

ESTIMATION OF TRANSIENT STORAGE PARAMETERS FROM A STREAM TRACER STUDY

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ABSTRACT: A stream tracer study was conducted in a 320-m reach of Indian Creek in Philadelphia. The objective was to investigate the role of geomorphology in the transport and exchange of a conservative tracer. The study reach has three geomorphically distinct sub-reaches. The experiments were simulated using the transient storage model, whose parameters were estimated by nonlinear optimization. Sub-reach averaged parameters were generally different highlighting the role of geomorphology; parameters estimated from sub-reach 1 provided relatively poor predictions for sub-reaches 2 and 3. Three forms of objective functions were used. The ordinary least square resulted in good fit around the peaks of the breakthrough curves and a relatively poor fit for the tail. The converse occurred when a weighted least square objective function was used.

KEY TERMS: stream tracer study; geomorphology; transient storage

INTRODUCTION

The transport of solutes in streams is affected by mechanisms such as transient storage and dispersion. Transient storage can occur when solute moves laterally into the banks of the stream, flows into the sediment bed or enters areas of the stream surface water that have slow moving or eddying pockets of water (Mullholland *et al* 1997; Fernald *et al*, 2001). The streambed and banks are commonly combined to form a region of the stream known as the hyporheic zone. The physical mechanism influencing the interaction between surface water and surface/subsurface storage zones is geomorphology (Harvey and Bencala 1993; Runkel, 1998). Changes in stream gradient, channel width, sediment composition, streambed topography, and stream curvature are examples of stream geomorphologic characteristics that influence the exchange.

Transient storage of stream water is studied due to the potential of stream water chemistry being altered from the biogeochemical reactions that occur within the active stream channel and hyporheic zone (Mcknight *et al*, 2002). These reactions occur due to the difference in biochemical properties between the sediments that are rich in microorganisms and the surface water that tends to be rich in dissolved oxygen (DO) and other dissolved nutrients, such as nitrate (Arboretum, 1995). Numerous studies have observed biological activity in the hyporheic zone where oxygen is supplied from the stream. For instance, Dahm *et al* (1987) reported that the average dissolved organic carbon (DOC) concentration increased from 12.5 mg/L in the well-oxygenated zones beneath the channel to 37.7 mg/l in the anaerobic zone at larger depths. Grimm and Fisher (1984) reported high metabolic rates of nitrate disappearance in the hyporheic zone. Mcknight *et al* (2002) examined the modification of DOC's concentration and composition when stream water interacted with chemically reactive streambed sediments.

This research proposed to determine role of stream geomorphology in the transport of conservative solutes in streams. This was evaluated by determining transient storage parameters generated from multiple breakthrough curves. Breakthrough Curves were developed from a tracer injection experiment in Indian Creek. The role of geomorphology was determined by (1) estimating parameters from a reach and using them to quality exchange at different scales (namely larger scales) and (2) relating the estimated parameters to geomorphology.

STUDY AREA

Indian Creek is located outside of the lower Piedmont section of the Wissahickon Watershed in Philadelphia, Pennsylvania. The studied reach consists of three geomorphically distinct sub-reaches (Figure 1). The first sub-reach (0-

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85 m) consists of three pool and three riffle sections with moderately sized stream widths, gradual stream slopes, and virtually free of large cobbles and large woody debris within the main channel. The second sub-reach (85-185 m) is more variable than the first section, which has a combination of large and small stream widths and much more large woody debris and large sized cobbles than the first section. The third sub-reach (185-323 m) is much different than the first. Large boulders, sharp stream bends, multiple step-pools, a channel split, steep gradients, and variable stream widths characterize the stream channel and banks. The second sub-reach may be viewed as a geomorphic transition zone between the first and third region. Stream gradients averaged 1.8% for the first sub-reach, 3.0 % for the second sub-reach, and 5.1% for the third sub-reach. Approximation of the stream flow rate was done by measuring cross-sectional area and stream water velocity. A *Global Flow Probe* velocity meter was used to measure stream water velocity. Results indicate that the stream flow rate is about $0.1 \text{ m}^3/\text{s}$. The bedrock underlying the region is Wissahickon Shist (National Institute for Environmental Renewal, 2000). Stream and gravel bar sediments are primarily composed of small pebbles (1 mm) to large boulders (0.5 m). The bank sediment is composed of silty clay. Average hydraulic conductivity's for the sediment bed and stream banks are 0.10 cm/s and $6.6 \times 10^{-5} \text{ cm/s}$. Physical measurements of the stream cross-sectional area were made in the first sub-reach. This was done so that the physicality of estimated parameters could be evaluated. The cross-sectional area (m^2) was measured for the following reach lengths: 0-21m; 0.43, 21- 51m; 1.29, 51-58m; 0.50; 58-69m; 0.46, and 69-85m; 0.38.

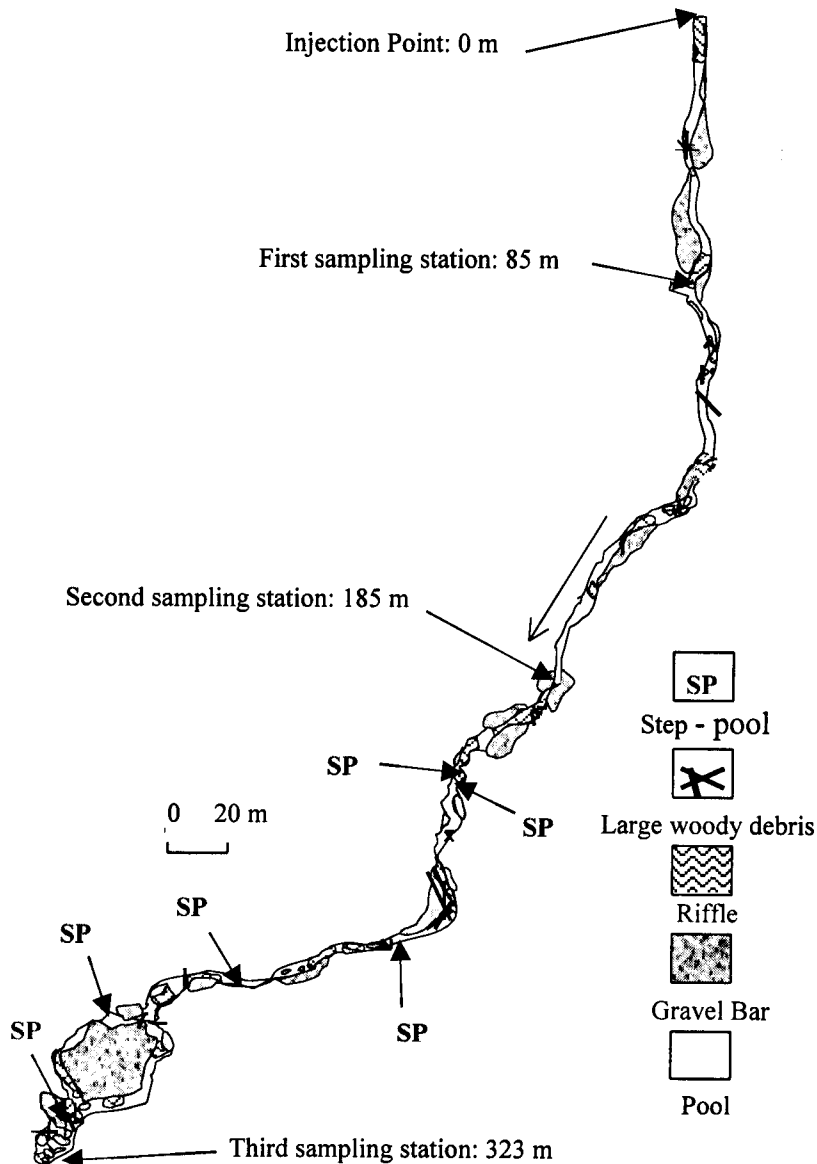


Figure 1. The studied stream reach at Indian Creek

METHODS

The exchange between streamwater and subsurface water is currently quantified using stream tracer studies (Bencala, 1983; Fernald *et al*, 2000). A stream tracer study consists of injecting a tracer into the streamwater at a selected location and monitoring streamwater concentration downstream. A breakthrough curve is obtained and used to determine exchange mechanisms affecting the transport of the tracer. The stream tracer experiment conducted at Indian Creek involved a “short” injection duration, which means that the tracer would not propagate far in the hyporheic zone. As a result, the main storage zones considered were the near surface hyporheic zone or sediment bed and the surface water “dead zones” (Runkel, 1998). The sizes of dead zones are as much of a function of geomorphology as the hyporheic zone, therefore, their dimensions are variable throughout a stream. Changes in stream flow- rate, stream curvature, cobble size, and large woody debris within the channel are major factors controlling these storage areas. Surface water storage zones can result from (1) turbulent eddies generated by large-scale bottom irregularities, (2) large but slowly moving zones along the sides of pools, and (3) well -mixed re-circulating zones located behind flow obstructions, such as cobbles, small boulders, and vegetation (Bencala and Walters, 1983). A decrease in stream flow rate coupled with an increase in cross-sectional area could create large storage areas. The inverse would be true for a larger flow rate with smaller cross-sectional areas.

The following methodology was pursued to obtain multiple breakthrough curves and estimate the stream transient storage parameters; (1) Conducted a stream tracer experiment and measured the streamwater concentration at downstream locations for various times (2) Stream exchange parameters were estimated using O-STREAM (Optimization Stream). This simulation code estimated the parameters using an objective function and equations (1) and (2). The transport parameters were linked to geomorphology by estimating spatially distributed values and using them to quality exchange at larger scales.

This tracer study focused on using a conservative tracer. It was assumed that transport of the tracer (solute) may be simulated using the one-dimensional advection- dispersion equation within the channel with additional terms that account for solute exchange with surface and subsurface storage zones. The governing equations that were used are:

$$\frac{\partial C}{\partial t} = -\frac{Q}{A} \frac{\partial C}{\partial x} + \frac{1}{A} \frac{\partial}{\partial x} \left(AD \frac{\partial C}{\partial x} \right) + \frac{q_{LIN}}{A} (C_L - C) + \alpha (C_s - C) \quad (1)$$

$$\frac{dC_s}{dt} = \alpha \frac{A}{A_s} (C - C_s) \quad (2)$$

where t and x are time and direction along the stream, respectively; C , C_s , and C_L are the concentrations of the stream, storage zones, and regional groundwater [M/L^3], respectively; Q is the in-stream volumetric rate [L^3/T]; D is the longitudinal dispersion coefficient in the stream [L^2/T]; A and A_s are the stream and storage-zone cross-sectional areas [L^2], respectively. The storage zone area, A_s , is the sum of the hyporheic zone area and the surface water storage zones; q_{LIN} is the lateral inflow rate from the banks per unit stream length [L^2/T]; α is the storage exchange coefficient [T^{-1}]. High values of α represent a higher ability for exchange between storage zones and streamwater. These parameters are estimated by fitting a simulated curve to an experimental breakthrough curve. The entire reach was divided into discrete segments. Equations (1) and (2) were applied to each segment to account for the change in the concentration in the main channel and the storage zones. Equations (1) and (2) were simulated using O-STREAM (Optimization Stream), a finite difference code developed in the Department of Civil and Environmental Engineering at Temple University.

Sodium Chloride (NaCl), a conservative tracer, was injected at a concentration of 54 g/l using a step-pulse method. The tracer was held in four 350 gallon high-density polyethylene tanks and released through a 5 cm manifold that was placed across the stream at the injection point. Prior to injection the tracer was well mixed and circulated throughout the tank to create uniform concentration. The tracer was pumped from the tanks through flexible 4 cm PVC hose to the manifold with a self-priming pump at 1 L/s. The entire injection time lasted 81 minutes. Three sampling station were located at 85m, 185, and 323 m as depicted in Figure 1. Samples were retrieved in pre-washed polyethylene bottles. The samples were analyzed for electrical conductivity, which were then converted to total dissolved solids (TDS). To do this, a calibration curve was developed using laboratory standards that had known TDS concentrations and a *Pinpoint* salinity monitor which had a sensitivity rage from 0.0 –200 mS. After analyzing each sample using this process a breakthrough curve was developed. Figures 2 through 5 show plots of observed data for all stations. O-STREAM was used for parameter estimation. O-STREAM consists of two modules: one module is a Fortran Code that solves equations (1) and (2) and the other is the optimization software GRG2 (Lasdon *et al*, 1978). GRG2 requires the user to provide it with an objective function to minimize. The objective function that we used is:

