Geomorphology 206 (2014) 403–420

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

# Characterization of land degradation along the receding Dead Sea coastal zone using airborne laser scanning

Sagi Filin [a,*], Yoav Avni [b], Amit Baruch [a], Smadar Morik [a], Reuma Arav [a], Shmuel Marco [c]

[a] Mapping and Geo-Information Engineering, Technion - Israel Institute of Technology, Haifa, 32000, Israel
[b] Geological Survey of Israel, Jerusalem, 95501, Israel
[c] Department of Geophysics and Planetary Sciences, Tel-Aviv University, Tel-Aviv, 69978, Israel

ARTICLE INFO

Article history:
Received 27 December 2011
Received in revised form 25 September 2013
Accepted 15 October 2013
Available online 24 October 2013

Keywords:
Soil erosion
Coastal processes
Gully incision
Sinkholes
Laser scanning
Dead Sea

ABSTRACT

The Dead Sea, the lowest place on the Earth's continents, was at its highest level in 1896, reaching an elevation of ~388.4 m below mean sea level (m.b.m.s.l) and ~390 m in the early 1920s. Since then it has almost constantly been dropping, reaching the level of 426 m.b.m.s.l in 2013. Since the late 1990s its level has been decreasing by approximately 1 my$^{-1}$. The rapid lake retreat accelerates large-scale environmental deterioration, including soil erosion, land degradation, rapid headcut migration and widespread development of collapse sinkhole fields. These geomorphic elements threaten the natural environment and anthropogenic infrastructure.

We provide an overview of the geomorphic processes in the form of soil erosion, channel incision, land degradation, and the development of collapse sinkholes. We take advantage of the high-resolution airborne laser scanning technology for three-dimensional detection of surficial changes, quantification of their volumes, and documentation of the present state of the terrain with utmost accuracy and precision. This type of information and the identification of future trends are vital for proper planning of any rapidly-changing environment.

## 1. Introduction

Environmental deterioration in arid and semi-arid regions is a cause for increased concern in the international community (e.g., Mainguet, 1991; UNCCD, 1995; Bruins and Lithwick, 1998; UNIYDD, 2006). This concern is driven by the urgent global need to protect the environment, in particular the soil cover, biomass, agricultural crops, and infrastructure; all are critical for maintaining the natural biodiversity and modern infrastructure.

Among the indicators for environmental deterioration in the semi-arid regions is the shrinkage of water bodies (e.g., Lake Chad, the Aral Sea, and the Dead Sea) mainly a consequence of increased usage of fresh water for irrigation and domestic needs (Yechieli et al., 1993; Glazovsky, 1995; Mainguet and Le'tolle, 1998). Due to the water-level drop, the newly exposed areas are subjected to erosion processes such as development of gullies and headcuts within unconsolidated coastal material (Campbell, 1989; Summerfield, 1991; Mainguet and Le'tolle, 1998; Avni et al., 2005). Channeling of fresh-water springs into newly developed deep gullies often causes destruction of wetland environments that previously existed along the lakes' coastal zone. These geomorphic changes may lead to total destruction of past environments and to the drying-up of the former fresh water wetlands that are subjected to de-watering, high evaporation and replacement by salty soils (Mainguet and Le'tolle, 1998; Avni et al., 2005; Bowman et al., 2007).

The Dead Sea level drop has reached rates of 1 my$^{-1}$ in the last decades and even higher in recent years (Fig. 1c). This higher rate is a result of the combined effects of human interference and long-term, small scale, climate-induced change of the water balance in the entire 42,000 km$^2$ drainage basin. This process has led to a large-scale shrinkage of the lake and to incision of numerous new gullies, which are gradually migrating upstream within the newly exposed coastal zone. Additionally, thousands of collapse sinkholes have developed since the 1980s within the newly exposed areas of the declining Dead Sea. Both sinkhole development and gully incision have caused heavy damage to the existing infrastructure and halted modern development along considerable parts of the Dead Sea shores (Avni et al., 2005; Abelson et al., 2006). As these ongoing processes threaten to inflict even greater damage in the future, it is important to characterize them and detect incipient destructive processes as early as possible.

To this end we analyze the results from an airborne laser scanning survey of the current geomorphic system configuration of the western coastal plain of the Dead Sea. Previously, these three dimensional processes have been monitored using either classical geodetic techniques or simple 2D interpretation of aerial analog images. This paper analyzes processes along the Dead Sea shores as an example for land degradation influenced by lowering lake levels. Because Dead Sea water levels have been well-documented since the 1920s and tectonic motions have been negligible during this relatively short period (Garfunkel et al., 1981), we can convert spatial data into time, e.g., the age of each fossil shoreline in this sequence as well as any exposed surface previously covered by the lake can be straightforwardly determined. The choice of airborne laser

---

* Corresponding author. Tel.: +972 4 829 5855; fax: +972 4 829 5708.
E-mail address: filin@technion.ac.il (S. Filin).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.10.013

scanning is motivated by the dense 3D description, the high accuracy of the data, and the level of detail that the system provides. The 3D information (point cloud) facilitates a high level of cost-effective automation in detection and analysis of geomorphic phenomena. These characteristics are of great value for detailed analysis of wide regions, for examining the evolution of existing phenomena, and particularly for detecting the appearance of new features, some of which are small, but significant in their lateral/cumulative effect.

## 2. Study area

The Dead Sea Basin (Fig. 1a,b), the lowest place on Earth's continents, is surrounded by active, fault-controlled escarpments, 600–1100 m high. The western escarpments are composed of Cretaceous limestone, dolomite and marl strata, whereas the eastern escarpment exposes older strata of late Precambrian to Cretaceous composed of volcanoclastic rocks, sandstone, limestone and dolomite (Sneh et al, 1998). During the Quaternary the Dead Sea Basin hosted a series of hypersaline lakes, the last of which is the Dead Sea. During glacial periods these lakes reached levels significantly higher than today. For example, the highest stand of Lake Lisan of the last glacial period was about 160 m below mean sea level (m.b.m.s.l). It was followed by a rapid drop and stabilized in the Holocene around 400 m.b.m.s.l with fluctuations of a few tens of meters (Klein and Flohn, 1987). The Dead Sea level in 1896 was ~388.4 m.b.m.s.l and ~390 m in the early 1920s. Since the 1930s, the construction of a dam at the outlet of the Sea of Galilee and an increased diversion of Jordan River water, the main source of water to the Dead Sea, caused a continuous level drop that accelerated since the 1970s. When levels dropped to 399.6 m.b.m.s.lin 1977, the southern shallow basin dried and the potash pans that were constructed there received the brine through channels from the northern basin. In 2013 the level of the lake was 426 m.b.m.s.l.

### 2.1. Modification of the geomorphic system

The geomorphic units associated with the rapid lake-level drop and the consequent instability of the geomorphic system consist of: i) *coastal flats* — a rapid widening of the western coastal plain, up to 3 km since 1930 till its present location, exposing two major substrates: coarse gravels deposited in proximal areas of alluvial fans and fine-grained mud composed of mainly silt and clay, which were deposited in the distal parts of the alluvial fans. As the lake retreats and the coastal zone widens, the mudflats become more dominant (Fig. 2a); ii) *newly exposed steep slopes* — attributed to either slopes developed along the distal edge of coarse alluvial fans, or to exposure of active-fault controlled slopes (Fig. 2b); iii) *deserted beach ridges* — related to wave action during spring storms. The position of each ridge marks the uppermost elevation that the lake level has reached during the end of the wet season, before the gradual retreat during the long, dry one (Fig. 2a,b); iv) *sinkholes* — observed in both the mudflats and alluvial fans. Deeper ones are found in the alluvial fans while shallower and wider ones in the mudflats (Abelson et al., 2006; Filin et al., 2011). In most cases the sinkhole formation is attributed to subsurface caverns that evolve by dissolution of a ~20–50 m deep salt layer because of the replacement of the hyper saline groundwater with present fresh water, as the local water table follows the drop of the lake level (Abelson et al., 2006; Yechieli et al., 2006; Filin et al., 2011). In some cases, sinkholes appear in swarms and large fields, up to 100 per site (Fig. 2c); v) *gullies* — which develop due to rapid incision within the exposed mud flats (Fig. 2d), commonly keep in pace by deepening and elongation in opposite directions: downstream toward the dropping lake and upstream toward the alluvial fans due to headcut migration and incision (Fig. 2e); and vi) *stream channels* — which developed at the outlet of major drainage basins within the gravelly fans and migrate downstream. Incision of both gullies and stream channels is accelerated during flash floods, which characterize the flow regime in the desert environment surrounding the Dead Sea. The rapid incision is endangering the modern infrastructure along the coast (Fig. 2f).

### 2.2. Sites analyzed in this study

Three localities have been selected for scanning, representing and illustrating various aspects of the Dead Sea's dynamic environment. Their description is from south to north (Fig. 1b).

**Ze'elim fan** (lat. 31°22′, long. 35°24′) — Located at the outlet of the Ze'elim ~250 km$^2$ drainage basin and spans an area of about 10 km$^2$. It was initiated during the late Pleistocene–Holocene transition, following the retreat of the Late Pleistocene Lake Lisan (Begin et al., 1974; Ken-Tor et al., 2001).

**Hever fan** (lat. 31°20′, long. 35°25′) — A major fan in the region, located at the outlet of the Hever 175-km$^2$ drainage basin and spans an area larger than 5 km$^2$. The fan is composed of coarse gravels and its outlet towards the receding lake features a pattern of delicate braided channels. Because of the coarse material, the channels here are wider and shallower than the gullies developed in the distal mudflat exposed in Ze'elim.

**Hazezon fan and Mineral Beach** (lat. 31°32′, long. 35°23′) — A resort in the central part of the Dead Sea, near the Hazezon outlet. The Hazezon creek, which drains an area of 41 km$^2$, forms a 0.7 km$^2$ fan composed of coarse Holocene fluvial pebbles. The Holocene fan is now incised by stream channels as a result of the lake retreat, similar to other Dead Sea fans. A wide mudflat on the southern side of the fan is dotted with an elongated cluster of sinkholes, striking north-northwest.

## 3. Methods

High-resolution airborne laser data for the three study sites about 30 km$^2$ in area were acquired using the Optech 2050 scanner, operating at 50 KHz. The flying altitude was ~500 m above ground level (m.a.g.l), leading to a sampling density of about 4 ptsm$^{-2}$. Determination of this point density was guided by the fine nature of some of the geomorphic features, e.g., small channels and embryonic sinkholes.

Validation of the laser scanning data accuracy was carried out via a GPS field survey. The new Israeli GPS virtual real-time network was used for this test as a reference station (enabling a measurement accuracy of about 2 cm horizontal and about 5 cm vertical). Comparison of the GPS survey (total of 200 measurements) to the laser scanning data shows a standard deviation of ± 10 cm with only eight points (4%) offset more than 25 cm.

As laser ranges are measured to objects illuminated by the laser beam, some returns arrive from the bare earth, while others from off-terrain objects. To analyze the region's morphology, off-terrain objects have been removed from the data. We applied a model proposed by Akel et al. (2007), which uses global orthogonal functions for a coarse separation of terrain and detached objects returns, and then introduces a surface refinement phase that adds fine terrain details that were skipped in the global phase. The global functions are given as a set of orthogonal polynomials whose coefficients are estimated robustly. Weights of points with a positive residual are reduced between iterations, thereby strengthening the influence of terrain points. The refinement phase adds points that conform to the general terrain shape via a local surface continuity test.

The relevant geomorphic features are characterized by a drop in the surface topography, forming a relatively sharp transition between the ground and object. Although a functional description which is driven by a gradient strength analysis ($\|\nabla_x^2 + \nabla_y^2\|$) may be appropriate, the rough

**Fig. 1.** The Dead Sea region and lake level variations. a) Location of the Dead Sea. b) Location of three observation areas. c). Lake level record since 1976. Episodes of level rise superposed on the general lowering appeared in 1981, 1992, and 2003.d) Lake level of the last two millennia (after Klein and Flohn, 1987).