Journal of Hydrology 517 (2014) 362–377

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Spatially distributed characterization of hyporheic solute transport during baseflow recession in a headwater mountain stream using electrical geophysical imaging

Adam S. Ward[a,b,*], Michael N. Gooseff[c], Michael Fitzgerald[d], Thomas J. Voltz[e], Kamini Singha[f]

[a] School of Public and Environmental Affairs, Indiana University, Bloomington, IN 47405, USA
[b] Department of Earth & Environmental Sciences, The University of Iowa, Iowa City, IA 52242, USA
[c] Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523, USA
[d] National Ecological Observatory Network, Boulder, CO 80301, USA
[e] University of Applied Sciences, Faculty of Civil Engineering/Architecture, Division of Water Sciences, Friedrich-List-Platz 1, 01069 Dresden, Germany
[f] Hydrologic Science and Engineering, Colorado School of Mines, Golden, CO 80402, USA

A R T I C L E I N F O

Article history:
Received 3 June 2013
Received in revised form 29 April 2014
Accepted 5 May 2014
Available online 27 May 2014
This manuscript was handled by Peter K. Kitanidis , Editor-in-Chief, with the assistance of Anthony Lee Endres, Associate Editor

Keywords:
Hyporheic
Hydrogeophysics
Solute transport
Baseflow recession
Electrical resistivity imaging
Temporal moment

S U M M A R Y

The transport of solutes along hyporheic flowpaths is recognized as central to numerous biogeochemical cycles, yet our understanding of how this transport changes with baseflow recession, particularly in a spatially distributed manner, is limited. We conducted four steady-state solute tracer injections and collected electrical resistivity data to characterize hyporheic transport during seasonal baseflow recession in the H.J. Andrews Experimental Forest (Oregon, USA). We used temporal moment analysis of pixels generated from inversion of electrical resistivity data to compress time-lapse data into descriptive statistics (mean arrival time, temporal variance, and temporal skewness) for each pixel. A spatial visualization of these temporal moments in the subsurface at each of five 2-D transects perpendicular to the stream was interpreted to inform transport processes. As baseflow recession progressed we found increasing first arrival times, persistence, mean arrival time, temporal variance, and coefficient of variation, and decreasing skewness. These trends suggest that changes in hydrologic forcing alter the relative influence of transport phenomena (e.g., advection vs. other transport processes such as dispersion) along flowpaths. Spatial coverage obtained from electrical resistivity images allowed for qualitative comparison of spatial patterns in temporal moments both at an individual cross-section as well as between cross sections. We found that geomorphologic controls (e.g., bedrock confinement vs. gravel wedge deposits) resulted in different distributions and metrics of hyporheic transport. Results of this study provide further evidence that hyporheic transport is highly variable both in space and through the baseflow recession period. Geophysical images differentiate advection-dominated flowpaths from those that are more affected by other transport processes (e.g., dispersion, mobile-immobile exchange).

1. Introduction and background

Despite a broad recognition of the ecological relevance of transport along hyporheic flowpaths (e.g., Boulton et al., 2010; Brunke and Gonser, 1997; Krause et al., 2011), relatively little is known about the distribution of hyporheic transport processes in the subsurface, and how this distribution changes with hydrological dynamics throughout a typical season. Recent field and numerical studies have demonstrated that travel time along hyporheic flowpaths is a primary control on associated biogeochemical cycling (Boano et al., 2010; Zarnetske et al., 2011). Indeed, studies by Battin (1999, 2000) demonstrate that hydrodynamics are a first-order control on ecological processes. Transport processes in the subsurface include advection, longitudinal dispersion along hyporheic flowpaths, and dispersion away from individual flowpaths (e.g., into less-mobile domains such as bound pore water). An improved ability to quantify spatiotemporally variable flow and transport patterns in the subsurface is necessary to predict ecologically relevant solute fluxes. Understanding the spatial distributions of temporal trends in hyporheic transport is a necessary step toward a process-based understanding of biogeochemical cycling in the subsurface and at the stream-reach scale.

* Corresponding author at: School of Public and Environmental Affairs, Indiana University, 430 MSB-II, Bloomington, IN 47405, USA. Tel.: +1 812 855 0635.
E-mail address: adamward@indiana.edu (A.S. Ward).

http://dx.doi.org/10.1016/j.jhydrol.2014.05.036
0022-1694/

Because the boundary conditions controlling hyporheic exchange can be dynamic during baseflow recession (e.g., hydraulic gradients), we expect that transport processes in the subsurface will respond to dynamic forcing. At the reach scale, several studies have documented changes in transient storage (interpreted as evidence of hyporheic exchange changes) under different flow conditions. Numerical studies of pumping exchange found hyporheic flowpaths contract due to ambient gaining conditions (Boano et al., 2008; Cardenas and Wilson, 2007). Several field studies report contraction of hyporheic flowpaths during periods of increased groundwater discharge to streams (e.g., Harvey and Bencala, 1993; Storey et al., 2003; Williams, 1993; Wondzell and Swanson, 1996; Wroblicky et al., 1998), though findings of Ward et al. (2012a) challenge this conceptual model, demonstrating surprisingly little linkage between hydraulic gradients and hyporheic extent. Furthermore, Wondzell (2006) completed tracer studies in steep headwater catchments in the H.J. Andrews Experimental Forest under two different baseflow conditions (4.5 and 1 L s^{-1} in Watershed 1, 10 and 3 L s^{-1} in Watershed 3), finding that hyporheic extent, evaluated as tracer arrival in a monitoring well network, was not changed during baseflow recession. In a modeling study of one of the watersheds in their 2006 study, Wondzell et al. (2009) concluded that even complex physical models are insufficient to predict the movement of solute through the hyporheic zone. This shortcoming is attributed to the inability to identify unique model solutions and invalidate all other solutions, a problem which arises in part because spatially discrete measurements are used to infer up-gradient behavior along flowpaths. Indeed, hydrologic modeling efforts attempting to simulate a limited number of point measurements are plagued by problems of equifinality (e.g., Beven, 1993, 2006); an infinite number of realizations of the upstream system (e.g., the hydraulic conductivity field) can adequately produce the observed data. An ongoing debate about the usefulness of such models in predicting solute transport and fluxes at the scale of individual flowpaths continues in the literature (e.g., Bredehoeft and Konikow, 1993; Hassan, 2004; Konikow and Bredehoeft, 1992; Oreskes et al., 1994; Poeter, 2007; Wondzell et al., 2009).

Of particular interest is the characterization of process dynamics (i.e., characteristics that change through time and are inherently linked to the movement of fluids in the subsurface; Binley et al., 2010; Koch et al., 2009). Indeed, electrical resistivity (ER) imaging of solute tracers in hyporheic zones has been demonstrated in recent field trials (Cardenas and Markowski, 2011; Ward et al., 2010b, 2012a; Toran et al., 2012). For example, Ward et al. (2012a) used time-lapse ER images of saline tracer movement along hyporheic flowpaths as one tool to parameterize groundwater flow and transport models. Time-lapse ER has also been interpreted to inform subsurface structure and hyporheic extent from ER imaging during solute tracer studies (Ward et al., 2012a, 2013b). Such imaging provides high spatial and temporal resolution of solute transport in situ relative to piezometer sampling, and addresses some limitations of reach-scale studies that infer upstream behavior based on limited downstream observations in the surface stream.

The use of ER to characterize groundwater flow and transport processes is common (e.g., Singha and Gorelick, 2005, 2006; Koestel et al., 2009; Ward et al., 2013b) despite inherent uncertainty in inverted ER images (e.g., Slater et al., 2002; Day-Lewis et al., 2005, 2007). For example, inversion results are known to be smeared in space due to regularization and time due to data collection limitations (e.g., Singha and Gorelick, 2005; Doetsch et al., 2012). Promising areas of research that addresses these limitations include the inversion of the temporal moments of the electrical resistivity data rather than calculation of the temporal moments from a series of inversions (e.g., Pollock and Cirpka, 2008, 2010, 2012) and inversion schemes where hydrogeological constraints are included in the inverse problem (e.g., Jardani et al., 2013; Pidlisecky et al., 2011). Despite the limitations of ER, the utility of spatially extensive electrical resistivity imaging and the interpretation of resulting time series is still useful in characterization of heterogeneous transport processes in the shallow subsurface (Doetsch et al., 2012; Ward et al., 2010b, 2012a,b; Menichino et al., 2012; Toran et al., 2012).

Here, we capitalize on our imaging of processes through time to interpret solute transport behavior. Both qualitative and quantitative interpretations of individual pixel or finite-element behavior during saline tracer studies have proven useful. Individual pixels in a soil column experiment demonstrated characteristic trends of advection–dispersion behavior of tracer-labeled water moving through the column (Binley et al., 1996). In a 2-D laboratory experiment, Slater et al. (2000) interpreted pixel breakthrough curves to quantify first arrival times of tracer at individual pixels and recommended comparison of pore fluid with pixel values in ER images in future studies. In a 3-D laboratory study, Slater et al. (2002) demonstrated broad agreement between pore fluid conductivity and pixel resistivity. Their study demonstrates the value of a densely sampled, spatially continuous data set to observe greater complexity in transport processes than was possible with their flow and transport modeling alone. Kemna et al. (2002) compared ER image behavior with advection–dispersion modeling of groundwater flow and transport and were able to observe more complexity in flowpath behavior than was present in their numerical simulations of flow and transport. In a synthetic study, Ward et al. (2013b) used temporal moment analysis of pixels in inverted geophysical images as a calibration target for numerical models of hyporheic transport.

Here, we use time series analysis of several time series of 2-D electrical resistivity tomograms to characterize transport of solutes along hyporheic flowpaths in the subsurface. In a modeling study, Ward et al. (2010a) interpret the spatial distribution of temporal moments of solute time series and raw ER data (as opposed to reconstructed images) to infer transport processes in the subsurface. Results of their simulations identified areas where advection dominates other transport processes in the subsurface. They speculate that a similar analysis could be completed using time-lapse ER images collected during a field study. Temporal moment analysis has been used to describe the transport of solutes in the subsurface in several studies (e.g., Cirpka and Kitanidis, 2000; Day-Lewis and Singha, 2008; Singha et al., 2007) and has also been used to describe flow and transport in coupled stream-aquifer systems (e.g., Gupta and Cvetkovic, 2000; Schmid, 2003). Cirpka and Kitanidis (2000) interpret temporal moments of simulated tracer breakthrough curves at points in the subsurface to derive apparent subsurface solute velocity and dispersivity. In a numerical study of hyporheic exchange, Singha et al. (2008) calculate temporal moments based on reach-averaged concentrations within the stream and subsurface, and suggest moments calculated at a higher spatial resolution would be appropriate if variability is expected across a domain of interest.

The overarching objectives of this study are to (1) quantify the heterogeneity in subsurface transport, and (2) assess how solute transport processes in the hyporheic zone change during seasonal baseflow recession. We expect that changing boundary conditions during baseflow recession will change temporal trends in hyporheic solute transport in the subsurface (for example, later mean arrival times and increased temporal variance and skewness of solute tracer time series). To achieve this objective, we apply temporal moment analysis to ER images to provide spatially distributed solute transport information in the subsurface (i.e., to quantify where and when advection, dispersion and mobile-immobile exchange are occurring). This is an application of the spatially distributed analysis of numerical simulations by Ward et al. (2010a) to inverted images based on field data. We conducted