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Coupled effect of flow variability and mass transfer on contaminant transport and attenuation in groundwater

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The driving mechanism of contaminant transport in aquifers is groundwater flow, which is controlled by boundary conditions and heterogeneity of hydraulic properties. In this work we show how hydrodynamics and mass transfer can be combined in a general analytical manner to derive a physically-based (or process-based) residence time distribution for a given integral scale of the hydraulic conductivity; the result can be applied for a broad class of linear mass transfer processes. The derived tracer residence time distribution is a transfer function with parameters to be inferred from combined field and laboratory measurements. It is scalable relative to the correlation length and applicable for an arbitrary statistical distribution of the hydraulic conductivity. Based on the derived residence time distribution, the coefficient of variation and skewness of contaminant residence time are illustrated assuming a log-normal hydraulic conductivity distribution and first-order mass transfer. We show that for a low Damkohler number the coefficient of variation is more strongly influenced by mass transfer than by heterogeneity, whereas skewness is more strongly influenced by heterogeneity. The derived physically-based residence time distribution for solute transport in heterogeneous aquifers is particularly useful for studying natural attenuation of contaminants. We illustrate the relative impacts of high heterogeneity and a generalised (non-Fickian) multi-rate mass transfer on natural attenuation defined as contaminant mass loss from injection to a downstream compliance boundary.