Geophysical Research Abstracts
Vol. 20, EGU2018-15466, 2018
EGU General Assembly 2018

Anomalous dispersion in natural channels: Effect of the vertical variation of the mixing coefficient in the porous bed

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Experimental evidence from field tracer studies have shown that the transport of solutes in streams and rivers is typically non-Fickian. In a recent work, Gónzalez-Pinzón et al. (2013) conducted a meta-analysis of experimental data from several stream tracer tests and found that the variance of the solute breakthrough curves (BTCs) increases superlinearly with the distance from the injection point, whereas the skewness is approximately constant with it. This behavior is inconsistent with classic 1-D solute transport models assuming Fickian dispersion in the main channel and transient storage in surface and subsurface dead zones. Even though some of these models are capable to reproduce the shape and the characteristic long-tail behavior of the breakthrough curves, the inconsistent scaling of the moments implies that the best-fit parameters depend on the distance from the injection point. The mechanisms that determine the non-Fickian scaling of the moments of the BTCs in natural channels are here investigated using 2-D and 3-D particle tracking simulations. Consistently with recent experimental and numerical studies on the vertical variation of the mixing coefficient in a porous bed below a turbulent flow, the transport of a solute in an open-channel flow over a semi-infinite flat porous bed is simulated assuming that the mixing coefficient in the porous medium decreases exponentially with depth. Results show that the longitudinal dispersion process in the surface water is superdiffusive over a broad range of temporal scales, and the skewness of the concentration distributions does not necessarily decrease with time and distance from injection even at large times. Sensitivity analysis and simplified mathematical modeling also show that, at large times, longitudinal dispersion is controlled by the cross-sectional profile of the in-bed transverse mixing coefficient, and by the difference between the average velocity in the channel and in the porous bed. The resulting concentration distributions can be approximated by a beta distribution with time-dependent parameters.

Although irregularities of the channel bed, such as bedforms, can induce advective flows in the sediment which in turn enhance mixing, the results show that anomalous dispersion in natural channels is primarily determined by diffusive processes in the hyporheic layer. Thus, the anomalous scaling of the BTC moments should not only be expected in channels with irregular bed topography or meanders, but also in straight channels with completely flat beds, provided that the bed is sufficiently deep. Results also show that the moments of the BTCs can exhibit complex patterns as a function of the vertical variation of the transverse mixing coefficient in the porous bed. An alternative 1-D formulation is proposed that better captures the physics of the transport process and an application is presented to stream tracer data.