

Isotopes of the Water Molecule as Quasi-Conservative Tracers in Managed Aquifer Recharge

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The management of freshwater resources is a cornerstone policy to adapt to growing demands and shifting environmental conditions. In turn, groundwater research has endeavoured to constrain subsurface flow dynamics, groundwater recharge, and contaminant transport. The efficacy of environmental isotope tracers to enable such research is tested within a managed aquifer recharge (MAR) system to characterise groundwater transfer functions between infiltration and abstraction waters. Using stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and tritium (^3H), which varies due to nuclear power plant (NPP) release waters, we track the movement of MAR through an unconsolidated aquifer from the infiltration site to a downgradient production borehole. High-resolution sampling (daily/weekly) with correlation-based peak-matching and non-parametric deconvolution techniques are integrated to reconstruct groundwater transit times and assess mixing proportions. Monte Carlo simulations further evaluate uncertainty in tracer-derived travel times by generating ensembles of plausible transfer functions that capture flow variability. These refined but efficient and cost-effective tracer methodologies allow breakthrough curves to be delineated and enhance the predictive capabilities of hydrogeological models for MAR performance. Significant correlations in input/output functions were found between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (7.1 days) and between d-excess and ^3H (21 days), highlighting the efficacy of ^3H as a quasi-conservative tracer in systems that contain NPP release waters. The insights gained contribute to a quantitative understanding of aquifer renewal rates and response windows, informing sustainable groundwater management under both natural and anthropogenic stressors. Ultimately, this work underscores the potential of isotope hydrogeology to guide water resource strategies and support resilient management practices in an era of increasing hydrological uncertainty.