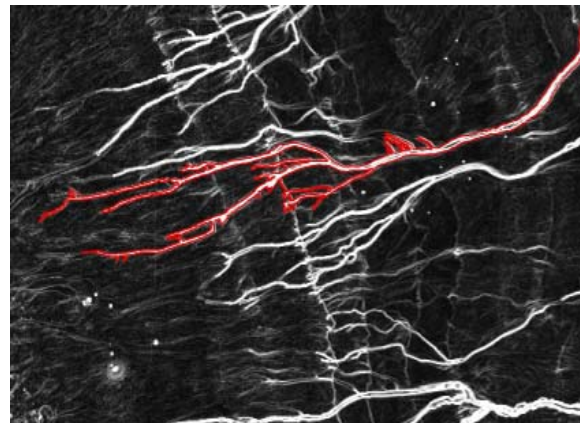
have been formed in the last decades. The sharp edges between the fan and the incising gullies that can be clearly seen in the data indicate that the application of the second derivative on the data (which are edges on the first derivative) will provide us with an edge map depicting the channel boundary. The extraction of the channel is currently carried out by the application of a line follower, particularly due to the forking and branching of the channel. Figure 4 also shows the realization of sinkholes in the data appearing as bright spots, again as a result of a sharp transition between the ground and the holes themselves. The very clear appearance of both sinkholes and gullies are strong indication to the appropriateness of LiDAR data as a tool for autonomous detection and for monitoring these phenomena.

## 4. RESULTS AND DISCUSSION

### 4.1 Validation and Accuracy

Validation of the laser survey has both qualitative and quantitative parts. Qualitative analysis concerned validating the features in the laser survey with their real appearance. Further to the fact that the features in the laser data correspond indeed to the actual shape (as Figures 2 and 3 also 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 LiDAR data show a *std.* of  $\pm 10$  cm with only 4% of the points (8 points) having offset bigger than 25cm. The positional accuracy was of high order as well.



**Figure 5.** Extracted boundary of gully from LiDAR data (overlaid on a gradient strength map).

### 4.2 Extraction of quantitative data

Other than the ability to detect geomorphic features and to characterize them properly in LiDAR data, the georeferenced 3D information allows also the extraction of quantitative information. Of particular importance is the extraction of volumetric information that provides us with direct knowledge of soil loss due to erosion.

The extraction of metric information from the data is demonstrated for the sinkholes and gullies. For the gullies,

volume measures, which account for soil loss, are computed as a summation of a sequence of prismoids volumes

$$V = \sum_{i=1,3,5}^{n-2} 2H \frac{S_i + 4S_{i+1} + S_{i+2}}{6} \quad [1]$$

with  $V$  the volume,  $S_i$  the area of the prismoid bases (bottom, intermediate, and top), and  $H$  the prismoid height. 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  $\sim 20,100 \text{ m}^3$  was computed. This measure provides us with a direct figure of the 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 Ze'elim fan enables the calculation of the total annual rate of the soil loss from this terrain. This procedure is vital for the prediction of the land degradation processes in the region and for future planning.

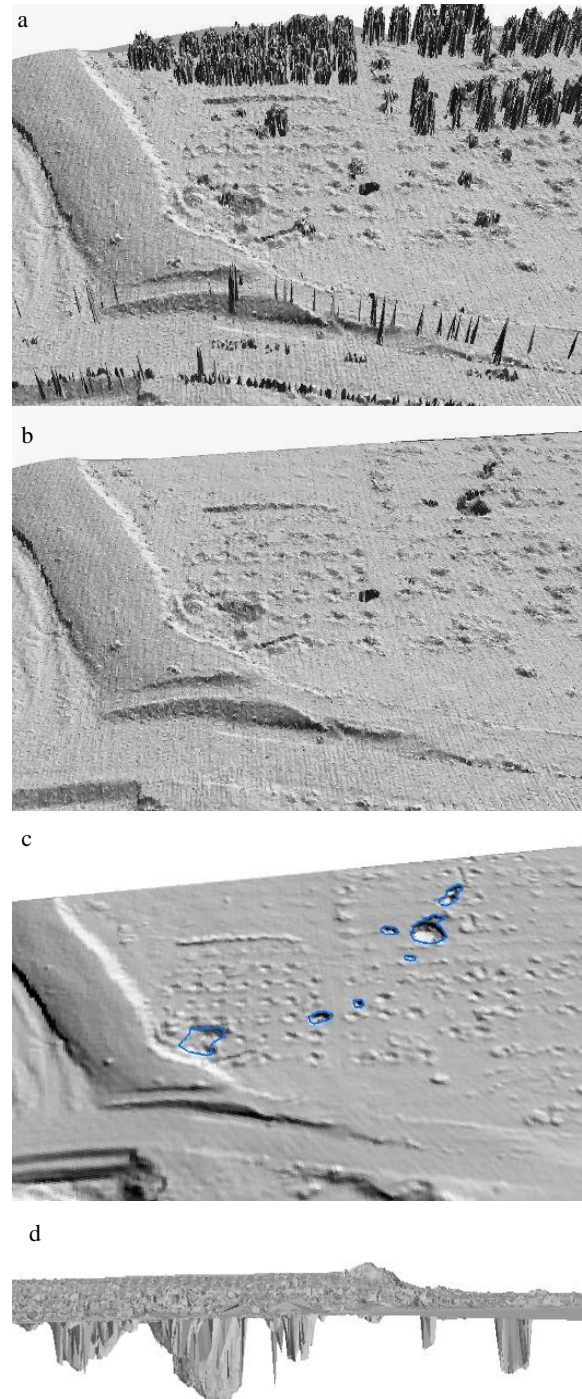
The detection and quantification of sinkholes is demonstrated on the example in Figure 6. Here sinkholes were formed inside a date orchard near Ein-Gedi (Figure 6.a). One can notice two sinkholes in front of the orchard and some small pits resulting from the extraction of date trees following the formation of sinkholes that brought to an end the agricultural activity in this area. Following the filtering of the data (Figure 6.b) one can notice that some additional sinkholes are inside the orchard. Following their detection, their delineated a boundary is shown in Figure 6.c. 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  $\text{m}^2$  and their measured depth reaches up to 6 m deep. We note that the ability to estimate the sinkhole depth is limited by the looking angle of the transmitted laser beam as well as the size of the sinkhole. The actual realization of the sinkholes in the point cloud is shown in Figure 6.d where one can see how they are well represented by laser scanning data. Application of our model on larger areas (not shown here) was capable of detecting and characterizing sinkholes in larger scale thereby providing geo-hazard map of this region and providing means to detect and analyze newly formed fields.

## 5. CONCLUSIONS

This paper demonstrated the ability of the LiDAR method to detect geomorphic features in the Dead Sea region. We see as very important the ability of the LiDAR technique to detect the sub-metric 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 LiDAR technique are of prime importance in describing and formulating 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 calculating 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. This type of information is critical for future planning in any active region.

The present paper focused on the Dead Sea region, which served as a filed 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 of the LiDAR method 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 6.** Detection of sinkholes, a) a shaded relief of a dates grove, b) data after filtering, where the sinkholes can be seen, c) delineated sinkholes, d) the point cloud from a side-looking view showing the sinkholes after filtering the points.

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