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A bottom-up approach: using residence time distributions and characteristic biogeochemical timescales to upscale multiphysics models of hyporheic exchange

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Residence time distributions (RTDs) and characteristic biogeochemical time scales (CBTSs) are integrated metrics that can be used to describe the biogeochemical evolution of water within hydrologic systems. RTDs describe the time that water and solutes are in contact with the system and strongly depend on the forcing and geomorphic features driving exchange and the system's hydraulic properties. On the other hand, CBTSs describe the time necessary for a biogeochemical transformation to take place and depend on the reaction type, solute concentrations entering the system, and chemical kinetics (or thermodynamics). Comparing RTDs and CBTSs allow us to evaluate the potential for transformation within the hydrologic system. In this work, we illustrate this approach with sinuosity-driven hyporheic zones; however, these concepts can be applied to other hydrologic systems. A two-dimensional, transient, numerical flow and transport model is used to illustrate the effect that dynamics, caused by deterministically generated flood events, has on flow fields and RTDs, and therefore on the character of the hyporheic zone as a biogeochemical reactor. A simple analytical model is used to estimate the CBTSs associated to the degradation of dissolved organic carbon in these hydrologic systems, which are compared to numerically-modeled RTDs and used to estimate the biogeochemical zonation within the HZ and its net biogeochemical response. Additionally, we use a multispecies, reactive transport model to assess this approach, paying special attention to those portions of the system with intermittent hyporheic contributions. In particular, transient flow results in time-varying hot-spot for biogeochemical reactions and induces the emergence of new modes on the dynamic RTDs, which are observed within the system and at the outlet. This parsimonious approach can be used as a predictive tool to quantify the potential of meanders as biogeochemical reactors at the watershed scale with the aid of historic discharge data, remote sensing data, and GIS processing techniques.