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Predicting Groundwater Residence Times in a Mountain System with Environmental Tracers and Bayesian Uncertainty Quantification

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Groundwater residence time distributions provide fundamental insights on watershed hydrological processes. However, our understanding of groundwater residence times is limited in mountain catchments that are challenging to instrument, span broad residence time distributions, and have highly variable recharge temperatures and elevations. Here, we use environmental tracers (CFC-12, SF_6, ^3H, and ^4He) to investigate groundwater residence times and mixing processes along a mountainous hillslope in the East River Watershed, Colorado, USA. We develop a Bayesian uncertainty quantification framework that applies a Markov-chain Monte Carlo (MCMC) approach to estimate groundwater mean residence time uncertainties assuming common lumped parameter models. Our novel groundwater residence time uncertainty analysis incorporates laboratory analytical errors; recharge elevation, temperature, and excess-air uncertainties calculated from dissolved noble gases; and *a-priori* uncertainties in mixing fractions between young soil water and old bedrock groundwater. We find that binary-mixing residence time distributions that consider separate young and old mixing fractions are needed to jointly predict the CFC-12, SF_6, ^3H, and ^4He observations, supporting the importance of flow-path mixing in this system. Our mean residence time estimates have considerably more uncertainty compared to typical lumped parameter model applications that solely propagate laboratory analytical errors. Our findings that the fractured bedrock hosts groundwater with a mixture of residence times ranging from decades to millenia suggests variable recharge dynamics and flowpath mixing along the hillslope. The enlarged mean residence time uncertainties highlight potential challenges, limitations, and future data needs when interpreting environmental tracers in complex mountainous systems. This work demonstrates the importance of characterizing groundwater systems with observations that are sensitive to transport over a broad range of residence times and performing robust uncertainty quantification.