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Modelling groundwater flow paths and transit time distributions in hard rock aquifers' critical zone based on porosity fields derived from resistivity tomography and magnetic resonance surveys

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Groundwater flow paths and transit time distributions in aquifers are controlled by spatial variations of hydrogeological properties, including storage properties. Their characterisation in the saturated, weathered/fractured critical zone of hard rock aquifers is challenging due to its high degree of spatial variability. Geophysical techniques including Electrical Resistivity Tomography (ERT) and Magnetic Resonance Soundings (MRS) were applied in conjunction to traditional borehole hydraulic, structural, and mineralogical investigations on a km-scale hillslope transect in a metamorphic rock aquifer in Ireland. Both ERT and MRS consistently revealed a high degree of structural heterogeneity along the hillslope characterized by several deep weathering zones, which allowed reconciling borehole hydraulic data and fracture mapping with weathering/fracturing spatial patterns. MRS also provided spatial variations of groundwater storage in the uppermost (<30 m) highly weathered bedrock, in the order of a few percents. In lower porosity bedrock units (fissured and unweathered zones), the lack of sensitivity of the MRS was complemented by deriving porosity from ERT through application of the Waxman and Smits petrophysical model constrained by clay mineralogical data. ERT predicted values further decreased with depth and towards the hilltop by up to three more orders of magnitude. A numerical groundwater model was subsequently implemented incorporating all previous information and compared to an alternative model that do not use the information provided by geophysics (i.e. the spatial heterogeneity of aquifer properties). The fully parameterized model (1) better honors the groundwater heads observed in boreholes and observed seepage zones on the hillslope, which match the deep weathering zones; (2) produces significantly longer and deeper flow paths influenced by spatial variations of weathering and fracturing; (3) overall produces larger transit time ranges and age mixing consistent with independent tritium data. The study demonstrates that conceptual and quantitative information provided by ERT and MRS allows spatial resolution of hard rock aquifer properties for which borehole and surface data are (in most cases) not sufficient to capture the critical zone's heterogeneity. Such information allows increased quantitative understanding and robust modelling of groundwater flow pathways and transit times in these structurally complex aquifers, which are both crucial to sustainable catchment-scale management of water resources.