



The extent of seawater circulation in the aquifer and its role in elemental mass balances: A lesson from the Dead Sea



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ABSTRACT

This paper shows for the first time a field-based estimation of the volume of dispersive density-driven long-term seawater circulation in coastal aquifers, which is crucial to the understanding of water–rock interaction and to the assessment of its potential impact on elemental mass balances in the sea. The Dead Sea is an ideal place for studying this type of circulation due to the absence of tides and the accessibility of the shallow fresh–saline transition zone. The unique antithetical behavior of ²²⁶Ra and ²²⁸Ra during seawater circulation in the Dead Sea aquifer, where ²²⁸Ra is added and ²²⁶Ra is removed, provides a robust new method for quantifying aquifer circulation. Here we estimate water circulation through the Dead Sea aquifer to be 400 million m³/yr (~2.5 million m³/yr per 1 km of shoreline), which is ~20% of the fresh water inflow prior to the 1960s. This large volume can affect trace element concentrations in the Dead Sea, e.g. it is a sink for ²²⁶Ra, Ba and U and a source for ²²⁸Ra and Fe. These results suggest that dispersive density-driven seawater circulation in aquifers may play an important role in mass balances in other lacustrine and oceanic settings.

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1. Introduction

Seawater circulation in coastal aquifers, which is a major component of submarine groundwater discharge (SGD), has been recognized as a process that affects trace element and nutrient mass balances of coastal areas (e.g. Simmons, 1992; Moore et al., 2008; Beck et al., 2013). SGD was shown to contribute Ca, Ba and Sr to the Bengal Basin in the same order of magnitude as river fluxes (Basu et al., 2001; Dowling et al., 2003). It was also suggested that groundwater involved in water–rock interaction affects oceanic ⁸⁷Sr/⁸⁶Sr ratios (Stein et al., 2000; Cochran et al., 2010), and recently Beck et al. (2013) presented a new Sr budget showing the contribution of SGD to the oceanic ⁸⁷Sr/⁸⁶Sr budget due to isotopic exchange in the subterranean estuary. Estimates of SGD vary over several orders of magnitude (a few to 10⁶ m³/yr per meter shoreline) due to the natural spatial variability in hydrological, geological and climatological parameters (Burnett et al., 2001; Taniguchi et al., 2002; Gallardo and Marui, 2006). In particular, the extent of seawater circulation could vary considerably de-

pending on the studied scale, from wave setup and tidal-driven short-term circulation (Robinson et al., 1998; Li et al., 1999), through seasonal (Michael et al., 2005; Gonnee et al., 2013a), and up to the multi-annual dispersive circulation along the fresh–saline water interface (Cooper, 1959). Determining the circulation type and time scale is highly important to the characterization of water–rock interaction and to the assessment of its impact on oceanic mass balances. In particular, while the short-term wave or tidal circulations are mainly related to short-term adsorption–desorption and redox processes (e.g. Charette and Sholkovitz, 2006; Beck et al., 2013), the multi-year dispersive circulation could involve longer-term processes such as the precipitation and dissolution of various minerals, and may have a greater potential to affect certain element budgets on a global scale. However, in an oceanic setting it is difficult to differentiate between the different types of circulation. The long-term behavior of the radium isotopes (²²⁶Ra and ²²⁸Ra) in the Dead Sea groundwater described in this paper provides a unique opportunity to quantify this circulation.

The objective of this paper is to highlight the importance of the dispersive seawater circulation for elemental mass balance of saline water bodies. In this study, we use the antithetic behavior of two radium isotopes during Dead Sea water circulation in the aquifer, where ²²⁶Ra ($t_{1/2} = 1600$ yr) decreases and ²²⁸Ra

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($t_{1/2} = 5.75$ yr) increases, in order to construct the radium mass balance of the Dead Sea and calculate the extent of the circulation.

1.1. Radium isotopes

There are four naturally occurring radium isotopes (^{226}Ra , ^{228}Ra , ^{223}Ra and ^{224}Ra), with half-lives ranging from several days to 1600 years. They are an integral part of the U and Th decay chains and due to their relatively high solubility they are enriched in groundwater (mainly saline) and commonly used as SGD tracers (e.g. Moore, 1996; Moore et al., 2008).

Radium sources in natural water include the decay of their radioactive parents (Th isotopes), dissolution and desorption from the solid surface, while their sinks include radioactive decay, coprecipitation with minerals and adsorption (Krishnaswami et al., 1982; Tricca et al., 2001; Kiro et al., 2012; Beck and Cochran, 2013). Their behavior in coastal aquifers has been shown to be sensitive to the fresh–saline transition zone dynamics and to aquifer heterogeneity, which is of great importance in the determination of the aquifer radium end member for SGD estimations (Michael et al., 2011; Gonnee et al., 2013b).

1.2. The Dead Sea system

The Dead Sea is highly enriched in radium isotopes (^{226}Ra , ^{228}Ra), which are 2–3 orders of magnitude higher than in the ocean (Stiller and Chung, 1984; Somayajulu and Rengarajan, 1987), compared with its salinity, which is only 10 times higher than the sea. The chemical composition of the Dead Sea is Ca-chloridic, which is the result of the evaporation of seawater, followed by halite precipitation and dolomitization of carbonates in the adjacent aquifer (Starinsky, 1974).

The Dead Sea water mass balance underwent significant changes during the past 50 yr due to anthropogenic intervention. This includes a drastic reduction in the Jordan River input (from ~ 1600 to ~ 100 million m^3/yr , Lensky et al., 2005) and an enhanced evaporation due to potash salt production, which caused a sharp lake level drop (reaching 1 m/yr) and an increase in the Dead Sea water salinity. The latter resulted in an overturn during the winter of 1979 and a change in the Dead Sea regime from meromictic (permanently stratified) to monomictic (Steinhorn, 1985). The total decrease of the lake volume from the 1970s is about 10–15% (Stiller and Chung, 1984; Lensky et al., 2005).

Studies of the meromictic Dead Sea from the late 1970s (Stiller and Chung, 1984; Chan and Chung, 1987; Somayajulu and Rengarajan, 1987; Chung and Craig, 2004) showed that the upper water mass contained higher activities of ^{226}Ra and ^{228}Ra than the lower water mass, which was attributed to the input from Ra-rich sources around the lake (Figs. 1, 2). The ^{226}Ra mass balance in the lake was used to determine the age of the Dead Sea meromictic structure (200–340 yr, Stiller and Chung, 1984; Chan and Chung, 1987; Chung and Craig, 2004). The possible interaction with the adjacent alluvial aquifer was not considered in this mass balance.

The alluvial aquifer adjacent to the Dead Sea is in direct hydraulic contact with the lake along most of its shoreline. It mainly consists of clastic fan delta deposits (gravel, sand and clay) intercalated with lacustrine sediments (e.g. clay, aragonite, gypsum and salt). Direct recharge by precipitation above the aquifer is negligible (precipitation < 100 mm/yr), and the main recharge is by lateral flow from the adjacent aquifers, including the Cretaceous carbonate aquifer on the Dead Sea western side and the

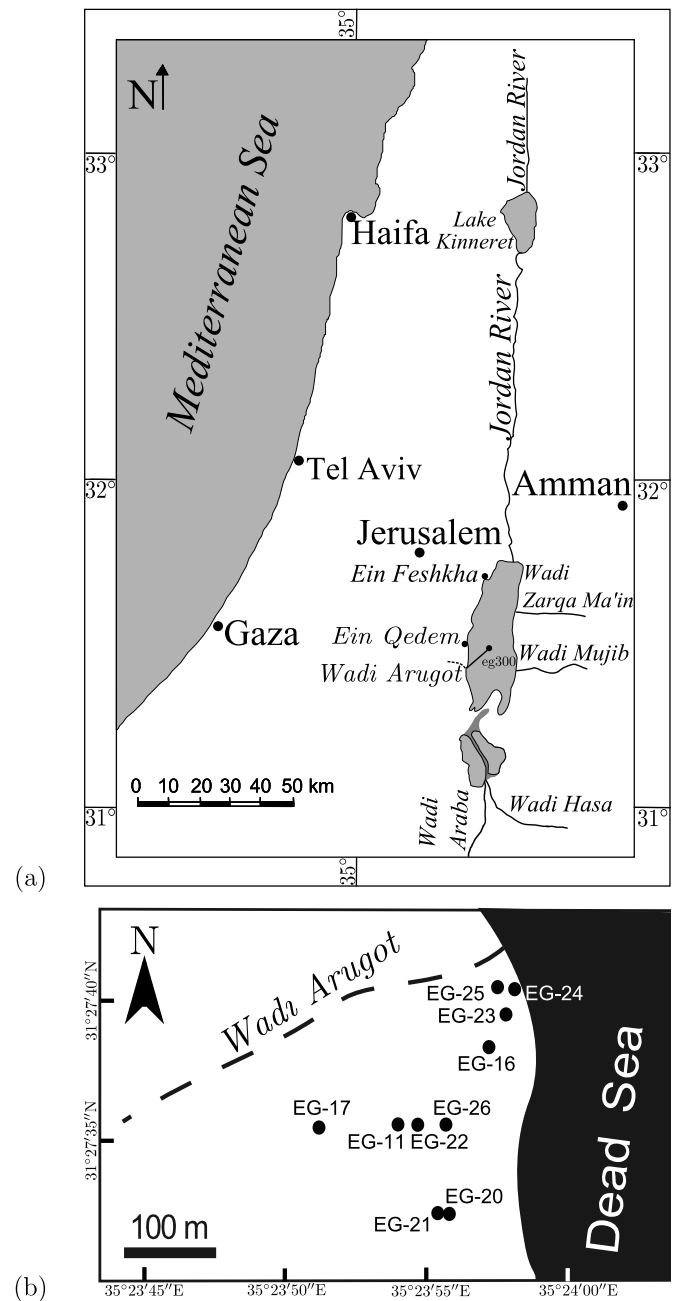


Fig. 1. (a) Location map of the Dead Sea and the main water sources of the lake, from which water was sampled. The sampling point of the profiles (eg300) and the sampling transect in the Dead Sea are marked. (b) Location map of the boreholes of Wadi Arugot, which is located on the western side of the Dead Sea.

carbonate and sandy aquifers on its eastern side (1–3 km from the lake), which are replenished in the highlands 10–30 km away.

The fresh–saline transition zone in the Dead Sea alluvial aquifer is very shallow due to the high density of the Dead Sea water. According to the Ghyben–Herzberg approximation, the depth of the transition zone in the Dead Sea coastal aquifer is 4.35 times the groundwater elevation, compared to 40 times in aquifers next to the ocean (Yecheili, 2000).

The hydraulic relationship between the Dead Sea and the alluvial aquifer is manifest in a relatively rapid water level response (several days) to lake level changes (Yecheili et al., 1995), with the response time varying according to the aquifer hydraulic param-

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