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Modeling unsteady lumped transport with time-varying transit time distributions

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Transit time distributions (TTD) offer a powerful tool for characterizing 'lumped' hydrologic transport (i.e. with few parameters, and without resolving the internal dynamics), but their general application for transport modeling has been hampered by the challenge of dealing with time-variable TTD. A way forward has emerged with the development of the 'age function' approach, but it has not been clear how to parameterize the age function, or how to interpret it physically and compare it to perceptual models. It also requires specification of the total storage, which is not possible in many cases of interest.

This paper presents a more general formulation for TTD modeling that addresses these limitations. Transport is parameterized in terms of a probability density function Ω that represents the relative contribution of age-ranked water in storage to the flux out. Other frameworks are shown to be a special case of this one if the total storage is known. A new equation is obtained describing the time-evolution of the TTD that does not require specification of the total storage. In fact, the storage can be indefinitely large, allowing pdfs with semi-infinite support to parameterize Ω. Classical equations for random-sampling ('completely mixed') and piston-flow type transport fall out as special cases of Ω at steady-state. Other choices for Ω yield TTD capable of replicating observed transport phenomena like heavy tails and fractal $1/f$-noise. Application of the model to long term and high frequency passive tracer datasets demonstrates its promise as a framework for new models of transport in time-variable landscape hydrologic systems with a unique ability to capture these important features.