Geophysical Research Abstracts
Vol. 12, EGU2010-1591, 2010
EGU General Assembly 2010

Inverse Modeling of Tracer Tests in Streams Undergoing Hyporheic Exchange

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Hyporheic exchange has been identified as a key process in solute transport, biogeochemical cycling, and ecosystem functioning of streams. Physical solute transport through the hyporheic zone may be characterized by the total flux of water exchange and the distribution of hyporheic travel times. The classical method of obtaining travel-time distributions is an artificial-tracer experiment, in which an easy to detect compound is injected into the river, and the breakthrough curve (BTC) is measured at an observation point further downstream in the river. This BTC is affected by in-stream transport and hyporheic exchange as expressed in the transient storage model for linear solute transport in rivers undergoing hyporheic exchange:

$$\frac{\partial c}{\partial t} + v\frac{\partial c}{\partial x} - D\frac{\partial^2 c}{\partial x^2} = q_{he}\left(\int_0^t p(\tau)c(t-\tau)\exp(-\lambda\tau)d\tau - c(t)\right) + q_{in}(c_{in} - c(t)) \qquad (1)$$

in which v and D are the velocity and dispersion coefficient, respectively, q_{he} is the hyporheic exchange flux, τ is the travel-time coordinate in the hyporheic zone, $p(\tau)$ is the probability density function of τ, λ is a first-order rate coefficient quantifying potential decay within the hyporheic zone, q_{in} expresses lateral inflow, and c_{in} is the corresponding concentration within that inflow.

The target quantities are the exchange flux q_{he} and the nonnegative travel time distribution $p(\tau)$ in the hyporheic zone. Common transient storage models use parametric distribution functions, such as the exponential, power-law, or log-normal distributions. By predefining the functional form of $p(\tau)$, however, important features such as multimodality may remain unnoticed.

We present a nonparametric approach of obtaining $p(\tau)$ jointly with the other transport parameters by fitting BTCs of conservative and reactive solutes. For regularization $p(\tau)$ is assumed autocorrelated, and nonnegativity is enforced by the method of Lagrange multipliers. The method extends a nonparametric deconvolution approach for the determination of transfer functions. It requires successive linearization (Gauss-Newton scheme), stabilized by a line-search, and forward simulation in the Laplace domain with numerical back-transformation.

Once the hyporheic travel-time distribution $p(\tau)$ has been identified, the transport model can be extended to include nonlinear reactions of river-borne compound within the hyporheic zone thus facilitating the simulation of biogeochemical cycling in streams undergoing hyporheic exchange.

This method has been tested by virtual conservative and reactive tracer experiments undergoing hyporheic exchange. Joint inversion of conservative and reactive tracer BTCs is essential for distinguishing the effects of in-stream dispersion from hyporheic exchange. Applications to field data are on the way.