

Incomplete mixing in a small, urban stream

Robert J. Ryan, Michel C. Boufadel*

Department of Civil and Environmental Engineering, Temple University, 1947 N 12th Street, Philadelphia, PA, 19122, USA

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Abstract

Conservative solute tracer experiments were conducted in Indian Creek, a small urban stream located in Philadelphia, Pennsylvania, USA. Estimated flow rates were between 46 L s^{-1} and 81 L s^{-1} , average stream width was 5.5 m and average stream depth was 0.2 m. Given these dimensions, most researchers would think it reasonable to assume that the stream is completely mixed vertically and horizontally. However, we found that the stream was not vertically completely mixed in a 1.0 m deep, 30 m long pool. The limited mixing was demonstrated by the vertical stratification of a tracer cloud which was completely mixed both laterally and vertically across the stream prior to entering the pool. We suggest that the cause of limited mixing is due to a balance between groundwater inflow and transverse dispersion at the cross-section. We show that the unsupported assumption of complete mixing may result in a wide range, and thus increased uncertainty, of the values of stream flow and longitudinal dispersion coefficient estimated from these data. We conclude that the assumption of complete mixing and one-dimensional modeling must be checked against actual field conditions, even in small streams.

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1. Introduction

Conservative tracer studies are a common tool used by many researchers to estimate field scale parameters for natural streams. The study consists of injecting a tracer into the stream at a specified location and monitoring its transport downstream. The results of tracer studies have been used to estimate transient storage characteristics, stream flow and dispersion in streams ranging from small first-order headwater streams to large rivers (D'Angelo et al., 1993; Morrice et al., 1997; Verstraeten et al., 1999; Fernald et al., 2001; Johansson et al., 2001; Kasahara and Wondzell, 2003). Test duration may be a few hours or many days, depending on the reach travel time and the duration of the injection. Typical conservative solutes include Br^- and Cl^- salts. Samples are collected at small time intervals and a breakthrough curve is developed for each monitoring station. The breakthrough curves can then be used to estimate dispersion and transient storage

characteristics as well as reach-averaged travel time, velocity, inflow, and cross sectional area using one of several well documented one-dimensional models such as OTIS (Bencala and Walters, 1983; Runkel, 1998), ASP (Wörman et al., 2002), STAMMT-L (Haggerty and Reeves, 2002), and ADZ (Beer and Young, 1983).

A fundamental issue that arises is whether the experimental design adequately addresses the uniqueness of the stream being studied. For example, small streams are often modeled assuming one-dimensional flow characteristics, with little if any confirmatory data. It is also implicitly assumed that once a tracer is completely mixed in a cross-section, it remains so downstream. For example, when a tracer is injected in the middle of the cross-section, it is commonly accepted that beyond a certain length, known as the mixing length (Fischer et al., 1979, p. 114), the tracer remains completely mixed in the cross-section.

In this paper we present results of a tracer test conducted in Indian Creek, a tributary of Cobbs Creek, located in Philadelphia, Pennsylvania. The results show that although the tracer was completely mixed at one location, segregation occurred at a downstream pool.

*Corresponding author. Tel.: +1 215 204 7871; fax: +1 215 204 4696.
E-mail address: boufadel@temple.edu (M.C. Boufadel).

2. Site description

Indian Creek begins as an urban stream in Montgomery County in southeast Pennsylvania, USA. The stream generally flows north to south and crosses into the western edge of the City of Philadelphia, where it is protected as part of the city's Fairmount Park system. The experimental reach is located approximately 480 m downstream of the City boundary, as shown in Fig. 1. The watershed at this location is heavily urbanized, though there is a wide (150–200 m) riparian corridor consisting of deciduous forest on steep valley sides (20–25% slope). The stream slope varied from a low of 0.006 through an approximately 30 m long pool to a high of 0.037 in the lower 74 m of the reach. The upper 246 m of the reach is a riffle/pool system with a stream bed of gravel/cobble substrate and substantial amounts of fine sand and silt were present during this study. The lower 74 m of the reach is a step/pool system and the substrate included a significant amount of large boulders ($d > 1$ m). The wetted channel was typically 5.5 m wide and 0.2 m deep at low flow ($50\text{--}60\text{ L s}^{-1}$). The width varied from 1 to 8.9 m, and the depth varied from 0.05 to 1.0 m.

Four monitoring stations were established as shown in Fig. 2. Station 1 was on the downstream side of a riffle, at $x = 91$ m (the coordinate x represents the alongstream distance from the injection point), where the stream narrowed to approximately 4 m.

Station 2 was located in a deep pool at 25 m downstream of Station 1 (i.e., $x = 116$ m). Station 3 was at $x = 246$ m, and Station 4 was at $x = 320$ m. As indicated in the cross-sections shown in Fig. 3, the stream topology changes from a shallow riffle area near Station 1 to a deep pool area

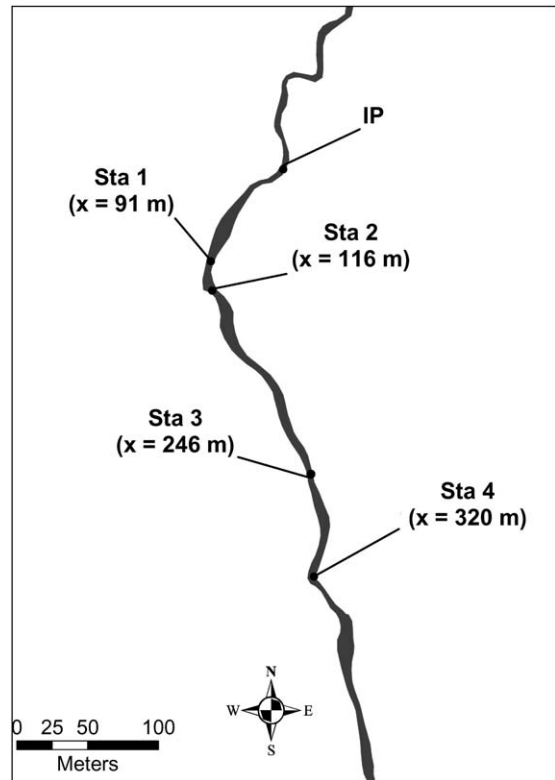


Fig. 2. Location of the monitoring stations within the study reach. X = the alongstream distance from the IP.

when approaching Station 2. Within this pool, the stream bank sloped from the left toward the center of the channel at approximately 6% to a depth of 1.0 m. Station 3 was located at the riffle/pool – step/pool demarcation point. At this point, the stream channel narrowed from approximately 7 m wide with a 2 m wide center gravel bar to approximately 1 m wide with exposed bedrock and large boulders along both banks. Station 4 was located where the stream historically split into two channels. A large flood in early August 2004 deposited significant amounts of sediment on the left side of the main channel, effectively blocking and closing off the left channel.

3. Methods

A stream tracer experiment was conducted in October 2004. Bromide was chosen as the conservative tracer because it does not absorb much to sediments and because its background concentrations were low (typically $< 0.2\text{ mg L}^{-1}$).

Stream flow at the Injection point (IP) was estimated based on velocity measurements obtained using a Global Flow Probe Model F201. A transect was laid out at the IP perpendicular to the direction of flow. The transect was divided into 10 equal intervals, each 0.3 m wide. Stream velocity was measured at the center of each interval, six tenths of the depth below the free surface using the Flow Probe. The volumetric flow rate for each interval was

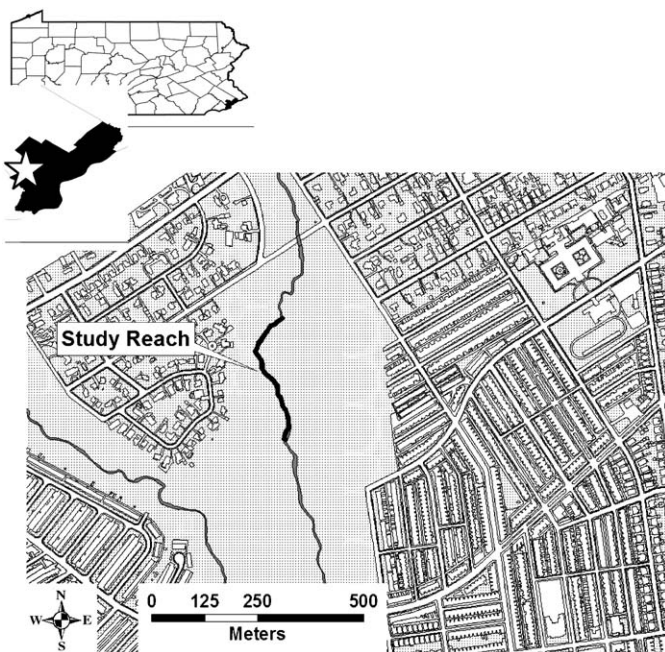


Fig. 1. Location of the study reach within the Indian Creek watershed, Philadelphia, Pennsylvania.

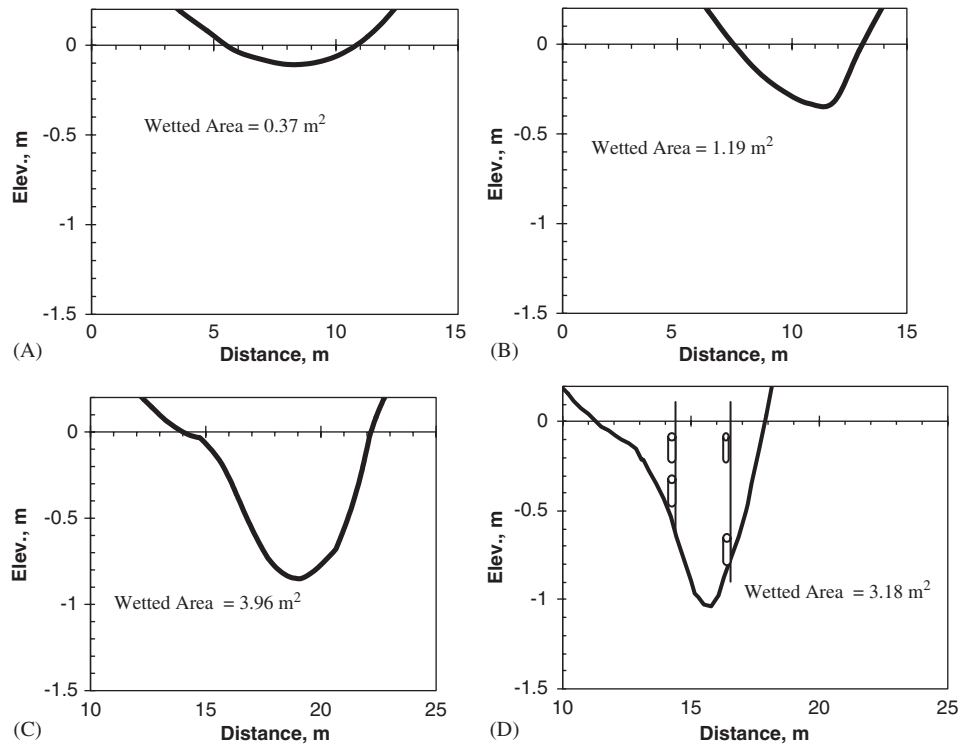


Fig. 3. Cross-sectional views of Indian Creek at: (A) Station 1; (B) 8 m downstream of Station 1; (C) 20 m downstream of Station 1; and (D) Station 2, 25 m downstream of Station 1. The locations of the autosampler intakes are shown in cross-section (D). All views are looking downstream. The water surface is indicated by the zero elevation.

calculated by multiplying the cross-sectional area of each interval (width of the interval times the depth at the midpoint of the interval) by the measured velocity. The total volumetric stream flow at the IP is then equal to the sum of the volumetric flow rates for each interval. The Flow Probe has an estimated error of approximately 10%.

Stream flow at the downstream monitoring stations was estimated using the dilution-tracer technique (Zellweger et al., 1989), assuming that the Br^- concentration of the inflow is equal to the upstream background concentration of Br^- as shown in Eqs (1–5).

At steady state, a mass balance on Br^- and stream flow yields:

$$Q_u C_u + Q_{inj} C_{inj} + Q_g C_g = Q_{sta} C_{sta} \quad (1)$$

and

$$Q_u + Q_{inj} + Q_g = Q_{sta}, \quad (2)$$

where Q is volumetric flow rate (L s^{-1}), C is the Br^- concentration (mg L^{-1}), u denotes upstream of the injection point, inj denotes injectate, g denotes net groundwater (or other) inflow, and sta denotes the downstream monitoring station.

If we assume that $C_u = C_g$ (and rename the value C_b) and also define $Q_b = Q_u + Q_g$, Eqs. (1 and 2) reduce to

$$Q_b C_b + Q_{inj} C_{inj} = Q_{sta} C_{sta} \quad (3)$$

and

$$Q_b + Q_{inj} = Q_{sta}. \quad (4)$$

Combining Eqs. (3 and 4) and rearranging yields

$$Q_{sta} = Q_{inj} + \frac{Q_{inj}(C_{inj} - C_{sta})}{C_{sta} - C_b}. \quad (5)$$

Thus, the flow at any monitoring station can be estimated from the measured injectate, background and station plateau Br^- concentrations, and the known injectate flow rate.

The stream flow measured at the IP was used to determine the total mass of sodium bromide (NaBr) needed to increase the instream concentration by two orders of magnitude from the background level which was typically less than 0.2 mg L^{-1} . Tracer injectate was created by slowly adding NaBr to a 1200 L tank as it was filled with stream water using a Burkes 1/3 hp centrifugal pump (model 3WPT3A) powered by a Coleman Maxa 3000 generator. The injectate solution was mixed by placing both the pump suction and the pump discharge in the injectate tank and running the pump for several minutes until the NaBr was completely dissolved. The pump was shut down and the discharge end of the pump was then connected to a 3 m long perforated PVC manifold which was placed across the stream approximately 25 cm above the water surface. The use of the manifold allowed for a more even distribution of injectate across the width of the

stream. The pump used in these experiments has a very high rated capacity ($>150 \text{ L min}^{-1}$). In order to limit the actual injection flow rate to the stream, it was necessary to utilize a by-pass (or a recycle line) which directed a portion of the injectate back to the suction side of the pump.

The injectate ($4433 \text{ mg L}^{-1} \text{ Br}^{-}$) was added to the stream at a constant rate of about 0.18 L s^{-1} for 106 min. The flow rate was checked using a King Instruments floating ball-type flow meter attached to the pump discharge. The exact volume of injectate was determined by multiplying the measured injection flow rate times the measured injection time period.

Stream water samples were collected either by hand or by the aid of autosamplers. Manual sampling was conducted by dipping 120 mL polypropylene bottles that had been triple rinsed in the stream prior to collecting the sample. Four autosamplers (ISCO Model 3700) were used. The samples were obtained by pumping a volume of 150 mL at a rate of 58.3 mL s^{-1} at times programmed in the autosamplers. The intake of the autosampler consists of a 12.5 cm long \times 3 cm diameter polypropylene cylinder with 20 perforations each 0.9 cm in diameter evenly distributed over the surface of the cylinder.

During a preliminary experiment conducted in August 2004, the extent of transverse mixing between the injection point and Station 1 was assessed. Measurements at Station 1 were obtained at the center of the channel and at 0.5 m from the center on both sides. Sampling at the center was conducted using the autosampler, whose sampling interval was set at 6.0 min. Samples at the sides were obtained by hand.

During the October 2004 experiment, the samples at Stations 1, 3, and 4 were obtained by hand from the center of the cross-sections. The sampling interval was 3 min. Those at Station 2 were obtained by four autosamplers, whose sampling interval was 6 min. The intakes of the autosamplers were arranged in a vertical grid as depicted in the cross-section for Station 2 shown in Fig. 3. Two intakes were situated at 3.0 m from the left bank where the water depth was 50 cm. They were placed vertically in the water column and centered at the depths of approximately 15 and 40 cm. The remaining two intakes were placed vertically in the water column at 5.5 m from the left bank and centered at the depths of approximately 15 and 90 cm. The total depth there was about 100 cm. The intakes are labeled TL (Top Left), BL (Bottom Left), TR (Top Right), and BR (Bottom Right). The placement of the intakes was done as follows. Two iron rods having a diameter of 1.25 cm were pounded into the streambed at 3.0 and 5.5 m from the left bank, and a 1.9 cm (5/8 inch) PVC tube was placed over each of them. The intakes were attached to the PVC tubes using cable ties.

Samples were analyzed using an Orion Ionanalyzer Model 407A with an Orion bromide specific electrode and an Orion single junction reference electrode. One out of every 10 samples was run in duplicate. This analytical method yielded a standard deviation of 5.3% of the reading.

4. Results

In August 2004, the width-to-depth ratio of Indian Creek decreased from 106 at $x = 84 \text{ m}$ to 49 at Station 1 ($x = 91 \text{ m}$) with no change in average stream depth between the two locations (7 cm). The maximum depth at Station 1 was just 15 cm. The streamflow at Station 1 was estimated to be 43.6 L s^{-1} .

The measured concentration values for Station 1 in August 2004 are reported in Fig. 4. Both the left and right edge of stream were sampled at 13:02 (at the peak concentration) and again at 13:52 (during the falling limb). At the peak, the right-hand side measured slightly higher (0.4 mg L^{-1}) than the left and center while during the falling limb, the left and right sides measured slightly higher (0.3 mg L^{-1}) than the center. The range in observed values across the stream is less than the estimated analytical uncertainty of our measurements ($\sim 0.6 \text{ mg L}^{-1}$).

In October 2004, the average depth at Station 1 was 11 cm and the maximum depth was 19 cm. The width-to-depth ratio decreased by 25% (from 56 to 42) within the 6 m section immediately upstream of Station 1. While not as dramatic as the reduction observed in August 2004, it is still significant since the average stream depth increased by just 1 cm (10–11 cm) within this section.

Fig. 5 shows the breakthrough curves for Stations 1 and 2 obtained from the stream tracer experiment of October 2004. The standard deviation of the plateau concentrations at Stations 1 and 2 varied from 0.16 to 0.38 mg L^{-1} . This is smaller than the standard deviation of the analytical method (5.3% of the reading or approximately $0.6\text{--}0.7 \text{ mg L}^{-1}$ at the observed plateau concentrations). Therefore, we used the standard deviation of our analytical method to analyze the plateau concentrations at each station. The plateau Br^{-} concentration at Station 1 averaged 13.6 mg L^{-1} . This was significantly higher than the mean observed plateau concentration at Station 2-TR (z -test, $p = 0.1$), 2-BR (z -test, $p < 0.0001$), 2-TL (z -test, $p = 0.02$) and 2-BL (z -test, $p = 0.008$). Fig. 6 shows the Station 2 breakthrough curves in more detail. There was no statistically significant difference in the plateau concentrations at Station 2-BL (13.1 mg L^{-1}), 2-TL (13.0 mg L^{-1}),

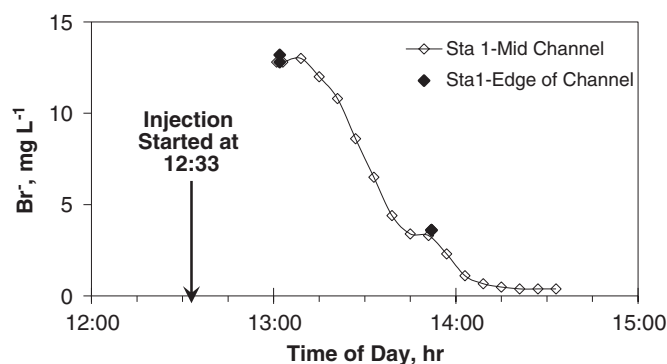


Fig. 4. The measured breakthrough curve for Station 1 for the August 2004 experiment.

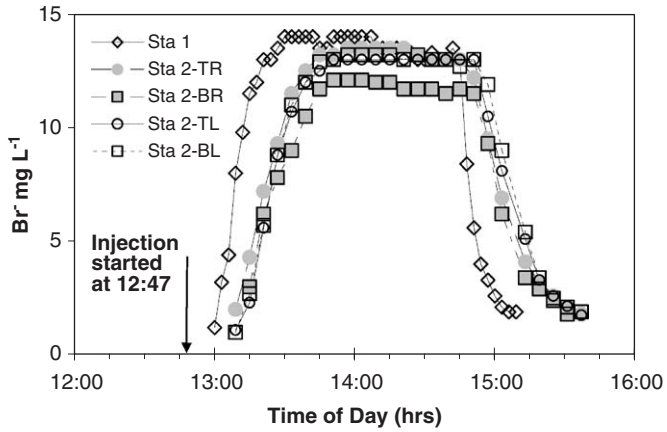


Fig. 5. The measured breakthrough curves for Stations 1 and 2 for the October 2004 experiment.

and 2-TR (13.3 mg L^{-1}). The plateau concentration at Station 2-BR (11.8 mg L^{-1}) was significantly lower than the observed plateau concentrations at the other points within the pool ($p < 0.001$).

4.1. Discharge

The measured stream flow at the IP in October 2004 was 57.8 L s^{-1} . The velocity across the stream at the IP varied from 0 to 0.32 m s^{-1} with an average of 0.18 m s^{-1} . Using the measured streamflow, background Br^- concentration, injectate flow rate and injectate concentration, the complete-mix in-stream Br^- concentration just downstream of the IP was estimated to be 13.9 mg L^{-1} . Table 1 shows the flow and velocity estimates for the study reach. The estimated flow at Station 1 was 57.6 L s^{-1} . This was essentially identical to the flow measured at the IP (57.8 L s^{-1}). Thus, there was essentially no groundwater inflow between the IP and Station 1. Cross-section average velocity slowed by a factor of 5 from Station 1 (0.1 m s^{-1}) to Station 2 (0.02 m s^{-1}) yielding a reach average velocity of 0.03 m s^{-1} .

The decrease in plateau concentrations from Station 1 to Station 2 (Fig. 5) indicates that streamflow increased from Station 1 to Station 2, regardless of which breakthrough curve data set is used. The flow rate at Station 2, computed based on the breakthrough curves, varied from 59.7 L s^{-1} (Station 2-TR, near the surface) to 66.6 L s^{-1} (Station 2-BR, near the streambed) (Table 1). The average of the estimated flow rates at Station 2 was 62.6 L s^{-1} .

4.2. Longitudinal dispersion

The one-dimensional (along the stream) convection–dispersion equation (Fischer et al., 1979, p. 51) is commonly

Table 1
Estimated stream flow and velocity for October 2004 experiment

Station	Stream flow ($\text{m}^3 \text{ s}^{-1}$)	Cross section average velocity (m s^{-1})	Reach average stream velocity (m s^{-1})
1	57.6	0.10	
1 + 8 m		0.05	
1 + 20 m		0.02	
2-BL	61.0		
2-TL	66.6		
2-BR	62.0		
2-TR	59.7		
Ave. of Station 2 estimates	62.4	0.02	0.03
3	76.8	0.49	0.06
4	80.6		0.08

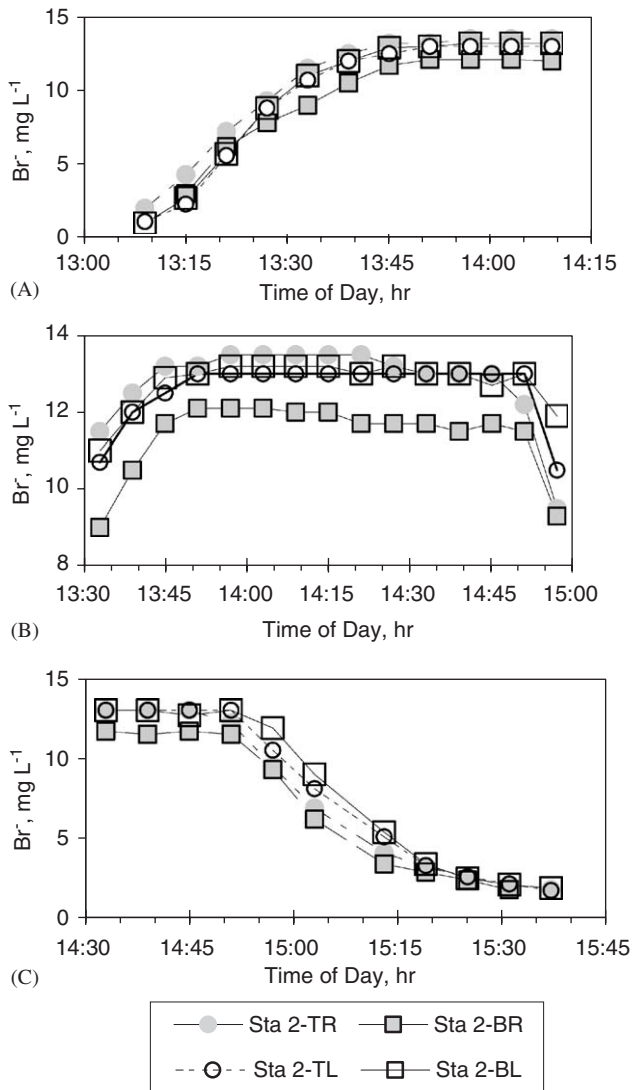


Fig. 6. An expanded view of the (A) rising limb, (B) plateau and (C) falling limb of the October 2004 tracer experiment at Station 2. Note the change in both the x- and y-scales.

used to describe solute transport in streams

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = D \frac{\partial^2 C}{\partial x^2}, \quad (6)$$

where C is the instream concentration (mg L^{-1}), t is time (s), u is the cross-section averaged longitudinal velocity (m s^{-1}), x is distance (m), and D is longitudinal dispersion ($\text{m}^2 \text{s}^{-1}$). The water velocity and the dispersion coefficient are uniform in space. The solution of Eq. (6) for a continuous input causing an initial concentration in the stream of C_0 is

$$C(x, t) = \frac{C_0}{2} \left[\operatorname{erfc} \left(\frac{x - ut}{\sqrt{4Dt}} \right) + \operatorname{erfc} \left(\frac{x + ut}{\sqrt{4Dt}} \right) \exp \left(\frac{ux}{D} \right) \right], \quad (7)$$

where $\operatorname{erfc}()$ indicates the complementary error function (Fischer et al., 1979, p. 51). If the analysis occurs at large values of time and/or distance, the second term within the parenthetical on the right-hand side of Eq. (7) has very little impact on the overall solution, and can be safely ignored. This leads to the following:

$$C(x, t) = \frac{C_0}{2} \left[\operatorname{erfc} \left(\frac{x - ut}{\sqrt{4Dt}} \right) \right]. \quad (8)$$

There are many methods for estimating D . A simple method that applies for an injection of finite time period is to utilize the slope of the rising limb of the breakthrough curve, assuming that these data are normally distributed. Then, by defining the “width” of the dispersion zone at each monitoring station by the 16th and 84th percentile of the plateau concentration (i.e. 2σ from the mean) D can be calculated as shown in Eqs. (9a and 9b).

$$D = (u\Delta t)^2 / (8t_{50}), \quad (9a)$$

where

$$\Delta t = t_{84} - t_{16} \quad (9b)$$

and t_s ($s = 16, 50, \text{ or } 84$) is the time to reach “ s ” percent of the plateau concentration.

Table 2 shows the estimated values of D based on the data from the October 2004 experiment. The dispersion

Table 2
Estimated dispersion coefficients based on the October 2004 experiment

Downstream station	Distance from injection point (m)	D ($\text{m}^2 \text{s}^{-1}$)
Sta.1	91	0.419
Sta. 2-TR	116	0.415
Sta. 2-BR	116	0.522
Sta. 2-TL	116	0.266
Sta. 2-BL	116	0.266
Ave. of Sta. 2 estimates	116	0.367
Sta. 2 Ave. BTC ^a	116	0.318
Sta. 3	246	0.339
4	320	0.358

^aThe average of the breakthrough curves at Station 2 (Fig. 7) was used to compute D .

coefficient is large in the upper 91 m of the reach, but decreases to reach a constant value as the scale increases. As expected, Station 2 gave multiple values of D . Stations 2-TL and BL gave the same value. The stations on the right gave considerably higher values, about double those on the left side.

5. Discussion

Station 1 was located 91 m downstream of the injection site. This distance is approximately 30 m longer than the maximum estimated mixing length using data from the October 2004 experiment and Eq. (10) (Harvey and Wagner, 2000).

$$L = \beta(uW^2/D), \quad (10)$$

where L is mixing length (m), u is reach average velocity (m s^{-1}), W is average stream width (m), D is dispersion coefficient ($\text{m}^2 \text{s}^{-1}$) and β is an adjustment factor whose value is between 1 and 10.

The assumption of complete mixing in the lateral direction is further supported by the reduction in width-to-depth ratio just upstream of Station 1 and the results of previous experiments. The assumption of complete mixing in the vertical direction is supported by the fact that Station 1 is located at the downstream side of a riffle and the stream averaged just 11 cm (19 cm maximum depth) in October 2004.

The presence of plateaus in the breakthrough curves of Station 2 for about an hour indicates that a local equilibrium had been achieved at these locations. This also indicates that even if the duration of the injection increases the cross-section at Station 2 would not be completely mixed. Thus the laterally and vertically, completely mixed tracer cloud which entered the pool has become vertically segregated. We attribute this vertical segregation of flow to groundwater inflow to Station 2.

A mass balance at any point at Station 2 involves the inflowing mass flow rate, the outflowing mass flow rate, transverse mixing, and groundwater flow. Prior to achieving a plateau in the solute concentration, the inflowing solute concentration will be reduced due to transverse and vertical mixing of the high concentration inflow with low concentration water already in the pool. However, the reduction in width-to-depth ratio between Station 1 and Station 2 (from 42 to 11) is primarily a function of increased depth which would hamper vertical mixing. This is evident in the approximately 6 minute lag observed in the time to reach plateau concentration at 2-TR compared to 2-BR. However, if mixing were the primary factor controlling the observed solute concentration in the bottom of the pool, this concentration should have reached a plateau equal to the surface concentration, albeit at a later time. Finally, both the surface and bottom of the pool should have reached a plateau concentration equal to the concentration observed at Station 1, the only inflow to the pool in the absence of groundwater inflow. Instead, we see

that both the plateau concentration at the surface and at the bottom of the pool are significantly lower than that observed at Station 1, indicating that groundwater with little if any bromide is entering the pool. Since the bottom of the pool had a significantly lower bromide concentration than the surface of the pool, it is logical to assume that the groundwater inflow location is near the bottom of the pool.

In other words, once the solute cloud has sampled as much of the pool as transverse and vertical mixing will allow, steady state will be achieved and a plateau concentration will be observed. At this point, the mass flow rate into the pool must equal the mass flow rate out of the pool. Thus, in the absence of groundwater inflow, the plateau concentration must equal the solute concentration of the surface water entering the pool. In Indian Creek, we observed an inflow concentration of 13.6 mg L^{-1} and plateau concentrations of just $11.8\text{--}13.3 \text{ mg L}^{-1}$ indicating that stream flow increased by approximately 2 to 15% between Station 1 and Station 2.

The plateau concentrations at Station 2-TR, TL and BL are not significantly different from each other indicating that the stream is laterally completely mixed at Station 2. This result is not surprising since the stream was laterally completely mixed at Station 1 and the cross-section average velocity decreased by a factor of 5 between Stations 1 and 2 (Table 1). Additionally, the width-to-depth ratio decreased from 42 at Station 1 to 11 at Station 2. Both the reduction in cross-section average velocity and width-to-depth ratio would reduce the mixing effect caused by transverse velocity shear. However, the solute concentrations at Station 2-TL and BL are consistently less than the concentration at 2-TR during the rising limb of the experiment (Fig. 6A) and consistently greater than the concentration at 2-TR during the falling limb of the experiment (Fig. 6B). This slight transverse parabolic shape is consistent with the effects of a small velocity shear in which friction reduces the stream velocity (and thus delays the arrival and departure of a solute tracer) near the bank (Rutherford, 1994). This lower velocity will result in less variation in the velocity and thus less mixing and dispersion near the bank compared to the center of the channel. Thus, Station 2-TR had a 56% higher estimated dispersion coefficient than Stations 2-TL or BL.

Analysis of this tracer cloud indicates that both inflow and transverse mixing play important roles in solute transport in Indian Creek. The reduced plateau concentrations at Station 2 compared to Station 1 are positive proof that inflow with little if any bromide is entering the stream within the pool. Since inflow would enter the stream from the streambed and banks, the inflow-induced transverse velocity vectors, in combination with the topology-induced transverse velocity vectors, would act to reduce transverse mixing by “pushing” the tracer cloud away from the stream bottom (Station 2-BR) and left stream bank (Stations 2-TL and 2-BL).

Most studies in small streams are conducted assuming a completely mixed stream both laterally and vertically. It

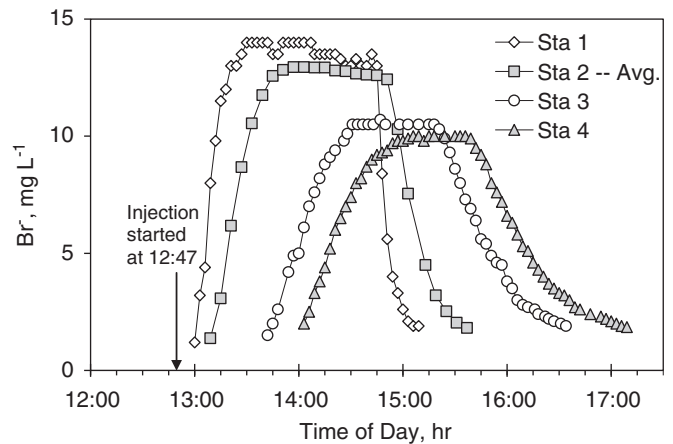


Fig. 7. The measured (Stations 1, 3 and 4) and ‘average’ (Station 2) breakthrough curves for the October 2004 experiment.

would be helpful to quantify the impact of this assumption when it is not valid. The dispersion estimates calculated for the upper 116 m of the reach (from the IP to Station 2) range from $0.266 \text{ m}^2 \text{ s}^{-1}$ (2-TL, 2-BL) to $0.52 \text{ m}^2 \text{ s}^{-1}$ (2-BR). The average value was found to be $0.367 \text{ m}^2 \text{ s}^{-1}$. However in most studies, one breakthrough curve is assumed to represent the cross-section and a dispersion coefficient is obtained based on it. For this reason, we evaluated the dispersion coefficient using an average breakthrough of the four breakthrough curves at Station 2 (Fig. 7). The resulting value of D ($0.316 \text{ m}^2 \text{ s}^{-1}$) is close to the average value of the dispersion coefficients computed for the four breakthrough curves. This agreement might explain the success of the one-dimensional convection dispersion equation in describing cross-section-average transport in streams.

The dispersion coefficient decreased when the length of the subreach under consideration increased. This is a somewhat surprising result. However, the first subreach had large pools in it in comparison with the subreaches further downstream. The presence of pools would increase the apparent dispersion when the convection–dispersion equation without dead zones was used as done herein (Eqs. (6)–(9)). This issue was addressed by (Nordin and Troutman, 1980, Eqs. (23) and (24)). It is thus possible that as the scale increased, the “signature” of the dead zones on the downstream breakthrough curves decreased causing the dispersion coefficient to decrease to a constant value (about $0.34 \text{ m}^2 \text{ s}^{-1}$, Table 2). Another way to look at this issue is by comparing to the theory of turbulent diffusion. Taylor (see Fischer et al., 1979, p. 67) demonstrated that a tracer plume in a turbulent regime spreads rapidly at short times; the rate is proportional to the square of time. The spreading rate decreases to become proportional to time at large times. The high spreading rate is due to the fact that the tracer plume has not “sampled” thoroughly the space. Because the mathematics of spreading by turbulent diffusion and shear dispersion are similar, one could envisage that the tracer plume in this study did not

sufficiently sample the first subreach due to the presence of large pools and dead zones. As the stream becomes steeper and the pools smaller downstream, the tracer plume becomes more mixed, resulting in a dispersion coefficient that is less than the value in the first subreach, but essentially constant.

6. Conclusions

Tracer studies and other field work are often undertaken assuming, without supporting documentation, that the stream is completely mixed in the vertical and lateral direction. We demonstrated that this assumption can be erroneous, even in a small urban stream such as Indian Creek located in Philadelphia, Pennsylvania. We conducted tracer studies and observed vertical flow stratification in a pool. We attributed this to groundwater inflow based on an analysis of breakthrough curves obtained from samples collected near the surface and near the bed of the stream. No significant transverse variation was observed in the plateau concentration of breakthrough curves obtained from samples collected on the left-hand and right-hand side of the channel. However, a slight lag in the rising and falling limb concentrations on the left-hand side compared to the right-hand side indicated that transverse velocity shear slowed the solute tracer cloud along the shallower left-hand side of the channel in relation to the deeper right side. The dispersion estimates for the reach from the IP to Station 2 varied by a factor of 2, depending on which breakthrough curve was used. Dispersion appeared to decrease in the downstream direction, possibly due to the fading “signature” of pools which may not have been completely sampled by the solute tracer cloud.

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