

## **Radium isotopes as a proxy for groundwater discharge and residence time in a fresh water lake: case study from the Sea of Galilee, Israel**

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During the past three decades radium isotopes have been extensively used to quantify the extent and the rate of groundwater discharge into coastal and estuarine environments, where fresh groundwater enters a more saline water body. One of the keys for the conservative behavior of radium in saline systems is the inverse dependence of its adsorption on salinity. In fresh groundwater radium is adsorbed, whereas in saline environment, the adsorbed radium is released to the aqueous phase. Here we examine an opposite scenario where saline groundwater discharges to a fresh water lake. We investigated the distribution of the radium isotope quartet in the Sea of Galilee (Cl~230 mg/l) and saline springs (Fuliya springs, Cl~2200 mg/l) that consist the major salt source for the lake.

Assuming that the saline spring of Fuliya represents the groundwater discharge to the lake, and that the measured radium activity in the lake is the residual of mixing, radioactive decay, and adsorption to bottom sediments and suspended particles, we conducted mass balance calculations for the different radium isotopes. Since the half-life of  $^{226}\text{Ra}$  (1600 y) is higher than the average water residence time (5.8 y), we neglect the decay factor for this isotope. We use the differences in the  $^{226}\text{Ra}/\text{Cl}$  ratios in the saline source ( $7.6 \times 10^{-3}$ ) and the lake water ( $1.8 \times 10^{-3}$ ) to calculate the relative depletion of  $^{226}\text{Ra}$  in the lake water. The  $^{226}\text{Ra}$  activity in the lake water ("Station A" in the center of the Sea of Galilee;  $^{226}\text{Ra}=0.44$  dmp/l) therefore represents only 24% of the groundwater  $^{226}\text{Ra}$  flux, whereas 76% is lost from solution by adsorption. The activities of the short-lived  $^{223}\text{Ra}$  (11.6 days) and  $^{224}\text{Ra}$  (3.6 days) in the lake ( $4 \times 10^{-4}$  and  $5.9 \times 10^{-3}$  dpm/l, respectively) represents only 2% and 4%, respectively, of the theoretical activities expected upon dilution. We show that the difference between the  $^{224}\text{Ra}/^{223}\text{Ra}$  ratios in the lake (15.64) and the saline source (4.71) is identical to the ratio of the decay constants of  $^{224}\text{Ra}$  and  $^{223}\text{Ra}$  (3.1). Since the adsorption coefficients of the short-lived radium isotopes depend on their decay constants,  $^{223}\text{Ra}$  with the longer half life would have selective

higher adsorption. Assuming an identical residence time in the lake for  $^{224}\text{Ra}$  and  $^{223}\text{Ra}$ , we use the ratio of the decay constants of  $^{224}\text{Ra}$  and  $^{223}\text{Ra}$  to calculate the relative proportions of radium that is lost by adsorption and by decay. Our mass-balance results show that only a small fraction of  $^{224}\text{Ra}$  and  $^{223}\text{Ra}$  is adsorbed (1% and 24%), and a significant fraction is removed by radioactive decay with a residence time of ~23 days. The lack of significant sinks for the radium short-lived isotopes implies that they can be used to quantify saline groundwater fluxes also in freshwater lakes.