# Monitoring changes along receding lake environments

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**Key words**: Change detection, Laser scanning, Dead Sea

## SUMMARY

The shrinkage of water bodies in semi-arid regions is a clear agent for land degradation processes. Newly exposed coasts, especially in shallow lakes, are subjected to erosion and channeling of fresh-water springs that lead to the destruction of wetland environments, salination, and headcut migration that endanger the natural environment, human population and infrastructures. To understand the actual impact that such regions are undergoing, the Dead Sea coastal plains offer a unique study site for environmental changes. In past decades, the Dead Sea level has been dropping in a rate of one meter per year and higher as a combination of human- and climate-induced effect on the water balance in the lake. As a consequence, collapse sinkholes have began appearing and new stream channels have been forming in the alluvial fans along its shores. In order to detect and quantify changes of geomorphic features, including sinkholes, gullies, and headcuts, we describe in this paper a methodology which is based on application of airborne laser-scanning technology. Use of laser scanning data facilitates the analysis of features that could not have been characterized by conventional means, let alone in detailed 3D. Furthermore, use of laser scans enables revealing inter-relations between the studied geomorphic features, and thereby a better understanding of their evolutional and developmental process. The paper details the methodologies for detecting such phenomena, accurately characterizing them, and determining their modification over time. The results of this study are of paramount importance for the development of appropriate strategies for future regional planning.

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## 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 Létolle, 1998; Bowman et al., 2004; Avni et al., 2005). In this regard, detection of changes in geomorphic environments plays a substantial role in monitoring and understanding these geomorphic processes, particularly in relation to the underlying mechanisms which drive their evolution. Over the years researches have monitored and studied geomorphological processes using either classical surveying techniques for small scale phenomena, or aerial photogrammetry for larger ones, mostly in two-dimensional space (Bowman et al., 2010; Andres et al., 2009; Cook et al., 2010).

Since most geomorphologic phenomena are three-dimensional in nature, related laser scanning research has expanded substantially, delivering high-resolution elevation models and significantly improving the monitoring of geomorphologic processes (Filin et al., 2006, 2010 ; Milan et al., 2008 ;Faux et al., 2009 ;Snyder et al., 2009 ;Perroy et al., 2010 ;Schürch et al., 2011). The dense three-dimensional description of wide areas that laser systems provide, their high level of accuracy, and the level of detail that can be noticed in range data, are key features that make airborne laser scanning technology optimal for this task (Filin and Avni, 2006) and are of great value for monitoring the evolution of existing phenomena and detecting the occurrence of new features either small or large in size (Filin et al., 2010; Snyder, 2009). In this context, this paper presents the use of airborne laser scanning for characterization and quantification geomorphic changes. It focuses on the Dead-Sea region as a case study, which offers a unique example of the effect of receding lake on processes that alter the surrounding environment. Dropping lake level in the last decades in a rate of over 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 have started evolving along the coastal plains in an accelerated rate; among them are the formation of collapse sinkholes and the incision of new channels (Figure 1). Both have halted development along parts of the Dead Sea lakeshores and endanger existing infrastructure (Avni et al., 2005). The effect of landscape reshaping processes on the environment, population, and infrastructure requires efficient means to monitor their evolution. Such means should support the coverage of wide regions and provide detailed information for monitoring and quantifying the undergoing changes.

**Figure 1.** left) Influence of gully incision processes on infrastructure, right) sinkhole field near a beach resort.

## 2. ENVIRONMENTAL CHANGES ALONG THE DEAD SEA COASTAL PLAINS

The Dead Sea 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 which is higher than 1 $my^{-1}$ in the last 10 years. The present level of the lake is 425 m.b.s.l., 33 m lower than the early 20th century high stand. The rapid, continuous level drop is causing a 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) mud flats around the lake, *ii*) exposure of steep slopes along the lake coasts, *iii*) rapid increase of areas affected by collapsed of sinkholes, and *iv*) intensive incision of streams and gullies in the newly exposed mud flats and within the alluvial fans (Figure 2).

The steep slopes, which are currently exposed along the coast, triggered 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. 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 damages to road pavement, bridges and accompanying infrastructure lines (i.e., Figure 1), and also preventing further development of the area. These changes are only supposed to increase in coming years (Avni et al., 2005).

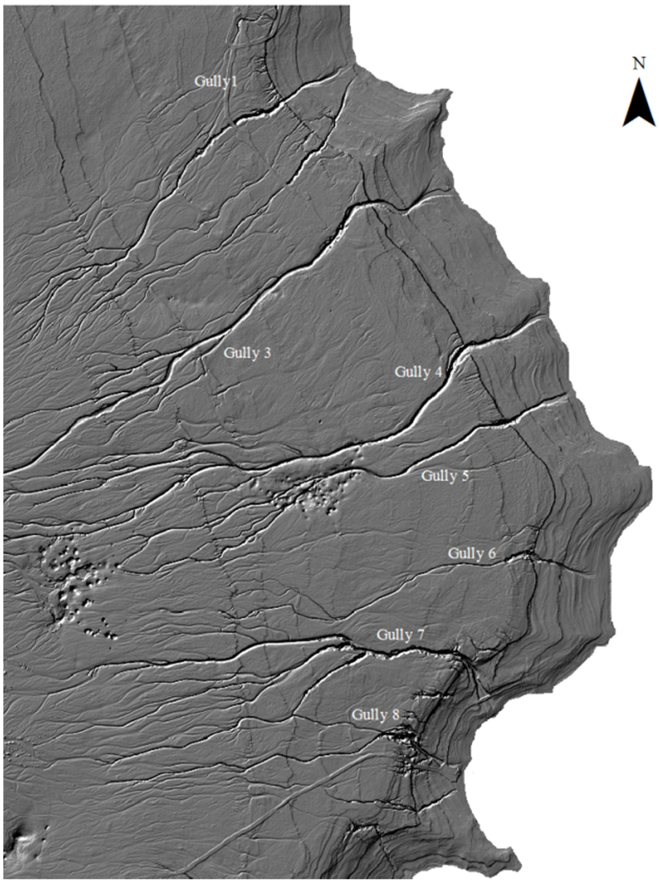


**Figure 2** A shaded relief map of the Ze'elim alluvial fan based on airborne laser scans showing the exposure of steep slope and the fan outlet, incision of gullies and development of collapse sinkholes.

## 3. DETECTION OF GEOMORPHOLOGICAL CHANGES VIA AIRBORNE LASER SCANS

To characterize the changes along the receding lake airborne laser scanning campaigns have been carried out as a means to characterize the geomorphic features in that region and their evolution. As the dense point cloud incurs a huge volume of data, which are hardly manageable and do not easily land themselves to manual processing, designated algorithms for handling and extracting information from the data have been developed, focusing on the extraction of the geomorphic features and their quantification. For the extraction of the terrain returns from the data, the methodology proposed in Akel et al. (2007) has been applied where needed. The quantification can be separated into two scales of analysis, a global one which attempts quantifying the total change and a local/finer one which analyzes specific features in the region.

### 3.1 Global scale analysis

A general assessement of the total change can be approached in a rather direct manner via subtraction of the surface models one from the other. Despite its simplistic form it provides a depiction of the total change in a rather immediate manner. For its application the two point clouds are transformed into the same gird system and the latter model is subtracted from the first.

$$Diff(i,j) = DEM_{epoch1}(i,j) - DEM_{epoch2}(i,j) \tag{1}$$

where $i,j$, are the indices of the surface model point. Nonetheless, a naïve subtraction will not consider the surface models accuracy. Thus a limit of detection is set by using accuracy measures which can either be derived from the data provider specifications or from field validation (i.e., GPS-RTK measurements). Detection limit will be:

$$m_{diff} = \sqrt{2}\, m_z \tag{2}$$

where $m_z$ is the accuracy estimate of the laser scanning data.

### 3.2 Detailed analysis

The global evaluation shows difficulties in analyzing the actual effect on geomorphic entities within the analyzed scene, calling for methods that can evaluate and quantify particular geomorphic features in detail. Key geomorphic features along the coastal plains are characterized by drop in the topography. 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., Mason et al., 2006), the rough surface texture that characterizes alluvial fans generates noisy responses which are hard to discriminate, and makes edge driven analysis hard to apply. Instead, we seek the actual features, which can be described as local extrema in the surface curvature. Thus, the characterization of terrain objects is implemented by principal curvature analysis. The two principal curvatures of a given point can be estimated by the eigenvalues, $\lambda_{\min}$ and $\lambda_{\max}$ of the Hessian form, **H**

$$\mathbf{H} = \begin{pmatrix} \dfrac{\partial^2 Z}{\partial x^2} & \dfrac{\partial^2 Z}{\partial x \partial y} \\ \dfrac{\partial^2 Z}{\partial x \partial y} & \dfrac{\partial^2 Z}{\partial y^2} \end{pmatrix} \tag{3}$$

with $Z$ the heights as derived from the airborne laser scanning data. The second order derivatives are computed numerically via:

$$\begin{aligned} \partial^2 Z/\partial x^2 &= \left(Z_{y_0,x_0+d} - 2\cdot Z_{y_0,x_0} + Z_{y_0,x_0-d}\right)\big/ d^2 \\ \partial^2 Z/\partial y^2 &= \left(Z_{y_0+d,x_0} - 2\cdot Z_{y_0,x_0} + Z_{y_0-d,x_0}\right)\big/ d^2 \\ \partial^2 Z/\partial xy &= \left(-Z_{y_0-d,x_0-d} + Z_{y_0-d,x_0+d} + Z_{y_0+d,x_0-d} - Z_{y_0+d,x_0+d}\right)\big/ (2d)^2 \end{aligned} \tag{4}$$

with $Z_{x,y}$, the surface elevation at point $x$, $y$, and $d$, half the window size. While polynomial derived estimations (e.g., Besl, 1988; Mitášová and Hofierka, 1993) can be considered an option, the numerical estimation is both computationally efficient and enables characterizing the variety of size, shape, form, and directions 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 multi-scale manner, searching for a "significant" response in different scale levels. In principle, the eigenvalues sign characterizes 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, for example, gully thalweg points should have a nearly zero curvature value (the flow direction). Deriving an 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 Eq. (4). Following the propagation of the elevation accuracy onto these parameters and onto the eigenvalues we obtain:

$$m_{\lambda_{\max,\min}} = \pm \frac{\sqrt{6}}{d^2} m_Z \tag{5}$$

with $m_\lambda$ the accuracy estimate of the eigenvalue, and $m_z$ the laser elevation accuracy. For gully detection, one eigenvalue should be positive while the other should theoretically equal to zero. Setting response-level bounds, $\varepsilon_1$ and $\varepsilon_2$ for the minimal detection level, we define a gully such that $\lambda_1 > \varepsilon_1$ and $|\lambda_2| \leq \varepsilon_2$. In setting the response level we consider ranging noise and the minimal detection level, $\Delta Z$ (minimal object response or detectable gully depth) which we define by the terrain's surface roughness. The minimal object response is defined as:

$$\lambda_1 \approx \frac{2\Delta Z}{d^2} \tag{6}$$

Using Eq. (6), a hypothesis test for $\lambda_1$ can be established with: $\mathrm{H}_0$: $\lambda_1 \leq 2 \cdot \Delta Z / d^2$ (indicating there is no channel there) vs. $\mathrm{H}_1$: $\lambda_1 > 2 \cdot \Delta Z / d^2$ as the null and alternative hypotheses (indicting there is a gully). The test for $\lambda_2$ has the form: $\mathrm{H}_0$: $\lambda_2 = 0$ vs. $\mathrm{H}_1$: $\lambda_2 \neq 0$. For a given confidence level $\alpha$, the two hypotheses define the detection bounds for shallow gullies:

$$\lambda_1 > z_{1-\alpha} \cdot m_\lambda + \frac{2\Delta Z}{d^2} \ \ \& \ \ |\lambda_2| \leq z_{1-\frac{\alpha}{2}} \cdot m_\lambda \tag{7}$$

with $z$, the normalized 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 characterization, 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.

## 4. RESULTS

Two airborne laser-scanning campaigns have been carried out along the Dead Sea coastal plains, aiming to study the geomorphic features in that region as well as detecting and quantifying their evolution. The first campaign was conducted in Nov., 2005 and the second in Oct., 2011. In both campaigns point density of ~4 point/$m^2$ was defined as the sampling density for the survey. The focus of this study is of features along the Ze'elim alluvial fan (lat. 31$^o$22', long. 35$^o$24') – located at the outlet of the Ze'elim drainage basin (~250 $km^2$), one of the largest basins along the Dead Sea coast, and spans an area of about 30 $km^2$.. Due to development plans in Ze'elim alluvial fan, there is a growing interest in the dynamics and mechanism of the morphological processes that this area is undergoing, aiming to estimate the rate and magnitude of gully incision as well as the development of collapse sinkholes in coming years (Avni et al., 2005, 2012; Bowman et al., 2007, 2010; Ben-Moshe et al., 2008; Meninger et al., 2009).

To analyze the evolution that the fan area has been undergoing in the past six years, Figure 3 shows the global change based on the elevation models subtraction. The minimal threshold for detection was set to 0.25 m, based on the estimated accuracy of range data which was assessed via GPS-RTK measurements. We focus here on three key components that the difference map reveals, including: modification of the fan surface, collapse sinkholes and evolution of gullies:

**Fan surface modification**: Figure 3 shows that the fan surface modification can be partitioned into two main sections: The western part, which is mostly composed of coarse alluvial sediments and has hardly gone any changes in the past six years, whereas the eastern part is sinking. The eastern mudflat part consists of fine grained alluvial cover, and is sinking at a magnitude of 0.25-0.75 m, most likely due to compaction of the silt which is drying out.

**Collapse sinkholes' evolution**: Changes in two sinkhole fields are also evident from the difference map (Figure 3). They dominate the central part of the fan and span ~250 × 300 $m^2$ each. The western field (denoted as #I), which in 2005 consisted of a few scattered sinkholes has expanded into a large field composed of sinkholes which are collapsing into one another. The evolution of this field is followed by another field, 500 m eastwards (denoted as #II). The evolution of this site resembles that of field #I: from a small set of isolated sinkholes into a large field, whose evolution is accelerating. We make note to two other fields in that region (, Figure 3, #III and IV) which can be considered as dormant and seem to reach a fossil state.

**Gully evolution**: the difference map (Figure 3) shows that gullies have also been developing mostly at their outlet towards the lake. Dominant incisions can be noticed at the southern end of the fan; there, two main gullies, #15 and #14, which form the outlet of the central and southern part of the fan, show an intensive incision which is characterized by deepening by more than 5 m. Contrasting these, the gullies in the central part show only moderate change. In the northern part, most of the gullies still active (e.g., #1, 3 and 4). As opposed to the wide ones at the south, they are characterized by their narrow linear form. From the 15 dominant gullies which developed until 2005, only nine remained active from 2005-2011, showing a 40% decrease in the number of active gullies.

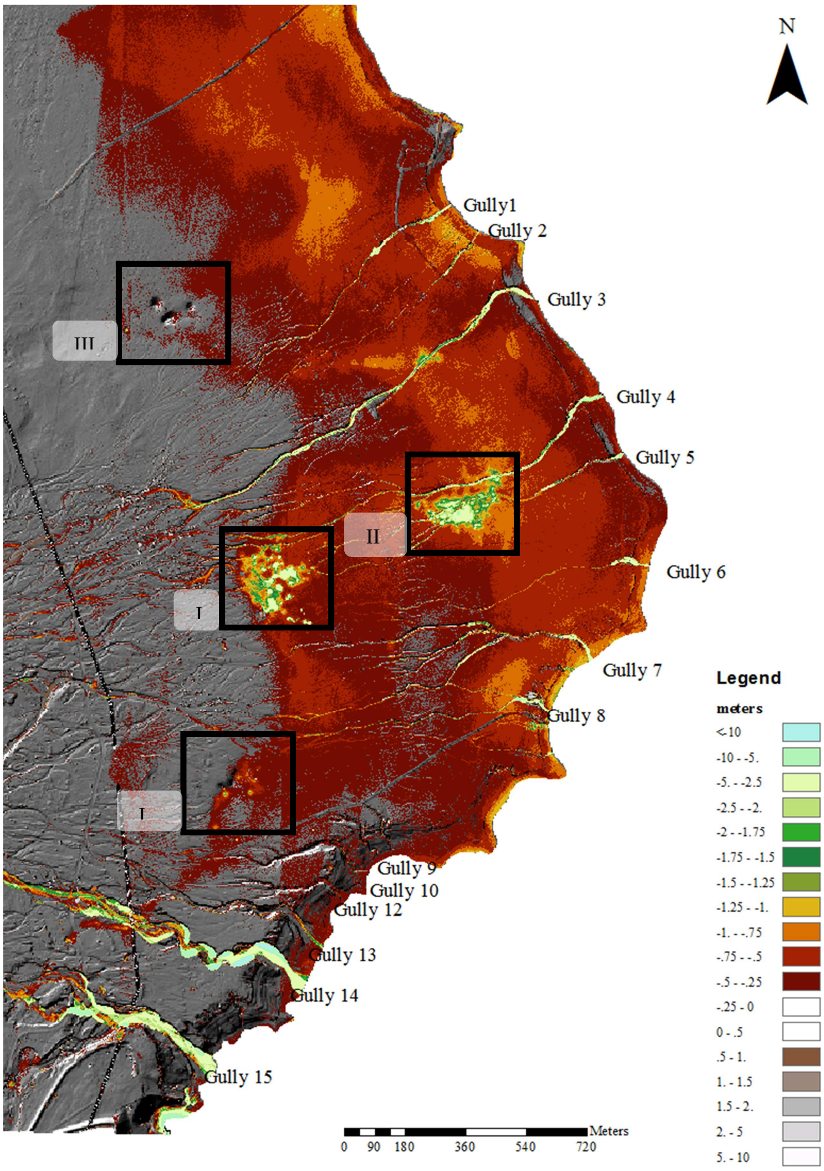


**Figure 3** Difference map between 2005-2011 scans over Ze'elim alluvial fan.

Whereas the global analysis provides an overview of the activity within the fan, it falls short in providing a detailed view of the evolution of individual features. Using proposed extraction model (Section 3.2) thalweg profiles and cross-sections have been extracted for gully #3 (Figure 3). The thalweg profile (Figure 4) shows the adaptation of the gully to the dropping sea level. This adaptation forms a knickpoint ~150 from the outlet, which is an indication to the incision process that this gully is undergoing. Towards its headcut the gully maintain an almost constant slope which appears similar to that of 2005. A backwards incision, though not substantial, is also observed at the knickpoint. The cross-section along the gully (Figure 5) shed light into the gully evolution process which deepens first. The widening process follows, mostly via sidewall collapse.

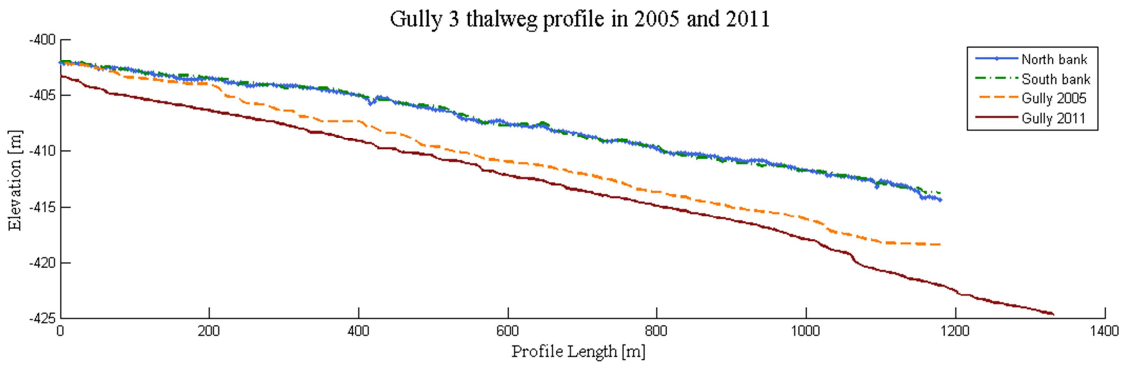


**Figure 4** Profile of gully #3 thalweg and banks as extracted from the 2005 and 2011 scans.

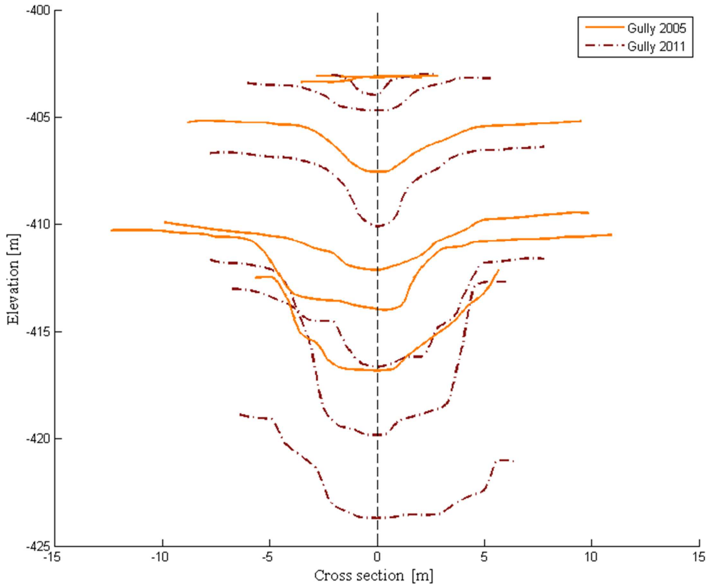


**Figure 5** Cross sections along gully #3 as extracted from the 2005 and 2011 scans

## 5. CONCLUSION

The paper studied the application of airborne laser scanning data to analyze the morphological changes along the shores of the receding Dead Sea. For the study a global analysis on a fan's scale, as well as detailed analysis of geomorphic features, has been proposed. Incorporation of both facilitates the characterization and quantification of the processes that the fan region is undergoing. The analysis revealed the development of gullies and collapse sinkhole fields in that region showing how some turn fossil while others are developing vigorously. Such analysis is vital for planning future development of the area, and limiting damages to infrastructure.

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 are known from other active regions on earth. As demonstrated here, the ability of the laser scanning technology to detect these features make it applicable for other regions around the globe facing geomorphic changes such as land degradation, soil erosion, gully formation and headcut migration.

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