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# Influence of distributed flow losses and gains on the estimation of transient storage parameters from stream tracer experiments

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ABSTRACT

Interactions between mobile stream water and transient storage zones have been the subject of careful attention for decades. However, few studies have considered explicitly the influence of water exchange between the channel and neighbouring hydrological units when modelling transient storage processes, especially the lateral inflow coming from hillslope contributions and outflow to a deep aquifer or to hyporheic flow paths extending beyond the study reach. The objective of this study was to explore the influence of different conceptualizations of these hydrologic exchanges on the estimation of transient storage parameters. Slug injections of sodium chloride (NaCl) were carried out in eight contiguous reaches in the Cotton Creek Experimental Watershed (CCEW), located in south-east British Columbia. Resulting breakthrough curves were subsequently analysed using a Transient Storage Model (TSM) in an inverse modelling framework. We estimated solute transport parameters using three distinct, hypothetical spatial patterns of lateral inflow and outflow, all based on variations of the same five-parameter model structure. We compared optimized parameter values to those resulting from a distinct four-parameter model structure meant to represent the standard application of the TSM, in which only lateral inflow was implemented for net gaining reaches or only lateral outflow for net losing reaches. In the five-parameter model, solute mass was stored predominantly in the transient storage zone and slowly released back to the stream. Conversely, solute mass was predominantly removed from the stream via flow losses in the four-parameter model structure. This led to contrasting estimates of solute transport parameters and subsequent interpretation of solute transport dynamics. Differences in parameter estimates across variations of the five-parameter model structure were small yet statistically significant, except for the transient storage exchange rate coefficient $\alpha$, for which unique determination was problematic. We also based our analysis on $F_{med}^{200}$, the fraction of median transport time due to transient storage. Differences across configurations in $F_{med}^{200}$ estimates were consistent but small when compared to the variability of $F_{med}^{200}$ among reaches. Optimized parameter values were influenced dominantly by the model structure (four versus five parameters) and then by the conceptualization of spatial arrangement of lateral fluxes along the reach for a set model structure. When boundary conditions are poorly defined, the information contained in the stream tracer breakthrough curve is insufficient to identify a single, unambiguous model structure representing solute transport simulations. Investigating lateral fluxes prior to conducting a study on transient storage processes is necessary, as assuming a certain spatial organization of these fluxes might set ill-defined bases for inter-reach comparisons. Given the difficulty in quantifying the spatial patterns and magnitudes of lateral inputs and outputs, we recommend small-scale laboratory tracer experiments with well-defined and variable boundary conditions as a complement to field studies to provide new insights into stream solute dynamics.



## 1. Introduction

Transient storage plays a key role in the transport and fate of solutes in streams. It encompasses hyporheic exchange and in-stream storage in pools or other regions of slow-moving water. Solute transport dynamics have often been characterized using tracer experiments at the reach scale. This technique involves the estimation of parameters in a transient storage model (TSM) to provide an optimal fit between the simulated tracer breakthrough curve and an experimental tracer breakthrough curve resulting from a controlled injection of dissolved tracer. Fitted model parameters reflect reach-integrated solute transport dynamics and are typically

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interpreted in relation to the magnitude of transient storage and its variation among streams and with stream discharge (Worman, 1998; Wondzell, 2006; Lautz and Siegel, 2007). Exchange between the stream water and the different transient storage zones has been modelled with a first-order mass transfer (Bencala and Walters, 1983), a one-dimensional diffusive flux (Jackman et al., 1984; Worman, 2000) or various probability density functions for residence time distribution such as power law or gamma distributions (Haggerty et al., 2000). All models show similar results for shorter time scales, but power law or gamma residence time distributions perform better for longer time periods (Haggerty et al., 2000). In recent years, many studies have modelled transient storage effects via the One-dimensional Transport with Inflow and Storage model structure (OTIS) (Runkel, 1998).

Due to their spatially integrated nature, reach-scale tracer experiments do not provide information on the sub-reach scale variability of solute transport dynamics. For instance, it is difficult to separate the effects of the hyporheic zone from that of in-stream pools on solute retention. Recent studies have attempted to differentiate the magnitude and timing of exchange with in-stream pools versus the hyporheic zone using one or more of the following approaches: tracer experiments on bedrock reaches, where hyporheic exchange can be assumed to be negligible; tracer experiments at the scale of individual channel units; and by using hydrometric measurements to provide an independent estimate hyporheic exchange via Darcy's law (Gooseff et al., 2005, 2008; Hall et al., 2002; Scordo and Moore, 2009; Stofleth et al., 2008).

In addition to the processes of advection, dispersion and transient storage, TSMs have to account for lateral inflow and outflow, especially for simulating nutrient transport. Water flow and solute mobilization usually originate on hillslopes with downslope flow and solute transport by surface and/or subsurface flow paths. Water and solutes then enter the stream directly or via the hyporheic zone, ultimately to be transported in the advective part of the stream. We define lateral inflow as the discharge from the hillslope (or deeper groundwater) to the stream and lateral outflow as the flow from the stream to deep infiltration into the groundwater and substratum or the flow through hyporheic flow paths that extend beyond the (spatial or temporal) domain of study. Mechanisms driving water delivery from or to the stream are highly variable in time and space across a broad range of landscapes and land uses (Genereux et al., 1993; Huff et al., 1982; Kuraś et al., 2008; Shaman et al., 2004).

The extent to which lateral inflow and outflow affect TSM parameterization has been widely overlooked. OTIS is most suited to the present study because its structure accounts for both lateral inflow and lateral outflow. A standard parameterization of lateral fluxes in OTIS first involves the computation of the reach water balance from the difference in measured discharge between the downstream and upstream boundaries of the experimental reach. Either lateral inflow or later outflow is then applied to the reach depending on whether it is net gaining or losing water, respectively. However, it is possible for a stream reach to alternate between gaining and losing segments over distances of tens to hundreds of meters (e.g., Story et al., 2003; Ruehl et al., 2006). In this situation, the standard approach would not provide an accurate representation of the solute mass balance, potentially distorting the parameters representing downstream transport and transient storage.

In the present study, we assess the sensitivity of a TSM parameterization to the specified spatial pattern of lateral fluxes from and to the stream using tracer experiments at the reach scale. Solute transport dynamics were simulated under three contrasting spatial configurations of lateral fluxes:

– The reach is concurrently gaining and losing water over its whole length.
– The upstream half of the reach is gaining water while its downstream half is losing water.
– The upstream half of the reach is losing water while its downstream half is gaining water.

Simulation results were compared to those from the standard application of the TSM. From the comparison of transient storage model simulations specific to each spatial configuration of lateral fluxes, we address the following questions: (1) Do fitted transient storage model parameters depend on the specification of the spatial configuration of lateral fluxes? (2) How large is the uncertainty caused by lack of knowledge of the spatial organization of lateral fluxes relative to the variability in fitted model parameters among reaches?

## 2. Study site description

Investigations were carried out in the 17.4 $km^2$ Cotton Creek Experimental Watershed (CCEW) located in the Kootenay Mountains in south-eastern British Columbia, Canada (Fig. 1). This study is part of a larger research project investigating snowmelt, runoff and sediment transport processes and their response to forest disturbances including logging practices and the ongoing mountain pine beetle epidemic. Mean annual precipitation in the area is 650 mm, with snow accumulation and melt being the dominant hydrological processes (Jost et al., 2007, 2009).

Stage is recorded at several locations within CCEW. Streamflow is measured using slug injections of salt following Moore (2005), and rating curves were developed to convert stage records to streamflow. The streamflow regime is characterized by a snowmelt-induced freshet with peak flows typically occurring in May, followed by a prolonged recession limb ending between September and October. Responses to rainfall events are superimposed on the main recession limb, with time scales typically ranging between a day and a week. The months of September and October are normally dominated by a baseflow period with no major rain events and fairly constant streamflow.

The stream network of a 5.7 $km^2$ sub-watershed was selected to carry out the present study. It encompasses two first-order streams draining two headwaters which merge into a second-order stream. Water level has been continuously recorded on a 15 min time step at four stream gauges since May 2005, three located upstream or downstream of the confluence and a fourth one at the outlet of the main sub-watershed (Fig. 2).

The stream channel features a step-pool–riffle morphology in the two headwaters and pool–riffle morphology in the lower main channel. Despite intensive logging activity in the whole CCEW, most of the riparian vegetation has been preserved in its original state. It is mainly composed of Engelmann spruce (*Picea engelmannii*) and balsam fir (*Abies lasiocarpa*) at higher elevations where the foothills are steep and the riparian zone poorly developed, and western red cedar (*Thuja plicata*) in the wetter and flatter lower part of the sub-basin. Deciduous trees such as alder (*Alnus tenuifolia*), trembling aspen (*Populus tremuloide*) and willow (*Salix sp.)* are typically the dominant understory riparian vegetation, especially in disturbed areas (old logging roadbeds and skid trails). In-stream wood pieces exert a strong influence on the stream morphology.

## 3. Methods

### 3.1. Solute transport modelling

We applied OTIS, a one-dimensional finite-difference solute transport model that solves for solute concentrations in the stream and transient storage zone (Runkel, 1998). OTIS accounts for