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Factors affecting hyporheic and surface transient storage in a western U.S. river

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SUMMARY

Hyporheic storage accounts for a significant fraction of solute residence time in small streams and has been shown to have a large effect on the transport of solutes. It is not clear whether this characteristic is preserved in larger streams and rivers, as increased discharge and decreased slope may reduce overall exchange between the channel and subsurface, and the size of surface storage zones may increase. Conservative tracer tests conducted in the Truckee River, a stream with mean annual discharge >0.5 $m^3\ s^{-1}$, were simulated with both one (1-SZ) and two-storage zone (2-SZ) transport models to quantify the relative role of surface transient storage (STS) and hyporheic transient storage (HTS) on the physical transport of solutes in a large stream. Tracer injections were conducted at two different discharge levels in two reaches with distinct geomorphic characteristics. STS was the dominant storage mechanism for all reaches and discharge levels and surface storage accounted for a larger fraction of median transport time (F^{200}_{MED}) than hyporheic storage in all but one case. Increased discharge significantly reduced the influence of the HTS (primarily) and STS zones on median transport time at the study site. Comparisons with studies of discharge and geomorphic effects on TS characteristics in other streams indicated differing physical controls on STS and HTS zones. Therefore, measurements such as slope, sinuosity, width, depth, and gross gains and losses of discharge need to be considered along with discharge. This work adds to the growing sentiment that up-scaling and prediction of stream storage characteristics based on discharge and channel properties is far from straightforward. Since biogeochemical processing occurs differently in the HTS and STS, two-zone storage models provide necessary representations of transport in river systems for studies focused on aspects of water quality. Extra parameters are required for model optimization but simple cross-section surveys (area and velocity) provide enough information to ensure enhanced parameter reliability.

1. Introduction

Water transports and mediates transformation in global biogeochemical cycles within and between the atmosphere, soil, freshwater, and oceans. Residence time represents the major factor influencing rates of transformation within these global storage zones (Heikkila et al., 2013; Laruelle et al., 2013; Misumi et al., 2013; Xia et al., 2013). Residence time of water and solutes in the various compartments traversed during the riverine hydrologic cycle drives spatial dispersion, local retention, and overall downstream transport (Botter et al., 2011; Haggerty et al., 2002; Perez et al., 2011). Specific to this work, stream channels are composed of different habitats, each with their own reaction rates, connectivity, and residence times. The relative contribution of these habitats to network scale residence time has only recently been explored (Briggs et al., 2010; Riml and Worman, 2011; Stewart et al., 2011). Stream channels can be partitioned into advective (main channel) and non-advective (transient storage) zones. In most cases, the majority of the river cross-sectional area, the highest velocities, and the greatest fraction of median transport time occur in the main channel (MC). Transient storage (TS) zones are flow paths with significantly reduced velocities, which influence solute retention because they extend residence times and increase exposure to biochemically reactive surfaces (Briggs et al., 2009; Dahm et al., 1998; Ensign and Doyle, 2005; Findlay, 1995).

Despite over a decade of research, the relative role of TS in solute residence and removal is still debated. Some studies suggest a strong correlation between TS and nitrogen removal (Faulkner and Campana, 2007; Hall et al., 2002; Thomas et al., 2003), whereas weaker correlations (Hall et al., 2002; Lautz and Siegel, 2007) and no correlations (Ensign and Doyle, 2005) between the two have also been reported. Conflicting results have been attributed

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to heterogeneity of TS hydraulics and biogeochemical processes across systems, within systems, and through time (Thomas et al., 2003). To clarify these dynamics, recent studies separate TS zones into surface (STS) and hyporheic (HTS) (Briggs et al., 2009, 2010; Marion et al., 2008; Stewart et al., 2011) because these two compartments can have significantly different hydraulic and biogeochemical conditions (Thomas et al., 2003).

STS zones include side pools or back eddies along the river channel (Gooseff et al., 2004), where water exchange from the channel is controlled by lateral dispersion (Fischer et al., 1979) and turbulent processes (Ghisalberti and Nepf, 2002). These are depositional zones that typically accumulate large stocks of organic matter (Hall et al., 2002). HTS zones are located beneath or adjacent to the water column where stream water is forced into sediments via head gradients as Darcian flow through porous media (Harvey and Bencala, 1993), interacts with microbial communities and groundwater, and then reenters the stream at some distance downstream. HTS zones facilitate water exposure to sediment biofilms and alternating oxic and anoxic environments (Stewart et al., 2011), which can have a large effect on the fate and transport of solutes (Gooseff et al., 2006; Gooseff et al., 2003). Solute exchange between STS and HTS zones are small compared with exchange between the main channel and TS zones.

Due to underlying differences in STS and HTS environments, biogeochemical processes in the two compartments are likely to differ and may be important to separate when modeling river dynamics (Argerich et al., 2011; Briggs et al., 2009, 2010; Hall et al., 2002; Stewart et al., 2011; Thomas et al., 2003). Connectivity and exchange between the MC and STS zones is generally greater than those between the MC and HTS zones (Briggs et al., 2010; Stewart et al., 2011) so that STS residence time has a greater effect on median transport time (Briggs et al., 2009, 2010). However, because water molecules spend more time in HTS zones than in STS zones, more solute retention can occur in HTS zones (Stewart et al., 2011). The greatest proportion of solute retention can occur in any of the three zones (Stewart et al., 2011) depending on the combination of hydraulic and reactivity parameters in each compartment.

Most TS studies in “large” streams with discharge >0.5 $m^3 s^{-1}$ (Faulkner et al., 2012; Fernald et al., 2006, 2001; Laenen and Bencala, 2001) including some conducted on the Truckee River (Knust and Warwick, 2009; Naranjo et al., 2012, 2013) focused on hyporheic exchange only. Only a few large stream system studies have been conducted outside of the Willamette River Basin, Oregon (Battin et al., 2008) and only a handful considered multiple TS zones (Anderson and Phanikumar, 2011; Hensley and Cohen, 2012). Few physical estimates of the relative size of the MC and TS zones (Briggs et al., 2010; Jackson et al., 2012) or changes in their relative size with varying discharge (Stewart et al., 2011; Ward et al., 2012) exist. Most estimates of MC and TS size are through model parameter fitting.

Transient storage exchange dynamics should be a function of stream size because many processes that drive exchange are strongly governed by channel morphology, which in turn may be specific to basin type (Battin et al., 2008; D'Angelo et al., 1993; Deng et al., 2010; Gooseff et al., 2007). Reach length has also been found to be an important factor when considering transient storage (Bottacin-Busolin et al., 2011; Gooseff et al., 2013). Most analyses have been performed using 1-SZ model, precluding distinction between STS and HTS, which may respond differently to increasing stream size. However, the 1-SZ model has been reported to sufficiently model overall TS processes in a previous study (Choi et al., 2000). STS has been found to be more influential to nutrient uptake than HTS in some systems (Ensign and Doyle, 2005), and be the primary storage mechanism in some small sand bed streams (Stofleth et al., 2008). It is possible that STS can facilitate photochemical reactions not possible during HTS that may be important to biogeochemical cycling (McKnight et al., 2002). As streams widen and canopy cover over the channel declines, high light availability can promote the growth of aquatic plants and microbes that cycle nutrients (Battin et al., 2008). Thus, STS may be particularly important to biogeochemical processes in larger streams where photo-mediated processes have more opportunity to influence stream water nutrient concentrations.

In this study we describe results of conservative tracer tests performed at different flow rates and geomorphic settings in the lower Truckee River, a stream whose water quality affects ecosystem health at low flows. Tracer tests and data analysis through modeling were designed to separately measure and quantify the influence of the HTS and STS zones. Our goals are to

1. determine the relative influence of the two TS zones on physical transport in a large stream system,
2. describe the dynamics of the TS zones under different flow rates and geomorphology within the study site, and
3. describe the dynamics of the TS zones under different flow rates and geomorphology between streams of different sizes.

Data analysis purposefully follows existing methods to facilitate comparison between the Truckee River and other tracer studies. This work comes at a time when a critical mass of tracer tests has led the community to question whether reach scale heterogeneity and equifinality of model parameter sets preclude generalization of TS characteristics based on geomorphic or hydraulic setting and whether up-scaling of TS characteristics to the network scale is possible from the reach scale (Gooseff et al., 2013; Ward et al., 2012, 2013). This study contributes to that debate by providing controlled tests specifically designed to model the relative influence of both the HTS and STS zones under different settings in a stream with larger discharge than has typically been reported in the literature.

2. Materials and methods

2.1. Two-zone storage transport modeling

A modified-USGS One-Dimensional Transport with Inflow and Storage (OTIS) model (Runkel, 1998) was used prior to collecting field data to direct logistics for both tracer studies described in Sections 2.4 and 2.6. The original code is publicly available and has been widely used in a variety of applications. This model employs the Crank-Nicolson finite difference method to solve the advection–dispersion-transient storage equations to describe 1-D transport in a channel with lateral inflow/outflow and exchange with a single storage zone, derived by Bencala and Walters (1983). In this study with conservative tracers, the traditional OTIS code was modified to allow for multiple storage zones (2-SZ):

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \frac{q_{LIN}}{A}(C_{LIN} - C) + \alpha_{HTS}(C_{HTS} - C) + \alpha_{STS}(C_{STS} - C) \quad (1)$$

$$\frac{\partial C_{HTS}}{\partial t} = -\alpha_{HTS}\frac{A}{A_{HTS}}(C_{HTS} - C) \quad (2)$$

$$\frac{\partial C_{STS}}{\partial t} = -\alpha_{STS}\frac{A}{A_{STS}}(C_{STS} - C) \quad (3)$$

where C is the MC solute concentration (mg L^{-1}), Q is the volumetric flow rate ($m^3 s^{-1}$), A is the MC cross-sectional area (m^2), D is the dispersion coefficient ($m^2 s^{-1}$), x is the distance downstream (m), t is time (s), q_{LIN} is the lateral inflow rate per unit length ($m^3 s^{-1}$ - m^{-1}), C_{LIN} is the solute concentration in the lateral inflow (mg L^{-1}), C_{HTS} is the solute concentration in the HTS zone (mg L^{-1}), C_{STS} is the