Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.34418

Inputs of trace metals through submarine groundwater discharge in the tidal flat system of the Yellow Sea

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Tidal flats are traditionally regarded as ultimate sinks for trace metals because of efficient particle scavenging and high sedimentation rates. Recent studies, however, suggest that benthic processes in tidal flats, including submarine groundwater discharge (SGD) and sediment diffusion, may transform tidal flats into effective sources of dissolved trace metals. To clarify this role, we investigated the distributions and fluxes of dissolved trace metals (Fe and Mn) across the tidal flat–continental shelf system of the Yellow Sea (YS), a macrotidal marginal sea characterized by one of the world's largest tidal flat regions and tidal ranges up to 9 m. Seawater samples were collected from coastal and offshore stations in June and August, 2024-2025. Activities of excess ^{222}Rn and dissolved ^{234}Th were measured to estimate SGD flux and particle scavenging rates, respectively. In both observation periods, the average trace metal concentrations in the coastal areas were higher compared to the offshore areas, particularly in June. Also, the trace metal concentrations generally increased with depth by up to two orders of magnitude, despite the rapid scavenging rates (~0.74 d^{-1}), suggesting substantial benthic sources. Using the observed data from June, we estimated the SGD-derived trace metal fluxes with a simple mass balance model that included input fluxes from rivers, atmosphere, and sediment diffusion and output fluxes through tidal mixing and scavenging. Our results indicate a large deficit in the coastal trace metal budget. We infer that this missing flux can be explained by SGD-derived inputs, given that significant SGD (~3.3 cm d^{-1}) occurred during the study period. The estimated SGD-derived trace metal inputs are comparable to fluxes independently calculated from porewater trace metal concentrations multiplied by the SGD flux. These results highlight that, despite rapid scavenging, the YS tidal flats function as a critical source of dissolved trace metals, with intense tidal forcing enhancing SGD-driven metal export to the marginal sea.