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Constraining Bedrock Groundwater Recharge Parameters and Residence Time Distributions in Mountain Systems with Environmental Tracers and Bayesian Uncertainty Quantification

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Bedrock groundwater recharge conditions and residence time distributions (RTDs) are fundamental components of mountain watershed hydrological systems, yet they are challenging to directly quantify and remain uncertain. Here, we use measurements of dissolved noble gases (Ne, Ar, Kr, and Xe) and environmental age tracers (CFC-12, ^{3}H, ^{3}He, and ^{4}He) to investigate groundwater RTDs from fractured bedrock wells located along a mountainous hillslope within the East River Watershed near Crested Butte, CO. We develop a Bayesian Markov-chain Monte Carlo (MCMC) framework to quantify noble gas recharge temperatures, elevations, and excess air parameter uncertainties in mountain systems. MCMC is then used to estimate bedrock groundwater mean residence times assuming multiple parametric RTD models and the inferred noble gas recharge parameter uncertainties. We find that formally including prior information on the recharge conditions within the MCMC analysis facilitates joint estimation of plausible recharge temperatures and excess air posterior distributions for the site. The fractured bedrock groundwater samples contain ^{3}H and CFC-12, in addition to elevated terrigenic ^{4}He, suggesting a mixture of waters characterized by residence times that are modern (<70 years) and pre-modern (>70 years). We show that binary-mixing RTD models with distinct young and old fractions are needed to explain the full suite of environmental tracers, further supporting the importance of groundwater mixing processes in this shallow fractured bedrock system. This work demonstrates a framework to constrain bedrock groundwater residence time distributions using multiple environmental tracers that account for uncertainties in noble gas recharge conditions. Our findings highlight the importance of characterizing mountain aquifer systems with observation datasets that are sensitive to transport over a broad range of residence times.