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Incomplete mixing in a small, urban stream

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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.

Keywords: Dispersion; Stream flow; Solute transport; Conservative tracer

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.

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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 (50–60 $L\,s^{-1}$). 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 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.

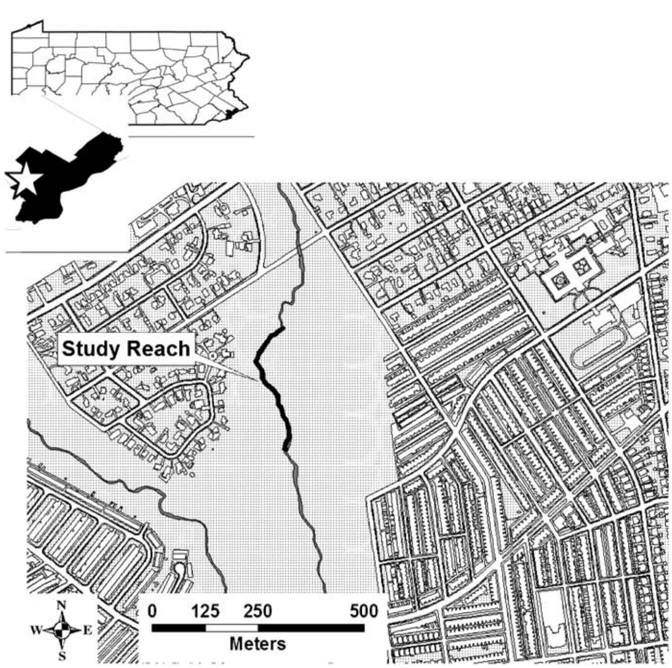

Fig. 1. Location of the study reach within the Indian Creek watershed, Philadelphia, Pennsylvania.

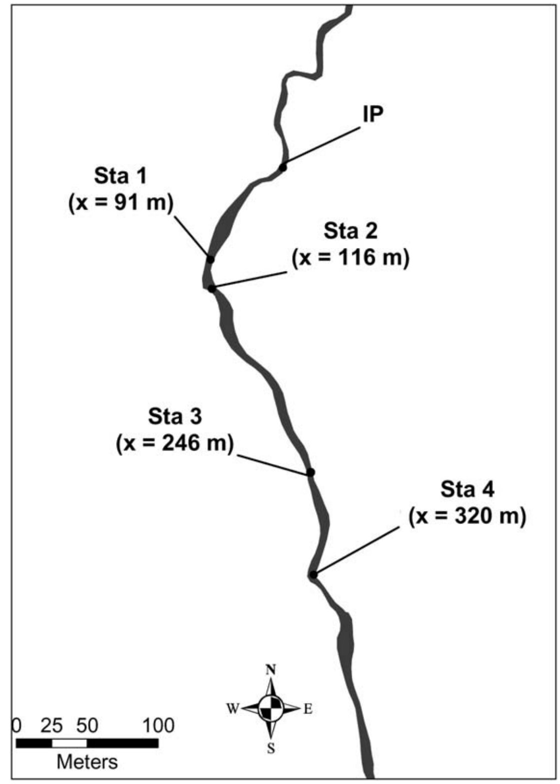

Fig. 2. Location of the monitoring stations within the study reach. X = the alongstream distance from the IP.

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 $< 0.2\,mg\,L^{-1}$).

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