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Tracing submarine groundwater discharge using radon (^{222}Rn) and radium isotopes (^{223}Ra and ^{224}Ra) in the tidal flat seawater of the Yellow Sea

HANBYUL LEE, SOJIN PARK AND GUEBUEM KIM
Seoul National University

We measured the activities of ^{222}Rn (half-life: 3.8 days), ^{223}Ra (half-life: 11.3 days), and ^{224}Ra (half-life: 3.6 days) to evaluate submarine groundwater discharge (SGD) in tidal flat areas of the Yellow Sea. The ^{222}Rn activities were measured using a real-time monitoring system together with NO_3^- and humic-like fluorescent dissolved organic matter ($FDOM_H$) sensors. ^{223}Ra and ^{224}Ra activities were measured using a radium delayed coincidence counter (RaDeCC). Both ^{223}Ra and ^{224}Ra activities were approximately 1.5 times higher in August relative to June, whereas excess ^{222}Rn activities and NO_3^- concentrations were approximately 10 times higher in June. Based on the ^{224}Ra mass balance model, SGD was estimated to be 0.28±0.31 m yr^{-1} in June and 0.55±0.30 m yr^{-1} in August, respectively. The elevated excess ^{222}Rn activities and NO_3^- concentrations in June were attributed to the occurrence of the maximum groundwater discharge within two days due to high tidal fluctuations during the observation period. However, in August, the occurrence of the maximum groundwater discharge a week before the observation period seems to result in an effective evasion of ^{222}Rn and a full consumption of NO_3. In addition, the ratios of NO_3^- to $FDOM_H$ concentrations in August (0.7±0.1) were lower than those in June (1.7±0.6), due to the prolonged biological consumption of NO_3^- relative to the more conservative $FDOM_H$. Our results suggest that radium isotopes together with ^{222}Rn enable the evaluation of the inflow history and the fluxes of SGD in the tidal flat of the Yellow Sea.