Quantification of Environmental Change in Receding Lake Environments

Sagi FILIN, Yoav AVNI, Amit BARUCH (Israel)

Key words: LiDAR, Geomorphology, Dead Sea, Land Degradation, Sinkholes.

SUMMARY

Environmental changes due to lake level drop 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 that characterize receding lake environments in high resolution using airborne laser scanning technology. These processes can be in the form of soil erosion, channel incision, land degradation, and the development of sinkholes. We study the Dead Sea region, where a lake level drop of almost one meter per year resulted in dramatic changes to the geomorphic system thereby 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.

Quantification of Environmental Change in Receding Lake Environments

Sagi FILIN, Yoav AVNI, Amit BARUCH (Israel)

1. INTRODUCTION

The shrinkage of water bodies in semi-arid regions are clear agents of land degradation processes as a result of the increasing usage of fresh water for irrigation and domestic needs (e.g., Lake Chad, the Aral Sea, and the Dead Sea). 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). In this regard, the Dead Sea basin offers a unique example to study the effect of receding lake on processes that alter the surrounding environment. Dropping lake level in the last decades in a rate of almost 1 my^{-1} (as a combined human- and climate-induced effect on the water balance in the lake) has altered the geomorphic equilibrium around the lake. Due to the rapid lake level drop, processes associated with land degradation has started evolving along the coastal plains in an accelerated rate; among them are the formation of collapse 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 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., 2003, 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.

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 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 – that 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. ENVIRONMENTAL CHANGES ALONG THE DEAD SEA COASTAL PLAINS

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 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 slops 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 batimetric 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 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.

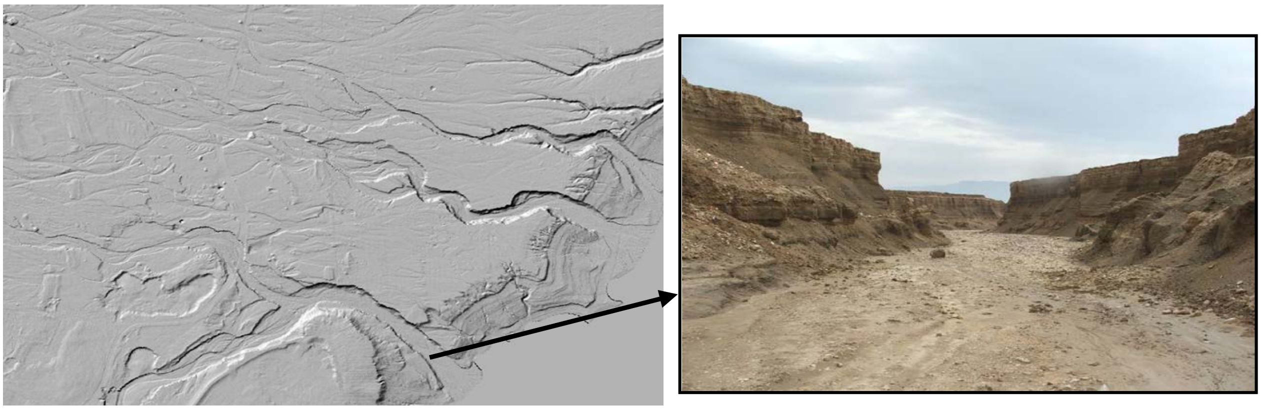

Figure 2. Channels formed in the last decades in the Ze'elim fan, left) a shaded relief map derived from laser scanning data, right) an image taken in this channel, showing its size and magnitude.

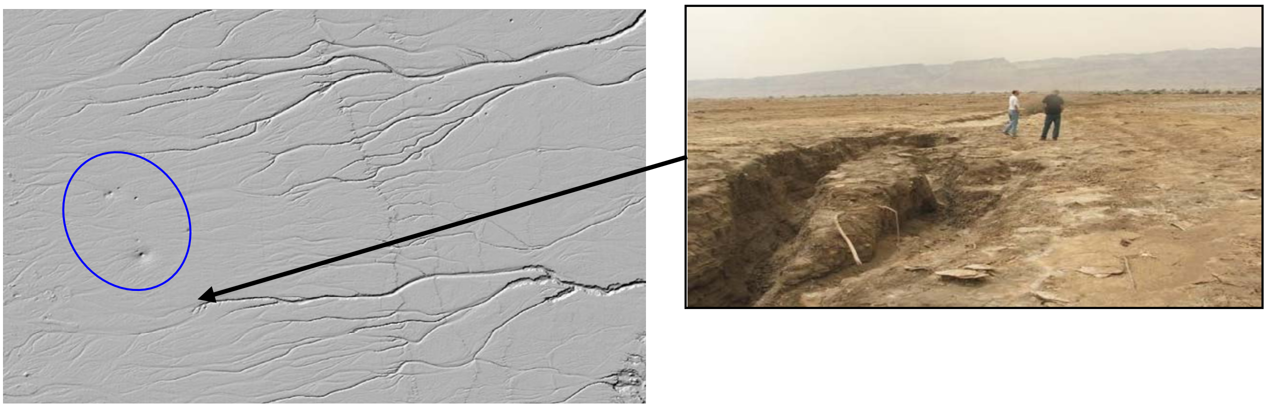

Figure 3. LiDAR derived shaded relief in the Ze'elim fan, noticeable features as the gullies, the well defined knick points, sinkholes, and the emerging, developing channels; right) an image showing the actual knick point and the developing channel emerging from it (people as scale).

4. 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 ~3 point/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 in time.

Validation of the laser survey was carried out both qualitatively and quantitatively. The 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 one clear observation that resulted from the study was their ability to reveal patterns that were difficult to detect from close range. The quantitative evaluation consisted of GPS field survey using the new Israeli GPS virtual real-time network that reaches 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 ±10 cm with only 4% of the points (8 points) having offset bigger than 25cm. The positional accuracy was of high order as well.

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 ~1 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.

5. 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 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.

5.1 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. (2007).

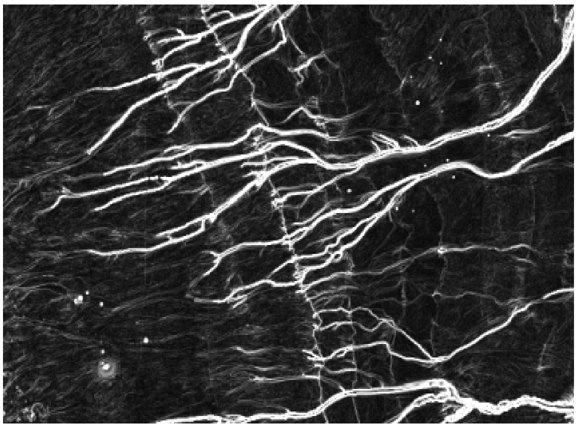

Figure 4. A LiDAR derived gradient strength map of the Ze'elim alluvial fan showing the clear realization of the gullies and sinkholes in the data.

5.2 Detection

Both gullies and sinkholes are characterized by the depression in the land they create – closed oval-like ones for the sinkholes and elongated linear ones 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 Ze'elim alluvial fan where gullies have been formed in the last decades.

The intensity variations between the fan and the incising gullies that can be clearly seen in the data indicate that the application of the second-derivative based analysis can provide us with information depicting 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 a strong indication to the appropriateness of LiDAR data as a tool for autonomous detection and for monitoring these phenomena.

5.3 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.

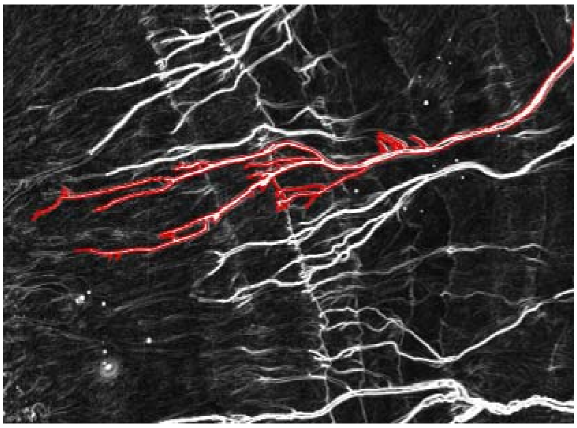

Figure 5. A boundary of a gully extracted from LiDAR data.

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

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

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 ~20,100 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.

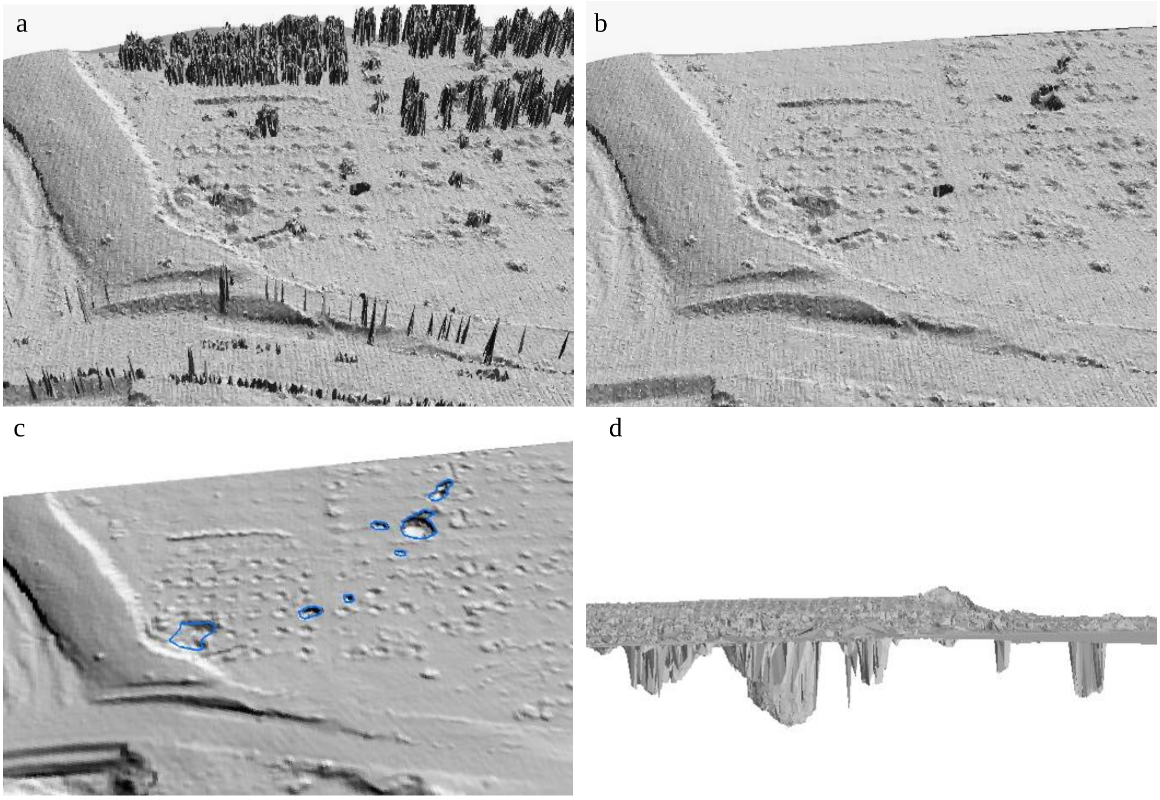

Figure 6. Detection of sinkholes, a) a shaded relief of a dates grove, b) data after filtering, where the sinkholes can be seen, c) delineated sinkholes, d) the point cloud from a side-looking view showing the sinkholes after filtering the points.

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 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. 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. Figure 7 shows a relatively large sinkhole field (in a site called Mineral beach), and the delineation of the sinkholes following the application of our model sinkholes of down to 1m diameter and 40 cm deep where detected.

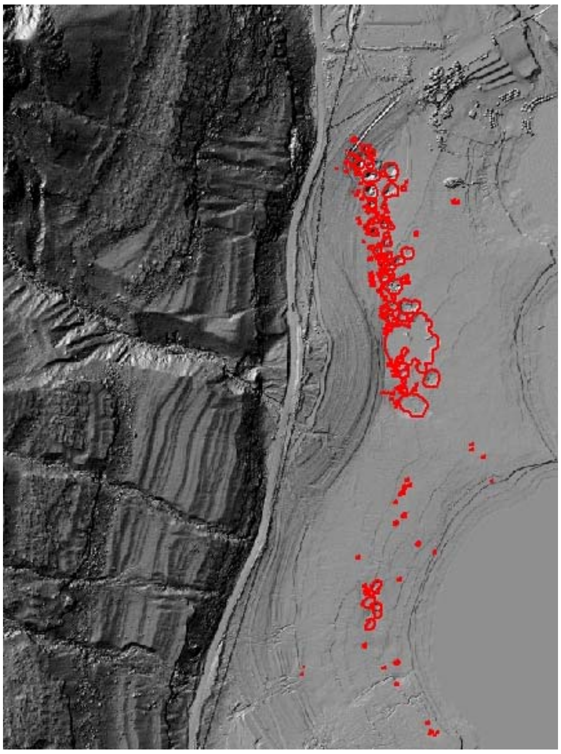

Figure 7. Results of the autonomous detection of sinkholes field (sinkholes encircled in red).

Level of Detection - our algorithm has managed detecting 97% of the sinkholes with 2% false alarm detections. The undetected sinkholes were ones shallower than 30cm deep. In summary, application of our model on larger areas 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.

6. 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 are known from other active regions on earth. As demonstrated here, the ability of the LiDAR method to detect these features make this methodology applicable for other regions around the globe facing geomorphic changes such as land degradation, soil erosion, gully formation and headcuts migration.

ACKNOWLEDGEMENTS

This research was supported in part by the Israeli Ministry of National Infrastructure. Dr. Filin would also like to acknowledge the kind support by the Bank Hapoalim endowment fund.

REFERENCES

Abelson, M., Yechieli, Y., Crouvi, O., Baer, G., Wachs., D., Bein, A., and Shtivelman, V., 2006. Evolution of the Dead Sea sinkholes. In Enzel, Y., Agnon, A and Stein, M eds., New frontiers in Dead Sea paleoenvironmental research. Geological Society of America Special Paper 401 p., 241-253.

Abo Akel N., Filin S., Doytsher Y., 2007. Orthogonal Polynomials Supported by Region Growing Segmentation for the Extraction of Terrain from LiDAR Data. PE&RS (in press).

Avni, Y., Zilberman, E., Shirav M., Katz, O., Ben Moshe, L., 2005. Response of the geomorphic systems along the western coast of the Dead Sea to sea level lowering and its implications on infrastructure. Report GSI/18/04.

Avni, Y., 2005. Gully incision as a key factor in desertification in an arid environment, The Negev Highlands, Israel. Catena 63: 185-220.

Bowman, D., Savoray, T and Devora, S., 2004. The influence of the drop in the Dead Sea level as a base level on the geomorphic system. Final report, submitted to the Dead Sea Drainage Authority (in Hebrew).

Chang, H., Ge, L., Rizos C., Milne T., 2004. Validation of DEMs Derived from Radar Interferometry, Airborne Laser Scanning and Photogrammetry by Using GPS-RTK. in Proceedings of IEEE GARSS conference. Anchorage, Alaska, 20-24 September, 5: 2815-18.

Lohani B. and Mason D.C., 2001. Application of airborne scanning laser altimetry to the study of tidal channel geomorphology ISPRS Journal of Photogrammetry and Rem. Sens., 56(2): 100-120.

Mainguet, M., and Le’tolle R., 1998. Human-made Desertification in the Aral Sea Basin: Planning and Management Failures. In H.J. Bruins and H. Lithwick (eds.). The Arid Frontier: Interactive Management of Environment and Development. Kluwer Academic Publishers, Dordrecht, 129-142.

Makean, J., and Roering, J., 2004. Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. Geomorphology 57: 331–351.

Marzolff, I., Ries, J., B., Albert K.-D., 2003. Kite aerial photography for gully monitoring in sahelian landscapes. in: Proceedings of the Second Workshop of the EARSeL Special Interest

Group on Remote Sensing for Developing Countries, 18-20 September 2002, Bonn, Germany, 2-13.

Ries J., B,. and Marzolff I., 2003. Monitoring of gully erosion in the central Ebro basin by large-scale aerial photography taken from remotely controlled blimp. Catena 50: 309-328.

Woolard J.W., and Colby J.D, 2002 .Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LIDAR: Cape Hatteras, North Carolina. Geomorp., 48(1): 269-87.

Wu, Y., and Cheng, H., 2005. Monitoring of gully erosion on the Loess Plateau of China using a global position system. Catena 63 154-166.

BIOGRAPHICAL NOTES

Dr. Sagi Filin graduated form the Technion - Israel Institute of Technology in Geodetic Engineering in 1989. In 1995 he received is M.Sc degree in Geodetic Engineering from the Technion and in 2001 his Ph.D. degree in Geodetic Sciences from The Ohio State University. From 2001 until 2004 he was with the Photogrammetry and Remote Sensing Section in Delft University of Technology. Since 2004 he is a faculty member in Civil and Environmental Engineering in the Department of Transportation and Geo-Information Engineering.

Dr. Yoav Avni graduated from the Hebrew University of Jerusalem in Geology and Physical Geography in 1985. In 1989 he received his M.Sc degree in Geology from the Hebrew University of Jerusalem and in 1998 his Ph.D. Since 1995 he is a researcher in the Geological Survey of Israel.

Mr. Amit Baruch graduated from the Technion - Israel Institute of Technology in Mapping and Geo-Information Engineering in 2006. He is currently pursuing his PhD degree in Mapping and Geo-Information Engineering at the Technion.

CONTACTS

Dr. Sagi Filin
Department of Transportation and Geo-Information Engineering
Faculty of Civil and Environmental Engineering
Technion – Israel Institute of Technology
Haifa 32000, ISRAEL
Email: filin@tx.technion.ac.il
Tel. + 972 4 829-5855
Fax: +972 4 829-5708

Dr. Yoav Avni
Geological Survey of Israel
Malkhe Yisrael 30,
Jerusalem 95501, ISRAEL
Email: yavni@gsi.gov.il
Tel. + 972 2 531-4345
Fax: +972 2 538-0688

Mr. Amit Baruch
Department of Transportation and Geo-Information Engineering
Faculty of Civil and Environmental Engineering
Technion – Israel Institute of Technology
Haifa 32000, ISRAEL
Email: amit@tx.technion.ac.il
Tel. + 972 4 829-2774
Fax: +972 4 829-5708