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Challenges to estimate surface- and groundwater flow in arid regions: The Dead Sea catchment

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HIGHLIGHTS

- This paper presents a trans-boundary approach to evaluate water fluxes into the Dead Sea.
- Independent methodologies were chosen to close the gap of data scarcity.
- The combination of remote sensing and fingerprinting reveals new insights into the submarine groundwater appearances.
- Regionalised recharge simulations permit preparation of future scenarios based on forecasted reduced precipitation.

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ABSTRACT

The overall aim of the this study, which was conducted within the framework of the multilateral IWRM project SUMAR, was to expand the scientific basement to quantify surface- and groundwater fluxes towards the hypersaline Dead Sea. The flux significance for the arid vicinity around the Dead Sea is decisive not only for a sustainable management in terms of water availability for future generations but also for the resilience of the unique ecosystems along its coast.

Coping with different challenges interdisciplinary methods like (i) hydrogeochemical fingerprinting, (ii) satellite and airborne-based thermal remote sensing, (iii) direct measurement with gauging station in ephemeral wadis and a first multilateral gauging station at the river Jordan, (iv) hydro-bio-geochemical approach at submarine and shore springs along the Dead Sea and (v) hydro(geo)logical modelling contributed to the overall aim.

As primary results, we deduce that the following:

(i) Within the drainage basins of the Dead Sea, the total mean annual precipitation amounts to 300 mm a^{-1} west and to 179 mm a^{-1} east of the lake, respectively.
(ii) The total mean annual runoff volumes from side wadis (except the Jordan River) entering the Dead Sea is approximately 58–66 × 10^6 m^3 a^{-1} (western wadis: 7–15 × 10^6 m^3 a^{-1}; eastern wadis: 51 × 10^6 m^3 a^{-1}).
(iii) The modelled groundwater discharge from the upper Cretaceous aquifers in both flanks of the Dead Sea towards the lake amounts to 177 × 10^6 m^3 a^{-1}.
(iv) An unexpected abundance of life in submarine springs exists, which in turn explains microbial moderated geo-bio-chemical processes in the Dead Sea sediments, affecting the highly variable chemical composition of on- and offshore spring waters.

The results of this work show a promising enhancement of describing and modelling the Dead Sea basin as a whole.

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1. Introduction

The riparians of the Dead Sea suffer from semiarid to arid climatic conditions with serious shortages of high-quality freshwater resources, aggravated by a dense and increasing population. However, to ensure the socioeconomic stability, intense exploitation of available water resources is necessary. That, in turn, requires a detailed knowledge about the amounts and mechanisms of fresh groundwater flux and the amount of surface runoff that results from precipitation. Consequently, a humongous amount of surveys were performed on that topic in the Dead Sea basin (among others, Al-Weshah, 2000; Avrahamov et al., 2010; Burg, 2006; Enzel et al., 2006; Frumkin et al, 2011; Gavrieli et al., 2001; Gvirtzman and Stanislyvsky, 2000; Katz and Starinsky, 2008; Laronne Ben-Itzhak and Gvirtzman, 2005; Lensky et al., 2005; Möller et al., 2003, 2007; Niemi et al., 2009; Oz et al., 2011; Salameh and El-Nasser, 1999, 2000; Salameh and Al Farajat, 2006; Shaliv et al., 2006; Yechieli, 2000; Yechieli et al., 1995, 2006, 1996). The *Best Available Data Report*, mutually published by the Tahal Group and the Geological Survey of Israel (TAHAL, 2010), conveys a comprehensive overview. Our below described approach relates to adding knowledge, on aspects that were or could not be gained before.

The hypersaline Dead Sea (total dissolved solids [TDS] = 367 g l^{-1}) is a terminal lake, situated within the Jordan–Dead Sea Rift (DSR) system. The lake consists of a deep northern basin (deepest point at −725 m mean sea level (msl.)) and a shallow southern basin. The latter would have been dried out but is artificially sustained by continuous pumping of water from the northern basin as it is used for commercial mineral production. Since the onset of dramatic anthropogenic interventions into the regional hydrological equilibrium during the 1960s, the natural northern basin, with a current (2013) water level at −427 m msl, continuously shrinks. As result of failure of the international community and the riparian countries, mainly the Jordan River, which was and is the major contributor to the lake, was subject to a row of unilateral water management schemes that reduced the discharge of the remaining Jordan River by about 90% from naturally >1,370 × 10^6 m^3 a^{-1} (Salameh, 1996) to 16–400 × 10^6 m^3 a^{-1} (Asmar and Ergenzinger, 2002; Holtzmann et al., 2005):

- In 1955–1964, King Abdullah and East Ghor Canals were constructed in the Kingdome of Jordan to divert about 25% of the natural flow of Yarmouk River (main contributor to the Lower Jordan River).
- In 1964, Lake Tiberias was embanked, which reduced its effluent and the resulting Lower Jordan River (LJR) by 90%, compared to the amount of water that left the lake prior to the dam.
- In 2009, Syria and Jordan reduced the discharge of the Yarmouk River again by the finalization of the Al-Wahda dam (Al-Taani, 2013) and several small-scale retention structures in the tributaries of the Yarmouk River.

Additionally, water budget influence originates from dam constructions in wadis along the eastern side of the Dead Sea (DS) and the growing potash companies in Jordan and Israel pumping out 500 × 10^6 m^3 a^{-1} from the Dead Sea into evaporation pans and restore about 250 × 10^6 m^3 a^{-1} of concentrated brines back (Lensky et al., 2005).

The resulting effects on the natural equilibrium of the Dead Sea were dramatic. While lake level under natural conditions (until 1950s) fluctuated negligibly around −395 m msl. (EXACT, 1998), the human impact dramatically reduced the amount of inflowing water. Accelerated by the high evaporation of 1.1–1.2 m a^{-1} (Lensky et al., 2005), the lake declines by ca. 1 m a^{-1}, comparable to 700 × 10^6 m^3 a^{-1} of volume loss (Gavrieli et al., 2006). As a serious effect, connected groundwater tables in surrounding mountain aquifers dropped accordingly (Yechieli et al., 2010). These fresh groundwaters discharge from the mountain aquifers and pass the recently exposed lakebed inducing suberosion structures that endanger infrastructure and tourism (Yechieli et al., 2006). Moreover, the dropping groundwater levels cause a vegetation dieback and desiccation of springs threatening endemic life in still existing ecosystems such as Ein Feshkha/Enot Zuqim along the shoreline.

Measurements of groundwater discharge along the shoreline of the lake cover the known onshore springs only (HSI, 2012). Submarine groundwater discharge, although visible, was not quantitatively detected yet. Similarly, gauging surface runoff is challenging, as there is only episodic water flow. If temporal runoff occurs, the measurement is pursued in an extreme environment with torrential water flow, accompanied by intense sediment transport. As a consequence, the time series of measurements of ephemeral wadi flows are almost not available.

Consequently, despite long, intense and valuable efforts carried out to investigate the effects of the dropping Dead Sea level on surrounding essential water resources, the complexity of interacting systems and the difficulty to measure certain states variables hindered to comprehensively determine amounts of surface runoff and groundwater discharge. These still open questions led to the here presented project, performed by a multilateral research team from Jordan, Israel, Palestine and Germany. Large efforts were undertaken to realise a holistic approach by combining evaluations of input (precipitation), transfer (recharge and surface runoff) and output (groundwater discharge) of water fluxes through ephemeral wadis, the surrounding aquifers and the exposed lakebed. An extensive geological database was developed and consequently high-resolution structural models for the upper Cretaceous aquifers on both sides of the lake were derived. On this basis, we built regional numerical groundwater flow models to investigate the groundwater regime in the Dead Sea drainage basin.

1.1. Hydrogeology of the study site

The western flank of the Dead Sea is represented by a mountain range, building the N-S-oriented backbone of Israel's and Palestine's water supply. It hosts two major lime- and dolostone aquifers of upper Cretaceous age, which crop out along the flank and beneath a buried lower Cretaceous sandstone aquifer. Inside the Graben, Quaternary fluviatile sediments around wadi mouths interfinger with the lacustrine to hypersaline lake sediments that form the heterogeneous coastal Dead Sea Group (DSG) aquifer (Fig. 1). Within the flank, structural features, observable as surface lineaments, may represent preferential groundwaters flow paths from recharge areas in the west towards the Dead Sea (Mallast et al., 2011) (Fig. 1A). At these locations, groundwater preferentially discharges from the DSG in large spring areas: Ein Feshkha, Kane/Samar, Mizpe Shalem, Qedem and Ein Gedi. In general, two spring types occur: (i) terrestrial springs, emerging along faults or sediment heterogeneities that incise erosion channels within the dry-fallen DSG sediments, and (ii) submarine springs that emerge on the lake's bottom in depths at least down to 30 m below lake level (Ionescu et al., 2012), establishing a density-driven buoyancy flow that can form visible circular patterns on the DS surface (Munwes et al., 2010) (Fig. 1B).

Groundwaters along the eastern flank occur within the equivalents of the west: (i) the lower Cretaceous sandstone and (ii) the upper Cretaceous limestone aquifer, respectively. However, contrastingly to the west, the lower Cretaceous sandstones crop out along the eastern shoreline. That sandstone aquifer, together with beneath situated older mostly sandy formations, forms the “lower aquifer,” which discharges through springs along the Dead Sea and within wadis (e.g., Zarqa Ma'in, Mujib, Wala, Shaqiq and Ibn Hammad). Its current replenishment is very low since its recharge occurs through the outcrops in the arid S and SE of Jordan (Salameh and Hammouri, 2008). Contrastingly, the upper Cretaceous limestone aquifer is replenished by recent precipitation in the eastern Graben shoulder and discharges after residence times of only some years (Ereifeg, 2006). While its natural discharge only occurs through some springs mainly in the headwaters of the wadis, its anthropogenic exploitation by pumping wells is essential for the socioeconomic welfare of Jordan.