Science of the Total Environment 544 (2016) 1045–1058

Contents lists available at ScienceDirect

Science of the Total Environment

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

New perspectives on interdisciplinary earth science at the Dead Sea: The DESERVE project

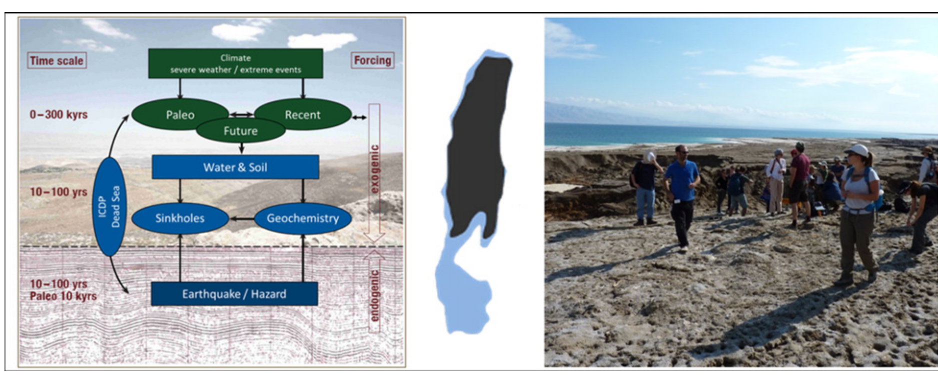
Christoph Kottmeier [a,*], Amotz Agnon [h], Djamil Al-Halbouni [b], Pinhas Alpert [i], Ulrich Corsmeier [a], Torsten Dahm [b], Adam Eshel [i], Stefan Geyer [d], Michael Haas [b], Eoghan Holohan [b], Norbert Kalthoff [a], Pavel Kishcha [i], Charlotte Krawczyk [f], Joseph Lati [i], Jonathan B. Laronne [g], Friederike Lott [a], Ulf Mallast [d], Ralf Merz [d], Jutta Metzger [a], Ayman Mohsen [j], Efrat Morin [h], Manuela Nied [a], Tino Rödiger [d], Elias Salameh [l], Ali Sawarieh [e], Benbella Shannak [k], Christian Siebert [d], Michael Weber [b,c]

[a] Karlsruhe Institute of Technology, Hermann von Helmholtz Platz 1, Eggenstein-Leopoldshafen, Germany
[b] GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[c] University of Potsdam, Potsdam, Germany
[d] Helmholtz Centre for Environmental Research GmbH — UFZ, Theodor-Lieser-Strasse 4, 06120 Halle, Germany
[e] Ministry of Energy and Mineral Resources (MEMR), Amman, Jordan
[f] Leibniz Institute for Applied Geophysics (LIAG), Stilleweg 2, 30655 Hannover, Germany
[g] Ben Gurion University of the Negev, Be'er Sheva, Israel
[h] The Hebrew University of Jerusalem, Jerusalem, Israel
[i] Tel Aviv University, Tel Aviv-Yafo, Israel
[j] An-Najah National University, Nablus, Palestine
[k] Al Balqa Applied University, As Salt, Jordan
[l] The University of Jordan, Amman, Jordan

HIGHLIGHTS

- An interdisciplinary effort of Earth Sciences in the Dead Sea region is undertaken.
- An observation network to monitor long time variability is installed.
- Fieldwork and modeling studies on coupled environmental processes
- Innovative measurement techniques are applied for the first time to the Dead Sea.
- New insights into sinkhole formation, flashflood genesis, and complex wind systems

GRAPHICAL ABSTRACT



New perspectives on interdisciplinary earth science at the Dead Sea: the DESERVE project. Christoph Kottmeier, Amotz Agnon et al.

ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form 1 December 2015
Accepted 1 December 2015
Available online 9 January 2016

ABSTRACT

The Dead Sea region has faced substantial environmental challenges in recent decades, including water resource scarcity, ~1 m annual decreases in the water level, sinkhole development, ascending-brine freshwater pollution, and seismic disturbance risks. Natural processes are significantly affected by human interference as well as by climate change and tectonic developments over the long term. To get a deep understanding of processes and their interactions, innovative scientific approaches that integrate disciplinary research and education are required. The

* Corresponding author.
E-mail address: Christoph.Kottmeier@kit.edu (C. Kottmeier).

http://dx.doi.org/10.1016/j.scitotenv.2015.12.003

Editor: D. Barcelo

Keywords:
Climate
Water balance
Flash floods
Seismicity
Sinkholes
Education

research project DESERVE (Helmholtz Virtual Institute Dead Sea Research Venue) addresses these challenges in an interdisciplinary approach that includes geophysics, hydrology, and meteorology. The project is implemented by a consortium of scientific institutions in neighboring countries of the Dead Sea (Israel, Jordan, Palestine Territories) and participating German Helmholtz Centres (KIT, GFZ, UFZ). A new monitoring network of meteorological, hydrological, and seismic/geodynamic stations has been established, and extensive field research and numerical simulations have been undertaken. For the first time, innovative measurement and modeling techniques have been applied to the extreme conditions of the Dead Sea and its surroundings. The preliminary results show the potential of these methods. First time ever performed eddy covariance measurements give insight into the governing factors of Dead Sea evaporation. High-resolution bathymetric investigations reveal a strong correlation between submarine springs and neo-tectonic patterns. Based on detailed studies of stratigraphy and borehole information, the extension of the subsurface drainage basin of the Dead Sea is now reliably estimated. Originality has been achieved in monitoring flash floods in an arid basin at its outlet and simultaneously in tributaries, supplemented by spatio-temporal rainfall data. Low-altitude, high resolution photogrammetry, allied to satellite image analysis and to geophysical surveys (e.g. shear-wave reflections) has enabled a more detailed characterization of sinkhole morphology and temporal development and the possible subsurface controls thereon. All the above listed efforts and scientific results take place with the interdisciplinary education of young scientists. They are invited to attend joint thematic workshops and winter schools as well as to participate in field experiments.

1. Introduction

The eastern Mediterranean is sensitive to historical and future climate changes (Alpert et al., 1997; Smiatek et al., 2011). The Jordan River catchment and Dead Sea are located within a narrow climatic transition zone. In the north, the annual precipitation is 600–800 mm, whereas in the south, there is an all-year arid climate with an annual precipitation of <150 mm (Schädler and Sasse, 2006). Over the last 2000 years, the climate and landscape in the Dead Sea region has changed dramatically (Bookman et al., 2004). This desertification-threatened region is affected by continual Dead Sea lake level declines, by occasional but life-endangering flash floods, ascending brines that pollute freshwater resources, by ongoing development of numerous sinkholes (topographic depressions formed by subsidence of the Earth's surface due to subsurface chemical dissolution), and by shifting tectonic plates that create risk from major earthquakes. All of which demonstrate the destructive potential of this unique environment. Climate change and the extensive exploitation of surface and groundwater have aggravated such environmental issues over the past four decades.

A major challenge in studying the environmental processes and aforementioned risks stems from their highly interconnected nature (Fig. 1). Through the extensive exploitation of surface water, the water balance of the Dead Sea is no longer in equilibrium and a quasi-steady lake level decline causes a change in groundwater level and groundwater flow paths. In connection with larger tectonic features, earthquakes and past sedimentation processes, these hydrological changes lead, for example, to sinkhole formation. Therefore, a joint effort of geological, geomorphological, hydrological, geophysical and meteorological methods is necessary to obtain a thorough understanding of the coupled processes, such as the understanding of all water budget components or the sinkhole formation process, which cannot be achieved by a narrow disciplinary approach.

The Helmholtz Virtual Institute known as the Dead Sea Research Venue, or DESERVE, aims to address this challenge. The institute is designed as an interdisciplinary and cooperative international research project that offers the unique opportunity to integrate disciplinary knowledge in geophysics, hydrology, and meteorology (Fig. 1). The integrated research activities are accomplished by a network of scientific institutions in countries neighboring the Dead Sea and are based on the development of cross-disciplinary activities in the region by the participating Helmholtz Centres. In contrast to other interdisciplinary or cross-cutting research initiatives like the TERENO station network in Germany (Zacharias et al., 2011) or the Critical Zones Observatories in the US (Anderson et al., 2008) that have a strong long-term focus, DESERVE focuses on the understanding of ongoing processes.

In this paper, we present how such research approaches and the application of recently developed measurement and modeling techniques to the extreme conditions of the Dead Sea can provide new perspectives to resolve recent scientific questions. This provides the basis for sustainable water resources management, environmental risk assessment and predictive modeling in the Dead Sea region. A major interdisciplinary outcome of the project is the installation of a common trans-boundary monitoring network as well as the incorporation of first time performed evaporation measurements of the Dead Sea brine into the coupled hydrological/hydrogeological models of the Dead Sea basin. Beyond that, common geomorphological, geophysical and hydrogeological investigations give new insight into the generation of sinkholes both on- and offshore. They suggest new process models and, thereby, define new research questions. For instance, the existence and peculiarity of a massive salt layer has to be interrogated.

First, the long-term interdisciplinary monitoring network of meteorological, hydrological, and seismic/geodynamic stations, which is established to investigate coupled processes, is described in Section 2. Sections 3, 4 and 5 provide the objectives and exemplary results from climate- and weather-related research and detail the investigations on the components of the water cycle, respectively. The next two sections address sinkhole phenomena and earthquake risks. The final section provides examples to illustrate the project's focus on promoting young scientists.

2. Establishment of an interdisciplinary observation network

In the Dead Sea basin and adjacent areas, drastic changes to climate, water availability, and tectonics may occur rapidly. To provide an understanding of related processes, estimation of risks, and prospects of future outcomes, a large and wide-ranging database of environmental variables is required. In the past, separate efforts were undertaken by each discipline to establish monitoring networks that could address disciplinary research questions. However, the climatic, hydrological, and tectonic processes in the Dead Sea region and elsewhere are coupled; therefore, the established measurement stations are intended to be used for the development of interdisciplinary research platforms.

DESERVE established and operates an interdisciplinary and trans-boundary monitoring network of advanced seismic, geodynamic, hydrological, geochemical and meteorological stations in the Dead Sea region. These multi-parameter-stations include broad-band seismometers and accelerometers to monitor dynamic ground motions, magnetotelluric

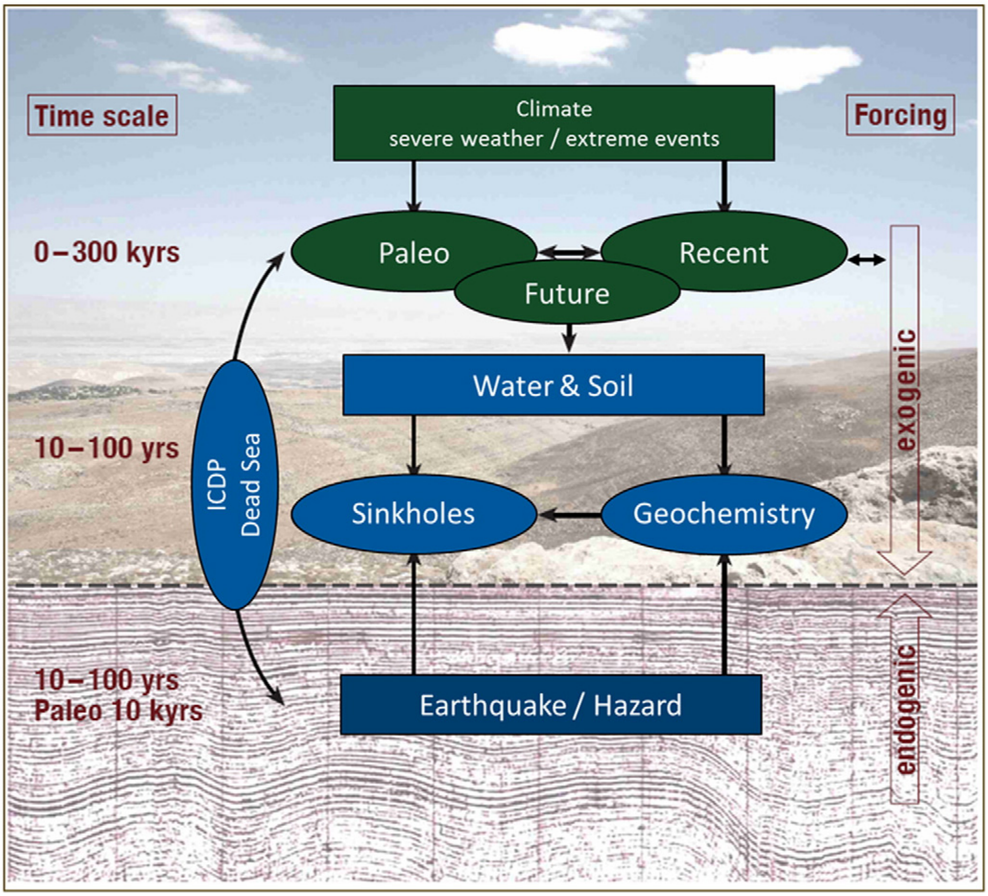


Fig. 1. Coupled processes in the Dead Sea region — overview of research activities within the virtual institute DESERVE. The figure shows schematically the interconnectivity between the climatological, hydrological and geological phenomena that affect the Dead Sea environment over different time scales. Endogenic processes are related to the Earth crust and act in general on long (decades up to millennia) time scales. In contrast, processes related to the soil, the water balance components and the atmosphere impact over various time scales ranging from minutes (e.g. storms) up to hundreds of years (pedogenesis). The Dead Sea drilling cores of the ICDP (International Continental Scientific Drilling Program) cover numerous time scales and relate to endogenic as well as exogenic processes. The displayed phenomena interact in quantitatively unknown ways and their impact on economy e.g. the industrial water evaporation, as well as on tourism and agriculture becomes increasingly important.

instruments to monitor magnetic field variations, and continuous GPS instruments to detect longer-term surface deformations, as well as to measure integrated atmospheric water vapor and soil moisture contents. For hydrological parameters, automatic water sampling and water-quality sensors measure and analyze rainfall and water discharge. Meteorological observations of air temperature, humidity, solar radiation, haze characteristics and wind systems as well as state-of-the-art evaporation measurements over water, bare soil and within vegetation are conducted to better understand atmospheric processes. Additionally, a purpose-built instrument setup has been developed to investigate the influence of atmospheric processes on seismicity. The temporally and spatially coincident measurements of climate, water, and solid earth and spatio-temporal combination of monitored variables can provide insight into the coupling of and interaction among climatic, hydrological, and tectonic processes.

An example of the combined use of data from different disciplines is the study of weather-induced signals in microseismicity. Seismic instruments record ground movements caused for example by tectonic ruptures, anthropogenic effects and atmospheric influences like wind. Whereas tectonic ruptures commonly represent desired signals in seismic recordings, the influence of wind affects the data quality and is often abstracted as seismic noise that superimposes desired signals (Holub et al., 2008; Holub et al., 2009; Withers et al., 1996).

The Dead Sea area is an ideal location to directly investigate the influence of wind on seismic data, because various local wind systems in summer and occasional storms in winter occur (see also Section 3). From March 2014 to February 2015, simultaneous meteorological and seismological measurements were conducted at a site near the Panoramic Complex in Jordan (Fig. 2, north eastern Dead Sea). We obtained 3-component seismic data from 15 temporary high-frequency and broadband stations in addition to 3-component wind speed data from a meteorological station with 20 Hz sampling.

High signal-to-noise ratios at the seismic stations and correlations between wind speed and seismic velocity amplitude are found. Data from 8 March 2014 reveal high amplitudes of ground velocity during a storm with wind speeds up to 20 m/s (Fig. 3). The high amplitudes in seismic data (Fig. 3B) correlate temporally with the high wind speeds obtained by the nearby meteorological station (Fig. 3C). Using Fourier and Stockwell transformations to estimate the power spectral density of the ground velocity, we can rate the effect of wind speed on the frequency domain of the seismic data. The energy density spectrum exposes temporal concurrences of high wind speeds and high energy in the frequency band of the seismological recordings. Cross correlations between the power spectral density and wind speed rise up to 0.75 and quantify the influence of wind speed on ground movement.

According to these data from multiple seismological stations, we detect a significant impact of high wind speeds on ground movement and related seismic measurements. Yet, deriving quantitative information on winds and atmospheric pressure in seismic signals needs interdisciplinary geophysical and atmospheric research; the latter is described in Section 3.

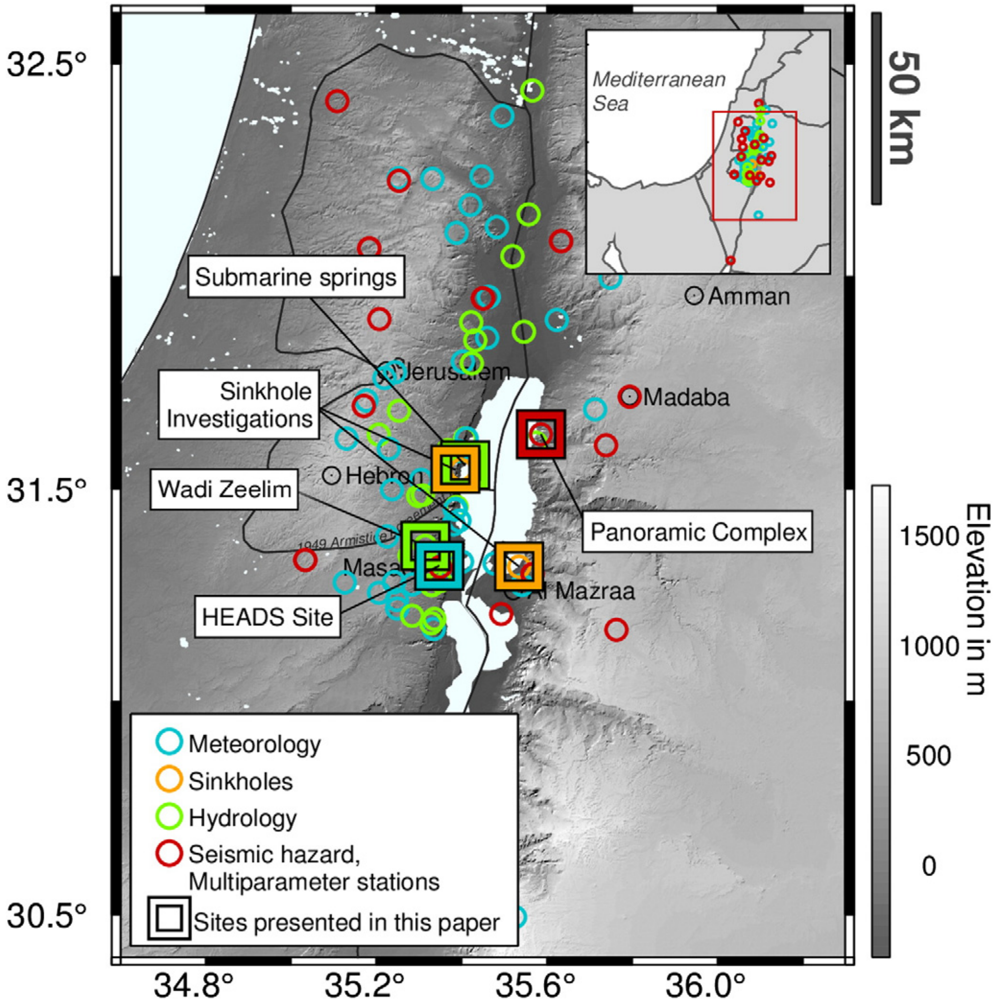


Fig. 2. Cross-border network of DESERVE monitoring and process-related measurement sites. It includes atmospheric observations, school weather stations, sinkhole site studies, earthquake hazard and geophysical multi-parameter observation sites, as well as hydrological observation sites of groundwater, wadi and river runoff.

3. Climate, weather, and atmospheric hazards

The Dead Sea basin and its adjacent areas are a natural laboratory for atmospheric research. It provides the thickest atmosphere on Earth (Dead Sea level air pressure is approximately 1070 hPa) leading to a unique radiation regime (Kudish et al., 2005). The complex terrain (Fig. 4A) triggers pronounced local wind systems and haze layers develop frequently in the valley.

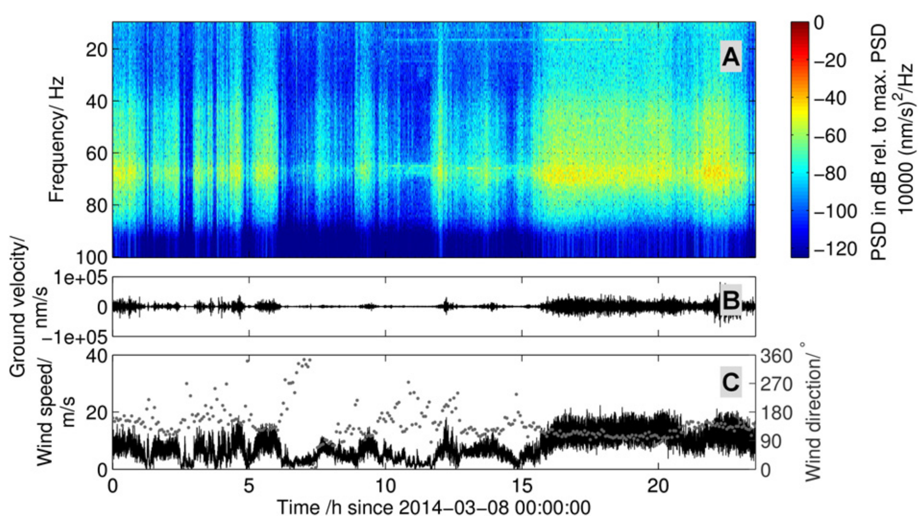


Fig. 3. Concurrence of ground motion and wind speed at the Panoramic Complex site in Jordan: (A) Power spectral density calculated from the seismic trace (B) with respect to time and frequency. (B) Ground motion as seismic velocity (East component) in nm/s at one out of 15 seismic stations. (C) Wind speed (black) and wind direction (gray) over time. All parameters displayed with respect to the same time axis.

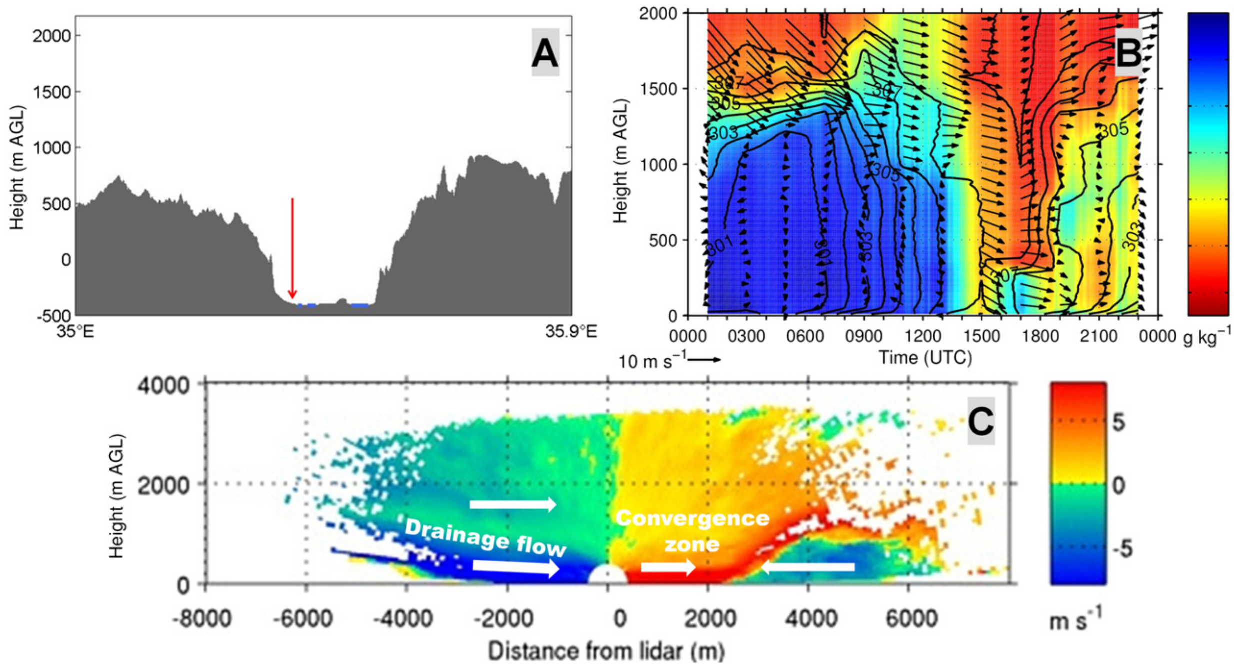


Fig. 4. Measurements performed at the western edge of the Dead Sea valley near Masada (position see A and Fig. 2): (A) East–west cross section of topography, (B) specific humidity (colored), potential temperature (black isolines) and horizontal wind vectors (arrows) obtained from microwave radiometer and radiosonde observations on 16 August 2014, (C) east–west cross section of Doppler lidar wind measurements (towards-lidar component) at 1800 UTC on 16 August 2014 during the HEADS campaign. Please note that the height in panel A is indicated in meters above sea level whereas the height in panel B and in panel C is indicated in meters above ground level. Ground levels equals the KITcube measurement site near Masada (panel A, red arrow).

The atmospheric processes in the Dead Sea valley are mainly driven by a unique combination of strong regional and local forcing. In particular, convection within the atmospheric boundary layer and thermally driven wind regimes have a distinct daily periodicity. Larger (synoptic) scale circulation patterns do not undergo a distinct diurnal cycle. These processes are likely responsible for the layered structure and varying composition of the haze in the Dead Sea valley (Levin et al., 2005; Holla et al., 2015). Such findings were previously based on limited point measurements and modeling studies (Shafir et al., 2008; Levin et al., 2005; Vogel et al., 2006; Shafir and Alpert, 2011). Applying adequate instrumentation, DESERVE tests the hypothesis that the haze layer above the Dead Sea is governed by the combination of orographically and thermally controlled flows, the energy balance over the lake and the surrounding terrain, local and regional aerosol sources and large-scale advection processes.

Meteorological observations are needed at different spatio-temporal scales to thoroughly assess these phenomena. To cover some of the most important scales, an assembly of ground-based in-situ and remote sensing instruments, which is known as the KITcube (Kalthoff et al., 2013), was installed. During the measurement campaign HEADS (1 to 31 August and 1 November to 7 December 2014) within DESERVE, atmospheric processes were monitored by Doppler lidar and radar techniques, a microwave radiometer, radiosoundings and the surface weather station network (see Section 2). The varying aerosol load, atmospheric flow, atmospheric stability, cloud cover, rainfall, surface properties (e.g., vegetation, soil), radiation balance components, surface sensible and latent heat flux, and water vapor based on satellite and ground-based remote sensing instruments have been obtained for typical summer and autumn/winter conditions. For instance, the recorded observations cover the diurnal cycle of boundary layer development, which governs the layered haze structure. Thermally driven regional and local wind systems that are responsible for the regional humidity and particulate transport have been studied to quantify their influence on haze development and air pollution.

The development of a well-mixed boundary layer during daytime and the formation of distinct layers of different winds characterize the lower atmosphere at the western edge of the Dead Sea valley near Masada (Fig. 4). Easterly sea breeze and upslope winds with low wind velocities and a specific humidity of up to 16 g kg^{-1} mark the boundary layer, whereas westerly winds and dry conditions indicate the free atmosphere. In the afternoon, dry and warm air masses from the Judean Mountains descend into the valley, just before a cold, shallow drainage flow from the same direction penetrates into the valley. The cross section of lidar-based wind measurements document the cessation of downslope winds 2 km east of Masada, where a convergence zone and presumably upward motion develops.

The observations are also used to drive and validate numerical model simulations for regional weather and climate tailored to improve process representations, precipitation predictions, regional climate descriptions, and haze layer predictions. Advanced models such as COSMO-ART (Vogel et al., 2009) or WRF-CHEM allow for a consistent treatment of meteorological variables as well as gases and aerosols. They will provide insight into the effect of aerosol particles on the radiation budget in the Dead Sea region and enable calculations of the visual range of the haze layer in relation to advection and Dead Sea circulation systems, whereas high resolution regional climate simulations with models such as COSMO-CLM are conducted to enable investigations of the effect of global warming and regional land-use changes on the atmospheric water balance, precipitation rates and terrestrial water availability.

Intensive measurement campaigns with various instruments combined with model studies improve our understanding of the governing atmospheric processes, aerosol transport and haze layer evolution on different spatio-temporal scales. In addition, they are highly important in assessing the atmospheric components of the water budget (precipitation and evaporation). As wind and solar radiation are controlling factors of Dead Sea evaporation which is discussed in more detail in Section 4.

4. Assessing Dead Sea water budget components

Water availability in the Dead Sea watershed has reached a critical stage. Because of the intense pumping of water from Lake Tiberias and

Yarmouk River, the modern Jordan River has been reduced to a small fraction (typically less than 10%) of its natural precursor. Combined with the brine-consuming salt industry at the southern Dead Sea basin, these man-made effects on water resources have accelerated Dead Sea level drop to a rate of ca. 1 m/year over the last 5 decades (Lensky et al., 2005). Therefore, a more intelligent and sustainable use of all water resources that considers climatic and socio-economic development, is urgently needed. This optimized use requires an understanding and quantitative assessment of all surface and subsurface flow and storage processes in the Dead Sea basin. None of the components, including surface water from rainstorms (Schädler and Sasse, 2006), groundwater from renewable aquifers, ascending brines from deep aquifers, and evaporative losses from the lake, can be easily and comprehensively assessed (Lensky et al., 2005; Siebert et al., 2014).

Therefore, new measurement and modeling techniques at different spatial and temporal scales are required to investigate and quantify the missing/unquantified components of the Dead Sea water budget (Fig. 5) and ultimately to serve as a basis for sustainable water resources management. For example, measurements need to assess (i) the actual evaporation rate of the Dead Sea waterbody (ii) the sublacustrine inflow of groundwater, which may become much larger in the future due to the lowering of the lake, and (iii) groundwater age distributions in the aquifers. Aquifers comprise not only shallow Upper Cretaceous limestone but also the much larger Lower Cretaceous and older aquifers. Current studies aim at receiving necessary information about residence times and migration velocities for numerical models. These measurements require common efforts of various disciplines, such as meteorology and hydrology.

Siebert et al. (2014) arrived at partly new quantitative estimates for the terms in the Dead Sea water balance equation (Eq. (1)):

$$\Delta V_{DS} = P + A_O + [A_{U\text{-upper}} + A_{U\text{-lower}} + A_{U\text{-deep}}] + JR + PW – DSW/PAC – E – \Delta V_{salt}, \quad (1)$$

where ΔV_{DS} is change in lake volume, P is direct precipitation, A_O is surface runoff from the direct drainage areas, $A_{U\text{-upper}}$, $A_{U\text{-lower}}$ and $A_{U\text{-deep}}$ are groundwater discharge from the upper, the lower and the deep aquifer, respectively, JR is inflow from the lower Jordan River, PW is pore water, DSW/PAC is the net abstraction of water from potash/salt factories in the south, E is evaporation and ΔV_{Salt} is the volume of the precipitating salt.

The actual evaporation of the Dead Sea had not been previously measured, and the previous estimates, which range between 1000 and 2000 mm/year (Stanhill, 1994; Salameh and El-Naser, 1999; Lensky et al., 2005) lack verification. With a current surface area of ~600 km^2, these estimates would result in an evaporation of 600–1200 × 10^6 m^3/year. This indicates the importance and associated uncertainty of the evaporation estimates in the water balance (see Fig. 5). Therefore, high-resolution eddy covariance measurements of evaporation have been performed for the Dead Sea in the framework of DESERVE. An energy balance station has been installed directly at the shoreline of the Dead Sea on a headland (Fig. 6). The flux footprint influencing the measurements represents the conditions over water when the wind direction is between 300° and 260°. Only when the wind direction is between 260° and 300° or when wind velocity is very low, does the flux footprint represent onshore conditions. Through this particular setting and the predominant local northerly to easterly wind systems (lake breeze and drainage flows, see Section 3), the flux footprint measured at the station mainly reflects the conditions over water. For wind directions between 260° and 300° an estimate of the evaporation is performed using a multiple regression approach. Gaps in the time series are closed by the median value of the corresponding time step in the respective month. Uncertainties as to this approach are estimated by the median absolute deviation of each inserted value. Since March 2014, continuous measurements enable a detailed analysis of the diurnal and intra-annual variations and driving forces of evaporation. After 1 year, the total amount of actual evaporation has been estimated as 935 ± 64 mm, which corresponds to (569 ± 38.4) × 10^6 m^3 for 2014. This value at the particular location is comparable to the estimated annual evaporation rate of 1100–1200 mm/year by Lensky et al. (2005). Together with the withdrawal of water for potash production (250 × 10^6 m^3/year; Gavrieli et al. (2004)) an annual volume of water approximating 820 × 10^6 m^3 is withdrawn from the lake and cannot be compensated by the aforementioned surface and subsurface inflows.

The measured annual cycle of evaporation is shown in Fig. 6. It reaches a monthly maximum of 114 ± 4 mm in July. Monthly and daily variability have been analyzed. Daily evaporation varies notably in the winter season when synoptic patterns gain more influence. For example, in November 2014, the daily evaporation values ranged between 0.84 mm/day and 6.85 mm/day (not shown). Further data analysis will provide a better understanding of the processes controlling evaporation. By linking these processes with atmospheric modeling, the data will help to improve estimates of Dead Sea evaporation.

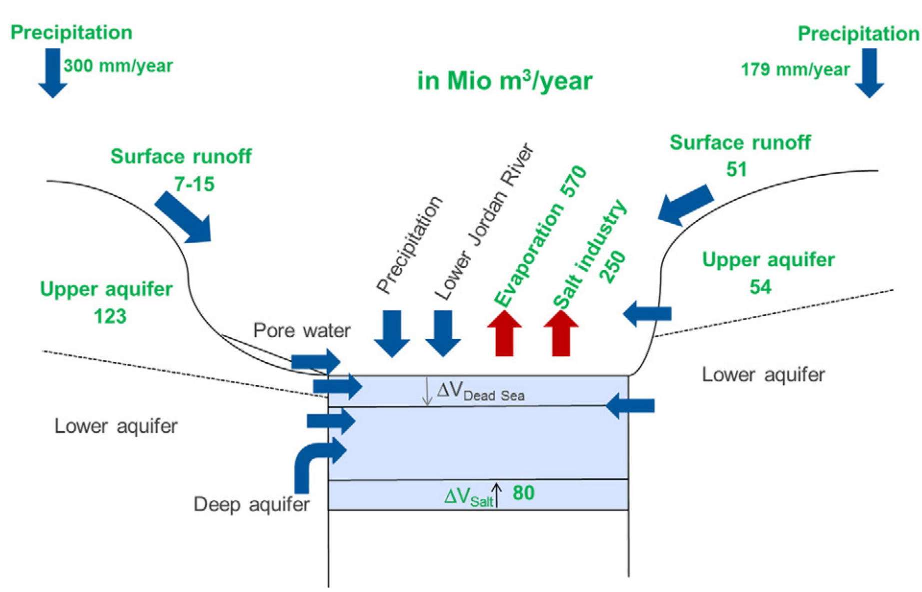


Fig. 5. Required parameters to calculate the water balance of the Dead Sea. The green figures are from Siebert et al., 2014 and from ongoing work within DESERVE. Gray variables are still under investigation.

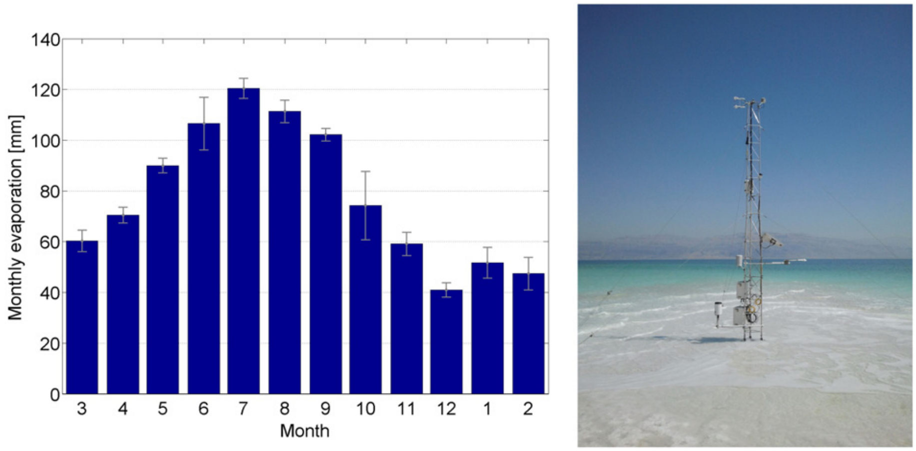


Fig. 6. Monthly actual evaporation rate from eddy covariance measurements on a headland at the shoreline of the Dead Sea from March 2014 until February 2015. Winds are prevailingly onshore, and the evaporation rate for periods of offshore winds is estimated using a multiple regression approach. Missing values are estimated by using a median daily cycle for each month. Uncertainty is indicated by the sum of the median absolute deviations over all missing values in one month.

The importance of submarine groundwater discharge and of groundwater discharge from the eastern and western lower aquifers is indicated by geochemical and remote sensing investigations of the groundwater discharge towards the lake, from on- and offshore springs, and by the admixture of thermalized brines close to the western shoreline. Because of the harsh conditions in the Dead Sea, the investigation of sublacustrine groundwater discharge (SGD) with respect to locations and driving mechanisms is a major challenge. As a starting point, large submarine spring fields have been explored by scuba divers in front of large onshore spring clusters along the western shore to map and sample the groundwater outlets (Ionescu et al., 2012) and to measure and model the vertical buoyant jet of a submarine point source (Munwes, 2012). Geochemical analyses of rare earth elements, ratios of major elements and of stable isotopes (e.g. $\delta^{18}O$, $\delta^{2}H$, $^{86/87}Sr$), of radio-isotopes (e.g. ^{36}Cl) and of dissolved gaseous phases (e.g. CH_4) in combination with microbial investigations on communities in on- and offshore springs show that the emerging groundwaters originate in the Cretaceous mountain range west of the graben. These groundwaters then get admixed with brines, which either ascend from deep aquifers or are hosted in the Quaternary sediments and a flow net developed within the Quaternary lake bed by microbially accelerated karstification of evaporitic minerals (Ionescu et al., 2012; Siebert et al., 2014, 2015).

The abundance and variety of SGD prohibit a sufficient quantification of its magnitude yet. Direct measurements in combination with large-scale remote sensing analyses of SGD-locations are required to understand their discharge pattern and to answer the question whether SGD occurs randomly or follows certain constraints, e.g. faults and cracks of neotectonic origin. It might be that such features are the initial pathways, which widen by microbial mediated karstification. The latter is proved by Ionescu et al. (2012) and by field observations. Analyzing and defining the controlling processes that lead to the abundant SGD is the only possible method to translate them into the numeric of a groundwater flow model (Gräbe et al., 2013; Strey, 2014).

To map the spring fields in their entirety, an autonomous jet-powered Sonobot (Fig. 7A) equipped with an S2C ultra-wideband echo sounder and dual-mode 340/680 kHz side-scan sonar units (Fig. 7B) was used in the Dead Sea during a survey campaign in late 2014 (Fig. 7C). Preliminary results show the applicability of the high-performance system. The high-resolution bathymetric and sonar information are promising. Detailed lake floor images enable the detection

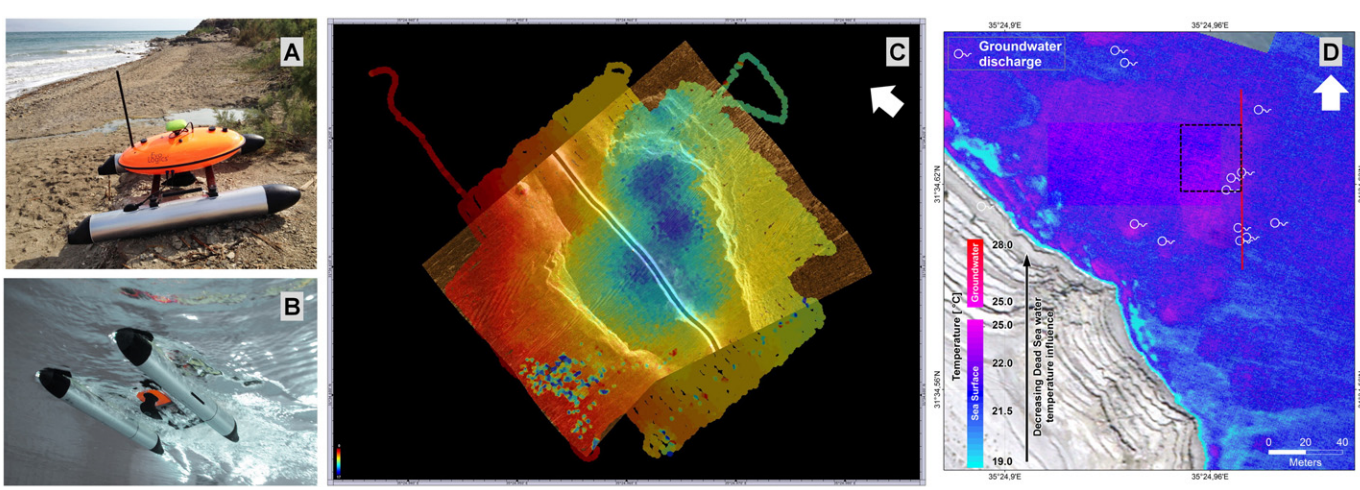


Fig. 7. An autonomous Sonobot was deployed along the western Dead Sea shore (A and B). An echo sounder (on bottom of the central orange chassis) and a side-scan sonar (black bar on the floater) transmitted combined high-resolution geo-referenced bathymetric echo sounding data and geo-referenced side-scan images (C). Prior to the Sonobot survey, an aerial thermal imaging campaign revealed thermal anomalies on the lake surface that indicate submarine springs (D). In (D), the black dotted square indicates the area of the Sonobot survey and highlights the presence of 3 springs situated along a nearly N–S trending linear feature (red line).

of faults, slumps, anomalous funnel structures and outlet dimensions (Fig. 7C). Upcoming measurement surveys will describe the sublacustrine environment.

These surveys will be combined with repeated airborne, unmanned aerial vehicle (UAV)-based, thermal campaigns to detect active and non-active springs and to obtain temporal information. Discharged groundwater has a distinct temperature that causes specific thermal anomalies on the sea-surface that differ from ambient water temperatures. These anomalies (see pinkish colors in Fig. 7D) qualitatively indicate unknown SGD locations. Anomaly sizes, temperature adaptions according to depth (from the echo sounder), as well as ambient and emerging water temperatures are parameters that will be exploited to infer discharge volumes in the Dead Sea water budget.

The data and process understanding obtained from the abovementioned measurements and analyses are important input parameters for transient hydrological models and numerical groundwater flow models. The hydrological model needs to account for supply groundwater recharge as well as surface runoff (see Section 5) and the numerical groundwater flow model has to comprise the whole stratigraphic column as well as the complete subsurface drainage basins of the respective aquifers. The linkage of both model types, as well as the qualitative and quantitative inputs serve to extrapolate the SGD quantities to the entire Dead Sea shoreline, to estimate groundwater flow rates, velocities, as well as flow paths. This will reveal hydrogeological conditions and states along the coastline and throughout the entire subterranean catchment area of the Dead Sea, and finally enable to investigate current and future anthropogenic influences on the decline of Dead Sea levels. To perform these assessments, all relevant hydrological system values (such as groundwater recharge or evaporation) and hydrogeological system values (such as geology, water level and intersections) must be reproduced. In addition to the validity of the data, the accuracy of the obtained values depends on data availability and their spatial/temporal distribution. For the geological model (Fig. 8) which is part of the numerical groundwater flow model of Jordan, over 1800 boreholes have been gathered and evaluated. A similar number will be used to assess the geology of the remaining subsurface Dead Sea drainage basin and thereby ensure the highest possible accuracy and detail level for geological and hydrogeological calculations.

The presented water balance components, evaporation and sublacustrine groundwater discharge, act on seasonal up to decadal time scales. In the short term runoff provides flash flood inputs of water that are further outlined in the next section.

5. Flash flood genesis and alert

In mountainous arid/semiarid regions flash floods are a rare but important phenomenon. Flash floods appear after strong or even moderate rain events, often due to intense (e.g. 1 mm/min) rainstorms lasting few minutes, (e.g., 5–10 mm total rainfall depth). Subsequently, surface runoff is generated within a short time period and often causes damage to infrastructure and loss of human life. In the Dead Sea region, where flash floods are common (Cohen and Laronne, 2005), the driving factors for flash floods are storms between October and May associated with synoptic scale storms and convection in the Mediterranean winter climate (Shentsis et al., 2012). In addition to the general weather conditions and storm characteristics (Yakir and Morin, 2011), the land surface, particularly the slope and lithology, is the most important parameter controlling runoff generation. A reliable flash-flood forecast for the region based on an in-depth understanding of flood generation and routing is of paramount value for preserving infrastructure, transportation and human life.

The objective of the DESERVE flash flood activities is to improve the monitoring and modeling tools for forecasting flash flood runoff in the Dead Sea and similar arid regions. There are two main challenges in forecasting flash floods. First is the reliable forecast of the spatio-temporal patterns of rainfall, due to the erratic and highly variable patterns of event rainfall compared to the scarce network of rainfall monitoring stations. We address this challenge by combining three different rainfall monitoring approaches. First, synoptic meteorological data (Fig. 9A) are the basis upon which rainfall data are analyzed. Second, meteorological data from available monitoring stations are collected and new meteorological stations are installed to fill network gaps (Fig. 9B). Data from rainfall stations are combined with a novel method to derive rainfall patterns from microwave attenuation effects in commercial cellular link data. The method offers great potential in flash flood forecasting (David et al., 2013) as it uses a huge network of already

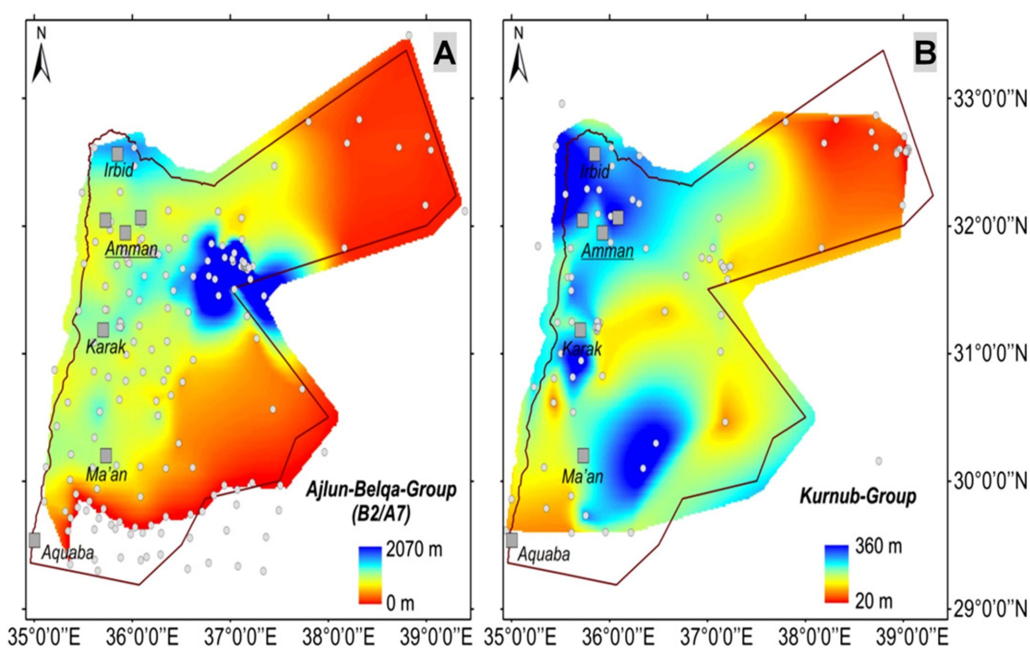


Fig. 8. Thickness maps of the major aquifer units in Jordan, which form the submarine drainage basin of the Dead Sea: the Ajloun-Belqa-Group (A) and the Kurnub-Group (B). This information is the basis of the conceptual model. Gray dots represent available borehole information for the layers.

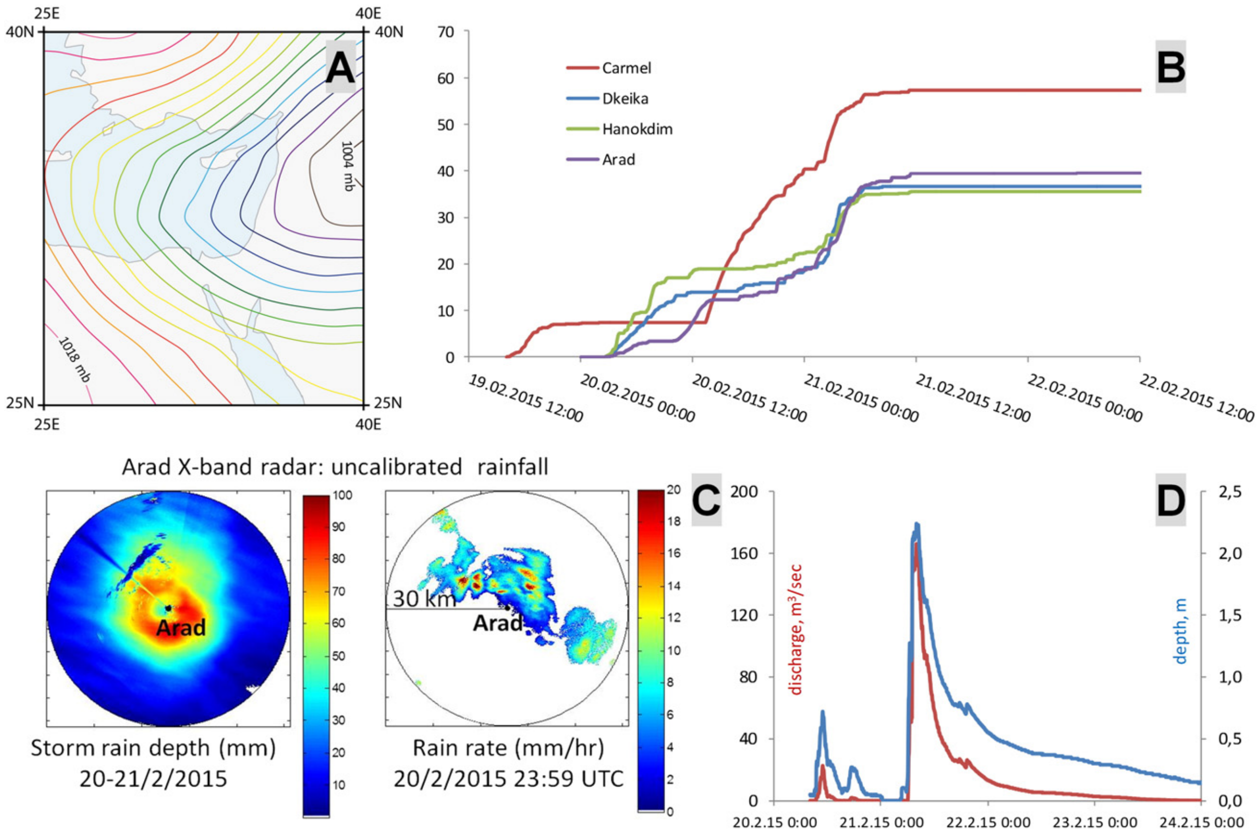


Fig. 9. Large flash flood on Feb. 20/21, 2015 in Wadi Zeelim: Surface pressure (A) and rainfall at four locations (Carmel: along the divide, Hanokdim and Dkeika in the basin) as measured by cellular-transmitting sensitive rainfall recorders (B) and X-band radar backscatter (C), and the resultant discharge hydrograph at the outlet (D).

existing cellular infrastructure. As a third independent approach, high-resolution precipitation data (0.01–1 km^2, 1–5 min) are obtained from C-band (regional) and X-band (local — Fig. 9C) radar systems (Morin et al., 2009; Kalthoff et al., 2013). The strength of traditional rainfall network data (Fig. 9B) is the highly reliable point measurement. However, the uncertainty in spatial rainfall patterns is high and can be compensated by the two aforementioned approaches, which provide information on the spatial variability of rainfall events. The second challenge of flash flood forecasting is a deeper understanding of runoff generation and routing within the wadis of the Dead Sea region, because observations of spatial variability of runoff along wadis during flash flood events are unavailable. Hence, the DESERVE team installed several runoff sensors at wadi outlets and their tributaries to monitor the spatial patterns of runoff generation and routing. An example of a large flash flood in Wadi Zeelim in February 2015 is shown in Fig. 9. The station on the Zeelim drains an area of 239 km^2 (260 km^2 to the sea) and is entirely devoid of permanent settlements, with shallow Reg soils in the upper basin and bare bedrock and taluses throughput the rest. The rainfall was caused by a deep trough extending SW from the eastern boundary with a minimum sea-level pressure (SLP) of 1003.3 hPa to the Dead Sea with a pressure of about 1006 hPa (Fig. 9A). The storm generated intense rainfall in the Judean Desert along the divide (Carmel) and in the basin (Hanokdim and Dkeika), which was measured by cellular-transmitting sensitive rainfall recorders (Fig. 9B) and indicated by X-band radar backscatter at midnight (Fig. 9C). During the event, 20 mm/h bursts and a total-event rain depth > 80 mm, which exceeded the annual average, were recorded. The result was a two-stage flash flood with a maximum depth exceeding 2 m, water discharge exceeding 160 m^3/s (Fig. 9D) and a total flood volume of 4,100,000 m^3.

The flashflood component of DESERVE is closely linked not only to the components of weather and climate (Section 3) but also to sinkholes (Section 6), as several processes of sinkhole formation depend on transmission losses - supply of low salinity floodwaters to the local groundwater.

6. Sinkhole formation and areas vulnerable to sinkhole formation

Sinkholes are enclosed topographic depressions that form by the gradual or sudden subsidence of the Earth's surface in areas of karstic (i.e., soluble) rocks. The ongoing development of sinkholes in the Dead Sea area began in the early 1980s, and the number of sinkholes has increased dramatically over the last fifteen years (Yechieli et al., 2006), with over three thousand sinkholes now documented. Subsidence related to sinkhole formation has caused severe damage to and continues to threaten vital infrastructure (roads, pipelines, dams) and economically important sites used for tourism, agriculture and industry.

The rate of sinkhole formation seems correlated with the rate of retreat of the Dead Sea (Yechieli et al., 2006; Shalev et al., 2006). This retreat may promote two mechanisms that influence surface subsidence, both of which are not fully understood yet. The first mechanism is a displacement of the salt water/groundwater interface that dips shallowly under the shoreline (Salameh and El-Naser, 2000). This allows groundwater that is under-saturated with soluble minerals, such as halite, gypsum and aragonite, to come into contact with a 10,000-year-old salt deposit (>20 m depth below surface) that has been in chemical equilibrium with a brine saturated with these minerals (Yechieli and Wood, 2002; Wust-Bloch and Joswig, 2006). The second mechanism is an increase in the potential energy of sub-surface groundwater flow as the regional base level is lowered. This increases the ability of ground water flow to not only dissolve the salt deposits but also to mechanically mobilize ('subrode') poorly-consolidated Quaternary lacustrine sediments that are interbedded with them and constitute a fine-layered alternation of clay, gypsum and aragonite (Arkin and Gilat, 2000; Garfunkel and Ben-Avraham, 1996). The DESERVE project focuses on two sites of intense sinkhole development: Ghor al Haditha and Mineral Beach on the eastern and western sides of the Dead Sea, respectively (Fig. 2). We follow an integrated shallow-to-deep approach for analyzing the problem of sinkhole formation in space and time.

Shallow investigations comprise the 3D mapping of both sinkhole sites at high spatial resolution (<5 cm) by using RGB-cameras mounted on Helikites and UAVs and the subsequent photogrammetric processing (Fig. 10). To provide deep information combinable with the previously obtained morphological information, geophysical surveys of different scale and penetration depths were combined for imaging the subsurface. From surface to depth, these techniques include ground penetrating radar, shear-wave seismic reflection (e.g., Krawczyk et al., 2012), and ambient noise measurements (e.g., Kühn et al., 2011) that have provided new high-resolution insights down to 100 m depth. This is the target interval in the area where the dissolution and breakdown processes associated with sinkhole formation are thought to operate. Together with the rock/soil properties and soil mechanical investigations, geophysically inferred subsurface information will be combined within a numerical modeling approach to simulate sinkhole formation by using the distinct element method (Holohan et al., 2011). This approach can provide an explicit understanding of the mechanical development of sinkhole collapse, as well as of the roles of key pre-collapse parameters, such as porosity, microseismicity and surface displacement.

Sinkholes at these sites are distributed within gravelly alluvial fan deposits or in recently exposed lacustrine sediments of the former Dead Sea bed (Fig. 10A). As in other sites around the Dead Sea, the sinkholes occur in belts or clusters, and the control factors are subject to debate (see Ezersky et al., 2013 vs. Closson and Abou Karaki, 2013). One hypothesis is that sinkhole alignments reflect concealed faults that act as conduits for groundwater flow due to their neotectonic activity. The sinkholes at Mineral Beach occur in belts with strike directions of ~340–350° and ~30–40°, which are similar to the strike directions of major fault systems in this area (Abelson, 2003). The sinkholes in the northern part of Ghor al Haditha also show a rough 24° alignment, which was previously interpreted as evidence of fault control (Closson et al., 2005). An alternative hypothesis is that the sinkhole distribution simply reflects the distribution of sub-surface salt deposits. In this 'salt-edge' hypothesis (Ezersky et al., 2013), sinkhole alignment reflects the intersection of distributed groundwater flow with soluble deposits that mark historical lake shorelines, which may or may not be fault controlled.

Local observations of sinkhole development and surface morphology in the southern part of Ghor al Haditha support another hypothesis related to focused groundwater flow in high-permeability subterranean pathways (possibly caves), coinciding in part with preceding wadi channels (Fig. 10A) (see also Taqieddin et al., 2000). In this region, the north–north-east aligned sinkhole cluster in the lighter-colored alluvial fan deposits (Fig. 10A) links shoreward with stream channels that cut into the darker-colored deposits of the former Dead Sea bed. These stream channels and the sinkhole alignment indicate a focused flow of water within or at the base of the alluvial fan. Satellite images (not shown here for brevity) reveal this sinkhole cluster coincides with a now-filled north–north-east-orientated channel that branched from the large Wadi Ibn Hammad to the south. In addition, an unusually large seaward migration of sinkhole activity with time has been observed in satellite and aerial imagery (Fig. 10A). This is compatible with a retreating freshwater/saltwater interface, but one that is perhaps enhanced by the focused groundwater flow. Although results are again not shown here for brevity, another surprising result of the initial geophysical survey at Ghor al Haditha is the absence of evidence (high amplitude shear wave reflections) for a thick (>2 m) salt layer that is expected from the 'salt edge' hypothesis (Krawczyk et al., 2015). Such observations at Ghor al Haditha differ from those at Mineral Beach and other sites, indicating that the control of sinkhole development is likely complex and site dependent.

Finally, analysis of the high-resolution DEM of the Ghor al Haditha area shows that the more or less circular shaped sinkholes that formed in the alluvial fan gravels have a higher depth-to-diameter ratio than those that formed in the soft lacustrine muds (Fig. 10A bottom). The

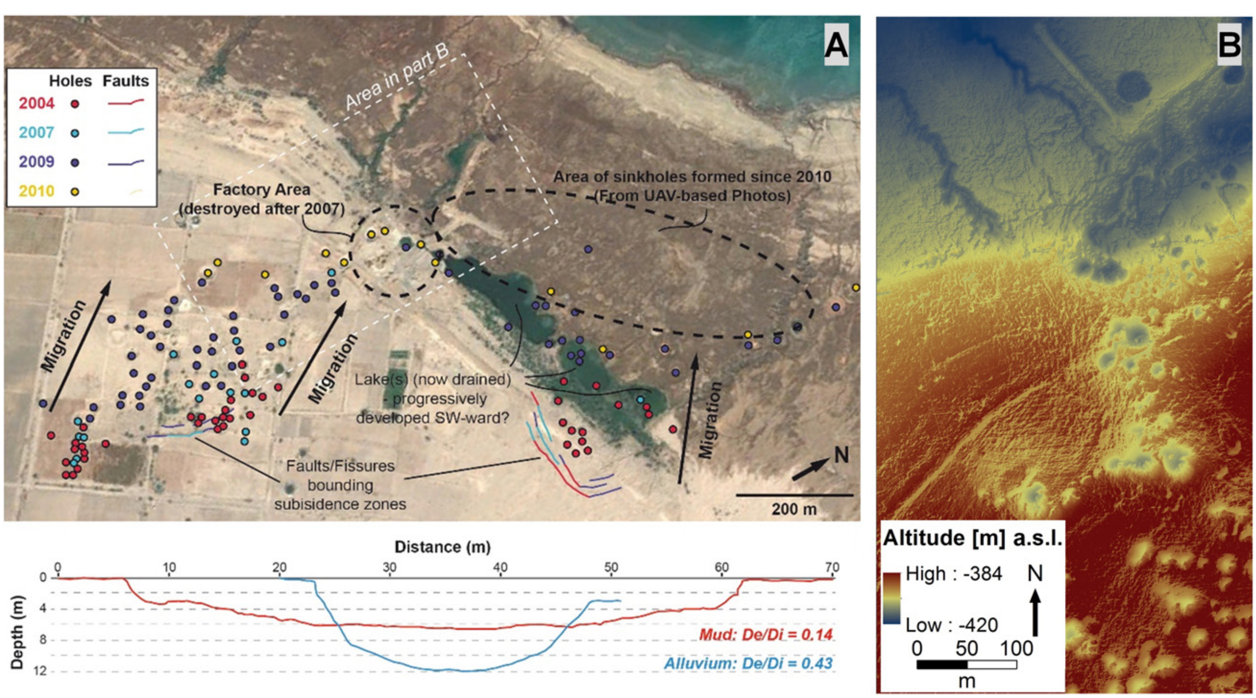


Fig. 10. (A) Spatial evolution of sinkholes in the southern part of Ghor al Haditha from 2004 to 2010. This is derived by analysis of satellite images publically available in Google Earth and by field observations. The initial analysis of ortho-photos and DEMs derived from Helikite-based photogrammetry surveys made in October 2014 indicates that the marked westward (seaward) migration pattern has continued at least until then. The topographic profiles below are taken from the UAV-derived DEM and are representative of sinkholes formed in alluvial fan deposits or in muddy lacustrine deposits. (B) Digital Elevation Model of the area around the sinkhole-destroyed mud factory site at Ghor al Haditha, as derived from Helikite aerial photography during field campaigns in October 2014.

sinkholes at Mineral Beach typically form in mud and are similar in structure to the mud sinkholes at Ghor al Haditha. These results indicate that soil cohesiveness and subsoil structure control the morphology of sinkholes and are likely to control the speed and mechanisms of their formation also (see Shalev and Lyakhovsky, 2012).

Over the next several years, repeated airborne and geophysical surveys will be undertaken at both sites to calculate subsidence rates and to monitor the development of subsidence features over time. An InSAR approach (Cosmo-SkyMed, TerraSAR-X) that exploits the UAV/Helikite-derived high resolution DEMs to correct for topographic phase contributions will also likely be applied. The combination and analysis of data from all of the applied methodologies will advance our understanding of the spatial and temporal development of sinkholes. Such advances are necessary to provide scientific recommendations and predictions of future sinkhole-prone areas and reduce sinkhole hazards in the Dead Sea area.

These investigations suggest a main hydrological control on the location of sinkhole formation, but the tectonic influences on sinkhole location or triggering are not clear yet. Even though the large-scale Dead Sea transform fault is some distance from the sinkhole sites, small-scale neo-tectonic faults and fractures could provide an important component by allowing pathways in the subsurface to open and channelize fluids. Information on such features and on how earthquakes related to them may trigger sinkhole collapse could be delivered by tuned seismological arrays or paleoseismological investigations (see Section 7).

7. Earthquake risk and paleo-reconstructions

In addition to the threat of flash floods (Section 5) and sinkholes (Section 6), the Dead Sea lies within a tectonically active region and is thus endangered by earthquakes. The largest tectonic feature in the region is the Dead Sea transform fault running along the Jordan Valley through the Dead Sea to the southern tip of the Sinai. The fault forms the plate boundary between the Sinai subplate and Arabian plate. Strong earthquakes (Mw > 7) resulting from the low slip rates (4–6 mm/year; Masson et al., 2015) of the two plates are rare but possible. The DESERVE project aims to investigate this threat by (i) investigating historical records of earthquake events by assessing damage to historical buildings and information collected by sediment analyses and (ii) deriving probabilistic seismic risk estimates that combine the likelihood of ground shaking with available information on exposed infrastructure in the region to determine the infrastructure's susceptibility to earthquake damage.

A link across numerous time scales has been provided by the recent International Continental Scientific Drilling Program (ICDP) in the Dead Sea. The cores recovered during this campaign provide long time scales (>100 millennia) of information, often at a seasonal resolution. Two environmental archives are embodied in these cores: hydrological fluctuations and seismic regimes. These data enhance the ability to fine tune and precisely decipher earthquake behavior from seismites. An example drill core is shown in Fig. 11 A. An exciting potential outcome is determining the effect of hydro-climatic fluctuations on seismic clustering. The seismic information (Agnon et al., 2014) will be integrated with data on basin development and rift tectonics, and the paleo-hydrological and paleo-climate information will be integrated and evaluated in a framework of regional and global climate modeling. The essential steps of this approach include reconstructing the geochemical–sedimentological–limnological history of the lakes at a high resolution (millennial–decadal–annual) and establishing the climatic history of the region (Torfstein et al., 2015; Neugebauer et al., 2015). This approach aims to detect the paleo-hydrology of the drainage area and behavior of abrupt hydrological–limnological events. The limnological–hydrological history of the Dead Sea water bodies is compared with regional and global climatic records and thus integrates the information with global paleo-climatic models. A high-resolution paleo-seismic record is therefore developed.

In the Dead Sea region, the local population is often not aware of the earthquake threat, which is similar to other moderately or lowly active seismic regions (e.g., Guéguen et al., 2007). The last earthquake that caused severe damage in large parts of the region ruptured around Jericho, 11 July 1927, Mw 6.2. Recently, the 1995 Mw 7.2 Nuweiba earthquake in the Gulf of Aqaba was a reminder of the threat. Its remoteness limited the damage to a small area.

Due to the rare nature of strong earthquakes, local building structures are often designed with inadequate seismic resistance. Building codes (earliest is for Israel since 1975) have only recently been established to mitigate the possible effects of seismic loads that result from seismicity in the region. Therefore, DESERVE aims to identify the

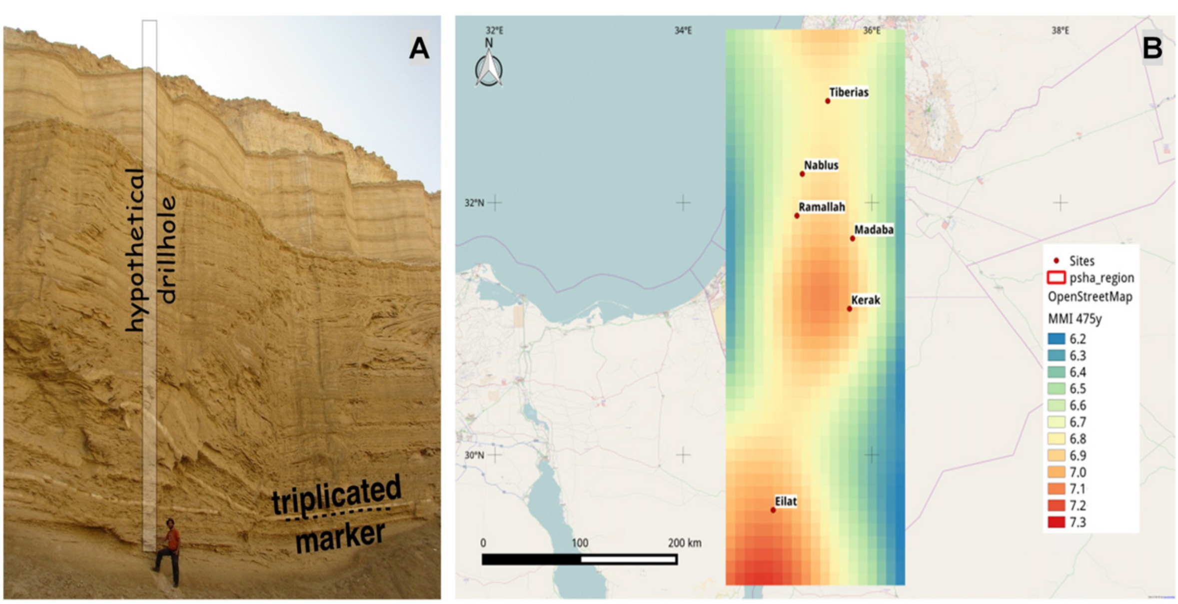


Fig. 11. (A) Late Pleistocene lacustrine (Lisan Formation) beds showing syndepositional slumping (person for scale), likely triggered by earthquakes. A prominent marker is shown to be triplicated in the overthrusted section. (B) Macroseismic intensity levels with a 10% probability of exceedance within 50 years (macroseismic intensity 6 = VI: slight damage to buildings; 7 = VII: slight to moderate damage to buildings).

natural threat of earthquakes (hazard) and to assess exposed buildings (exposure) as well as their susceptibility to earthquake-induced damage (vulnerability) by applying recently developed methods by Pittore and Wieland (2012). In cooperation with DESERVE partners in the region (An-Najah National University Nablus, Geological Survey of Israel, Jordan Seismological Observatory), the seismic risk, or potential consequences of earthquakes, will be estimated for six cities in the region: Eilat and Tiberias (Israel), Kerak and Madaba (Jordan), and Nablus and Ramallah (Palestine Authorities). To achieve this goal, up-to-date seismological methods for seismic hazard assessment are combined with civil engineering expertise (to determine building types) and seismic engineering expertise (to estimate building vulnerabilities from census information, satellite remote sensing and mobile mapping campaigns using an omni-directional camera system). Fig. 11B shows the location of the selected cities and their seismic hazard estimates expressed in terms of the macroseismic intensity derived within DESERVE. In combination with the distribution of building types, so called fragility curves that express the probability of different damage levels for each building type when experiencing ground shaking of a given macroseismic intensity, provide all necessary information for the subsequent calculation of seismic risk.

8. Promotion of interdisciplinary education of young scientists

All of the above-listed efforts and perspectives call for interdisciplinary research and the active involvement of young scientists. The promotion and interdisciplinary education of young scientists at the bachelor's, master's and PhD levels is considered an important issue that requires cooperative efforts. Within DESERVE, this is achieved in various ways.

At present and as a result of previous research and cooperation in the Dead Sea region, the participating Helmholtz Centres have involved young scientists (12 females, 14 males) from Jordan (2), Israel (12), and Germany (12) at the bachelor's (3), master's (13), and PhD (10) levels. The participation in the interdisciplinary field campaigns helps to build communication and analytical skills as a prerequisite for developing independent researchers. Involved students participate in the measurement and analysis of data for their theses, including data resulting from the HEADS atmospheric measurement campaign (Section 3) or the sinkhole surveys (Section 6) in DESERVE.

Current graduate schools from a number of universities, such as the Graduate School for Climate and Environment (GRACE) at the Karlsruhe Institute of Technology and the Porter School of Environmental Studies at Tel Aviv University, are involved. These schools offer developed modules beyond the science courses of the respective universities to improve hard and soft skills. The courses are open to all DESERVE students.

The first DESERVE Winter School covering various topics of meteorological and hydrological sciences was successfully conducted over a two-week period in November/December 2014 at Masada (Israel). DESERVE welcomed 25 participants from universities and research institutions, in particular master's and PhD students with diverse educational backgrounds (ranging from geophysics to hydrology and meteorology) and a common interest in the Dead Sea region. After two introductory days on the geology, climate, biology, and economy of the region, the Winter School focused on hydrological and meteorological aspects. Internationally recognized researchers from DESERVE and invited experts held lectures on DESERVE research topics, such as rainfall runoff processes, regional energy balance, convection and hydrochemistry. The lectures were accompanied by exercises and field trips to combine theory and practice.

9. Conclusions and outlook

Three years after its foundation, the Virtual Institute DESERVE has been successful in establishing new inter-disciplinary and international cooperation in the Dead Sea area. Examples of its scientific prospects are shown in this paper and demonstrate the high potential for obtaining new insight into environmental key processes in particular the development of wind systems (Section 3), evaporation and groundwater movement (Section 4), extreme runoff events (Section 5), sinkhole genesis (Section 6) as well as tectonics (Section 7). While the focus of the first phase of DESERVE was on the implementation of an interdisciplinary monitoring network and on the execution of field campaigns to monitor and to characterize the environmental processes, the second phase of DESERVE (2015–2017) will broaden the process of understanding by fully elaborating the results from ongoing measurements and modeling efforts. Based on this understanding, DESERVE will provide a state-of-the-art seismic hazard assessment as well as the first quantitative estimate of seismic vulnerability and risk, a toolbox of methods and techniques to detect and characterize sinkholes at their very early stage of development, as a contribution to a sinkhole hazard map, and a flash flood warning system. Such predictive tools are indispensable for the safety of human lives, infrastructure, and transport.

The consolidated cooperation between the partner institutions from Germany, Israel, Jordan, and the Palestine Territories involving the new generation of interlinked young scientists emerging from DESERVE sets the basis for the scientific and societal outreach of DESERVE. DESERVE pursues four long-term perspectives:

i. Continued monitoring of environmental changes in the atmosphere, hydrosphere, and geosphere based on the advanced instrumentation that has been installed. The current state and rate of change of the environmental variables shall be assessed and future changes predicted. When possible, the operation of the different long-term installations will be integrated into the national networks already in operation or under construction.
ii. Process understanding, e.g. for sinkhole genesis, is not only crucial for the Dead Sea area, but also for other areas faced with the formation of salt-related sinkholes e.g. Northern Germany. Due to the rapid environmental changes, the Dead Sea region is an outstanding test site and a knowledge transfer can take place to other regions that experience these events over longer time scales.
iii. The anthropogenic impact on the Dead Sea environment, in particular on land and water resources, is extensive. The monitoring network combined with an improved process understanding enables the construction of a knowledge base, which is required to predict the consequences of major planned human interferences, such as the Red Sea – Dead Sea Conduit or the transfer of salt deposits from the evaporation ponds to the Dead Sea.
iv. The knowledge gained on e.g. the quantification of the water balance components, as well as on seismic vulnerability and risk is beyond pure academic interest. It provides fundamentals for an integrated water resources management and for the mitigation of natural risks and so highly impacts the economy, tourism and even human life in the region. Therefore, a knowledge transfer from scientists to decision-makers is essential. Furthermore, capacity building and training structures to raise public awareness and to involve the new generation of young scientists is essential. For instance, DESERVE has already started to construct a trans-boundary meteorological monitoring network at schools in the Dead Sea area to educate schoolchildren to the role and influence of weather on their lives as well as their environment.

Acknowledgments

DESERVE is funded by the Helmholtz Association of German Research Centres as a Virtual Institute (VH-VI-527) from 2012 to 2017. Research activities performed in DESERVE were made possible by additional financial contributions from DESERVE partner institutions. We acknowledge technical, administrative and personnel support from various institutions and individuals as listed below.

Institute	Involvement
Agricultural Research Organization — the Volcani Centre, Bet-Dagan, Israel	Provision of surface evaporation flux measurements.
Arab Potash Company (APC), Jordan (Emad Talafeha)	Cooperation in measurements during HEADS 2014.
Dead Sea and Arava Science Centre, Israel (Yael Maor, David Seveloff)	Provision of major support in obtaining permissions and organizing HEADS 2014.
Dead Sea Drainage Authority, Israel	Provision of funds and equipment for renewing hydrometric stations and rain recorders.
Dead Sea Works (DSW), Israel	Provision of meteorological data; cooperation in measurements.
En Gedi Spa Hotel Complex, Israel (Uri Prigal)	Allowance to use measurement sites and provision of logistical support.
Evologics GmbH, Germany	Cooperation in developing strategies to survey large coastal areas.
Geological Survey of Israel (GSI), Israel (Yossi Yechieli)	Cooperation on seismic risk estimates for Israeli cities; SGD and groundwater network development along the coastline of the Dead Sea; advice on sinkhole areas and salinization problems.
Helmholtz-Zentrum Dresden-Rossendorf, Germany	Provision of 36 Cl-isotope analysis.
Hydrological Service of Israel (Gavriel Weinberger, Amir Givati, Udi Galili) Royal Military Academy, Brussels, Belgium	Cooperation with respect to Cosmo SkyMed data.
Israel Institute for Biological Research, Ness Ziyyona, Israel	Operation of tethersonde during HEADS 2014.
Israel Nature and Parks Authority, Ein Feshkha, Israel (Eldad Hazan)	Provision of support and close cooperation during sampling campaigns.
Israel Nature and Parks Authority, Masada, Israel (Eitan Campbell)	Cooperation in HEADS 2014 campaign. Installation of the meteorological station at Masada.
Israel Water Authority, Mekorot, Israel Mekorot Co. Il, Israel	Cooperative investigations of groundwater systems in the Judean Mountains; climate station network partner.
Jordan Seismology Observatory (JSO), Jordan	Cooperation on seismic risk estimation for Jordanian cities to integrate mobile mapping and remote sensing techniques.
Kinneret Limnological Laboratory, Israel	Provision of laboratory space and equipment for chemical and biological analyses of water samples by graduate students.
Leibniz Institute for Freshwater Ecology and Inland Fisheries, Germany	Cooperation in the development of geochemical and microbiological solutions for the flow net.
Lower Jordan River Drainage Authority	Provision of funds and local maintenance for the Old Gesher station.
Palestinian Water Authority, Palestine	Cooperative investigations of groundwater systems in the Judean Mountains; climate station network partner.
Rescue team, Megilot Dead Sea, Israel (Omar Cohen and Jake Ben Zaken)	Provision of search and rescue support during observations.
Royal Society for the Conservation of Nature (RSCN), Jordan	Installation of the meteorological station at the Panoramic Complex. Integration of meteorological measurements in the permanent exhibition at the museum.
Tel Aviv University, Israel (Eduard Karat)	Provision of support in handling customs issues and obtaining various permissions.
The Hashemite Kingdom of Jordan, Meteorological Department, Jordan	Cooperation in launching radiosondes during HEADS 2014 in Jordan.
The Hashemite Kingdom of Jordan, Ministry of Water and Irrigation, Jordan	Cooperation in groundwater investigations in Jordan.
TU Bergakademie Freiberg, Germany	Cooperation in submarine exploration of groundwater springs.

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