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Integrating environmental tracer data with numerical modeling to constrain the ever-elusive depth of mountain groundwater circulation

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The depth of active groundwater circulation (below which flow is a negligible component of the watershed hydrologic budget) is a key feature of mountain bedrock aquifers, governing stream response to climate variability and the amount of subsurface flow to lower-elevation basins. However, characterizing permeability-depth relationships that control active circulation depth remains a fundamental challenge in mountain hydrology, and examples of robust constraints are rare. Circulation depths assigned in numerical models of mountain groundwater flow are thus typically highly uncertain, limiting the reliability of model results. In this study we utilize three 75-100 m deep boreholes to constrain groundwater flow rates at different depths in a mountain hillslope underlain by fractured metamorphic rock. The approach uniquely combines surface and borehole geophysics, discrete-interval aquifer tests, discrete-depth hydrologic monitoring, and 3H/3He groundwater ages from nested wells, all synthesized through numerical modeling of coupled heat and fluid transport. Flow rates are primarily constrained by interpreted maximum 3H/3He ages combined with fracture porosity estimates from borehole nuclear magnetic resonance logs. Preliminary results suggest that active groundwater circulation occurs to a depth of at least 60 m. The active zone can be coarsely divided into a shallow 23-m deep weathered layer with higher permeability overlying a deeper, less permeable unweathered layer. The deeper layer accommodates ~60% of the drainable bedrock storage and ~25% of the bedrock groundwater flow, meaning its exclusion from a watershed hydrologic model could lead to significant inaccuracies in model predictions (such models commonly extend to depths of only 10-20 m). The modeling also suggests important lateral bedrock permeability variations linked to slope position that may be typical for mountain crystalline-rock aquifers. This study demonstrates a valuable application of groundwater age data in numerical modeling and underscores the importance of discrete-depth data collection for maximizing the scientific value of individual mountain boreholes.