Geomorphology 293 (2017) 53–68

Contents lists available at ScienceDirect

Geomorphology

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

High-resolution InSAR constraints on flood-related subsidence and evaporite dissolution along the Dead Sea shores: Interplay between hydrology and rheology

Maayan Shviro[a,b], Itai Haviv[a,*], Gidon Baer[b]

[a] Department of Geological and Environmental Sciences, Ben-Gurion University, Beer Sheva, Israel
[b] Geological Survey of Israel, Jerusalem, Israel

ARTICLE INFO

Keywords:
Sinkholes and subsidence
InSAR
Fluvial geomorphology
Dead Sea

ABSTRACT

Sinkhole generation and land subsidence are commonly attributed to dissolution of subsurface layers by under-saturated groundwater and formation of cavities. Along the Dead Sea (DS) shorelines, this process also involves seasonal flash floods that are drained into the subsurface by existing and newly formed sinkholes. We quantify the contribution of flash-floods to salt dissolution and land subsidence using high-resolution interferometric synthetic aperture radar (InSAR). Subsidence rates during a 3-year period (2012–2015) were calculated from 57 COSMO SkyMed X-band interferograms bracketing major flood events and intra-flood periods in 21 sinkhole sites. The sites are located within channels and alluvial fans along the western shores of the Dead Sea, Israel. The observed subsidence reaches maximum rates of ~2.5 mm/day, accumulating in specific sites to 500 mm/year. In most of the sinkhole sites a gradual increase in the annual subsidence rate is observed during the 3-year study period. Three different modes of response to floods were observed: (1) sites where floodwater is not directly channeled into sinkholes do not respond to floods; (2) sites adjacent to active channels with sinkholes are unaffected by specific floods but their subsidence rates increase gradually from early winter to mid-summer, and decay gradually until the following winter; and (3) sites in active channels with sinkholes are characterized by an abrupt increase in subsidence rates immediately after each flood (by a factor of up to 20) and by a subsequent quasi-exponential subsidence decay over periods of several months. In these latter sites, subsidence rates after each flood are temporally correlated with alternating groundwater levels in adjacent boreholes. The rapid rise in groundwater head following floods increases the hydraulic gradient of the under-saturated groundwater and hence also the groundwater discharge and the dissolution rate of the subsurface salt layer. A subsequent quasi-exponential water level drop results in similar deceleration in dissolution and subsidence rates, with a similar characteristic decay time of about 150 days. The observed subsidence decay pattern may also be explained by viscoelastic relaxation of the overburden in response to instantaneously-formed dissolution cavities. Utilizing a Kelvin viscoelastic model, we show that the contribution of this process is most probably < 30% of the total observed subsidence and is sensitive to the sediment mechanical properties. On a broader scale, this study demonstrates how high-resolution InSAR measurements can improve our understanding of subsurface dissolution and subsidence processes and provide independent constraints on the mechanical properties of heterogeneous alluvial sediments.

1. Introduction

Salt karst has become an increasing geohazard around the globe, in particular where it is associated with collapse sinkholes and land subsidence (Martinez et al., 1998; Galloway et al., 1999). Sinkholes and gradual dissolution-induced subsidence are often interrelated, with subsidence occurring before, during and after the actual sinkhole collapse (Paine et al., 2012; Nof et al., 2013; Jones and Blom, 2014; Intrieri et al., 2015). Enhanced subsidence above subsurface evaporite layers has been observed along ancient and modern alluvial channels (Gutiérrez, 1996; Benito et al., 1998; Klimchouk and Aksem, 2005; Guerrero et al., 2008; Avni et al., 2016), due to drainage of flood water into the evaporite layers and a subsequent increase in evaporite dissolution and surface subsidence. Periods characterized by high dissolution and subsidence rates along these streambeds result in generation of local depositional basins with thickened alluvial fill

* Corresponding author.
E-mail address: haviv@bgu.ac.il (I. Haviv).

http://dx.doi.org/10.1016/j.geomorph.2017.04.033
Received 7 November 2016; Received in revised form 19 April 2017; Accepted 20 April 2017
Available online 04 May 2017

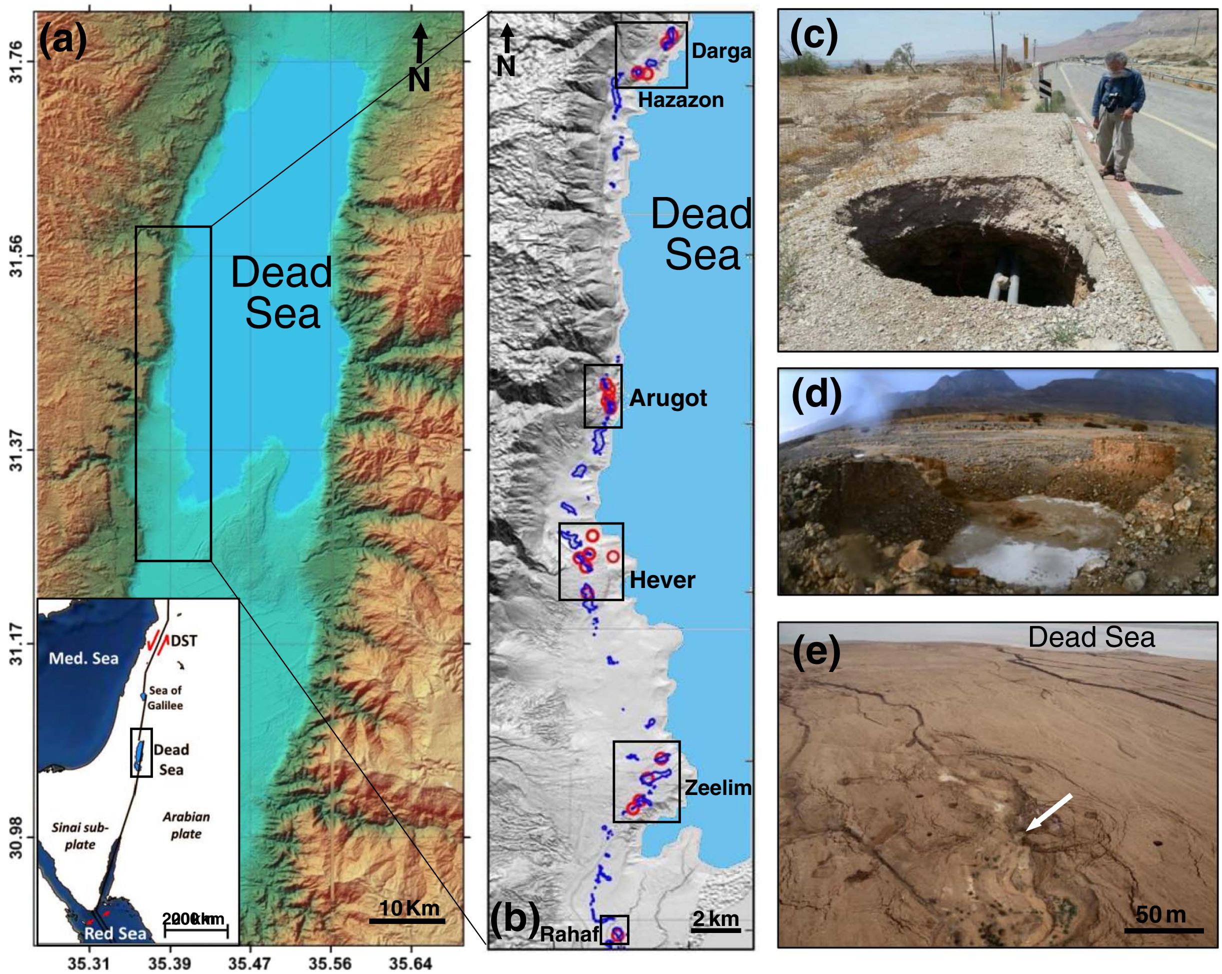

Fig. 1. Sinkholes and subsidence sites along the Dead Sea basin. (a) Location of the study area along the Dead Sea northern water body. Note the Dead Sea western escarpment. The inset delineates the setting of the Dead Sea basin along the Dead Sea Transform plate boundary (DST). (b) Sinkhole distribution and site locations. Blue polygons delineate the distribution of sinkholes along the Dead Sea western shore. 21 sites which were examined using InSAR are marked by red circles. (c) Sinkhole damage to infrastructure next to highway 90 (Arugot site). (d) Flood water swallowed by a sinkhole in the Hever fan, 20 February 2015. See Fig. SM6 and https://youtu.be/LeIvul4YlTA. The sinkhole has formed within interbedded clay and consolidated gravel. (e) Flood water swallowed by an in-channel sinkhole (white arrow), Zeelim mudflats, December 2013. Note the extent of the subsiding zone around the specific sinkholes. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
Photo: Assaf Tsabar.

(Guerrero et al., 2008) and/or reversal of flow directions (Avni et al., 2016).

The factors controlling the mode of ground surface response to subsurface dissolution and the spatial and temporal extent of flood-related subsidence are not yet fully understood. While long-term observations concerning sediment thickness variations in ancient alluvial deposits may shed light on temporal changes in subsidence and aggradation (Guerrero et al., 2008), real-time subsidence measurements may discriminate between the effects of sediment properties, drainage patterns and dissolution processes. For example, the response of incompetent and unconsolidated clay sediments to dissolution of an underlying salt layer has been shown to be more immediate and widespread compared to that of competent, brittle and consolidated gravel (Abelson et al., 2006; Avni et al., 2016). Numerical simulations demonstrate that sediment viscosity plays an important role in the temporal response of the surface to subsurface cavity growth (Shalev and Lyakhovsky, 2012), whereas for areas dominated by consolidated sediments, elastic behavior approximates the subsidence pattern well (Atzori et al., 2015).

In order to quantify the governing relations between flash-floods, sinkholes, salt dissolution and land subsidence, and to evaluate the potential effect of sediment properties on subsidence patterns we utilize high-resolution interferometric synthetic aperture radar (InSAR) measurements of ground subsidence within channels and alluvial fans along the western shores of the Dead Sea. We first generate a 3-year time-series of subsidence rates in sinkhole sites within and away from active channels. Then, we compare these data to a coeval time series of groundwater level in adjacent boreholes. Finally, we calculate the possible viscoelastic response of the overlying sediments to a subsurface cavity growth and estimate its contribution to the total observed subsidence. Our results enable us to estimate sinkhole and subsidence development patterns adjacent to active channels and help evaluate potential geo-hazards. On a broader scale, we demonstrate the effect of fluvial infiltration pathways on dissolution-induced subsidence and alluvial depositional history in karst-prone regions.

2. Geological and hydrological background

The Dead Sea (DS), the lowest place on the terrestrial globe, is located along the DS Transform, a ~1000 km-long plate boundary separating the Arabian plate from the African plate (Fig. 1a) (e.g., Freund, 1965; Garfunkel, 1997). The DS water level is currently at about 430 m below sea level and has been dropping at a rate of > 1 m per year since the 1960s. The drop is attributed to a negative balance between water influx (precipitation and damming effects) and out-fluxes (evaporation and industrial consumption). The DS is separated