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Time subordination: a way forward for the closure problem in hydrologic prediction?

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A key challenge for advancing hydrologic prediction is the formulation of theories that can be applied at the scale of landscape elements, such as hillslopes, while accounting for the spatial heterogeneity of hydrologic properties (such as the hydraulic conductivity) at smaller scales. These so called 'closure relations' must be meaningful at the scale at which they are applied, and must account for the flux across the boundaries of a landscape element without resolving the interaction of the flux with the spatial structure of element directly.

Hillslope-scale descriptions of one such flux, subsurface stormflow discharge, have been developed from the hydraulic theory of flow, but typically assume spatial homogeneity (or deterministic variations) in these properties. In straight steep hillslopes these models suggest that recharge impulse will move at a constant velocity from the point where it enters to the hillslope base, producing a piston-like flow response. Heterogeneity in the hydraulic conductivity creates variation in these velocities, leading to responses with exponential or heavy (power-law) tails. This suggests that the heterogeneity imposes a temporal memory on the motion of the impulses. In this work we propose the use of subordination as a basis for constructing hillslope-scale closure relations for this flux under appropriate conditions. This approach randomizes the time that the recharge impulses spend in motion as they move through the hillslope by convolving the piston response with a stable subordinator.

Through comparisons with synthetic data generated from numerical hillslope simulations with physically realistic parameters we show that the solutions to the subordination piston approach faithfully reproduce both early and late time characteristics of heavy-tailed flow responses from moderate to highly heterogeneous hillslopes. Moreover the parameters of the subordinator show quantitative links to the statistical properties of the heterogeneous random fields. These findings suggest that subordination is a promising approach for developing hillslope closure relations parameterized with physically measurable properties of a watershed.